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FOREWORD

The **main practical result** of the current stage of works in the field of Artificial intelligence is not only the creation of the next-generation intelligent computer systems ensuring effective interaction in solving comprehensive problems, but also the creation of a technological complex that ensures the rapid and high-quality building of such systems. This collection of scientific papers "Open semantic technology for intelligent systems design" is dedicated to these issues.

The development of this technological complex requires solving the following problems:

- clear identification of the logical-semantic level of intelligent computer systems, which abstracts from all possible options for the technical implementation of these systems (including the use of fundamentally new computers focused on their hardware support);
- development of an ontology for the design of intelligent computer systems and unification of the description of their logical-semantic models;
- ensuring the platform-independent character of the logical design of intelligent computer systems, the result of which is a unified description of the logical-semantic models of the designed systems;
- use of the methodology for component design of intelligent computer systems, which is based on a constantly replenished library of reusable components of these systems (reusable subsystems, knowledge base components, knowledge processing agents, user interface components);
- ensuring semantic compatibility of reusable components of intelligent computer systems and semantic compatibility of these systems themselves, as well as technologies for their design and support of subsequent stages of their life cycle.

The **main topic** of the collection of scientific papers "Open semantic technology for intelligent systems design" is various aspects of convergence and integration that ensure the transition to intelligent computer systems of a new generation and the corresponding technology of integrated support of their life cycle:

- convergence and integration of various models for information representation and processing in intelligent computer systems of a new generation:
 - convergence and integration of various knowledge types in the knowledge bases of intelligent computer systems of a new generation;
 - convergence and integration of various problem-solving models in intelligent computer systems of a new generation;
 - convergence and integration of various types of interfaces for intelligent computer systems of a new generation;
- convergence and integration of various directions of Artificial intelligence in order to build a general formal theory of intelligent computer systems of a new generation;
- convergence and integration of design technologies for various components of intelligent computer systems of a new generation in order to build a comprehensive technology for designing intelligent computer systems of a new generation;
- convergence and integration of technologies to support various stages of the life cycle for intelligent computer systems of a new generation in order to build a technology for integrated support of all stages of the life cycle for intelligent computer systems of a new generation;
- convergence and integration of various types of human activities in the field of Artificial intelligence (research activities, development of technological complex, applied engineering, educational activities) to increase the level of coherence and coordination of these activities, as well as to increase the level of their complex automation with the help of semantically compatible intelligent computer systems of a new generation;
- convergence and integration of various types and fields of human activities, as well as means of complex automation of this activity with the help of intelligent computer systems of a new generation.

The **main directions** of the collection of scientific papers «Open semantic technology for intelligent systems design»:

- Requirements for intelligent computer systems of a new generation;
- Principles underlying intelligent computer systems of a new generation;

- Requirements for the semantic representation of information. The universal language of the semantic representation of knowledge;
- Ontological stratification of the semantic representation of knowledge bases in intelligent computer systems of a new generation;
- An agent-oriented hierarchical model of hybrid problem solvers based on the semantic representation of knowledge bases;
- An ontological model of multimodal interfaces for intelligent computer systems of a new generation;
- A model of understanding information coming from outside, based on the semantic representation of knowledge bases;
- Flexibility, stratification, reflexivity, and learnability of intelligent computer systems of a new generation;
- Unification, standardization, and semantic compatibility of intelligent computer systems of a new generation consistency of concepts and terms;
- Interoperability (the ability to interact effectively) of intelligent computer systems of a new generation the ability to understand each other, negotiate, and coordinate their actions in the collective solution of complex problems;
- An integrated technology for designing intelligent computer systems of a new generation;
- Platforms for the implementation of intelligent computer systems of a new generation. Software platforms and associative semantic computers focused on the implementation of intelligent computer systems of a new generation;
- Convergence of logical-semantic models of intelligent computer systems of a new generation and architectures of associative semantic computers providing interpretation of these models. Wave programming languages;
- Principles underlying the Technology of integrated support of the life cycle for intelligent computer systems of a new generation;
- A global Ecosystem of intelligent computer systems of a new generation, providing complex convergence and automation of all kinds of human activities.

The collection contains 49 articles. The editorial board of the collection thanks all the authors who submitted their articles. For publication, scientific experts selected the best of the submitted papers, many of them were revised in accordance with the comments of the reviewers.

We also thank the experts for their great work in reviewing articles in close cooperation with the authors, which allowed increasing the level of presentation of scientific results and also created a platform for further scientific discussions.

We hope that, as before, the collection will fulfill its main function — to promote active cooperation between business, science, and education in the field of Artificial intelligence.

Editor-in-chief Golenkov Vladimir

ПРЕДИСЛОВИЕ

Основным **практическим результатом** текущего этапа работ в области Искусственного интеллекта является создание не только интеллектуальных компьютерных систем следующего поколения, обеспечивающих эффективное взаимодействие при решении комплексных задач, но и создание технологического комплекса, обеспечивающего быстрое и качественное построение таких систем. Этим вопросам посвящён, данный сборник научных трудов «Открытые семантические технологии проектирования интеллектуальных систем».

Разработка указанного технологического комплекса требует решения следующих задач:

- чёткого выделения логико-семантического уровня интеллектуальных компьютерных систем, который абстрагируется от всевозможных вариантов технической реализации этих систем (в том числе и от использования принципиально новых компьютеров, ориентированных на их аппаратную поддержку);
- разработки онтологии проектирования интеллектуальных компьютерных систем и унификации описания их логико-семантических моделей;
- обеспечения платформенно независимого характера логического проектирования интеллектуальных компьютерных систем, результатом которого является унифицированное описание логико-семантических моделей проектируемых систем;
- использования методики компонентного проектирования интеллектуальных компьютерных систем, в основе которой лежит постоянно пополняемая библиотека многократно используемых компонентов этих систем (многократно используемых подсистем, компонентов баз знаний, агентов обработки знаний, компонентов пользовательских интерфейсов);
- обеспечения семантической совместимости многократно используемых компонентов интеллектуальных компьютерных систем и семантической совместимости самих этих систем, а также технологий их проектирования и поддержки последующих этапов их жизненного цикла.

Основная тема сборника научных трудов «Открытые семантические технологии проектирования интеллектуальных систем» — различные аспекты конвергенции и интеграции, обеспечивающие переход к интеллектуальным компьютерным системам нового поколения и соответствующей технологии комплексной поддержки их жизненного цикла:

- конвергенция и интеграция различных моделей представления и обработки информации в интеллектуальных компьютерных системах нового поколения:
 - конвергенция и интеграция различных видов знаний в базах знаний интеллектуальных компьютерных систем нового поколения;
 - конвергенция и интеграция различных моделей решения задач в интеллектуальных компьютерных системах нового поколения;
 - конвергенция и интеграция различных видов интерфейсов интеллектуальных компьютерных систем нового поколения;
- конвергенция и интеграция различных направлений Искусственного интеллекта в целях построения общей формальной теории интеллектуальных компьютерных систем нового поколения;
- конвергенция и интеграция технологий проектирования различных компонентов интеллектуальных компьютерных систем нового поколения в целях построения комплексной технологии проектирования интеллектуальных компьютерных систем нового поколения;
- конвергенция и интеграция технологий поддержки различных этапов жизненного цикла интеллектуальных компьютерных систем нового поколения в целях построения технологии комплексной поддержки всех этапов жизненного цикла интеллектуальных компьютерных систем нового поколения;
- конвергенция и интеграция различных видов человеческой деятельности в области Искусственного интеллекта (научно-исследовательской деятельности, развития технологического комплекса, прикладной инженерии, образовательной деятельности) для повышения уровня согласованности и координации этих видов деятельности, а также для

повышения уровня их комплексной автоматизации с помощью семантически совместимых интеллектуальных компьютерных систем нового поколения

 конвергенция и интеграция самых различных видов и областей человеческой деятельности, а также средств комплексной автоматизации этой деятельности с помощью интеллектуальных компьютерных систем нового поколения.

Основные **направления** сборника научных трудов «Открытые семантические технологии проектирования интеллектуальных систем»:

- Требования, предъявляемые к интеллектуальным компьютерным системам нового поколения;
- Принципы, лежащие в основе интеллектуальных компьютерных систем нового поколения;
- Требования, предъявляемые к смысловому представлению информации. Универсальный язык смыслового представления знаний;
- Онтологическая стратификация смыслового представления баз знаний в интеллектуальных компьютерных системах нового поколения;
- Агентно-ориентированная иерархическая модель гибридных решателей задач, основанных на смысловом представлении баз знаний;
- Онтологическая модель мультимодальных интерфейсов интеллектуальных компьютерных систем нового поколения;
- Модель понимания информации, поступающей извне, основанная на смысловом представлении баз знаний;
- Гибкость, стратифицированность, рефлексивность и обучаемость интеллектуальных компьютерных систем нового поколения;
- Унификация, стандартизация и семантическая совместимость интеллектуальных компьютерных систем нового поколения согласованность понятий и терминов;
- Интероперабельность (способность к эффективному взаимодействию) интеллектуальных компьютерных систем нового поколения — способность к взаимопониманию, договороспособность, способность к координации своих действий при коллективном решении комплексных задач;
- Комплексная технология проектирования интеллектуальных компьютерных систем нового поколения;
- Платформы реализации интеллектуальных компьютерных систем нового поколения. Программные платформы и ассоциативные семантические компьютеры, ориентированные на реализацию интеллектуальных компьютерных систем нового поколения;
- Конвергенция логико-семантических моделей интеллектуальных компьютерных систем нового поколения и архитектур ассоциативных семантических компьютеров, обеспечивающих интерпретацию указанных моделей. Волновые языки микропрограммирования;
- Принципы, лежащие в основе Технологии комплексной поддержки жизненного цикла интеллектуальных компьютерных систем нового поколения;
- Глобальная Экосистема интеллектуальных компьютерных систем нового поколения, обеспечивающая комплексную конвергенцию и автоматизацию всевозможных видов человеческой деятельности.

Сборник содержит 49 статьи. Редакция сборника благодарит всех авторов, представивших свои статьи. Для публикации научными экспертами были отобраны лучшие из представленных работ, многие из них были переработаны в соответствии с замечаниями рецензентов.

Мы также благодарим экспертов за большой труд по рецензированию статей в тесном взаимодействии с авторами, который позволил повысить уровень изложения научных результатов, а также создал платформу для дальнейших научных дискуссий.

Надеемся, что, как и прежде, сборник будет выполнять свою основную функцию — способствовать активному сотрудничеству между бизнесом, наукой и образованием в области искусственного интеллекта.

Главный редактор

Голенков Владимир Васильевич

On Some Ontological Issues of Intelligent Systems Development in Control, Mechanics and Mechanical Engineering

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Abstract—The paper is devoted to the topic of development of artificial intelligence (AI) technologies. The connection of artificial neural networks (ANN) and corresponding ontologies, creation of reliable local language models are considered. An applied definition of AI as a problem statement rather than a set of specific technologies is proposed. Relevant AI technologies are considered in comparison with mathematical modeling using the examples of a number of critical purpose technical systems. Some risks and prospects associated with the development of AI are discussed.

Keywords—artificial intelligence, artificial neural networks, ChatGPT, ontology

I. Introduction

It is written in an open letter "Pause Giant AI Experiments: An Open Letter. We call on all AI labs to immediately pause for at least 6 months the training of AI systems more powerful than GPT-4." on the Future of Life Institute website on March 22, 2023:

- "AI systems with human-competitive intelligence can pose profound risks to society and humanity";
- "we must ask ourselves: Should we let machines flood our information channels with propaganda and untruth? Should we automate away all the jobs, including the fulfilling ones? Should we develop nonhuman minds that might eventually outnumber, outsmart, obsolete and replace us? Should we risk loss of control of our civilization?"

E. Musk at the AI Safety Summit (November 1-2, 2023, UK) said in particular:

- "AI systems with human-competitive intelligence can pose profound risks to society and humanity";
- "we must ask ourselves: Should we let machines flood our information channels with propaganda and untruth? Should we automate away all the jobs, including the fulfilling ones? Should we develop nonhuman minds that might eventually outnumber, outsmart, obsolete and replace us? Should we risk loss of control of our civilization?"

- "We have for the first time the situation where we have something that is going to be far smarter than the smartest human."
- "It's not clear to me if we can control such a thing, but I think we can aspire to guide it in a direction that's beneficial to humanity."
- "But I do think it's one of the existential risks that we face and it is potentially the most pressing one if you look at the timescale and rate of advancement."

These are quotes from experts deeply immersed in the field of AI, not about the possibilities and prospects of AI, but about AI being more of an "existential threat", a "danger to society and humanity". And yet, a threat to what specific part of humanity is actually meant?

Most of these concerns have been about large language models, so let's consider one seemingly innocuous language example next.

II. On the task of constructing an absolute structure – ontology

In the sixties of the twentieth century, during the socalled linguistic turn in philosophy, the task of searching for the original structure of language, meta-language, in order to better understand, improve, universalize, and improve communication arose. The solution to this problem was sought through research in structural linguistics and semiology [1], [2]. Achievements in these fields could partly contribute to the development of modern programming languages at that time, and vice versa, the emergence of such languages confirmed the fundamental possibility of finding a meta-language. At that moment of rapid development of these fields of knowledge it seemed that just a little more and the goal would be reached. Only a couple of nuances remained to be solved: figure out the case of the pipe, for example (see Fig. 1)

It would seem that everything is clear: a smoking pipe is a pipe. However, what do we see in Fig. 1? A pipe? No – physically it does not exist. Maybe its image? It seems so, but what about the inscription that says it is not a tube? Could it be that the inscription indicates that it is an image of a pipe and not a real pipe? But on the other hand this image of a pipe and the inscription beneath it are one and the same – Rene Magritte's painting "The Treachery of Images". But is it the painting of the pipe as a physical object – the signified, the pipe as an image – the signifier, the inscription that negates the signified or the signified?

To deal with this issue, the famous French philosopher Michel Foucault wrote a whole essay "This is not a pipe", where he considered these and many other issues related to the relationship between signified and signifier. It would seem that it is enough to read this book and understand everything. But if, as shown in Fig. 1, we turn to the image of, perhaps, a girl who is probably looking at or photographing a painting ... or looking at the signified – the pipe, or its image, or the inscription ... Worse still, what are we looking at when we turn to the bottom of Fig. 1?



Figure 1. To the problem of the relationship between the signified and the signifier

It seems that if we can't even figure out a simple object like a pipe, then how do we use language for more meaningful and pressing things?

But in ordinary life, we understand each other relatively well. We can write working programs in many programming languages. After all, we write the laws that govern our lives in language. Maybe, in principle, we should not ask ourselves these questions, because this example seems to be detached from life and purely scholastic? On the other hand, there are many examples of language use where there is not only misunderstanding, but sometimes deliberately misleading others or even oneself, for example, in social networks, financial matters, love affairs. It is even worse if such malicious use of language is practiced, for example, by a large language model trained on a huge corpus of texts and capable of misleading us, theoretically endlessly and relentlessly.

Let's try to enlist the help of the big language model ChatGPT, and ask it "What does a painting by Rene Magritte "It is not a pipe" mean?"

ChatGPT's response is as follows: "The painting by Belgian surrealist painter René Magritte, officially titled La Trahison des images (The Treachery of Images), depicts a pipe and an inscription underneath it in French: "Ceci n'est pas une pipe" ("This is not a pipe"). At first glance, this image seems illogical: it is obvious that a pipe is painted on the canvas. However, the meaning of this picture is much deeper.

With this work, Magritte addresses fundamental questions about the relationship between image, language and reality. The basic idea is that the image of an object is not the object itself, it only represents the object. The painting draws attention to the trap of perception, making the viewer realize that even the most realistic illustration is just an image, a drawing on a canvas, and not an objective reality.

Magritte thus emphasizes the gap between signs (words or images) and reality, pointing to the unreliability of our perception and the capacity of language to convey the truth and essence of the world around us. It also makes us think about how communication and our perception of reality is organized through the lens of symbols and images."

This answer is interesting not because of its content, but because of its existence, structuredness, logical coherence. But before the query, this answer did not exist; all possible answers, including those considered earlier, potentially existed. Thus, it is the query that sets the context, if you will, the simplest concrete ontology in the informational sense, for example, in the form of a request to tell about a picture, that allows us to get a meaningful and possibly useful answer. In fact, such a request can be seen as the cause of the "collapse of the language function" leading to an answer – the result of the work of a large language model by analogy with the collapse of the wave function in quantum mechanics

There is no answer before the query – the formation of context, the setting of ontology. Perhaps that is why, without a context, it was not possible to find the metastructure of language, being lost in an endless chain of signifiers referring to each other.

From an applied point of view, it seems important that through large language models we begin to better understand and feel the structures of language, learning the art of promt – to properly "collapse a language function", avoiding incorrect or useless answers, "model hallucinations".

By improving this art and the language models themselves, we can direct the development of AI technologies to the creation of reliable local language models, including the creation of ontologies of intelligent systems for structuring, criterion distillation of input and output data.

Reliable local language models may be applied to

- operational support of managerial and (scientific) technical decision-making, including preparation of reference materials and analysis of primary data;
- creation of operating systems for robotic systems, including anthropomorphic ones, on their basis;
- solving the tasks of forecasting and planning the effective work of organizations and departments, with the prospect of creating a "state plan".

But still, what are big language models and artificial intelligence in general?

III. Definitions of artificial intelligence

There are many different definitions of AI, data, for example

- Encyclopedia Britannica: "artificial intelligence (AI), the ability of a digital computer or computercontrolled robot to perform tasks commonly associated with intelligent beings;
- Oxford Dictionary: "the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages";
- Wikipedia: "Artificial intelligence (AI) is the intelligence of machines or software, as opposed to the intelligence of humans or animals. It is also the field of study in computer science that develops and studies intelligent machines. "AI" may also refer to the machines themselves".

However, all of these definitions are made by us – human beings.

What does artificial intelligence itself think of itself? Let's consider the definition of AI given by the ChatGPT large language model:

"Artificial intelligence (AI) refers to the ability of machines or computer systems to perform tasks that typically require human intelligence, such as learning, reasoning, problem-solving, perception, and natural language processing. AI involves the development of algorithms, models, and systems that can analyze data, learn from experience, and make decisions based on the patterns and insights derived from the data. AI technologies can be used in various applications, such as speech recognition, image and video analysis, autonomous vehicles, and personalized recommendation systems." That may be the best definition here. Indeed, who better than artificial intelligence to define you

Note that all these definitions are unified in one thing: AI performs tasks that are usually characteristic of humans. These tasks include learning, thinking, problem solving, perception, visual and textual information processing, and translation.

What is the difference between artificial intelligence technology and traditional mathematical modeling?

It's no secret that some students are now using various AI systems to generate, for example, their diplomas. Let's take advantage of their current experience and ask ChatGPT to solve this task:

"Mathematical modeling based on physical principles is not typically considered to be part of the domain of artificial intelligence (AI). While mathematical modeling is an important aspect of many fields, including AI, it is generally not considered to be AI in and of itself."

AI generally refers to the development of algorithms and models that enable machines to perform tasks that would normally require human intelligence. This often involves techniques such as machine learning, natural language processing, and computer vision, which are used to enable machines to perceive, reason, learn, and adapt to changing environments. These techniques are typically not used in mathematical modeling based on physical principles, which instead relies on mathematical equations and physical laws to describe and predict the behavior of physical systems.

That being said, there are certainly areas where AI and mathematical modeling can overlap. For example, AI techniques can be used to optimize and improve the accuracy of mathematical models, or to extract insights from large datasets generated by physical systems.

Logically, this answer follows from the above definition, and suggests that AI technologies, corresponding algorithms and models allow machines to solve problems that humans normally solve. These are, for example, as shown in Fig. 2, computer vision systems that allow to accompany a person, identify empty spaces in a parking lot, identify specific microorganisms in biological laboratory tests [3], [4].



Figure 2. Examples of application of artificial intelligence technologies

In turn, mathematical modeling is not based on human experience and capabilities, but on physical principles. It makes it possible to learn, see for example Fig. 3, about mechanical states of such investigated objects as a cutting tool of an agricultural combine, a fan, our teeth, something that is beyond human control [5], [6].



Figure 3. Examples of application of mathematical modeling

The difference seems clear. But what if we turn to more complex objects? Who will cope with the task of analyzing and making the right decisions better than artificial intelligence technology or mathematical modeling?

IV. Tribo-fatigue bomb

Consider a catastrophic phenomenon called the tribofatigue bomb [7]–[9].

In the eighties of the last century in the Soviet Union it was decided to modernize the Kostroma thermal power plant to a capacity of 1200 MW. This was to be a big step forward, since at that time the power plants operating in the union had only half that capacity. The USA already had such powerful power plants. But their development was gradual 300, 500, 600, 800 MW. It was decided to skip the intermediate stages in Kostroma. A special turbogenerator with a diameter of about 1 m and a length of 23 m was built (see Fig. 4).



Figure 4. Example of catastrophic failure of rails and a powerful generator

It took two years to build. It was planned that the turbine generator would operate for 25 years before overhaul, but after only 4 months the turbine generator was taken out of service. It happened because of intensive cracking in it. It was unsuitable for repair and a new turbogenerator had to be manufactured for a long time. During this time the employees were unemployed and the economic losses were enormous. What happened?

The so-called tribo-fatigue bomb exploded.

Why did it explode? The special state commission that investigated the causes of the catastrophe showed that cracks began to appear in an unexpected place: at the edges of the vent on the surface of the turbine generator shaft. This area was considered to be virtually unloaded because the contact pressure between the vent valve and the edges of the vent was very low.

It turned out that the interaction of small local contact stresses and small fatigue stresses due to volumetric cyclic deformation resulted in explosive damage growth under so-called fretting fatigue conditions.

To predict such a phenomenon, conventional mechanomathematical models based on addition or superposition of stresses were not sufficient. It was necessary to develop new models that would allow predicting the onset of catastrophic damage at low stress loads.

Let's turn to another example of catastrophic injury.

More than a hundred specific rail damages are known in reference books for railway transportation: cracks, chips, wear of various shapes. However, in these reference books there is no sharp bending of the rail and destruction of the rail into small parts, as shown in Fig. 4 a,b. And it is precisely such catastrophic damage that can lead not only to large economic losses, but also to loss of human lives.

Could modern artificial intelligence technologies as we understand them, such as artificial neural networks, pattern recognition, and deep learning, have helped in this case? Most likely, they would be of little use, since these catastrophic events are rare, and an artificial neural network to predict them would have nothing to train on

In order to predict such phenomena, specific models and technologies are also needed to provide the necessary practical guidance.

V. Applied definition of artificial intelligence

Let us begin our discussion of these models and technologies with an applied definition of artificial intelligence, with which we can form the requirements for these models.

Artificial intelligence is proposed to be understood as automated (computer) systems capable to

- collect data,
- analyze them,
- synthesize new information,
- make decisions,
- implement them.

How does this definition differ significantly from the definitions given earlier? Let us leave this question open for now.

Let us consider examples of compliance with this definition. Fig. 5 shows a number of systems of responsible purpose: wheel-rail system, tire-asphalt-concrete, oil flow-oil pipeline section, cutting tool of agricultural combine and even biomechanical system of human dentition [9]–[11].

At first sight, these systems are not connected in any way. However, all these systems are united by the fact that they consist of at least two bodies interacting at some contact area, and at least one of the interacting bodies experiences non-contact volumetric deformation: tension-compression, bending or torsion.

In order to work with such complex systems, a new scientific direction called tribo-fatigue was created in Belarus. Tribo-fatigue studies wear and fatigue damage and failures of active systems of machines and components. In turn, an active system is a mechanical system in which the friction process in any of its manifestations and noncontact variable load are simultaneously applied.

In order to ensure efficient operation, integral quality of the considered systems of responsible purpose, a corresponding methodology of sequential problem formulation and solution was created (see Fig. 6). Let us compare this methodology with the proposed applied definition of artificial intelligence

- data collection model of interaction of n deformable bodies under complex loading,
- information analysis model of combined threedimensional stress-strain state,
- synthesis of new information volumetric damage model, risk forecasting,
- decision making limit state model.

The implementation of the adopted solutions, for example, the application of a new structural material MONICA (2 in 1 - strength and endurance of steel, processability of cast iron) [12] for the manufacture of tribophatic systems and their elements in order to ensure their efficient operation remained outside the methodology.

Let us return, now, to the applied definition of artificial intelligence.

It differs from traditional ones by not reproducing human capabilities. It was shown above that human capabilities can be replaced by mathematical modeling capabilities. And just as technical vision reproduces the capabilities of human vision, so artificial neural networks can use data from numerical experiments based on the application of physically based mathematical models as a basis for prediction.

Still, you should consult an expert here.

ChatGPT agreed with the presented argumentation and proposed a number of directions combining the efforts of artificial intelligence technology and mathematical modeling: optimization, simulation, data analysis and control systems:

"Optimization

Artificial intelligence techniques such as evolutionary algorithms, neural networks and reinforcement learning can be used to optimize mathematical models. This involves finding the best set of model parameters that fit a given set of data or minimize some objective function.

Simulation

Mathematical models can be used to simulate the behavior of complex systems such as weather patterns, fluid flows, and electrical circuits. Artificial intelligence techniques can be used to improve the accuracy and efficiency of these simulations by optimizing models, reducing computational complexity, or managing uncertainty in the input data.

Data analysis

Mathematical models can be used to analyze and interpret data from physical systems such as sensor data or experimental measurements. Artificial intelligence techniques can be applied to extract patterns and insights from large datasets using machine learning algorithms, clustering techniques or anomaly detection.

Control systems

Mathematical models can be used to design and optimize control systems such as robotic arms, autonomous vehicles or industrial processes. Artificial intelligence techniques can be applied to improve the robustness and adaptability of these systems using reinforcement learning, fuzzy logic or expert systems."

From all of the above, it seems to follow that artificial intelligence is more of a task rather than an object or specific (neural network) models and technologies.

VI. Joint application of ANN and mathematical

Let's consider a special task – the study of interaction of different continuous media, for example, liquid and solid as in the case of oil and a section of oil pipeline. An important applied task for this system is to take into account the influence of internal corrosion damage in pipes that have been in long-term operation for more than 30 years. The calculations show a significant influence of these corrosion damages on the amount of wall friction due to turbulent vortices.

In addition, thinning of the pipe in the defect area itself leads to an increase in stresses. To study the stress-strain state in the vicinity of the corrosion damage, a series of several dozen numerical experiments were performed for different values of in-line pressure, damage depth, length and width.

In engineering practice, it is certainly difficult to perform such calculations on a systematic basis. Therefore, to build an automated decision support system for repair or replacement of pipes, approximation of the obtained calculation data was built using both an artificial neural network and a polynomial based on the least squares method (see Fig. 7).

It turned out that both methods are generally suitable for solving the problem of interpolation between calculated points within the boundaries of the numerical experiment. The approximation of stress intensity using a neural network and a polynomial have errors of about 4.1% and 8%, respectively. However, the artificial neural network is better suited for the extrapolation problem beyond the boundary of the numerical experiment data:



Figure 5. Multielement tribofacial systems and application of the new structural material MONICA for their fabrication



Figure 6. Methodology of sequential problem formulation and solution (in Russian)

its error (about 6.7%) is about half that of the polynomial approximation (about 14.8%). This is an important conclusion about the great potential of application of artificial neural network, allowing due to its multilayer architecture to take into account complex nonlinear effects.

These results allow predicting the stress-strain state for a complex configuration of corrosion damage obtained by in-line diagnostics methods. Such a prediction becomes the basis for making technological decisions.

Let us consider another example of constructing an approximating model that exhibits the positive effect of hierarchical structure, based on mechanical experiments.

For example, attempts to plot the apparent temperature dependence of ultimate stresses in uniform, semilogarithmic and logarithmic coordinates for different materials and different test conditions have been quite ineffective, as shown in Fig. 8 for a relatively small number of 136 test results.

To build models of such mechanothermodynamic (MTD) systems [13] with high predictive ability, it was necessary to take into account that the effective energy (entropy) fluxes leading to the appearance of primary damage and caused by sources of different nature, at irreversible changes in the system are not summarized – they interact in a complex way.

The concept of Λ -interactions – development (accumulation) of internal damages in the system elements, determined by the unity and struggle of opposite processes of physical hardening-reinforcement, was introduced. Therefore, the interaction functions should take three classes of values $\Lambda > 1$, $\Lambda = 1$, $\Lambda < 1$.

Let the factors generating damage in the MTD system correspond to thermodynamic T, mechanical M (volumetric σ and surface (frictional) τ) loading. Then the simplest expression for determining the effective energy has the following form

$$U_{\Sigma}^{eff} = [(U_{\sigma}^{eff} + U_{\tau}^{eff})\Lambda_{\sigma\setminus\tau} + U_{T}^{eff}]\Lambda_{T\setminus M}.$$
 (1)

The structure (1) is essentially hierarchical: first, the effective energy is determined in the interaction of the force σ and friction τ components, then – in the interaction of the mechanical M and thermal T components. This structure can be represented as a graph (Fig. 9, a) or a corresponding hypergraph (Fig. 9, b).

The most important feature of the MTD model is the consideration of the limit state, for example, at the onset of plasticity or fatigue failure:

$$U_{\sum}^{eff} = U_0, \tag{2}$$

where the limiting internal energy density U_0 is treated as the initial activation energy of the fracture process.

The model of the MTD-system (1)-(2) allows to take into account force, temperature and friction loads and to describe failures of the system elements according to different signs of the critical state: volumetric destruction – separation into parts; surface destruction – ultimate wear, and in the special case of thermo-force loading (see Fig. 9), which showed correspondence to 600 experimental data with a high (more than 0.722) correlation coefficient.

Thus, we can distinguish two main effects of interaction between ANN and physically based mathematical models and results of physical experiments.

Direct effect (for modeling): ANNs, due to their multineuron and multi-layer structure, are able to choose the best approximation of the desired model and take into account the essentially nonlinear nature of the latter, providing significantly better interpolation and extrapolation of experimental data than traditional approaches (e.g. polynomial approximation).

Back effect (for ANN): results of numerical modeling based on physical principles, physical experiments are cleaned well-structured data for ANN training, allowing to reduce the training sample size and simplify the network architecture.

VII. To the introduction

Let's go back to I. Musk's quote in the introduction: "But I do think it's one of the existential risks that we face and it is potentially the most pressing one if you look at the timescale and rate of advancement."

Indeed, the risks of using artificial intelligence systems are largely related to the possibility of their influence on public opinion regarding the most important issues in society. One vivid example is the Cambridge Analytica products used in the 2016 US elections.

Also not so much dangerous as disconcerting may be the high competence of artificial intelligence systems in areas of human activity that have traditionally been considered creative and inaccessible for reproduction by a "machine": fine arts, literature.

We should not be upset, however, because we ourselves are, in a sense, the product of a very long "evolutionary learning" process. And it seems that it will be long before there will be a single complex AI system that would be able to draw a picture, compose a poem, catch a fish, solve a differential equation, build a house and eat a cutlet, which somewhat reduces the fear of "machine revolt".

Undoubtedly, artificial intelligence systems may dramatically accelerate scientific and technological progress, allow society to evolve faster, taking into account its true aspirations (neural networks based on physical models, "smart" ecosystems, "public services", "one window", sectorial computing and analytics platforms).

The essence of Musk's excitement seems to be revealed by the core of his quote "It's not clear to me if we can control such a thing ...". If by "we control" we mean control (including by means of closed proprietary



Figure 7. Application of neural networks for prediction of maximum stresses in the vicinity of corrosion damage in the main pipeline



Figure 8. Attempts to construct explicit dependences of endurance limit on temperature for metallic materials in logarithmic (a) and semi-logarithmic (b) in semi-logarithmic (c) and uniform (d) coordinates



Figure 9. Scheme of energy interaction

code) by the largest transnational corporations and the "visionaries" representing them in the interests of their own and the individual states that supervise them, then, of course, such control should be avoided at all costs.

Therefore, the choice of the direction and method of using AI, for example, in building an e-government is a complex task, the solution to which should be based on achieving consensus with the involvement of all stakeholders and on the basis of the most objective assessment of the balance of consequences of their application.

VIII. Hypotheses

The consequences of the application of artificial intelligence technologies is a relevant and important topic for a comprehensive discussion, in which no final judgments have yet been made as to what and for whom these consequences will be and no decisions have been made. Therefore, instead of a conclusion, this paper proposes some hypotheses that may be both confirmed or refuted.

Artificial intelligence is more of a problem statement, a broad area of research and development, rather than an object or specific (neural network) models and technologies.

The control of artificial intelligence systems should be in the interest of society as a whole, not of individuals or groups (financial and industrial), by consensus, involving all stakeholders and assessing the balance of its implications as objectively as possible.

In the case of large language models, a query (promt) forming the context – ontology, can be the cause of "collapse of the language function", leading to an answer - the result of the large language model, by analogy with the collapse of the wave function in quantum mechanics

The development of AI technologies is expedient in the direction of creating reliable local language models, including those based on ontologies of intelligent systems for structuring, criterion distillation of input and output data.

Reliable local language models may be applied to

• operational support of managerial and (scientific) technical decision-making, including preparation of



Figure 10. Fundamental mechanothermodynamic function of limit states of different modern materials (in Russian)

reference materials and analysis of primary data;

- creation of operating systems for robotic systems, including anthropomorphic ones, on their basis;
- solving the tasks of forecasting and planning the effective work of organizations and departments, with the prospect of creating a "state plan".

Two main effects of the interaction between ANNs and physically based mathematical models and the results of physical experiments can also be emphasized.

Direct effect (for modeling): ANNs, due to their multineuron and multi-layer structure, are able to choose the best approximation of the desired model and take into account the essentially nonlinear nature of the latter, providing significantly better interpolation and extrapolation of experimental data than traditional approaches (e.g. polynomial approximation).

The back effect (for ANNs): the results of numerical simulations based on physical principles are cleaned well-structured data for ANN training, allowing to reduce the training sample size and simplify the network architecture.

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О НЕКОТОРЫХ ОНТОЛОГИЧЕСКИХ ВОПРОСАХ РАЗВИТИЯ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ В УПРАВЛЕНИИ, МЕХАНИКЕ И МАШИНОСТРОЕНИИ

Щербаков С. С.

Работа посвящена теме развития технологий искусственного интеллекта (ИИ). Рассмотрены связь искусственных нейронных сетей (ИНС) и соответствующих онтологий, создание достоверных локальных языковых моделей. Предложено прикладное определение ИИ как постановки задачи, а не множества конкретных технологий. На примере ряда технических систем ответственного назначения рассмотрены соответствующие технологии ИИ в сравнении с математическим моделированием. Обсуждены некоторые риски и перспективы, связанные с развитием ИИ.

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Linguistic Justification for the Creation of a Lexical Analyzer on a Semantic Basis

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Abstract—The article examines in detail the logical, semantic and metasemantic paradoxes that arise when mixing theory and metatheory during the description of hierarchical systems, explains their significance for linguistics, provides examples of the internal contradictions in the Parts of Speech theory causing large-scale errors in the Natural Language Processing large-scale errors in the Natural Language Processing, and substantiates the creation of a lexical analyzer based on Parts of Language and the Theory for Automatic Generation of Knowledge Architecture (TAPAZ-2).

Keywords—paradox, Parts of Speech, Parts of Language, Signs of Syntax Alphabet, language categories, delineation procedures, lexical analyzer, Natural Language Processing, inventing machine

Introduction

The reliability of syntactic rules depends entirely on the accuracy of determining the place of signs in the language hierarchy, i.e. on the correct interpretation for the content of linguistic patterns used by the intellect at a subconscious level as a basis for organizing the language by sequentially dividing it into parts. Any exceptions made here only indicate mathematical and semantic errors of the researcher, because language is determined in the same way as any other system. The correctness of the interpretation for the content of linguistic patterns, in turn, depends on the degree of its formalization only then is it possible to prove the consistency of the consequences. In this regard, we recall the statement of A. Tarski that the description of a language is only transparent when it leads to the creation of its formalized version [1].

Why, despite the incredible efforts of scientists in various fields of knowledge, has natural language still not been formalized? Perhaps linguistic semantics cannot be formalized at all? Many linguists with a "classical philological education" are sure of this, although the founders of modern linguistics were not so categorical on this matter. Let us recall, at least, two striking, but opposite statements belonging to the famous European linguist Emile Benveniste:

"Some linguists reproach Saussure for a propensity to emphasize paradoxes in the functioning of language. But language is actually the most paradoxical thing in the world, and unfortunate are those who do not see this" [2, p. 37];

"To imagine a stage of language as "primal" as one would wish, but nevertheless real and "historical," in which a certain object would be *denominated* as being itself and at the same time something else, and in which the relation *expressed* would be a relation of permanent contradiction – a non-relating relation – in which everything would be itself and something else, hence neither itself nor the other, is to imagine a pure chimera" [2, p. 71–72].

Let us consider the paradox detected by B. Russell in 1902 in Foundations of Arithmetic by G. Frege, the first attempt at set-theoretic constructions. In any modern branch of knowledge, it is customary to operate with the concept of a set, which, as Yu. A. Shikhanovich wrote in his book Introduction to Modern Mathematics, "is so basic that it is difficult, at least today, to define it using simpler concepts" [3, p. 13]. A set is the usual name for any collection of any objects – its elements.

Most sets do not belong to themselves as elements. For example, the set of *cats* is not itself *a cat*, the set of *tables* is not itself *a table*, the set of *words* is not itself *a word*, etc. However, there are sets that belong to themselves as elements. For example, the set of *forests* is also itself *a forest*, the set of *sands* is also *sand*, the set of *waters* is also *water*, etc. Let us imagine some set *A*, the subsets of which include all sets that do not belong to themselves, for example, the set of all *hares*, which is not itself *a hare*, the set of all *boots*, which is not itself *a letter*, etc.

Now we consider the set A itself, recalling that it consists of all sets that do not belong to themselves. If the set A does not belong to itself, then it belongs to itself, because it includes all sets that do not belong to themselves; if it does belong to itself, then it does not belong to itself. In any case, it turns out that the set A simultaneously belongs to itself and does not belong to itself [4, p. 2].

Few linguists, even those who have read articles on formal semantics, know that this dramatic episode nearly drove the author of predicative second-order logic and founder of logical semantics to suicide, that G. Frege unsuccessfully tried to resolve this unfortunate paradox until the end of his life, and throughout the 20th century mathematics through the formalization of the metalanguage had difficulty getting rid of the contradictions in its foundations. Neither predicate calculus [5], nor Boolean algebra [6], nor pseudo-physical and modal logic [7], nor Cantor's theory of sets [8] have been able to formalize the language semantics: mathematics still did not have its own means for transformation of expressions and logic did not have its own means for its representation. To the credit of the Belarusian science, essential progress in this area was achieved by V. V. Martynov in creating a semantic coding approach [9].

Contradiction in mathematics meant the collapse of bridges in engineering. The bridges of linguists did not fall until problems of the intellectual interface in humancomputer communication arose, the main reason for which was, as V. V. Martynov repeatedly emphasized, **the ambiguity of statements in unlimited natural language** [9, p. 12].

The contradiction, which was called the mathematical paradox of B. Russell, turned into a disaster for the ideology of mathematics, causing a chain reaction of repeated proofs for theorems that seemed to have been solved once and for all. It still conceals the main danger for multidimensional mathematical constructions. Another, already semantic, paradox was detected by K. Grelling and L. Nelson in 1908 following Russell's paradox.

Let us group the adjectives so that the first ones – autological – denote a feature that they themselves possess, and the second ones – heterological – denote a feature that they themselves do not possess. For example, the adjectives polysyllabic (self also consists of many syllables) and English (self also belongs to the English language) are autological, in contrast to the heterological adjectives monosyllabic and Russian; but the adjective pycckuŭ will already be autological.

Now we try to analyze the adjective *heterological* itself. If this adjective denotes a feature that it itself possesses, then it is non-heterological, and if it is non-heterological, then, by definition, it is heterological. Continuing the topic, we can cite the well-known paradox of the liar in its ancient or medieval interpretation: "*I am lying! – If at this moment I am really lying, then I am no longer lying, and if I am not lying, then, by asserting the opposite, I am lying*" (Eubulides); "What Plato said is false," says Socrates. "What Socrates said is true," says Plato" (Chrysippus) [10].

It is clear from the examples that such contradictions arise when mixing the level and the meta-level, theory and meta-theory, language and meta-language. The set *A* in Russell's paradox is a meta-level in relation to the subsets included in it, so considering the elements of the meta-level together with the elements of the level inevitably leads to a contradiction.

In other words, **paradoxes are a consequence of incorrect description of hierarchical systems, and not a property of these systems themselves**. Unfortunately or fortunately, almost all systems of our threedimensional space are hierarchical, including natural language. Hence, the simplest and most reliable protection against paradoxes is to prohibit the inclusion of different level elements in the one level analysis, as well as the application of the same mathematical function to heterogeneous objects.

"To exclude such contradictions from an axiomatic theory, H. Rasiowa & R. Sikorski considered, it is necessary to describe its language precisely, i. e. the set of sentences of the theory and the set of signs used to build these sentences. In this way we avoid contradictions caused by a collision between the theory and its metatheory, that is, by including metatheoretical statements in the theory. This inclines us to introduce still greater precision in the construction of mathematical theories and leads to the concept of *formalized theories*, in which not only the properties of the primitive notions are given in an exact way by means of a set of axioms, but also the language of the theory is precisely defined" [11, p. 146–147].

However, for the formalized description of hierarchical systems, the greatest danger is posed by **metasemantic paradoxes** due to their hidden and fundamental nature. They affect the foundations of our primary perception of the World and manifest themselves in attempts to formally substantiate definitions and conclusions without taking into account their semantic counterparts. It is curious that semantics nevertheless seeps into formalisms in the form of **finite** or **non-finite technology**. It is no coincidence that the outstanding Italian mathematician G. Peano was inclined to the opinion that the set theory is more linguistics than mathematics.

As an example of inference rules, we will cite the paradox of the *conditional* or *material implication "if* A, *then* B", which is true when: 1) its basis and its consequence are true; 2) the basis is false, and the consequence is true; 3) both the basis and the consequence are false, and establishing its truth does not presuppose a semantic connection between the statements. In classical logic, such an implication is false only in one case: when the basis is true, and the consequence is false; if B is true, then the entire implication is true, regardless of the truth of A or its semantic connection with B.

With this approach, the statements "*If there is life* on the Sun, then Beijing is a big city", "*If two plus* two is four, then it is time to plant potatoes" are true. Conditional implication is true even when A is false, and

this does not take into account the truth of B or the connection of A with B. For example, the statement "If the Sun is a cube, then the Earth is a triangle" will be true. Obviously, conditional implication does not fit well with a common sense understanding of cause and effect.

As a result, logicians were forced to turn to semantics. In 1912, C. Lewis put forward the idea of strict *implication* [12], which partially reflected the semantic connection between the antecedent and the consequent in a conditional statement. However, it soon became clear that strict implication itself is not free of paradoxes, so in the middle of the 20th century, the German logician W. Ackermann [13] and the American logicians A. Anderson and N. Belnap [14] proposed replacing strict implication with relevant implication, which, in their opinion, resolved the paradoxes of both material and strict implication. Now implication was understood as logical consequence, i.e. the transition from premises to reasonably deducible conclusions, and the semantic definition of logical consequence took the form: "From A follows B, if it cannot be that A is true and B is false".

Since the semantic connection between A and B in logical consequence **was declared but not formalized**, the meanings of the words "reasonably" and "in sense" could acquire different interpretations, so the relevant implication only postponed, but did not solve the problem of logical paradoxes. Moreover, the definition of logical consequence contained a hidden circle, since the words "is deducible" and "follows" used in it were synonyms of the word "implies". As shown by the cross-analysis of interpretations of the word meaning through a synonymous series conducted by Yu. N. Karaulov, the semantic circle occurs after a maximum of five occurrences [15].

An example of a semantic circle in the Dictionary of the Russian Language by S. I. Ozhegov: "To assure. The same as to convince (in 1 meaning)" [16, p. 713]. "To convince. 1. To assure" [16, p. 712]. As a result, the definition of the relevant implication automatically fell into the category of primary undefined concepts, thereby losing any semantic significance. With primary undefined concepts, the situation, from the metasemantic paradoxes point of view, was even worse.

It is known that in order to define some concept A, it is necessary to select a simpler concept B for it, and in order to define concept B, it is necessary to select an even simpler concept C for it; in the end, inevitably, there was some concept D, for which it was no longer possible to select a simple concept. In such a case, there was only one thing left: to compare primary, undefined concepts with each other. In other words, one can only talk about men in comparison with women. If nature had not created women, one would have to talk about some anthropomorphic creatures, but not about men.

The initial (primary, undefined) concept of the set

theory, which became the basis of many sections of modern mathematics – general topology, general algebra, functional analysis, etc., is *a set*, which is considered as a collection, a tuple, an ensemble of elements, etc. Here, the synonymous series has no meaning, since it inevitably leads to a semantic circle: **"a set is a collection, and a collection is a set**." Further, it is proposed to operate with "single-element" and even "empty" sets, which, from the standpoint of semantics, immediately levels the concept of "set": **if everything around is a set, including a single one, then there is no set**.

It is further proposed to consider that any set, in addition to proper subsets, has two "improper" ones – the set itself and some "empty" set, and there is an infinite number of such "empty" sets. Here, in addition to the hidden metasemantic paradox in the description of primary concepts, we have Russell's mathematical paradox, together with the paradoxes of Galileo [17], Hausdorff [18], and Banach-Tarski [19]. As we can see, **all the logical difficulties associated with the substantiation of the mathematical doctrine of infinity, when moving to the general theory of sets, only become even more acute.**

Since the second half of the 20th century, the influence of set theory on mathematics has significantly decreased due to the achievement of generalizations without explicit use of its apparatus, in particular, with the help of category-theoretical tools, by means of which it was possible to generalize practically all variants of set theory in *topos* theory. American mathematicians F. Lawvere [20] and M. Tierney [21] defined categorical analogues of operations on sets using **the basic categorical construction of the limit – an elementary topos,** i. e. a Cartesian closed category with a classifier of sub-objects. In a similar way, as it turned out, it is possible to categorically describe all possible constructions for the formation of new sets from existing ones.

Intuition convinces us that the infinity of combinatorics generated by a finite alphabet and a finite set of rules for construction and transformation has some limitations in hierarchical systems. Why, for example, do Russians say "достать из-под шкафа" ("to get something from under the cupboard") but not "достать из-над шкафа" ("to get something from above the *cupboard*"), i. e. from the mezzanine? Why do they say "выйти в коридор" ("to go out into the corridor") but not "войти в коридор" ("to enter the corridor")? Apparently, such limitations are purely semantic. The ancient Greeks and Romans felt this well in the example of the paradox of Hercules and the tortoise: the infinity of small numbers was somehow miraculously resolved. In other words, infinity arises where we do not understand something, and operating with it without semantics leads to scholasticism.

If we want to build a working system for artificial

modeling of intellectual activity, then the design of its knowledge base should be homomorphic to the architecture of the World Model created by the intellect in a natural way, i. e. it should meet the principles of visibility, obviousness and compliance with common sense. Of the existing scientific theories, the most suitable for this are **the Topos Theory**, **the Theory of Groups**, **the Euclidean-Hilbert Geometry [22]**, **Quantum Physics and the Universal Semantic Code by V. V. Martynov**.

"At this point the problem that haunts all of modern linguistics arises: the relationship between form and meaning, wrote Emile Benveniste. Many linguists would like to reduce it to the notion of form alone but somehow they cannot succeed in freeing themselves of the correlative, meaning. What has not been attempted in order to avoid, ignore, or expel meaning? It has been useless; this Medusa's head is always there at the center of language, fascinating those who contemplate it" [2, p. 106–107].

I. Contradictions in the foundations of the Russian language academic grammar

Let us check some popular linguistic theories for paradoxes. Russian grammarians suggest analyzing sentences of the form "Omeq - yumenb" (literal translation "Father – a teacher") according to the scheme GS(N₁) – GP(N₁): "Grammatical Subject is a name in the nominative case: grammatical predicate is a formally subordinate form of the name; in the paradigm structure, the nominative case in the grammatical predicate can alternate with the instrumental" [23, p. 551]. This approach does not stand up to criticism even at the first reading, since the verb δ_{blmb} (to be) appears in the past or future tense: " $Omeq \delta_{bln}$ ($\delta y dem$) yumenem" ("Father was (will be) a teacher"), and even in the present tense the verb is not difficult to restore: "Omeq ecmb yumenb" ("Father is a teacher").

"It emerges, first, that the nominal sentence cannot be considered as lacking a verb. It is just as complete as any other verbal utterance. Furthermore, we cannot consider it a sentence with a zero copula, for in Indo-European there are no grounds for establishing a zero-form/full-form correspondence between the nominal sentence and the verbal sentence containing "to be". <...> Otherwise, there is not really an equation between the subject and the nominal term with verbal function" [2, p. 137–138]¹.

It is curious that the authors of Russian grammars are not even embarrassed by the fact that the role of the grammatical predicate is played by a noun in the nominative case, although traditionally such a form of the noun is assigned to the grammatical subject. As a result, it is necessary to resort to tricks, calling the phrase " $\delta \omega_L n$ (*будет*) *учителем*" ("*was* (*will be*) *a teacher*") the grammatical predicate and qualifying it as a compound nominal. Here, there is already a mixing of levels in syntactic analysis – the role of the grammatical subject is played by a word, but the role of the grammatical predicate is played by a group of words (a words-combination).

The relationship between a word and a combination of words is hierarchical: a word is included in a combination of words, a combination of words is included in a sentence, a sentence is included in a text. The paradox is manifested in the impossibility to continue analyzing the sentence when building up its syntactic structure "Father was (will be) a very good teacher of Russian", since the entire part of the sentence after the word "father" automatically becomes the grammatical predicate. If syntactic analysis were accompanied by at least minimal semantic support, relied at least on school definitions of the grammatical subject and grammatical predicate, because, as H. Reichenbach wrote, "pseudo-problems arise, if we look for truth where definitions are needed" [24, p. 15], it would be possible able to avoid a dead end in parsing the sentence. Who is the sentence talking about? - About the father "father" is the grammatical subject. Who is (was / will be) the father? - Is (was / will be) a teacher. Or: What properties does (did, will) the father have? - The properties of a teacher "are (were / will be)" is the grammatical predicate and "a teacher" is the grammatical object. Next step, the grammatical attributes "good" and "language" are detected for the grammatical object "teacher" and then the grammatical attributes "very" and "Russian" are detected for the grammatical attributes "good" and "language". The syntactic formula of the sentence is: $GS + [GP] + Attr_2 + Attr_1 + GO +$ $Attr_4 + Attr_3$, where GS is the grammatical subject, GP is the grammatical predicate, GO is the grammatical object, Attr are the grammatical attributes with indices of the property accumulation order; the + (plus) sign indicates the order by which parts of the sentence are connected, and the brackets [] indicate a possible reduction of the grammatical predicate under certain conditions.

Two conclusions follow from the analysis. First: in Russian, **the role of a grammatical object can be played by a sign in the nominative case**, which is easy to agree with, since in grammatical objects the forms of the nominative and accusative cases tend to coincide, sometimes despite the animate or inanimate nature of the nouns.

"The category of inanimate nouns includes nouns denoting a collection of living beings (народ "people", monna "crowd", взвод "platoon", стая "flock", рой "swarm", группа "group", etc.), as well as collective nouns such as молодёжь "youth", крестьянство "peasantry", детвора "children", пролетариат "proletariat", etc. <...> For animate nouns of the neuter

¹ Compare: "A father is a teacher, but a teacher is not necessarily a father (a teacher maybe a mother and so on)". For more details, see: Hardzei A. The Principles of Calculating the Semantics of Subject Domains. Minsk, Belarusian State University Publ., 1998, pp. 33–35. (In Russian).

gender, as well as for inanimate ones, the accusative case form in the singular coincides with the nominative case form. For example: Ах, как я люблю это пустое существо! – простонал Павел Петрович "Оh, how I love this empty creature! -- moaned Pavel Petrovich" (Turgenev). The same is observed in feminine nouns with a zero ending in the nominative case: вижу рысь, мышь "I see a lynx, a mouse". <...> The names of microorganisms fluctuate between animate and inanimate nouns: *микроб* "microbe", бацилла "bacillus", инфузория "infusoria", бактерия "bacterium", амёба "amoeba", etc. They have two accusative case forms: изучать микробов and микробы "to study microbes"; рассматривать вирусов and вирусы в микроскоп "to examine viruses under a microscope"; уничтожать бацилл and бациллы "to destroy bacilli". <...> The words mun "type", образ "image", xapakmep "character" are used as inanimate nouns, which are the names of characters in works of art: создать сильный характер "to create a strong character"; охарактеризовать отрицательные типы и положительные образы; "to characterize negative types and positive images" [25, p. 100–101].

Second: the comparison degrees of adjectives and adverbs need to be clarified, since the words очень (сильно) "very (much)", самый "most", чрезвычайно "extremely", etc. not only play an independent role in the sentence, allowing the question очень какой? - очень хороший "very what? -- very good", самый какой? самый красивый, "most what? – most beautiful", чрезвычайно какой? – чрезвычайно быстрый "extremely what? - extremely fast", but are also able to act as an independent sentence: Ты хочешь пойти в театр? – Очень! "Do you want to go to the theater? – Very much!", therefore they cannot be considered auxiliary means of constructing analytical forms of superlative degrees of adjectives or adverbs, which means that these degrees do not exist, otherwise, we again get a mixture of the level (word) and the meta-level (words combination) and face Russell's paradox.

Incidentally, it should be noted that equating the combination of a functional sign with a notional sign to an ordinary fragment of phrase, i. e. to a combination of notional signs, is a serious mistake, since the so-called "functional Parts of Speech" do not belong to language, but to metalanguage, and denote facts of language, not facts of the World Model. For example, the preposition на "on" is used to construct locatives of the form на cmone "on the table", but not to denote individs that play the role of a locus in the World Model. The preposition на "on" disappears if the structure of the sentence is brought into line with the structure of the World Model: "The surface of the table holds the book" instead of "The book lies on the table". Since "functional Parts of Speech" do not play independent roles in a sentence and are not parts of the sentence, in order to avoid

Russell's paradox, they must be excluded from the Parts of Speech and classified as **Signs of Syntax Alphabet**, **i. e. auxiliary syntactic means (at the macrolevel** – prepositions, postpositions, particles, conjunctions, etc., at the microlevel – flexions, prefixes, infixes, postfixes, etc.) that serve for connecting the components of language structures and the formation of morphological paradigms.²

Let us consider the sentence Он очень быстро бегает "He runs very fast". It is obvious that on "he" and *beraem* "runs" are related as an individ and his temporary characteristics. Compare: "If a doctor in the forest chops down a tree, then at this time he is not a doctor, but a woodcutter". Chopping down trees is a temporary occupation for a doctor. If the doctor refuses to heal and only chops down trees, then he really does turn into a woodcutter, which is confirmed in the language by semantic-syntactic transformations: врачевать людей "heal people" > врачующий людей "(a man that) healing people" > врач "healer"; рубить лес "cut the wood" > рубящий лес "(a man that) cutting wood" > лесоруб "woodcutter". Let us denote the individual OH "he" by the symbol *i*, then the process бегать "to run" will be written as f(i). If *becaem "runs"* is characteristics of the individ он "he", then быстро "quickly" is characteristics of his characteristics. It is impossible to say он быстро "he quickly", we can only say that быстро бегает "runs quickly". In other words, the relations between the characteristics быстро "quickly" and *beraem "runs"* are hierarchical, which indicates a superposition of the functions f(f(i)) or the degree of the function $f^2(i) = f(f(i))$. If *beraem "runs"* is characteristics of the individ on "he", and быстро "quickly" is characteristics of his characteristics, then очень "very" is characteristics of his second characteristics, i. e. characteristics of characteristics of his characteristics. We can not say он очень "he very", just as we can not say очень бегает "runs very", we can only say очень быстро "very quickly", so the relationships between the characteristics очень "very" and быстро "quickly" are also hierarchical: $f^{3}(i) = f(f^{2}(i)) = f(f(f(i)))$. Thus, in the hierarchy of characteristics beraem "runs" has the first degree, быстро "quickly" has the second degree, and очень "very" has the third degree. The adverb in Russian comes from the short form of the neuter adjective: *он хороший* \rightarrow *он хорош* "*he is good*", она хороша "she is good", оно хорошо "it is good". ³ It is not surprising that the paradigms of their degrees are close and intersect, to the point of erasing the boundary

² The term *Signs of Syntax Alphabet* is borrowed from: Rasiowa H., Sikorski R. The Mathematics of Metamathematics. 2nd edn. Waszawa, Polish Scientific Publishers, 1963, pp. 151–154.

³On the primacy of the full and secondary nature of the short form of the Russian adjective, see: Kurilovich E. Lexical Derivation and Syntactic Derivation. In : Essays on Linguistics. Moscow, Foreign Literature, 1962, p. 60 [26].

in intensive forms: самый хороший "the best", but очень хорошо and очень хороший "very good"; строгий \rightarrow строже \rightarrow более строгий and строго \rightarrow строже \rightarrow более строго "strict \rightarrow stricter \rightarrow *more strict". By the way, the intensive form allows only the question how? - строже "stricter", but not at all which one? The hierarchy of degrees of constant characteristics can be conveniently traced using the example of самый красивый бежевый цвет "the most beautiful beige color". What color is i? – It is бежевый "beige" p(i), what kind of бежевый "beige"? It is красивый "beautiful" $p(p(i)) = p^2(i)$, what kind of красивый "beautiful"? It is самый "the most" $p(p(p(i))) = p(p^2(i)) = p^3(i)$. Although in Russian we can say красивый цвет "а beautiful color" (when *самый цвет "the most color" or *самый бежевый "the most beige" is inadmissible), nevertheless, красивый "beautiful" occupies the second position in the hierarchy of characteristics, because in an unclear situation, the restoration of the first characteristics is required. What color exactly is characterized as beautiful? - It is beige. It follows that бежевый "beige" has the first degree, красивый "beautiful" has the second degree, and самый "the most" has the third degree. It is generally accepted that degrees of comparison are the prerogative of the majority of qualitative adjectives [25, p. 129]. It is not explained why not all of them. But with the correct semantic analysis, the answer is simple: intensive evaluative forms are absent from all signs of the first degree, regardless of their "quality". These include, for example, signs of the basic color palette: белый "white", жёлтый "yellow", красный "red", зелёный "green", синий "blue", чёрный "black", etc., if they are not to be confused with homonymous epithets: белый "white" - ясный "clear", чистый "pure", бледный "pale"; жёлтый – старый "old", больной "sick", увядший "withered"; красный "red" – горячий "hot", красивый "beautiful", стыдливый "bashful"; зелёный "green" – незрелый "immature", молодой "young", неопытный "inexperienced"; синий "blue" – уставший "tired", замёрзший "frozen", побитый "battered"; <u>чёрный</u> "black" – тёмный "dark", грязный "dirty", мрачный "gloomy". Metaphors are conditioned by the characteristic color symptoms of the properties manifestation. Compare: чёрный "black" → чернее "blacker" = мрачнее "darker", но коричневый "brown" \rightarrow (?), оранжевый "orange" \rightarrow (?), уль*трамариновый "ultramarine"* \rightarrow (?). The division of adjectives into qualitative, relative and possessive also raises doubts. Firstly, opposition is always binary. A ternary opposition arises when the whole is first divided into two parts, then one part is divided into two more, with the other part remaining undivided, which results in a confusion of the level and the micro level, and we face Russell's paradox. Secondly, in epistemology it is customary to contrast quality with quantity. But

the relative adjectives деревянный "wooden", утренний "morning" and the possessives мамин "mother's", "ичительский" teacher's denote the same quality as the "qualitative" круглый "round" and мятый "crumpled", as opposed to the adjective-numeral *smopoŭ* "second" (which / what?). Grammarians of the Russian language claim that qualitative adjectives directly name various attributes of objects, while relative ones do so indirectly: "The attribute of an object in them indicates various relationships: to an object (compare: железная кровать "iron bed" vs. кровать из железа... "a bed made of iron ... "), to a person (compare: мамино пальто "mother's coat" vs. пальто мамы... "coat belonging to mother..."), to a place (compare: загородная поездка "a town out trip" vs. поездка за город... "a trip out of town ... "), to time (compare: утренние сообщения "morning messages" vs. сообщения, сделанные утром "messages made in the morning ..."), to an action as a property (compare: ... раздвижной стол "apart sliding table" vs. стол, который раздвигается "a table that slides apart..."), to a number (compare: *wecmoŭ* стол "sixth table" vs. шесть столов "six tables..."), etc." [25, pp. 127-128]. However, upon closer examination it turns out that qualitative adjectives also indicate a variety of relationships: sweet, bitter - to taste; white, blue - to color; sonorous, quiet - to sound; soft, smooth to coating; narrow, long - to shape; wise, kind - to individual character, etc. It would be correct to divide adjectives first into qualitative and quantitative, and then qualitative ones into relative and possessive. Then it would be clear that in the combinations of omyos ремень "fathers' belt", мамина сумка "mother's bag", собачья будка "doghouse", кофейный запах "coffee smell", and finally, лисья морда "fox's muzzle", the role of definition is played by possessive adjectives, and in the combinations of кофейный сервиз "coffee set", лисья шуба "fox's fur coat", by relative adjectives, because afox's muzzle belongs to a fox, unless it is a metaphor (Ax ты, лисья морда! "You, fox's muzzle!"), and a fox's fur *coat* no longer belongs to a fox, unless it is a metonymy (По сугробам бегала лисья шуба "A fox's fur coat ran through the snowdrifts").

Unfortunately, the contradictions in the classification of Speech Parts are fundamental in nature and it is impossible to eliminate them all. For example, along with nouns, adjectives, verbs and adverbs denoting, respectively, objects, attributes of objects, processes and attributes of processes, pronouns and numerals are distinguished as independent Parts of Speech, which in content are varieties of nouns on "he", smo "this (is)", soceme "eight" or adjectives ezo "his", smom "this (thing)", socьmoü "eighth". The word cmonosas "canteen" (place for eating), contrary to morphology, is considered a noun, while the word *bez* "running" with verbal semantics is also among the nouns. Interjections include words expressing but not naming emotions and expressions of will [25, p. 257]. At the same time, in the phrase *A desuua xu-xu-xu da xa-xa-xa!* "And the maiden hi-hi-hi and ha-ha-ha!" the words *xu-xu-xu* "hi-hi-hi" and *xa-xa-xa* "ha-ha-ha" are considered interjections, although they denote a process and play the role of a grammatical predicate [27].

The listed errors are sufficient to agree not only with the restrained statements of F. de Saussure and O. Jespersen that "We are then dealing with a defective or incomplete classification; the division of words into substantives, verbs, adjectives, etc. is not an undeniable linguistic reality" [28, p. 109-110], and their "definitions are very far from having attained the degree of exactitude found in Euclidean geometry" [29, p. 58], but also with the rather harsh statements of L. Tesnière: "This classification, which rests on vague and sterile empiricism and not on a precise and fertile doctrine, does not stand up to scrutiny. <...> All evidence indicates that a good classification cannot rest simultaneously on multiple characteristics. We must therefore separate essential characteristics from secondary ones, or, to borrow terminology from logic, to distinguish dominant characteristics from subordinate ones. The principle of subordination leads to the establishment of a hierarchy of criteria, the most important of which serves to determine the classes and the second most important of which serves to determine the subclasses" [30, p. 45] and F. F. Fortunatov: "The division into Parts of Speech that is accepted in our grammars (and has come to us from ancient grammarians) represents a mixture of grammatical classes of words with their non-grammatical classes and therefore cannot have scientific significance (emphasis added -A.H.). For example, 1) verb, 2) noun, 3) pronoun in Russian, Greek and Latin do not represent correlative classes of words in the grammatical classification of words..., but in the non-grammatical classification they also do not form correlative classes of words, since, for example, the difference between a noun and a pronoun on a non-grammatical basis has nothing in common with the difference between a noun and a verb" [31, p. 166].

It is impossible to formalize a contradictory doctrine in which any statement is "provable". It is not surprising that the developers of *the Semantic Web* project, despite their titanic efforts to standardize the technology, have still not succeeded in achieving machine readability of Internet pages in the direction from morphological analysis to syntactic and semantic, as well as constructing a top-level ontology "from below", i. e. by reducing to it numerous empirical subject ontologies implemented in different standards [32], since **there is no one-toone correspondence between morphology, syntax and semantics**. "Language is a process of communication between people, and is inextricably enmeshed in the knowledge that those people have about the world. That knowledge is not a neat collection of definitions and axioms, complete, concise and consistent. Rather it is a collection of concepts designed to manipulate ideas. It is in fact incomplete, highly redundant, and often inconsistent" [33, p. 26]. If the goal of Web semantization set by the head of the W3C Consortium T. Berners-Lee in 2001 [34] had been achieved, then modern computing power, both hardware and software, including large language models and other neural network algorithms for deep machine learning and big data processing, would already have allowed the Internet to be transformed into a Global Artificial Intelligence - so called Giant Global Graph (GGG). However, first it will be necessary to solve the problem of automatic semantic markup of natural language content, the main stumbling block of which was the incorrect operation of the lexical analyzer, which generated critical errors in syntactic analysis and catastrophic errors in semantic analysis.

II. Language categories

Metasemantics of language categories or semantics of language semantic categories is the content of language patterns that form the basis for distinguishing parts of language in a paradigm [35]. The reliability of syntactic rules depends entirely on the accuracy of determining the place of signs in the language hierarchy, i. e. on the correct interpretation of the language patterns content used by the intellect at a subconscious level as the basis for ordering the language by sequentially dividing it into parts. Any exceptions made here only indicate mathematical and semantic errors on the part of the researcher, because language, like any other system⁴, is always determined ⁵. The correctness for the interpretation of a linguistic pattern content, in turn, depends on the degree of its formalization – only then is it possible to prove the consistency of the consequences. The Theory for Automatic Generation of Knowledge Architecture (TAPAZ), which includes the Deductive Theory of Language and its Pre-Description⁶, is effective in solving this issue and allows us to identify the following semantic categories.

A. The World Model, language and metalanguage

The primary level of signs semantic stratification consists of Language Parts – subsets of the language

⁵ Contradictions arise not in the system, but during its implementation in a material where some system has already been implemented, and therefore are not systemic, but intersystemic in nature. Hence, for example, the *ideal pendulum* system, widely known in physics and described by differential equations, is easier to implement in metal or stone than in wood or paper. For more details on this, see: Melnikov G. P. Systemology and Language Aspects of Cybernetics. Moscow, Sov. Radio, 1978, 368 pp. (In Russian).

⁶ See: Hardzei A. The Principles of Calculating the Semantics of Subject Domains. Minsk, Belarusian State University Publ., 1998, 156 pp. (In Russian).

⁴ See the works on general systems theory by A. A. Bogdanov [36], T. Kotarbinski [37], L. von Bertalanffy [38], K. Boulding [39],

N. Wiener [40], W. R. Ashby [41], J. von Neumann [42], etc.

system, the elements of which are signs with a common, extremely abstract pattern in their aspect of meaning, and **Signs of Syntax Alphabet** – auxiliary means of syntax (at the macro level – prepositions, postpositions, conjunctions, particles, etc., at the micro level – inflections, prefixes, postfixes, infixes, etc.), serving to connect the constituents of language structures and the formation of morphological paradigms [43, p. 11]. Signs of Syntax Alphabet do not belong to the language, but to the metalanguage (the language that interprets another language), because they denote not the facts of the World Model, but the facts of the language; they do not play independent roles in a sentence.

B. The individ and individ's attribute 7

Parts of Language are subsets of the language system, the elements of which are signs with a common, extremely abstract pattern in their aspect of meaning. They are divided into *substantives (taigens)*, denoting individs, for example: книга "book", стол "table", восемь "eight", мы "we", and predicatives (yogens), denoting the attributes of individs, for example: бежать "run", коричневый "brown", смело "boldly", очень "very". They differ in four parameters:

1) semantic - if, as a result of substituting the diagnosed element to the left of ..., a marked sentence is obtained, then it is a predicative, if unmarked - then a substantive, for example: Бег вызывает исталость "Running causes fatigue", but "*Does the city cause ...?" [44, pp. 17–19]; to increase the reliability of the test and to exclude metaphors like *Город вызываem...? "The city causes (evokes) admiration", we recommend using the opposite procedure: if to the right of ..., when ... the diagnosed element in the role of the grammatical predicate turns the sentence into a correct one and semantically identical to the sentence with ... causes ..., then it is a predicative, otherwise it is a substantive, and any rewriting of affixes is allowed, for example: \mathcal{A} устаю тогда, когда бегаю "I get tired, when I run", but in the case of *Я восхищаюсь тогда, когда горожу? "*I feel admiration, when I city?" the correct sentence is Я восхищаюсь тогда, когда нахожусь в городе "I feel admiration, when I am in the city" with the diagnosed element in the role of the grammatical circumstance, therefore, *ber "run"* is a predicative, and *ropod "city"* is a substantive [45, p. 71];

- syntactic in an expanded sentence, predicatives occupy central positions, substantives – marginal ones [44, pp. 17–25], for example: "Спутник меняет орбиту" "The satellite changes orbit";
- 3) syntagmatic in non-composite taigens the modificator (defining component) comes first, and the actualizator (defined component) comes second, which is often collapsed into a suffix or erased: принимающее устройство "receivingdevice" → приём-ник "receiv-er", булочная лавка "bakery shop" → булочная-ø "bakery-ø"; in non-composite yogens, on the contrary, the actualizator comes first (often collapsed into a prefix or erased: делать круг "make a circle" → о-кружать "en-circle", бежать галопом "run at a gallop" → ø-галопировать "ø-gallop"), and the modifier comes second ⁸;
- 4) paradigmatic predicatives have a degree, substantives do not. Variable predicatives of the first degree denote a variable attribute of an individ, that is, a process in which he participates (e. g., to squeeze); variable predicatives of the second degree denote an attribute of an attribute of an individ (e. g., quickly \rightarrow to run quickly)⁹; variable predicatives of the third degree denote an attribute of an attribute of an attribute of an individ (e.g., *very* \rightarrow *quickly* \rightarrow *to run*). The second and third degrees of predicatives can be positive or negative. Predicatives of the second and third positive degrees clarify the meanings of predicatives of the first degree (e. g., to run very quickly), and predicatives of the first degree - the meanings of predicatives of the second and third negative degrees (e. g., very much \rightarrow to love \leftarrow to run, i. e. to love running very much ¹⁰). Positive or negative sign of the third degree in predicatives is determined syntagmatically: if a predicative of the third degree relates to a predicative of the second positive degree (to run very quickly), then it has a positive sign, if to a predicative of the second negative degree (to love reading very much), then

⁹ The name *evaluative* is appropriate for variable predicatives of the second degree, since their semantics can be measured: быстро "fast", быстрее "faster", очень быстро "very fast".

¹⁰ Predicatives of the second negative degree are conveniently called *modal* by analogy with modal verbs in the Greco-Latin classification.

⁷ For two types of pattern, see: Hardzei A. Foundations of Combinatory Semantics. L. V. Rychkova (ed.) Collection of Papers on Lexicography Vocabulum et vocabularium [The Word and the Lexicon]. Grodno, Grodno State University Publ., 2005, pp. 32–35. (In Russian); Hardzei A. Semantics of Metasemantics. In : Scientific Notes of the V. I. Vernadsky Tauride National University. Series : Philology, vol. 20 (59). 1, Simferopol, 2007, pp. 126–133.

⁸ On the nominative unit and its contraction, see also: Hardzei A. The Principles of Calculating the Semantics of Subject Domains. Minsk, Belarusian State University Publ., 1998, 156 pp. (In Russian); Martynov V. V. Language Categories. The Semiological Aspect. Moscow, Science Publ., 1982, 192 pp. (In Russian); Martynov V. V. Semeiological Foundations of Computer Science. Minsk, Science and Technology Publ., 1974, 192 pp. (In Russian); Martynov V. V. Foundations of Semantic Coding. Experience of Knowledge Representation and Transformation. Minsk, European Humanitarian University Publ., 2001, 140 pp. (In Russian); Rozwadowski, J. Słowotworstwo i znaczenie wyrazów. In : Wybór pism. Warszawa, PWN, 1960, t. 3. Językoznawstwo ogòlne, s. 21–95. (In Polish).

it has a negative sign [45, pp. 74-75].

We note that the semantic categories of the World Model, individ, and individ's attribute pertain to the World Theory; language, Part of Language, taigen (substantive), yogen (predicative) pertain to the Theory of Language; metalanguage, Sign of Syntax Alphabet pertain to the Theory of Metalanguage. In our further presentation, the names of the categories of the World Theory and the Language Theory will coincide (for example, single-place vs. multi-place characterize both the World Model and the Language), but they should be distinguished, since the semantic categories of the World Theory depend on the observer's point of view (at the micro level, a tree is perceived as a system of individs root + trunk + crown, at the macro level – as a whole individ, a separate tree), and the semantic categories of the Language Theory and the Metalanguage Theory, i. e. linguistic and metalinguistic semantic categories are independent (the Russian sign dependent "a tree" always denotes one individ, деревья "trees" denote a group of individs; the Russian preposition *e* "in" is always used to construct locatives of inclusion положить книгу в ящик письменного стола "to put a book in a desk drawer", but not exclusion *положить книгу вне ящика письменного стола "*to put a book outside a desk drawer"). A strict distinction between the categories of the World Theory, the Language Theory, and the Metalanguage Theory is necessary to achieve consistency of analysis and avoid Russell's paradox.

C. Expanded and reduced formation

In developing the idea of A. V. Isachenko on semantic condensation [46, p. 338], Parts of Language with minimal semantic condensation are called expanded; these are either *composite* stable combinations of signs with an obvious two-component structure of free (morphologically integrally formed) stems and/or roots, such as хвойный лес "coniferous forest", научно обоснованный "scientifically proven", покрыть краской "cover with paint" or complex signs with a two-component structure of connected (truncated) stems and/or roots, such as водопад "waterfall", солнцезащитный "sunscreen", злословить "backbite". Reduced Parts of Language are those with the maximum degree of semantic condensation, these are either *contracted* Parts of Language with hidden two-component combinations of connected (truncated) stems or roots with stems or roots condensed into affixes, such as приём-ник "receiv-er" ← принимающее устройство "receiving device", npeкрасный "beauti-ful" ← очень красивый "very beauty", o-кружать "en-circle" ← делать круг "make a circle", or constricted Parts of Language, which are combinations of free stems or roots with erased but semantically

reconstructed stems or roots ¹¹, such as *nasep* "laser" \leftarrow light amplification by stimulated emission of radiation, булочная-ø "bakery-ø" ← булочная лавка "bakery shop", *ø-галопировать* "ø-gallop" ← бежать галопом "run at a gallop". The ambiguity of categorical semantics of taigens and yogens in diachrony creates favorable conditions for their conversion in synchrony by rearranging taigens from marginal positions of a syntactically expanded sentence to central ones, and yogens from central to marginal ones: (Я) ремонтирую дверной замок "I repair the door lock" vs. (Я) замыкаю дверь "I lock the door". In synchrony, conversion closely interacts with affixation and in the process of sign compression can be considered as its degenerate case, especially in languages with developed morphology: столовая комната "canteen area" → столов-ка "cant-ina" → столовая-ø "canteen".

D. Informational and physical localization

A fragment of the World Model, including the roles of all participants in the event ¹², is defined as physical or informational by the nature of the interaction of individs: if the subject's shell acts as an instrument, then the impact is physical: *to treat* (physical yogen) \rightarrow *doctor, medicine, patient* (physical taigens), if its surroundings, then it is informational: *to teach* (information yogen) \rightarrow *teacher, knowledge, student* (information taigens).

E. Constant and variable feature

Substantives (taigens) and predicatives (yogens) are divided into *constants* and *variables*, depending on whether they denote the sets of homogeneous individs *i*const, for example: 'idea', 'horse' (constant substantives) or the sets of heterogeneous individs *i-var*, for example: 'it', 'this' (variable substantives), whether they denote the set of properties of individs p(i): 'mental', 'gray' (constant predicative) or the sets of functions of individs f(i), i. e., the processes in which individs are involved: 'to think', 'to gallop' (variable predicative). Some syntactic rules, for example, the order of grammatical attributes, require additional division of constant taigens and yogens into proper and common, which select an individ and individ's attribute from a homogeneous set Muhck (city Minsk), минский (Minsk region), or, conversely, include in a homogeneous set город "city", городской "urban"; besides, it is advisable to divide variable taigens and

¹¹ For etymological procedures for reconstructing the twocomponent nature of signs, see: Martynov V. V. Etymology and Hidden Two-Component of the Word. In : Studia etymologica Brunensia 2. Praha, 2003, pp. 81–91. (In Russian).

¹² Subject – the originator of the action, object – the recipient of the action, instrument – a performer of the action, the closest individ to the subject, mediator – i. e. mediator of the action – the closest individ to the object. For more information on the World Model and its structure, see: Hardzei A. Foundations of Combinatory Semantics. L. V. Rychkova (ed.) Collection of Papers on Lexicography Vocabulum et vocabularium [The Word and the Lexicon]. Grodno, Grodno State University Publ., 2005, pp. 32–35.

constant yogens condensed from them into *personal* and *impersonal*, denoting the first person (persons) in the role of an observer (observers) '*I*', '*my*' ('*we*', '*our*'), the second person (persons) in closest environs of the observer (observers) '*you*', '*yours*' ('*you*', '*yours*'), and the third person (persons) in distant environs of the observer (observers) '*he*', '*she*', '*it*', '*his*', '*hers*' ('*they*', '*theirs*') or, conversely, not directly denoting anybody in environs of the observer (observers) '*someone*', '*everyone*' ¹³.

F. Qualities and quantities

The procedure of delimitation is based on the passage to the limit, the most important operation of mathematical analysis. "The basis of this operation is the fact that the distance between any two points on the real line is defined. A number of fundamental facts from analysis are not connected with the algebraic nature of the set of real numbers $< \ldots >$, but depend only on those properties of real numbers which are related to the concept of distance" [47, p. 16]. If a sign denotes a number or a feature (property, function) of a number or a feature (property, function) of number and a geometric figure, then it is quantitative; if a sign denotes a geometric figure or a feature (property, function) of a geometric figure, then it is qualitative, for example, dea "two", emopoù "second", складывать "to add" are quantitative signs (constant taigen, constant yogen and variable yogen), дуэт "duet", двустворчатый "bivalve", соединять "to connect" are qualitative. It is convenient to call quantitative constant informational taigens and yogens numerical, ¹⁴ quantitative variable informational and physical taigens - *measured*. ¹⁵ Qualitative variable taigens and qualitative constant reduced vogens are additionally divided into indicative smo "this (is)", mo "that (is)", *smom* "this (thing)", mom "that (thing)", and arbitrary белый "white", каменный "stone (house)", indicating and, accordingly, not indicating an individ and individ's attribute in the closest or distant environs of the observer. Numerical and arbitrary taigens are divided into interrogative сколько "how many", кто "who" and narrative oduh "one", sce "all", ¹⁶ and arbitrary yogens are divided first into relative белый "white", картонный "cardboard (packaging)", denoting features that relate to an individ, and possessive чей "whose", собачий

"dog's", denoting features that belong to an individ, ¹⁷ then into interrogative который "which", чей "whose" and narrative картонный "cardboard (packaging)", собачий "dog's".

G. Single-place and multi-place

Single-place taigens and yogens name one individ or one attribute of an individ (шкаф "cabinet", коричневый "brown", открыть "to open once"), while multiplace ones name a set of individs or a set of attributes of individs (мебель "furniture", яркий "bright", открывать "to open twice"). In complex cases, the power of Language Parts is determined procedurally: single-place taigens and yogens name a whole set, while multi-place ones name a whole set and some part of it, for example: *depebo "a tree"* is a single-place taigen (a part of a tree is not a tree, but a crown, trunk, or root), *nec "a forest"* is a multi-place (a part of a forest is also a forest). Compare with the morphological category of number: the lexeme Афины "Athens" has a plural form, while the lexeme мебель "furniture" has a singular form, but the former is a single-place taigen, while the latter is a multi-place one; in the lexeme cadbi "gardens", the semantic and morphological categories coincide.

H. Intensities and extensiveness

Intensive taigens and yogens denote a whole set and some part of it, represented by a proper subset with the number of individs greater than, or equal to, one: nec "forest", мебель "furniture", порошок "powder", яркий "bright", иметь "to have" and extensive ones denote a whole set and some part of it, represented by a group of subsets with the number of individs greater than, or equal to, one: trees, forests, powders, шагать "to step (many times)", i. e. intensive signs denote a set as a whole one, and extensive ones denote a set as a set. In complex cases, the procedure of minimization is used: if the power of the set denoted by the sign either cannot be reduced at all, i. e. it is impossible to single out a separate individ from the set, for example, *boda "water"*, or it is reduced to one, when the name of a set with the number of individs greater than one coincides with the name of one of its individs, for example, nanomo "coat", then the sign is intensive; if the limit of reducing the power of the set is two or more individs, then the sign is extensive, for example, деревья "trees". For a number of variable yogens, intensity is equivalent to *iterativity*.

I. Positive and negative degree

An important distinguishing feature of yogens is their degree. The *first degree* yogens denote the individ's

¹³ Compare with personal pronouns in the Greco-Latin classification of Speech Parts.

¹⁴ Numerical taigens are a type of informational taigens that name numbers: два "two", десять "ten", сто "one hundred", тысяча "one thousand".

¹⁵ Compare with cardinal and ordinal numerals, as well as with measured words in the Greco-Latin classification.

¹⁶ The terms are borrowed from the paradigm of sentences, which as speech unites are divided by form into narrative and interrogative, by purpose into affirmative (containing an assertion) and imperative, by evaluation into positive and negative, by expressiveness into epic and exclamatory [48, p. 228].

¹⁷ Compare with demonstrative, interrogative and possessive pronouns, as well as qualitative, relative and possessive adjectives in the Greco-Latin classification. Note that the traditional opposition of qualitative and relative adjectives does not stand up to criticism (see paragraph 1 of this article).
attribute жёлтый "yellow", сжимать "to squeeze", the second degree yogens denote the attribute of the attribute тёмный "dark", темно-коричневый "dark brown", быстро "fast", быстро бежать "to run fast", the *third degree* yogens denote the attribute of the attribute of the attribute (ультра "ultra", ультра/темнокоричневый "ultra dark brown", очень "very", очень быстро бежать "to run very fast"). The second and third degrees of yogens can be positive or negative. The second and third positive degree yogens specify the meanings of the first degree yogens *ультра/темно*коричневый "ultra dark brown", очень быстро бежать "to run very fast", and the first degree yogens specify the meanings of the second and third negative degree yogens очень рад видеть "very glad to see", очень любить бегать "to love running very much". The third positive or negative degree of yogens is determined syntagmatically: if the third degree yogen refers to the second positive degree yogen очень быстро бежать "to run very fast", then it is positive, if the third degree yogen refers to the second negative yogen очень любить читать "to love reading very much", then it is negative.

J. Resultativeness and non-resultativeness

Constant yogens are always resultative. A variable yogen is *resultative* if it denotes the subject's impact on object₁ or on object₂ with object₁ as a constant attribute of object₂ (deep impact); a variable yogen is *non-resultative* if it denotes the subject's influence on the closest environs of object₁ (i. e. on object₂), and object₁ is not a constant attribute of object₂ (superficial impact ¹⁸). Such is, for example, the difference between the variable yogens *Budemb* "*to catch sight of*" and *cmmpemb* "*to look*", i. e. one can *look*, but not obtain a result (*to catch sight of*). Graphically, the difference between a resultative and non-resultative yogens is depicted as follows (Fig. 1):

- 1 -- object;
- 2 closest environs of object;
- 3 subject;

(dotted line) denotes an object as a constant attribute of its closest environs.



Figure 1.

¹⁸ Deep impact changes the object, superficial impact can only move it.

K. Completeness and incompleteness

Variable yogens that name a completed or uncompleted process are classified as completed *bpan* "took" and, accordingly, uncompleted *bpëm* "take".

L. Brevity and duration

Variable yogens denoting a short process *открыть* "*open*" are short, those denoting a long process *открывать* "*be opening*" are long.

The listed semantic categories of language allow us to formulate one-to-one rules in syntax and solve many important syntactic problems. For example, in relation to analytical applicative languages, such as Chinese, to derive the law of the Chinese syntax main line, which consists in alternating taigens with yogens in the role of the principal parts of a sentence in the basic sentence position, and to construct the Virtual String of Chinese syntax in the form of the complicated Chinese sentence generalized model, in which all its parts are realized ¹⁹.

III. Paradigm of Language Parts

A. The General Paradigm

The General Paradigm of taigens and yogens is graphically depicted in Fig. 2–3. Its purpose is to show the general in the hierarchy of Language Parts. For the sake of compactness and transparency of the presentation, the paradigmatic detailing of taigens is given using the example of constricted Parts of Language, and the paradigmatic detailing of yogens is given using the example of contracted Parts of Language; composite, complex, and contracted taigens are subdivided similarly to constricted ones, and composite, complex, and constricted yogens – similarly to contracted ones; the division of informational taigens and yogens is isomorphic to the division of physical ones.

B. The Special Paradigm

The Special Paradigm is focused on the difference in the hierarchical structure of taigens (Fig. 4) and yogens (Fig. 5). It is derived from the General Paradigm by introducing additional hierarchical levels that are characteristic only of taigens or only of yogens. It was the Special Paradigm that made it possible to start creating a lexical analyzer based on semantic rather than morphological categorical features within the framework of the scientific assignment and the research work of the same name "The Development of Artificial Intelligence Technologies Based on a Lexical Analyzer

¹⁹ See: Hardzei A. Virtual String as a Syntactical Code of a Sentence (by the examples of the Chinese language). Proceedings of International Research Conference "Language, society and problems of intercultural communication". Grodno, Grodno State University Publ., 2007, pt. 2, pp. 349–358. (In Russian); Hardzei A. New Edition of the Virtual String of Chinese Syntax. In : The Paths of the Middle Kingdom. Minsk, Minsk State Linguistic Univ. Publ., 2025, iss. 12, pt. 1, pp. 25–37. (In Russian).



Figure 2. The General Paradigm of Taigens *All original lexical borrowings are constricted



Figure 3. The General Paradigm of Yogens

**Only when designating a physical process (*denume nupor*). Constricted physical quantitative single-place and multi-place extensive yogens in Russian have not been found; a contracted physical quantitative single-place variable is, for example, yogen *ypabensmb*, contrated physical variable quantitative multi-place extensive is yogen *ypabensmb*.

and Knowledge Bases" of the subprogram "Digital Space Technologies, Human, Social and State Security 1.1.7" (Resolution of the Presidium of the National Academy of Sciences of Belarus dated September 11, 2023, No. 28).

In the Special Paradigm, as in the General Paradigm, for the sake of compactness and transparency of presentation, the paradigmatic detailing of taigens is given using the example of constricted Parts of Language, and the paradigmatic detailing of yogens is given using the example of contracted Parts of Language; composite, complex and contracted taigens are subdivided similarly to constricted ones, and composite, complex and constricted yogens -similarly to contracted ones; the division of physical and informational taigens and yogens is isomorphic; proper taigens and yogens do not have stratification; constant physical modal yogens, and single-place qualitative evaluative variable yogens have not yet been detected in the Russian language, examples of constant informational modal yogens are: возможный "possible", возможнее "more possible", вероятный



Figure 4. The Special Paradigm of Taigens *Only when designating information individs.



Figure 5. The Special Paradigm of Yogens

**Constant physical modal yogens and single-place qualitative evaluative variable yogens have not yet been detected in the Russian language; examples of contant informational modal multi-place yogens are: вероятный, вероятнее.

***Only when designating the attributes of physical individs.

"probable", вероятнее "more probable", etc.

Conclusion

The Special Paradigm of Language Parts is, in general, sufficient for the analysis of the syntax of applicative languages, such as Chinese. Its prospects for English and Russian are also beyond doubt, because by the stepwise division of the set of taigens and the set of yogens into subsets and subsets of subsets, any level of discreteness in the representation of linguistic units is achieved. In support of this, we will give several examples for further recursive detailing of the Special Paradigm as applied to the Russian language (Figs. 6–8). The time paradigm for variable yogens (Fig. 8) displays the **temporal meta-transformation** in the ontological aspect (*past* vs. *future*) ²⁰: *Cecmpa прочла книгу "The sister read the book" Cecmpa прочтёт книгу "The sister*

 20 They differ in the *point of singularity* on the time scale: before it is the past, after it is the future.

will read the book" and in the gnoseological aspect (present vs. future in the past)²¹: Сестра читает книгу "The sister is reading the book" Сестра читала бы книгу "The sister would read the book" [49, p. 29].



Figure 6. The Genus Paradigm of Taigens



Figure 7. The Aspect Paradigm of Variable Yogens



Figure 8. The Time Paradigm of Variable Yogens

In conclusion of the article, we note that in TAPAZ-2 the top-level ontology is specified constructively using an oriented Knowledge Graph with a total number of vertices $S_n \approx 8, 2 \times 10^{245}$, built on a Semantic Classifier of 112 macroprocesses and a sheet of 32 roles of individs calculated by TAPAZ-2 algebra [50], which provides a unique opportunity to create a system for Natural Language Processing taking into account the already known properties of the semantic analyzer, which is based on an optimized version of the TAPAZ-2 Knowledge Graph (a graph suitable for processing by modern technical means [51], i. e. now is possible to solve the problem from top to bottom: from the semantic analyzer to the syntactic and lexical one. The advantage and effectiveness of this approach compared to existing methods are obvious [52]. The implementation of this task will be a decisive step in the creation of an inventive machine.

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ЛИНГВИСТИЧЕСКОЕ ОБОСНОВАНИЕ СОЗДАНИЯ ЛЕКСИЧЕСКОГО АНАЛИЗАТОРА НА СЕМАНТИЧЕСКОЙ ОСНОВЕ

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Подробно рассматриваются логические, семантические и метасемантические парадоксы, возникающие при смешении теории и метатеории во время описания иерархических систем, объясняется их значение для лингвистики, приводятся примеры внутренней противоречивости учения о частях речи, вызывающей масштабные ошибки при обработке данных на естественном языке, обосновывается создание лексического анализатора в парадигме частей языка и теории автоматического порождения архитектуры знаний (ТАПАЗ–2).

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Evolution of Cybernetic Systems: from Computer Systems with Strong Intelligence to Superintelligent Human-Machine Communities

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Abstract—The article considers the key features of cybernetic systems, their evolution and parameters that determine the level of their intelligence and self-organization. Hierarchical systems of parameters characterizing the current capabilities and speed of development of cybernetic systems, as well as factors contributing to the acceleration of their evolution are considered. Special attention is paid to semantically close concepts related to the level of intelligence of cybernetic systems and to the evolution processes of both individual and multi-agent cybernetic systems. The prospects of next-generation intelligent computer systems and the complex technology of their development and maintenance are considered. Finally, the impact of technological evolution on the development of human society is discussed, and the idea of the Global Human-Machine Community is proposed.

Keywords—artificial intelligence, cybernetic system, evolution, multi-agent system, OSTIS, ecosystem, human-machine system

I. INTRODUCTION

The current state of *artificial intelligence technology* can be characterized as follows:

- the illusion of well-being
- is very labor-intensive to develop and maintain modern *intelligent computer systems*
- is labor-intensive to combine modern *intelligent computer systems* into complex intelligent multiagent computer systems.
- the inability of <u>modern</u> computers to implement intelligent computer systems, which leads to artificial complication of intelligent computer systems and to decrease of their performance.

The analysis of the above circumstances allows us to conclude that the problems of the current state of the theory and practice of *artificial intelligence*

- have <u>fundamental</u> methodological reasons and require rethinking of the fundamental foundations of the theory of *intelligent computer systems* and technologies of their development, maintenance and operation
- requires a transition to a <u>a fundamentally new</u> <u>generation of intelligent computer systems</u> and their corresponding technologies.

Challenges cited include:

- 1) The problem of convergence and integration of various aspects of new generation intelligent computer systems and the corresponding technology of complex support of their life cycle:
 - Convergence and integration of different models of information representation and processing in new generation intelligent computer systems:
 - Convergence and integration of different types of knowledge in knowledge bases of new generation intelligent computer systems;
 - Convergence and integration of different models of problem solving in new generation intelligent computer systems;
 - Convergence and integration of different types of interfaces of new generation intelligent computer systems;
 - Convergence and integration of different directions of artificial intelligence in order to build

a general formal theory of intelligent computer systems of new generation;

- Convergence and integration of design technologies of various components of new generation intelligent computer systems in order to build a comprehensive design technology of new generation intelligent computer systems;
- convergence and integration of technologies to support various stages of the life cycle of new generation intelligent computer systems in order to build a technology of complex support of all stages of the life cycle of new generation intelligent computer systems: design, reproduction, operation, monitoring, modernization;
- convergence and integration of various human activities in the field of artificial intelligence (research activities, development of technological complex, applied engineering, educational activities) to increase the level of coherence and coordination of these activities, as well as to increase the level of their complex automation with the help of semantically compatible intelligent computer systems of new generation;
- convergence and integration of the most diverse types and areas of human activity, as well as means of complex automation of this activity with the help of intelligent computer systems of the new generation.
- 2) The problem of ensuring the explainability of intelligent computer systems and increasing the level of trust in them.
- Development of methods and means of decentralized situational management of agents' activity at different levels of hierarchical multi-agent systems.
- 4) The problem of creating self-developing and, in particular, self-learning intelligent computer systems.
- 5) The problem of ensuring interoperability of intelligent computer systems: semantic compatibility, mutual understanding and coordination of intelligent computer systems in the process of collective problem solving [1].

At present, the technological evolution of human society is transitioning to a fundamentally new technological mode, based on the development and expansion of applications of Artificial Intelligence technology in various fields and types of human activity. This requires a systematic approach to the creation of the next generation of applied *intelligent computer systems*, as well as a fundamental rethinking of the principles of organization of human activity with the help of such systems, which will turn from <u>user-controlled</u> tools performing complex tasks into sufficiently independent partners of joint activity. This systemic rethinking of the organization of humanmachine activity should ensure the highest possible level of *synergetic effect* when integrating various types and areas of this activity and exclude the eclectic connection of a variety of specialized technologies, which is fraught with high overhead costs "at the junctions".

The modern differentiation and local (short-sighted) nature of the development of various directions of *artificial intelligence*, as well as the development of means of informatization of various spheres (branches) of human activity, the lack of <u>complex</u>, systemic approach in solving these problems have led to the fact that behind the "trees" the "forest" of informatization and intelligentization created by us became poorly visible and plunged into a thick "fog". The key approach to overcoming these difficulties is the *convergence* of various directions of artificial intelligence and various branches of human activity.

It is most logical to justify the necessity of such convergence on the basis of General Theory of Evolution of Cybernetic Systems and, in particular, intelligent computer systems. The ability to evolve, (i.e., to increase the level of self-organization and, in particular, to self-evolve) is a basic property of cybernetic systems. If a cybernetic system does not pay proper attention to it, the regression of this system is inevitable.

II. Cybernetic Systems

A. Cybernetic System Concept

cybernetic system

- := [open dynamic system that interacts with its environment on the basis of its *internal information* model of the environment (its subjective picture of the world).]
- \Rightarrow explanation*:

[A fundamental distinguishing feature of *cu*bernetic systems is that each of them has a processor-memory, which stores and processes the internal information model of the environment of the corresponding cybernetic system. The specified information model with the help of **processor-memory** has a high enough level of **flexibility** and high speed of change, which allows *cybernetic system* to timely and adequately respond to changes in the *external environment* and manage its own *activity*. Thus, the key factor in the efficiency (quality) of a cybernetic system is the structure and content of its internal information model of the environment. Accordingly, the key concept underlying the *cybernetic system* is the concept of *information* (*information construct*).]

 \Rightarrow note*:

[The environment of cybernetic system includes all the objects it affects and, in particular, all the cybernetic systems with which it interacts.]

:= [dynamic system, actively, independently and purposefully interacting with its environment]

 $:= explanation^*:$

[dynamic system, capable of maintaining its integrity, performing various actions and carrying out some activities, i.e. capable of being an active subject (agent) of some actions and some private (specialized) activities]

 $:= explanation^*:$

[dynamic system, which is based on such properties as purposefulness, autonomy, homeostatic activity, self-organization, evolvability, learnability, intelligence, which determine the quality (level of development) of this dynamic system]

 \Rightarrow note*:

[With respect to *cybernetic systems* we can speak of the following *dynamic systems*:

- *dynamic system*, which is investigated by the cybernetic system and is a part (fragment) of its *environment*.
- dynamics of the process of accumulating and refining information about the *dynamic system* under study the history of *situations* and *events* occurring in this system.
- dynamics of the process of accumulation and refinement of *information* about a certain set (class) of systems similar to the system under study the dynamics of evolution of *factual information* about the investigated *subject domain*.
- dynamics of the evolution of the *ontology* of the investigated *subject domain*, i.e. the evolution of knowledge about properties and regularities in this *subject domain*.
- dynamics of the problem-solving processes in this domain.
- dynamics of the evolution of methods, techniques and tools for solving problems in a given subject domain.

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\Rightarrow note*:
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[The environment surrounding a cybernetic system changes its state also under the influence of the cybernetic system itself. I.e. the mentioned medium, as well as the *cybernetic system* "living" in this medium, are *dynamic systems*. However, in the *memory* (in the information space) of each *cybernetic system*, the dynamics of its environment and the dynamics of its own behavior in this environment are described by <u>static information</u> *constructs*. In the simplest case — this is a "frameby-frame" description of the sequence of states of the described *dynamic systems*.

Nevertheless, the dynamics of the very information constructions stored in the memory of cybernetic systems (located in its information space) also takes place. But the essence of this dynamics (the essence of *information processes* in the information space) is different - it is either processes of solving cybernetic system various tasks, or the processes that carry out imitation modeling (emulation) of real processes occurring in the external environment, or *processes* aimed at improving the quality of the current state of *information* stored in *memory* (information space), or processes of accumulating (collecting) and analyzing information about the environment (about situations, events and processes occurring in it).

B. Classification of cybernetic systems

$cybernetic\ system$

 \Rightarrow subdividing*:

- *individual cybernetic system biological organism*
- $\bullet \ multi-agent \ cybernetic \ system$
 - \coloneqq [distributed cybernetic system]
 - := [cybernetic system, in which its memory, processor, interface and the stored internal information model of the environment are distributed (to some extent virtual)]
 - := [cybernetic system, which is a collection of cybernetic systems that are agents of a multi-agent system, interacting with each other through their interface facilities and possibly through a special communication environment]
 - \Rightarrow subdividing*:
 - {● two-level multi-agent cybernetic system
 ∷= [multi-agent cybernetic system all of whose agents are individual cybernetic systems]
 - hierarchical multi-agent cybernetic system
 - ≔ [multi-agent cybernetic system, wherein there is at least one agent that is a multi-agent cybernetic system]

 $\begin{array}{c} \\ \Rightarrow subdividing^*: \end{array}$

}

- {
 natural cybernetic system
 - := [cybernetic system of natural (biological) origin] ⇒ subdividing*:

- individual cybernetic system of natural origin
- multi-agent cybernetic system of natural origin
- }
- computer system
 - := [artificial cybernetic system]
 - ≔ [cybernetic system implemented as a technical system]
 - \coloneqq [cybernetic machine]
 - \Rightarrow subdividing*:
 - {• individual computer system
 - multi-agent computer system
 - }
- natural-artificial cybernetic system
 - := [cybernetic system containing both natural and artificial components]
 - \Rightarrow subdividing*:
 - {• individual natural-artificial cybernetic system
 - multi-agent natural-artificial cybernetic system

 \supset human-machine cybernetic system

$human-machine\ cybernetic\ system$

 \Rightarrow subdividing*:

}

- {• human-machine individual cybernetic system
 - := [system consisting of a mechanically (manually) operated *machine* (active tool) and a user operating the machine]
 - \Rightarrow note*:

[The controlled *machine* specified here is not a *cybernetic system*.]

- human-machine multi-agent cybernetic system
 ⇒ subdividing*:
 - {• human-machine dual-agent cybernetic system
 - := [bi-agent cybernetic system consisting of a *individual computer system* that may have <u>different</u> levels of *intelligence* and a human (user) interacting with the system]
 - human-machine multi-agent cybernetic system with more than two agents ⇒ note*:

 \Rightarrow note*:

[Such a multi-agent human-machine cybernetic system may include any number of interacting human and computer systems. The architecture of such systems may vary:

- individual computer system and many users;
- multi-agent computer system

and one user;

• multi-agent computer system and many users;

}

}

multi-agent cybernetic system \Rightarrow subdividing*:

1

- synergetic multi-agent cybernetic system
 [multi-agent cybernetic system that has achieved high efficiency in organizing the interaction of its agents]
- nonsynergetic multi-agent cybernetic system
 - ≔ [multiagent cybernetic system, contradictions and inconsistency between the actions of various agents of which significantly reduce the rate of evolution of the multiagent cybernetic system or lead to stagnation or even self-destruction]
 - ≔ [multi-agent cybernetic system on a deadend evolutionary trajectory]

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}
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\Rightarrow subdividing*:
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{● population

- := [multi-agent system, within which new agents are self-reproducing with the transfer of knowledge and experience accumulated by the population [2]]
- multi-agent system that is not a population

 $\begin{array}{c} \\ \end{array} \\ \Rightarrow note^*: \end{array}$

[The general structural decomposition of cybernetic systems into memory, processor, sensor and effector complexes is also true for *multi-agent cybernetic systems*. Only in the case of *multiagent cybernetic system* the above components are distributed (distributed over the agents of the *multiagent cybernetic system*).]

- \Rightarrow subdividing*:
 - {• individual cybernetic systems team
 - hierarchical multi-agent cybernetic system
- } \Rightarrow subdividing*:
 - {• multi-agent cybernetic system with a fixed number of agents
 - multi-agent cybernetic system with a non-fixed number of agents

⇒ explanation*: [Agents can disappear and reappear - like in a population]

- ⊃ multi-agent cybernetic system with an expandable number of agents
- }

$multi-agent\ system$

 \Rightarrow subdividing*:

- {● multi-agent cybernetic system ⊂ cybernetic system
- multi-agent embedded information processing subsystem

 \subset embedded information processing subsystem

[Multi-agent and customized can be not only a cybernetic system but also an embedded information processing subsystem.]

should be distinguished *

 \ni {• cybernetic system

- embedded information processing system
- }
- \ni {• multi-agent cybernetic system
 - multi-agent embedded information processing system
 - multi-agent system
 - $\Leftarrow union^*$:
 - {• multi-agent cybernetic system
 - multi-agent embedded information processing system

}

- \ni {• multi-agent cybernetic system
 - multi-agent processor-memory
 - ⊂ multi-agent embedded information processing subsystem
 - }

distributed internal information model of the environment of a multi-agent cybernetic system

⋮ [virtual unification (integration) of internal information models (subjective pictures of the world) stored in the memory of <u>all</u> agents of the corresponding multi-agent cybernetic system]

 \Leftrightarrow analog*:

- distributed memory of multi-agent cybernetic system
- distributed processor of multi-agent cybernetic system
- distributed sensor subsystem of multi-agent cybernetic system
- distributed effector subsystem of a multi-agent cybernetic system

should be distinguished*

- *∋* {• multi-agent cybernetic system
 - agent-centric problem solver for individual cybernetic system
 - := [individual cybernetic system problem

solver representing a hierarchy of virtual multi-agent information processing systems, each level of which is a multi-agent system whose activity is interpreted by a multi-agent system at a lower level of the hierarchy and/or is a multi-agent system that interprets the activity of a multi-agent system at a higher level of the hierarchy]

or event in the memory of an individual

- agent-oriented processor of individual cybernetic system
 - [processor, which is a collection of agents that can function in parallel (simultaneously) and each of which reacts (is initiated) to its corresponding situation

}

${\it C.} \ \ {\it General\ structure\ of\ cybernetic\ systems}$

cybernetic system

cybernetic system

- \Rightarrow generalized part*:
 - physical shell of the cybernetic system
 - $\bullet \quad internal \ environmental \ information \ model$

sensor

 \coloneqq [receptor]

- := [means of generating the value of the parameter (sign) corresponding to this sensor and determining the current state of the observed fragment of the external environment]
- := [mean of information perception]

effector

 \coloneqq [environmental influencer]

environment

- \Rightarrow generalized decomposition*:
 - {• external environment
 - I
 - \Rightarrow generalized decomposition*:
 - $\{\bullet physical shell of the cybernetic system \\ \Rightarrow generalized decomposition^*:$
 - complex of sensors and effectors of a cybernetic system
 - cybernetic system memory
 - cybernetic system processor
 - cybernetic system enclosure
 - 0 0
 - internal environmental information model

.

}

}

[All these components of a cybernetic system can be either localized (local) or <u>distributed</u> (virtual) depending on the structural type of the cybernetic system]

}

:= [external environment of a cybernetic system, and this cybernetic system itself, including all its components, including the internal information model of the environment]

 \Rightarrow note*:

[The internal information model of the environment describes the model itself, including a description of its dynamics]

 \Rightarrow note*:

[The environment of a cybernetic system includes everything that is not the combined information stored in the memory of the corresponding cybernetic system. Therefore, the environment of a cybernetic system includes its entire physical shell]

processor-memory of cybernetic system

\Rightarrow explanation*:

[This is, conventionally speaking, the internal (embedded) analog of a cybernetic system that:

- with the help of external sensors of the cybernetic system, as well as internal sensors and processor-memory effects forms its own internal subjective environment, which is a reflection (information model) of the external environment of the cybernetic system;
- permanently improves this internal information model of the external environment of the cybernetic system;
- controls external effectors and sensors of the cybernetic system, performing purposeful control of the impact on the external environment of the cybernetic system and its physical shell, as well as purposeful monitoring of the state of this external environment and its own physical shell;

]

cybernetic system processor

- := [knowledge base processing machine]
- := [set of functional means of the corresponding cybernetic system, which has sufficient completeness (integrity) for functional support of the activity of the said cybernetic system (for interpretation of information stored in the memory of the cybernetic system)]
- := [internal pseudo-cybernetic system of information processing, the environment of which is the

memory of the corresponding cybernetic system]

:= [pseudo-cyber system embedded in the corresponding cybernetic system and processing information stored in the memory of the said cybernetic system with the help of the processor of this system (with the help of means of analyzing the stored information constructs and means of their transformation)]

should be distinguished *

- \ni {• cybernetic system processor
 - cybernetic system problem solver
 - ≔ [hierarchical system of interpretation of various methods (programs) of processing situations and events occurring in the memory of a cybernetic system stored in the memory]
 - \Rightarrow note*:

[The lower level of activity of the problem solver of a cybernetic system is the direct activity of the processor of that cybernetic system]

}

should be distinguished*

- \ni {• memory
 - \coloneqq [cybernetic system memory]
 - unified aggregate information stored in the memory of a cybernetic system
 - ≔ [dynamic information model of the environment of the corresponding cybernetic system, describing (reflecting) this environment with the required degree of detail]
 - ≔ [all the information stored in the memory of a cybernetic system]
 - \supset knowledge base
 - ≔ [structured aggregation of information stored in the memory of a cybernetic system]
 - }

$internal\ environmental\ information\ model$

- ≔ [part of the cybernetic system state, which is used by processor and sensory-effector complex to organize activity (behavior, functioning) of the cybernetic system in the process of its interaction with its external environment, with its physical shell and with its internal information environment (i.e. internal information model of the environment)]
- := [internal information model of the environment surrounding the relevant cybernetic system]
- := [subjective worldview of a cybernetic system]
- $\supset knowledge \ base \\ \Rightarrow note^*:$

[The term is used to name subjective worldviews in cybernetic systems with a sufficiently high level of development (self-organization)]

- ≔ [semantically structured internal information model of the environment of an intelligent cybernetic system]
- ≔ [integrated information construct stored in the memory of a cybernetic system]
- \Rightarrow note*:

[The presence of an internal information model of the environment in a cybernetic system means that the cybernetic system "lives" simultaneously in two worlds — in the external real world and in the internal world of its information model (reflection) of this external real world.]

$cybernetic\ system\ environment$

≔ [world viewed through the "eyes" of the corresponding concrete cybernetic system and including one's own self (one's own physical shell and internal information model of the environment, i.e. one's own subjective picture of the world), as well as the environment external to oneself (the part of the environment that is outside one's own physical shell).]

$embedded \ information \ processing \ subsystem$

 \Rightarrow explanation*:

[embedded information processing subsystem is not strictly speaking a *cybernetic system*. Nevertheless, it can be regarded as an analog of a cybernetic system, namely, as a cybernetic system whose external environment is the *memory* of the corresponding *individual cybernetic system* and the information stored in this memory]

 \supset processor-memory of individual cybernetic system

- ≔ [maximum embedded information processing system]
- := [embedded information processing system that is not a subsystem to another embedded information processing system]

physical shell of a cybernetic system

- := [material shell of cybernetic system]
- := [body of a cybernetic system]
- := [internal (material) physical environment of a cybernetic system]
- \Rightarrow generalized decomposition*:
 - **{•** cybernetic system memory
 - cybernetic system processor
 - complex of sensors and effectors of a cybernetic system
 - other material subsystems, providing the exchange of substances and energy with the external environment of the cybernetic system

}

 \Rightarrow note*:

[The physical envelope of a cybernetic system is subject to the constant destructive effects of the external environment — this must be counteracted]

cybernetic system interface

- := frequently used term*:
- [interface]
- \Rightarrow generalized part*:

sensory-effector complex of a cybernetic system \Rightarrow generalized decomposition*:

- {● sensory subsystem of a cybernetic system
 ⇒ generalized part*: sensor
- effector subsystem of cybernetic system
 ⇒ generalized part*:
- effector

}

should be distinguished*

- \ni {• cybernetic system
 - ≔ [solver of external tasks of purposeful interaction with the external environment and its own physical shell of the cybernetic system by means of its sensors and effectors]
 - processor-memory of cybernetic system
 - ≔ [solver of information tasks of the cybernetic system and, among others, tasks of controlling sensors and effectors of the cybernetic system, providing the necessary detail of solving external tasks of the cybernetic system]
 - embedded information processing subsystem
 ⇒ note*:

[The result of the integration of all the information processing subsystems embedded in a *cybernetic system* is the *processormemory* of that cybernetic system]



$cybernetic\ system\ memory$

- := [environment within which the sensors of a cybernetic system and its processor create and update an internal information model of the environment of said cybernetic system, which said cybernetic system uses to organize its activities]
- ≔ [memory environment of a cybernetic system — the environment for storing and processing information (stored information constructs)]

D. Relationships and operations defined on the set of cybernetic systems

cybernetic system

\Rightarrow defined relationship*:

{• environment*

- := [be the environment from the point of view of (for) a given cybernetic system]
- \Rightarrow explanation*:

[The environment of each cybernetic system and, accordingly, the description (model) of this environment includes:

- of this cybernetic system itself (itself, its own self, internal environment),
- external environment (environment outside of the self)
-]
- \Rightarrow explanation*:

[Accordingly, the information model (description) of the environment formed by each cybernetic system is the construction of a picture of the world common to all cybernetic systems, but with the obligatory description of what I am and how I am related to this world.]

- \Rightarrow second domain*: environment
- external environment*

 \Rightarrow second domain*: external environment

- self*
 - \Rightarrow second domain*:
 - Ι
- physical shell of cybernetic system*
 - ⇒ second domain*: physical shell of cybernetic system
 - \Rightarrow generalized decomposition*:
 - **{•** sensor complex
 - effector complex
 - processor-memory of cybernetic system
 - }
 - \Rightarrow note*:

[Information messages between cybernetic systems are also exchanged through the sensor and effector complexes of the said cybernetic systems]

- sensor and effector complex*
 - ≔ [complex of means providing direct <u>physical</u> interaction with its external environment and physical shell*]
 - ⇒ second domain*: sensor and effector complex
- sensor complex*
 - ≔ [complex of tools for analyzing the physical state of one's external environment and physical shell*]
 - := [system of sensors (receptors) of a cyber-

netic system, providing input (perception) of information about the state (situations) and processes (events) in the environment*]

- := [sensory subsystem of a cybernetic system*]
- \Rightarrow second domain*:
 - sensor complex
 - \Rightarrow generalized part*: sensor
- sensor*
 - \coloneqq [receptor*]
 - \Rightarrow second domain*: sensor
 - := [receptor]
- effector complex*
 - $\coloneqq [\text{complex means of impact on its external} \\ \text{environment and physical shell*}]$
 - ≔ [system of effectors (including motor, mechanical), which are instruments of direct (physical) impact of a cybernetic system on the environment*]
 - := [effector subsystem of a cybernetic system]
 - \Rightarrow second domain*:
 - effector complex
 - \Rightarrow generalized part*:
 - effector
- effector*
- \Rightarrow second domain*: effector
- cybernetic system memory* \Rightarrow second domain*:
- cybernetic system memory • internal environmental information model*
 - \Rightarrow second domain*:
 - internal environmental information model
- cybernetic system processor*
 - ≔ [complex of means providing analysis of the state and changes in the state of the internal information model of the environment*]
 - \Rightarrow second domain*:
 - $cybernetic\ system\ processor$
- processor-memory of cybernetic system*
 - \Rightarrow second domain*:
 - processor-memory of cybernetic system
 - \Rightarrow generalized decomposition*:
 - **{•** cybernetic system processor
 - cybernetic system memory
 - }
 - \Rightarrow note*:

[This decomposition is not always possible. Not all cybernetic systems can be clearly divided into processor and memory]

 \Rightarrow generalized part*:

 $embedded \ information \ processing \\ system$

- ≔ [deep seamless integration of the processor and memory of an individual cybernetic system when the processor is distributed over memory and memory elements become processor elements at the same time]
- cybernetic system enclosure*
 ⇒ second domain*:

cybernetic system enclosure

- memory*
 - ≔ [physical environment in which the information model of the surrounding (external) environment of a given cybernetic system is stored and processed*]
 - \Rightarrow second domain*: memory
- cybernetic system interface*
 ⇒ second domain*:
 cybernetic system interface
- }

external environment

- := [environment of the cybernetic system]
- ⋮= [world surrounding a cybernetic system, viewed through the prism of its interaction with this world and including its own external environment, its own physical shell and its own picture of this world, i.e. its own (subjective) internal information model of the environment]
- \Rightarrow note*:

[The environment of a cybernetic system also includes the <u>self</u> internal information model (description) of this environment. In other words, the internal information model of the environment includes not only the description of its own external and internal environment, but also the description of this internal information model of the environment itself. It is nothing but metainformation about this internal information model.]

Ι

- := [Pointer to the sign of self]
- := [Singleton, the only element of which is the sign of the cybernetic system in whose memory the sign is located]
- := [Pointer to the sign of the cybernetic system that it is]
- \Rightarrow note*:

[As part of the internal information model of the environment, a cybernetic system can store a description of a sufficiently large number of cybernetic systems with which it interacts (in particular, a description of its users). But out of the whole set of described cybernetic systems, each cybernetic system must select a description of itself, which is necessary, at least, for realizing (comprehending) itself and its activity in the environment.]

$cybernetic\ systems$

\Rightarrow set operation*:

- convergence of cybernetic systems
 - ⊃ convergence of internal information models of the environment of cybernetic systems*
 ≔ [convergence of cybernetic systems' subjective pictures of the world*]
 - \supset semantic compatibility enforcement
- confluence of individual cybernetic systems*
- division of individual cybernetic system*
- collaboration of cybernetic systems into a collective*

E. Key features of cybernetic systems

cybernetic system

 \Rightarrow principle underlying*:

- presence of an internal information model of the environment (subjective picture of the world)
 - \Rightarrow note*:
 - [The flexibility of this model creates the conditions for self-evolution.]

 \Rightarrow note*:

[The basis for the functioning (behavior) of cybernetic systems is the use of an internal picture of the world (i.e., information processing).

The main leitmotif (strategic goal) of a cybernetic system, regardless of the awareness of this goal setting, is the evolution of the cybernetic system, i.e. increasing the level of its self-organization.]

- evolvability (unconscious, externally implemented)
 - \Rightarrow principle-prerequisite*:
 - $\bullet \quad \textit{flexibility}$
 - stratification
- self-evolving
 - \Rightarrow principle-prerequisite*:
 - reflectivity
 - expanding the diversity (specialization) of different components while increasing their synergy
- [Intelligent system lives in several worlds at the same time:
 - In the real external world (in the simplest case, the external world is its users end users and developers of different status)

• In the internal world (the world of situations and events occurring in its memory, which stores the internal information model of some fragment of the external world and is processed by agents)

In this case, both external and internal worlds can be decomposed into dynamic subject domains (into several private worlds). In each of these worlds the system simultaneously lives in the present (current), past and future time.]

evolutionary level of cybernetic system ^

 \coloneqq [intelligence ^]

 \coloneqq [intelligence level^]

:= [ability to maintain and increase one's level of selforganization[^]]

The key property of cybernetic systems is their ability to evolve (improve), including the ability to evolve independently (i.e. self-evolution). This ability is conditioned by the cybernetic system's internal information model of its environment (internal subjective picture of the world around it). The fundamental advantage of this information model is that its transformation (carried out with the help of the cybernetic system processor) has a much lower labor intensity compared to the labor intensity of transformation of the environment described by this information model.

The high speed of evolution of cybernetic systems is ensured by the flexibility of the internal information model of the environment and, as a consequence, by the simplicity of modification (transformation) of this model.

The environment itself can also be transformed, but it is much simpler and faster to transform its information model:

- to forecast the dynamics (changes) of this environment, which is not caused by own activities;
- to plan its transformation by its effectors;
- to model (foresee) the consequences of their actions in the external environment.

Since a cybernetic system is based on an internal information model of its environment, it is important how this information model is organized, what language it is represented in (what is the syntax and denotational semantics of this language), how the search for demanded information constructs (fragments of the information model) is carried out, and how these constructs are transformed [3].

should be distinguished*

∋ {• information construct that is a fragment of the internal information model of the environment

• information construct, which is a message transmitted between cybernetic systems

}

III. SYSTEM OF PARAMETERS DETERMINING THE GENERAL LEVEL OF INTELLIGENCE (LEVEL OF SELF-ORGANIZATION) OF A CYBERNETIC SYSTEM

intelligence

- \coloneqq [intellect]
- \in complex parameter
- ≔ [complex parameter characterizing the general level of development of cybernetic systems[^]]
- ≔ [complex parameter characterizing the general level of *self-organization of a cybernetic system* and defined by:
 - by the achieved current state of selforganization (achieved capabilities of the cybernetic system to preserve itself, its integrity, neutralizing destructive effects of the external environment, as well as capabilities to influence the environment);
 - by the achieved rates of its evolution (rates of increase in the level of self-organization of the *cybernetic system*);
 - acquired and evolved abilities of the *cybernetic system* to maintain and increase the rate of its evolution.

]

 \Rightarrow note*:

[It is important to emphasize that the overall level of *intelligence* (level of self-organization) of a cybernetic system is determined not only and not so much by what capabilities it has at the current moment, but by how fast and thanks to what it <u>evolves</u>. In other words, the main property of a cybernetic system is the level of its **ability to evolve**^, modernizing, transforming itself (sometimes with the help of other subjects — teachers, developers) in various directions and preferably as fast as possible.]

 \Rightarrow note*:

[cybernetic system is characterized not only by an overall comprehensive assessment of its current state, but also by an assessment of <u>speed</u> (rate) of increase (improvement) of the qualitative level of this state, as well as by an assessment of the available potential (opportunities, abilities) of the system <u>accelerate</u> the increase of the qualitative level of its state.]

[Specification of the concept of *intelligence*[^] by listing all the *parameters-factors*^{*} whose values determine the value (level) of the *intelligence*[^] of a cybernetic system. That is, the enu-

 $[\]Rightarrow$ note*:

meration of *parameter-factors*^{*} corresponding to the parameter *intelligence*[^] is nothing but a systematized indication of the requirements for *intelligent cybernetic systems*]

\Rightarrow parameter-factor*:

- current level of cybernetic system capability ^
 - := [power, variety, quality, utility (for the cybernetic system) and integrity of the current activities that the cybernetic system is able to perform at the current moment^]
 - := [current cyber system capability level^]
 - ≔ [current level of self-organization of cybernetic system[^]]
 - := [overall current level of capability of a cybernetic system as it interacts with its environment, which includes not only its external environment, but also its physical shell, and its internal information model of the environment^]
 - := [current skill level of *cybernetic system*^]
 - ⋮= [volume and variety of tasks for which the cybernetic system has the necessary information resources and has mastered methods and techniques for managing its own *effectors* and *external tools*]
 - := [multiple technologies mastered by the cybernetic system^]
 - ≔ [current level of intelligent potential (intelligent form) of the cybernetic system[^]]
 - := [achieved value of the cybernetic system's action potential (power and efficiency of this potential)^]
 - := [current level of knowledge, skills and understanding[^]]
 - \Rightarrow note*:

[The activity of a cybernetic system should not stop, first of all, because the destructive impact of the external environment on a cybernetic system never stops and must be counteracted. The activity (life) of a cybernetic system is like riding a bicycle you cannot stop, you will lose balance.]

 $\Rightarrow epigraph^*$:

[Your life is 10% dependent on what happens to you and 90% dependent on how you react to those events.]

 \Rightarrow author*:

John Maxwell

 $\Rightarrow epigraph^*$:

[I'm not a product of my circumstances, I'm a product of my decisions] \Rightarrow author*:

Steven Covey

speed of evolution of cybernetic system ^

- ≔ [current value of the rate of increase of the level of self-organization of the cybernetic system[^]]
- ≔ [current value of cybernetic system evolution rate[^]]
- := [rate of increase in the current level of selforganization — the level of power, quality, utility and integrity of cybernetic system activity^]
- := [level of ability (adaptability) of a cybernetic system to evolve both with the help of external actors (teachers, developers) and independently^]
- \coloneqq [evolutionary]
- ≔ [evolutionary potential of a cybernetic system — the ability to increase the level of action potential (level of capability) of a cybernetic system^]
- ≔ [rate of increase of the current level of cybernetic system capability^]
- ≔ [ability of a cybernetic system to evolve unconsciously, to evolve blindly]
- ≔ [ability of a cybernetic system to evolve (including learning)[^]]
- := [level (quality, rate) of evolutionary activity of a cybernetic system — the activity in anticipation, which brings benefit not at the present moment, but later (and it is not known exactly when and in what exactly this benefit will consist)^]
- := [speed of evolution of knowledge, skills and understanding[^]]

• accelerating evolution of cybernetic system ^

- := [level of development of acquired and evolvable abilities of a cybernetic system that support and enhance its own evolutionary rate]
- ≔ [ability (adaptability) to evolve itself (possibly with the help of other entities teachers, developers)^]
- := [level of knowledge of the laws of evolution and the resulting level of awareness, activity and autonomy to carry out the evolutionary process^]
- ≔ [ability of a cybernetic system to control its own evolution, to independently and purposefully organize its evolution on the basis of knowledge of the laws of evolution^]
- ≔ [meta-capability of cybernetic system to increase the level of its activity potential[^]]
- ≔ [ability of a cybernetic system to develop (to raise the level of) its ability to raise the level of its activity potential^]

- := [metaevolutionary potential of the cybernetic system[^]]
- ≔ [ability of a cybernetic system to increase its evolutionary potential]
- ≔ [ability of a cybernetic system to increase its rate of evolution]
- ≔ [ability of a cybernetic system to create (improve) conditions to increase its evolutionary rate^]
- ≔ [ability of a cybernetic system to evolve its ability to evolve[^]]
- := [ability of a cybernetic system to conscious, sense, purposeful self-evolution[^]]
- ≔ [ability of a cybernetic system to learn how to evolve better and better]
- \Rightarrow note*:
 - [Cognition of the laws of evolution (knowledge of beneficial, harmful, and dead-end evolutionary paths) and their proper application greatly accelerates the evolutionary process]
- \Rightarrow note*:
 - [A cybernetic system must not only be able to evolve (including learning), but also be able to learn how to evolve (including learning) better — that is, the highest form of evolutionary ability of a cybernetic system is to move to the meta-level of the evolutionary process]
- ≔ [level (quality) of meta-evolutionary activity of a cybernetic system, aimed at making the evolutionary process not "blindly", but to bring the maximum possible benefit and as soon as possible^]
- □ [rate of evolution of the very evolutionary activity of developing knowledge, skills and understanding[^]]

should be distinguished *

- \ni {• current level of cybernetic system capability ^
 - ≔ [current level of cybernetic system intelligence capability^]
 - evolution of cybernetic system
 - \subset process
 - \coloneqq [evolutionary process]
 - ≔ [process of increasing the level of selforganization]
 - cybernetic system evolution rate ^
 - := [evolutionary potential[^]]
 - \coloneqq [evolutionary]
 - := [ability of a cybernetic system to evolve[^]]
 - ≔ [ability of a cybernetic system to carry out its own evolution or to facilitate its evolution if it is carried out by other entities^]

acceleration of cybernetic system evolution ^ }

IV. HIERARCHICAL SYSTEM OF PARAMETERS DEFINING THE CURRENT LEVEL OF CYBERNETIC SYSTEM CAPABILITIES

current cybernetic system capability level $^{\Rightarrow}$ parameter-factor*:

- cybernetic system memory capacity ^
- functional capacity of the processor-memory of the cybernetic system ^
 - := [diversity of actions and the integrity of the whole set of classes of actions performed by the processor-memory of a cybernetic system while processing the internal information model of the environment stored in its memory]
- cybernetic system processor performance ^
- quality of internal information model of the environment ^
- variety of possible influences of cybernetic system effectors on the external environment and on the cybernetic system's own physical shell^
- total number and variety of types of sensors of a cybernetic system ^
- diversity and efficiency of utilization of the technologies possessed by the cybernetic system[^]

 \Rightarrow note*:

[The concept of *technology* used by a cybernetic system should be understood broadly enough — as a set of *methods*, information *resources*, and *tools*, which allow a cybernetic system to carry out *activities* corresponding to this technology in the presence of necessary *source data* (both informational and material). In relation to the *cybernetic system* (as an executor) the *technologies* used by it can be:

- internal (purely informational), requiring the use of only its own processor as a tool and not requiring the use of receptors and effectors of the cybernetic system;
- external, not requiring the use of external tools;
- external, requiring the use of external tools

[technological evolution of cybernetic systems, that is, the expansion of their capabilities and the improvement of the technologies they use, is an important but not the only direction of the evolution of cybernetic systems]

- self-sufficiency in the use of technology that the cybernetic system possesses ^
 - := [level of autonomy in performing various activities within a multi-agent cybernetic system[^]]
- interoperability ^
 - ≔ [ability of a cybernetic system, which is an agent or potential agent of at least one multi-agent cybernetic system, to effectively (useful) interact with other agents of the specified multi-agent cybernetic systems^]
 - ≔ [ability of a cybernetic system to engage in "social" behavior^]
 - := [level of socialization of the cybernetic system[^]]
 - := [agent socialization parameter^]
 - ≔ [quality of cybernetic system as an agent of multi-agent cybernetic systems[^]]
 - := [social characteristic (socialization level) of the cybernetic system^]
 - ≔ [quality of performing the role of an agent in multi-agent cybernetic systems[^]]
 - ≔ [quality of social behavior]
 - \Rightarrow parameter-factor*:
 - capability of understanding ·-- [ability to build rapport with
 - := [ability to build rapport with partners]
 - ⇒ parameter-factor*: ability to ensure semantic compatibility with partners^
 - consent
 - $\Rightarrow epigraph^*$:

[People are lonely because they build walls instead of bridges.] \Rightarrow author*:

- Stanislaw Jerzy Lec
- $\Rightarrow epiqraph^*:$

[Of the two quarreling, the one who is smarter is to blame]

- ability to coordinate one's own actions with the actions of partners^
- ability to participate in the formation (creation) of new multi-agent systems ^
- ability of a cybernetic system to effectively participate in increasing the level of synergy of the multi-agent cybernetic system of which it is an agent^
- ability of a cybernetic system to effectively participate in the training of a multi-agent cybernetic system of

which it is an agent

- ability of a cybernetic system to participate in decentralized organization of collectively performed activities of a multi-agent cybernetic system of which it is an agent^
- ability to be an agent of multiple multi-agent cybernetic systems ^
- responsibility ^
 - := [responsibility to partners (agents)[^]]
 - ≔ [ability of a cybernetic system to understand (realize) what it should (must) do, what it is obliged not to do, and what are the consequences of violating these rules of behavior^]
 - \Rightarrow parameter-factor*:
 - ethical responsibility^
 := [ethical responsibility^]
 := [moral responsibility^]
 - Initial responsibility ^
 legal responsibility ^
 := [legally compliant responsibility ^]
 - willingness to take responsibility ^
- controllability ^
 - $\coloneqq [ability to \underline{subordinate} where needed^]$
- ability to recognize that you are being used (manipulated, parasitized, iqnored)[^]
- ability to resist manipulation by other agents ^
- absence of manipulative tendencies
- decisiveness level
- self-esteem adequacy
- \Rightarrow note*:

[The parameter *interoperability* corresponds not only to *individual cybernetic systems*, but also to *multiagent cybernetic systems*, because multi-agent cybernetic systems can also be agents of multi-agent cybernetic systems (hierarchical multiagent systems), and several of them at the same time.]

- synergy level
 - ≔ [quality of organization of useful interaction between components of a cybernetic system[^]]
 - ≔ [efficiency of the organization of "collective" problem solving in a multi-component cybernetic system^]
 - ⇒ narrowing the parameter over the domain of definition*:
 - level of synergy of individual cybernetic

 $system \hat{}$

≔ [level of hybridization of individual cybernetic system[^]]

- level of synergy of multi-agent cybernetic system ^
 - \Rightarrow parameter-factor*:
 - minimum level of interoperability of cybernetic system agents ^
 - achieved level of mutual understanding between agents ^
 - achieved level of contractual capacity ^
 - achieved level of distribution of responsibility (duties) between agents for solving regular (regularly occurring) tasks[^] ⇒ explanation^{*}:

This implies a priori decomposition of staff tasks into subtasks, distribution of these subtasks among agents, each of which should not only individually perform its subtask, but also clearly (first of all, informationally) interact with other agents, knowing a priori with whom and how. The process of collective solution of a staff task — this is what is called a business process.

• accomplished level of ability to collectively solve abnormal problems

 \Rightarrow note*:

[Decentralized organization of agent interaction is necessary for quick and most competent (for a given multiagent cybernetic system) response to abnormal (unanticipated) situations and events.]

- achieved level of ability of agents of a multi-agent cybernetic system to coordinate their actions to keep collectively performed actions (processes) within certain limits according to predetermined parameters
- diagram of the distribution of the level of interoperability across all agents of a multi-agent cybernetic system

- diagram of semantic compatibility level distribution over all pairs of agents of a multi-agent cybernetic system
 - ≔ [diagram of the distribution of the level of coincidence of subjective worldviews across all pairs of agents of a multiagent cybernetic system]
- level of independence of the cybernetic system in the process of realization of "vital" activities important for it ^

 \Rightarrow parameter-factor*:

- level of autonomy of the cyber system
 in the process of ensuring its security^
 := [level of self-preservation capability of a cybernetic system^]
 - ≔ [level of cybernetic system's ability to independently maintain its integrity in interaction with the external environment and in preventing (neutralizing) destructive (including malicious) and not always predictable impact on the physical shell of the cybernetic system, as well as on the internal information model of the cybernetic system's environment]
 - \Rightarrow note*:

[This refers to both physical and information security]

• level of independence of the cybernetic system in the process of its material support ^

 \Rightarrow note*:

[It refers to the logistical and energetic provision of a cybernetic system with the necessary conditions of existence ("life") — the conditions that maintain the necessary capability of the system]

- ≔ [level of a cybernetic system's ability to take care of itself]
- level of independence of the cybernetic system in the process of implementation of frequently performed activities corresponding to its specialization ^
- level of independence of the cybernetic system in solving a priori unintended tasks ^
 - := [level of independence of the cybernetic system in solving abnormal tasks^]
- the capacity for appropriate and purposeful behavior ^

quality of the internal information model of the environment $\hat{}$

\Rightarrow parameter-factor*:

- volume of internal environmental information model ^
- multiplicity of knowledge included in the internal information model of the environment ^

 \Rightarrow note*:

[The most important type of knowledge stored in the *memory of a cybernetic system* is various kinds of methods (programs) for solving problems, the implementation (interpretation) of which is carried out by means of a program-controlled hierarchical reduction (detailing) of the problems to elementary subtasks, which are directly executed by the processor or *effectors of the cybernetic system.*]

- consistency and syntactic error-free internal information model of the environment ^
- semantic correctness of the internal information model of the environment[^]
 := [adequacy of the internal information model of the environment[^]]
 - := [match between the described fragment of the environment and the fragment of the information model of this environment[^]]

• semantic completeness of the internal information model of the environment ^

- := [sufficiency of information contained in the internal information model of the environment for the cybernetic system to solve its actual tasks, including tasks corresponding to its purpose^]
- \Rightarrow note*:

[the level of semantic completeness of the internal information model of the environment is determined by the number of information holes present in it, as well as by the size of these holes]

• information purity ^

:= [amount of information trash[^]]

completeness of self-description

 \Rightarrow note*:

[This parameter characterizes the necessary condition for a cybernetic system to acquire the ability of reflexivity]

- \Rightarrow parameter-factor*:
 - existence, sufficiency and variety of means of explicit designation and specification of actions performed by the cybernetic system, as well as plans, processes (protocols) and methods of their execution[^]

 \Rightarrow note*:

[The presence of means to describe the actions performed by a cybernetic system means that the cybernetic system performs these actions consciously, sensely, with understanding. In other words, it means that the cybernetic system knows what it is doing]

 \Rightarrow note*:

[The set of actions performed by a cybernetic system is categorized into two classes:

- informational actions performed in memory and transforming the internal information model of the environment
- external actions performed to transform the external environment or one's own physical shell

L

syntactic and semantic compatibility of knowledge included in the internal information model of the environment ^

 \Rightarrow note*:

[This is about the "depth" and "seamlessness" of the integration of the knowledge included in the *internal information model of the environment*. This requires a common *universal language* to represent all kinds of knowledge]

\Rightarrow parameter-factor*:

- coherence of denotational semantics of all signs (first of all, concepts) included in the internal information model of the environment, as well as coherence of all terms (names) corresponding to these signs^
- closeness of the representation of the internal information model of the environment to the semantic representation[^]

 \Rightarrow note*:

[semantic representation of the internal information model of the environment greatly simplifies problem solving:

- of convergence and integration of different knowledge
- of establishing semantic compatibility between agents
- of searching for points of intersection of interests between agents

- level of structuring and systematization of the internal information model of the environment with the help of various types of metainformation ^
 - \Rightarrow note*:
 - [We are talking about description tools whose object is the internal information model of the environment itself]
- level of development of language tools used in the internal information model of the environment to describe the structure and principles of functioning of its own physical shell
- ability of a cybernetic system to minimize the number of entities under consideration required to perform its actions
 - ≔ [ability to minimize the number (set) of entities under consideration necessary to solve a task (to achieve a goal, to perform an action), as well as to implement the entire complex of activities of a cybernetic system]
 - := [ability of a cybernetic system to adhere to Occam's Razor]
 - \Rightarrow epigraph*: Occam's Razor Principle

=

[It is foolish to exert more effort than is necessary to achieve a goal...Do not add more essence than necessary]

 \Rightarrow author*:

 $William \ of \ Occam$

ability to behave in an expedient and purposeful manner

 \Rightarrow parameter-factor*:

- ability to set goals and plan actions[^]
 - ≔ [ability to generate objectives (goals) and plans for their fulfillment (achievement) that is, to generate a hierarchical system of reducing the original task to lower-level subtasks]
 - ≔ [ability of a cybernetic system to qualitatively generate and initiate goals (tasks)[^]]
 - ≔ [ability of a cybernetic system to make quality decisions[^]]
 - ≔ [ability of a cybernetic system to qualitatively plan its actions and forecast their results and possible consequences (including negative ones)^]
 - ≔ [ability to build a clear and consistent system of its goals, including strategic goals of the highest level and a hierarchical system of tactical goals[^]]

- ability to adequately assess one's capabilities
 i= [ability of a cybernetic system to adequately (corresponding to reality) self-evaluate to realize what tasks and how well the system can solve^]
- ability of a cybernetic system to realize (highlight) the tasks (actions) that must be performed[^] ⇒ note^{*}:

[A mandatory task is either a selfpreservation task or a task that corresponds to the purpose (duties) of the cybernetic system.]

 ability of a cybernetic system to intelligently combine its mandatory actions and its optional actions for the current moment ⇒ note*:

> [The actions (intentions, desires) of a cybernetic system that are optional for the current moment include, in particular, actions aimed at its evolution.]

- ability of a cybernetic system to make sufficiently high-quality forecasts of significant and, above all, dangerous for the system situations and events in the environment[^]
 - ≔ [ability of a cybernetic system, in the course of its activity, to form and take into account its predictions — hopes and fears (fears)^]
- ability to recognize their main (strategic) goals (attitudes, motives, constraints, principles) and, accordingly, to distinguish their beneficial effects on the environment from possible harmful effects ^
 - := [ability to understand right and wrong]
- appropriateness and correctness of goal-setting ^
 - ≔ [ability to plan one's behavior in exact accordance with the main goals (attitudes, motives)^]
- appropriateness and purposefulness of direct behavior
 - ≔ [ability to carry out behavior in accordance with one's goals and plans]
- purposefulness^{*}
- $\Rightarrow epigraph^*$:
 - [It's not enough to wish: you have to do] \Rightarrow author*:
 - Johann Wolfgang Goethe
 - $\Rightarrow epigraph^*$:

[Whatever your dream is — start working on it! And then the real miracles will begin to happen in your life.]

- \Rightarrow author*:
 - Johann Wolfgang Goethe

- ≔ [ability of a cybernetic system to achieve the set goals (to solve the set tasks) both if the methods of solving these tasks are known and if these methods are currently unknown]
- := [targeting]
- := [matching goal, plan, and action[^]]
- ≔ [activity to perform an action, to achieve a goal[^]]

ability to understand $\widehat{}$

- := [level of cybernetic system's ability to understand^]
- := [ability to understand (evaluate) new information[^]]
- \Rightarrow parameter-factor*:
 - ability to understand messages from other cybernetic systems
 - \Rightarrow parameter-factor*:
 - ability to understand commands or requests received from other cybernetic systems of varying levels of complexity, and in particular to assess the feasibility, timeliness, and quality of their execution
 - ability to assess the importance and relevance of the information being acquired[^]
 - ability to understand sensory information (in particular to detect and recognize important objects, situations, events, processes)^

V. HIERARCHICAL SYSTEM OF PARAMETERS DETERMINING THE RATE OF EVOLUTION OF A CYBERNETIC SYSTEM

cybernetic system evolution rate ^

 \Rightarrow note*:

- [Parameters-factors of this parameter are parameters specifying (detailing) the rate of evolution of the cybernetic system by all parameters (attributes), which specify the *current level of capabilities of the cybernetic system* by increasing the values of these parameters. Thus, there is a correspondence between the parameters defining the current level of capabilities of the cybernetic system and the parameters defining the Speed of evolution of the cybernetic system.]
- ≔ [level of development of acquired and improved abilities of a cybernetic system that support and enhance its own evolutionary rate]
- := [ability to improve oneself, to develop]
- \Rightarrow parameter-factor*:
 - overall adaptability of a cybernetic system to its evolution by external subject-teachers ^
 :=

[ability to be a receptive, flexible object of the evolutionary process "in the hands" of other subjects^]

 \Rightarrow note*:

[When we talk about the evolution of a cybernetic system with the help of teachers, we mean the creation of a temporary multiagent cybernetic system, one of the agents of which is the evolving cybernetic system and the other agents are — its teachers, tutors, trainers, psychologists, developers] note*:

 \Rightarrow note*:

[The evolution of a cybernetic system is not only its learning (improvement of knowledge and skills), but also the improvement (modernization) of its physical shell (its body)]

- \Rightarrow parameter-factor*:
 - ability of a cybernetic system to be trained by external actors ^
 - ≔ [cybernetic system's ability to be a good student]
 - ability of a cybernetic system to modernize (transform) its physical shell, carried out by external entities ^
- o overall ability of a cybernetic system to self-evolve
 - := [ability of a cybernetic system to be both the object and subject of evolution[^]]
 - $\coloneqq [ability of a cybernetic system to self$ $evolve^]$
 - \coloneqq [self-evolving]
 - \Rightarrow parameter-factor*:
 - self-learning[^]
 ≔ [ability of a cybernetic system to learn itself[^]]
 - ability of a cybernetic system to independently modernize (transform) its physical shell^
- learnability [^]
 - := [cybernetic system's ability to learn^]
 - := [ability of a cybernetic system to evolve its internal information model of the environment^]
 - \Rightarrow note*:
 - [The internal information model of the environment includes not only a description of the environment itself, but also includes a description of oneself (one's own self) and a description of how to interact with the environment itself and with the internal information model of the environment]
 - ≔ [ability of a cybernetic system to expand and improve the quality of its *internal*

information model of the $environment^{]}$

- $\coloneqq [\mathrm{progressiveness}^{\widehat{}}]$
- \coloneqq [developmental]
- $\coloneqq [\mathrm{improvement}^{\hat{}}]$
- := [ability to reshape one's own worldview]

 $\Rightarrow epigraph^*$:

- [The most important thing not knowledge, skills and abilities, but the ability to use them effectively in their activities, as well as the ability to improve them and quickly acquire new knowledge and skills] criarent^{*}:
- $\Rightarrow epigraph^*:$

[The mind, once expanded, will never return to its former boundaries] \Rightarrow author*:

Albert Einstein

 \Rightarrow note*:

- [Learnability as an increase in the quality (accuracy) of solving problems of the same class (method improvement) should be distinguished from the expansion of the <u>number</u> of methods]
- \Rightarrow note*:
 - [If an intelligent system can only solve learning tasks, unlimitedly expand and systematize knowledge, skills and abilities, then it is potentially universal in the sense that it can learn anything, including solving any task.]
- \Rightarrow parameter-factor*:
 - ability of a cybernetic system to be trained by external actors ^
 - $\coloneqq [\text{ability to be a good student}]$
 - \Rightarrow explanation*:

[Teacher (trainer, tutor, developer) — is a subject (cybernetic system), which transfers the knowledge and skills known to it into the memory of the learner. Here the teaching methodology and qualitative management of the learning process are important.]

- self-learning^
 - := [ability of a cybernetic system to act as both student and teacher^]
 - ≔ [ability of a cybernetic system to independently perform its own learning^]

:= [level of independence of cybernetic system in the process of its training^]

- \Rightarrow parameter-factor*:
 - ability of a cybernetic system to learn from its own experiences and mistakes ^

- ability of a cybernetic system to learn independently from the experience of other cybernetic systems ^
 - \Rightarrow parameter-factor*:
 - ability of a cybernetic system to learn independently from the experience of other cybernetic systems by imitating and analyzing the activities of those systems[^]
 - ability of a cybernetic system to learn independently from the experience of other cybernetic systems by utilizing the knowledge and skills accumulated by these cybernetic systems^ ⇒ note*:

[Such training requires that the cybernetic system to be trained be an agent of a multicybernetic agent system in which the experience of all its agents is captured in the shared public memory of that multi-agent system, which may be either a distributed memory (distributed across agents) or the memory of a corporate agent (corporate system) that is part of said multi-agent system

- ability to navigate modern information sources ^
- ability to understand modern information sources ^
- ability to analyze and improve one's cognitive activity ^
- ability to detect and eliminate contradictions and syntax errors in the internal information model of the environment[^]
- ability to detect and fix information holes in the internal information model

of the $environment^{}$

- ability to detect and remove information garbage from the internal information model of the environment[^] ⇒ explanation^{*}:
 - [Information garbage is unnecessary (redundant) or easily recoverable information]
 - ≔ [ability to detect and forget unnecessary information[^]]
- flexibility of the internal environmental information model ^
 - := [labor intensity of modification (editing, reconfiguration, restructuring) of the internal information model of the environment^]
- stratification of the internal information model of the environment ^ := explanation*:
 - [quality of structuring the internal information model of the environment designed to minimize the size of the activatable area of this internal information model, <u>sufficient</u> to solve each initiated task^]
- ability of a cybernetic system to understand ^
 - ≔ [ability to converge the different knowledge included in the internal information model of the environment, or to converge externally acquired knowledge and "immerse" it in the internal information model of the environment]
 - ≔ [ability to realize (comprehend) the new acquired information and to immerse (bind, link) the new information more deeply into the context of the current state of the entire internal information model of the environment]
- cognitive motivation and activity of cybernetic system ^
 - ⊨ [cognitive activity^]

 \Rightarrow epigraph*:

[One day you stop learning, and you start dying.]

 $\Rightarrow author^*:$ Albert Einstein

 \Rightarrow note*:

[Cognitive activity can occur in two ways:

• in width — expansion of the studied part of the environment (expansion of the number of sub-

ject domains, expansion of the number of known facts within a subject domain).

- in depth improving the system of acquired knowledge
-]
- reflexivity of the cybernetic system ^ = explanation*:

[the ability of a cybernetic system to analyze its own and, first of all, insufficiently effective behavior (its own experience in solving various tasks) and especially to analyze its own mistakes^]

- ≔ [ability to be aware of one's actions, to make sense of and focus one's behavior^]
- ≔ [ability of a cybernetic system to realize what it is doing, as well as how and why^]
- \Rightarrow parameter-factor*:
 - ability to distinguish between qualitative understanding and illusionary understanding
 - ≔ [ability to distinguish sufficiently deep (valid) understanding from insufficiently complete (superficial) understanding, which does not ensure its qualitative (reliable) use in the organization of cybernetic system activity^]
- $\Rightarrow epigraph^*$:

[A smart man is not the one who knows a lot, but the one who knows himself]

 \Rightarrow author*:

Johann Wolfgang Goethe \Rightarrow epigraph*:

[Awareness of your imperfection brings you closer to perfection] \Rightarrow author*:

Johann Wolfgang Goethe

 \Rightarrow epigraph*:

[True greatness begins with understanding your own nothingness] \Rightarrow author*:

Johann Wolfgang Goethe

 \Rightarrow epigraph*:

[You can act and you know why you act, but you don't know why you know that you know how to act.] $\Leftarrow quote^*$:

Rose name

- \Rightarrow author*:
- $Umberto \ Eco$
- motivation to progress ^
 - ≔ [purposeful (conscious) developmental attitude^]
 - := [hunger, desire for progress]
- capability to progress
 - := [ability to progress[^]]
 - \coloneqq [capacity]
- determination for progress
 - \coloneqq [activity^]
 - \coloneqq [cognitive activity[^]]
- \coloneqq [cognitive]
- courage
 - ≔ [absence of fear of the unknown, contradictions, cognitive dissonance[^]]
- supergroupsign

 \Rightarrow note*:

[In order to simplify morphisms between similar information constructs (desire for isomorphism of analogies, permanent restructuring of the world picture).]

- ability to adjust the system of concepts used ^
 - \Rightarrow note*:

[In order to minimize the number of concepts used (following Occam's Razor Principle).]

- ability to restructure the internal
 - information model of the environment $\hat{} \Rightarrow explanation^*$:

The increase in the level of intelligence is not limited by the number of facts (and knowledge), but is determined by the way these facts and knowledge are interpreted (explained, conceptualized) within the framework of expanding personal experience (individual subjective picture of the world). Each new information acquired or generated by the cybernetic system forces to rethink the whole picture of the world. The evolution of the world picture is not just an accumulation of knowledge, but also the ability of the cybernetic system to restructure its own world picture.

- ability to minimize contradictions[↑]
 ⇒ [cognitive dissonance coping]
- ability to minimize explicit information holes^
- ability to detect and eliminate synonymy of signs ^

- ability to detect patterns, generate hypotheses ^
- hypothesis-supporting ability
 - ability to improve one's learning ability
 ∷ [ability to continually improve one's ability to learn]
- multiplicity of types of knowledge and skills evolving during cybernetic system training ^
 - ≔ [multiple directions in which cybernetic system training is most active^]
- ability of a cybernetic system to converge and deeply (seamlessly) integrate the knowledge it acquires[^]
 - ≔ [ability of a cybernetic system to move from the eclectic accumulation of the knowledge it acquires to their harmonization and systematization with the help of appropriate meta-language tools^]
- ability of a cybernetic system to modernize (transform) its physical shell^

 \Rightarrow parameter-factor*:

- ability of a cybernetic system to modernize (transform) its physical shell, carried out by external entities[^]
 := [ability to modernize the physical shell using external entities[^]]
- ability of a cybernetic system to independently modernize (transform) its physical shell^
- flexibility of the physical shell of a cybernetic system ^
 - ≔ [modifiability (modernizability, reconfigurability, transformability) of the physical shell (body) of a cybernetic system^]
- ability of a cybernetic system to increase its level of autonomy^
 - ≔ [ability to increase one's independence, selfsufficiency, self-reliance]
- ability of a cybernetic system to increase its level of interoperability[^]
- ability of a cybernetic system to increase its level of synergy

 \Rightarrow note*:

[It is about improving the quality (efficiency) of the organization of interaction between the components of a cybernetic system (components of an individual cybernetic system or agents of a multi-agent cybernetic system)]

- \Rightarrow parameter-factor*:
 - ability of a cybernetic system to

 $increase \ its \ level \ of \ hybridization \ \widehat{}$

- \Rightarrow explanation*:
 - [Hybridization of a cybernetic system implies convergence and subsequent deep (diffuse, seamless) integration of components of a cybernetic system — different kinds of knowledge (including programs), different kinds of problem-solving models, different components of a multimodal interface, different agents of a multi-agent system.]
- \Rightarrow parameter-factor*:
 - ability to converge between components of a cybernetic system^

⇒ note*: [It refers to the convergence (convergence, compatibility) of the components of an individual cybernetic system as well as the agents of a multiagent cybernetic system]

- ability to perform deep integration of cybernetic system components^
- := [evolutionary]
- := [ability to evolve (to increase self-organization)[^]]
- ≔ [speed of evolution (quality improvement) of cybernetic system[^]]
- := [speed (first derivative) of the process of evolution (quality level increase) of a cybernetic system[^]]
- := [labor intensity of cyber system quality improvement^]
- ⇒ decreasing a parameter by its domain of definition*:
 - evolution of a class of cybernetic systems ^
- evolvability of a particular cybernetic system[^]
 ⇒ parameter-factor*:
 - evolvability by external actors (teachers, developers)^
 - self-evolving^
 - *flexibility* ^
 - := [modifiability^]
 - plasticity?
 - reconfigurability ^
 - $\bullet \quad rearrangeability \, \hat{} \\$
 - transformability ^
 - stratifiability ^
 - reflexivity of external actors carrying out evolution (teachers, developers)^
 - ability to self-reflect (to analyze one's own activity for its effectiveness)[^]

VI. Accelerating the evolution of cybernetic systems

accelerating cybernetic systems evolution

≔ [ability to grasp the theory of evolution and use it for your own evolution]

- \Rightarrow parameter-factor*:
 - ability of a cybernetic system to optimize the distribution of priorities of evolution rates by different parameters (directions) in each period of time in order to maximize the complex effect ^
 - ability of a cybernetic system to determine the strategy of the evolutionary process[^] ⇒ note^{*}:
 - [A cybernetic system must be able to intelligently plan its evolution, clearly aligning strategic and tactical objectives with its motivation and abilities]
 - ability to formalize methods of evolution of cybernetic systems and permanent improvement of these methods, as well as the evolution of the theory of evolution itself

The laws of evolution of individual cybernetic systems and collective cybernetic systems have many similarities, but also significant differences. The unity and struggle of individual cybernetic systems with the external environment should change into unity and struggle with the external environment of multi-agent cybernetic systems, but not between its agents.

Laws of evolution of cybernetic systems:

- In the evolution of cybernetic systems, not only the increase in the values of parameters that determine the level of intelligence (level of selforganization) of a cybernetic system and indicate different directions of the evolutionary process, but also the balance (harmony) of evolution rates (velocities) in all these directions is important;
- This balance (distribution of importance) of cybernetic system evolution directions depends significantly on the stage of cybernetic system evolution what was unimportant at previous stages may become key for the current stage.
- If a cybernetic system does not evolve, it degrades. Evolution must be permanent.
- The evolution of a multi-agent cybernetic system is determined by the diversity, intelligence and interoperability of agents, as well as by the improvement of the principles of organizing the interaction of agents (i.e. the evolution of their synergy) — the competition of intelligent agents is a brake on the evolution of a multi-agent cybernetic system
- Collectives of non-intelligent agents dead-

end branches of the evolution of multi-agent cybernetic systems (example — swarm multi-agent systems).

- multi-agent cybernetic system
 ⊂ multi-agent system
- The cybernetic system's knowledge of the laws of evolution a factor in the acceleration of evolution

The ability of a cybernetic system at each stage of its evolution to competently correct (refine) the distribution of importance of the directions of its further evolution is the main factor of evolution acceleration. If this ability is absent — there is a danger of "falling" into a dead-end branch of evolution.

General principles of evolution of cybernetic systems:

- to expand the scope and increase the semantic power of the *internal information model of the environment* (expansion and deepening of knowledge)
- extension *multiplicity* of components for different types of components
 - of knowledge base fragments
 - of problem-solving models
 - of agents of multi-agent systems
- *convergence* of different components (from eclectic diversity to *synergy*)
 - of knowledge base fragments
 - of problem-solving models
 - of agents of multi-agent systems
- *stratification* and fractality.
 - multilevel, hierarchy
 - to increase synergies within each level and between levels
- *universalization* of problem-solving methods, models and agents

The current evolutionary level (current stage of evolution) of a cybernetic system determines:

- principles underlying the self-organization of this system;
- of directions (tactics and strategy) of further evolution of the mentioned system.

$\begin{tabular}{ll} deadlocked branch of cybernetic system \\ evolution \end{tabular}$

- ≔ [cybernetic system on a dead-end branch of its evolution]
- ≔ [cybernetic system with limited evolutionary possibilities]
- \Rightarrow note*:

[The main reasons for the inhibition of the evolutionary process and even more so for the emergence of fundamentally insurmountable limitations for further increase in the intelligent level of cybernetic systems are:

- imbalance of different evolutionary directions
- insufficient attention to the convergence of components of cybernetic systems and, as a consequence, the lack of synergy effect
- insufficiently high level of intelligence of cybernetic systems that are combined into multiagent cybernetic systems
- insufficiently high level of interoperability (socialization) among agents of multi-agent cybernetic systems
-]

deadlocked branch of the evolution of individual cybernetic systems

- \subset deadlocked branch of cybernetic system evolution
- ⊃ an individual cybernetic system that does not allow for convergence, deep integration and synergy of all the different kinds of components all the different kinds of knowledge used, problem-solving models, all the different kinds of interfaces
 - ≔ [individual cybernetic system that is not hybrid or that is hybrid but not capable of extending a diversity of knowledge types, problemsolving models, and interfaces]

Key evolutionary directions:

- Transition from eclectic diversity of components to their synergy (harmony)
 - from eclectic diversity of knowledge to its convergence and systematization
 - from eclectic diversity of problem-solving models to their convergence and seamless integration (to hybridization)
 - from the diversity of specialization of agents in multi-agent systems to their convergence (compatibility), interoperability and synergy
- Increase the number of hierarchy levels
- Branches of the evolution of cybernetic systems:
- evolution of customized artificial cybernetic systems
- transition from individual to multi-agent artificial cybernetic systems (from collectives of weakly intelligent cybernetic systems to collectives of intelligent systems from swarm intelligence to superintelligence).
- the individual evolution of human beings
- the evolution of human collectives
 - the instrumental evolution of humans
 - * from passive tools to machines
 - * to computer systems
 - * to intelligent computer systems

* to a superintelligent human-machine community.

should be distinguished*

- \ni {• evolution of cybernetic system
 - evolution of the internal information model of the cybernetic system environment
 - evolution of a cybernetic system problem solver
 - evolution of cybernetic system memory
 - \bullet evolution of the cybernetic system processor
 - evolution of the interface of a cybernetic system with the external environment and its own physical shell

 - $\bullet \ learning \ cybernetic \ system$
 - $\bullet \ {\it self-evolving} \ {\it cybernetic} \ {\it system}$
 - self-learning cybernetic system
 - }

VII. System of key concepts semantically

SIMILAR TO THE PARAMETERS DEFINING THE LEVEL OF INTELLIGENCE OF CYBERNETIC SYSTEMS

A. Information constructs, languages and semantic representation of information, types of knowledge, knowledge bases

information construction

- \coloneqq [information]
- ⊃ information construct stored in memory
 ⊃ sense representation of information

language

- \supset universal language
- \supset natural language
- \supset artificial language
 - \supset language of semantic representation
- \supset specialized language
- \supset formal language

sense representation of information

- := [sense representation of the information construct]
- \coloneqq [sense construction]
- \coloneqq [meaning]
- := [invariant of the diversity of forms of representation of an information construct]
- := [refined semantic network]
- \Rightarrow principles underlying*:
 - [• [Each sign, which is a part of the semantic representation of an information construction, enters the information construction once, i.e. there is no synonymy of signs within each semantic construction]

[Each character included in a semantic information construction is an elementary fragment of this information construction, i.e. a fragment whose structure analysis is not required in the process of syntactic analysis, semantic analysis and understanding of the semantic information construction]

 \Rightarrow note*:

[Thereby, letters, words, phrases are not used to represent signs in semantic constructions]

- [The semantic information construction includes only signs and, accordingly, does not include such fragments as delimiters, limiters]
- [The set of signs that make up semantic information constructions is divided into the following three classes:
 - class of binary oriented mappings, each of which denotes either some binary oriented relation between some signs included in the semantic construction, or some binary oriented relation between the described entities denoted by the corresponding signs. Such mappings will be called arcs;
 - class of binary non-oriented mappings, which we will call edges and which have a denotational semantics similar to binary oriented mappings;
 - The class of signs that are not binary bindings (such signs will be called nodes included in semantic constructions).
- The direct relationship between the signs included in a semantic construction is syntactically specified by two binary oriented incident relations:
 - The ratio of the incidence of bindings with the corresponding bound signs, which can be signs of any kind;
 - The ratio of the incidence of the incoming arcs with the corresponding linked signs.
- [Alphabet of syntactically distinguished elements of semantic constructions is defined by additional partitioning of the class of arcs, class of edges and class of nodes into corresponding subclasses, each of which has a clear denotational semantics]
- [The operation of integration (unification) of semantic constructions is reduced to the theoretical-multiplicative unification of all elements of these constructions (all signs included in their composition) with identification (gluing) of synonymous signs, i.e. those signs from different unified constructions that

denote the same described entities]

} \Rightarrow properties*:

- [Sense information constructions are non-linear (graph) structures, because the signs of described entities, which are represented once in a sense construction, can have an unlimited number of connections with other signs]
- [Any information corresponds to its unambiguous semantic representation, i.e. all variants of semantic representation of any information are not only semantically equivalent, but also syntactically equivalent, connected by isomorphism, which pairs of correspondence connect synonymous signs]
- }

should be distinguished*

- \ni {• sense*
 - ⊨ [Relationship linking information constructs to their semantic representation]
 - sense
 - ≔ [sense representation of information (information construct)]
 - := [sense representation of information]
 - := [naked representation of information, devoid of any details that are not directly related to the described situations, events, processes, structures (i.e., which are not <u>signs</u> of the components of the described <u>objects</u>)]
 - \Rightarrow note*:

[The meaning of the information is not in the signs of the entities in question, but in the configuration of the relationships between them]

- \supset semantic representation of the internal information model of the environment
 - ≔ [semantic representation of the subjective picture of the world]
- language of semantic representation
- \Rightarrow subdividing*:
 - specialized semantic representation language
 - universal semantic representation language
 - \ni SC-code

}

- \Rightarrow subdividing*:
 - graphic language of semantic representation
 - language of internal semantic representation in the memory of a cybernetic system
 - $\ni \ SC\text{-}code$

}

- sense memory
- \subset associative memory

}

should be distinguished*

- \ni {• sense representation of information
 - language of semantic representation
 ⇒ SC-code
 - alphabet of the language of the meaning space
 - sense*
 - semantic space
 - semantic distance between characters
 ⇒ note*:
 - in the semantic space
 - semantic proximity of semantic constructions
 ⇒ note*:
 - [in the semantic space]
 - morphism of semantic constructions
 - }

$convergence \ of \ information \ constructs$

- := [reducing information constructions to <u>syntactically</u> equivalent form (to the same syntax and to <u>maximum</u> possible use of synonymous signs by transforming the original information constructions into semantically equivalent ones)]
- {• semantic compatibility of cybernetic systems ^
 - ≔ [level of semantic compatibility of cybernetic systems^]
 - \in parameter
- learning cybernetic system ^
 - := [learning level of cybernetic system[^]]
 - \in parameter
- $\} \\ \Rightarrow note^*:$

[Semantic compatibility of cybernetic systems is the most important factor in significantly increasing the level of their learnability, because in the presence of semantic compatibility of a cybernetic system with other cybernetic systems, a cybernetic system becomes a social subject capable of quickly acquiring new knowledge not only independently (in the process of individual interaction with the environment), but also in a "ready-made" form from other subjects.]

semantic cyber interoperability ^

- ≔ [degree of semantic compatibility between two cybernetic systems[^]]
- \in parameter
- \Rightarrow quote*:

[[]The meeting of two people is– the meeting of two

chemical elements. The reaction may not happen, but if it does — both are changed.]

 \Rightarrow author*:

Karl Gustav Jung

 \Rightarrow area of definition*:

 $pair \ of \ cybernetic \ systems$

 \Leftarrow parameter-factor*:

 $understanding \ of \ cybernetic \ systems$

≔ [level of understanding between two cybernetic systems]

 \Rightarrow note*:

[Semantic compatibility is a necessary but not sufficient condition (factor) for mutual understanding.]

should be distinguished *

- ∋ {• semantic compatibility of cybernetic systems[^]
 ∈ parameter
 - \Rightarrow area of definition*: a pair of cybernetic systems
 - ability to ensure semantic compatibility with partners^
 - \in parameter
 - \Rightarrow area of definition*: cybernetic system

}

knowledge

- $\supset task$
 - \supset question
- \supset definition
- \supset method
 - \supset information processing program
 - \supset program of external goal-directed behavior
- \supset protocol
 - := [description of the action performed]
- \supset ontology
- \supset subject domain

B. actions, tasks, task classes, methods, task types, intelligent tasks

task

- \supset explicitly initiated (formulated) task
- ⊃ task situation that is not an explicitly stated initiated task
 - \Rightarrow note*:

[Often, these non-explicit tasks are various problem situations in the knowledge base, such as:

- contradictions or errors in the internal information model of the environment (contradictory situation, cognitive dissonance)
- information garbage

- information hole
- a dangerous (harmful) situation (event) in the environment (a situation in which something must be done)

]

 \Rightarrow note*:

[All problems and classes of problems <u>could</u> be formulated]

 \Rightarrow subdividing*:

- $\{\bullet\ procedural\ formulation\ of\ the\ problem$
- declarative problem statement
- }

should be distinguished*

- ⇒ {• level of ability to perform a given action (a given task) or a given activity
 - ≔ [level of skill and ability to perform a given action (given task) or given activity]
 - ≔ [how capable (trained, skilled) a cybernetic system is to perform a given job]
 - level of willingness of a given cybernetic system to perform a given action
 - ≔ [willingness (motivation) to solve a given task or perform an activity of a given type in a given area]
 - := [how much and what the cybernetic system wants to do]
 - level of activity (performance, energy) of a cybernetic system in performing a given job
 - ≔ [how much time, effort, resources a cybernetic system spends on work]
 - level of responsibility (seriousness of attitude) of the cybernetic system to the result of this work (doer/simulator)

}

should be distinguished *

- *∋* {• quality goal-setting ability^
 - \Rightarrow area of definition*: cybernetic system
 - quality of goal-setting ^
 - \in parameter
 - \Rightarrow area of definition*: action
 - \Rightarrow parameter-factor*:
 - relevance and timeliness of goal setting ^
 - quality of generated goals and plans[^] ⇒ parameter-factor^{*}:
 - end should not justify the means
 - goal must not contradict higher-level goals ^
 - strategic goal should not be sacrificed for tactical goals ^

}

C. understanding, explanation, ability to understand, ability to explain

$understanding\,\hat{}$

 \Rightarrow questions*:

- if we understand this kind of understanding
- whether we can distinguish between qualitative (deep) understanding and less qualitative
- whether we can test understanding (in humans and in intelligent computer systems)
- if we have a high enough level of understanding
- $\Rightarrow problems^*$:
 - not a high enough level of understanding
 - individual understanding
 - of understanding between people
 - of understanding between intelligent computer systems and users
 - mutual understanding between intelligent computer systems
 - the basis of understanding is the presence of a sufficiently powerful and qualitative subjective picture of the world (context)
 - modern education teaches knowledge, skills, but not the ability to understand
 - needs understanding tests
 - mutual understanding it is a coincidence of world pictures (semantic compatibility, unification)
- \Rightarrow testing*:
 - the level of understanding of some entity is determined by the power, quality, originality of the semantic neighborhood of the sign of this entity in one's subjective picture of the world (including comparisons, analogies ...)
 - level of information understanding it is the quality of the semantic neighborhood of the sign of this information construct, as well as the quality of the semantic neighborhoods of all signs included in this information construct
 - understanding often requires moving to a higher-level view of the system — and to a meta-language
- \Rightarrow note*:

[The basis for improving understanding is the semantic structuring of the internal information model of the environment (world picture, knowledge base).

One should teach not only knowledge and skills — but also systematization of the knowledge base (teach the rules of semantic structuring of the knowledge base).]

should be distinguished*

- \ni {• understanding ability
 - \in parameter
 - understanding
 - \subset process
 - ⊃ understanding the information stored as part of the internal information model of the environment
 - \supset understanding of the object of study
 - \supset understanding sensory information
 - ⊃ understanding by a computer system of a message received from another computer system
 - ⊃ user's understanding of the message received from the computer system
 - ⊃ understanding by the computer system of the user's message
 - }

should be distinguished*

- \ni {• *ability to understand*
 - ≔ [ability to understand the meaning (essence) of the value, significance, quality of acquired or independently produced (deduced) information]
 - \Rightarrow explanation*:

[Understanding new information is not only about using it in the current moment (as a reaction to the current situation), but also about saving it for use in any unpredictable circumstances when needed. Therefore, any information should be <u>immersed</u> in the context of the current state of the subjective picture of the world, i.e. placed in such a place in the structure of this picture of the world, where it can be easily found.

This is the essence of the difference between training artificial neural networks and training intelligent computer systems (from the evolution of the <u>all</u> knowledge base)]

- understanding
 - := [understanding the meaning]
 - := [understanding the essense]
 - \Rightarrow note*:

[To understand some information — is to determine how important it is to the goals that a cybernetic system is pursuing, and to determine how and when (under what circumstances) that information is to be used]

- \Rightarrow questions*:
 - [• [What is meaning]
 - [What is the process and result of un-

derstanding:

- Translation into semantic language (language of semantic representation of information)
- Establishing links (immersion) of the semantic representation of the understood information into the current state of the internal information model of the environment

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}
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should be distinguished*

1

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\ni {• understanding
```

}

- depth of understanding ^
- ability to understand
- mutual understanding
- level of understanding between the agents of a multi-agent cybernetic system ^

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}
```

understanding

- \supset understanding the information perceived by your own sensors
- ⊃ understanding messages from other cybernetic systems (from other agents in the same multi-agent system)
- ⊃ understanding the real entities of the external environment
 - ⊃ understanding the external objects that the cybernetic system acts on
 - ⊃ understanding of external actors (their behavior)
 - ⊃ understanding of external situations, events, processes
 - \supset understanding your own physical shell
 - \supset understanding your own goals and behavior
- \supset understanding the abstract entities of the internal information model of the environment
 - \supset understanding of the concepts used
 - ⊃ understanding the fragments of the internal information model

 \supset understanding your own information processes \Rightarrow epigraph*:

[Heard a bell ringing, don't know where it is] $\Rightarrow epigraph^*$:

- $[{\rm I}$ don't get upset if people don't understand me,
- I get upset if I don't understand people.]
- \Rightarrow author*:
- Confucius
- \Rightarrow explanation*:

[To understand — is to consider the object of study not only at the level of its internal structure, but also at the <u>meta</u> level — to establish what it is a part of, what classes it is an element of, what analogs it has and how it differs from its analogs. So, for example, to understand Euclidean geometry, it is necessary not only to know axioms, theorems, basic concepts, proofs, methods of solving geometric problems, but also what geometries are still known, what is the field of application of Euclidean geometry, and so on.]

 \Rightarrow note*:

[It should be emphasized that knowing and knowing are not the same as understanding. It is possible to have some knowledge and even to be able to use this knowledge in the process of solving various problems, but to understand it all very superficially. Note, however, that the methodology for testing knowledge and skills is quite clear, whereas the methodology for testing understanding requires considerable development.]

 \Rightarrow note*:

[The need for cybernetic systems that are aware of what they are doing and, in particular, of the consequences of their actions, that understand what they are doing and why they are doing it, will increase. Otherwise, there will be no further technological progress.]

 $\Rightarrow epigraph^*$:

[The bee collects honey and knows how to do it. Only the beekeeper realizes that she is collecting honey for him.]

the ability to understand ^

\Rightarrow parameter-factor*:

- ability to understand the state and dynamics of the external environment ^
 - ≔ [ability to understand the causes and predict the consequences of current situations, events, processes]
- ability to understand the behavior (including goals) of external actors[^]
- ability to increase the level (quality, reliability) of understanding^

```
\Rightarrow epigraph^*:
```

- [If you can't explain it to your grandmother, you don't understand it.]
- \Rightarrow author*:
 - Albert Einstein
- $\Leftarrow epigraph^*$:
- ability to $explain^{}$
- $\Rightarrow epigraph^*$:
 - [Everyone hears only what he understands.]
 - \Rightarrow author*:
 - Johann Wolfgang Goethe

should be distinguished*

- \ni {• learning^
 - := [ability to learn, to acquire and assimilate new knowledge and skills[^]]
 - ability to understand
 := [ability to understand acquired knowledge and skills[^]]
 - $\substack{ \} \\ \Rightarrow note^*: }$

[These are fundamentally different levels of ability. Knowing and understanding are not the same thing.]

should be distinguished *

- \ni {• understanding
 - $\in \ activity$
 - := [immersing new information into one's internal information model of the environment]
 - $\bullet \ quality \ of \ understanding \ \widehat{} \\$
 - := [degree of understanding]
 - := [level of understanding[^]]
 - $\bullet \ explanation$
 - := [transmitting information (message) that allows something to be better (more adequately) understood]
 - \Rightarrow explanation*:
 - [The process of *understanding* can be interpreted as an explanatory (explaining) dialog with oneself, that is, as a process of *explaining* to oneself the relevant entity to be explained]
 - quality of explanation ^
 - := [explanation clarity]
 - \coloneqq explanation*:
 - [indicator of how easy it is to understand the essence of an explained entity — a concept, a material object, a connection, a pattern, a problem, a proof, an information construct (text, message) of any kind]
 - $\bullet \ ability \ to \ understand$
 - $\bullet \ explanation \ ability$
 - learning
 - understanding test
 - := [test requiring meta-level metaknowledge and metacognition]
 - $\bullet \ explanation$
 - }

should be distinguished *

- \ni {• understanding
 - \in process
 - ≔ [process of solving the problem of understanding]
 - result of understanding
 - \coloneqq [sufficiently complete but compact specifi- *explanation*

cation (description) of the entity to be understood, containing all <u>basic information</u> about the entity (its relations with entities at the same level of the entity hierarchy, and its place within entities at a higher level of the hierarchy)]

- := [result of solving the problem of understanding]
- understanding task

:= [statement of the task of understanding the specified entity]

}

should be distinguished*

- \ni {• understanding
 - \subset information process \subset action
 - depth of understanding ^
 - ≔ [quality of execution of the understanding process[^]]
 - := [level of understanding[^]]
 - := [degree of understanding[^]]
 - object of understanding
 := [understood entity]
 - \Rightarrow note*:

[The object of understanding can be any entity — an event, situation, process, action, activity (behavior of some cybernetic system), any external or internal information construct, etc.]

- ability to understand
 - ≔ [level of ability of a cybernetic system to grasp the essence (including causes and consequences) of an event, phenomenon, subject, and so on]

}

$depth \ of \ understanding \ \hat{}$

\Rightarrow explanation*:

[depth of understanding is determined by the number of essential connections of the understood entity (object of understanding) with the current state of the internal information model of the environment (subjective picture of the world), which is considered as the context of the understood (investigated) entity. In other words, the depth of understanding is determined by <u>informative</u> of the semantic neighborhood of the sign of the understood (investigated) entity in the subjective picture of the world. Consequently, the depth of understanding is determined by the quality (informativeness, semantic power) of the subjective picture of the world itself.]

:= [explanation of behavior]

 $\Rightarrow note^*:$ {

should be distinguished*

∋ {• simulation of a person explaining the solution to a particular problem

 \Rightarrow explanation*: [By approximating similar explanations]

on a large number of such explanations — on a large statistical sample (dataset).]

• logical-semantic explanation of how a generative artificial neural network constructed this imitation of a human explanation

 \Rightarrow note*:

[In addition to the explanation of how the problem was solved, there must be evidence (justification) that the solution process is correct and the result can be trusted.]

```
}
```

}

should be distinguished*

 \ni {• process of problem solving

- explanation of the problem-solving process
- explanation of the problem-solving process
 - ≔ [this explanation of how the problem was solved by decomposing the solution process into interrelated subprocesses, in which for each specified subprocess its operational semantics (its meaning) is further explained]

}

It is intuitively clear that the ability (ability) to understand is a necessary property (ability) of intelligent cybernetic systems. It is also obvious that the level of understanding in people and intelligent computer systems requires a significant increase in connection with the transition to a new technological mode. In addition, the level of <u>mutual understanding</u> needs to be significantly increased.

The problem of *high level of understanding*, or rather the problem of providing *high level of un-derstanding* — the key problem of the current stage of development of Artificial Intelligence technologies and the development of Mankind. Both intelligent computer systems and Humanity must adequately understand what they are doing.

Understanding involves structuring the knowledge base and associativity of search procedures. Knowledge base structuring should have <u>universal</u> subjectindependent principles — all new (acquired) knowledge should be immersed (placed) in the knowledge base so that it can be easily found in situations,

- 1) that are inherently unpredictable.
- 2) in which it is not known a priori what knowledge stored in memory can be useful

D. Learning, self-learning, and learnability

should be distinguished*

- ∋ {• current state of the internal environmental information model[^]
 - ≔ [current level of development of subjective picture of the world (knowledge and skills of the cybernetic system)^]
 - parameter-factor*:
 current level of cybernetic system
 development^
 - *learning*
 - \subset process
 - := [process of expanding and improving the quality of the internal information model of the environment (subjective picture of the world)]
 - *equalized part*: evolution of a cybernetic system*
 - study tempo^
 - learning ^
 - \coloneqq [learning ability]
 - ⇐ parameter-factor*: evolutionary potential^ := [evolutionary]

}

should be distinguished *

- \ni {• learning
 - ≔ [improvement and/or expansion of knowledge and, in particular, skills]
 - \supset learning with a teacher
 - \supset self-learning
 - $\bullet \ learnability \, \hat{} \\$
 - \coloneqq [learning ability^]
 - := [training labor intensity^]
 - factors that ensure learning
 - \coloneqq [properties that enable learning]

}

$\begin{array}{c} learning \\ \rightarrow & amplemation \end{array}$

\Rightarrow explanation*:

The most important type of tasks solved by a cybernetic system are learning tasks aimed at expanding the knowledge and skills used by the cybernetic system, which in turn leads to an expansion in the number and variety of tasks solved by the cybernetic system]

≔ [process of solving a meta-problem aimed at increasing the number of problems to be solved and improving the quality of their solution]

$learnability \hat{}$

- := [learning ability]
- \Rightarrow note*:

[A high level of *understanding* is a necessary factor in *understanding* is a high level of *understanding*. Indeed, a deep *understanding* of situations and events occurring in the *environment* and, in particular, a *deep* understanding of the acquired *information* is the foundation of the *learning* process of a cybernetic system.]

should be distinguished *

- \ni {• educatedness ^
 - ⋮ [volume and quality of acquired knowledge, skills and abilities]
 - \Rightarrow parameter-factor*:
 - volume of internal information model of cybernetic system environment ^
 - quality of the internal information model of the cybernetic system environment[^]
 - highly educated cybernetic system
 - ≔ [cybernetic system capable of solving intelligent problems]
 - \Rightarrow note*:

[In order to be able to solve intelligent problems, one must have a high level (amount and quality) of knowledge, skills, and abilities]

}

E. Convergence, interoperability, synergy in individual cybernetic systems, hybrid cybernetic systems, synergy in multi-agent cybernetic systems, interoperability

should be distinguished*

- \ni {• compatibility^
 - semantic compatibility of cybernetic systems
 - information construct compatibility
 - convergence
 - synergy

 \ni {• compatibility^

- $:= [closeness^{}]$
- := [convergence^]
- \Rightarrow area of definition*:
- family of cybernetic systems or their components
- \Rightarrow parameter-factor*:

- couple compatibility ^
- semantic compatibility ^
 - \coloneqq [level of understanding[^]]
- convergence
- \coloneqq [compatibility upgrade process]
- ability to increase mutual understanding (semantic compatibility) — to converge one's worldview and that of one's partners[^]
- }
 }
 → {• hybridity level^
 - := [multiplicity and compatibility of components^]

 $. \Rightarrow note^*$:

[The basis of a customized cybernetic system with a high level of hybridity is a common platform]

- synergy level
 - := [component interaction efficiency[^]]

 \Rightarrow note*:

[For a multi-agent cybernetic system with a high level of hybridity — this is the unification of the messaging language (language of communication) and the basis for combating the Babylonian pandemonium syndrome and the information crisis.]

[The greatest friendship exists between extreme opposites. The opposite nourishes the opposite, while the similar receives nothing from the similar.]

 \Rightarrow author*: Plato

should be distinguished*

- \ni {• synergy level
 - ≔ [efficiency of interaction of cybernetic system components[^]]
 - \coloneqq [synergy]
 - ≔ [quality (efficiency) of interaction of components of a complex dynamic system[^]]
 - synergy level increase
 - \in process
 - := [transition of a cybernetic system from chaos to order, to efficient interaction of its components]
 - ⊃ increased synergy of individual cybernetic system components
 - ⊃ increasing the level of synergy of agents in a multi-agent cybernetic system
 - capability to increase synergy
 - \Rightarrow decomposition by domain of definition*:
 - ability of an individual cybernetic system to increase its level of synergy[^]
 - ability of a multi-agent cybernetic system to increase its level of synergy ^
 - }

}

synergy

- \coloneqq [effective communication[^]]
- ⇒ necessary condition*: convergence of diverse components
- := [resonance of interacting components[^]]
- \supset synergy of the components of the world picture := [deep (seamless) integration]
- ⊃ synergy of information processes and different problem-solving models[^]
- ⊃ agent synergy of multi-agent cybernetic system ^ ⇒ condition*:
 - $interoperability\,\hat{}$
- $\Rightarrow factor^*$:
 - interoperability of all agents
 - efficiency of interaction organization
 ⇒ component*:
 - standard mode of interaction (regulated with clear distribution of roles and responsibilities)
 - emergency regulated mode
 - emergency unregulated treatment under unforeseen circumstances
 - evolution
- := [component synergy level[^]]
- ⊃ synergy of fragments of the internal information model of the environment[^]
- \supset synergy of methods
- \supset synergy of problem-solving models ^
- \Rightarrow explanation*:

[synergy is a kind of "creative" resonance of activity of all components of a cybernetic system (resonance can also be destructive — selfdestructive).]

cybernetic system component synergy ^

- := [degree of depth of interpenetration and seamless integration of cybernetic system components^]
- := [level of efficiency of interaction of cybernetic system components^]
- \Rightarrow explanation*:

[This parameter characterizes the most important direction in the evolution of cybernetic systems, which consists in the transition from the eclectic connection of various (including heterogeneous) components of cybernetic systems (e.g., using the "black boxes" methodology, which does not take into account the internal structure of the connected components) to a more effective interaction of components, which involves taking into account the internal structure of the connected (integrated) components.]

 \Rightarrow note*:

In the course of evolution of cybernetic systems,

synergies are manifested at different structural levels of these systems:

- at the level of integration of different components of the internal information model of the environment (different types of acquired knowledge)
- at the level of integration of various components of the cybernetic system problem solver (including various problem solving models)
- at the level of integration of various components of the multimodal interface of a cybernetic system
- at the level of organization of interaction between different agents of a multi-agent cybernetic system (including agents with different specializations)

] $\Rightarrow note^*$:

[Increasing the level of synergy of the components of cybernetic systems implies *convergence* of these components and their subsequent integration as deep as possible (seamless). Let us emphasize that a very promising basis for this *convergence* and integration of cybernetic systems components is the *semantic representation of information*, the key advantage of which is that this representation of information is a <u>invariant</u> variety of semantically equivalent forms of representation of the same information.]

 \Rightarrow note*:

[A prerequisite for synergy between the components of a cybernetic system is their *semantic compatibility* (semantic compatibility between knowledge base components, problem solver components, different sensors and sensor configurations, and different agents of multi-agent systems). The key factor in ensuring semantic compatibility is the use of *universal language of internal semantic representation of information* in the memory of cybernetic systems. The main advantage of such language is the unambiguity of information representation, i.e. the absence of a variety of variants of representation of the same information.]

 \Rightarrow note*:

[The increasing synergy of the components of cybernetic systems, being an important direction in the evolution of cybernetic systems, is to some extent opposed to the dialectical law of unity and struggle of opposites. In order for the selforganization of a cybernetic system to resist the destructive impact of the external environment, it <u>inside itself</u> must move from the unity and struggle of opposites to the unity and <u>synergy</u> of opposites, which in multi-agent cybernetic systems means the need to move from conflict and competitive interaction, from the search for compromise solutions to the search for consensus, to improve the quality of self-organization. In intelligent multi-agent cybernetic systems, the competition of agents is not a stimulus but a brake on evolution]

should be distinguished*

- \ni {• hybridity level^
 - \in parameter
 - ≔ [level of compatibility of the diversity of components of a cybernetic system[^]]
 - $\bullet \ hybridization$
 - ≔ [evolution of a cybernetic system by (in the direction of) increasing the level of hybridity]
 - := [transition of a cybernetic system from an eclectic variety of components to a harmonious integrated system, to a systematized variety]
 - := [systematization]
 - \subset direction of evolution
 - \subset cybernetic system activity
 - ⊃ hybridization of individual cybernetic system
 - ≔ [convergence and deep integration of different kinds of knowledge and problemsolving models]
 - ⊃ hybridization of multi-agent cybernetic system
 - := [convergence of different specialized agents of a multi-agent cybernetic system]

}

$interoperability \hat{}$

- := ["socialization" (level of "socialization") within various a priori unknown communities (collectives) of cybernetic systems^]
- := [semantic and interoperability of cybernetic systems^]
- := [ability of a cybernetic system to effectively, purposefully interact with other cybernetic systems in the process of collective (distributed) and decentralized solution of complex tasks^]
- ≔ [ability of a cybernetic system to be a useful member of various teams^]

should be distinguished*

- \ni {• homeostasis
 - ≔ [self-preserving the constancy of one's inner state]

- $\coloneqq [\text{homeostatic activity}]$
- \subset activity
- level of homeostasis
 - \in parameter
 - := [homeostasis quality]
- }

 \ni {• adaptation

- activity
 adaptability^
 - := [level of cybernetic system's ability to adapt^]
 - := [ability of a cybernetic system to adapt to changes in the conditions of its existence (environment) in order to (1) at least maintain its viability and (2) at most increase its level of development^]

}

VIII. The Evolution of Individual Cybernetic Systems

$A. \ stimulus \text{-} responsive \ individual \ cybernetic \ system$

\Rightarrow explanation*:

[A stimulus-responsive individual cybernetic system is a converter (transformer) of sensory signals into signals that control effectors (subsystems that directly affect the external environment or their own physical shell). If the said transducer becomes flexible, capable of distinguishing its successful reactions from erroneous ones and capable of correcting its erroneous reactions (i.e. capable of learning from its mistakes), then such a transducer becomes the processor-memory of a stimulus-response cybernetic system.]

$B. \ individual \ cybernetic \ system \ with \ sign \ memory$

\Rightarrow explanation*:

[The transition from stimulus-responsive individual cybernetic systems to individual cybernetic systems with sign memory means the separation of the processor-memory of a cybernetic system into a memory that stores the sign information model of the environment and a processor that performs changes in the state of this stored sign information model. This separation does not necessarily have to be realized physically (as, for example, it happens in modern computers).]

 \Rightarrow semantically close sign*:

• sign

 $:= explanation^*:$

[fragment of an information construct that is an image (representation) of the corresponding described entity]

• atomic sign
- := [sign that does not include other signs]
- \subset sign
- $non-atomic \ sign$
- \coloneqq [sign-expression]
- \coloneqq [sign consisting of several characters]
- \subset sign
- sign construction
 - \subset information construction := [information]
- internal sign construction
 := [symbolic construct stored in the memory of the corresponding cybernetic system]
- sense representation of information
 ≔ [sense sign construction]
- external sign construction
 - ≔ [symbolic construct that, for a given cybernetic system, is or is part of either a received or transmitted message]

C. task-oriented individual cybernetic system

 \Rightarrow explanation*:

[An individual cybernetic system that operates in its memory with the formulations of the tasks it has done, is doing, or expects to do, and is therefore to some degree "aware" of what it has done, is doing, or expects to do.]

- \Rightarrow direction of evolution*:
 - expanding the variety of formulations of the problems to be solved

 \Rightarrow note*:

[These are operational problem statements and declarative problem statements — goal statements]

- expanding the sense variety of tasks to be solved
- expanding the total number of tasks to be solved
- expanding the number and variety of problem-solving methods and models used
- gaining the ability to generate new problem formulations
 - ⇒ private evolutionary direction*: acquiring the ability for goal-setting
- acquiring the ability to solve not only those problems whose solution methods are known, but also problems whose solution methods are not currently available
- acquiring the ability to solve problems in the face of non-factors (incompleteness, inaccuracy, unreliability,...)
- shifting from using only operational problem statements to using goal statements as well
 ⇒ explanation*:

[The organization of information processing in cybernetic systems is dominated by semantic analysis of initiated goals and semantic analysis of information that is semantically close to these goals (such semantically close information is *goal context*). The context of a given goal determines the task situation corresponding to that goal, and therefore determines the way and path to achieve the specified goal.

Why cybernetic systems should be able to solve tasks that have a declarative formulation, i.e. formulation of the goal (result). Because most often in real practice tasks are formulated in a declarative way. At the same time, the solution of such tasks generally involves the analysis of the goal and context, construction of a solution plan, and search for appropriate methods (programs). Besides, each goal generally corresponds to a large number of ways to achieve it (variants of problem solution).

Thus, the most important type of knowledge stored in the memory of intelligent systems and underlying the organization of information processing in these systems are the descriptions of their pursued *objec*tives, solved tasks. In this sense intelligent systems "realize" their tasks, goals, "know" what they are doing. Goals can be informational (such goals will be called questions) and external, aimed at changing the external environment. The main source of goals that are set for an intelligent system are its users. Nevertheless, in the process of achieving such goals, the intelligent system can generate (set for itself) new auxiliary goals aimed at achieving the original user goals. In addition, some general goals can be embedded in the system and at the stage of its design. Such goals can include:

- to ensure the safety of users
- to ensure your own safety
- to continuously improve their knowledge and skills to improve the efficiency of service to users
- and so on

Let us emphasize that the semantic diversity of goals that an intelligent system can achieve, and, in particular, the diversity of types of questions it can answer, largely determines the level of development of this system. An intelligent system should be able to answer not only those questions that can be handled by traditional information systems based on modern databases, but also questions like why, why, how, what it is, how the given objects are related to each other, what is the similarity or difference of the given objects, what analogs (antipodes) of the given object are known, whether the given statement is true, what properties the objects of the given class have, and so on.]

- expansion of the variety of types of problems solved by a cybernetic system and corresponding expansion of the problem-solving models used
 - ⇒ private evolutionary direction*: acquiring and expanding the ability to solve intelligent problems

$intelligent \ task$

 \Rightarrow explanation*:

[intelligent task — a task for which the corresponding method of its solution stored in the memory of a cybernetic system is either not available (not known) at the current moment or fundamentally impossible due to the dependence of the process of solving this task on a large number of unpredictable circumstances and conditions. Intelligent tasks include proof tasks, hypothesis generation tasks, tasks of planning behavior in real conditions and, in particular, in real time, design tasks and many others.]

 \Rightarrow note*:

[The absence of a *method* known to the cybernetic system and guaranteeing solutions to the *intelligent problem* is compensated for by the fact that the cybernetic system can store in its memory not *methods* for different types of intelligent problems, but *strategies* of their solution, which do not guarantee the solution, but describe how intelligent problems can be reduced to subtasks for which the corresponding methods are known. It should be emphasized that the library of these strategies (methods) describing the solution of various types of intelligent problems, as well as the library of methods, should be constantly expanded and improved in a cybernetic system.]

${\it D.}$ individual cybernetic system with a structured internal information model of the environment

 $\Rightarrow epigraph^*$:

- [From data and databases to knowledge and knowledge bases]
- [From data science to knowledge science] \Rightarrow direction of evolution*:
 - evolution of meta-language tools that provide a description not of the environment itself, but

of the internal information model of this described environment

- := [evolution of linguistic means of structuring and systematization of fragments of *internal information model of the environment*]
- increasing the level of independence of evolution (improvement) of methods (programs) stored as part of the internal information model of the environment and evolution of information used and processed with the help of these methods (evolution of processed data)
- increasing the level of formalization of meaning − for the information being processed ⇒ note*:
 - [It is about creating a common formal language to represent the data being processed, with a well-defined denotational semantics and completely independent of the programming languages used in the cybernetic system.]
- increasing the semantic power of the internal information model of the environment
- increasing the power of associative access to information stored as part of the internal information model of the environment ⇒ explanation*:
 - [Associativity of access is determined by the presence of subject-independent and simple enough metaprocedures for searching answers to questions of different semantic types. And the maximum completeness of such access means that at <u>final</u> set of the specified metaprocedures the search of answers to questions of any semantic type is provided.

In other words, the completeness of associative access is the presence of universal and rather simple metaprocedures that allow either to find in the memory of an intelligent system an answer to any question posed to this system, or to establish the fact of absence of such an answer at the current moment. This is the essence of the full (ultimate) form of associative access to information stored in the memory of a computer system.]

• increasing the level of general unification of representation of different types of knowledge included in the internal information model of the environment, and, in particular, blurring the boundaries between the representation of stored methods (stored programs) and the representation of information processed with the help of these methods (processed data) \Rightarrow note*:

[The concept of processed information (processed data) is relative, as some programs may be processed by other programs.]

- acquiring the ability to analyze and improve the quality of its internal information model of the environment (its knowledge base)
 ⇒ note*:
 - [It means analyzing the completeness (integrity, sufficiency) of the knowledge base, detecting and possibly eliminating information holes and inconsistencies.]
- increase the level of activity of knowledge included in the knowledge base
 - \Rightarrow note*:

[Activity of knowledge means that the very fact of entering some knowledge into the knowledge base can initiate or put the corresponding information processes on hold. This is one of the factors of organizing situational decentralized management of information processes in a cybernetic system.]

E. hybrid individual cybernetic system

≔ [individual cybernetic system operating with a wide variety of types of knowledge, including types of methods (programs) stored in memory as part of its internal information model of the environment, as well as a wide variety of models of problem solving, i.e. skills of interpretation of methods of problem solving stored in memory] ⇒ note*:

[The essence of a hybrid individual cybernetic system is the transition from the eclectic diversity of its components to a high level of compatibility and synergy, based on a universal language of semantic representation of the internal information model of the environment.]

- := [individual cybernetic system based on a deep convergence of different models of knowledge representation, different models of problem solving, different channels and means of interaction with the external environment.]
- := [individual cybernetic system having multimodal knowledge base, multimodal solver, multimodal interface]
- \Leftarrow union*:
 - individual cybernetic system with hybrid problem solver
 - ≔ [individual cybernetic system with a wide variety and synergy of different problemsolving models]
 - individual cybernetic system with a hybrid internal information model of the environment
 :=

[individual cybernetic system with a wide variety and synergy (compatibility) of different types of knowledge included in the internal information model of the environment]

- individual cybernetic system with hybrid multimodal interface
 - ≔ [individual cybernetic system with a wide variety and synergy of different kinds of sensors and effectors, i.e. different kinds of perceived primary information (including received messages in different languages) as well as different kinds of influences on the external environment]
 - \Rightarrow note*:

[In particular, the level of synergy of the interface components of an individual cybernetic system is determined by the quality of sensorimotor coordination in performing complex types of actions]

}

F. learnable individual cybernetic system

- ≔ [individual cybernetic system with a high level of learnability and, consequently, a high level of flexibility, stratification and reflection]
- \Rightarrow note*:

[Learnability of a cybernetic system is a key characteristic of a cybernetic system that determines its rate of evolution]

G. self-sufficient individual cybernetic system \Rightarrow note*:

[An independent individual cybernetic system must be aware of itself, i.e. have knowledge about itself (its own self) — about its capabilities, its <u>destination</u>, its <u>obligations</u> and <u>responsibilities</u>, its moral and ethical principles (rules). That is, an independent cybernetic system must have a high level of reflexion, must be able to take care of itself and maintain the necessary level of its capability, must be able to make decisions independently, and must consider itself to a certain extent an independent *subject* of the corresponding activity]

$cybernetic\ system\ self-sufficiency$

- \Rightarrow parameter-factor*:
 - ability of free (independent) goal-setting
 - ability to plan independently to achieve goals
 - ability to achieve goals, realize one's plans purposefulness

$\it H.\ individual\ cybernetic\ system\ with\ strong\ intelligence$

:= [strongly intelligent individual cybernetic system]
:= explanation*:

[individual cybernetic system that has passed all conventionally allocated stages of evolution of individual cybernetic systems and has reached a high level of development in the corresponding directions of evolution:

- on the development of stimulus-response behavior; {item on the development of sign memory;
- on developing task-oriented behavior;
- on the development of an internal information model of the environment;
- to expand the diversity and synergy of different kinds of components of the individual cybernetic system;
- to enhance learning;
- to increase the level of autonomy in all its activities.
-]

 \Rightarrow note*:

[While emphasizing that an individual cybernetic system with strong intelligence must:

- to have a *reasoning ability* (to make inferences, to solve complex logical problems)
- to have the *ability to understand* and develop an internal information model of the environment.
- 1

IX. Evolution of multi-agent cybernetic systems

The level of *intelligence* (level of self-organization) of any cybernetic system is determined by the degree of development of cybernetic system components and the quality of organization of their interaction at all structural levels of the cybernetic system. All this is also true for multi-agent cybernetic systems, but with one very important clarification. The point is that multi-agent cybernetic systems (as well as embedded multi-agent information processing systems) have a very important feature — their agents have a high degree of self-activity and, as a consequence, unpredictability of behavior. Moreover, in the process of evolution of cybernetic systems, the degree of their independence increases. Correspondingly, the degree of unpredictability of their behavior also increases. Therefore, the main leitmotif of organizing the activity of a multi-agent cybernetic system and, in particular, the organization of its evolution (primarily, increasing the level of *synergy* of interaction between its agents) is to support high rates of agents' evolution (including increasing the level of their independence) and to prevent contradictions between the goals and activities of a multi-agent cybernetic system and the goals and activities of its agents. Improvement of methods

and means of ensuring contractual capacity, i.e. the ability to coordinate positions (including goals), as well as ensuring the ability to coordinate (harmonize) the actions of the agents of a multi-agent cybernetic system in the course of performing these actions are the most important factors of its evolution.

In other words, without permanent immunity support against the Babylonian pandemonium and information crisis syndrome, as well as the Swan, Cancer and Pike syndrome, the progress of a multi-agent cybernetic system is impossible. Moreover, at a certain stage of evolution of a multi-agent cybernetic system, the competition of its agents ceases to be a stimulus for its evolution.

One of the important directions in the evolution of cybernetic systems is the transition from a set of independent cybernetic systems to their collectives – multi-agent cybernetic systems capable of collectively solving problems that each member (agent) of these collectives alone is either fundamentally unable to solve, or can, but for an unacceptably long period of time. Let us emphasize that this transition from a set of independent cybernetic systems to their collectives can generate hierarchical multi-agent cybernetic systems with an unlimited number of hierarchy levels from sets of *individual cybernetic systems* to collectives of individual cybernetic systems, from sets of collectives of individual cybernetic systems to collectives of collectives of collectives of individual cybernetic systems. In addition, agents of some hierarchical multi-agent cybernetic systems can have different structures — can be individual cybernetic systems, collectives of individual cybernetic systems, collectives of collectives of collectives of individual cybernetic systems, and so on. Let us emphasize that only such an approach to the creation of a branched hierarchical network of cybernetic systems distributed over the space of their external environment will provide an unlimited increase in the level of development of this environment (the level of "expansion" of a cybernetic system).

X. New Generation Intelligent Computer Systems

new generation intelligent computer systems \Rightarrow principles underlying*:

- textual representation of knowledge in memory intelligent computer systems
- the use of a *universal language of semantic knowledge representation* common to all intelligent computer systems in the form of *refined semantic networks*
- structurally-reconfigurable (graphodynamic) memory organization of intelligent computer

systems, in which knowledge processing is reduced not so much to changing the state of the stored *signs*, but to changing the configuration of links between these *signs*

- semantically unrestricted associative access to information stored in intelligent computer systems memory, in a given pattern of arbitrary size and arbitrary configuration
- situational decentralized control of information processes in the memory of intelligent computer systems, realized by means of agent-oriented model of knowledge processing, in which initiation of new information processes is carried out not by transferring the control to the corresponding a priori known procedures, but as a result of occurrence of corresponding situations or events. in the memory of an intelligent computer system, because «The main problem of computer systems is not the accumulation of knowledge, but the ability to activate the necessary knowledge in the process of problem solving» (D.A. Pospelov)
- the transition to semantic *problem-solving models*, which are based on taking into account not only syntactic (structural) aspects of the processed information, but also *semantic* (semantic) aspects of this information – «From data science to knowledge science»
- ontological stratification of knowledge bases of intelligent computer systems as hierarchical system of subject domains and their corresponding ontologies
- clear specification of syntax and semantics of the whole variety of languages of interaction between users and intelligent computer systems, including language tools for user interface management, introduction into the composition of the intelligent computer system of the corresponding help-subsystems, providing a significant reduction of the language barrier between users and intelligent computer systems, which will significantly increase the efficiency of operation of intelligent computer systems
- minimizing the negative influence of the human factor on the efficiency of exploitation. intelligent computer systems by realizing an interoperable (partnership) style of interaction not only between the intelligent computer systems themselves, but also between the intelligent computer systems and their users. Responsibility for the quality of the collaborative activity should be shared

between all partners

- $\Rightarrow publications^*$:
 - [4]
 - [5]

XI. COMPLEX TECHNOLOGY FOR DEVELOPMENT AND MAINTENANCE OF NEW-GENERATION INTELLIGENT COMPUTER SYSTEMS

The proposed technology of complex life cycle support of new-generation intelligent computer systems is named **OSTIS technology** (Open Semantic Technology for Intelligent Systems) [4], [5]. Accordingly, the new-generation intelligent computer systems being developed using this technology are called **ostis**systems. The OSTIS technology itself is realized in the form of a special textitostis-system, which is called **OSTIS Metasystem** and whose knowledge base contains:

- The formal theory of *ostis-systems*;
- OSTIS Standard and OSTIS Technologies (*OSTIS Standard*);
- The core of the Reusable Component Library (*OSTIS Library*);
- Methods and tools for life cycle support of ostissystems and their components.
- The current state of OSTIS Technology has been tested on a range of applications as well as at annual OSTIS conferences that have been specifically organized for this purpose since 2011

The current state of OSTIS Technology allows not only to continue the work on the development of this technology, but also to start the work on its complex use to transfer the current level of informatization of the Republic of Belarus to a fundamentally new level, based on the mass application of semantically compatible and effectively *self* interacting with each other intelligent computer systems of new generation. The main problem here lies not in the intelligent computer systems themselves, but in the necessity of *rethinking* informatization of various branches to ensure their semantic compatibility, stratification, convergence and, ultimately, to simplify the relevant information resources and information processes as much as possible – eclectic, myopic, uncoordinated implementation of information resources and processes artificially and significantly complicates the informatization of already very complex types and types of information.

XII. The Technological Evolution of Human Society

The following processes underlie the unrestricted evolution of multi-agent cybernetic systems:

• is the process of expanding the hierarchical structure of a multi-agent cybernetic system:

- adding <u>new</u> cybernetic systems as agents of a multi-agent cybernetic system
- inclusion of already existing cybernetic systems as an agent in an existing multi-agent cybernetic system (a cybernetic system that is part of a hierarchical multi-agent cybernetic system can be an agent of several multi-agent cybernetic systems that are part of this hierarchical multi-agent cybernetic system at the same time).
- is the process of preliminary preparation of new cybernetic systems for their inclusion in a hierarchical multi-agent cybernetic system as agents:
 - formation of the necessary "qualifications" for these future agents, taking into account their specialization (roles within the corresponding multi-agent cybernetic systems).
 - intelligence formation for the specified potential agents at the level of *strong intelligence*
 - of developing a high level of *interoperability* in these potential agents.
 - formation of a high level of *synergy* in potential agents, if they are multi-agent cybernetic systems.
- permanent support of high level *synergy* of all multi-agent cybernetic systems included in the evolving *hierarchical multi-agent cybernetic system*.

We can talk about three vectors of evolution of cybernetic systems:

- evolution of individual cybernetic systems
- evolution of collective <u>individual</u> cybernetic systems.
- evolution of hierarchical multi-agent cybernetic systems

Dead-end branches of the evolution of multi-agent cybernetic systems are:

- Multi-agent cybernetic systems, in the course of their evolution, increasing the level of *interoperability* of their agents and increasing the overall level of *synergy* of multi-agent cybernetic systems are not the <u>priority</u> directions of their evolution. Examples are many modern human communities and organizations
- Multi-agent cybernetic systems whose agents do not possess strong intelligence or are fundamentally incapable of reaching the level of strong intelligence in the course of their evolution during their existence. Examples are swarms of bees, anthills, swarms of fish, birds, mammals, and other animals
- Multi-agent cybernetic systems that have no publicly_available picture of the world for all

agents and permanently improved by all agents, which accumulates and systematizes the experience acquired by all agents of a multi-agent cybernetic system in the course of its activity. At the same time, this publicly available picture of the world can be either concentrated in the memory of one of the agents, or completely distributed among the agents

- multi-agent cybernetic systems that have no current diversity of agent types or agent specialization (in particular, the distribution of agent responsibilities).
- multi-agent cybernetic systems whose agents have no possibility to flexibly change their current specialization (current qualification). We emphasize that the most important factor of intelligence of a multi-agent cybernetic system is a high level of diversity of agents transformed into their flexible convergence and synergy
- Multi-agent cybernetic systems, in the process of evolution of which the rate of evolution of technologies (methods and means) of training and retraining of their agents is <u>delayed</u> from the rate of evolution of the multi-agent cybernetic system itself in other directions. Let us note that agents of multi-agent cybernetic systems can be not only computer systems, but also people (we will call such multi-agent cybernetic systems human-machine communities)

From the point of view of the theory of evolution of cybernetic systems, the highest form of technological development of *human society* is *superintelligent* multi-agent cybernetic system, the agents of which are people and intelligent computer systems possessing strong intelligence and a high level of interoperability. But in order to create this superintelligent multiagent cybernetic system (superintelligent human*machine community*) it is necessary to provide strong intelligence and high level of interoperability not only for all artificial agents of this community (for all intelligent computer systems), but also for all people. The latter is a serious challenge for the modern system of education, the main goals of which should be not only the formation of knowledge, skills and competences necessary for effective participation in professional activity in the corresponding specialties, but also the systematic formation of the general picture of the world and, in particular, the formation of understanding of the directions (tendencies) and stages of evolution of the superintelligent humanmachine community. Besides, the most important goal of education should become not only the formation of a strong level of intelligence in people, but also the formation of a high level of *interoperability* (socialization), necessary for competent functioning as an agent

of the superintelligent human-machine community.

Let us also emphasize that in order to create *super-intelligent human-machine community* it is necessary to provide not only *strong intelligence* and high level of *interoperability* of all agents of this community (both artificial and natural), but also high level of *synergy* of their interaction. For this purpose it is necessary to permanently analyze and improve the principles of organization of this interaction, which is one of the most important directions of evolution of the *superintelligent human-machine community*.

$agent \ of \ the \ superintelligent \ human-machine \ community$

- ⊃ user of superintelligent human-machine community
 - \Rightarrow note*:
 - [Different users within the same community may have different responsibilities (different roles).]
 - \Rightarrow note*:

[The same person can be a user (member) of more than one community at the same time]

- \supset personal user assistant of the superintelligent
 - human-machine community

 \Rightarrow note*:

[The interaction of each user with all other agents of the superintelligent human-machine community is carried out <u>only(!)</u> through his personal assistant, which allows to provide a high level of automation of interaction of each user with all users of this community, as well as with all artificial agents of this community.]

 \Rightarrow note*:

[If a person is a user of multiple superintelligent human-machine communities simultaneously, his personal assistants for all of these communities are integrated (merged) into a physically single integrated personal assistant, which provides comprehensive and coordinated automation of the user's activities across all communities of which he is an agent.]

- \supset corporate system of superintelligent
- human-machine community

 \Rightarrow explanation*:

[This system ensures the coordination of the activities of all agents of the respective community, combining both centralized and decentralized management techniques in a reasonable manner]

Examples of specialized superintelligent humanmachine communities are:

• superintelligent human-machine community for development and maintenance of new generation intelligent computer systems

- superintelligent human-machine community for the development of technologies for the development and maintenance of new-generation intelligent computer systems
- superintelligent human-machine community for research and development activities in the field of Artificial Intelligence
- superintelligent human-machine community for Artificial Intelligence educational activities
- superintelligent human-machine community to develop strategy and tactics for the development of activities in the field of Artificial Intelligence (integration of all previous ones)

The final stage of technological evolution of human society is the transition from a set of independent specialized superintelligent human-machine communities to their unification (integration) in the *global superintelligent human-machine community*, which is a hierarchical system of interconnected and synergetically interacting specialized superintelligent human-machine communities of different purposes.

The development of a permanently evolving architecture of such a *Global Human-Machine Community* is the key practical task of the current stage of development of Cybernetics and, in particular, Artificial Intelligence. It is obvious that to solve this problem it is necessary to reduce interdepartmental and interdisciplinary barriers, to ensure interdisciplinary convergence, unification and standardization, as well as to increase the level of interoperability and synergy.

XIII. CONSLUSION

At present, many countries have adopted a strategy for the development of work in the field of *artificial intelligence* at the state level, which is necessary to harmonize and coordinate research and application activities.

At the current stage of work in the field of *artificial intelligence*, the following trends are relevant:

- transition from differentiation of approaches and directions to their convergence and deep integration;
- transition from compromise solutions to consensus-based solutions;
- transition from competition to complementary and mutually beneficial interaction;
- transition from highly specialized solutions to flexible, adaptive and potentially universal solutionsPospelov1986, Varshavsky1984;
- transition from syntactic compatibility to logicalsemantic compatibility of intelligent computer systems on the basis of formalization of meaning and semantic representation of knowledge;
- transition to hierarchical multi-agent models for solving complex problems [6]–[8];

- transition from centralized to decentralized control of agent interaction in multi-agent systems [7], [8];
- situational management of the process of solving complex problems, taking into account changes in the context (conditions) of problem solving [6];
- Increasing the level of agent interoperability;
- orientation on *intelligent computer systems* of fundamentally new generation that meet modern requirements;
- search for approaches to effective hardware support of *intelligent computer systems* of the next generation in the form of universal computers of the new generation;
- Improving the quality of information resources and combating the information crisis.

The overwhelming majority of actual problems of the current stage of development of theory, technologies and application of *intelligent computer systems* require unification and coordination of efforts of all specialists working in the field of *artificial intelligence*. [9], [10].

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ЭВОЛЮЦИЯ КИБЕРНЕТИЧЕСКИХ СИСТЕМ: ОТ КОМПЬЮТЕРНЫХ СИСТЕМ С СИЛЬНЫМ ИНТЕЛЛЕКТОМ К СУПЕРИНТЕЛЛЕКТУАЛЬНЫМ ЧЕЛОВЕКО-МАШИННЫМ СООБЩЕСТВАМ

Белоцерковский А. М., Голенков В. В., Головко В. А., Гулякина Н. А., Краснопрошин В. В., Недзьведь А. М., Шункевич Д. В.

В статье рассматриваются ключевые особенности кибернетических систем, их эволюции и параметров, определяющих уровень их интеллекта и самоорганизации. Рассматриваются иерархические системы параметров, характеризующих текущие возможности и скорость развития кибернетических систем, а также факторы, способствующие ускорению их эволюции. Особое внимание уделено семантически близким понятиям, связанным с уровнем интеллекта кибенетических систем, и процессам эволюции как индивидуальных, так и многоагентных кибернетических систем. Рассматриваются перспективы интеллектуальных компьютерных систем нового поколения и комплексная технология их разработки и сопровождения. В завершение обсуждается влияние технологической эволюции на развитие человеческого общества, предлагается идея Глобального человеко-машинного сообщества.

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Conditions for the Practical Application of Artificial Intelligence in Healthcare

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Abstract—The development of artificial intelligence (AI) technologies and their implementation in various industries and spheres of human activity has become one of the key modern trends, and the medical sphere is no exception. The article examines the conditions for the practical application of AI in healthcare, highlights the main stages of technology implementation, and analyzes the main challenges that arise during the implementation of such projects. The authors of the article emphasize the importance of a systematic approach, including analysis of the current state, setting goals and objectives, organizing teams, communication and monitoring, as well as piloting and testing solutions. The article also considers basic aspects related to the legislative framework, economic efficiency and personnel training for the successful implementation of projects in healthcare.

Keywords—healthcare, artificial intelligence, digital development of healthcare, implementation of AI.

I. Introduction

The development of artificial intelligence (AI) is one of the most relevant trends in the development of modern technologies, influencing most areas of activity, including healthcare. The introduction of AI in this area involves improving the quality of medical care and enabling doctors to focus on more complex tasks that require human participation. However, during the implementation of such projects, a number of problems and contradictions arise that require detailed analysis. This article examines the conditions and stages of the introduction of AI in healthcare, including organizational, legal, technical and personnel aspects. The authors of the article note that the proposed approach is not unique to the healthcare industry, and believe that it can be applied to other national industries and areas of activity.

II. Stages of forming conditions for the practical application of AI

A. Basic conditions for the use of AI.

In order to effectively apply and implement AI technologies, it is necessary to define the main stages of this process, which include:

- Analysis of the current situation.
- Determine what problems AI solves.
- Calculate the economic effect.
- Determine what resources we have available.

Before you begin implementing AI, it is important to analyze the current state of affairs, i. e. to determine the "initial data". At this stage, it is important to understand the following aspects:

It is necessary to carry out an analysis of contradictions. The authors of the article note the works of Genrikh Altshuler with his theory of inventive problem solving (TRIZ), 40 basic techniques for eliminating technical contradictions as a good approach to understanding the process of identifying contradictions. TRIZ has been and is used today to train engineers by such wellknown companies as Procter& Gamble, Motorola, Ford, Siemens, Phillips, 3M, LG and others. TRIZ is based on the collection and analysis of arrays of information on inventive solutions, differentiation of these arrays by levels of complexity of resolving contradictions, identification of techniques and methods for resolving contradictions [1]. TRIZ methods and tools are applicable to solving inventive problems not only in engineering, but also for non-technical systems. TRIZ is used in practice to develop a creative personality, solve inventive problems in various fields, including medicine [2].

To determine whether there is readiness to adopt new things, it is important to consider several factors. Depending on the context – whether it is the introduction of new technologies, changing habits, adopting a new idea, or something else – the approach may differ. Here are some key steps to help determine whether there is readiness [5], [6].

Defining the target audience. It is important to understand who exactly will be the main consumer of the innovation. Different groups of people may react to changes differently. Having defined the target audience, it is easier to assess its attitude to the innovation.

For example, young people are often quicker to adopt technological innovations, while older generations may need additional support and training.

Analysis of change perception. Willingness to change depends on how potential customers perceive the possible consequences of introducing something new. If they see advantages, the likelihood of adoption increases. However, if people are afraid of risks or negative consequences, resistance can be significant.

Research of barriers. It is necessary to identify potential barriers that may prevent the adoption of the new. Barriers may be related to lack of knowledge, lack of resources, fear of the unknown or organizational limitations.

The balance of need and simplicity is a concept of the optimal combination of the functionality of the implemented solution with the minimization of the complexity of its use. A successful digital product is one that effectively solves consumer problems while maintaining a user-friendly and simple interface.

Determine what final economic result can be expected, including the cost-benefit balance.

Calculating the economic effect of implementing a new project, technology or process is an important stage of planning and assessing the feasibility of investments. The economic effect shows what expected benefit can be obtained after implementing the new. The key stages of calculating the economic effect are:

determination of costs: investments, operating expenses, etc.;

revenue assessment: direct income, cost savings, cost reduction,

payback period;

social effect (benefit).

Identify the different types of assets that can be managed: finance, people, time.

B. Formation of goals and objectives. Development of a strategy (plan) of actions

The formation of goals and objectives is the basis for further development of an action plan.

Goals and objectives of practical application of AI in healthcare:

- improving the quality and accessibility of medical care. The introduction of digital technologies and standards will improve the accessibility and quality of medical care;
- reducing the workload of the doctor by transforming current processes. Automation of routine tasks will allow doctors to focus on more complex aspects that require human participation;
- development of medical technologies. AI contributes to the creation of new methods of prevention, diagnosis and treatment, and the production of medicines;
- reduction of healthcare costs. Optimization of processes will allow to significantly reduce costs;
- personalization of medical services, which will allow the formation of a full volume of medical information about the patient, taking into account his/her characteristics.

The strategy (plan) of actions defines the path to achieving goals and objectives and includes the following steps:

- publication of a country-specific regulatory legal act that will define the regulator in the field of AI, its powers and the powers of interested participants;
- definition of the concept, namely: consolidation of the principles and approaches to the development of AI in the country;
- defining a strategy by setting goals and objectives, the AI development system in the country, industry roles and tasks;
- formation of industry policy for the implementation and development of AI in healthcare.

These are the primary organizational and legal steps for separating AI into a separate, independent scientific and technological direction.

C. Organizing and preparing the team. Communication and monitoring

Organizing and preparing a team is an important step, since the use of AI requires dedicated and competent specialists in the field. The preparation process consists of the following stages:

- organization and management of the team. The creation of a multi-level management system will allow for effective coordination of actions;
- coverage of activities, public discussion of issues;
- training and preparation. It is necessary to ensure training of medical and technical specialists to work with new technologies;
- allocation of applied areas. Allocation of applied projects into separate areas or groups, which will allow focusing on individual projects and speed up implementation.

Effective communication and control over the execution of tasks will help to avoid possible problems and increase the efficiency of implementation. This stage involves:

- formation of a common understanding of the process among the participants. Ensuring interoperability of processes, participants and systems. The ability of the participating processes, systems and participants to achieve common goals at the business process level;
- professional expertise, that is, discussion of results and problems with experts and search for solutions;
- systemic communication, the presence of connections and the need for communication;
- communication monitoring. Constant monitoring of the project implementation will help to promptly identify and correct errors. (tracking and regulating the communicative behavior of participants).

D. Piloting, testing and evaluation of results

As part of the piloting, testing and evaluation stage of the intermediate results of this stage, the following is carried out:

- conducting a pilot. Organizing and conducting pilot testing, checking the system's performance in real conditions;
- threat model. Identification of potential threats and risks, models for their response and minimization;
- prototype testing. Implementation of the tested prototype, debugging;
- identification and elimination of errors. Conducting trial operation, eliminating errors identified during trial operation;
- evaluation of results. Analysis of the results of piloting, testing and trial operation.

III. Practical application of AI in healthcare

There are many information systems in use in healthcare organizations of the Republic of Belarus, but they do not meet the basic characteristics of AI.

Information systems that are related to AI must be able to work with big data technologies, self-learn, and seamlessly integrate with other information systems.

For reference. Currently, the definition of AI is given within the framework of the Resolution of the Council of Ministers of the Republic of Belarus dated April 21, 2023 No. 280 "On measures to implement the Decree of the President of the Republic of Belarus dated April 7, 2022 No. 136.

Artificial intelligence is a set of technological solutions that allows simulating human cognitive functions (including self-learning and finding solutions without a predetermined algorithm) and obtaining results when performing specific tasks that are comparable to the results of human intellectual activity, and includes information and communication infrastructure, software, processes and services for data processing and finding solutions [10].

A preliminary analysis of the current state of affairs in digital healthcare development points to the need for a systemic rethinking of approaches to the implementation of AI. To do this, it is necessary to:

- identify emerging contradictions and their relevance to digital development in the field of AI;
- develop an intelligent ecosystem for digital development of healthcare;
- eliminate technological and regulatory contradictions in the implementation of AI in practice.

Working with emerging contradictions in digital development in the field of AI involves not only identifying them, but also searching for potential solutions.

The approaches to identifying and resolving contradictions based on TRIZ are mentioned above, the methods of which can also be used to solve problems in the field of medicine. The application of TRIZ principles allows for effective work with emerging contradictions, which is especially relevant when implementing innovative technologies [7], [8].

A. Basic principles of TRIZ

TRIZ is based on several key principles [3], [4]:

The law of contradictions. Any improvement of one parameter of the system often worsens another parameter. The task is to find a compromise or eliminate the contradiction by introducing additional elements or changes in the system.

Resource Utilization: The solution must utilize the available system resources (materials, energy, space, time).

Ideality. An ideal system is one that performs its function, but is itself absent as a material object.

Evolutionary approach. The system develops according to certain laws of evolution, and the task is to predict the direction of this evolution.

For example, with the growth of medical data, it is necessary to maintain the quality of medical care. Minimizing the heterogeneity of medical data formats should not interfere with maintaining the variety of medical information systems. The solution to these contradictions can be the introduction of new methods of information processing that do not depend on data formats [9].

B. Application of TRIZ in medicine

Development of new drugs. TRIZ can be used to find solutions to overcome limitations of existing drugs, such as side effects, toxicity or inefficiency. For example, it is possible to find ways to improve the delivery of active substances to the body or to reduce the dosage of the drug without losing therapeutic effectiveness.

Creation of new medical devices. TRIZ helps in the development of devices that solve specific clinical problems, such as portable diagnostic devices, robotic systems for surgery, or exoskeletons for patient rehabilitation.

Optimization of medical procedures. TRIZ can be used to optimize medical procedures such as surgeries, rehabilitation, or prevention. For example, it is possible to develop methods that reduce the trauma of surgeries or speed up the recovery of patients.

Resolving ethical dilemmas. TRIZ can help find compromise solutions in cases where moral or ethical conflicts arise, for example, when determining priorities in providing medical care or making decisions about stopping treatment.

Improving the efficiency of medical care. TRIZ can help optimize processes in hospitals and clinics, reduce queues, reduce errors and increase patient satisfaction.

Let's consider an example of using TRIZ to develop a new method of treating Parkinson's disease. One of the main problems in treating this disease is the need for constant medication, which causes side effects and inconvenience for the patient. Using TRIZ, we can propose a solution based on the implantation of a miniature device that will deliver the drug directly to the brain through special channels. This will avoid side effects and ensure a constant supply of the necessary substance to the desired area of the brain.

C. Advantages of using TRIZ in medicine

Innovativeness. TRIZ stimulates creativity and out-ofthe-box thinking, which leads to the creation of unique and effective solutions.

Efficiency. The use of TRIZ allows finding optimal solutions to problems, minimizing costs and maximizing results.

Universality. TRIZ methods can be applied in almost any area of medicine, from the development of new drugs to the organization of work of medical institutions.

Scientific approach. TRIZ is based on the analysis of patterns and trends, which ensures the scientific validity of the proposed solutions.

D. Limitations and Challenges

Despite the obvious advantages, the use of TRIZ in medicine faces a number of limitations and challenges:

Requires a deep understanding of the subject area. To successfully apply TRIZ, it is necessary to have a good understanding of a specific medical task, which requires the participation of specialists with a high level of professional training.

Direct analogies are not always obvious. Some medical problems are so specific that direct analogs from other areas may be absent, which complicates the application of standard TRIZ tools.

Ethical and legal aspects. The medical field has strict regulations and standards that must be taken into account when developing any innovations.

TRIZ provides powerful tools for resolving complex contradictions that arise in medical practice. By applying various TRIZ principles and methods, effective and innovative solutions can be found that improve the quality of medical care, reduce risks, and increase patient satisfaction.

Several examples of resolving contradictions that may arise in medical practice using TRIZ.

Contradiction 1: Effectiveness vs. Side Effects Problem:

Some drugs are highly effective in treating diseases, but cause serious side effects, which reduces their suitability for widespread use.

Solution:

Using TRIZ principles, such as separation in time and space, the following options can be proposed:

Creation of combination drugs, where one component neutralizes the side effects of another.

Development of methods for controlled release of the active substance to minimize the concentration of the drug in the blood outside the affected area.

Introduction of auxiliary components into the drug that block unwanted reactions of the body.

Contradiction 2: Minimally Invasive Treatment vs. Diagnostic Accuracy.

Problem:

Minimally invasive procedures such as endoscopy or laparoscopy allow for less traumatic interventions for the patient, but they may limit diagnostic accuracy and control over the surgical field.

Solution:

The application of the principle of "ideality" in TRIZ can lead to the following solutions:

Development of high-tech imaging tools such as a high-resolution microscopic camera built into an endo-scope.

The use of robots to perform operations, which increases the accuracy of manipulations and reduces the risk of error.

Use of ultrasound navigation to accurately determine the location of organs and tissues.

Contradiction 3: Duration of Procedure vs. Speed of Action.

Problem:

Many medical procedures take a long time to complete, which creates discomfort for patients and a workload for medical staff. However, speeding up the process can negatively affect the quality of treatment.

Solution:

You can apply the principle of dynamism from the TRIZ arsenal:

Automation of routine stages of the procedure using specialized equipment.

Performing multiple tasks in parallel during a single procedure, such as simultaneously administering contrast material and collecting diagnostic data.

Optimization of the sequence of actions to reduce the overall procedure time.

Contradiction 4: Individualized Treatment vs. Scalability.

Problem:

Individualized treatments tailored to the individual patient demonstrate better results, but are difficult to scale and expensive. Mass production of drugs and methods, on the other hand, is cheaper but less effective for each individual case.

Solution:

Using the idea of complexity sharing, we can propose: Personalized test kits to determine the most appropriate treatment option.

Creating machine learning algorithms that provide personalized recommendations based on big data.

Modular treatment systems where the basic components are universal and additional elements are customized for a specific patient.

Contradiction 5: Accuracy of Diagnosis vs. Time of Diagnosis.

Problem:

Highly accurate diagnostic methods, such as MRI or genetic testing, are time-consuming and resourceintensive, which delays treatment. Faster methods, such as rapid tests, are often less accurate.

Solution:

Let's apply the "anti-object" principle:

Combining rapid preliminary screening with subsequent diagnostic clarification using a highly accurate method.

Development of automated systems for interpreting test results, which speeds up the data processing process.

The use of TRIZ in medicine opens up new horizons for finding solutions to complex clinical problems. This method allows going beyond traditional approaches and offers innovative ways to overcome existing problems. However, successful integration of TRIZ into medical practice requires joint efforts of doctors, scientists and engineers, as well as consideration of all regulatory requirements and ethical aspects.

In addition, it is necessary to develop an intelligent ecosystem for digital healthcare development, which is a collection of all digital healthcare systems, as well as an intelligent metasystem - a top-level subsystem for managing the healthcare ecosystem, the purpose of which is to integrate data from medical systems.

E. Intellectual ecosystem of digital development of healthcare of the Republic of Belarus

The intelligent ecosystem of digital development of healthcare in the Republic of Belarus is a system of interconnected digital platforms, services and solutions aimed at improving the quality of medical care, increasing the efficiency of medical institutions and improving the health of the country's population. This ecosystem includes a number of components, each of which contributes to the overall digital transformation of the industry.

Components of the intelligent ecosystem:

an electronic medical record stores the patient's entire medical history, examination results, doctor's orders and other important medical data. It is available to doctors in real time, which facilitates the process of diagnosis and treatment;

telemedicine allows doctors to consult patients remotely using video conferencing and other modern means of communication. This is especially useful for residents of remote regions who find it difficult to get to specialized clinics;

an artificial intelligence is used to analyze large volumes of medical data, helping doctors make more informed decisions. For example, AI can be used for early diagnosis of diseases, predicting treatment outcomes, and selecting individual treatment plans;

modern digital diagnostic technologies, such as computed tomography, magnetic resonance imaging and ultrasound, allow us to obtain high-quality images of internal organs and tissues, which significantly increases the accuracy of diagnostics;

robots are used in surgery to perform complex operations with high precision. They are also used to rehabilitate patients after injuries and operations;

management information systems make it possible to automate many administrative processes in healthcare institutions, such as scheduling appointments, maintaining patient records, and managing medication inventories;

educational platforms provide physicians and other healthcare professionals with access to the latest scientific research and technology, as well as continuing education and retraining programs;

mobile applications for patients allow them to monitor their health, make appointments with doctors, receive notifications about appointments, and monitor compliance with doctor's recommendations;

biometric technologies are used to identify patients and protect sensitive medical information. For example, fingerprint or iris scanning can replace traditional passwords and access cards;

blockchain can be used to securely store and exchange medical data between different institutions and specialists. This ensures the integrity and confidentiality of the information.

F. Benefits of an Intelligent Ecosystem

Improving the quality of health care. With access to a complete medical history and modern diagnostic technologies, doctors can make more accurate diagnoses and prescribe effective treatment.

Increasing the availability of medical services. Remote consultations and telemedicine make medical care accessible to residents of all regions of the country, regardless of their place of residence.

Cost reduction. Automation of administrative processes and the use of modern technologies allow to reduce the costs of maintaining medical institutions and increase their efficiency.

Personalized treatment. Big data analysis and the use of artificial intelligence allow us to select individual treatment regimens, which increases their effectiveness and reduces the risk of side effects.

Security and privacy. The use of biometrics and blockchain ensures the protection of personal medical information and prevents unauthorized access to data.

G. Challenges and Prospects

Despite significant progress in developing the intellectual ecosystem of digital healthcare in Belarus, certain challenges remain:

Technical and infrastructure limitations. Some regions of the country may lack the necessary infrastructure for the full functioning of digital services, such as broadband Internet and modern telecommunications networks. Staffing shortages: Insufficient numbers of qualified IT professionals and healthcare workers with the necessary digital skills may slow down the pace of innovation.

Regulatory barriers: Difficulties with regulation and standardization of digital health services may hinder the rapid development of the ecosystem.

However, despite these difficulties, the future looks very promising. The Government of the Republic of Belarus is actively investing in the development of digital healthcare, creating conditions for the introduction of new technologies and improving the quality of medical care for the population.

The metasystem will be a domain knowledge base and a multi-agent intelligent system. Multi-agent systems are AI platforms that include several independent and interactive agents capable of solving various problems. The role of agents can be played by AI models, software, robots, and much more. Their joint use will allow solving complex problems, while conventional AI is focused on creating agents for specific use cases.

The metasystem will allow to implement:

- providing an intelligent natural language interface with users;
- automation of the execution of requests from users and, above all, healthcare organizers with logical and semantic verification of correctness;
- intelligent integration of applied medical systems;
- intellectual support for the implementation of scientific research, including in the field of healthcare organization;
- formation of subject knowledge bases for specific sections and subsections of medicine and the use of these bases for training industry specialists, testing knowledge and checking the correctness of texts;
- intellectual support for making management decisions at different levels of management;
- intellectual support for making medical decisions in practical medicine, including telediagnostics and teleconsultation modes;
- functions of a universal natural language reference system for doctors and patients with role differentiation;
- intelligent forecasting of processes based on various logical and mathematical models, including statistical ones.

Conclusion

For the successful implementation of AI in healthcare, it is necessary to take a systematic approach to solving emerging problems. The most important tasks are to eliminate technological and regulatory contradictions in the implementation of AI in practice, for this it is necessary:

 develop high-level regulatory legal acts in the field of digital development, including the use of AI technologies in the country's healthcare;

- develop a conceptual framework in the field of application of artificial intelligence in healthcare;
- prepare draft regulatory legal documents in the field of application of artificial intelligence in healthcare.

The implementation of AI in practice requires not only technical preparation, but also a detailed approach to issues of legality, ethics and readiness for change on the part of all participants in the process.

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УСЛОВИЯ ПРАКТИЧЕСКОГО ПРИМЕНЕНИЯ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ЗДРАВООХРАНЕНИИ

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Развитие технологий искусственного интеллекта (ИИ) и внедрение их в различных отраслях и сферах жизнедеятельности человека стало одним из ключевых современных трендов, не исключением является и медицинская сфера. В статье рассматриваются условия практического применения ИИ в здравоохранении, выделяются основные этапы внедрения технологий, а также анализируются основные вызовы, возникающие при реализации таких проектов. Авторы статьи подчеркивают важность системного подхода, включающего анализ текущего состояния, постановку целей и задач, организацию команд, коммуникацию и мониторинг, а также пилотирование и апробацию решений. Рассмотрены также базовые аспекты, связанные с законодательной базой, экономической эффективностью в здравоохранении.

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Approaches of Neuro-Symbolic Integration: Large Language Models and Knowledge Bases

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Abstract—The paper reviews modern approaches to the integration of neural network and symbolic artificial intelligence, including architectures using generative models in combination with knowledge bases and agents. Special attention is paid to the limitations of large language models (LLMs) in solving problems related to long-term context, as well as RAG-type mechanisms and modern agent-based systems are analyzed. An architecture of intelligent systems based on OSTIS Technology is proposed, in which LLMs are integrated into the problem solver. The necessity of formal description of generative AI methods as part of the problem solver is substantiated.

The authors emphasize the advantages of moving the knowledge base from the position of a source of context for LLMs to the position of a shared semantic memory that combines different types of knowledge, from problem descriptions and solution models to the history of agent interaction. This approach provides automatic verification of knowledge, accumulation of experience and transparency of decisions.

Keywords—neurosymbolic AI, logical-semantic models, artificial neural networks, large language models, knowledge base, ontologies, intelligent systems architecture, OS-TIS Technology

I. Introduction

Symbolic and neural network approaches to building artificial intelligence (AI) have historically been developed based on different principles: the former on logical-semantic structures, rules and knowledge bases, the latter on learning from examples and generalization. For decades, attempts have been made to combine the strengths of both approaches to create more versatile and explainable intelligent systems. However, it is only in recent years, with the growing capabilities of large language models and the development of the corresponding infrastructure, that the integration of these approaches has received a new breath and is reaching the application level. The urgency of finding effective hybrid solutions has become particularly important with the rapid proliferation of generative models capable of producing text, code, and other types of data at a near-human level. Despite their impressive capabilities, they face limitations in solving problems that require knowledge management, logical reasoning, long-term memory, and decision transparency. These limitations are driving the rethinking of intelligent systems architectures and the implementation of solutions that combine the flexibility of artificial neural networks (ANNs) with the formal rigor of logicalsemantic models.

In this paper, current approaches to the integration of neural networks and logical-semantic models are reviewed, and we propose our own approach to integrating artificial neural networks (including large language models) with a knowledge base and a problem solver.

II. Modern approaches to the integration of artificial neural networks and logical-semantic models

Studies of integrations of neural network and symbolic approaches to AI have developed into a separate direction – neurosymbolic AI [1]. In the works [2]–[5] an analysis of various approaches to the integration of these approaches, including their advantages and limitations, is presented.

In recent years, systems that combine various AI methods within a single architecture have been actively developed. Special attention is paid to the integration of ANNs with knowledge bases, which in foreign studies are increasingly referred to as knowledge graphs [6], [7].

Let us consider the key directions and approaches to the implementation of such integration.

A. ANNs as a sensor of an intelligent system

This approach is that ANNs serve as sensors that extract information from various inputs (text, images, sounds) and translate them into formats suitable for use in a knowledge base. For example, ANNs extract entities and relationships from textual data or images. The information obtained by ANNs is further used to solve various problems within an intelligent system [8]–[11].

The main advantage of this approach is the ability to integrate ANNs with a knowledge base to extract knowledge from various sources without human involvement. However, the quality of the extracted knowledge depends on the quality of the input data and the accuracy of the ANNs.

B. Knowledge base for processing and verification of training datasets and ANN output data

In modern problems solved with ANNs, the requirements to the degree of semantic consideration in the solution are constantly growing. Taking into account the peculiarities of ANNs, the degree of semantic consideration is increased by searching for logical and semantic contradictions in the ANNs training and output data. In case of detection of such contradictions in the output data it becomes possible to adjust the ANNs weights in the process of training. In addition, based on knowledge bases, synthetic data can be generated, which is then used to train ANNs, which is especially useful in cases where the amount of real data is limited or difficult to obtain [12]–[14].

This approach improves the accuracy and validity of results through logical reasoning. However, it requires a complex system of logical rules and knowledge, and is problematic to scale for large amounts of data.

C. ANNs process and generate fragments of the knowledge base

The approach has received a major boost due to the introduction of graph neural networks capable of taking graph structures as input. Such networks are used to predict relationships in the knowledge base [15], classify and cluster fragments of the knowledge base [16].

The main advantage of this approach is the ability to work with complex graph data structures and identify new relationships between entities. However, it requires the development of specialized graph neural networks for specific classes of problems.

D. Knowledge base for explaining how ANNs work

In this approach, the knowledge base stores logical rules that correspond to specific neural elements or layers of ANNs. This approach is part of the Explainable AI trend [17] and is designed to solve the classic problem of ANNs – the "black box" problem [18]. ANNs are trained on historical data, they are not able to explain

why exactly such results were obtained. The essence of this approach to solving this problem is to try to generate plausible logical rules that are put in correspondence with the stages of computation within the ANNs. When the ANNs operate, the stages of computation that had the greatest impact on the result are evaluated, and then a chain of logical rules is constructed to explain it [19]–[21].

The main advantage of this approach is the ability to ensure that ANNs solutions are explainable at some level, but it requires a complex system of logical rules and knowledge, which is not always applicable for ANNs with a large number (billions) of parameters.

E. Neurosymbolic architectures for sustainable continual learning

Research in continual learning has identified one of the key problems of ANNs – **catastrophic forgetting**, in which training a model on new data leads to complete or partial loss of previously learned knowledge [22].

In the paper [23] the NeSyBiCL (Neuro-Symbolic Brain-Inspired Continual Learning) framework is presented, which consists of three main modules: a convolutional neural network (CNN) for feature extraction, ANN for fast inference (System 1), and a symbolic mechanism based on knowledge graphs (System 2). In the symbolic mechanism, information from problems is formalized in the form of entities (graph nodes) and relations (graph edges). Problems are solved by logical inference based on these knowledge graphs.

The basic idea is that while ANNs are prone to catastrophic forgetting, the symbolic mechanism, due to its representation of knowledge as graphs and logical inference, may be more resistant to this problem. The interaction between the two systems ensures knowledge transfer, with the symbolic mechanism being resistant to catastrophic forgetting but less accurate than ANNs. The authors show an average 41% reduction in forgetting on two composite benchmarks.

F. Summary

All the problems solved by the above approaches are undoubtedly relevant, but their solutions are often narrowly focused on a specific problem from some subject domain. Neural network and logical-semantic models of problem solving are used in a clearly defined sequence, are manually integrated with each other and are not aimed at solving complex problems of arbitrary formulation. The figure 1 shows the scheme of interaction of AI modules integrated into an intelligent system in a "manual" way.

III. Race of generative models: opportunities, limitations, benchmarks

The development of neurosymbolic approaches opens new opportunities for integrating ANNs with knowledge



Figure 1. Scheme of interaction between the problem solver and AI modules integrated in a "manual" way

bases, which allows solving complex problems in various domains. However, in parallel, generative models such as large language models are being actively developed, showing impressive results in text processing and generation. Understanding the current state of these technologies is essential in order to assess their potential and capabilities in future integrations with other components of intelligent systems. This chapter reviews the current state of generative AI and large language models.

The current rapid development of neural network models for natural-language information processing began with the publication of a revolutionary paper "Attention is All You Need" in 2017, which marked the emergence of a new architecture for neural network models – the attention-based transformer [24]. Transformer models do not use recurrent feature layers to implement them.

The key advantages that transformer networks have are:

- Self-attention a mechanism that allows the model to take context into account at any distance (unlike recurrent neural networks, which suffer from loss of context as the test fragment being analyzed increases);
- 2) Parallelization ability to learn faster;
- 3) Scalability the ability to build deep and broad models.

With the ability to represent any data (video, audio sequences, single images, etc.) in the format of a sequence of numerical representations (embedding vectors) that can then be processed by the model, Transformers have become the cornerstone of all major SOTA models for processing natural language, visual (computer vision) and multimodal information.

The next milestone in the development of Transformers can be considered the emergence of the BERT architecture in 2018, which has significantly improved the quality of NLP problem solving [25].

In 2019, there is a research shift towards Causal Language Models (CLMs). Unlike Masked Language Models (e.g., BERT), whose application focuses on text

comprehension problems, CLMs are used for text generation. The research findings have led to the ability to apply a single model to multiple problems without the need for fine-tuning.

The year 2020 marked the launch of OpenAI's GPT-3, which kicked off the race for large language models as the basis for realizing commercial products [26]. The key milestones in this race were:

- PaLM [27], Chinchilla [28] (2022): the development of these models showed that it is not only the size of the models that matters in implementation, but also the effectiveness of their training;
- OPT [29], BLOOM [30] (2022) were attempts to create open analogs of GPT-3;
- LLaMA [31] (2023) a compact model achieving excellent quality, which started a wave of fine-tuning applications by a wide range of professionals, not only scientists and practitioners;
- LoRA [32] (2021) / QLoRA [33] (2023) the introduction of easy ways to fine-tune and run LLMs on consumer GPUs.

The time period of 2022–2024 was the development of instructional fine-tuning (GPT-3.5, InstructGPT [34] – mass training of models to follow human instructions). This made the way of interacting with AI systems more understandable and efficient. In addition, models began to be trained in step-by-step reasoning and tool invocation (Chain-of-Thought [35], Toolformer, ReAct [36]).

The time period of 2024-2025 can be characterized as the emergence of reasoning models (Claude 3, DeepSeek R1, GPT-4, o3, o4-mini, etc.) and the blossoming of multimodal models (GPT-4V, Gemini, Claude 3 – text and image processing models). These models are widely used in the fields of medicine, industrial design, law, etc.

The future development of LLMs is determined by industry leaders who have the resource capabilities to implement training of such models and their deployment. These are such companies as OpenAI, Google DeepMind, Meta, xAI, various Chinese and Russian organizations. Among the main trends can be identified:

- Development of AGI models (Artificial General Intelligence) – models capable of performing any intellectual problem at the human level or higher, demonstrating versatility, flexibility, and self-learning ability in various domains.
- Focus on "rational agents" by designing language models with an emphasis on making their behavior as consistent as possible with the principles of rational decision-making.
- 3) Emphasis on openness and accessibility of models.
- 4) Intensive development in closed and open formats.

Currently, various benchmarks are used to compare large language models. The main ones are: AIME 2024, GPQA Diamond, HLE (Humanity's Last Exam), MMLU (Massive Multitask Language Understand-

ing), ARC (AI2 Reasoning Challenge), GSM8K, HEL-LOWORLD, HumanEval, MT-Bench, Arena Elo.

For example, **AIME 2024** – a benchmark with "Olympiad math problems" taken from the actual 2024 round. AIME is the second in a series of two rounds used as a qualifying round for the U.S. Math Olympiad. It is attended by those in the top percent of the first round, approximately 3,000 people from across the country.

GPQA Diamond – a benchmark that contains questions in biology, physics, and chemistry, but such that even PhDs from these fields and with internet access get only 65% correct (spending no more than half an hour on each problem) [37].

Humanity's Last Exam (HLE) – a benchmark covering 3,000 unambiguous and easily verifiable academic questions in math, humanities, and science provided by nearly 1,000 subject matter experts from more than 500 institutions in 50 countries, providing expert-level human performance on closed-ended academic questions. It was developed in partnership with the Center for AI Safety and Scale AI [38].

Other benchmarks aim to test models in different aspects, e.g. **GSM8K** tests models for correct arithmetic and reasoning, **ARC** tests models for logic and common sense, **MT-Bench** tests models for general dialog competence, **Arena Elo** crowdsources ratings from people (e.g. **Chatbot Arena**). Large language model rankings are regularly updated for new models and common benchmark types [39].

IV. Large language models and long-term memory

Large language models have shown impressive results in text processing and generation, but they also have their drawbacks, such as limited context and lack of builtin ability to deal with external sources of information. To overcome these limitations, researchers are actively developing new approaches such as **RAG** (Retrieval-Augmented Generation) [40] that allow models to retrieve and utilize external data, which is an attempt to provide such models with long-term memory. In addition, approaches to integrating these models with agents are explored to enable intelligent systems to autonomously interact with the environment. This chapter considers how RAG and similar approaches are used to improve the capabilities of large language models, and explores the role of agents in this context.

RAG is an architectural approach in which a large language model accesses external data through search before generating a response. Unlike classical LLMs, systems built using RAG:

- keep up-to-date as there is the possibility of updating knowledge;
- are controlled (only sources that have been explicitly selected are used);

• is explainable in the sense that it is possible to determine where the information for an answer came from.

A common RAG application architecture (fig. 2) includes the following components:

- User Interface. The entry point for interacting with the system. Receives natural language (NL) user requests and passes them to the context manager. Provides visualization of responses and input error handling.
- **Context Manager.** Generates query context by accessing repositories, ranks results, passes them to LLMs, and provides source citations to justify responses.
- Vector Database. Provides vector-based context search by comparing the embedding vectors of document fragments stored there with the embedding vector of the user's question. Other search options are also available, such as keyword search.
- Knowledge Graph/Knowledge Base. Stores structured knowledge in the form of semantic relationships. Allows you to search related entities extracted from documents [41].
- Large Language Model (LLMs). Generates natural language responses using promts and context from repositories. Can be a cloud service or an on-premises model.
- **Storage Manager.** Responsible for document preprocessing and indexing. Includes structure parsing, text extraction, and repository interaction.



Figure 2. Common architecture of modern RAG applications

In addition to the ability to actualize knowledge and explain decisions, the development and deployment of various AI agents that extend the functionality of LLMs is becoming increasingly important.

The LLMs AI agent is a software module that allows the LLMs not only to generate a response to a user request based on context from various repositories, but also to perform actions using external tools. In addition, AI agents can interact with each other. Tools are external components or implementations of problem-solving models that an agent can use when executing a query.

Examples of tools are: search, calculator, calendar, various forms, parsers, API requests. Modern large language models can interact with tools by means of agents, call them with the required parameters, and use the responses received from tools.

For example, if a user needs to find a cheap airfare and book a hotel near a train station, he formulates a query. The AI agent, receiving the query, searches for airline tickets for the specified destination, compares prices, goes to the hotel website, and books the room. In this example, the LLMs AI agent contains a number of components that allow it to perform the above actions:

- planning (what needs to be done);
- implementation (which tools to use);
- memory (how to store intermediate data);
- observation (how to process the results of tool calls).

Popular libraries and frameworks that implement work with agents include: LangChain, LangGraph, CrewAI, AutoGen, BabyAGI, OpenAI Functions / Tools API.

Figure 3 shows a common architecture of systems that utilize AI agents.

Despite significant progress in RAG applications and the use of LLMs AI agents providing a new wave of automation in various domains, existing approaches still face a number of fundamental challenges:

- Knowledge quality and consistency issues. Context stores can contain conflicting information, leading to incorrect agent inferences.
- Limited self-learning and experience accumulation issues. Agent actions are typically not captured in context stores, which prevents error analysis and system improvement. Communication between agents, agents and repositories, agents and tools takes place either in natural language or through specialized protocols. Examples of such protocols are Model Context Protocol (MCP) and Agent2Agent (A2A). There are also no effective mechanisms for accumulating and transferring experience between different systems.
- Explicability and transparency issues. Some agent decisions remain non-transparent, especially if their justification does not fall within the context of LLMs, which makes it difficult to trace causal relationships between agent's actions and the final

result. It is worth noting that ensuring transparency in modern AI systems is key in many applications, and in some domains, mandatory [42].

The evolution of intelligent systems requires a shift from simple problem-solving to hybrid systems with advanced mechanisms for self-analysis, continuous improvement, and synergy of different problem-solving models.

V. Proposed Approach

Current approaches to building intelligent systems show a clear tendency to centralize the architecture around LLMs, where external repositories, including knowledge bases, play a supporting role. However, as described in the previous chapter, this approach has significant limitations.

Hybrid intelligent systems ([43], [44]) are designed to overcome such limitations through unified memory and synergy of different problem-solving models.

A. General Architecture

In this paper, we propose to use the OSTIS Technology [44] to build multi-agent systems, which is used to design and implement **ostis-systems** – intelligent systems that solve complex problems based on the unification of knowledge and problem-solving models. A unified semantic network with a set-theoretic interpretation is used as a formal basis for representing knowledge and problem-solving models within the framework of OSTIS Technology. Such a representation model is called SC-code (Semantic computer code) [44]. The elements of the semantic network are called sc-nodes and sc-connectors (sc-arcs, sc-edges).

The basis of ostis-systems is an architectural paradigm that goes back to the classical principles of building intelligent systems. It is based on three interrelated components: interface, knowledge base and problem solver.

Interface realizes interaction with the user, including natural language. The interface communicates with the problem solver through a knowledge base.

A knowledge base provides a structured representation of information using semantic networks and ontologies. The basis of the knowledge base is a hierarchical system of **subject domains** (SDs) and their corresponding **ontologies** [45]. Ontologies contain descriptions of concepts necessary to formalize knowledge from the corresponding SDs ontology. Any knowledge describing some problem, its context and specification of solution methods can be represented in the form of SC-code constructions. By representing knowledge in machinereadable code instead of NL-texts, it becomes possible to automatically verify and improve the quality of the knowledge base.

The knowledge base may contain NL-texts. Due to the possibility to regulate the degree (depth) of formalization it becomes possible to regulate the labor intensity of



Figure 3. Common architecture of systems utilizing AI agents

knowledge base development. Thus, a gradual transition from NL-texts to partially formalized texts in SC-code is provided.

Problem solver deals with processing of knowledge base fragments using various problem solving models, including logical inference models, neural network models, graph-based problem solving models, etc. At the operational level, such processing is reduced to adding, searching, editing and deleting sc-nodes and scconnectors of the knowledge base. At the semantic level, such an operation is a *action performed in the memory of the subject of the action*, where, in general, the subject is the ostis-system, and the knowledge base is its memory.

An action is defined as the process of one entity (or some set of entities) influencing another entity (or some set of other entities) according to some goal [46]. Actions are performed according to given problems. A problem is a formal specification of some action sufficient for some entity to perform it. Depending on the specific class of problems, both the internal state of the intelligent system itself and the required state of the external environment can be described [44].

The ostis-systems problem solver is based on a decentralized multi-agent architecture. Each agent is engaged in interpreting actions and, consequently, sc-agents are engaged in solving problems. Communication between agents takes place only through the knowledge base via the event mechanism as follows: an agent or interface generates a problem in the knowledge base and informs in its description that it needs to be solved. Other agents react to this event and, if they can solve it, solve it and leave the solution in the knowledge base. The event of the solution occurrence is reacted to by the agent that put the problem in the knowledge base.

Figure 4 shows the multi-agent architecture of the ostissystems problem solver.

In such an architecture, the knowledge base moves from the position of a source of context for large language models to the position of a shared semantic memory, in which various types of knowledge describing problems, their context, models of problem solving (including tools), actions of agents, history of problem solving, etc. are represented in a unified form. This provides the following advantages:

- **Knowledge coherence.** Knowledge bases of ostissystems use a hierarchy of subject domains with well-defined semantic links. SC-code provides unified representation, eliminating inconsistencies through an automatic verification mechanism.
- Self-learning through reflexive mechanism of experience accumulation. A decentralized multiagent architecture captures all agent actions directly in the knowledge base. Each action is formalized with an explicit goal, creating a complete history of actions. Unlike MCP-type protocols, where there is no communication through shared memory, scagents operate with formalized knowledge that allows the reproduction and analysis of decision chains.
- Explainability through semantic transparency. Agent actions are always linked to specific pieces of the knowledge base, providing an explicit link between inputs, problem-solving models, and outputs. Unlike "black-box' LLMs, where reasoning is



Figure 4. Multi-agent architecture of ostis-systems problem solver.

generated post facto, sc-agents generate solutions through deterministic transformations of SC-code constructions, preserving the complete chain of inference.

• Decentralized coordination of agents. The absence of a centralized orchestrator reduces failure risks. Agents interact exclusively through the knowledge base event mechanism, which ensures horizontal scalability and fault tolerance of the system as a whole.

As will be shown later, the proposed architecture does not deny the use of large language models, but assigns them a strictly defined role within the overall system.

B. Role of language models in the system

In the architecture of ostis-systems, LLMs are integrated as specialized agents with well-defined functions. Examples of problems that can be solved by LLMs in ostis-systems are:

Bidirectional Knowledge Translation. LLMs provide the transformation between NL-texts and formal knowledge representations in SC-code. In the input phase, models structure textual data according to the system ontologies, automatically generating nodes and relations in the knowledge base. In the output phase, they create natural-language explanations strictly tied to specific knowledge fragments

in the SC-code. Solving the classic problem of knowledge-based systems – the need for manual formalization – is greatly facilitated (but not completely solved) by using LLMs.

- 2) Context-dependent generation. The generation of LLMs responses is based on the context extracted from the knowledge base. LLMs retrieve semantically verified context from the knowledge base, which eliminates the possibility of "hallucinations" and increases the accuracy of responses.
- 3) **Decomposition a problem into subproblems.** LLMs can be used to analyze complex problems, decomposing them into atomic subproblems based on the problem classification described in the knowledge base.
- 4) Forming a solution plan. Since all problem solving models available to the system are specified in the knowledge base, LLMs can retrieve these specifications along with the problem formulation and build a solution plan for the problem, including specifying the sequence of agent invocation, input and output specifications, quality metrics, etc. If LLMs are used to solve subproblems, the solution plan includes additional promts that may be selected or generated from a knowledge base based on past problem solving experience.

The integration of LLMs into ostis-systems archi-

tecture provides a balance between automating natural language processing and preserving the semantic rigor characteristic of formal methods of knowledge representation. It opens up a wide range of classes of problems that can be solved using LLMs within ostis-systems.

C. Prospects for the development of the approach

The development of the described approach opens new horizons due to the synergy of formal methods of knowledge representation and processing and generative models. Examples of directions for further research are:

 Ecosystem. The concept of Ecosystem is one of the key concepts in OSTIS Technology [44]. Ecosystem of ostis-systems implements a fundamentally new approach to the organization of intelligent systems, where problem solving is carried out through the integration of specialized solvers from different intelligent systems in an integrated distributed knowledge base consisting of knowledge bases of intelligent systems included in the Ecosystem.

Users interact not with individual systems, but with a personal assistant, which acts as an interface to the Ecosystem. The history of problem solving, general SDs updates is available to all systems within the Ecosystem, which ensures reflection and knowledge accumulation at the level of the entire Ecosystem, rather than individual systems.

This shifts the focus from training LLMs and increasing their context window, to training the shared long-term memory, which is the integrated knowledge base of the Ecosystem. The experience of intelligent systems from different subject domains (medicine, education, manufacturing) will be accumulated in a single ecosystem. Figure 5 shows the architecture of the OSTIS Ecosystem, indicating the role of large language models.

2) Training large language models on knowledge base fragments. The development of the OSTIS ecosystem and the expansion of knowledge bases on SC-code are shaping a fundamentally new type of dataset for LLMs training: instead of unstructured NL-texts, models have access to verified semantic constructs with explicit connections between concepts. This opens up hypothesized benefits, including reduced "hallucinations" and increased inference accuracy.

The key hypothesis is that training LLMs on SCcode fragments shifts the focus from text generation to knowledge transformation: models learn to operate with formal constructs rather than mimic language patterns.

 Explainability and comprehension testing. Despite advances in generative models, the fundamental question of whether AI systems truly "understand" the problems being solved remains open [47]. Modern LLMs show impressive abilities to simulate meaningful responses, but their conclusions are often based on statistical patterns rather than on conscious work with semantics. The increased influence of semantics on problem solving described in the proposed approach has a good chance of advancing researchers in solving the comprehension problem.

VI. Conclusion

In conclusion, it is necessary to emphasize the prospect of integrating neural network and symbolic approaches to create hybrid intelligent systems. The proposed approach moves the knowledge base from the position of a source of context for large language models to the position of shared semantic memory. This architecture allows combining knowledge about problems, their context, solution models, agent actions and solution history into a single form.

Key advantages are knowledge consistency through the use of a hierarchy of subject domains and SC-code, selflearning through a reflexive experience mechanism in a decentralized multi-agent architecture, and explainability through semantic transparency where agent actions are mapped to specific pieces of the knowledge base.

Further research and development in this area will contribute to the development of next-generation intelligent systems that can effectively integrate neural network and logical-semantic models to solve a wide range of problems.

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Figure 5. The architecture of the OSTIS Ecosystem and the place of large language models in it

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ПОДХОДЫ К НЕЙРО-СИМВОЛИЧЕСКОЙ ИНТЕГРАЦИИ: БОЛЬШИЕ ЯЗЫКОВЫЕ МОДЕЛИ И БАЗЫ ЗНАНИЙ

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В статье рассматриваются современные подходы к интеграции нейросетевого и символьного искусственного интеллекта, включая архитектуры, использующие генеративные модели в сочетании с базами знаний и агентами. Особое внимание уделяется ограничениям больших языковых моделей (LLMs) при решении задач, связанных с долгосрочным контекстом, а также анализируются механизмы типа RAG и современные агентные системы. Предлагается архитектура интеллектуальных систем на базе Технологии OSTIS, в которой LLMs интегрированы в решатель задач. Обосновывается необходимость формального описания методов генеративного ИИ в составе решателя задач.

Авторы подчёркивают преимущества перехода базы знаний с позиции источника контекста для LLM в позицию общей семантической памяти, объединяющей различные виды знаний – от описания задач и моделей их решения до истории взаимодействия агентов. Такой подход обеспечивает автоматическую верификацию знаний, накопление опыта и прозрачность принимаемых решений.

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Approaches to the Study of Semantic Space and Integrated Logical Inference Models Using Similarity, Difference and Other Measures

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Abstract-Approaches to the analysis of proximity, similarities, and differences in knowledge structures are considered for the purpose of extracting meaning from data and knowledge. Approaches and models for representing knowledge with operational semantics for component-based design of intelligent systems are discussed. An ontology of generalized measures and relations of difference and similarity, including similarity relations, has been developed. A class of pre-order scales and measures on structures with operational semantics has been proposed, along with an investigation of their algebraic properties. The concept of operational-informational space has been clarified. A model of the semantics of fuzzy temporal logic is proposed for specifying knowledge structures with operational semantics based on previously suggested parameterized fuzzy logic. For the ontological structures corresponding to the obtained results and the three levels of semantic analysis, principles of their integration are formulated as metric subspaces of the semantic space.

Keywords—Semantic space, Generalized measure, Similarity measure, Similarity relation, difference relation, Dynamic system entropy, operational information space, fuzzy temporal logic, CTL*, Reo Coordination Language, Semantic metric space, Logical inference model integration, preorder scale, modian, quasisimilarity, quasieuclid relation, quasireflexive relation, quasitransitive relation, quasireflexive relation, semantic unification

I. Inroduction

For the new generation of intelligent systems [11], [52] it is important to strive for convergence of knowledge processing processes. This also applies to the processes of logical inference, including classical and non-classical deductive, inductive, abductive logical inference [4], etc. One of the primary mechanisms in analysis tasks that precede data and knowledge processing is inductive logical inference, which is based on difference and similarity relations [14]. In the presence of knowledge non-factors [12], these relations are characterized by means of non-classical logics [4], [14], [40] based on the notion of measure [10], [15]. Measures [16], as well as attributes, are closely related to such knowledge attribute as scaling [13]. Measures are also used in the study of spatial properties

and relations and the definition of metrics [19], [20], [33], including semantic metrics [16], [17].

II. Review

Similarity and difference relations appear in the sources in one of the following contexts: as reflexive relations and irreflexive relations (ij-reflexive and ij-irreflexive relations) [21], as relations used in inductive inference methods and mechanisms [4], in fuzzy logic [14], as relations of formation of concepts and ontological structures in knowledge processing processes [18], [22]. The name of relations of "similarity" and "difference" in the second case is not quite good, more suitable names would be "relations of conceptual confirmation" or "relations of conceptual refutation".

In case of presence of non-factors characteristic for the stages of analysis of incoming data (texts) for the purpose of analysis of their sense [23], [24], relations can be characterized by means of attributes taking values on the ordinal or numerical (metric) scale [16]. In this case, the analysis can take place at several levels [24] (essentiallysystematic, relationally-phenomenological, intensionallylogical), which correspond to their own ordinal and metric scales. Such attributes and scales can serve as the basis for models of topological, metric, pseudometric (etc.) semantic spaces for ontological structures. Organization of ontological structures into semantic spaces with the help of scales and attributes can ensure minimization of duplication of meanings and optimization of mechanisms of search and knowledge processing in knowledge bases, including logical inference.

One of the main properties of the similarity relation is reflexivity; a similarity relation can be reflexive, quasireflexive, left and right quasireflexive, weakly left and right quasireflexive [36].

Among the properties of similarity relations that serve to distinguish the corresponding subclasses of similarity relations, the following can be identified:

symmetricity, transitivity, quasi-transitivity, left Euclidean, right Euclidean, Euclidean, and others.

One of the basic properties of the difference relation is irreflexivity; the similarity relation can be irreflexive, quasi-irreflexive, left and right quasi-irreflexive, weakly left and right quasi-irreflexive.

Among the properties of difference relations that serve to distinguish the corresponding subclasses of similarity relations, the following symmetry, antitransitivity and others can be identified.

The main classes of measures that can be used both to characterize similarity relations and for subsequent logical inference are: monotonicity, subadditivity, additivity, superadditivity, submodularity, supermodularity, modularity.

For efficient logical inference in distributed multiagent systems and transition from observed facts and phenomena to rules and regularities, it is necessary to move from static structures to dynamic ones, from denotational semantics to operational semantics. In this case, efficiency can be ensured by parallel reduction of the original task into subtasks that are distributed among agents. In this connection, it is necessary to take into account not only the semantics of classical logic models, but also the operational semantics of logic models oriented to dynamic subject areas [28], and the game semantics of logic models [51] oriented to subject areas considering agents' interaction.

For the purpose of integrating different types of operational semantics ("big" and "small step"), a model of operational-information space [25] was proposed.

Reo Coordination Language (RCL) [26] is an example of such a model and language, which allows to design integrable reusable components based on a unified semantic framework [29] with different semantics descriptions ranging from category-theoretic to logical and semantics of probabilistic automata and automata with constraints [27]. However, the relation of its semantics to the semantics of "big step" is poorly described; from the point of view of denotational semantics, RCL is also insufficiently unified.

When analyzing, including within the semantic space, models of knowledge processing and representation, it is necessary to identify various attributes and measures. One of the key measures is entropy. As for the analysis of graph structures and their corresponding matrices, several definitions of entropy are known: von Neumann entropy [30], entropy of spectral values [32] and others. One of the most general notions of entropy is the Hinchin entropy [31]. The concept of entropy is closely related to the notions of convergence and divergence [35], which are closely related to the relations of similarity and difference [33], [34].

When taking into account non-factors in logical inference processes, including inductive, abductive and deductive, it is required to integrate models using fuzzy measures, relational semantics of temporal and spatiotemporal logics [42], [43]. It is also important to take into account the similarities and differences between the logic models themselves and the knowledge structures in the problems they are used to solve.

As a result of the integration of the above approaches, their ontological models, and convergence of the corresponding problem solving processes, a certain model is formed that can be organized as a semantic space, i.e., have spatial features [46]–[50] when knowledge is scaled [13].

To model and study the sense space [44], the paper uses models and methods of discrete mathematics, graph theory, and mathematical logic.

The semiotic conceptual approach [13] based on notions (concepts) is also used. Each concept has a name (term), a denotation (referent) and a significat.

A concept is understood as a sign that has an extension and an intension by analogy to the formal concepts of the analysis of formal concepts [57].

The basic thesis: the meaning of a concept is completely determined by its signifier (extensional closure).

Structural and metric features [9], [25] that are resistant to ontology structure changes are used in modeling the semantic space. The model of unified knowledge representation [6], [21], whose texts are understood as associative, symmetric, pseudo-orgraphic generalized formal languages [25], is used for representation.

Definition 1. An associative generalized formal language is Λ if and only if, in its texts, there is a generalized string of Δ symbols of length n in addition to T symbols:

$$\exists T \exists \Delta \exists n \left(\emptyset \subset \left(\left(\Delta^n \cup T \right)^* \cap \Lambda \right) / (T^*) \right).$$
 (1)

Definition 2. A symmetric generalized formal language is Λ if and only if for any Δ^n :

$$\left(\left(\emptyset \subset \Delta^n \cap \Lambda \right) \to \left(\Delta^n \subseteq \Lambda \right) \right). \tag{2}$$

Definition 3. A (Pseudo(or))graph generalized formal language Λ , if and only if there exists A for any T, Δ , n:

$$\Lambda \subseteq \left(A^2 \cup A\right)^*; \\ \left(\left(\emptyset \subset \left(\left(\Delta^2 \cup T\right)^n \cap \Lambda\right) / (T^n)\right) \to (\Delta \subseteq T)\right).$$

$$(3)$$

The approach to modeling the semantic space [6], [44] can be referred to the theoretical-synthetic (interior) approaches based on unification. Unification assumes that for a set of notations $N = C \cup I$ (signs $S \subseteq C$, concepts C and names (terms) I), there is a set of values (meanings) E, between which correspondences are defined.

Correspondence between symbols and their meanings:

$$v_N \subseteq N \times E. \tag{4}$$

Similarity relation t_N , tolerance of meanings (values):

$$t_N \stackrel{def}{=} v_N \circ \left(v_N^{-1} \right). \tag{5}$$

The projection of t_N onto the set of concepts C is the equivalence relation of meanings:

$$\sim_C \stackrel{def}{=} t_N \cap (C \times C) \,. \tag{6}$$

The equivalence relation \sim_C forms equivalence classes C_{\sim_C} , between which and the signs of S there is a bijection $C_{\sim_C}| \leftrightarrow |S$, with (denotation function) $d_N \stackrel{def}{=} v_N \circ (C \times E)$ is an injection: $S| \leftrightarrow E$.

The unification is to go by the similarity relation $t_N \circ (\sim_C \cap (C \times S))$ from the N signs to the S signs.

The semantic normalization of [45] in the languages of the knowledge representation model used assumes that primary meanings $F \subseteq 2^{N \cup F}$ are selected among the meanings $E \subseteq 2^{N \cup F}$.

III. Generalization of the notion of measure

A. Kinds of generalized measures

Let us introduce the notion of a generalized measure. Let us first consider the notion of an ordered commutative monoid.

Definition 4: An ordered commutative monoid:

$$\langle M, \{ \trianglelefteq, \boxplus \} \rangle \tag{7}$$

satisfies the properties:

$$\{0_M\} \times \{0_M\} \subseteq \trianglelefteq \subseteq M \times M; (a \in M) \to (a \trianglelefteq a); ((a \trianglelefteq b) \land (b \trianglelefteq a)) \to (a = b); ((a \oiint b) \land (b \trianglelefteq c)) \to (a \oiint c); (a \boxplus 0_M) = a; (a \boxplus b) = (b \boxplus a); ((a \boxplus b) \boxplus c) = (a \boxplus (b \boxplus c)); (a \in M) \to ((a \oiint 0_M) \lor (0_M \trianglelefteq a)); (a \trianglelefteq b) = ((a \boxplus c) \trianglelefteq (b \boxplus c)).$$

$$\{0_M\} \times \{0_M\} \in (a \boxplus c) \bowtie (b \boxplus c)\}.$$

$$\{0_M\} \times \{0_M\} \in (a \boxplus c) \oiint (b \boxplus c)\}.$$

Definition 5. An ordered commutative monoid bounded from above is an ordered commutative monoid satisfying the additional property:

$$M \times \{\top_M\} \subseteq \trianglelefteq \subseteq M \times M. \tag{9}$$

Definition 6. An ordered commutative monoid bounded from below is an ordered commutative monoid satisfying the additional property:

$$\{\bot_M\} \times M \subseteq \trianglelefteq \subseteq M \times M. \tag{10}$$

Definition 7. A linearly ordered commutative monoid is an ordered commutative monoid satisfying the additional property:

$$((a \in M) \land (b \in M)) \to ((a \trianglelefteq b) \lor (b \trianglelefteq a)).$$
(11)

Definition 8. An ordered commutative group is an ordered commutative monoid satisfying the additional property:

$$\exists b \, (a \boxplus b) = 0_M. \tag{12}$$

Definition 9. A forward well-ordered commutative monoid is an ordered commutative monoid satisfying the additional property:

$$(A \subseteq M) \rightarrow (\exists \bar{a}(((\emptyset \subset A \times \{\bar{a}\}) \land (A \times \{\bar{a}\} \subseteq \trianglelefteq)) \land (13)) \land (A \times \{a\} \subseteq \trianglelefteq) \rightarrow (\{\bar{a}\} \times \{a\} \subseteq \trianglelefteq)))).$$

Definition 10. A backward well-ordered commutative monoid is an ordered commutative monoid satisfying the additional property:

$$(A \subseteq M) \to \\ \exists \underline{a}(((\emptyset \subset A \times \{\underline{a}\}) \land (A \times \{\underline{a}\} \subseteq \trianglelefteq)) \land (\{a\} \times A \subseteq \trianglelefteq) \to (\{a\} \times \{\underline{a}\} \subseteq \trianglelefteq))).$$
(14)

Definition 11. Generalized measure is defined as

$$\mu \in M^X,\tag{15}$$

where M is the support of an ordered commutative monoid.

Definition 12. A generalized measure bounded from below is a generalized measure satisfying the additional property:

$$\perp_M \trianglelefteq \mu\left(\chi\right). \tag{16}$$

Definition 13. A generalized measure bounded from above is a generalized measure satisfying the additional property:

$$\mu\left(\chi\right) \trianglelefteq \top_{M}.\tag{17}$$

Definition 14. A bounded measure is a generalized measure bounded from above and below. A special case of a bounded measure is a finite-bounded measure.

Definition 15. A basis measure is a generalized measure bounded from below satisfying the additional property:

$$\exists x \left(\mu \left(x \right) = \bot_M = 0_M \right). \tag{18}$$

Definition 16. Regular (normalized) measure is a (basis) generalized measure bounded from above satisfying the additional property:

$$\exists x \left(\mu \left(x \right) = \top_M = 1_M \right). \tag{19}$$

Definition 17. A preorder-monotone measure is a generalized measure such that there is a preorder (a reflexive transitive binary relation) \leq for which:

$$(a \leq b) \to (\mu(a) \leq \mu(b)). \tag{20}$$

Given a scale $\langle \langle \langle X, \Sigma \rangle, \langle Y, \{\rho\} \rangle \rangle, \sigma \rangle$, where $\sigma \in Y^X$, and $\rho \subseteq Y \times Y$ is the preorder relation (reflexive and transitive similarity relation) characterized by the predicate-measure $\pi \in M^Y$:

$$\pi = (\rho \times \{1_M\}) \cup (((Y \times Y) / \rho) \times \{0_M\}).$$
(21)

Such given scale will be called a pre-order scale. Definition 18. Filtering ϕ is:

$$\varphi\left(\langle \sigma, \rho, \chi \rangle\right) \stackrel{def}{=} \left\{ \left((\sigma \circ \rho) \circ \left(\sigma^{-1} \right) \right) (\chi) \right\}.$$
 (22)

Definition 19. Nominal (λ -nominal) measure satisfies:

$$\psi_{\lambda}\left(\langle\sigma,\rho,\chi\rangle\right) \stackrel{def}{=} |X/\varphi\left(\langle\sigma,\rho,\chi\rangle\right)| - \lambda * |\varphi\left(\langle\sigma,\rho,\chi\rangle\right)|.$$
(23)

When λ equals 0 the measure is called the mode measure, when λ equals 1 it is called the meda measure.

Definition 20. Medium (λ -medium) measure:

$$\mu\left(\chi\right) \stackrel{\text{def}}{=} \left| \left| \varphi\left(\left\langle \sigma, \left\{\pi^{-1}\left(1_{M}\right)\right\}, \chi\right\rangle\right) \right| - \left| \varphi\left(\left\langle\sigma, \left\{\pi^{-1}\left(1_{M}\right)\right\}^{-1}, \chi\right\rangle\right) \right| \left| + \left| \psi_{\lambda}\left(\left\langle\sigma, \left\{\pi^{-1}\left(1_{M}\right)\right\}^{-1} \cup \left\{\pi^{-1}\left(1_{M}\right)\right\}, \chi\right\rangle\right) \right|.$$

$$(24)$$

When λ equals 0, the measure is called a modian measure, when λ equals 1, it is called a median measure.

Definition 21. The centroid (τ -centroid) of δ of measure μ is:

$$\delta\left(\mu\right) \stackrel{def}{=} \lim_{\tau \to \varepsilon} \sqrt[\tau]{\sum_{\chi \in X} \left(\mu\left(\chi\right)\right)^{\tau}}.$$
 (25)

Let a sigma-algebra be given.

1.0

$$\langle \Sigma, \{\cap, \cup, \bar{}\} \rangle \tag{26}$$

A measurable space (of sets) on X is also given:

$$\langle X, \langle \Sigma, \{\cap, \cup, \bar{}\} \rangle \rangle,$$
 (27)

where $\Sigma \subseteq 2^X$.

As an ordered commutative monoid we will further consider as an ordered commutative monoid by default:

$$\langle \mathbb{R}, \{\leq, +\} \rangle$$
. (28)

Definition 22. A monotone measure (of sets) is a generalized measure on a measurable space $\langle X, \langle \Sigma, \{ \cap, \cup, \bar{} \} \rangle$ that satisfies the additional property:

$$\left(A\subseteq B\right) \rightarrow \left(\mu \left(A\right) \trianglelefteq \mu \left(B\right) \right) . \tag{29}$$

Definition 23. A monotone Sugeno measure is a monotone measure (of sets) satisfying the additional property:

$$\mu\left(\lim_{k\to\omega}\bigcup_{i=1}^{k}A_{i}\right) = \lim_{k\to\omega}\left(\mu\left(\bigcup_{i=1}^{k}A_{i}\right)\right).$$
 (30)

Definition 24. A subadditive measure is a monotone measure (of sets) satisfying the additional property:

$$\mu\left((A/B) \cup (B/A)\right) \trianglelefteq \mu\left(A/B\right) \boxplus \mu\left(B/A\right).$$
(31)

Definition 25. Superadditive measure is a monotone measure (of sets) satisfying the additional property

$$\mu(A/B) \boxplus \mu(B/A) \trianglelefteq \mu((A/B) \cup (B/A)).$$
(32)

Definition 26. An additive measure is a monotone measure (of sets) satisfying the additional property:

$$\mu\left(A/B\right) \boxplus \mu\left(B/A\right) = \mu\left(\left(A/B\right) \cup \left(B/A\right)\right).$$
(33)

Definition 27. A submodular measure is a monotone measure (of sets) satisfying the additional property:

$$\mu\left((A/B) \cup (B/A)\right) \boxplus \mu\left((A/B) \cap (B/A)\right) \leq \boxplus \mu\left(A/B\right) \mu\left(B/A\right).$$
(34)

Definition 28. A supermodular measure is a monotone measure (of sets) satisfying the additional property:

$$\mu \left(A/B \right) \boxplus \mu \left(B/A \right)$$

$$\exists \mu \left((A/B) \cup (B/A) \right) \boxplus \mu \left((A/B) \cap (B/A) \right).$$

$$(35)$$

Definition 29. A modular measure is a monotone measure (of sets) satisfying the additional property:

$$\mu(A/B) \mu \boxplus (B/A) = \mu((A/B) \cup (B/A)) \boxplus \mu((A/B) \cap (B/A)).$$
(36)

Definition 30. A necessity measure is a monotone measure (of sets) on a backward well-ordered monoid satisfying the following additional properties:

$$\mu((A/B) \cap (B/A)) = \min(\{\mu(A/B)\} \cup \{\mu(B/A)\}) \\ \mu(\bigcap_{i} A_{i}) = \inf(\{\mu(A_{i}) | i\}).$$
(37)

Definition 31. A possibility measure is a monotone measure (of sets) on a forward well-ordered monoid satisfying the additional properties:

$$\mu \left((A/B) \cup (B/A) \right) = \max \left(\{ \mu (A/B) \} \cup \{ \mu (B/A) \} \right) \\ \mu \left(\bigcup_{i} A_{i} \right) = \sup \left(\{ \mu (A_{i}) | i \} \right).$$
(38)

Definition 32. A symmetric measure is a monotone measure (of sets) satisfying the additional property:

$$(|A/B| = |B/A|) \to (\mu(A/B) = \mu(B/A)).$$
 (39)

B. Measures and metrics

Special kinds of measures are: pre-metric, quasi-metric, pseudometric, metric, ultrametric, metametric, etc.

Theorem 1. Let $\lambda \geq 1$ be a pseudometric space with pseudometric π and a metric space with metric μ on the set X. Then $\langle X, \rho \rangle$ is a metric space where

$$\rho\left(\langle \chi, \gamma \rangle\right) = \left(\left(\mu(\langle \chi, \gamma \rangle)^{\lambda}\right) + \left(\pi(\langle \chi, \gamma \rangle)^{\lambda}\right)\right)^{\left(\lambda^{-1}\right)}$$
(40)

or

$$\rho\left(\langle \chi, \gamma \rangle\right) = \max\left(\left\{\mu\left(\langle \chi, \gamma \rangle\right)\right\} \cup \left\{\pi\left(\langle \chi, \gamma \rangle\right)\right\}\right). \quad (41)$$

IV. Relations of similarity and difference

V. Kinds of similarity and difference relations

Based on the introduced measures, let us consider types (characteristic functions) of similarity and dissimilarity relations. We will consider some types of n-ary similarity relations, but mainly we will consider types of binary similarity relations.

The 1-2-similarity relation is a special case of the ijsimilarity relation.

Definition 33. A right 1-2-similarity relation is an n-ary relation satisfying:

$$(\mu\left(\langle x_1, x_2, x_3, \dots x_n \rangle\right) = 1) \rightarrow (\exists c \left((\mu\left(\langle c, x_2, x_3 \dots x_n \rangle\right) = 1\right) \land (\mu\left(\langle c, x_1, x_n \dots, x_3 \rangle\right) = 1))).$$
(42)

Definition 34. A left 1-2-similarity relation is an n-ary relation satisfying:

$$(\mu\left(\langle x_1, x_2, x_3, \dots, x_n \rangle\right) = 1) \rightarrow (\exists c \left((\mu\left(\langle x_1, c, x_3, \dots, x_n \rangle\right) = 1\right) \land (\mu\left(\langle x_2, c, x_n, \dots, x_3 \rangle\right) = 1))\right).$$
(43)

Definition 35. A 1-2-similarity relation is a right and left 1-2-similarity relation.

Definition 36. A total right 1-2-similarity relation is an n-ary relation satisfying:

$$(\langle x_1, x_2, x_3, \dots x_n \rangle \in X^n) \rightarrow (\exists c \left(\left(\mu \left(\langle c, x_2, x_3 \dots x_n \rangle \right) = 1 \right) \land \left(\mu \left(\langle c, x_1, x_n \dots, x_3 \rangle \right) = 1 \right) \right) \right).$$
(44)

Definition 37. A total left 1-2-similarity relation is an n-ary relation satisfying:

$$(\langle x_1, x_2, x_3, \dots, x_n \rangle \in X^n) \rightarrow (\exists c \left((\mu \left(\langle x_1, c, x_3 \dots x_n \rangle \right) = 1 \right) \land (\mu \left(\langle x_2, c, x_n \dots, x_3 \rangle \right) = 1)) \right).$$
(45)

Definition 38. A total 1-2-similarity relation is an total right and total left 1-2-similarity n-ary relation.

Obviously, a relation of (left\right) total 1-2 similarity is a relation of (left\right) 1-2 similarity.

Example. The ternary 1-2-similarity relation is satisfied:

$$(\mu(\langle x, y, z \rangle) = 1) \rightarrow (\exists c ((\mu(\langle c, y, z \rangle) = 1) \land (\mu(\langle c, x, z \rangle) = 1))).$$
(46)

The 1-2-reflexive relation is a special case of the ij-reflexive relation.

Definition 39. A 1-2-reflexive relation is an n-ary relation satisfying:

$$(\langle x_1, x_2, x_3, \dots x_n \rangle \in X^n) \to (\mu \left(\langle x_1, x_1, x_3 \dots x_n \rangle \right) = 1).$$
(47)

Obviously, any 1-2-reflexive relation is a 1-2-similarity relation.

Definition 40. A right 1-2-quasi-reflexive relation is an n-ary relation satisfying:

$$(\mu\left(\langle x_1, x_2, x_3 \dots x_n \rangle\right) = 1) \to (\mu\left(\langle x_1, x_1, x_3 \dots x_n \rangle\right) = 1)$$
(48)

Definition 41. A left 1-2-quasi-reflexive relation is an n-ary relation satisfying:

$$(\mu(\langle x_1, x_2, x_3 ... x_n \rangle) = 1) \to (\mu(\langle x_2, x_2, x_3 ... x_n \rangle) = 1)$$
(49)

Definition 42. A 1-2-quasireflexive relation is an n-ary right and left 1-2-quasireflexive relation.

Obviously, any 1-2-reflexive relation is 1-2-quasireflexive.

Definition 43. A right similarity (binary similarity relation) is a binary relation satisfying:

$$(\mu(\langle a,b\rangle)=1) \to (\exists c\,((\mu(\langle c,a\rangle)=1) \land (\mu(\langle c,b\rangle)=1))).$$

Definition 44. A left similarity (binary similarity relation) is a binary relation satisfying:

$$(\mu(\langle a, b \rangle) = 1) \to (\exists c ((\mu(\langle a, c \rangle) = 1) \land (\mu(\langle b, c \rangle) = 1))).$$
(51)

Definition 45. A similarity (binary similarity relation) is a right and left similarity binary relation.

Definition 46. A total right similarity is a binary relation satisfying:

$$(\langle a,b\rangle \in X \times X) \to (\exists c \left((\mu \left(\langle c,a \rangle \right) = 1 \right) \land (\mu \left(\langle c,b \rangle \right) = 1))).$$
(52)

Definition 47. A total left similarity is a binary relation satisfying:

$$(\langle a,b\rangle \in X \times X) \to (\exists c \left((\mu \left(\langle a,c\rangle\right) = 1\right) \land (\mu \left(\langle b,c\rangle\right) = 1))).$$
(53)

Definition 48. Total similarity is a total right and total left similarity binary relation.

Definition 49. Right quasisimilarity is a binary relation satisfying:

$$(\mu\left(\langle a,b\rangle\right)=0)\to\left(\exists c\left((\mu\left(\langle c,a\rangle\right)=1\right)\wedge\left(\mu\left(\langle c,b\rangle\right)=1\right))\right).$$

Definition 50. Left quasisimilarity is a binary relation satisfying:

$$(\mu(\langle a,b\rangle)=0) \to (\exists c\,((\mu(\langle a,c\rangle)=1) \land (\mu(\langle b,c\rangle)=1)))\,.$$
(55)

Definition 51. A quasi-similarity is a right and left quasisimilarity binary relation.

A reflexive binary similarity relation will be called a stable similarity relation, otherwise a binary similarity relation will be called an unstable similarity relation. similarity relations are defined below.

Quasireflexivity of binary relations, the left and right quasireflexivity of binary relations is defined in the standard way as a special case of 1-2-quasireflexivity.

Other useful properties of similarity and binary relations are defined below.

Definition 52. Right antiquasireflexivity of a binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=0\right)\wedge\left(\neg\left(a=b\right)\right)\right)\rightarrow\left(\mu\left(\langle a,a\rangle\right)=1\right).$$
(56)

Definition 53. Left antiquasireflexivity of a binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=0\right)\wedge\left(\neg\left(a=b\right)\right)\right)\rightarrow\left(\mu\left(\langle b,b\rangle\right)=1\right).$$
(57)

Definition 54. Antiquasireflexivity of a binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=0\right)\wedge\left(\neg\left(a=b\right)\right)\right)\rightarrow\left(\mu\left(\langle b,b\rangle\right)=1\right).$$
(58)

Definition 55. Weak right quasireflexivity of a binary relation:

$$((\mu(\langle a,b\rangle)=0)\wedge(\neg(a=b))) \rightarrow ((\mu(\langle a,a\rangle)=1)\wedge(\mu(\langle b,b\rangle)=1)).$$
(59)

Definition 56. Weak left quasireflexivity of a binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=1\right)\wedge\left(\mu\left(\langle b,a\rangle\right)=0\right)\right)\rightarrow\left(\mu\left(\langle b,b\rangle\right)=1\right).$$
(60)

Definition 57. Weak quasireflexivity of a binary relation:

$$\begin{array}{l} \left(\left(\mu\left(\langle a,b \rangle\right) = 1 \right) \land \left(\mu\left(\langle b,a \rangle\right) = 0 \right) \right) \rightarrow \\ \left(\left(\mu\left(\langle a,a \rangle\right) = 1 \right) \land \left(\mu\left(\langle b,b \rangle\right) = 1 \right) \right). \end{array}$$

$$(61)$$

The symmetric stable similarity relation will be called the convergence relation. The transitive stable similarity relation will be called the resemblance relation.

Definition 58. Weak transitivity of a binary relation:

$$(((\mu(\langle a, b \rangle) = 1) \land (\mu(\langle b, c \rangle) = 1)) \land ((\mu(\langle c, b \rangle) = 0) \land (\mu(\langle b, a \rangle) = 0))) \rightarrow (\mu(\langle a, b \rangle) = 1).$$
(62)

Definition 59. Antiantitransitivity of a binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=0\right)\wedge\left(\mu\left(\langle b,c\rangle\right)=0\right)\right)\rightarrow\left(\mu\left(\langle a,c\rangle\right)=1\right).$$
(63)

Definition 60. Quasitransitivity of a binary relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle a, b \rangle\right) = 1\right) \land \left(\mu\left(\langle b, c \rangle\right) = 1\right) \right) \land \\ \left(\left(\mu\left(\langle c, b \rangle\right) = 0\right) \land \left(\mu\left(\langle b, a \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\left(\mu\left(\langle a, c \rangle\right) = 1\right) \land \left(\mu\left(\langle c, a \rangle\right) = 0\right) \right). \end{array}$$

$$\tag{64}$$

Definition 61. Euclidean binary relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 1 \right) \land \left(\mu\left(\langle c, a \rangle\right) = 1 \right) \right) \lor \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 1 \right) \land \left(\mu\left(\langle a, c \rangle\right) = 1 \right) \right) \right) \to \\ \left(\mu\left(\langle b, c \rangle\right) = 1 \right). \end{array}$$

$$(65)$$

Definition 62. Left Euclidean binary relation:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=1\right)\wedge\left(\mu\left(\langle a,c\rangle\right)=1\right)\right)\rightarrow\left(\mu\left(\langle b,c\rangle\right)=1\right).$$
(66)

Definition 63. Right Euclidean binary relation:

$$\left(\left(\mu\left(\langle b, a \rangle\right) = 1\right) \land \left(\mu\left(\langle c, a \rangle\right) = 1\right)\right) \to \left(\mu\left(\langle b, c \rangle\right) = 1\right).$$
(67)

Definition 64. Sub-Euclidean binary relation:

$$(((\mu(\langle b, a \rangle) = 1) \land (\mu(\langle c, a \rangle) = 1)) \land ((\mu(\langle a, b \rangle) = 1) \land (\mu(\langle a, c \rangle) = 1))) \to (\mu(\langle b, c \rangle) = 1).$$
(68)

Definition 65. Quasi-Euclidean binary relation:

$$(((\mu(\langle b, a \rangle) = 1) \land (\mu(\langle c, a \rangle) = 1)) \land ((\mu(\langle a, b \rangle) = 0) \land (\mu(\langle a, c \rangle) = 0))) \rightarrow (\mu(\langle b, c \rangle) = 1)$$

$$(((\mu(\langle b, a \rangle) = 0) \land (\mu(\langle c, a \rangle) = 0)) \land ((\mu(\langle a, b \rangle) = 1) \land (\mu(\langle a, c \rangle) = 1))) \rightarrow (\mu(\langle b, c \rangle) = 1).$$
(69)

Definition 66. Left quasi-Euclidean binary relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 1\right) \land \left(\mu\left(\langle c, a \rangle\right) = 1\right) \right) \land \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 0\right) \land \left(\mu\left(\langle a, c \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle b, c \rangle\right) = 1 \right). \end{array}$$
(70)

Definition 67. Right quasi-Euclidean binary relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 0\right) \land \left(\mu\left(\langle c, a \rangle\right) = 0\right) \right) \land \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 1\right) \land \left(\mu\left(\langle a, c \rangle\right) = 1\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle b, c \rangle\right) = 1 \right). \end{array}$$
(71)

Definition 68. Left antidivergence of a binary relation:

$$\left(\left(\mu\left(\langle a,c\rangle\right)=0\right)\wedge\left(\mu\left(\langle b,c\rangle\right)=0\right)\right)\rightarrow\left(\mu\left(\langle a,b\rangle\right)=1\right).$$
(72)

Definition 69. Right antidivergence of a binary relation:

$$\left(\left(\mu\left(\langle c,a\rangle\right)=0\right)\wedge\left(\mu\left(\langle c,b\rangle\right)=0\right)\right)\rightarrow\left(\mu\left(\langle a,b\rangle\right)=1\right).$$
(73)

Definition 70. Antidivergence of a binary relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 0\right) \land \left(\mu\left(\langle c, a \rangle\right) = 0\right) \right) \lor \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 0\right) \land \left(\mu\left(\langle a, c \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle b, c \rangle\right) = 1 \right). \end{array}$$
(74)

Definition 71. Quasi-difference (binary quasi-difference relation):

$$(\mu (\langle a, b \rangle) = 1) \rightarrow$$

$$(\exists \alpha (\exists c ((\alpha \in \{-1, 1\}) \land ((\mu (\langle a, c \rangle) + \alpha = \mu (\langle b, c \rangle)) \lor (\mu (\langle c, a \rangle) + \alpha = \mu (\langle c, b \rangle)))))).$$
(75)

Definition 72. Total quasi-difference (total binary quasidifference relation):

$$(\langle a, b \rangle \in X \times X) \rightarrow (\exists \alpha (\exists c ((\alpha \in \{-1, 1\}) \land ((\mu (\langle a, c \rangle) + \alpha = \mu (\langle b, c \rangle)) \lor (\mu (\langle c, a \rangle) + \alpha = \mu (\langle c, b \rangle)))))).$$
(76)

Definition 73. Right quasi-difference:

$$(\mu(\langle a, b \rangle) = 1) \rightarrow$$

$$(\exists c((\mu(\langle a, c \rangle) = 1 + \mu(\langle b, c \rangle)) \lor \qquad (77)$$

$$(\mu(\langle b, c \rangle) = 1 + \mu(\langle a, c \rangle)))).$$

Definition 74. Total right quasi-difference:

$$(\langle a, b \rangle \in X \times X) \rightarrow (\exists c((\mu(\langle a, c \rangle) = 1 + \mu(\langle b, c \rangle)) \lor (\mu(\langle b, c \rangle) = 1 + \mu(\langle a, c \rangle)))).$$

$$(78)$$

Definition 75. Left quasi-difference:

$$(\mu(\langle a, b \rangle) = 1) \rightarrow$$

$$(\exists c((\mu(\langle c, a \rangle) = 1 + \mu(\langle c, b \rangle)) \lor \qquad (79)$$

$$(\mu(\langle c, b \rangle) = 1 + \mu(\langle c, a \rangle)))).$$

Definition 76. Total left quasi-difference:

$$(\langle a, b \rangle \in X \times X) \to (\exists c((\mu(\langle c, a \rangle) = 1 + \mu(\langle c, b \rangle)) \lor (\mu(\langle c, b \rangle) = 1 + \mu(\langle c, a \rangle)))).$$
(80)

Definition 77. Left and right quasi-difference:

$$(\mu(\langle a, b \rangle) = 1) \rightarrow$$

$$(\exists c((\mu(\langle a, c \rangle) = 1 + \mu(\langle b, c \rangle)) \lor$$

$$(\mu(\langle b, c \rangle) = 1 + \mu(\langle a, c \rangle))))$$

$$(\mu(\langle a, b \rangle) = 1) \rightarrow$$

$$(\exists c((\mu(\langle c, a \rangle) = 1 + \mu(\langle c, b \rangle)) \lor$$

$$(\mu(\langle c, b \rangle) = 1 + \mu(\langle c, a \rangle)))).$$
(81)

Definition 78. Total left and right quasi-difference:

$$\begin{array}{l} (\langle a,b\rangle \in X \times X) \rightarrow \\ (\exists c((\mu (\langle a,c\rangle) = 1 + \mu (\langle b,c\rangle)) \lor \\ (\mu (\langle b,c\rangle) = 1 + \mu (\langle a,c\rangle)))) \\ (\langle a,b\rangle \in X \times X) \rightarrow \\ (\exists c((\mu (\langle c,a\rangle) = 1 + \mu (\langle c,b\rangle)) \lor \\ (\mu (\langle c,b\rangle) = 1 + \mu (\langle c,a\rangle)))). \end{array}$$

$$(82)$$

One of the basic properties of difference relations is irreflexivity.

Other useful properties of binary and difference relations are defined below.

Definition 79. Right quasi-reflexivity:

$$\left(\mu\left(\langle a,b\rangle\right) =0\right) \rightarrow\left(\mu\left(\langle a,a\rangle\right) =0\right) . \tag{83}$$

Definition 80. Right antiquasi-reflexivity:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=1\right)\wedge\left(\neg\left(a=b\right)\right)\right)\to\left(\mu\left(\langle a,a\rangle\right)=0\right).$$
(84)

Definition 81. Left quasi-reflexivity:

$$(\mu(\langle a, b \rangle) = 0) \to (\mu(\langle b, b \rangle) = 0).$$
(85)

Definition 82. Left antiquasi-reflexivity:

$$\left(\left(\mu\left(\langle a,b\rangle\right)=1\right)\wedge\left(\neg\left(a=b\right)\right)\right)\rightarrow\left(\mu\left(\langle b,b\rangle\right)=0\right).$$
(86)

Definition 83. Quasi-reflexivity:

$$(\mu(\langle a,b\rangle)=0) \to ((\mu(\langle a,a\rangle)=0) \land (\mu(\langle b,b\rangle)=0)).$$
(87)

Definition 84. Antiquasi-reflexivity:

$$((\mu(\langle a,b\rangle)=1)\wedge(\neg(a=b))) \rightarrow ((\mu(\langle a,a\rangle)=0)\wedge(\mu(\langle b,b\rangle)=0)).$$
(88)

Definition 85. Antitransitivity:

$$((\mu(\langle a, b \rangle) = 1) \land (\mu(\langle b, c \rangle) = 1)) \to (\mu(\langle a, c \rangle) = 0).$$
(89)

Definition 86. Antiantiantitransitivity:

$$((\mu(\langle a, b \rangle) = 0) \land (\mu(\langle b, c \rangle) = 0)) \to (\mu(\langle a, c \rangle) = 0).$$
(90)

Definition 87. Weak antitransitivity:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle a, b \rangle\right) = 1\right) \land \left(\mu\left(\langle b, c \rangle\right) = 1\right) \right) \land \\ \left(\left(\mu\left(\langle c, b \rangle\right) = 0\right) \land \left(\mu\left(\langle b, a \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle c, a \rangle\right) = 0 \right). \end{array}$$
(91)

Definition 88. Antiquasi-Euclidean relation:

$$(((\mu(\langle b, a \rangle) = 1) \land (\mu(\langle c, a \rangle) = 1)) \land ((\mu(\langle a, b \rangle) = 0) \land (\mu(\langle a, c \rangle) = 0))) \rightarrow (\mu(\langle b, c \rangle) = 0) \land (\mu(\langle b, c \rangle) = 0)) \land (((\mu(\langle b, a \rangle) = 0) \land (\mu(\langle c, a \rangle) = 0)) \land ((\mu(\langle a, b \rangle) = 1) \land (\mu(\langle a, c \rangle) = 1))) \rightarrow (\mu(\langle b, c \rangle) = 0).$$

$$(92)$$

Definition 89. Left antiquasi-Euclidean relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 1\right) \land \left(\mu\left(\langle c, a \rangle\right) = 1\right) \right) \land \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 0\right) \land \left(\mu\left(\langle a, c \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle b, c \rangle\right) = 0 \right). \end{array}$$

$$\begin{array}{l} (93) \\ \end{array}$$

Definition 90. Right antiquasi-Euclidean relation:

$$\begin{array}{l} \left(\left(\left(\mu \left(\left\langle b, a \right\rangle \right) = 0 \right) \land \left(\mu \left(\left\langle c, a \right\rangle \right) = 0 \right) \right) \land \\ \left(\left(\mu \left(\left\langle a, b \right\rangle \right) = 1 \right) \land \left(\mu \left(\left\langle a, c \right\rangle \right) = 1 \right) \right) \right) \rightarrow \\ \left(\mu \left(\left\langle b, c \right\rangle \right) = 0 \right). \end{array}$$
(94)

Definition 91. Anti-Euclidean relation:

$$\begin{array}{l} \left(\left(\left(\mu \left(\langle b, a \rangle \right) = 0 \right) \land \left(\mu \left(\langle c, a \rangle \right) = 0 \right) \right) \lor \\ \left(\left(\mu \left(\langle a, b \rangle \right) = 0 \right) \land \left(\mu \left(\langle a, c \rangle \right) = 0 \right) \right) \right) \rightarrow \\ \left(\mu \left(\langle b, c \rangle \right) = 0 \right). \end{array}$$
(95)

Definition 92. Left anti-Euclidean relation:

$$((\mu(\langle a,b\rangle)=0) \land (\mu(\langle a,c\rangle)=0)) \to (\mu(\langle b,c\rangle)=0).$$
(96)

Definition 93. Right anti-Euclidean relation:

$$((\mu(\langle b,a\rangle)=0) \land (\mu(\langle c,a\rangle)=0)) \to (\mu(\langle b,c\rangle)=0).$$
(97)

Definition 94. Antisub-Euclidean relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 0\right) \land \left(\mu\left(\langle c, a \rangle\right) = 0\right) \right) \land \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 0\right) \land \left(\mu\left(\langle a, c \rangle\right) = 0\right) \right) \right) \rightarrow \\ \left(\mu\left(\langle b, c \rangle\right) = 0 \right). \end{array}$$
(98)

Definition 95. Left divergent relation:

$$\left(\left(\mu\left(\langle a,c\rangle\right)=1\right)\wedge\left(\mu\left(\langle b,c\rangle\right)=1\right)\right)\rightarrow\left(\mu\left(\langle a,b\rangle\right)=0\right).$$
(99)

Definition 96. Right divergent relation:

$$\left(\left(\mu\left(\langle c, a \rangle\right) = 1\right) \land \left(\mu\left(\langle c, b \rangle\right) = 1\right)\right) \to \left(\mu\left(\langle a, b \rangle\right) = 0\right).$$
(100)

Definition 97. Left and right divergent relation:

$$\begin{array}{l} \left(\left(\left(\mu\left(\langle b, a \rangle\right) = 1 \right) \land \left(\mu\left(\langle c, a \rangle\right) = 1 \right) \right) \lor \\ \left(\left(\mu\left(\langle a, b \rangle\right) = 1 \right) \land \left(\mu\left(\langle a, c \rangle\right) = 1 \right) \right) \right) \to \\ \left(\mu\left(\langle b, c \rangle\right) = 0 \right). \end{array}$$
(101)

Similarity and difference relations can be classified according to the field of definition and its relation to the type of the subject area: similarity and difference relations of biological species, chemical similarity and difference relations, similarity and difference relations of physical processes [32], [34], [35]. From the point of view of knowledge representation, including within the semantic space, the following types of binary relations can be distinguished among similarity and difference relations.

Relations of similarity and difference of ontological structures on the basis of syntactic features: qualitative (structural) and quantitative (including – measures) [55]. For example, similarity and difference by absence of cycles on the incident links of signs, by the number of types of alphabet elements: nodes and edges. A separate example of similarity relation is the relation of coincidence of elements of ontological structures [21].

Relations of similarity and difference of static ontological structures on the basis of semantic attributes (attributes of denotational semantics, primarily related to essentially-systematic properties): qualitative (structural), quantitative (including measures). For example, similarity and difference by the presence of substructures of a certain kind (subgraphs, motifs), morphisms between structures (semantically stable), similarity and difference of signs of sets by their power, similarity and difference of signs by the power of extensional closures (essential, fullyconnected, etc.). Similarity and difference of (semantically stable) structures (extensional closures) by the number of elements of a given kind, by the number of morphisms, by the number of substructures, motifs, by spectral characteristics of structures and other invariants. The ontology of morphism relations, which are similarity relations, was developed earlier and is part of the ontology of measures and similarity and difference relations [25].

Relations of similarity and difference of dynamic ontological structures on the basis of semantic attributes (attributes of operational semantics, primarily related to relationally-phenomenological properties): qualitative (structural), quantitative (including measures). For example, similarity and difference in properties of operations [7] (determinacy, reversibility, returnability, etc.), spatio-temporal properties [1], [42], possibility of simulation [5], [7], [43]. Similarity and dissimilarity in measures of information quantity, computational complexity (spatio-temporal), period [25], degree of parallelism, etc.

Relations of similarity and difference of ontological structures on the basis of semantic-logical attributes (attributes of semantics related primarily to intensionally-logical properties): qualitative (structural), quantitative (including – measures). For example, similarity relations by the kind and structure of utterance forms, statements and axiomatizations, by logical consequence, by the measure of truth and other quantitative features.

Separate types of similarity and difference relations are meta-relations of similarity and difference.

A. Meta-relations of similarity and difference

The meta-relations of similarity include binary metarelations of equality, equivalence, morphisms of binary relations, binary meta-relations of closures of binary relations: reflexive, symmetric and transitive closures, etc.

The meta-relations of difference include binary metarelations of non-trivial permutations. Binary metarelations of nontrivial permutations, in particular, the binary meta-relations of the complement of a binary relation (up to the Cartesian square of the domain of its definition) can be referred to meta-relations of difference.

In the study of semantic space, static ontological structures at the entity-system level (semantic), which are stable to the addition of new fragments of ontologies, can be investigated first of all. Previously, the hereditary finite ontological structures of classical and non-classical [61] kinds were investigated (see fig.1), and their ontology was constructed on the basis of morphisms between them, which are special cases of similarity relations (see fig.2). Topological characterizations of ontological structures exploit the transitive closure (similarity meta-relations) of the membership relations associated with the extensional concepts, elements of ontological structures.

The introduction of the metric on these structures encounters the fact that the topology of semantically stable structures is directional (oriented), so the transition to the metric requires a symmetric closure of the corresponding topological relations, i.e., the application of a similarity meta-relations. In addition, due to the flexibility of the knowledge representation model used, this metric is obtained bounded (maximal value). The only way to ensure metric distinction of elements of ontological structures, while preserving integer values of the metric, is to increase the dimensionality of the space. As it has already been established, under some natural requirements for the distinction of elements of ontological structures, the dimensionality of space in this case will grow linearly with the number of elements in the [56] structure. A metric in a multidimensional space can be obtained by introducing one-dimensional metrics on each dimension and integrating them through the application of Theorem 1. In this case, metrics are introduced for canonical forms of ontological structures in order to ensure unambiguity of semantically stable metrics, allowing to pass to a canonical metric space integrated into a semantic space in accordance with the metamodel of semantic space [25]. Examples of metrics besides the distance between elements in the ontological structure can also be the powers of symmetric differences (sets of elements) of element's extensions, sets of elements of extensional (essential, fully-connected) closures, their sections, etc. The metrics can also be the power of symmetric differences (sets of elements) of extensional elements. However, to be able to fully work with such a metric space, ontological structures must be fully represented (defined).

VI. Measures and similarity in models with operational semantics

A. Operational information space

Definition 98. An operation-information space [25] is given by a transition relation R between configurations from set C, set of operations O, set of operators (command or instructions) K, set of parameters P, and set of values V.

$$R \subseteq C \times C$$

$$O \subseteq 2^{V^2 \times V} \cup 2^{V \times V^2}$$

$$C \subset 2^{K \cup P \cup (P \times (V \cup K)) \cup (K \times (O \cup P))}$$
(102)

The introduced space can be considered as texts of a generalized formal language [25] in some alphabet A.

$$K \cup O \cup P \cup V \subseteq A^{(*^*)}.$$
(103)

Let us enumerate the structural (syntactic) properties of configurations.

Statement 1. Operators and parameter values are distinguishable in each configuration.

$$(c \in C) \to (c \cap (P \times (K \cap V)) = \emptyset).$$
(104)

Statement 2. In each configuration, operations and parameters are distinguishable.

$$(c \in C) \to (c \cap (K \times (O \cap P)) = \emptyset).$$
(105)



Figure 1. General classes of finite structures

Statement 3. If an operator has two input parameters, it has one output parameter.

$$(c \in C) \rightarrow ((k \in c \cap K) \rightarrow ((l \cap (\{k\} \times P)| = 2) \rightarrow (|c \cap (P \times \{k\})| = 1))).$$

(106)

Statement 4. If an operator has one input parameter, it has at most one output parameter.

$$(c \in C) \rightarrow ((k \in c \cap K) \rightarrow ((l \in C \cap K))) \rightarrow ((l \in C \cap (P \times \{k\})) \leq 2))).$$

$$(107)$$

Statement 5. Each operator has at least one and no more than two input and output parameters.

$$(c \in C) \to ((k \in c \cap K) \to ((1 \le |c \cap (\{k\} \times P)| \le 2) \land (1 \le |c \cap (P \times \{k\})| \le 2))).$$
(108)

Relation of the operational semantics of "big" and "small step". Operational (semantic) properties of configurations:

$$(\langle c, s \rangle \in R) \sim \exists q ((q \in 2^{(c \cap K)} / \{\emptyset\}) \land (s \cap (P \times V)) = \\ \left(c \cap (P \times V) / \bigcup_{k \in q} (\delta (\langle c, k \rangle))_1 \right) \cup \bigcup_{k \in q} (\delta (\langle c, k \rangle))_2 t)).$$

$$(109)$$

i.e., the transition can be made only to the next configuration that contains results of all operations of some non-empty set of commands and does not contain input data processed by operations of commands from this set.

Definition 99. Changes (possible) resulting from an operation on command k in configuration c:

$$\delta\left(\langle c, k \rangle\right) \in \Delta\left(\langle c, k \rangle\right). \tag{110}$$

Definition 100. The set of (possible) changes resulting from an operation on command k in configuration c:

$$\begin{aligned} \Delta(\langle c,k\rangle) \stackrel{def}{=} \\ \{\langle r, \{(c \cap (\{k\} \times P))(k)\} \times \{((c \cap (\{k\} \times O))(k))(v)\} \rangle \\ | \{v \in \times_{p \in r} \{p_2\}\} \land (r \in \Lambda(\langle c,k\rangle)) \} \end{aligned} \tag{111}$$

Definition 101. The set of values of k command inputs in configuration c:

$$\Lambda\left(\langle c, k \rangle\right) \stackrel{def}{=} \left\{ x \left| x = \bigcup_{p \in \Gamma(\langle c, k \rangle)} \left\{ \langle p, (c \cap (\Gamma(\langle c, k \rangle) \times V))(p) \rangle \right\} \right\}$$
(112)

Definition 102. The set of command inputs k in configuration c:

$$\Gamma\left(\langle c,k\rangle\right) \stackrel{def}{=} \left\{ x \left| x = \left(c \cap \left(P \times \{k\}\right)\right)^{-1}(k) \right\}.$$
 (113)

Statement 6. The number of configurations to which a transition is possible is equal to the number of all possible



Figure 2. Ontology of morphisms

different changes caused by the operations of all possible non-empty instruction sets:

$$\begin{pmatrix} (c \in C) \to \\ \left(\left| \{R\left(c\right)\}\right| = \left| \left\{ \bigcup_{k \in q} \Delta\left(\langle c, k \rangle\right) \left| q \in \left(2^{c \cap K} / \{\emptyset\}\right) \right\} \right| \right).$$

Operational-information space allows to connect the operational semantics of "small step" with the operational semantics of "big step". The operational-information space can be viewed as a topological space on a graph with a transitive closure R or a metric space with a symmetric closure R. Similarly as a topological or metric space each of the configurations can be considered.

The operational-information space, having similarities with the model-parametric spac [60], is oriented to support the implementation of knowledge base components with complex operational semantics (see Reo Coordination Language [26]) and the design of problem-solving models for intelligent systems based on reusable and reusable components as a unified semantic model [29]. On the other hand, the high degree of unification of ontological structures of the operational-information space allows us to consider it as a subspace of the semantic space [25], [44].

The design of problem-solving models for intelligent systems relies on the previously discussed technological principles, which include the typology of reusable components, consistent with the general classification of tasks [7]. It is also important to observe the properties of coreturnability and parareversibility in the development and adaptation of the intellectual system (and its components) [54], which, if necessary, allows to pass to the returnability of operations realized by the system (component), along with the coreturnability being the basis of its repeated and multiple application for solving tasks of the same class.

Since the operational semantics within the framework of

the operational-information space is reduced to the relation of becoming [25] coordinated with the denotational semantics, the operational-information space is a model not only for studying the properties of internal operations and corresponding processes, but also the phenomena and processes conditioned by the interaction of the intellectual system with the external environment, i.e. related to cognition. Thus, on this basis by means of mechanisms of semantic logging of events (repeated or not), methods of analyzing protocols of processes and phenomena, by revealing relations of similarity and difference, the study of spatial-temporal, causal relations and attributes between phenomena, subjects and objects [43] is carried out. The introduction of corresponding order relations, which allow to specify and investigate topological properties, as well as the introduction of measures, which allow to specify and investigate metrical, including spatio-temporal, properties, complements the topology and metrics of the semantic space [25].

B. Measures of dynamic structures

Let us consider pseudo-orgraphs corresponding to some orgraphs of configurations of information-operational space. Let us introduce a binary (meta)operation of the tensor product of pseudo-orgraphs and the relation to be a divisor of the tensor product of pseudo-orgraphs.

Definition 103. Tensor product of pseudo-orgraphs [7]:

$$G \times_G H = \langle V_G, E_G \rangle \times_G \langle V_H, E_H \rangle \stackrel{def}{=} \langle V_G \times V_H, \{ \langle \langle y, v \rangle, \langle u, w \rangle \rangle \, | \, \langle \langle y, u \rangle, \langle v, w \rangle \rangle \in E_G \times E_H \, \} \rangle.$$
(115)

Definition 104. The divisor of the tensor product of pseudo-orgraphs.

$$(G \upharpoonright_G H) \sim (\exists X ((H = (G \times_G X)) \lor (H = (X \times_G G)))).$$
(116)

Let us consider the time-averaged entropy E of [25] wave fronts of the equilibrium state of a knowledge processing model (system) with a pseudo-orgraphic structure of returnable operations. Returnable operations are one of the three key features for constructing a general classification of operations and the tasks (problems) solved with their help [7].

Theorem 2: Entropy *E* is a \upharpoonright_G -monotone measure:

$$(G \upharpoonright_G H) \to (E(G) \le E(H)). \tag{117}$$

The entropy E satisfies four properties of the Hinchin entropy.

Property 1. The entropy of a system s is a function only of the probabilities of its n states $P(s) = \{p_1(s)\} \times \{p_2(s)\} \times \dots \times \{p_n(s)\}$:

$$E \in (Range(E))^{\bigcup_{s} P(s)}.$$
 (118)

Property 2. For any system s with n states it is true that:

$$E\left(P\left(s\right)\right) \le E\left(\left\{n^{-1}\right\}^{n}\right),\tag{119}$$

where $E\left(\left\{n^{-1}\right\}^n\right)$ is the entropy of a system with uniform probability distribution of *n* states.

Property 3. If n + 1th state $p_{n+1}(s) = 0$ is added to the system s, the entropy will not change.

Property 4. The entropy of the set of two independent systems s and m is of the form:

$$E\left(P\left(s\otimes m\right)\right) = E\left(P\left(s\right)\right) + E\left(P\left(m\right)\right).$$
(120)

Statement 7. The entropy for classes of isomorphic (multi)pseudo-orgraphs is $[\times_G]_{\cong}$ -additive measure in the algebra of the complement $\overline{[\,]_{\cong}}$, the GCD $[\wedge_G]_{\cong}$ and the LCM $[\gamma_G]_{\cong}$ of some class of isomorphic (multi)pseudo-orgraphs $[\bigcirc]_{\cong}$ and the classes of their tensor product divisors:

$$E\left([G]_{\cong}[\times_G]_{\cong}[H]_{\cong}\right) = E\left([G]_{\cong}\right) + E\left([H]_{\cong}\right).$$
(121)

Some properties of the operations of this algebra:

$$\begin{pmatrix} [G]_{\cong}[\upharpoonright G]_{\cong} ([G]_{\cong}[\curlyvee G]_{\cong}[H]_{\cong}) \\ (([G]_{\cong}[\land G]_{\cong}[H]_{\cong}) [\upharpoonright G]_{\cong}[G]_{\cong}) \\ (([G]_{\cong}[\curlyvee G]_{\cong}[H]_{\cong}) [\Join G]_{\cong} ([G]_{\boxtimes}[\land G]_{\cong}[H]_{\cong})) = \\ ([G]_{\boxtimes}[\bowtie G]_{\cong}[\bowtie]_{\boxtimes}) \\ (\overline{[G]}_{\boxtimes}[\urcorner G]_{\boxtimes}\overline{[H]}_{\cong}) = \overline{[([G]_{\boxtimes}[\land G]_{\boxtimes}[H]_{\boxtimes})]}_{\overline{[G]}_{\cong}} = [G]_{\cong}.$$

$$(122)$$

The proposed measure differs from the von Neumann entropy [30], the Laplacian entropy (Kirchhoff matrix [32]) and the normalized Laplacian [32] of an oriented graph (multipseudo-orgraph).

$$E\begin{pmatrix} 0 & 1 & 1\\ 0 & 0 & 1\\ 2 & 0 & 0 \end{pmatrix} = (0.8 * \ln(2) - \ln(5)) / \ln(2)$$
(123)

There are similarities and differences between models with operational semantics based on the introduced measure, also based on it we can consider convergence and divergence measures [35].

The following transformations allow us to introduce meta-operations and specify the change of a dynamic system, analogous to the way a semiotic system specifies the change of a formal system [13]. Thus, the dynamics of the system can be described along more than one temporal axis.

Addition of multipseudo-orgraphs. Examples:

(0	1	1	0)	(0	0	0	1) (0	1	1	1	
0	0	0	1	0	0	0	0		0	0	0	1	
0	0	0	1	0	0	0	0	=	0	0	0	1	
2	0	0	o /	$\begin{pmatrix} 1 \end{pmatrix}$	0	0	0	$) \ ($	3	0	0	0 /	
(0	1	1	2	(0	0	0	1) (0	1	1	1	
0	0	0	1	0	0	0	0	1.1	0	0	0	1	
0	0	0	1	0	0	0	0	+	0	0	0	1	
4	0	0	o /		0	0	0	$) \ ($	3	0	0	0 /	
												(124)

Vertex permutation (permutation matrix is used). Example:

Splitting vertices of a multipseudo-orgraph using diagonal rectangular matrices. Examples:

$$\begin{pmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1/\sqrt{2} & 0 \\ 0 & 1/\sqrt{2} & 0 \\ 0 & 0 & \sqrt{2} \end{pmatrix} * \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 2 & 0 & 0 \end{pmatrix} * \begin{pmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 1 & 2 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 4 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \sqrt{3}/\sqrt{2} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} * \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 2 & 0 & 0 \end{pmatrix} * \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & \sqrt{3}/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 \end{pmatrix}$$
(126)

Inverse transformation (gluing) of vertices using diagonal rectangular matrices. Example:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 0 & 0 & \sqrt{2}/\sqrt{3} \end{pmatrix} * \begin{pmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 \end{pmatrix} \\ \begin{pmatrix} \sqrt{2}/\sqrt{3} & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 2 & 0 & 0 \end{pmatrix}$$
(127)

VII. Logic models. Integration, parametrization, generalization

A. Similarity, inductive logical inference and multivalued logics

Logic models aimed at supporting and integrating deductive, abductive, and inductive logical inference mechanisms citebTaxonomy, in particular those based on the application of the DSM-method and the JSM-method, use multi-valued [4] logics. DSM-method and JSMmethod, multi-valued [4] logics are used. These logics are based on four-valued logic using non-associative binary logic operations of conjunction and disjunction, which requires consideration of non-binary logic operations. Increasing the number of values allows us to rebalance the complexity between the operational and denotational semantics of logics of the corresponding [40] class. For example, we can eliminate the use of nonbinary logical operations in such logics, by switching from four-valued logics to six-valued logics. The DSM method and the JSM method are based on mechanisms that utilize similarity and dissimilarity features and relations.

B. Integration of logical models of knowledge processing

Previously, a model and principles for integrating logical models of knowledge processing have been proposed [5].

An important property during integration is the possibility of bisimulation [58].

It should be noted that when integrating logical models of knowledge processing, it is important to consider the support of different types of semantics [4], [37], [38], [38]–[41]: axiomatic, algebraic, relational and others. In this regard, let us consider the integration of temporal logics and fuzzy logics on the basis of parameterized fuzzy logics.

Table I Integrated logic models

Semantics	Double-valued logic	Multi-valued logic			
			Fuzzy logic		
Predicate Logic	+	+	+		
Modal Logic	+	+	+		
Temporal logic	+	+			

C. Parameterized temporal fuzzy logic

Let us consider the generalization of parameterized fuzzy logics [53] to temporal logics.

Definition 105. Fuzzy negation:

$$\mu_{\sim\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \sim^{P}_{\lambda} \mu_{\alpha}\left(\langle\chi,\pi\rangle\right).$$
(128)

It is usually true for fuzzy negation:

$$\mu_{\sim\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} 1 - \mu_{\alpha}\left(\langle\chi,\pi\rangle\right). \tag{129}$$

Definition 106. Fuzzy conjunction:

$$\mu_{\alpha\tilde{\wedge}\beta}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \left(\mu_{\alpha}\left(\langle\chi,\pi\rangle\right)\tilde{\wedge}^{P}_{\lambda}\mu_{\beta}\left(\langle\chi,\pi\rangle\right)\right).$$
(130)

In particular, for a fuzzy disjunction of causal properties (case when triangular norm [8] is minimum) it is true:

$$\mu_{\alpha \bar{\wedge} \beta} \left(\langle \chi, \pi \rangle \right) = \inf \left(\left\{ \mu_{\alpha} \left(\langle \chi, \pi \rangle \right) \right\} \cup \left\{ \mu_{\beta} \left(\langle \chi, \pi \rangle \right) \right\} \right).$$
(131)

Definition 107. Fuzzy disjunction:

$$\mu_{\alpha\tilde{\vee}\beta}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \left(\mu_{\alpha}\left(\langle\chi,\pi\rangle\right)\tilde{\vee}^{P}_{\lambda}\mu_{\beta}\left(\langle\chi,\pi\rangle\right)\right) = \mu_{\sim\left((\sim\alpha)\tilde{\wedge}(\sim\beta)\right)}\left(\langle\chi,\pi\rangle\right).$$
(132)
Definition 108. Fuzzy strict disjunction:

$$\mu_{\alpha \preceq \beta} \left(\langle \chi, \pi \rangle \right) \stackrel{\text{def}}{=} \left(\mu_{\alpha} \left(\langle \chi, \pi \rangle \right) \stackrel{\vee P}{_{\lambda}} \mu_{\beta} \left(\langle \chi, \pi \rangle \right) \right) = \mu_{(\alpha \tilde{\vee} \beta) \tilde{\wedge} ((\sim \alpha) \tilde{\vee} (\sim \beta))} \left(\langle \chi, \pi \rangle \right).$$
(133)

Definition 109. Fuzzy implication:

$$\mu_{\alpha \rightsquigarrow \beta}\left(\langle \chi, \pi \rangle\right) \stackrel{def}{=} \left(\mu_{\alpha}\left(\langle \chi, \pi \rangle\right) \rightsquigarrow_{\lambda}^{P} \mu_{\beta}\left(\langle \chi, \pi \rangle\right)\right).$$
(134)

Definition 110. Fuzzy equivalence:

$$\mu_{\alpha \simeq \beta} \left(\langle \chi, \pi \rangle \right) \stackrel{def}{=} \left(\mu_{\alpha} \left(\langle \chi, \pi \rangle \right) \simeq^{P}_{\lambda} \mu_{\beta} \left(\langle \chi, \pi \rangle \right) \right) = \mu_{(\alpha \rightsquigarrow \beta) \tilde{\wedge} (\beta \rightsquigarrow \alpha)} \left(\langle \chi, \pi \rangle \right).$$
(135)

Definition 111. Fuzzy existence:

$$\mu_{\tilde{\exists}\gamma\alpha(\gamma)}\left(\langle\chi,\pi\rangle\right) \stackrel{\text{def}}{=} \tilde{\exists}_{\lambda}^{P}\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right) = \tilde{\vee}_{\lambda}^{P}\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right).$$
(136)

In particular, it is true for the fuzzy disjunction of causal properties (the case of minimum as triangular norm):

$$\mu_{\tilde{\exists}\gamma\alpha(\gamma)}\left(\langle\chi,\pi\rangle\right) = \sup\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right). \quad (137)$$

Definition 112. Fuzzy univeral quantor:

$$\mu_{\tilde{\forall}\gamma\alpha(\gamma)}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{\forall}_{\lambda}^{P}\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right) = \tilde{\wedge}_{\lambda}^{P}\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right).$$
(138)

In particular, this is true for the fuzzy conjunction of causal properties (case the triangular norm is the minimum):

$$\mu_{\tilde{\forall}\gamma\alpha(\gamma)}\left(\langle\chi,\pi\rangle\right) = \inf\left(\left\{\mu_{\alpha(\tau)}\left(\langle\chi,\pi\rangle\right)|\tau\right\}\right). \quad (139)$$

Definition 113. Maximal routes through a vertex in a model:

$$\Phi\left(\langle\chi,\iota\oplus\tau,\tau,E,V\rangle\right) \stackrel{def}{=} \left(\left(\Psi\left(\langle\chi,\pi,E^{-1},V\rangle\right)\wedge\right. \\ \Psi\left(\langle\chi,\tau,E,V\rangle\right)\right)\wedge\left(\iota\in\times_{k<|\pi|}^{k=0}\left(\{\pi_{k+1}\}^{-1}\right)\right)\right). \tag{140}$$

Definition 114. Maximal half-routes from a vertex in a finite returnable model:

$$\hat{\Psi}\left(\langle \chi, \pi, E, V \rangle\right) \stackrel{def}{=} \left(\left(\Theta\left(\langle \chi, \pi, E, V \rangle\right) \land \left(\exists q\left(\left(\pi_{|\pi|}\right)_{2} = (\pi_{q})_{1}\right)\right)\right) \land \left(\bigcup_{k=0}^{k<|\pi|} \{\pi_{k+1}\} \in \left(V_{+}^{V}\right)\right)\right). \tag{141}$$

Definition 115. Maximal half-route from a vertex in the model:

$$\Psi\left(\langle \chi, \pi, E, V \rangle\right) \stackrel{def}{=} \left(\Theta\left(\langle \chi, \pi, E, V \rangle\right) \land \Xi\left(\langle \chi, \pi, E, V \rangle\right)\right)$$
(142)

Definition 116. Half-route from a vertex in the model:

$$\Theta\left(\langle \chi, \pi, E, V \rangle\right) \stackrel{def}{=} \left(\left(\chi = (\pi_1)_1\right) \land \left(\pi \in E^{|\pi|}\right)\right) \land \left(\left((j \in \mathbb{N}/\{0\}) \land (j < |\pi|)\right) \rightarrow \left((\pi_j)_2 = (\pi_{j+1})_1\right)\right).$$
(143)

Definition 117. Maximality of half-routes from a vertex in the model:

$$\Xi\left(\langle\chi,\pi,E,V\rangle\right) \stackrel{def}{=} \left(\left(|\pi| \notin \mathbb{N}\right) \lor \left(\neg\tau\left(\Theta\left(\langle\chi,\tau,E,V\rangle\right) \land \left((\tau=\pi\oplus\langle\varepsilon\rangle) \land (\varepsilon\in E)\right)\right)\right)\right).$$
(144)

Definition 118. Fuzzy operator "sometimes in the future":

$$\tilde{\mathbf{F}}_{\lambda}^{P}\left(\left\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right)|\Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right)\wedge\Phi\left(\langle\gamma,\pi,\tau,E,V\rangle\right)\right\}\right).$$

$$(145)$$

The following expression is valid for models of returnable operations:

$$\mu_{\tilde{\mathbf{F}}\alpha}(\langle \chi, \pi \rangle) = \sup\left(\{\mu_{\alpha}\left(\langle \gamma, \pi \rangle\right) | \Phi\left(\langle \chi, \pi, \tau, E, V \rangle\right) \land \Phi\left(\langle \gamma, \pi, \tau, E, V \rangle\right)\}\right),$$
(146)

and instead of Ψ , just check $\hat{\Psi}$.

CTL* [59] operator version.

$$\mu_{\mathbf{\tilde{F}}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \mu_{\alpha\tilde{\vee}\tilde{F}\alpha}\left(\langle\chi,\pi\rangle\right). \tag{147}$$

Definition 119. Fuzzy operator "always in the future":

$$\mu_{\tilde{G}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \\ \tilde{G}_{\lambda}^{P}\left(\left\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right) \left| \Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right) \wedge \Phi\left(\langle\gamma,\pi,\tau,E,V\rangle\right)\right.\right\}\right).$$
(148)

The following expression is valid for models of returnable operations:

$$\mu_{\tilde{G}\alpha}\left(\langle\chi,\pi\rangle\right) = \\ \inf\left(\left\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right) \middle| \Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right) \land \Phi\left(\langle\gamma,\pi,\tau,E,V\rangle\right)\right\}\right), \tag{149}$$

and instead of Ψ , just check $\hat{\Psi}$.

CTL* operator version.

$$\mu_{\tilde{\mathbf{G}}\alpha}\left(\langle \chi, \pi \rangle\right) \stackrel{def}{=} \mu_{\alpha \wedge \tilde{\mathbf{G}}\alpha}\left(\langle \chi, \pi \rangle\right). \tag{150}$$

Definition 120. Fuzzy operator "sometimes in the past":

$$\mu_{\tilde{P}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{P}_{\lambda}^{P}\left(\left\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right)\right\}\right) \Phi\left(\left\langle\chi,\pi,\tau,E^{-1},V\right\rangle\right) \wedge \Phi\left(\left\langle\gamma,\pi,\tau,E^{-1},V\right\rangle\right)\right).$$
(151)

The following expression is valid for models of returnable operations:

$$\mu_{\tilde{P}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \sup(\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right) \\ \Phi\left(\langle\chi,\pi,\tau,E^{-1},V\rangle\right) \land \Phi\left(\langle\gamma,\pi,\tau,E^{-1},V\rangle\right)\}),$$
(152)

and instead of Ψ , just check $\hat{\Psi}$.

Definition 121. Fuzzy operator "always in the past":

$$\mu_{\tilde{\mathrm{H}}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{\mathrm{H}}_{\lambda}^{P}\left\{\left\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right)\right\} \\ \left|\Phi\left(\langle\chi,\pi,\tau,E^{-1},V\rangle\right)\wedge\Phi\left(\langle\gamma,\pi,\tau,E^{-1},V\rangle\right)\right\}\right). \tag{153}$$

The following expression is valid for models of returnable operations:

$$\mu_{\tilde{H}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \inf\{\{\mu_{\alpha}\left(\langle\gamma,\pi\rangle\right) \\ \left|\Phi\left(\langle\chi,\pi,\tau,E^{-1},V\rangle\right) \land \Phi\left(\langle\gamma,\pi,\tau,E^{-1},V\rangle\right)\}\right),$$
(154)

and instead of Ψ , just check $\hat{\Psi}$.

Definition 122. Fuzzy possibility operator:

$$\mu_{\tilde{\Diamond}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{\Diamond}^{P}_{\lambda}\left(\left\{\mu_{\alpha}\left(\langle\gamma,\iota\rangle\right) \left|\Phi\left(\langle\chi,\iota,\tau,E,V\rangle\right)\right.\right\}\right).$$
(155)

The following expression is valid for models of returnable operations:

$$\mu_{\bar{\Diamond}\alpha}\left(\langle\chi,\pi\rangle\right) = \sup\left(\left\{\mu_{\alpha}\left(\langle\chi,\iota\rangle\right) | \Phi\left(\langle\chi,\iota,\tau,E,V\rangle\right)\right\}\right),\tag{156}$$

and instead of Ψ , just check $\hat{\Psi}$.

Definition 123. Fuzzy necessity operator:

$$\mu_{\tilde{\square}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{\square}^{P}_{\lambda}\left(\left\{\mu_{\alpha}\left(\langle\chi,\iota\rangle\right) \left|\Phi\left(\langle\chi,\iota,\tau,E,V\rangle\right)\right.\right\}\right).$$
(157)

The following expression is valid for models of returnable operations:

$$\mu_{\tilde{\Box}\alpha}\left(\langle\chi,\pi\rangle\right) = \inf\left(\left\{\mu_{\alpha}\left(\langle\chi,\iota\rangle\right) | \Phi\left(\langle\chi,\iota,\tau,E,V\rangle\right)\right\}\right).$$
(158)

Definition 124. Fuzzy operator "next":

$$\frac{\mu_{\tilde{\bigcirc}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \tilde{\bigcirc}^{P}_{\lambda} \\ \left(\left\{\mu_{\alpha}\left(\langle(\tau_{1})_{2},\pi\rangle\right) | \Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right)\right\}\right), \tag{159}$$

i.e.

$$\mu_{\tilde{\bigcirc}\alpha}\left(\langle\chi,\pi\rangle\right)\in\left(\left\{\mu_{\alpha}\left(\langle(\tau_{1})_{2},\pi\rangle\right)|\Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right)\right\}\right).$$
(160)

Let it:

$$\mu_{\tilde{0}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{aef}{=} 1,\tag{161}$$

and

$$\mu_{\widetilde{(k+1)}\alpha}\left(\langle\chi,\pi\rangle\right) \stackrel{def}{=} \left(\widetilde{k+1}\right)_{\lambda}^{P} \\
 \left(\left\{\left(\mu_{\alpha}\left(\langle\chi,\pi\rangle\right) \tilde{\wedge}_{\lambda}^{P} \mu_{\widetilde{k}\alpha}\left(\langle(\tau_{1})_{2},\pi\rangle\right)\right) | \Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right)\right\}\right), \\
 (162)$$
i.e.

$$\mu_{\widetilde{(k+1)}\alpha}\left(\langle\chi,\pi\rangle\right) \in \left(\left\{\left(\mu_{\alpha}\left(\langle\chi,\pi\rangle\right)\tilde{\wedge}_{\lambda}^{P}\mu_{\widetilde{k}\alpha}\left(\langle(\tau_{1})_{2},\pi\rangle\right)\right)|\Phi\left(\langle\chi,\pi,\tau,E,V\rangle\right)\right\}\right).$$
(163)

Definition 125. Fuzzy operator "until":

$$\mu_{\alpha \tilde{\rightarrow} \beta} \left(\langle \chi, \pi \rangle \right) \stackrel{def}{=} \\ \tilde{\neg}_{\lambda}^{P} \left(\left\{ \left(\mu_{\beta} \left(\langle (\tau_{k})_{1}, \pi \rangle \right) \tilde{\wedge}_{\lambda}^{P} \mu_{\widetilde{(k-1)}\alpha} \left(\langle \chi, \pi \rangle \right) \right) \\ |\Phi \left(\langle \chi, \pi, \tau, E, V \rangle \right) \wedge \left((k \in \mathbb{N}) \wedge (k \leq |\tau|) \right) \right\} \right),$$
(164)

i.e.

$$\begin{aligned}
& \mu_{\alpha \xrightarrow{\sim} \beta} \left(\langle \chi, \pi \rangle \right) \in \\
\tilde{\exists}_{\lambda}^{P} \left(\left\{ \left(\mu_{\beta} \left(\langle (\tau_{k})_{1}, \pi \rangle \right) \tilde{\wedge}_{\lambda}^{P} \mu_{\widetilde{(k-1)}\alpha} \left(\langle \chi, \pi \rangle \right) \right) \\
& \Phi \left(\langle \chi, \pi, \tau, E, V \rangle \right) \wedge \left((k \in \mathbb{N}) \wedge (k \le |\tau|) \right) \right\}, \\
\end{aligned}$$
(165)

Examples (see figure.3 and tables II, III):



Figure 3. Structure example

Table II Fuzzy temporal logic formula "sometimes" operators examples

χ	π	α	$\tilde{F}\alpha$	$\tilde{G}\alpha$	$\tilde{P}\alpha$	$\tilde{H}\alpha$	Õα
1	< <1,2>,<2,1> >	T	\perp	\perp	\perp	\perp	\perp
1	<<1,2>,<2,3>,<3,1>>	\perp	Т	\perp	Т	\perp	\perp
2	< <2,1>,<1,2> >	\perp	\perp	\perp	\perp	\perp	\perp
2	<<2,3>,<3,1>,<1,2>>	T	Т	\perp	Т	\perp	Т
3	< <3,1>,<1,2>, <2,1>, <1,2>,<2,3> >	Т	T	T	T	T	Ţ
3	<<3,1>,<1,2>,<2,3>>	Т	Т		Т	1	\perp

D. Metrics in logical models

For logical models, one can identify: their order relations and topology associated with a logical consequence relation, corresponding measures associated with classes of logical formulas and propositions. Thus, a (pseudo)metric space formed by classes of logically equivalent formulas and a metric expressing the difference of values of propositions (can be computed as a fuzzy strict disjunction) can be considered. This metric induces pseudometrics on instances of these classes.

Integration of pseudometric spaces of the intensionallylogical level can be realized similarly to the integration of metric and pseudometric spaces of the essentially-systematic and relationally-phenomenological levels with the help of Theorem 1.

For the technical realization of metric subspaces of the semantic space, we propose to consider structures based on k-d trees, in which dimensions are selected according to the highest value of the informativeness feature. The number of selected dimensions for indexing elements of ontology structures using k-d trees should be sublinear. In the presence of non-factors that do not allow the formation of a replenishment-resistant metric space for ontological structures, it is proposed to use conditionally stable attributes of metacognition structures of ignorance with respect to these ontological structures. Thus, these attributes will not be absolutely stable. However, in the process of accumulation of additional knowledge about ontological structures, elimination of non-factors (ignorance) and integration of replenishment-resistant metrics within the framework of additional dimensions, it is proposed to ensure

Table III Fuzzy temporal logic formula "until" and necessity examples

χ	π	$(\sim \alpha) \tilde{\multimap} \alpha$	$\Diamond \alpha$	$\tilde{\Box}\alpha$	$\hat{\mathbf{A}}\mathbf{F}\alpha$	$\tilde{\Box}\tilde{F}\alpha$
1	< <1,2>,<2,1> >	\perp	\perp		T	\perp
1	<<1,2>,<2,3>,<3,1>>	\perp	1	1	T	\perp
2	< <2,1>,<1,2> >	\perp	1	1	T	\perp
2	<<2,3>,<3,1>,<1,2>>	\perp	1	1	Т	\perp
3	< <3,1>,<1,2>, <2,1>, <1,2>,<2,3> >	Т	Т	т	т	T
3	<<3,1>,<1,2>,<2,3>>	Т	Т	Т	T	\perp

convergence of the corresponding formed metric space to the metric space based on stable attributes by means of parameterization.

VIII. Conclusion

The review of existing approaches to analyzing semantic relations, identifying meaning in data and knowledge, similarity and proximity of knowledge structures has been carried out. The ontology of measures of similarity and similarity relations of elements and knowledge structures in ontologies was developed. The model of operational information space oriented to the creation of intelligent systems based on reusable and reusable components was proposed, which provides semantic unification and integration of models with operational semantics of "big step" and "small step" within the semantic space. Also, the monotone measure expressing the entropy of the equilibrium state of information processing models using the model of returnable computation was proposed. The algebra of transformations of the models on which this measure is defined was considered. The model of semantics of the parametrized fuzzy temporal logic language was developed and proposed which provides the computation of fuzzy truth values for fuzzy CTL* language operators and other temporal logic operators on the models coordinated with denotational and operational semantics of the unified semantic knowledge representation model. The principles of construction on the basis of generalized measures and relations and similarity of semantic space models that take into account topological and metric properties of ontological structures at the essentially-systematic, relationally-phenomenological and intensionally-logical levels are formulated.

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ПОДХОДЫ К ИССЛЕДОВАНИЮ СЕМАНТИЧЕСКОГО ПРОСТРАНСТВА И МОДЕЛЕЙ ИНТЕГРИРОВАННОГО ЛОГИЧЕСКОГО ВЫВОДА С ИСПОЛЬЗОВАНИЕМ МЕР СХОДСТВА, РАЗЛИЧИЯ И ДРУГИХ МЕР

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Рассмотрены подходы к анализу близости, сходств и различий стуктур знаний для выявления смысла в данных и знаниях, подходы и модели представления знаний с операционной семантикой для компонентного проектирования интеллектуальных систем. Разработана онтология обобщённых мер и отношений различия и сходства, включая отношения подобия. Предложен класс предпорядоковых шкал, меры на структурах с операционной семантикой, проведено исследование их алгебраических свойств. Уточнено понятие операционно-информационного пространства. Предложена модель семантики нечёткой временной логики для спецификации структур знаний с операционной семантикой на основе ранее предложенной параметризованной нечёткой логики. Для онтологических структур, соответствующих полученным результатам и трём уровням семантического анализа, сформулированы принципы их интеграции как метрических подпространств смыслового пространства.

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OSTIS Platform — a Framework for Developing Intelligent Agents Based on Semantic Networks

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Abstract—This paper examines AI agent frameworks and introduces the OSTIS Platform as a solution to limitations in current approaches. It analyzes the principles of AI agents, evaluates frameworks like LangGraph, CrewAI, AutoGen, Semantic Kernel, and LlamaIndex, and details the advantages of the OSTIS Technology. These advantages include a unified semantic basis and deep knowledge representation. The paper will also discuss the implementation of OSTIS Platform and agent-driven models, highlighting their potential for advancing intelligent systems.

Keywords—AI, Agent AI, intelligent systems, OSTIS, *OSTIS Platform*, ostis-systems, semantic networks, SC-code, knowledge base

I. INTRODUCTION

The development of artificial intelligence has witnessed remarkable progress in recent years, particularly in the realm of intelligent agents – software entities capable of autonomous decision [1] – making and problem-solving. These agents have become fundamental components in AI systems across various domains, from virtual assistants to complex robotic systems. As AI applications grow increasingly sophisticated, the need for robust frameworks to facilitate agent development has become critical.

AI agents represent a paradigm shift in software development, moving from passive programs that merely respond to inputs toward active entities that can sense their environment, reason about it, and take actions to achieve goals. These intelligent agents work through continuous cycles of perception, reasoning, and action, adapting to changes in their environment and learning from experiences. Their applications span diverse domains including robotics, virtual assistants, smart environments, and simulation systems.

Current frameworks for developing AI agents, including *LangGraph* [2], *AutoGen* [3], *CrewAI* [4], *LlamaIndex* [5], and *Semantic Kernel* [6], have made significant contributions to this field. Each offers distinct approaches to agent orchestration, from *LangGraph*'s workflow-oriented architecture to *CrewAI*'s role-based collaborative model. However, despite their strengths, these frameworks exhibit fundamental limitations that restrict their effectiveness in addressing complex, cross-domain problems.

These limitations [7]–[10] include shallow integration of problem-solving methods, where frameworks often focus on specific problem-solving paradigms without providing a unified semantic foundation. Additionally, existing frameworks struggle with flexibility and scalability, making them less suitable for large-scale or highly dynamic AI systems. The complexity of maintaining and updating developed agents represents another significant challenge, stemming from the lack of a unified semantic basis for integrating diverse problem-solving methods.

The OSTIS Platform [11], [12] emerges as a comprehensive solution to these challenges, offering a framework specifically designed for developing intelligent agents based on semantic networks. Unlike traditional approaches, OSTIS Platform integrates diverse problemsolving methods on a <u>common semantic basis</u>, enabling the creation of complex, interconnected knowledge models capable of addressing nuanced problems.

This paper examines the principles and implementation of the OSTIS Platform, highlighting its advantages over existing frameworks and detailing its event-driven and agent-driven models. By providing a unified semantic basis and deep knowledge representation capabilities, the OSTIS Platform establishes a robust foundation for building intelligent agents capable of tackling complex real-world problems more effectively than existing frameworks.

II. STATE OF THE ART

In recent years, the development of intelligent agents – computer programs that can make decisions and act by themselves – has become a major area in artificial intelligence (AI) [1], [13]–[15]. Many software tools, called frameworks, have been created to help build these agents. These frameworks aim to make it easier to design, build, and manage systems that can act on their own, learn, and solve different types of problems.

A. What are AI agents

- AI agents are like digital workers. They can:
- sense what is happening around them (using data or sensors);

- think about what to do next (using rules or goals);
- take actions to reach their goals.

How AI Agents Work

AI agents can be defined as software programs that use AI techniques to perform tasks autonomously.

AI agents work by following a basic cycle of perception, reasoning, and action [16]:

- 1) The agent receives information about its environment through sensors or other data sources.
- The agent uses this information to make decisions based on its goals, rules, and models of the environment.
- 3) The agent takes actions to achieve its goals, which can involve interacting with the environment or other agents.

This cycle is repeated continuously as the agent adapts to changes in its environment and learns from its experiences.

Role of AI agents in modern systems

They are used in a wide range of applications, including [1], [13], [14]:

- robots that move and interact with the world;
- virtual assistants (like Siri or Alexa);
- smart homes and cities that control lights, heating, or traffic;
- systems that simulate groups of people or organizations.

What makes an AI agent framework

AI agent frameworks provide the infrastructure and tools needed to build autonomous systems that can perceive, reason, plan, and take actions to achieve specified goals [17]. These frameworks extend the capabilities of large language models with orchestration, planning, memory, and tool-use capabilities, transforming them into systems that can interact with their environment and make decisions based on available information.

At their core, AI agent frameworks solve several challenging aspects of agent development:

- managing context and persistent memory across interactions;
- enabling structured interaction with external tools, APIs, and data sources;
- making logical decisions based on available information;
- planning multi-step processes to achieve complex goals;
- and evaluating performance and improving reliability.

B. Overview of existing frameworks

Several popular AI agent frameworks have gained traction due to their diverse capabilities [18], [19]:

• LangGraph [2], [20] extends the LangChain ecosystem with a graph-based architecture that treats agent

steps as nodes in a directed graph. Developed by the creators of LangChain, it uses graph-based technology to create detailed workflows for AI agent systems. *LangGraph* provides scalable infrastructure, an opinionated API for user interfaces, and an integrated developer studio for streamlined deployment and development [21]–[23].

- *AutoGen* [24] borns out of Microsoft Research, Auto-Gen frames agent interactions as asynchronous conversations among specialized agents. This approach reduces blocking, making it well-suited for longer tasks or scenarios requiring real-time concurrency. AutoGen supports free-form chat among many agents and is backed by a research-driven community [3], [25].
- *CrewAI* [26] is an open-source Python framework that simplifies the development and management of multi-agent AI systems. It assigns specific roles to agents, enabling autonomous decision-making and facilitating seamless communication. CrewAI supports both sequential and hierarchical task execution modes, providing a user-friendly platform for creating and managing multi-agent systems [4], [26].
- *LlamaIndex* [27] excels in retrieval-centric applications by integrating retrieval-augmented generation (RAG) with indexing capabilities. This synergy allows for extensive data lookup and knowledge fusion, making it ideal for use-cases revolving around data retrieval [5].
- Semantic Kernel [6], [28] is Microsoft's .NET-first approach to orchestrating AI "skills" and combining them into full-fledged plans or workflows. It supports multiple programming languages and focuses on enterprise readiness, including security, compliance, and integration with Azure services. Semantic Kernel allows for the creation of a range of skills, some powered by AI and others by pure code, making it popular among teams integrating AI into existing business processes.

C. Comparison of frameworks

The table I summarizes the key features and limitations of each framework [7]–[10].

D. Other limitations of existing frameworks

Despite their strengths, these frameworks face other significant limitations:

1) Shallow integration of problem-solving methods. Most frameworks focus on specific problem-solving paradigms, such as procedural or declarative methods, without providing a unified semantic basis for integrating diverse approaches [29], [30]. For example, AutoGen excels in conversation-based workflows but lacks support for declarative knowledge representation.

Framework	Architecture	Key Features	Strengths	Limitations	Best use cases
LangGraph	Graph- based archi- tecture, workflow- oriented	 Explicit workflow graphs State persistence Human-in-the- loop support 	 Fine-grained control LangChain integration 	 Steep learning curve LangChain depen- dency 	 Complex workflows Research Multi-agent systems
AutoGen	Multi- agent conversa- tional	 Asynchronous agent messaging GUI support Tool/human inte- gration 	 Multi-agent support Flexible Python/.NET 	 Requires prompt engineering Possible looping issues 	 Conversational AI Collaboration Enterprise solutions
CrewAI	Role-based collabora- tive	 Pythonic annotations UI-driven engine 700+ integrations Logging 	 Beginner-friendly Rapid prototyping 	 Less suited for single-agent Smaller community 	 Teamwork Project management Healthcare
LlamaIndex	Data- centric, retrieval- focused	 Knowledge graph integration Vector database support Query routing 	 Data integration Knowledge- intensive tasks 	 Not focused on or- chestration Needs pairing with other frameworks 	 Data analysis Research Knowledge agents
Semantic Kernel	Plugin- based, modular	 Multi-language support Memory manage- ment Enterprise security Plugins 	 Enterprise-ready Microsoft ecosystem 	 Focus on C# Steep learning curve 	 Enterprise applications Document processing

Table I Comparison of AI agent frameworks

- Limited flexibility and scalability. Frameworks like LangGraph and AutoGen struggle with scalability and flexibility, making them less suitable for largescale or highly dynamic AI systems [31].
- 3) Lack of support for complex tasks. Existing frameworks often focus on specific tasks or domains, lacking the versatility needed to tackle complex, cross-domain problems [31]. For instance, CrewAI's limited orchestration strategies restrict its ability to handle complex workflows.
- 4) *Maintenance complexity.* The lack of a unified semantic basis for integrating diverse problemsolving methods leads to increased complexity in maintaining and updating developed agents. This complexity arises from the need to manage multiple paradigms without a common foundation, making it difficult to ensure consistency and adaptability across different components [31], [32].
- 5) *Lack of standardization and interoperability*. The diversity of agent architectures and communication protocols leads to integration and management challenges. The lack of standardization makes it difficult to unify practices and ensure seamless interoperability across platforms and vendors [31].

E. Advantages of OSTIS Platform

The OSTIS Platform addresses these limitations by providing a comprehensive framework for developing intelligent agents based on semantic networks. The OSTIS Technology [33] offers several key advantages:

- Unified semantic basis. The OSTIS Technology integrates diverse problem-solving methods (both declarative and procedural) on a common semantic basis, allowing for the creation of complex, interconnected models that can handle diverse and nuanced information [34]–[37].
- *Deep knowledge representation.* The *OSTIS Technology* utilizes semantic networks to represent knowledge, enabling rich, interconnected models that can address complex tasks more effectively than existing frameworks [12], [34].
- *Flexibility and scalability.* The modular design of *OSTIS Technology* ensures that systems can scale efficiently without compromising performance, making it suitable for large-scale AI applications [38], [39].
- Adaptability and learning. ostis-systems are designed to adapt to changing conditions and learn from interactions, enhancing their effectiveness in dynamic

environments [40].

The key factor hindering the development of systems where various problem-solving models could be freely integrated is the lack of compatibility among different problem-solving approaches. This stems from the absence of a common formal framework that would enable the implementation of models in such a way that they can be easily integrated into a single system and supplemented with new models as needed [32], [41].

Having established the advantages of the OSTIS Platform, the following section will delve into the principles of its implementation.

III. PRINCIPLES OF IMPLEMENTATION OF OSTIS-PLATFORMS

All intelligent systems developed according to the principles of the OSTIS Technology are commonly referred to as ostis-systems. Each ostis-system consists of an sc-model, including a knowledge base, problem solver, a user interface, and an ostis-platform on which the sc-model is interpreted [30], [38]. An sc-model of an ostis-system constitutes a logical-semantic model of that system described in SC-code, the language of universal information encoding. An ostis-platform represents a hardware-implemented computer or a software emulator for interpretation of sc-models of ostis-systems [42].

Implementations of *ostis-platform* may vary, but each should adhere to basic principles described in [12].

In contrast to traditional computer systems, ostis systems orient towards:

- <u>independence</u> from the implementation of a particular ostis-platform;
- storage of information in a <u>unified</u> and <u>semantically compatible</u> form (in *SC-code* [43]);
- <u>event-oriented</u> and <u>parallel processing</u> of this information.

The principles of ostis-systems are provided by a concrete implementation of the ostis-platform. Within each *ostis-platform*, there exists:

- a shared semantic memory that allows [44]:
 - storage of information constructions belonging to SC-code (sc-texts);
 - storage of information constructions not belonging to SC-code (images, text files, audio and video files, etc.);
 - storage of subscriptions to occurrences of events in memory;
 - initiation of agents after events appear in memory;
 - the use of a programming interface to work with SC-code and non-SC-code information constructions, including:
 - * operations to create, search, modify, and delete constructions in the memory;
 - * operations for subscribing to the occurrence of events in the memory;

- * operations for controlling and synchronizing processes in the memory;
- * programming interface for creating platformdependent agents;
- an interpreter of the *SCP* asynchronous-parallel programming language, which is a platform-independent programming interface that implements platformindependent operations on the shared semantic memory.

IV. About SC-machine

sc-machine [45] is the core of the *OSTIS Platform* [11], designed to emulate semantic computer behavior by storing and processing knowledge in the form of semantic networks. At its foundation, *sc-machine* functions as a graph database management system that enables efficient storage, retrieval, and manipulation of knowledge graphs within a shared memory structure called *sc-memory*.

Key features of *sc-machine* are:

- 1) Unified knowledge representation. sc-machine uses SC-code, a universal knowledge representation language, to encode both declarative (facts, data structures, documentation) and procedural (agents, algorithms, workflows) knowledge. This approach ensures semantic compatibility and interoperability across different intelligent systems.
- 2) Agent-based processing. The system leverages an agent-based architecture, where agents are autonomous components that process knowledge graphs, execute tasks, and solve problems. Agents can be implemented in various languages, including C++ and SCP Language, and interact with scmemory through well-defined APIs.
- Event-driven workflow. sc-machine includes an event manager that supports asynchronous, event-based processing. Agents are triggered by events in the knowledge base, enabling dynamic and parallel task execution.
- 4) *Extensible APIs.* The platform provides native C++ APIs, as well as network APIs via the sc-server (WebSocket/JSON), allowing integration with external applications and services.
- 5) *Tools. sc-machine* includes tools such as sc-builder, which loads *SCs-code* files into storage, and sc-server, which exposes the knowledge base over the network for remote access and manipulation

V. Event-driven model within the OSTIS Platform

The sc-machine uses event-driven model to manage processing sc-constructions. The *sc-memory* stores *SC-code* constructions, which are graph structures, then any kind of events, occurring in *sc-memory*, is related to changes in these graph constructions [46].

These are methods that generate events:

- GenerateConnector,
- EraseElement,
- SetLinkContent.

They publish events to an event queue without needing to know which consumers will receive them. These components filter and distribute events to appropriate consumers. They manage the flow of events and ensure that they reach the correct destinations. Event consumers are the components that listen for and process events. Event consumers can be modules, agents or something else.

Within the OSTIS Technology, events are considered only situations in which relationships have changed or new relationships have been generated, or link content have been changed, or some sc-element have been erased.

The *sc-machine* provides functionality for subscribing to the following elementary types of sc-events:

- ScElementaryEvent is base class for all scevents, it can be used to handle all sc-events for specified sc-element;
- ScEventAfterGenerateConnector, emits each time, when sc-connector from or to specified sc-element is generated;
- ScEventAfterGenerateOutgoingArc, emits each time, when outgoing sc-arc from specified sc-element is generated;
- ScEventAfterGenerateIncomingArc, emits each time, when incoming sc-arc to specified sc-element is generated;
- ScEventAfterGenerateEdge, emits each time, when sc-edge from or to specified sc-element is generated;
- ScEventBeforeEraseConnector, emits each time, when sc-connector from or to specified sc-element is erasing;
- ScEventBeforeEraseOutgoingArc, emits each time, when outgoing sc-arc from specified sc-element is erasing;
- ScEventBeforeEraseIncomingArc, emits each time, when incoming sc-arc to specified sc-element is erasing;
- ScEventBeforeEraseEdge, emits each time, when sc-edge from or to specified sc-element is erasing;
- ScEventBeforeEraseElement, emits, when specified sc-element is erasing;
- ScEventBeforeChangeLinkContent, emits each time, when content of specified sc-link is changing.

All these sc-events classes are inherited from ScElementaryEvent class. ScElementaryEvent class is inherited from ScEvent class that is an abstract class.

The ScElementaryEventSubscription class serves as the base class for all sc-event subscriptions.

It is utilized to capture all sc-events for a specified scelement.

Each sc-event subscription constructor, excluding the ScElementaryEventSubscription constructor, requires three parameters:

- context is an object of ScMemoryContext used to interact with sc-events.
- subscriptionElementAddr is an object of ScAddr representing the sc-element that needs to be monitored for a specific sc-event.
- delegateFunc is a delegate to a callback function that will be invoked upon each event emission. The callback function signature is void delegateFunc(TScEvent const &), where TScEvent corresponds to the respective sc-event class.

The constructor for the *ScElementaryEventSubscription* class takes four parameters:

- context is An object of ScMemoryContext used for sc-event handling.
- eventClassAddr is an object of ScAddr representing the sc-event class.
- subscriptionElementAddr is an object of ScAddr for the sc-element to be monitored.
- delegateFunc is a delegate to a callback function invoked on each event emission, with the signature void delegateFunc(ScElementaryEvent const &).

These constructors are private and cannot be called directly.

All sc-event classes are located in core keynodes:

- ScKeynodes::sc_event_after_generate _connector;
- ScKeynodes::sc_event_after_generate _outgoing_arc;
- ScKeynodes::sc_event_after_generate _incoming_arc;
- ScKeynodes::sc_event_after_generate _edge;
- ScKeynodes::sc_event_before_erase _connector;
- ScKeynodes::sc_event_before_erase _outgoing_arc;
- ScKeynodes::sc_event_before_erase __incoming_arc;
- ScKeynodes::sc_event_before_erase __edge;
- ScKeynodes::sc_event_before_erase _element;
- ScKeynodes::sc_event_before_change __link_content.

They can be used as eventClassAddr for CreateElementaryEventSubscription.

The table II describes the parameters of the callback function, named in the figures. If no parameter name is provided in the figure, it defaults to an empty value. Here, context is a pointer to an object of the ScAgentContext class.

VI. AGENT-DRIVEN MODEL WITHIN THE OSTIS Platform

The sc-machine employs an agent-driven model for knowledge processing. This model facilitates message exchange between agents through shared memory. Agents can be added or removed without affecting others, promoting decentralized and independent initiation. The *sc-machine* API in C++ provides tools for creating, managing, and integrating agents within the *sc-machine* [47].

Within the OSTIS Technology, agents are classified as either platform-independent or platform-dependent [47]. Platform-independent agents are implemented using SC-code, interpreted by the scp-machine [48]. Platform-dependent agents are implemented using the sc-machine API in C++.

Agents react to events (sc-events) in *sc-memory*. An agent is triggered when a subscribed sc-event occurs. The primary initiation condition defines the sc-event that awakens the agent. Upon awakening, the agent checks its full initiation condition. If successful, it initiates and executes an action using an agent program. After execution, the agent checks for a result [47].

Since the OSTIS Platform 0.10.0 [45], the API for agents has been significantly modified—transitioning from code generation to template-based programming. New classes and methods have been introduced for working with agents:

- Two base classes for all types of agents [47]:
 - The ScAgent class for implementing agent classes that respond to any elementary events in sc-memory.
 - The ScActionInitiatedAgent class for implementing agents that respond to events of initiated actions in sc-memory.
- The ScAgentContext class for working with ScEvent events, ScEventSubscription subscriptions, and ScWait and ScEventWaiter waiters [49].
- The ScAction class for handling actions in scmemory.
- The ScAgentBuilder class for managing dynamic agent specifications [50].
- The ScKeynodes and ScModule classes have been simplified for use [51].

ScAgent can be compared to a person who reacts to any sc-events in their environment. For instance, if someone shouts "Fire!", this person immediately responds and starts acting according to a plan to help in the situation. In terms of ScAgent, this means the agent reacts to any elementary sc-events in sc-memory. ScActionInitiatedAgent is similar to a person who waits for a specific signal to start an action. For example, if someone says "Begin the rescue operation!", this person knows exactly what to do and starts acting. In the case of ScActionInitiatedAgent, the agent reacts to events related to the initiation of specific actions in sc-memory.

The key scientific distinction between these agent architectures lies in their event-processing mechanisms and behavioral complexity. While ScAgent exhibits stimulusresponse patterns characteristic of purely reactive architectures, ScActionInitiatedAgent demonstrates targeted responsiveness with higher-level goal orientation.

VII. AGENT SPECIFICATION

A. Agent specification relations

The agent specification within the *OSTIS Technology* is a formalized approach to defining and managing agents, which are entities responsible for performing transformations in sc-memory of ostis-systems. This approach includes [52]:

- 1) Agents are described using a set of ontologies that define their concept, roles, and relationships. These ontologies also provide formal tools to synchronize the actions performed by agents in sc-memory.
- The specification ensures compatibility and synchronization of sc-agent actions within the semantic network, contributing to the seamless operation of intelligent systems developed under the OSTIS Technology.

The agent's specification includes:

- its primary initiation condition,
- action class it performs,
- initiation condition,
- result condition,
- key sc-elements used during action execution,
- and other details.

Storing agent specifications in a knowledge base provides several benefits [29], [52]:

- 1) Agent specifications allow for easy modification or extension of agent behavior without needing to rewrite code. This makes the system more flexible and adaptable to new conditions.
- By storing specifications in a knowledge base, it becomes easier to manage agent behavior, add new agents, or remove existing ones without affecting other parts of the system.
- Agent specifications help understand how and why agents make decisions, which is crucial for debugging and optimizing the system.
- Agent specifications provide a unified representation of their behavior, facilitating integration with other system components and understanding their interactions.

Class	Description
ScElementaryEventSubscription	A
	<pre>auto subscription = context-> CreateElementaryEventSubscription(eventClassAddr, subscriptionElementAddr, [](ScElementaryEvent const & event) -> void { // Handle sc-event. }); </pre>
ScEventAfterGenerateConnector (simi-	
larly ScEventAfterGenerateOutgoingArc, ScEventAfterGenerateIncomingArc and ScEventAfterGenerateEdge)	<pre>auto subscription = context-> CreateElementaryEventSubscription< ScEventAfterGenerateConnector<sctype:: constpermposarc="">>(subscriptionElementAddr, [](ScEventAfterGenerateConnector<sctype:: constpermposarc=""> const & event) -> void { // Handle sc-event. }); </sctype::></sctype::></pre>
ScEventBeforeEraseConnector (similarly	
ScEventBeforeEraseOutgoingArc, ScEventBeforeEraseIncomingArc and ScEventBeforeEraseEdge)	<pre>auto subscription = context-> CreateElementaryEventSubscription< ScEventBeforeEraseConnector<sctype:: constpermposarc="">>(subscriptionElementAddr, [](ScEventBeforeEraseConnector<sctype:: constpermposarc=""> const & event) -> void { // Handle sc-event. }); </sctype::></sctype::></pre>
SCEVENTBEIOFEEFASEElement	<pre>auto subscription = context-> CreateElementaryEventSubscription< ScEventBeforeEraseElement>(subscriptionElementAddr, [](ScEventBeforeEraseElement const & event) -> void { // Handle sc-event. }); </pre>
ScEventBeforeChangeLinkContent	<pre>auto subscription = context-> CreateElementaryEventSubscription< ScEventBeforeChangeLinkContent>(subscriptionElementAddr, [](ScEventBeforeChangeLinkContent const & event) -> void { // Handle sc-event. }); </pre>

 Table II

 Types of sc-event subscription in sc-memory

Thus, storing agent specifications in a knowledge base is a key aspect of supporting complex agent-based systems and allows for the creation of more effective and adaptive solutions.

Key to this API are the relations that define the agent's specification, connecting the agent to events, actions, conditions, key elements, and its program. The denotational semantics of these relations define their meaning in specifying agent behavior, while the operational semantics describe how the *sc-machine* uses these relations during agent execution (table III).

This specification can be represented in a *knowledge* base using SC-code [53] or programmatically using the sc-machine API in C++.

Consider an abstract sc-agent for calculating the power of a set. The following *SCs-code* (listing 1) and *SCg-code* (figure 1) illustrates its specification:

The agent specification is directly involved in its invocation process.

B. Agent call process

Below is a detailed enumeration of the steps in this process, followed by a sequence diagram (figure 2) illustrating the flow of operations.

- 1) *Event occurrence.* When a specific sc-event occurs in sc-memory, the system checks for any agents subscribed to that event type.
- 2) *Checking primary initiation condition.* The primary initiation condition defines the sc-event that will trigger the agent. This condition acts as a preliminary filter.
- 3) *Checking full initiation condition.* Upon an event, the agent checks its full initiation condition. This is a more detailed check to ensure the agent should execute.
- 4) *Action initiation*. If the full initiation condition is met, the agent initiates an action of a specified class.
- 5) Agent program execution. The agent executes its program (defined in the DoProgram method). This program performs the agent's task, processing input and generating output.
- 6) *Checking result condition.* After executing its program, the agent can check if a result condition is met, which might involve verifying the outcome of the action.

C. Ways of providing agent's specification

The sc-machine API provides two methods for implementing agents in C++:

- when the agent's specification is represented in the knowledge base;
- when the agent's specification is represented directly in C++ code.

Agent specifications can be static, dynamic, or semidynamic.

- 1) *Static agent specification* is provided externally in the agent's class (via overriding public getters). It is not stored in the knowledge base (see Static agent specification).
- 2) Dynamic agent specification is provided in the knowledge base or initially in the code but is automatically saved into the knowledge base. Use the API of ScModule and ScAgentBuilder classes (see Dynamic agent specification).
- Semi-dynamic agent specification is provided in the knowledge base or initially in the code and appended externally (via overriding public getters, see Semidynamic agent specification).

D. Static agent specification

This section discusses implementing an agent with a static specification. For dynamic agent specifications, see Dynamic agent specification.

Two main classes are used for implementing agents: ScAgent and ScActionInitiatedAgent.

ScAgent

It is a base class for agents in C++. This class provides implemented methods to retrieve elements of the agent's specification from the knowledge base. All these methods can be overridden in agent class [47].

A distinction should be made between an abstract sc-agent as a class of functionally equivalent sc-agents described in the knowledge base and ScAgent as a C++ class that implements an API to work with abstract sc-agents in the knowledge base.

This class can be used for all types of platformdependent agents. Agents of this class react for events in the knowledge base, check the full initiation condition. If the check is successful, generate, initiate and perform the action. After that, they check full result condition. The example using this class is represented in listing 2.

```
// File my_agent.hpp
  #pragma once
3
  #include <sc-memory/sc_agent.hpp>
4
  // The agent class should inherit from
       the ScAgent class and specify the
      template argument as the sc-event
       class. Here,
       ScEventAfterGenerateIncomingArc<
      ScType::ConstPermPosArc> is the type
       of event to which the given agent
       reacts.
  class MyAgent : public ScAgent<</pre>
7
    ScEventAfterGenerateIncomingArc<ScType
8
         ::ConstPermPosArc>>
  {
9
  public:
10
    // Here, the class of actions that the
11
          given agent performs should be
         specified.
     // Here 'GetActionClass' overrides '
12
         GetActionClass' in 'ScAgent' class
         . This overriding is required.
    ScAddr GetActionClass() const override
13
         ;
```

Relation identifier	Denotational semantics	Operational semantics
nrel_primary_initiation	Specifies the initial event in sc-memory that	The system checks for agents subscribed to an
_condition	triggers the agent. Indicates which event will	event type. The relation is used to determine
	cause the agent to "awaken."	if an agent is subscribed to that event.
nrel_sc_agent_action	Specifies the type or class of actions that	If the full initiation condition is met, the agent
_class	the agent is designed to perform. Defines the	initiates an action of the class specified by
	agent's role or the kind of actions it's capable	this relation. Determines what "action" will
	of executing.	be created when the agent starts to perform a
		task.
nrel_initiation_condition	Encapsulates a pair of conditions: the initiation	Upon awakening, the agent checks its full ini-
_and_result	condition (a detailed check after the primary	tiation condition. After executing its program,
	condition) and the result condition (a check	the agent checks if the result condition is met.
	after the action's execution).	These conditions allow the agent to verify its
		context and the outcome of its actions.
nrel_sc_agent_key	Defines the set of key knowledge elements	During the agent's program execution, this
_sc_elements	that the agent needs to access and manipulate	relation identifies the specific SC-elements
	during its operation. These are important	needed by the agent, allowing the agent to
	concepts or data structures the agent relies	quickly locate and use them.
	on.	
nrel_sc_agent_program	Specifies the actual code or program that the	The agent executes the program specified by
	agent executes. This is the implementation	this relation. This program processes input,
	of the agent's logic, defining how the agent	interacts with the knowledge base, and gener-
	processes input and generates output.	ates the desired output based on the agent's
		purpose.
nrel_inclusion	This relation connects an abstract sc-agent	-
	to a concrete implementation of that agent.	
	It specifies implementations of an abstract	
	agent, which can be implemented in C++	
	or SC-code. It is important for linking the	
	general specification of an agent to its specific	
	implementation details.	

Table III

DENOTATIONAL AND OPERATIONAL SEMANTICS OF RELATIONS IN AGENT SPECIFICATION

```
// Here, the program of the given
14
         agent should be implemented. This
         overriding is required.
     ScResult DoProgram(
15
16
       ScEventAfterGenerateIncomingArc<
17
         ScType::ConstPermPosArc> const &
             event.
       ScAction & action) override;
18
19
20
     // Other user-defined methods.
21
   };
```

Listing 2. Definition of an agent inheriting ScAgent class

It is possible to override DoProgram without sc-event argument (listing 3).

```
// File my_agent.hpp
2
  #pragma once
3
  #include <sc-memory/sc_agent.hpp>
4
5
  class MyAgent : public ScAgent<
    ScEventAfterGenerateIncomingArc<ScType
7
         ::ConstPermPosArc>>
8
9
  public:
    ScAddr GetActionClass() const override
10
    ScResult DoProgram(ScAction & action)
11
        override;
12
     // Other user-defined methods.
13
  };
14
```

Listing 3. Definition of an agent inheriting ScAgent class with one-argument DoProgram

Any existing event types can be specified as a template argument to the ScAgent class. For example, an agent can be created that will be triggered by an sc-event involving the removal of an sc-element (see listing 4).

```
// File my_agent.hpp
1
  #pragma once
2
3
  #include <sc-memory/sc_agent.hpp>
4
5
  class MyAgent : public ScAgent<
6
       ScEventBeforeEraseElement>
7
  public:
8
    ScAddr GetActionClass() const override
9
         ;
    ScResult DoProgram(
10
       ScEventBeforeEraseElement const &
11
           event, ScAction & action)
           override;
12
     // Other user-defined methods.
13
  };
14
```

Listing 4. Example of an agent triggered by removing sc-element

```
ScActionInitiatedAgent
```

ScActionInitiatedAgent facilitates the implementation of agents that execute actions initiated by other agents. It requires passing the action class node rather than manually checking the initiation condition.

This class is only applicable for agents triggered by generating an outgoing sc-arc from the action_initiated class node (listing 5).

```
// Abstract sc-agent
  agent_calculate_set_power
2
  <- abstract_sc_agent;
3
  => nrel_primary_initiation_condition:
4
      // Class of sc-event and listen (subscription) sc-element
5
       (sc_event_after_generate_outgoing_arc => action_initiated);
  => nrel_sc_agent_action_class:
7
      // Class of actions to be performed by agent
8
      action_calculate_set_power;
  => nrel_initiation_condition_and_result:
10
      (..agent_calculate_set_power_initiation_condition
11
          => ..agent_calculate_set_power_result_condition);
12
  <= nrel_sc_agent_key_sc_elements:
13
  // Set of key sc-elements used by this agent
14
15
  {
16
      action_initiated;
17
      action_calculate_set_power;
18
      concept_set;
      nrel_set_power
19
20
  };
21
  => nrel_inclusion:
22
      // Instance of abstract sc-agent; concrete implementation of agent in C++
       agent_calculate_set_power_implementation
23
24
       (*
           <- platform_dependent_abstract_sc_agent;;
25
           // Set of links with paths to sources of agent programs
26
27
           <= nrel_sc_agent_program:
28
           {
               [github.com/path/to/agent/sources]
29
               (* => nrel_format: format_github_source_link;; *)
30
31
           };;
       *);;
32
33
  // Full initiation condition of agent
34
  ..agent_calculate_set_power_initiation_condition
35
36
  = [*
37
      action_calculate_set_power _-> .._action;;
      action_initiated _-> .._action;;
38
       .._action _-> rrel_1:: .._set;;
39
      concept_set _-> .._set;;
40
41
  *];;
  // Agent should check by this template that initiated action is instance of
42
  // class `action_calculate_set_power' and that it has argument.
43
44
  // Full result condition of agent
45
46
  ..agent_calculate_set_power_result_condition
47
  = [*
48
       .._set _=> nrel_set_power:: _[];;
49
  *];;
  // Agent should check by this template that action result contains
50
  // sc-construction generated after performing action.
51
```

Listing 1. An example of abstract sc-agent spefication represented in SCs-code

// File my_agent.hpp 1 #pragma once 2 3 #include <sc-memory/sc_agent.hpp> 4 5 // The agent class should inherit from 6 the ScActionInitiatedAgent class. 7 class MyAgent : public ScActionInitiatedAgent 8 public: 9 10 // Here, the class of actions that the given agent performs should be specified. $\ensuremath{{\prime}}\xspace$ // This overriding is required. 11 ScAddr GetActionClass() const override 12

```
// Here, the program of the given
13
        agent should be implemented.
14
    // This overriding is required.
    ScResult DoProgram(
15
16
      ScActionInitiatedEvent const & event
          , ScAction & action) override;
    // Here 'ScActionInitiatedEvent' is
17
         type of event to which the given
         agent reacts.
18
    // Other user-defined methods.
19
20
  };
```

Listing 5. Definition of an agent inheriting ScActionInitiatedAgent class



Figure 1. An example of abstract sc-agent spefication represented in SCg-code



Figure 2. Sequence diagram of agent call

ScActionInitiatedAgent has default GetInitiationConditionTemplate that returns template that can be used to check that initiated action is action with class of specified agent.

ScActionInitiatedEvent is alias for ScEventAfterGenerateOutgoingArc with subscription sc-element action_initiated.

Required Methods

GetActionClass

This method retrieves the action class performed by the agent. If the abstract sc-agent for this agent class lacks an action class, the method throws utils::ExceptionItemNotFound. See listing 6.

```
// File my_agent.cpp
  #include "my_agent.hpp"
2
  #include "keynodes/my_keynodes.hpp"
3
  ScAddr MyAgent::GetActionClass() const
5
6
     / A valid sc-address of the action
         class must be specified, and the
         action class must be one of the
         following types: 'receptor_action
         ', 'effector_action',
         behavioral_action', or '
information_action'. Otherwise,
         the given sc-agent cannot be
         subscribed to the sc-event.
    return MyKeynodes::my_action;
8
```

Listing 6. Implementation of GetActionClass method

```
DoProgram
```

This method is executed when the agent successfully checks the initiation condition. The agent processes an input construction and generates an output construction (listing 7).

```
ScResult MyAgent::DoProgram(
      ScActionInitiatedEvent const & event
      , ScAction & action)
2
  {
    // Class 'ScAction' encapsulates
        information about sc-action. The
        provided action is action that the
         given agent performs right now.
        It belongs to 'MyKeynodes::
        my_action' class. If agent
        inherits 'ScActionInitiatedAgent'
        class then this agent performs
        action initiated externally. If
        agent inherits 'ScAgent' then this
         agent generates action, initiates
         and performs new action, not
        provided externally. Actions are
        copyable and movable. 'ScAction'
        is inherited from 'ScAddr'.
    // 'ScActionInitiatedEvent' class is
        event type on which the given
        agent is triggered. It is
        encapsulate information about sc-
        event. The provided event is event
         on which the agent is triggered
        right now. It has methods to get
        information about initiated sc-
        event: 'GetUser', 'GetArc',
        GetSubscriptionElement',
        GetArcSourceElement '.
6
    // Main logic of agent...
```

9	<pre>// The action state must be specified</pre>					
	at all ends of the agent program.					
	'FinishSuccessfully' sets the					
	action as '					
	action_finished_successfully'. The					
	'ScResult' object cannot be					
	generated via a constructor					
	because it is private.					
10	<pre>return action.FinishSuccessfully();</pre>					
11	}					

Listing 7. Implementation of DoProgram method

The ScAgent class has a field m_context, an object⁹ of the ScAgentContext class, which can be used⁰ to complete operations in sc-memory. The ScAgent class also has a field m_logger, an object of the ScLogger class, for logging code.

If sc-exceptions are not caught in DoProgram, then sc-machine will catch them, finish the action with an_2^1 error, and issue a warning about it.

Handling action arguments

Various methods are available for retrieving $action_5^4$ arguments to simplify code (listings 8 and 9).

```
1 ScResult MyAgent::DoProgram(
2 ScActionInitiatedEvent const & event,
3 ScAction & action)
3 {
4 auto [argAddr1, argAddr] = action.
GetArguments();
5 // Some logic...
7 return action.FinishSuccessfully();
9 }
```



```
ScResult MyAgent::DoProgram(
    ScActionInitiatedEvent const & event,
2
        ScAction & action)
3
    ScAddr const & argAddr1 = action.
4
        GetArgument(ScKeynodes::rrel_1);
5
    // Parameter has ScAddr type.
6
    // Some logic...
7
8
    return action.FinishSuccessfully();
9
10
```

```
Listing 9. Retrieving action arguments via GetArgument method 3
```

Retrieving action arguments

ScResult MyAgent::DoProgram(ScActionInitiatedEvent const & event, 2 ScAction & action) 3 { ScAddr const & argAddr1 = action.GetArgument 4 (1); // size_t // This would be the same if ScKeynodes:: 5 rrel_1 were passed instead of 1. 6 // Some logic... 8 return action.FinishSuccessfully(); 9 10



```
ScResult MyAgent::DoProgram(
ScActionInitiatedEvent const & event,
ScAction & action)
{
    ScAddr const & argAddr1
    = action.GetArgument(1, MyKeynodes::
        default_text_link);
    // If the action does not have the first
        argument, MyKeynodes::default_text_link
        will be returned.
    // Some logic...
```

return action.FinishSuccessfully();

Listing 11. Retrieving action argument with a default value

Using ScAction as ScAddr

1

3

4

5

6

7

8

9

10

2

4

6

8

1

2

5

7

4

```
ScResult MyAgent::DoProgram(
   ScActionInitiatedEvent const & event,
        ScAction & action)
{
   // The ScAction object can be used as ScAddr.
   ScIterator3Ptr const it3 = m_context.
        CreateIterator3(action, ..., ...);
   // Some logic...
```

return action.FinishSuccessfully();

Listing 12. Using ScAction as ScAddr

Handling action result

```
ScResult MyAgent::DoProgram(
   ScActionInitiatedEvent const & event,
        ScAction & action)
{
   // Some logic...
   action.FormResult(foundAddr1, generatedAddr1,
        ...);
   // Or the 'UpdateResult' method can be used
        for this.
   return action.FinishSuccessfully();
}
```

Listing 13. Forming an action result

```
ScResult MyAgent::DoProgram(
   ScActionInitiatedEvent const & event,
        ScAction & action)
{
   // Some logic...
   action.SetResult(structureAddr);
   return action.FinishSuccessfully();
}
```

Listing 14. Setting an action result

Handling action finish state

```
ScResult MyAgent::DoProgram(
   ScActionInitiatedEvent const & event,
        ScAction & action)
{
   // Some logic...
   if (/* case 1 */)
       return action.FinishSuccessfully();
```

```
else if (/* case 2 */)
8
9
       return action.FinishUnsuccessfully();
10
     else
       return action.FinishWithError();
11
12
   }
```

Listing 15. Finishing an action with different statuses

```
ScResult MyAgent::DoProgram(
     ScActionInitiatedEvent const & event.
2
         ScAction & action)
   {
3
4
     action.IsInitiated(); // result: true
     action.IsFinished(); // result: false
5
     action.IsFinishedSuccessfully(); // result:
6
         false
7
     // Some logic...
8
9
     return action.FinishSuccessfully();
10
```

Listing 16. Checking action status

Optional methods **GetAbstractAgent**

1

11

2

3

4

This method searches for an abstract agent for an agent of the specified class. If the agent implementation for this agent class is not included in any abstract sc-agent, GetAbstractAgent will throw a utils::ExceptionItemNotFound.

```
ScAddr MyAgent::GetAbstractAgent() const
{
  // A valid sc-address of the abstract agent
      must be specified here. Otherwise, the
      given sc-agent cannot be subscribed to an
       sc-event.
 return MyKeynodes::my_abstract_agent;
```

Listing 17. Overriding the GetAbstractAgent method

Remember, if only this method and the required methods are overridden, other getters will return elements of the specification for the specified abstract agent. All non-overridden getters call GetAbstractAgent.

GetEventClass

This method searches for the sc-event class to which the agent class is subscribed. It will throw a utils::ExceptionItemNotFound if the abstract sc-agent for this agent class does not have a primary initiation condition.

```
ScAddr MyAgent::GetEventClass() const
2
  {
     // It is necessary to specify a valid sc-
3
         address of the event class. Otherwise,
         the given sc-agent cannot be subscribed
         to an sc-event.
    return ScKeynodes::
4
         sc_event_after_generate_outgoing_arc;
   }
5
```

Listing 18. Overriding the GetEventClass method

GetEventSubscriptionElement

This method searches for the sc-event subscription sc-element that initiates the sc-event. It will throw a utils::ExceptionItemNotFound if the abstract sc-agent for this agent class does not have a primary initiation condition.

```
ScAddr MyAgent::GetEventSubscriptionElement()
    const
```

```
// It is necessary to specify a valid sc-
    address of the sc-event subscription sc-
    element. Otherwise, the given sc-agent
    cannot be subscribed to an sc-event.
return ScKeynodes::action_initiated;
```

Listing 19. Overriding the GetEventSubscriptionElement method

Do override GetEventClass and not GetEventSubscriptionElement for agents with statically specified sc-event types. Such code cannot be compiled. Override them if agent class inherits from ScAgent<ScElementaryEvent> (ScElementaryEventAgent).

ScModule

2

}

This class is a base class for subscribing/unsubscribing agents to/from sc-events. It's like a complex component that contains connected agents.

To subscribe agents to sc-events, implement module class (listing 20) and call Agent methods to subscribe agents (listing 21).

```
// File my_module.hpp
  #pragma once
2
  #include <sc-memory/sc_module.hpp>
5
  class MyModule : public ScModule
6
7
  };
```

Listing 20. Definition of module class inheriting ScModule class

```
// File my_module.cpp:
  #include "my-module/my_module.hpp"
2
  #include "my-module/keynodes/my_keynodes
      .hpp"
  #include "my-module/agent/my_agent.hpp"
5
  SC_MODULE_REGISTER(MyModule)
7
    // It initializes static object of '
        MyModule' class that can be used
        to call methods for subscribing
        agents to sc-events.
    ->Agent<MyAgent>();
9
    // This method subscribes the agent
10
        and returns an object of MvModule.
         MyAgent is inherited from
        ScActionInitiatedAgent. It points
        to the module to which the agent
        class MyAgent should be subscribed
         to the sc-event of adding an
        outgoing sc-arc from the sc-
        element action_initiated. This is
        a default parameter in this method
         for subscribing agent classes
         inherited from
        ScActionInitiatedAgent.
```

Listing 21. Subscribing agent via module class

The Agent method should be called without arguments for agent classes that inherit from ScActionInitiatedAgent. However, for agent classes that inherit from ScAgent, the Agent method should be called while providing an sc-event subscription sc-element.

A module subscribes agents when the sc-memory initializes and it unsubscribes them when the sc-memory shutdowns.

Additionally, a module can be used to subscribe a set of agents (see listing 22).

```
// File my_module.cpp:
  #include "my-module/my_module.hpp"
3
4
  #include "my-module/agent/my_agent1.hpp"
  #include "my-module/agent/my_agent2.hpp"
5
  #include "my-module/agent/my_agent3.hpp"
6
  #include "my-module/agent/my_agent4.hpp"
  #include "my-module/agent/my_agent5.hpp"
8
0
  SC_MODULE_REGISTER(MyModule)
10
     ->Agent<MyAgent1>()
11
12
    ->Agent<MyAgent2>()
13
    ->Agent<MyAgent3>()
    ->Agent<MyAgent4>()
14
     ->Agent<MyAgent5>()
15
    // ...
16
17
    ;
```

Listing 22. Subscribing several agents via module class

If initialization of non-agent objects in a module is required, the Initialize and Shutdown methods can be overridden in the module class (see listings 23 and 24).

```
1 // File my_module.hpp:
2 class MyModule : public ScModule
3 {
4 + void Initialize(ScMemoryContext *
context) override;
5 + void Shutdown(ScMemoryContext *
context) override;
6 };
```

Listing 23. Definition of module class with overriding Initialize and Shutdown methods

```
// File my_module.cpp:
  #include "my-module/my_module.hpp"
2
3
  #include "my-module/agent/my_agent.hpp"
4
5
  SC_MODULE_REGISTER (MyModule)
6
     ->Agent<MyAgent>();
8
   + // This method will be called once.
9
   + void MyModule::Initialize(
10
       ScMemoryContext * context)
11
   +
12
       // Implement initialize of non-agent
        objects here.
13
   + // This method will be called once.
14
  + void MyModule::Shutdown(
15
       ScMemoryContext * context)
  + {
16
       // Implement shutdown of non-agent
17
       objects here.
```

18 + }

Listing 24. Implementation of module class with overriding Initialize and Shutdown methods

E. Dynamic agent specification

Modules allow to subscribe agents with dynamic specification provided in knowledge base or in code. Dynamic specification can be changed by other agents.

The ScModule class includes the AgentBuilder method. This method can be called with an agent class, providing the keynode of the agent implementation specified in the knowledge base, or by calling methods after this to set the specification elements for the given agent [50].

ScAgentBuilder

The AgentBuilder method creates object of ScAgentBuilder class that is needed to initialize agent specification from code or from knowledge base.

Loading initial agent specification in C++.

An initial specification for an agent class can be defined in code using the ScAgentBuilder (see listing 25).

1	// File my_module.cpp:
2	<pre>#include "my-module/my_module.hpp"</pre>
3	
4	#include "my-module/agent/my_agent.hpp"
5	
6	SC_MODULE_REGISTER(MYMOdule)
7	-/Agencoulder <myagenc ()<="" th=""></myagenc>
0	abstract sc agent '
9	->SetAbstractAgent (MvKeynodes::
ĺ	my abstract agent)
10	->SetPrimaryInitiationCondition({
11	// Event class must belong to '
	sc_event '.
12	ScKeynodes::
	<pre>sc_event_after_generate_</pre>
	outgoing_arc,
13	ScKeynodes::action_initiated
14	})
15	// The action class should be one of
	the following types:
16	// 'receptor_action', '
	behavioral action or
17	// 'information action'
18	->SetActionClass(MvKeynodes::
	my action class)
19	->SetInitiationConditionAndResult({
20	MyKeynodes::my_agent_initiation_
	condition_template,
21	MyKeynodes::my_agent_result_
	condition_template
22	})
23	->FinishBuild();

Listing 25. Definition of initial agent specification

So, the initial specification for an agent can be loaded into the knowledge base from the code. It can be modified or left unchanged, depending on the specific problem.

If a specification for an agent already exists in the knowledge base, no new connections will be generated, i.e., there will be no duplicates. All provided arguments must be valid; otherwise, the module will not be subscribed, as errors will occur. If the specification for an agent is not already in the knowledge base, all the methods listed after the AgentBuilder call must be invoked.

At the end of the list following the AgentBuilder call, the FinishBuild method must be called; otherwise, the code cannot be compiled.

Loading agent specification from knowledge base.

If a specification for an agent exists in the knowledge base, written in *SCs-code* or *SCg-code*, then the implementation of the agent can be specified.

Write the scs-specification (see listings 26) (or scg-specification (figure 3)) for the agent and use it to subscribe the agent within a module (listing 27).

```
1 // File my_module.cpp:
2 #include "my-module/my_module.hpp"
3 
4 #include "my-module/agent/my_agent.hpp"
5 
6 SC_MODULE_REGISTER(MyModule)
7 ->AgentBuilder<MyAgent>(ScKeynodes::
my_agent_implementation)
8 ->FinishBuild();
```

Listing 27. Subscribing agent with dynamic specification within ScModule class

If the specification of an agent is not complete in the knowledge base, the module will not be subscribed, as errors will occur. Other correctly specified agents will be subscribed without errors.

F. Semi-dynamic agent specification

Semi-dynamic agent specification is a hybrid approach that combines the advantages of both static and dynamic agent specifications within the *OSTIS Platform*. In this approach, part of the agent's specification is stored in the knowledge base and can be modified at runtime, while another part is defined directly in the agent's source code by overriding public getter methods.

Key features of semi-dynamic specification are:

- 1) *Partial storage in the knowledge base*. Some specification elements (such as initiation conditions or key sc-elements) are defined in the knowledge base, allowing them to be analyzed and modified by other agents during system operation.
- 2) *Partial implementation in code.* Other specification elements (such as the action class or the agent's program) are implemented directly in the agent's code, providing fast access and execution.

When to use semi-dynamic specification:

- 1) When certain aspects of agent behavior require high performance, while others need to be adaptable at runtime.
- In systems where some specification elements are frequently accessed and should be retrieved quickly, while others may change.
- 3) For incremental migration from static to dynamic specification.

Implementation example

```
// File my_agent.hpp
   #pragma once
2
   #include <sc-memory/sc_agent.hpp>
5
  class MyAgent : public ScAgent<</pre>
6
       ScEventAfterGenerateIncomingArc<
       ScType::ConstPermPosArc>>
7
   ł
  public:
8
     // Static part: action class is
9
         defined in code
     ScAddr GetActionClass() const override
10
11
       return MyKeynodes::my_action;
12
13
14
15
     // Static part: agent program
         implemented in code
16
     ScResult DoProgram(ScAction & action)
         override
17
       // Agent logic implementation
18
19
       return action.FinishSuccessfully();
20
21
     // Dynamic part: initiation condition
22
         retrieved from knowledge base
23
     ScAddr GetInitiationCondition() const
         override
24
     {
       ScAddr abstractAgent =
25
           GetAbstractAgent():
       if (!abstractAgent.IsValid())
26
         return ScAddr::Empty;
27
       ScAddr result =
28
           FindInitiationConditionInKB(
           abstractAgent);
29
       return result.IsValid() ? result :
           ScAgent::GetInitiationCondition
            ();
30
31
     // Other methods can be similarly
32
         implemented
33
  };
```

Listing 28. Example of a semi-dynamic agent specification

Subscribing agent with semi-dynamic specification

1	// File my_module.cpp
2	<pre>#include "my-module/my_module.hpp"</pre>
3	<pre>#include "my-module/agent/my_agent.hpp"</pre>
4	
5	SC_MODULE_REGISTER(MyModule)
6	->AgentBuilder <myagent>(MyKeynodes::</myagent>
	my_agent_implementation)
7	<pre>// Only dynamic parts of the</pre>
	specification are set here
8	->SetInitiationConditionAndResult({
9	MyKeynodes::my_agent_initiation
	_condition_template,
10	MyKeynodes::my_agent_result
	_condition_template
11	})
12	->FinishBuild();

Listing 29. Agent subscribing with semi-dynamic specification

```
// Specification of agent in knowledge base.
  my_abstract_agent
2
   <- abstract_sc_agent;
3
4
  => nrel_primary_initiation_condition:
       (sc_event_after_generate_outgoing_arc => action_initiated);
5
  => nrel_sc_agent_action_class:
      my_action_class;
7
   => nrel_initiation_condition_and_result:
       (my_agent_initiation_condition_template
           => my_agent_result_condition_template);
10
   <= nrel_sc_agent_key_sc_elements:
11
   {
12
13
       action_initiated;
       my_action_class;
14
15
       mv class
   };
16
17
   => nrel_inclusion:
18
       my_agent_implementation
19
       (*
           <- platform_dependent_abstract_sc_agent;;
20
21
           <= nrel_sc_agent_program:
22
           {
23
                [github.com/path/to/agent/sources]
24
                (* => nrel_format: format_github_source_link;; *)
25
           };;
26
       *);;
27
  my_agent_initiation_condition_template
28
29
   = [*
       my_action_class _-> .._action;;
30
31
       action_initiated _-> .._action;;
       .._action _-> rrel_1:: .._parameter;;
32
33
   *]::
34
  my_agent_result_condition_template
35
36
  = [*
37
      my_class _-> .._my_node;;
38
   *];;
```

Listing 26. An example of dynamic agent specification represented in SCs-code

G. Comparative analysis of types of agent specifications

Agent specification in the *OSTIS Platform* can be implemented in three principal ways: static, dynamic, and semidynamic. Each approach offers distinct advantages and trade-offs, making them suitable for different development scenarios.

Static agent specification is defined entirely in the agent's source code by overriding public getter methods of the ScAgent or ScActionInitiatedAgent classes. This method ensures maximum performance and predictability, as the specification is hardcoded and not affected by changes in the knowledge base. It is ideal for agents whose behavior is fixed and does not require runtime adaptation. However, modifying the agent's behavior requires changes to the source code and recompilation, which can limit flexibility in dynamic environments.

Dynamic agent specification is stored in the knowledge base, either defined directly in SCs/SCg-code or loaded via the ScAgentBuilder API. This approach allows agent specifications to be modified at runtime by other agents or system components, supporting greater flexibility and adaptability. It is particularly useful in systems where agent behavior must evolve in response to changing data or requirements. The trade-off is a potential performance overhead due to the need to query the knowledge base for specification details, and the increased complexity of ensuring that all specification elements are correctly defined and synchronized.

Semi-dynamic agent specification combines elements of both static and dynamic approaches. Some parts of the specification – typically those that are performance-critical or rarely changed – are defined in code, while others are stored in the knowledge base and can be modified at runtime. This hybrid method offers a balance between performance and flexibility, enabling developers to optimize access to critical specification elements while still allowing for dynamic adaptation where needed. However, it introduces additional complexity, as developers must carefully manage the division between static and dynamic components to avoid inconsistencies.

The implementation of agent specifications in the *OSTIS Platform* establishes a clear mapping between semantic relations in the knowledge base and program interfaces. Table IV demonstrates this correspondence.



Figure 3. An example of dynamic agent specification represented in SCg-code

Table V summarizes the main characteristics of each specification type.

VIII. CONCLUSION

The OSTIS Platform marks a major step forward in intelligent agent frameworks by introducing an architecture grounded in semantic networks, effectively overcoming key limitations of current approaches.

By establishing a unified semantic foundation, *OSTIS Platform* enables integration of diverse problem-solving methods, supporting the development of advanced AI systems that can tackle complex, cross-domain challenges beyond the reach of conventional frameworks.

The sc-machine, as the central component of the OSTIS Technology, delivers critical features including unified knowledge representation, agent-based processing, event-driven workflow, and extensible APIs. This infrastructure supports the development of intelligent agents that can operate autonomously within a shared semantic environment, reacting to events and executing tasks based on their specifications.

The event-driven model in *OSTIS Platform* allows agents to process semantic constructions by responding to specific events in sc-memory, supporting decentralized and independent knowledge processing. Agents can be added or removed without disrupting others, ensuring system robustness and flexibility.

The agent-driven model enhances adaptability and autonomy by enabling agents to exchange messages via shared memory, fostering collaborative decision-making and dynamic response to new situations.

The flexible specification system for agents – offering static, dynamic, and semi-dynamic approaches – provides developers with multiple options for implementing agents according to their specific requirements. This flexibility, combined with the platform's robust API for creating, managing, and integrating agents, makes *OSTIS Platform* a versatile framework suitable for diverse AI applications.

As the field of artificial intelligence continues to evolve, the *OSTIS Platform* stands as a promising foundation for developing next-generation intelligent systems.

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Relation Identifier	ScAgent (ScActionInitiatedAgent) Method	ScAgentBuilder Method
nrel_primary_initiation	ScAddr GetEventClass()	ScAgentBuilder *
_condition	const and Sch	Addr SetPrimaryInitiationCondition(
	GetEventSubscriptionElement() co	nst std::tuple <scaddr, scaddr=""> const</scaddr,>
		<pre>& primaryInitiationCondition)</pre>
		noexcept
nrel_sc_agent_action	ScAddr GetActionClass() const	ScAgentBuilder *
_class		SetActionClass(ScAddr const &
		actionClassAddr) noexcept
nrel_initiation_condition	ScAddr GetInitiationCondition()	ScAgentBuilder *
_and_result	const and ScAddr GetResultCondition	on() SetInitiationConditionAndResult(
	const	std::tuple <scaddr, scaddr=""> const</scaddr,>
		<pre>& initiationConditionAndResult)</pre>
		noexcept
nrel_sc_agent_key_sc	-	-
_elements		
nrel_sc_agent_program	ScResult DoProgram(ScAction &	-
	action)	
nrel_inclusion	-	-

Table IV AGENT SPECIFICATION RELATIONS AND CORRESPONDING API METHODS

Specification at-	Static agent specification	Dynamic agent specification	Semi-dynamic agent specification
tribute			
Definition loca- tion	In the agent's class (by overriding public getters of the ScAgent or ScActionInitiatedAgent classes).	In the knowledge base or initially in code (using the API of ScModule class and the API of the ScAgentBuilder class) but automatically saved into the knowledge base.	In the knowledge base or initially in code (using the API of ScModule class and the API of the ScAgentBuilder class) and supplemented externally (via overriding public getters of ScAgent or ScActionInitiatedAgent classes).
Persistence	Not stored in the knowledge base.	Stored in the knowledge base.	Partially stored in the knowledge base, partially defined in the code.
Mutability	Changes in the knowledge base do not affect the specification, as it is defined in the code.	Other agents can modify the specifica- tion.	Some parts of the specification can be changed dynamically, others are defined in the code.
Use Case	 Implementing an agent in C++ for the first time. Minimizing the number of searches in the knowledge base. 	Analyzing and modifying the specifica- tion by other agents.	Changing some parts of this specifi- cation, while allowing other parts of specification to have fast access.
Implementation method	Overridingpublicget-tersoftheScAgentorScActionInitiatedAgentclasses.classes.state	Using the API of the ScModule class and the API of the ScAgentBuilder class.	Combination of defining the specifica- tion in the knowledge base and overrid- ing public getters of agent classes.
Example scenario	An agent that always performs the same task with predefined parameters.	An agent that changes its behavior de- pending on the data in the knowledge base.	An agent that uses part of the speci- fication from the knowledge base and defines part in the code for optimization.
Key characteris- tics	Requires overriding the GetActionClass and DoProgram methods.	Provides the ability to analyze and mod- ify the agent's specification by other agents.	Combines the advantages of static and dynamic specifications.
Event handling	The agent reacts to events in the knowl- edge base, checks the initiation condi- tion, generates and executes an action.	The agent reacts to events in the knowl- edge base based on its dynamically changing specification.	The agent reacts to events based on a combination of static and dynamic specifications.
Applicability	When the agent specification should not change dynamically and is defined in the code.	When the agent specification should be able to change dynamically during system operation.	When it is needed to change some parts of the specification, but quick access to other parts defined in the code is required.

Table VAGENT SPECIFICATION TYPES

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ПЛАТФОРМА OSTIS – ФРЕЙМВОРК ДЛЯ РАЗРАБОТКИ ИНТЕЛЛЕКТУАЛЬНЫХ АГЕНТОВ НА БАЗЕ СЕМАНТИЧЕСКИХ СЕТЕЙ

Зотов Н.В.

Данная статья рассматривает фреймворки для создания ИИ-агентов и представляет OSTIS Platform как решение существующих ограничений современных подходов. В работе анализируются принципы построения ИИ-агентов, проводится оценка таких фреймворков, как LangGraph, CrewAI, AutoGen, Semantic Kernel и LlamaIndex, а также подробно описываются преимущества технологии OSTIS. К этим преимуществам относятся единая семантическая основа и глубокое представление знаний. В статье также рассматривается реализация платформы на базе Технологии OSTIS и моделей, управляемых агентами, акцентируя внимание на их потенциал в развитии интеллектуальных систем.

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Models and Tools for Designing Adaptive User Interfaces of Intelligent Systems Ecosystem

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Abstract—This article discusses the principles of automation of user actions with the help of personal assistants, models of adaptive user interfaces of Ecosystem of intelligent systems, as well as means of individual editing of models of such interfaces.

Keywords—user interface of the OSTIS Ecosystem, OS-TIS Ecosystem, personal assistant, Web LLM Agent, knowledge base editing

I. Introduction

Modern technology has given rise to countless services and systems designed to address diverse needs. However, this abundance has created a major challenge: users must learn the intricacies of each system's unique *user interface*, making the interaction cumbersome and time-consuming. Many *user interfaces* are unintuitive, requiring specialized skills just to perform basic tasks, forcing users to constantly adapt rather than focus on their goals.

This is where a *personal assistant* becomes essential. By serving as a unified intermediary, it eliminates the need to master every *user interface* individually. Instead of struggling with inconsistent designs, users can rely on the *personal assistant* to seamlessly navigate systems, translating their intent into the right actions across platforms.

The solution, therefore, lies in prioritizing *personal* assistants that simplify and standardize interactions with the *Ecosystem of intelligent systems*. By acting as a single point of control, they improve usability, reduce learning curves, and dramatically improve efficiency. The future of seamless technology is not just a better user experience: it is an assistant that bridges the gap between users and the *Ecosystem of intelligent systems*.

The purpose of this article is to analyze existing solutions to this problem and an approach to eliminating this problem using the *OSTIS Technology*.

II. State of the art

Currently, in order to solve the problem of usability of various information services and unification of *user interfaces*, the following is used:

• *personal assistants* that simplify the processes of user interaction with various systems;

• standards of protocols and *application interfaces* that simplify the integration and interaction of various systems with each other.

Digital *personal assistants* are programs based on artificial intelligence technologies that help users perform everyday tasks, such as scheduling, managing contacts, searching for information, reminding about important events, etc. [1]–[4].

Nowadays many companies try to develop their own *personal assistants*, and the first company that managed to integrate such an agent into their operating systems was Apple when they introduced Siri [5] in 2010. Soon after, many other companies implemented assistance in the same area in order to help people perform ordinary everyday actions (Microsoft Cortana [6], Google Now [7], LG Voice Mate [8], [9]).

The *user interface* of the *personal assistant* must represent the system as a single unified set of back-end task assistants, enabling the user to conduct a dialog in which it is easy to switch between these domains. This involves getting user input commands either as text or speech and processing the natural language input to understand it [10].

While a *personal assistant* streamlines user interactions, it does not inherently resolve the deeper issue of cross-system compatibility. Standardized protocols and *Application Programming Interfaces* can fight this difficulty but a complete solution requires building an *Ecosystem* of semantically interoperable systems where services seamlessly understand and integrate with one another.

The study [9], introduces LISSA, a *personal assistant* designed to support students in a Virtual Education Space (VES). This VES acts like a smart *Ecosystem*, similar to an Internet of Things (IoT) network, where independent intelligent tools work together while adapting to user needs. By integrating LISSA into this system, students get effective learning help, and the assistant can easily grow to handle more tasks in the future.

Several years of active development of *large language models*(*LLMs*) have provided developers with new opportunities to approach problem solving. It is achieved by the

ability of *LLM* to suggest a solution for a task that is not very precisely described.

Some of the most popular branches of works in the *LLM* environment and other neural network methods and tools are recognition of the elements of the user interface, automation of user interface actions and generation of user interfaces by a text description.

For frontend software development, commercial and open-source tools such as Vercel's V0, Imagica and OpenV0 have attracted considerable interest using the capabilities of *LLM* [11]. These applications adeptly transform user-provided textual or visual prompts into concrete, well-structured high-fidelity *user interfaces*, along with their associated frontend code, providing substantial support to designers and developers.

It has become possible for systems to have a set of primitive actions, and the system itself will decide in what order to perform these primitive actions. Examples of such primitive actions might be:

- to open a web page;
- to click a button;
- to fill in a text input field;
- to read some string from a page;
- to recognize an image.

Thus the performance of some action in the system can be broken down into a sequence of similarly primitive actions, and the task of deciding in what order and with what arguments these actions will be performed can be delegated to the *LLM*.

Entities that perform primitive user interface actions are called *Web LLM Agents* or *UI LLM Agents* [12].

A Web LLM agent uses the set of states of the agent in which it can be and some *context* in which the agent operates. The *context* includes the set of allowed actions, the history of actions performed, results of performed actions, actions that were not performed due to their lack of helpfulness, and the agent's environment, that is, a description of what is happening on the screen. At each step, the agent uses the instructions, the environment (screen), the set of allowed actions, and the history of executed actions to select the most appropriate action for the situation, which may or may not change the agent's state. Action selection and action execution occur until the agent reaches the final state or until the maximum number of actions given to the agent to complete the task has been performed.

All allowed states are manually selected and described in detail by the developer. This is done to make it easier for agents to use the information about the state in which they are currently in. Observations of the environment that will come from the outside are thought out, and an example of an observation coming to the agent is provided. In the example of such an observation, the parameters to be changed are replaced by placeholders, so that the real values with which the agent interacts can be substituted for them. The final goal and a detailed description of how to act in each state are also given.

In order to prevent the *LLM* from suggesting actions that are currently unavailable, a set of allowed actions is defined for each state. This may resemble a finite-state machine in which transitions do not necessarily change the state of the machine. An alternative or complement to this approach is to add the actions of all buttons on the page to the set of allowed actions. This would increase the agent's capabilities, but there is a risk that it would be more difficult for the agent to choose which action to take at the moment.

Examples of agent's states for the task of buying a product that meets user's requirements is shown on Figure 1.

It is possible to use several *LLMs*, so that one model reasoned and described what is on the page, what should be achieved and what are the options in current state, and the other *LLM* made a decision on what action to perform based on this reasoning.

[13] describes an approach on how to adapt the LLM UI Agent to various *user interfaces* with recognition of elements of the webpage in order to adapt to unseen websites and domains. The authors review a method for learning with fine-tuning and human demonstration for solving this task. Similar solution parses regions of *user interfaces* screenshots into structured elements, which can be used as an input for the *LLM* for suggesting next action [14].

III. Proposed approach

The analysis shows that users should not need to search through countless services to find what they need. Instead, a network of <u>compatible</u>, interconnected services should work invisibly in the background. For this to succeed, all resources and tools must seamlessly understand each other (semantic compatibility). The user's *personal assistant* and not the user should handle selecting the right service for each task.

Thus, when implementing digital *personal assistants*, it is necessary to ensure their scalability and adaptability to user needs. This means that the system should be able to automatically adapt to changes in user behavior, taking into account their preferences, work characteristics, and other factors.

The OSTIS Technology allows creating <u>semantically compatible systems</u> (ostis-systems) that are able to process user requests and problems, taking into account their context and meaning. This is achieved through the use of semantic networks that allow describing knowledge and the connections between it. Also, the OSTIS Technology provides scalability and flexibility of the system, which allows it to adapt to changes in user behavior and needs [15].

The OSTIS Technology provides a universal language for the semantic representation (encoding) of information



Figure 1. Web LLM Agent's states for the task of buying a product

in the memory of *intelligent computer systems*, called the *SC-code*. Texts of the *SC-code* (sc-texts) are unified semantic networks with a basic set-theoretic interpretation, which allows solving the problem of compatibility of various knowledge types. The elements of such semantic networks are called *sc-elements* (*sc-nodes* and *sc-connectors*, which, in turn, depending on orientation, can be *sc-arcs* or *sc-edges*). The *Alphabet of the SC-code* consists of five main elements, on the basis of which *SCcode* constructions of any complexity are built, including more specific types of *sc-elements* (for example, new concepts). The memory that stores *SC-code* constructions is called semantic memory, or *sc-memory* [16].

The architecture of each *ostis-system* includes a platform for interpreting semantic models of *ostis-systems*, as well as a *semantic model of the ostis-system* described using the *SC-code* (*sc-model of the ostis-system*). In turn, the *sc-model of the ostis-system* includes the *sc-model of the knowledge base*, *sc-model of the interface*, and *scmodel of the problem solver*. The principles of the design and structure of *knowledge bases* and *problem solvers* are discussed in more detail in [17] and [18], respectively. The principles of the *sc-model of the user interface* were described in the articles [19], [20], and [21], on which this article is based.

Within the OSTIS Technology, the concept of the OSTIS Ecosystem is introduced [22].

The *OSTIS Ecosystem* is a socio-technical network, which is a collective of interacting:

- ostis-systems themselves;
- users of the specified *ostis-systems* (both end-users and developers);
- some computer systems that are not ostis-systems (they can be used as additional information resources or services).

The objectives of the OSTIS Ecosystem are:

• rapid implementation of all agreed changes in *ostis*-systems;

- permanent maintenance of a high-level of mutual understanding between all the systems that are part of the *OSTIS Ecosystem*, as well as all their users;
- corporate solution of various complex problems requiring the coordination of several (most often a priori unknown) *ostis-systems* and possibly some users.

Within the OSTIS Ecosystem, the concept of a personal ostis-assistant is specified. A personal ostis-assistant is the ostis-system, which is a personal assistant of the user within the OSTIS Ecosystem. Such a system provides opportunities:

- to analyze user activity and form recommendations for its optimization;
- to adapt to the mood of the user, their personal qualities, the general environment, the problems that the user most often solves;
- to permanently train the assistant in the process of solving new problems, while learnability is potentially unlimited;
- to conduct a dialog with the user in natural language, including in speech form;
- to conduct a dialog with various systems within the Ecosystem;
- to provide answers to questions of various classes, while asking counter-questions in case the system does not understand something;
- to independently receive information from the entire environment, and not just from the user (in text or speech form).

At the same time, the system can both analyze available information sources (for example, on the Internet) and analyze the physical world surrounding it, for example, surrounding objects or the appearance of the user.

Advantages of the *personal ostis-assistant*:

• the user does not need to store different information in different forms in different places: all information is stored in a single *knowledge base* compactly and without duplication;

- thanks to unlimited learnability, assistants can potentially automate almost any activity, not just the most routine one;
- thanks to the *knowledge base*, its structuring, and the means of searching for information in the *knowledge base*, the user can get more accurate information more quickly.

Since the user interaction with the OSTIS Ecosystem occurs only through a personal ostis-assistant, the user interface of the OSTIS Ecosystem for the user is the user interface of their personal ostis-assistant. Such an interface should be adaptive, intelligent, and multimodal. The structure of such an interface was proposed in the work [21].

The model of the *adaptive user interface* occupies a significant place in such an interface. The model of the *adaptive user interface* consists of the model of the *knowledge base* of the *adaptive user interface* and the model of the *problem solver* of the *adaptive user interface*. In its turn the model of the *knowledge base* of the *adaptive user interface* is a union of the model of user interfaces and components of user interfaces, the model of the user context, the model of the external information constructions and external languages, the model of incoming and outgoing messages of intelligent systems and the model that contains methodology of user interface design. The model of user actions, the model of the environment and the model of devices.

The ostis system design is based on a component-based approach. That means that any system can use prepared library of components that will reduce the time that the creation of a system requires and enlarge the functionality of the system and the efficiency of the design. That components are created with the use of the OSTIS Technology which makes them easy to integrate in any ostis system.

All components are stored as fragments of the *knowl-edge base* of the *ostis system* which makes them ready to be used by decision making processes described earlier.

A unique feature of the OSTIS Technology is ensuring the <u>compatibility</u> for the components of ostis-system knowledge bases, ostis-system problem solvers, and ostissystem interfaces due to a <u>single unified formal basis</u>. Thus, a user interface component for its work must usually include not only a description of its visual characteristics in the knowledge base but also components of the problem solver (for example, sc-agents), as well as the necessary fragments of some subject domain.

As it was shown in previous works [23], it is already possible to integrate *LLM* interactions into the *OSTIS Technology*, and due to that it is possible to create context for UI LLM Agents, manage static and dynamic prompts creation and collect purposes and abilities of *user interfaces* and *problem solvers* of the systems that

create Ecosystem.

The advantages of the *OSTIS Technology*, and in particular the transparency it provides, will make it much more efficient for web agents to operate while handling user needs. Action planning makes better results in cases when each component of each system in thoroughly specified.

Another helpful trait of *ostis systems* is that each *user interface* element is described in the *knowledge base*, making it possible for agents to know how to interact with it and to know what it can be used for. That helps with adding an ability to explain the reasoning of choosing specific button to press or any other interface action.

For navigating between different *ostis systems* in the *Ecosystem* in order to find the one that can solve the required task, the summary of the components in each system can be used by agents. That summary, combined with other context parts, such as current state, previous actions and results of those actions and description of states, may be successfully retrieved, compiled as a part of a dynamic prompt and used as input for *LLM*.

One of the key aspects of having large *knowledge bases* is having proper and convenient tools for visualising and editing parts of that knowledge graph. Current *Ecosystem* of *ostis systems* supports two languages for knowledge visualisation: SCn and SCg. The first one has syntax and semantic rules based on indents and special symbols. In comparison based on that principle SCg does not use any additional rules for knowledge visualisation. It has just nodes and connectors between nodes and connectors that are directly represent sc-nodes and sc-connectors in *knowledge base* and it should take a couple of minutes to teach someone how to write and read SCg code.

In order to generate new parts of the *knowledge base*, personal tools for *knowledge base* editing should be accessed by personal assistant.

For easier integration of new visualisation formats for *personal assistants* that will meet any users needs, it was decided to create a pipeline of agents that take some sc-structure and desired format and translate that sc-structure into the provided format.

Problem solver for translating an sc-structure

 \Rightarrow decomposition of abstract sc-agent*:

- *Abstract sc-agent for dividing a structure* ⇒ note*:
 - [The structure is divided into connectivity components]
 - implementation*:
 - C++ language
 - Abstract sc-agent for main key sc-element selection

 \Rightarrow note*:

 \Rightarrow

[For each connectivity component

and each structure the main key sc-element is selected (it may be that initially the main key element is absent or there are several of them, but after that step each connectivity component is having only one main key sc-element)]

- $\Rightarrow implementation^*: C++ language$
- Abstract sc-agent for classifying a structure
 - \Rightarrow note*:

[Each connectivity component is classified to be a logical rule, weighed graph, scp-program etc.]

 $\Rightarrow implementation^*: \\ C++ language$

• Abstract sc-agent for sc-elements ordering

 \Rightarrow note*:

[For each connectivity component, semantic ordering of all key elements takes place (the order in which this connectivity component will be perceived when reading)]

 $\Rightarrow implementation^*: C++ language$

• Abstract sc-agent for translating into visualisation

 \Rightarrow note*:

[Translation into the given visualization language takes place: SCn or SCg]

- $\Rightarrow implementation^*: \\ C++ language$
- Abstract sc-agent for translating into an external format

 \Rightarrow note*:

- [The translation to the external format of the target user interface interpreter]
- $\Rightarrow implementation^*: \\ C++ language$

}

The result of applying this sc-agents pipeline is shown on Figure 2. This visualisation is aimed at eliminating intersections of connectors and it is easier to perceive fragments of the *knowledge base*.

Agents are always able to get description of elements placed on the screen because proposed approach suggests usage of an agent-oriented model for interpreting the semantic model of *adaptive user interfaces*. That model is able to generate *user interface* based on the task the user is trying to complete and adapts to the user's environment and actions.

IV. Conclusion

The article analyses the problem of the existence of a large number of tools that are similar in functionality but different in appearance, which makes it difficult for users to comfortably meet their needs. Modern approaches use neural network methods such as recognizing *user interface* elements by screenshot, *Web LLM Agents* and generating interfaces by description. This problem can be solved by utilizing a standard for *user interface* design and using that standard to create *adaptive user interfaces*.

It is proposed to use the OSTIS Technology Standard to reduce the impact of heterogeneous interfaces. A structured knowledge base created using the proposed model of *adaptive user interfaces* will simplify the process of creating *user interfaces*.

Suggested approach assumes the use of the OSTIS Technology, which includes the OSTIS Ecosystem and personal ostis-assistants to ensure effective and comfortable user interaction with the Ecosystem. OSTIS Technology ensures that actions that system perform are transparent and it is possible to explain the need of each action performed.

Within the proposed approach, the user interface of the OSTIS Ecosystem is considered as the user interface of a personal ostis-assistant, since the user interacts with the Ecosystem only through their personal assistant. The principles of the user interface of the OSTIS Ecosystem were described, with the main one being the usage of the component approach to design and the possibility for a personal assistant to use any user interface component within the OSTIS Ecosystem. Models for the user interface of the OSTIS Ecosystem were proposed and tool for that interface is described, using the example of a personal tool for knowledge base editing.

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Figure 2. SCg visualised using sc-agents pipeline

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МОДЕЛИ И СРЕДСТВА ПРОЕКТИРОВАНИЯ АДАПТИВНЫХ ПОЛЬЗОВАТЕЛЬСКИХ ИНТЕРФЕЙСОВ ЭКОСИСТЕМЫ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ Садовский М. Е., Жмырко А. В.,

Тищенко В. Н.

В статье рассматриваются принципы автоматизации действий пользователя при помощи испльзования персональных ассистентов, модели адаптивных пользовательских интерфейсов Экосистемы интеллектуальных систем, а также средства индивидуального редактирования моделей таких интерфейсов.

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Software Framework for the Development of Intelligent Systems with Integrated Spatially Referenced Data

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Abstract—The paper considers a software framework for designing intelligent systems with integrated spatially referenced data, built on the principles of ostis-systems. The structure of the software framework is described, the description of the main components and their interaction is given. Design stages and methodology of designing this class of intelligent systems are considered.

Keywords—OSTIS, intelligent system with integrated spatially referenced data (ISRD), software framework, design stages, design methodology

I. Introduction

Systems with integrated spatially referenced data are an effective tool in the emerging global trend of organizational and technical support for the digital development of society, which is achieved through the introduction of information and communication technologies and advanced production technologies in sectors of the national economy and spheres of society. To this end, the Republic of Belarus has developed and approved the State Programme 'Digital Development of Belarus' for 2021-2025 [1], [2], and the projects envisaged for implementation include the use of artificial intelligence technologies. The key objectives of this program are:

- create favorable conditions to ensure and support the processes of digital development;
- improve the national information and communication infrastructure and services provided on its basis;
- improving the implementation of government functions through the creation of a comprehensive digital infrastructure for interdepartmental information interaction, the formation of a modern system for the provision of public services based on the principles of proactivity and multichannelization of their provision;
- ensuring the availability of education based on the application of modern information technologies both to improve the quality of the educational process and to prepare citizens for life and work in the digital economy;

- improving the quality of medical care for the population, accessibility of services provided by the health care system, awareness of the population about the state of health, epidemiological situation on the basis of modern technological solutions;
- development of digital economy tools in various sectors of the national economy, providing for the application of advanced production technologies in production and foreign economic activity processes, formation of necessary conditions for preserving and improving the competitiveness of Belarusian enterprises in the global market;
- improving the level of comfort and safety of life of the population through the creation and implementation of "smart cities" technologies, including systems for remote monitoring and accounting of the housing stock, energy consumption, environmental conditions, video analytics and other;
- improvement of the information security system ensuring legal and safe use of solutions implemented as part of the digital development of the Republic of Belarus, building trust, ensuring conditions for safe provision and receipt of electronic services (formation of "digital trust").

According to the Decree of the Council of Ministers of the Republic of Belarus of April 21, 2023 No 280 "On measures to implement the Decree of the President of the Republic of Belarus of April 7, 2022 № 136" [3] artificial intelligence is a set of technological solutions that allows to imitate human cognitive functions (including self-learning and search for solutions without a predetermined algorithm) and to obtain in the performance of specific tasks the results comparable to the results of human intellectual activity, and includes informationcommunication.

Currently, there is a surge of work in the field of creating intelligent question-answering systems based on generative models of artificial intelligence, using neural networks, and dialog using chatbots such as ChatGPT. However, despite the possibility of supporting dialog with the user, such systems cannot generate answers using spatial data because they are not trained on such a set of information. In addition, the generated answers may be unreliable ('fake'). For example, a question like 'What is the distance between house 15 on Kirov Street in Minsk and house 204 on Pushkinskaya Street in Minsk (a fictitious address with a non-existent street and house)?' different chatbots generated either a specific answer, which in reality cannot be, or a reference to the use of cartographic services.

The above circumstances indicate the current demand for a class of intelligent systems with integrated spatially referenced data.

The technology that allows to realize the tasks of digital development of society is the open complex technology of development of intelligent systems based on semantic networks [4] (OSTIS technology - Open Semantic Technology for Intelligent Systems). The main provisions and principles of this technology are described in [5], the principles of creation and unified design models in [6], [7].

OSTIS technology is based on the following principles [8]:

- orientation on semantic unambiguous representation of knowledge in the form of semantic networks having basic theoretical-multiple interpretation, which provides the problems of diversity of forms of representation of the same meaning, and the problems of ambiguity of semantic interpretation of information constructions;
- use of associative graph-dynamic model of memory;
- use of agent-oriented model of knowledge processing;
- realization of OSTIS technology in the form of intellectual Metasystem IMS [9], which itself is built on OSTIS technology and provides design support for computer systems developed on OSTIS technology;
- ensuring in the designed systems a high level of flexibility, stratification, reflexivity, hybridity, compatibility and, as a consequence, learnability.

Systems built on this technology are called ostissystems, and the universal abstract language of semantic networks (SC-code) or semantic code is used as a language tool for knowledge representation. In this case, knowledge bases of ostis-systems have semantic representation, and the knowledge and skills interpreter is a library of agents that process the knowledge base and manage situations and events in this knowledge base [8].

At the same time, the systems developed using this technology do not have the disadvantages of systems based on generative models (ChatGPT [10] type systems), because it is not the generation of new data, which are similar to the training data, but the relationships between

the actual data and knowledge of the subject area are established, which ensures the reliability of conclusions based on knowledge.

For the design of intelligent systems with integrated spatial data on the basis of technology OSTIS proposed, described in the works [11], [12] semantic model ISRD, based on the ontology of spatial objects, provided user communication in the formal language of questions [13], [14] and developed means of automation and information support of the design process of this class of systems, including the formation of components ISRD [15].

An important point that reduces the ISRD development time on the one hand, and on the other hand — increases their functionality, is the availability of tools for designing such systems. In this case, the technology of ISRD design should be oriented to the multiple use of functional components of the system in order to reduce the time of design and development of application systems. Thus, this study is about creating a software framework for designing intelligent systems with integrated spatially referenced data.

Designing semantically compatible intelligent systems with integrated spatially referenced data requires the development of software tools on the OSTIS – Ostis Geography platform to implement spatially referenced data and subsequently use them in applied intelligent systems to solve problems to be solved in specific subject areas.

II. Structure of an intelligent system with integrated spatially referenced data

The structural diagram of the program complex is presented in Figure 1.

The development concept assumes that some of the tools and components being developed are necessary for the development of various ISRD class application systems. Therefore, ready-made components can be reused. Such components can be information components, such as knowledge bases, as well as software components, such as problem solver agents or viewers and editors included in user interfaces.

Due to the above circumstances, we will distinguish the minimum set of components necessary for the design of an ISDS, which we will call the ISRD core. The ISRD kernel consists of [15]:

- 1) Knowledge base:
 - ontology of terrain objects and phenomena;
 - characteristics of terrain objects and phenomena;
- 2) Problem solver:
 - stack of mapping agents:
 - agents for calculating geometric features,
 - agents for determining the type of localization,



Figure 1. Program Complex Structure.

- agents for interfacing with various map systems and services, measurement systems and time intervals,
- agents for establishing topological relationships;
- search agents,
- sophisticated search agents,
- logical inference agents,
- transaction calculation agents;
- 3) User interface:
 - map interface:
 - work with point objects,
 - work with linear and polylinear objects,
 - work with area objects;
 - map viewer.

The software package includes a module for implementation of spatially referenced data (map processor). The task of the map processor is to represent such data from external sources, such as map services, registers and cadastres that use spatial data in the form of drawings. Such data are translated into semantic memory for further processing by software agents to derive inferences.

Implementation of spatial data from external data sources is performed by the map and plan processor. The input of the map and plan processor receives data from external sources and is semantically linked to the knowledge stored in the knowledge base. If there is no necessary terrain object or plan corresponding to the input data in the knowledge base, a fragment of the knowledge base with the description of the terrain object or spatial object is formed in the knowledge base. The processor of maps and plans also performs geocoding for further use in the process of output as a result of work of agents providing solution of the set tasks in some subject area. The following types of platform-dependent agents are supported: in C++, Java (Kotlin) and Python. In addition, the possibility of implementing agents in the basic knowledge processing language SCP (Semantic Code Programming) internal to OSTIS-systems is supported.

The ISRD core includes subject-independent components of knowledge bases, problem solver and map interface, i.e. such components, the information about which or the way of processing or displaying do not depend on the subject area. For knowledge bases, such components include the ontology of spatial objects, as well as the knowledge base of terrain objects, for which geocoding and semantic linking with characteristics (semantic attributes) have been performed earlier. As subjectindependent components of the problem solver there are agents for calculating geometric characteristics, determining localization types, agents for interfacing with various cartographic systems and services, measurement systems and time intervals, agents for establishing topological relationships.

III. Map query using spatially referenced data from OpenStreetMap service

The peculiarity of the software toolkit is to provide access to external cartographic or spatial data, which are provided by cartographic services. In this case, the cartographic data collected by the community of interested users include almost complete description of terrain objects of the entire Earth, thus there is no need to collect cartographic material in the design of application systems, but verification and selection of spatial data existing in the map service [11]. Due to this fact, there is no need to store a huge amount of data, because spatial data are stored in map services, and the task is reduced to the selection of necessary for solving the problems of the subject area map data, or spatially related data. A typical situation of interaction is considered in Figure 2 for the case when the external map service is based on OpenStreetMap technology and requests to the map service are realized in the Overpass query language [16].



Figure 2. Interaction with external map service OpenStreetMap.

IV. Cartographic query when using spatially referenced data from the Yandex.Maps service

Displaying the results on the map, implemented using the Yandex.Maps service [17], is performed in a specialized sc-window. For this purpose, data in the WGS-84 coordinate system are represented in the YMapsML data format (xml-format for geodata representation developed by Yandex).

The transformation sequence is shown in Figure 3 and includes the following steps.



Figure 3. Sequence of converting the response to the user into a map view

Step 1 *Parsing the sc-construction of the answer.* This step highlights the *coordinate** relation bundle.

Step 2. Determining the type of object localization. This step determines one of three localization types: point object, linear object, area object, depending on the number of coordinate pairs in the coordinate relation bundle*.

Step 3. Select the name of the geographic object for the purpose of further geocoding and determining to which class of terrain objects the searched object belongs.

Step 4. Form a description of the displayed geographic object as a map object in the form of xml markup in the YMapsML geodata representation language. For example, for geocoding the object of the city of Minsk, considered as a point object we will have:

<ymaps:GeoObject> <gml:name> Minsk
```
</gml:name>

<gml:description>

city

</gml:description>

<gml:Point>

<gml:pos>

27.548621 53.903364

</gml:pos>

</gml:Point>

</ymaps:GeoObject>
```

Step 5. Forming a unique name of the xml document and sending it to the ymapserver.appspot.com server under this name. The generated document name is stored in the contents of the sc-window node, which is in a set of sc-windows for outputting map data with YMapsML format.

Step 6. Upload from the server using JavaScript API of the "Yandex.Maps" service, generated in step 4 xml-document and map rendering.

V. Displaying information about a terrain object

The display of information about the terrain object is performed by means of OSTIS [9] Metasystem and map interface and includes the following steps:

- search for semantic neighborhood of a given terrain object (i.e. spatial relations between a given terrain object and other terrain objects, as well as geosemantic characteristics of a given terrain object;
- determine geographic codes of territorial terrain objects, in which a given terrain object is located, as well as other terrain objects connected by spatial relations with a given terrain object;
- obtaining cartographic data on territorial terrain objects and their correlation with information on territorial terrain objects in the knowledge base;
- determination of terrain object class;
- visualization of semantic neighborhood of a given terrain object in the map language.
- VI. Design methodology for intelligent systems with integrated spatially referenced data

For the purpose of mass development of intelligent systems with integrated spatially referenced data, the design methodology of this class of systems is included in the means of automation and information support of design. Based on the design principles of semantically compatible intelligent systems, the design methodology of intelligent systems with integrated spatially referenced data includes the following design stages.

Step 1. Deployment of OSTIS technology components for the design and operation of systems designed in accordance with the open integrated technology for the development of intelligent systems based on semantic networks.

Step 2. Deployment of components of the core of intelligent systems with integrated spatially referenced data.

At this stage, the components of the ISRD core are deployed, which is necessary to install the developed components of the spatial object ontology, the problem solver, including the main agents for processing spatially referenced data, the question language interpreter, and the software components of the mapping interface. The use of the ISRD core components allows to create at this stage of design the application systems with minimal functional purpose.

Step 3. Formulating the knowledge base.

In this stage, the knowledge base is built, which consists of the following sub-stages.

Substep 3.1. Compiling the table of contents of the knowledge base of the designed semantic reference system, structuring the knowledge base and dividing it into elementary fragments - atomic sections with indication of atomic section types.

Substep 3.2. Compiling a question book that includes a formal language record of all question types included in the system.

Substep 3.3. Create a list of key objects of the subject area. Concepts, definitions, and terms act as objects in various subject areas.

Substep 3.4. Create a knowledge base ontology, i.e. a complete description of all the objects included in the system, specifying their properties, relations, use cases, etc..

Step 4. Integration of knowledge bases with spatial knowledge. Selection of cartographic material for a given terrain area, translation and loading into the knowledge base with the establishment of topological relations between terrain objects using the ontology of terrain objects.

At the 3rd and 4th stages, the knowledge base is filled with knowledge of the subject area with linkage to the cartographic material, i.e. recording of all initial texts of the knowledge base of the designed semantic reference system. Such texts include answers to all types of questions from the collection of questions and texts of atomic sections of the knowledge base of the intelligent system.

Step 5. Development of problem solver components.

If necessary, development of additional agents required to solve the tasks of the subject area is performed.

Step 6. Integration with generative intelligence models (large language models, or LLM models).

If necessary, generative intelligence models are plugged in.

Step 7. Implementation.

This stage involves final specification of the knowledge base of the semantic reference system and certification of the developed ip components (intellectual property components that can be used in re-design). The evolution of ISRD class application systems in their development and design stages is shown in Figure 4.



Figure 4. Design stages of intelligent systems with integrated spatially referenced data.

At stages 3-7 of design, the ISRD developer can decide to return to any previous stage, which corresponds to the rapid prototyping technology, when a prototype of the system with minimal functionality is created and the ISRD functionality is subsequently built up. In this case, the prototype with minimal functionality is obtained after the 2nd stage of design, i.e. after the deployment of components of the core ISRD.

Thus, it is possible to get ready-to-use prototypes of intelligent systems faster due to the use of evolutionary and incremental design methodology of ISRD class application systems.

For a fixed area, the same spatially related data are used in different application domains: epidemiology, construction, environmental protection, creation of digital twins of enterprises, mobile robotics systems, etc., which makes it necessary to align ontologies of subject areas with terrain objects and phenomena and thus provides a vertical (subject-oriented) level of ISRD design.

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ПРОГРАММНЫЙ КОМПЛЕКС ДЛЯ ПРОЕКТИРОВАНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ С ИНТЕГРИРОВАННЫМИ ПРОСТРАНСТВЕННО-СООТНЕСЕННЫМИ ДАННЫМИ

Самодумкин С. А.

В работе рассматривается программный комплекс для проектирования интеллектуальных систем с интегрированными пространственно-соотнесенными данными, построенных по принципам ostis-систем. Описана структура программного комплекса, приведено описание основных компонентов и их взаимодействие. Рассмотрены этапы проектирования и методика проектирования данного класса интеллектуальных систем.

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Principles of Automation of Development of Open Projects Based on the Ecosystem of Intelligent Computer Systems of the Next Generation

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Abstract—The article is intended for researchers, developers, and practitioners in the fields of artificial intelligence, knowledge engineering, and intelligent system design who seek to build, extend, or integrate <u>semantically compatible</u> intelligent systems.

It is particularly relevant for those interested in:

- developing modular, reusable, and interoperable intelligent systems using open-source technologies;
- applying formal ontological methods and SC-code for knowledge representation and reasoning;
- implementing multi-agent problem solvers and integrating them with semantic knowledge bases;
- leveraging OSTIS Technology for educational, research, or industrial applications requiring adaptability, scalability, and semantic compatibility;
- research practical workflows, including installation, configuration, and testing, through real-world examples such as the ostis-example-app.

Presented the guide assumes a basic familiarity with concepts in artificial intelligence, ontologies, and software development, but provides detailed, step-by-step instructions suitable for both newcomers and experienced professionals in the domain.

Keywords—OSTIS, open source project, ecosystem, basic specification, OSTIS, OSTIS Project, OSTIS Technology, OSTIS Guide, ostis-system, SC-code, knowledge base, problem solver, agent, ostis-example-app, ostis-web-platform, ostis-metasystem

I. Introduction

Currently, a significant number of diverse projects aimed at automating the development of various software products are being developed. In particular, the creation of open-source projects is especially relevant.

Open-source projects [1] are a powerful tool that enables the development of high-quality software by combining the efforts of developers and users worldwide. However, open-source projects come with a range of advantages and disadvantages.

Advantages of open-source projects:

- large user and developer community;
- rapid identification and fixing of bugs;
- opportunity for collaborative use and code enhancement.

Disadvantages of open-source projects:

- potential vulnerabilities if the project is not properly maintained;
- unpredictability in terms of support and updates.

The development of open-source projects offers many advantages but is also associated with a number of challenges. Here are some of them [1]:

- 1) Coordination and management. Open-source projects often involve numerous contributors, which can lead to difficulties in coordinating work and managing the project. Without a clear strategy and role distribution, confusion may arise.
- Diverse expertise levels. Participants may have varying levels of knowledge and experience, which can impact work quality. Training and support for newcomers are essential.
- Lack of motivation. Volunteers may lose interest or motivation if they do not see progress or receive proper recognition for their work. This can result in delays and reduced project quality.
- Conflicts and disputes. Differing opinions on development directions, architecture, or technology can lead to conflicts. Mechanisms for resolving disputes must be established.
- Code quality. Maintaining uniform code standards is challenging, as contributors may follow their own practices. This complicates integration and testing.
- Licensing and legal issues. Misunderstanding or misapplying licenses can cause legal problems. Proper documentation and adherence to licensing terms are critical.

- Documentation challenges. Documentation may be insufficient or outdated, hindering new contributors' understanding and limiting project growth.
- Funding. While many open-source projects rely on volunteers, funding may be necessary for infrastructure, hosting, or other resource-intensive needs.
- 9) Dependence on external factors. Projects may depend on changes in ecosystems (e. g., dependencies or external libraries), affecting their development and maintenance.
- Diverse opinions. A flood of ideas and proposals can overwhelm the team and complicate decisionmaking. Clear processes for discussion and implementation are vital.

These challenges can be successfully addressed through effective organization, active communication, and a flexible approach to project management.

An open-source project is not merely one whose source code is made publicly available, but rather a project developed and improved by entire communities of specialists working collaboratively to evolve and refine it.

Naturally, managing, developing, and maintaining such a project—preserving its integrity and functionality—is far more complex compared to projects with centralized management.

II. Project classification

A project is a temporary endeavor aimed at creating a unique product, service, or result [2].

Let us consider the main types of projects:

1) By dominant activity:

- research,
- creative,
- applied,
- informational,
- adventure, gaming, role-playing;
- 2) By subject domain:
 - single-subject a project within the scope of one academic discipline,
 - *interdisciplinary* integrating knowledge from two or more fields,
 - transdisciplinary projects at the intersection of disciplines or beyond traditional subject boundaries;
- 3) By coordination nature:
 - open,
 - closed;
- 4) By number of participants:
 - individual,
 - paired,
 - group;
- 5) By duration:
 - short-term,

- medium-term,
- long-term;
- 6) By geographical scope:
 - district, region, territory,
 - interregional, international.

This is not an exhaustive classification. Thus, developing tools capable of adapting to diverse project types remains a relevant challenge today. Knowing the project type or at least its goal allows for determining the model.

In this work, we focus on projects classified by coordination nature.

Coordination in open projects refers to a set of measures and processes aimed at ensuring effective collaboration among all project participants. It is often characterized by open access to information and the involvement of a wide range of stakeholders. Open projects may relate to scientific research, software development, social initiatives, and other fields.

Let us examine key aspects of coordination in open projects:

- 1) *Communication*. Establishing clear communication channels among participants. Examples include messaging apps, email lists, forums, or collaboration platforms (e.g., GitHub, Slack).
- Work organization. Creating an efficient team structure and role distribution. This may involve appointing coordinators responsible for specific project aspects and forming working groups.
- Documentation. Maintaining detailed records of project progress, outcomes, and decisions. Documentation helps onboard new participants and ensures transparency.
- Task management. Using project management tools (e.g., Trello, Asana, Jira) to track tasks and deadlines, enabling efficient task allocation and progress monitoring.
- 5) *Feedback*. Regularly gathering input from participants on workflows and results.
- 6) Community engagement. Open projects often rely on community input. Creating opportunities for stakeholder involvement and idea collection drives project development.
- Monitoring and evaluation. Conducting regular assessments to identify progress and domains for improvement.

Effective coordination requires active management and attention to detail to achieve set goals.

Open-source development refers to the process of creating software with publicly accessible source code, which anyone can use, modify, and distribute. This model offers numerous advantages and unique characteristics [3].

Key aspects of open-source project development:

• Open source code. The program's source code is accessible to everyone, enabling users to study, modify,

and improve the software.

- *Community*. Development is often collaborative, involving contributors from around the world. The community actively participates in idea discussions, bug fixes, and providing support.
- *Licenses*. Open-source projects are governed by licenses that define how the code may be used. Popular licenses include GPL, MIT, Apache, and others, each with specific terms regulating use and distribution.
- *Flexibility and adaptability*. Users can tailor the project to their needs by adding new features or modifying existing ones.
- *Security.* Open code allows users to audit it for vulnerabilities and fix issues. However, this also means malicious actors can analyze the code to exploit weaknesses.
- *Documentation*. Successful open-source projects typically include comprehensive documentation, simplifying adoption and use. Documentation covers installation, configuration, and usage guidelines.
- *Examples of successful projects*. Many well-known projects are open-source, including the Linux operating system, Apache web server, Git version control system, Python programming language, and more.

General stages of software development:

- *Idea*. Everything begins with an idea, a problem to solve, or a feature to implement.
- *Planning*. Defining the project structure, timelines, and resource allocation.
- *Coding*. Writing code, including tests and documentation.
- *Testing*. Identifying and correcting flaws. Opensource projects often rely on external feedback to enhance quality.
- *Release*. Publishing the first version for users to adopt.
- *Feedback and evolution*. Post-release, the project evolves based on input from users and the community driving its development.

Automation of open project development is a crucial aspect that enhances code quality, accelerates development processes, and simplifies collaboration among project contributors. Below are key principles to guide automation in open projects:

- *Version control systems*. Enable efficient management of code changes and streamline collaborative work.
- *Test automation*. Rapidly identify errors, thereby improving code reliability.
- *Continuous integration and deployment (CI/CD)*. Automate building, testing, and deployment to expedite releasing changes to production.
- Code documentation and comments. Simplify onboarding for new contributors and ensure documen-

tation stays current.

- *Static code analysis and formatting tools*. Enforce uniform code style and prevent common errors.
- *Dependency management and automated updates*. Mitigate risks from outdated libraries and enhance project security.
- *Containerization*. Simplify environment setup for developers and avoid dependency conflicts across projects.
- *Task management and feedback systems*. Foster community engagement and streamline collaboration for existing and new contributors.
- *Training and knowledge sharing*. Document best practices, create tutorials, and provide guides to accelerate contributor onboarding.

By adhering to these principles, development teams can significantly improve efficiency and the overall quality of open projects.

III. Unification of specifications for documentation in next-generation intelligent computer systems

To ensure both the system and developers uniformly understand the semantics of concepts used, it is necessary to specify not only the concepts themselves but also the associated fragments of knowledge bases and, consequently, entire sections of relevant subject domains [4]. Let us examine the subject domain of basic specifications.

A. Subject domain of basic specifications

The unification of concept specifications in knowledge bases is described within the *subject domain of basic specifications*. This domain must contain descriptions of all possible *classes of entities with unified basic specifications* and the *basic specifications* of various entities.

Subject domain of basic specifications

- \in subject domain
- *⇐* specific subject domain*:
 - Subject domain of semantic neighborhoods
 - maximum class of research objects':
 - basic specification

 \ni class of research objects':

- class of entities with unified basic specifications
- basic specification
- basic specification of the basic specification concept

research relation':

- basic specification
- generalized basic specification

Importantly, in this subject domain, *basic specification** is a binary directed non-role relation linking an

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entity of the *class of entities with unified basic specifications* to its *basic specification*, indicating which part of the specification serves as the entity's foundational definition.

Meanwhile, generalized basic specification* is a binary directed non-role relation connecting a specific class of entities with basic specifications to its basic specification, signifying that the class has a defined set of core properties for specifying its entities.

B. Class of entities with unified basic specifications

Within the subject domain of basic specifications, the concept of a *class of entities with unified basic specifications* is defined.

class of entities with unified basic specifications

:= [a class where all entities share a common set of properties essential for their basic description]

note*: [Some classes may include subclasses with additional basic specifications unique to those subclasses]

C. Basic specification

basic specification

 \Rightarrow

- \subset specification
- := [a set of core properties shared by entities within a class]
- ⇒ [the minimal property set required to describe each entity in a class]
- \Rightarrow note*:

[Every entity in a class must have its basic properties defined according to the class characteristics]

 \Rightarrow note*:

[Basic specifications describe recommended minimum properties for class entities but are not strictly mandatory. They streamline knowledge base development and prevent redundant concepts.]

Notably, the *basic specification* class itself is also a *class of entities with unified basic specifications*. This allows formalizing the *basic specification of the basic specification concept*.

basic specification of basic specification concept \Rightarrow note*:

- [This reflects properties required in every basic specification]
- \Leftarrow generalized basic specification*:
 - basic specification
- \Rightarrow generalized decomposition*:
 - (• specification of generalized basic specification
 - specification of generalized decomposition

• specification example

' example': basic specification of a person ⇐ basic specification*:

 \ni

 \Rightarrow

basic specification of a person

Each *basic specification* is decomposed into specifications of individual properties, which must themselves adhere to strict rules. Below is an example formalizing the *specification of a generalized basic specification*.

specification of generalized basic specification

- generalized decomposition*:
 - sign of the specified object
 - class of entities with unified basic specifications
 - arc linking the class to the specified object
 - arc belonging to the generalized basic specification relation
 - generalized basic specification
 - \Rightarrow template*:

template for describing generalized basic specifications

⇒ illustration*: SCg-text. Template for describing

generalized basic specifications



The template for generalized basic specifications is shown in Figure 1.

template for describing generalized basic specifications



Figure 1. SCg-text. Template for describing a generalized basic specification

IV. Guide to developing and using semantically compatible intelligent systems based on OSTIS Technology

Let's look at it further a comprehensive guide to the development and application of semantically compatible intelligent systems using OSTIS Technology based on basic specifications. OSTIS Project is an open-source project designed to address the challenges of interoperability, modularity, and scalability in intelligent system design. Step-by-step methodologies are provided for constructing ontologically structured knowledge bases and implementing agents for problem solving. The practical workflow is illustrated through the ostis-exampleapp, demonstrating installation, extension, and testing procedures. The guide emphasizes the advantages of OSTIS Project, including plug-and-play integration, platform independence, reflexivity, and support for parallel information processing, making it a robust foundation for next-generation intelligent systems.

V. OSTIS Project

A. About OSTIS Project

OSTIS Project [5], [6] is an open-source initiative focused on developing and promoting Open Semantic Technology for Intelligent Systems (OSTIS) [7]. The infrastructure of the OSTIS Project is hosted within the OSTIS-AI organization on GitHub [8]. It comprises multiple repositories, with the following being key components:

- 1) The *ostis-web-platform* repository [9] provides tools for installing and developing ostis-systems. It includes a knowledge base with top-level ontologies, semantic network interpreters, component manager, and web-oriented interface [10].
- 2) The *ostis-metasystem* repository [11], [12] contains comprehensive intelligent system designed to automate and manage all stages of the life cycle of ostis-systems [13].
- 3) The *ostis-example-app* repository [14] demonstrates the basic capabilities of ostis-systems, including knowledge base, problem solver, and web interface.

B. About OSTIS Technology

The OSTIS Technology enables the creation of semantically compatible intelligent systems that can seamlessly integrate various types of knowledge and problemsolving models [15], allowing them to adapt and solve new problems efficiently.

The *OSTIS Technology* has been applied in various domains, including fuzzy systems, data analysis, and knowledge management, demonstrating its versatility.

C. Why OSTIS

The OSTIS Technology is not just another AI project; it's an open-source technology designed to revolutionize how we build intelligent systems. The primary goal of the OSTIS Technology is to address the limitations of current intelligent systems, which are often monolithic, difficult to modify, and expensive to develop [16].

By providing a universal framework for representing information using *SC-code (Semantic Computer code)* [17], the *OSTIS Technology* enables the creation of modular, reusable components that can be easily combined across different systems [18].

D. Key advantages of OSTIS

The main advantages of the OSTIS Technology include:

- 1) *Plug-and-Play Integration*. Seamlessly add new problem-solving models or knowledge without complex overhead [18], [19].
- Universal Components. Reusable components reduce development time and effort across different ostis-systems [19], [20].
- Reflexivity. ostis-systems can analyze themselves, identify errors, and optimize performance – a hallmark of true intelligence [4], [21].
- 4) *Platform Independence*. ostis-systems can be implemented on various platforms, paving the way for semantic computers [10], [22].
- 5) *Parallel Processing*. Designed for efficient parallel information processing, especially beneficial for semantic computers [23].

E. Key features of SC-code

SC-code serves as the backbone of the *OSTIS Technology*. It is a universal language designed to represent knowledge, models, and interfaces uniformly [21]. The code is based on a minimal alphabet consisting of five elements that enable non-linear representation suitable for semantic associative computers [23].

The main features of *SC-code* include [21]:

- 1) Universality. Represents any information uniformly.
- Non-linearity. Suitable for semantic associative computers.
- 3) Basic Alphabet. Comprises just five elements.
- 4) *Flexibility*. Can represent knowledge, models, and interfaces.

F. How to use OSTIS

To effectively use OSTIS, developers can start with the *ostis-example-app* [14]. Refer to the Getting started with OSTIS section for detailed instructions on installing and launching this example of an ostis-system.

VI. Getting started with OSTIS

A. About ostis-example-app

The OSTIS Project provides an example of a system that can be supplemented with new components to create a new system of any orientation. It's called *ostis-example-app*. Its sources can be found here [14].

The *ostis-example-app* serves as a practical entry point for understanding and utilizing *OSTIS Technology*. This application exemplifies the core components of an ostissystem, including its knowledge base, problem solver, and user interface. B. Key features of ostis-example-app

The main features of ostis-example-app include:

- Knowledge base. The knowledge base is structured using SC-code, enabling semantic representation that supports modularity and extensibility [24], [25]. It allows the integration of diverse knowledge domains without requiring significant modifications to the system architecture.
- Problem solver. Utilizing a multi-agent approach, the problem solver integrates various models for addressing complex tasks [26]. This architecture ensures adaptability and scalability in solving new classes of problems.
- 3) *User interface*. The user interface is also described using SC-code, providing semantic compatibility with other system components [27]. This ensures seamless interaction between users and the intelligent system.

C. Step-by-step guide to using ostis-example-app

To utilize the capabilities of *ostis-example-app*, follow these steps:

- 1) Enshure prerequisites:
 - Install Git: https://git-scm.com/book/en/v2/ Getting-Started-Installing-Git [28].
 - Install Docker & Docker Compose: https://www. docker.com/get-started [29].

Before proceeding with installation, ensure that system meets all prerequisites. Docker is recommended for its ability to provide a consistent environment across platforms.

2) Clone repository of ostis-example-app:

```
1 git clone https://github.com/ostis-
apps/ostis-example-app.git
2 cd ostis-example-app
3 git checkout 0.10.0
4 git submodule update --init --
recursive
```

Cloning the repository gives you access to the source code and all necessary submodules required.

3) Build docker images of ostis-example-app:

```
docker compose build
```

Building Docker images ensures that all dependencies are correctly configured within isolated containers.

4) Build knowledge base of ostis-example-app:

```
docker compose run --rm machine
    build
```

5) Start ostis-example-app:

```
1 docker compose up
2 # Access interface at http://
    localhost:8000/
3 # To stop system use 'docker
    compose stop'
4 # Rebuild KB after changes in '.scs
    ' or '.gwf' files
```

Starting the system launches all services defined in the Docker Compose configuration file. Accessing the interface allows users to interact with the intelligent system.

6) To rebuild after changes in '.scs' or '.gwf', repeat step 4.

VII. Step-by-step guide to developing and using intelligent system within the OSTIS Technology

This section presents a step-by-step algorithm for developing an ostis-system, both by extending the *ostis*-*example-app* and by building a system from scratch.

A. Developing an ostis-system using ostis-example-app

Before proceeding to develop an ostis-system from scratch, it is often convenient to use the ready-made *ostisexample-app* as a starting point. This approach allows you to quickly become familiar with the structure of ostissystems, experiment with knowledge base extensions, and implement new problem-solving agents without the need to design all components from the ground up. The following steps outline how to adapt and extend an ostissystem using *ostis-example-app*.

1) Clone template repository:

- download the *ostis-example-app* repository, which provides a ready-to-use project structure with a knowledge base, problem solver, and web interface (see Getting started with OSTIS).
- 2) Modify knowledge base:
 - edit or extend SC-code sources in the knowledge-base/ directory to add or adapt domain-specific concepts, relations, and others (see Step-by-step guides to developing and using knowledge base within the OSTIS Technology).
- 3) Extend problem solver:
 - add new agents or modify existing ones in the problem-solver/directory to implement the required logic (see Step-by-step guides to developing and using problem solver within the OSTIS Technology);
 - register and configure agents as needed.
- 4) Rebuild and launch the system:
 - rebuild the system (e.g., using Docker or CMake, as described in the *ostis-example-app* documentation Getting started with OSTIS);

• start the system and access the web interface to test and use extended ostis-system.

5) Test and iterate:

• after any changes to the knowledge base or problem solver, rebuild the system to apply updates.

B. Developing an ostis-system from scratch

In cases where the requirements for the intelligent system are highly specific or when full control over the system architecture is needed, it may be preferable to develop an ostis-system from scratch. This approach involves designing the project structure, configuring dependencies, and developing all core components independently. The steps below describe the general workflow for building an ostis-system from the ground up.

- 1) Configure project:
 - organize directories for the knowledge base, problem solver, interface, and configuration files;
 - set up required dependencies (e.g., *sc-machine* [30]) using a package manager such as Conan;
 - configure the build system (e.g., CMake) for compiling agents and linking with necessary libraries (see Configuring project for new ostis-system).
- 2) Develop knowledge base:
 - design and formalize ontologies, concepts, and relations in SC-code, following *OSTIS Technology* methodological guidelines (see Step-by-step guides to developing and using knowledge base within the OSTIS Technology);
 - organize the knowledge base into sections and subject domains.
- 3) Implement problem solver:
 - develop agents that implement the logic for solving tasks relevant to required domain (see Stepby-step guides to developing and using problem solver within the OSTIS Technology);
 - ensure agents interact correctly with the knowledge base.
- 4) Develop user interface:
 - if needed, implement or configure the web interface for user interaction with the system.
- 5) Build and launch the system:
 - build the knowledge base and problem solver;
 - launch the system and verify its functionality.
- 6) Test and iterate:
 - test the system, add new features, and refine knowledge and agent logic as needed;

In both approaches, after every change to the knowledge base or agents, rebuild the system to apply updates [14].

C. Configuring project for new ostis-system

Step 1. Define project structure

Create a basic directory structure for an ostis-system project (listing 1).

1	ostis-system-example/
2	knowledge-base
	sources (.scs, .gwf) defining
	ontologies, rules, and facts
3	problem-solver
	agents implementing problem-
	solving logic
4	CMakeLists.txt
	configuration for agents and
	dependencies
5	conanfile.txt
	package manager specification
	for agent dependencies
ļ	

Listing 1. Project directory structure

Step 2. Configure dependencies with Conan Specify Conan package manager configuration [31] for required components (listing 2).

1	[requires]
2	<pre>sc-machine/0.10.0 # Specifies</pre>
	that the project requires the
	sc-machine library version
	0.10.0
3	gtest/1.14.0 # Specifies
	that the project requires the
	gtest library version 1.14.0
4	5 1
5	[generators]
6	CMakeDeps # Generator
	for creating dependency
	information files for CMake
7	CMakeToolchain # Generator
ŕ	for creating a toolchain file
	for CMake
°	[]avout]
9	emake lawout # Uses the
10	atandard project layout
	standard project layout

Listing 2. Conan dependencies

Step 3. Define CMake build system Define main CMake configuration file [32] for build setup (listing 3).

```
1 # Minimum required CMake version

2 cmake_minimum_required(VERSION

3 3.24

4 )

5 # Set C++17 standard

6 set(CMAKE_CXX_STANDARD 17)

7 # Project definition

8 project(my-ostis-system VERSION

0.10.0 LANGUAGES C CXX)
```

```
9 # Version policy configuration
  cmake_policy(SET CMP0048 NEW)
10
11
  # Output directories
12
      configuration
  set (CMAKE_RUNTIME_OUTPUT
13
      _DIRECTORY
      ${CMAKE_BINARY_DIR}/bin
14
15
  )
  set (CMAKE LIBRARY OUTPUT
16
      _DIRECTORY
       ${CMAKE_BINARY_DIR}/lib
17
  )
18
  set (SC EXTENSIONS DIRECTORY
19
       ${CMAKE_LIBRARY_OUTPUT
20
          _DIRECTORY } / extensions
21
  )
22
  # Looking for sc-machine package
23
       for implementing agents
  find_package(sc-machine
24
       REQUIRED
25
26
  )
27
  # Looking for GTest package for
28
      testing agents
  include (GoogleTest)
29
  find_package (GTest
30
       REQUIRED
31
32
33
  # Include problem solver
34
      subsystem
  add_subdirectory(
35
       ${CMAKE_CURRENT_SOURCE_DIR}/
36
          problem-solver
37
  )
```

Listing 3. CMake configuration

Step 5. Install basic tools for development environment

```
# Ubuntu/Debian (GCC)
1
  sudo apt update
2
3
  sudo apt install --yes --no-
4
     install-recommends \
      curl \
      ccache \setminus
6
      python3 \
7
      python3-pip \
8
      build-essential \
      ninja-build
10
  # macOS
```

```
2 brew update && brew upgrade
3 brew install \
```

4 curl \
5 ccache \
6 cmake \
7 ninja

For Linux distributions that doe support apt, ensure following packages are installed:

- *curl*: A tool for transferring data with URLs;
- *ccache*: A compiler cache to speed up compilation processes;
- *python3* and *python3-pip*: Python 3 interpreter and package installer;
- build-essential: Includes a C++ compiler, necessary for building C++ components;
- *ninja-build*: An alternative build system designed to be faster than traditional ones.

Step 6. Install Conan package manager

- Install pipx following the instructions based on operating system: https://pipx.pypa.io/stable/installation/ [33].
- Check CMake version and if it less than 3.24 update it:

```
pipx install cmake
pipx ensurepath
```

- Install Conan and restart the terminal:
 - pipx install conan
 - 2 pipx ensurepath
 - 3 **exec** \$SHELL

Step 7. Install sc-machine libraries

sc-machine [30] is the core software platform of the OSTIS Technology, designed to emulate semantic computer behavior by storing and processing knowledge in the form of semantic networks. At its foundation, *sc-machine* functions as a graph database management system that enables efficient storage, retrieval, and manipulation of knowledge graphs within a shared memory structure called *sc-memory*.

• Add the ostis-ai repository [34] for Conan packages:

```
conan remote add ostis-ai
https://conan.ostis.net/
artifactory/api/conan/
ostis-ai-library
conan profile detect
```

• Install *sc-machine* libraries from ostis-ai repository using Conan:

```
1 # Fetch sc-machine libraries
and builds missing
dependencies
2 conan install . --build=
missing
```

sc-machine libraries – the core components of the OSTIS Platform, used to develop C++ agents.

Step 8. Install sc-machine binaries and scp-machine [35] extensions

• Install *sc-machine* binaries and extensions. The installation process differs slightly between Linux and macOS:

```
# Fetch release archive with
1
     sc-machine binaries and
     extensions for Linux
2 curl -LO https://github.com/
     ostis-ai/sc-machine/
     releases/download/0.10.0/
     sc-machine-0.10.0-Linux.
     tar.gz
 # Unpack fetched release
3
     archive
 mkdir sc-machine && tar -xvzf
4
      sc-machine-0.10.0-Linux.
     tar.gz -C sc-machine --
     strip-components 1
 # Remove unneccessary sources
5
 rm -rf sc-machine-0.10.0-
     Linux.tar.gz && rm -rf sc
     -machine/include
 # Fetch release archive with
     sc-machine binaries and
     extensions for macOS
 curl -LO https://github.com/
2
     ostis-ai/sc-machine/
     releases/download/0.10.0/
     sc-machine-0.10.0-Darwin.
     tar.gz
 # Unpack fetched release
3
     archive
 mkdir sc-machine && tar -xvzf
4
      sc-machine-0.10.0-Darwin
     .tar.gz -C sc-machine --
     strip-components 1
 # Remove unneccessary sources
 rm -rf sc-machine-0.10.0-
```

6 rm -rf sc-machine-0.10.0-Darwin.tar.gz && rm -rf sc-machine/include

sc-machine binaries are pre-compiled executables that provide the runtime environment for the ostis-system: build knowledge base source and launch the ostis-system.

• Install *scp-machine* extensions. The installation process differs slightly between Linux and macOS:

```
2 curl -LO https://github.com/
     ostis-ai/scp-machine/
     releases/download/0.1.0/
     scp-machine-0.1.0-Linux.
     tar.gz
 # Unpack fetched release
     archive
 mkdir scp-machine && tar -
     xvzf scp-machine-0.1.0-
     Linux.tar.gz -C scp-
     machine --strip-
     components 1
 # Remove unneccessary sources
5
 rm -rf scp-machine-0.1.0-
6
     Linux.tar.gz && rm -rf
     scp-machine/include
 # Fetch release archive with
```

```
scp-machine extensions
     for macOS
 curl -LO https://github.com/
2
     ostis-ai/scp-machine/
     releases/download/0.1.0/
     scp-machine-0.1.0-Darwin.
     tar.gz
 # Unpack fetched release
     archive
 mkdir scp-machine && tar -
4
     xvzf scp-machine-0.1.0-
     Darwin.tar.gz -C scp-
     machine --strip-
     components 1
 # Remove unneccessary sources
5
 rm -rf scp-machine-0.1.0-
6
     Darwin.tar.gz && rm -rf
     scp-machine/include
```

The following sections (Step-by-step guides to developing and using knowledge base within the OSTIS Technology and Step-by-step guides to developing and using problem solver within the OSTIS Technology) provide methodologies outlined for developing *knowledge bases* and *problem solvers* within *OSTIS Technology*.

VIII. Step-by-step guides to developing and using knowledge base within the OSTIS Technology

A. About knowledge base of ostis-systems

Developing and utilizing knowledge bases within the *OSTIS Technology* requires a structured, ontology-driven approach [15] to ensure semantic compatibility, modularity, and interoperability across ostis-systems. This section provides methodological guidelines for constructing and applying knowledge bases that adhere to the *OSTIS Standard* [4].

Key principles underpinning this process include:

- *Semantic formalization*. Knowledge is represented using SC-code, enabling machine-readable and human-understandable structures [18].
- *Hierarchical organization*. Knowledge bases are divided into modular sections, each corresponding to a specific subject domain, with inheritance mechanisms ensuring consistency across layers [21].
- *Ontological integrity*. Each section must comprehensively define its concepts, relations, and rules, avoiding redundancy and ensuring logical coherence [36].

By following the next steps, developers can ensure their systems align with the *OSTIS Standard's* requirements for scalability, maintainability, and interoperability [4].

B. Guide to formalizing section of knowledge base using SCs-code

Step 1. Specify didactic structure of section

A section of a knowledge base is a modular, ontologically complete, and semantically formalized component that represents all knowledge relevant to a particular subject domain, supporting hierarchical organization and integration within the overall knowledge base [25].

Create a directory for the section within the knowledge-base/ hierarchy (listing 4). Inside this directory, create .scs source (e.g., section_subject_domain_of_sets.scs) and specify didactic structure of the section: identifiers, definitions, explanations, notes, and quotes related to the section (listing 5).

```
1 knowledge-base/
2 +|-- section_subject_domain_of
__sets/
3 +| |--
section_subject_domain_of
__sets.scs
```

Listing 4. Section directory

section_subject_domain_of_sets.scs

```
section_subject_domain_of_sets
1
 => nrel_main_idtf:
2
      [Section. Subject domain of
3
          sets]
      (* <- lang_en;; *);
4
  => nrel_idtf:
5
          [Section of knowledge
              base, describing sets
              ]
           (* <- lang_en;; *);
7
  => nrel_idtf:
8
      [Formalized description of
9
          set-theoretic concepts]
      (* <- lang_en;; *);
10
```

```
nrel_idtf:
      [Mathematical foundation for
12
           collections and their
          operations]
      (* <- lang_en;; *);
13
  <- sc_node_structure;
14
  <- section;
15
  => nrel_definition: [
16
      Set theory serves as the
17
          cornerstone of modern
         mathematics, providing a
          rigorous framework for
          defining collections of
          distinct objects.
          Fundamental operations
          such as union,
          intersection, and
          complement enable
          systematic manipulation
          of these collections.
          This formalism underpins
          advanced mathematical
          disciplines and finds
         practical utility in
          computer science (data
          structures), logic, and
          data analysis.
  ];
18
  => nrel_explanation: [
19
      Set theory is fundamental in
20
          mathematics as it
         provides a way to
          describe collections of
          objects. It includes
          operations like union,
          intersection, and
          complement, which allow
          us to combine and
          manipulate sets.
         Understanding sets is
          crucial for advanced
         mathematical concepts and
          has practical
          applications in fields
          like computer science and
          data analysis.
  ];
21
  => nrel_note: [
22
      An important aspect of sets
23
          is that they do not
          consider the order of
          elements or duplicates.
          This means {a, b} is the
          same as {b, a} or {a, b,
         b}. Additionally, sets
```

```
have been a subject of
historical development,
notably through Georg
Cantor's work in the late
19th century.
24 ];
25 => nrel_quote: [
26 The essence of mathematics
lies in its freedom (
Georg Cantor, 1883)
27 ];
```

Listing 5. Section. Subject domain of sets

Step 2. Specify decomposition of section

Identify the sub-sections into which the described section can be decomposed: add a decomposition statement in section_subject_domain_of_sets.scs (listing 6), and create directories, .scs sources for each sub-section (listing 7), and specify basic information for sub-sections (listings 8 and 9).

section_subject_domain_of_sets.scs

```
1
1
 section subject domain of sets
2
 // information, specified above
3
     . . .
  + => nrel_section_decomposition:
      <
      section_subject_domain_of
  +
5
     basic concepts of sets,
      section_subject_domain_of
     _set_operations
  + >;;
```

Listing 6. Decomposition of section of subject domain of sets

```
knowledge-base/
  |-- section_subject_domain_of
2
      _sets/
 +|
      |--
3
     section_subject_domain_of
     _basic_concepts_of_sets/
 +|
          |--
      4
     section_subject_domain_of
     _basic_concepts_of_sets.scs
 +|
     |--
     section_subject_domain_of
     _set_operations/
 +|
      | |--
6
     section_subject_domain_of
     _set_operations.scs
      | ---
  7
      section_subject_domain_of
      _sets.scs
```

Listing 7. Subsection directories

section_subject_domain_of_basic
_concepts_of_sets.scs

<pre>section_subject_domain_of_basic</pre>	
_concepts_of_sets	
<pre>=> nrel_main_idtf:</pre>	
[Section. Subject domain of	
basic concepts of sets]	
(* <- lang_en;; *);	
=> nrel_idtf:	
[Basic concepts of set	
theory]	
(* <- lang_en;; *);	
<- sc_node_structure;	
<- section;;	

Listing 8. Section. Subject domain of basic concepts of sets

section_subject_domain_of_set
_operations.scs

1	<pre>section_subject_domain_of_set</pre>
	_operations
2	=> nrel_main_idtf:
3	[Section. Subject domain of
	set operation]
4	(* <- lang_en;; *);
5	=> nrel_idtf:
6	[Set operations]
7	(* <- lang_en;; *);
8	<- sc_node_structure;
9	<- section;;
	L

Listing 9. Section. Subject domain of set operations

Step 3. Specify subject domain for given section

A *subject domain* is a comprehensive structure that organizes all relevant objects, their classifications, the relations between them, and any additional components necessary to fully describe the domain of investigation []. *Subject domain* is a structure that includes:

- the main research (described) objects;
- classes of research objects;
- links, the components of which are the research objects;
- classes of the above-mentioned links (i.e. relations);
- classes of objects that are neither the research objects nor the above-mentioned links, but are components of these links.

Define the subject domain describing all investigated entities within the section: create a file named subject_domain_of_sets.scs in the section directory (listing 10) and specify didactic structure of subject domain (listing 11).

```
knowledge-base/
|-- section_subject_domain_of
__sets/
```



Listing 10. Location of subject domain

subject_domain_of_sets.scs

```
section_subject_domain_of_sets =
1
  [*
2
  subject_domain_of_sets
3
  => nrel_main_idtf:
4
      [Subject domain of sets]
5
      (* <- lang_en;; *);
  => nrel_idtf:
7
      [Subject domain of set
          theory]
       (* <- lang_en;; *);
9
      [Subject domain, in which
10
          research objects are sets
          1
      (* <- lang_en;; *);
11
  <- sc_node_structure;
12
  <- subject_domain;
13
  *];;
14
```

Listing 11. Subject domain of sets

Step 4. Specify child subject domains for given subject domain

List child subject domains that are hierarchically subordinate to the current domain. Add child subject domains in subject_domain_of_sets.scs (listing 12).

```
subject_domain_of_sets.scs
```

```
1 section_subject_domain_of_sets =
2 [*
3 subject_domain_of_sets
4 // information, specified above
    ...
5 <= nrel_child_subject_domain:
6     subject_domain_of_discrete
        _mathematics;
7 => nrel_child_subject_domain:
```



Listing 12. Child subject domains

Step 5. Identify classes of objects for given subject domain

List the classes of objects researched within the corresponding subject domain (listing 13).

Distinguish between maximal and non-maximal classes of objects:

- *maximal class* is a class for which there is no other class in the subject domain that is a superset.
- non-maximal class is a class for which there exists another class in the subject domain that is a superset.

subject_domain_of_sets.scs

1	sectio	on_subject_domain_of_sets =
2	[*	
3	subjec	t_domain_of_sets
4	// inf	formation, specified above
5	+ -> r	rel_maximal_research
	0]	oject_class:
6	+ cc	oncept_set;
7	+ -> r	rel_not_maximal_research
	_0]	oject_class:
8	+ cc	<pre>oncept_finite_set;</pre>
9	+ cc	<pre>oncept_infinite_set;</pre>
0	+ cc	<pre>oncept_countable_set;</pre>
1	+ cc	<pre>oncept_uncountable_set;</pre>
2	+ cc	<pre>oncept_cantor_set;</pre>
3	+ cc	oncept_multiset;
4	+ cc	oncept_fuzzy_set;
5	+ cc	oncept_crisp_set;
6	+ cc	oncept_set_of_sets;
7	+ cc	<pre>oncept_non_reflexive_set;</pre>
8	+ cc	oncept_reflexive_set;
9	+ cc	oncept_formed_set;
20	+ cc	oncept_unformed_set;
21	+ cc	oncept_empty_set;
22	+ cc	oncept_singletone;
23	+ cc	oncept_pair_set;
24	+ cc	oncept_cantor_pair;
25	+ cc	oncept_triple_set;
26	+ cc	<pre>oncept_oriented_set;</pre>
27	+ cc	<pre>oncept_cartesian_product;</pre>
28	+ cc	oncept_boolean;
29	*] ;;	

Listing 13. Classes of objects in subject domain of sets

Step 6. Identify research relations for given subject domain

Determine the relations being explored in the section (listing 14).

```
subject_domain_of_sets.scs
```

```
section_subject_domain_of_sets =
2
  [*
  subject_domain_of_sets
3
  // information, specified above
4
      . . .
  -> rrel not maximal research
5
      _object_class:
      // other research classes of
6
           objects
           concept_boolean;;
7
    -> rrel_research_relation:
8
      nrel_membership;
  +
9
      rrel_example;
10
  +
  +
      nrel_inclusion;
11
      nrel_strict_inclusion;
  +
12
      nrel_set_power;
  +
13
      nrel_equinumerous;;
14
  +
15
  *];;
```

Listing 14. Research relations in subject domain of sets

Step 6. Integrate into ostis-system

Knowledge base of ostis-system needs to be built before launching the system or after making changes. To load the formalization result into the ostis-system, run the command shown in listing 15 in terminal.

./sc-machine/bin/sc-builder -i
 knowledge-base -o kb.bin - clear

Listing 15. Build knowledge base

This command builds the knowledge base from the .scs and .gwf sources in the knowledge-base directory, creating the kb.bin file. The -clear flag clears the knowledge base before building.

C. Guide to formalizing concepts using SCs-code

In the context of the *OSTIS Standard*, an object is usually defined as either a concept, i.e. an abstract entity that combines other *abstract* or *concrete entities*, or an instance of a concept, i.e. a concrete entity.

Concepts can be absolute or relative. *Absolute concepts* denote the same attributes of some group of concepts or entities, *relative concepts* — connections and relations between other concepts or entities.

Formalizing absolute concepts (classes)

To formalize absolute concepts, which are classes or sets of objects with common properties.

Step 1. Specify didactic structure of class

Create .scs source (e.g., concept_set.scs) (listing 16) and specify sc-identifiers for class in various external languages to ensure cross-referencing and integration with other systems (listing 17).

```
knowledge-base/
1
   |-- section_subject_domain_of
2
      _sets/
       |--
3
      section_subject_domain_of
      _basic_concepts_of_sets/
          |--
       4
      section_subject_domain_of
      _basic_concepts_of_sets.scs
       |--
5
      section_subject_domain_of
      _set_operations/
      | |--
6
      section_subject_domain_of
      _set_operations.scs
       |-- concepts/
7
           |-- concept_set.scs
 +|
       8
       |--
      section_subject_domain_of
      _sets.scs
       |-- subject_domain_of_sets.
10
      SCS
```

Listing 16. Location of concept_set source

concept_set.scs

```
concept set
  => nrel_main_idtf:
2
        [set]
3
        (* <- lang en;; *);
4
  => nrel_idtf:
5
        [set of signs]
6
        (* <- lang_en;; *);
7
  => nrel definition:
8
        [A collection of distinct
9
       objects where:
       \forall x, y \in S : x \neq y \Rightarrow \texttt{count}(x) = 1
10
       and order is irrelevant]
11
        (* <- lang_en;; *);
12
        [A = \{x \mid P(x)\} where P is a
13
      membership property]
        (* <- lang_en;; *);
14
  => nrel_example:
15
        [\mathbb{N} = \{1, 2, 3, \ldots\} - set of
16
       natural numbers]
        (* <- lang_en;; *);
17
  => nrel_key_properties:
18
        [Unordered: \{a, b\} = \{b, a\}]
19
        (* <- lang en;; *);
20
        [Unique elements:
21
       \{a, a, b\} \equiv \{a, b\}
        (* <- lang_en;; *);
22
       [Extensionality:
23
       A = B \iff \forall x (x \in A \leftrightarrow x \in B)]
        (* <- lang_en;; *);
24
```

```
25 <- sc_node_class;
26 <- concept;</pre>
```

Listing 17. Didactic structure of concept_set

Step 2. Specify theoretical set relations

Describe connections with other sc-elements to establish relationships between concepts (listing 18).

concept_set.scs

```
concept_set
  // information, specified above
2
      . . .
  + => nrel subdivision: {
3
      concept_finite_set;
  +
4
      concept_infinite_set
5
  + };
6
  + => nrel_subdivision: {
7
      concept_cantor_set;
  +
      concept_multiset
9
  + };
10
  + => nrel_subdivision: {
11
12
      concept_crisp_set;
      concept_fuzzy_set
13
  + };
14
  + => nrel_subdivision: {
15
      concept_reflexive_set;
16
       concept_non_reflexive_set
17
  +
  + };
18
  + <= nrel_subdividing: {</pre>
19
      concept_oriented_set;
20
      concept_non_oriented_set
21
  + };
22
  + => nrel_strict_inclusion:
23
  +
      concept_empty_set;
24
       concept_singletone;
25
  +
      concept_pair_set;
  +
26
      concept_triple_set;
27
```

Listing 18. Theoretical set relations of concept_set

Step 3. Specify instances

List instances of the described concept to provide concrete examples (listing 19).

concept_set.scs

```
concept set
 // information, specified above
2
  +
   -> rrel_example:
3
      set_of_natural_numbers;
4
      set_of_atoms_in_the_universe
  +
5
     ;
      set_of_all_continuous
  +
6
     _functions;
```

Listing 19. Examples of instances of concept_set

Formalizing relative concepts (relations)

To formalize relative concepts, which are relations between objects.

Step 1. Specify didactic structure of relation

Create .scs source (e.g., nrel_inclusion.scs) (listing 20) and specify sc-identifiers in various external languages to ensure cross-referencing and integration with other systems (listing 21).

1	knowledge-base/
2	<pre> section_subject_domain_of</pre>
	_sets/
3	
	<pre>section_subject_domain_of</pre>
	_basic_concepts_of_sets/
4	
	<pre>section_subject_domain_of</pre>
	_basic_concepts_of_sets.scs
5	
	<pre>section_subject_domain_of</pre>
	_set_operations/
6	
	<pre>section_subject_domain_of</pre>
	_set_operations.scs
7	concepts/
8	concept_set.scs
9	relations/
10	+ nrel_inclusion.scs
11	
	<pre>section_subject_domain_of</pre>
	_sets.scs
12	<pre> subject_domain_of_sets.</pre>
	SCS

Listing 20. Location of nrel_inclusion source

```
nrel_inclusion.scs
```

```
nrel inclusion
1
  => nrel_main_idtf:
2
       [subset]
3
        (* <- lang_en;; *);
  => nrel_idtf:
5
       [subset relation]
6
       (* <- lang_en;; *);
7
  => nrel_definition:
8
       [Binary relation where
9
      A \subseteq B \iff \forall x (x \in A \to x \in B)]
       (* <- lang_en;; *);
10
  => nrel_example:
11
       [\{1,2\} \subseteq \{1,2,3\}]
12
13
        (* <- lang_en;; *);
14 <- concept_binary_relation;</pre>
  <- concept_non_role_relation;
15
```

Step 2. Specify theoretical set relations Describe connections with other sc-elements to establish relationships between relations (listing 22).

Listing 21. Didactic structure of nrel_inclusion

nrel_inclusion.scs

```
nrel_inclusion
  // information, specified above
2
       . . .
  + => nrel inclusion:
3
       nrel_strict_inclusion (*
4
  +
          => nrel_comment:
  +
5
             [Hierarchy: A \subset B \Rightarrow A \subset B
6
             but A \subseteq B \Rightarrow A \subset B];
  +
7
             [Strict inclusion
  +
8
       requires: \exists x \in B : x \notin A];;
  + *);
```

Listing 22. Theoretical set relations of nrel_inclusion

Step 3. Specify relation domains

Specify the domains of the relation to define the sets of objects involved (listing 23).

```
nrel_inclusion.scs
```

```
nrel_inclusion
1
 // information, specified above
2
      . . .
  + => nrel_first_domain:
3
     concept_set (*
         => nrel_comment:
  +
4
            [Left operand must be a
  +
5
     set: \forall A \in Set];;
  + *);
6
  + => nrel_second_domain:
7
     concept_set (*
         => nrel_comment:
  +
8
           [Right operand must be a
9
  +
       set: \forall B \in Set];;
  + *);
10
```

Listing 23. Domains of nrel_inclusion

Step 4. Specify domain of definition

Define the domain of definition of the relation to specify where it applies (listing 24).

nrel_inclusion.scs

```
1 nrel_inclusion
2 // information, specified above
    ...
3 + => nrel_definitional_domain:
    concept_set (*
4 + => nrel_comment:
5 + [It is a union of the
    first and second domains.];;
6 + *);
```

Listing 24. Definitional domain of nrel_inclusion

Step 5. Specify properties of relation

Describe the properties of the relation to clarify its nature (listing 25).

nrel_inclusion.scs

```
nrel_inclusion
2 // information, specified above
     <- concept_reflexive_relation
       (*
       => nrel_comment:
  +
        [Inherits reflexivity:
5
      \forall S(S \subseteq S)];;
  + *);
6
    <- concept_antisymmetric
7
  +
       _relation (*
  +
       => nrel comment:
8
       [Inherits antisymmetry:
9
  +
      (A \subseteq B \land B \subseteq A) \Rightarrow A = B];;
  + *);
10
  + <- concept_transitive_relation
11
        (*
       => nrel comment:
  +
12
        [Inherits transitivity:
  +
13
       (A \subseteq B \land B \subseteq C) \Rightarrow A \subseteq C
      enabling hierarchy chains];;
14 + *);
```

Listing 25. Properties of nrel_inclusion

Step 6. Specify examples of connectivity of relation Describe a examples of a connectivity of the specified relation to illustrate its use (listing 26).

nrel_inclusion.scs

```
nrel_inclusion
  // information, specified above
2
     -> (concept_countable_set =>
3
      concept_finite_set) (*
  +
         => nrel comment:
4
  +
            [Hierarchy:
5
      FinSet \subseteq CountableSet \subseteq Set];;
  + *);
6
    -> (concept_set => concept_set
7
      );
    -> (concept_finite_set =>
  +
8
      concept_empty_set) (*
         => nrel_comment:
  +
9
            [\emptyset \subseteq S \ \forall S \in Set];
  +
10
11 + *);;
```

Listing 26. Examples of connectivities of nrel_inclusion

IX. Step-by-step guides to developing and using problem solver within the OSTIS Technology

A. About problem solver of ostis-system

While the knowledge base provides the semantic foundation through SC-code ontologies, the problem solver implements actionable logic via sc-agents that interact dynamically with this knowledge. B. Guide to developing and using platform-dependent agent of problem solver in C++ within the OSTIS Technology

General algorithm

All agents in C++ represent some classes in C++. To implement an agent in C++, the following common steps are performed:

- 1) Write input (initial) construction and output (result) construction of the future agent in SC-code.
- 2) Create folder with source and header files for scagent implementation.
- Write CMakeLists.txt file. CMake is used to build projects in C++.
- 4) In the header file, define a class in C++ for the agent and specify at least the class of actions that the agent performs and its program. In such class, primary initiation condition, initiation condition, and result condition can also be specified.
- 5) In the source file, implement all declared methods of the agent's class. Additional methods can also be implemented and used in an agent program. All C++ and OOP tools can be used as much as possible.
- 6) Create file and implement class for keynodes used by the implemented agent.
- 7) Implement class for module for subscribing the implemented agent.
- 8) Write tests for the implemented agent.

When research set theory applications, one common task involves computing the power or cardinality of a set. Consider an example of implementing an agent to count power of a given set. This agent would be designed to determine the number of elements within the set, providing insights into its size and structure.

Step 1. Specify inputs and outputs of agent

The initial construction of the agent might look like this (listing 27 and figure 2):

```
1 ..action
2 <- action_calculate_set_power;
3 <- action_initiated;
4 -> rrel_1: ..some_set;;
5
6 ..some_set
7 -> ..element_1;
8 -> ..element_2;
9 -> ..element_3;;
```

Listing 27. Initial sc-construction for agent in SCs-code

The result sc-construction of the agent might look like this (listing 28 and figure 3):

```
1 ..some_action
2 => nrel_result: [*
3 ..some_set => nrel_set_power:
      [3];;
4 *];;
```



Figure 2. Initial sc-construction for agent in SCg-code

Listing 28. Result sc-construction for agent in SCs-code



Figure 3. Result sc-construction for agent in SCg-code

In addition to agents that initiate actions themselves and then perform these actions, there is a need to implement agents that perform actions initiated by other agents. For this class of agents, it is much easier to generate an initial initiation construction in the knowledge base.

Step 2. Create folder with source and header files for agent

Create folder for agent implementation (listings 29, 30 and 31).

1	problem-solver/
2	set-agents-module/
3	CMakeLists.txt

Listing 29. Problem solver directory structure

1	set-agents-module/
2	agent/
3	<pre> sc_agent_calculate_set</pre>
	_power.hpp
4	<pre> sc_agent_calculate_set</pre>
	_power.cpp
5	CMakeLists.txt

Listing 30. Agent module directory structure

CMakeLists.txt

```
add_subdirectory(${
    CMAKE_CURRENT_SOURCE_DIR}/set
    -agents-module)
```

Listing 31. CMake build configuration for problem solver

Step 3. Write CMakeLists.txt file

The CMakeLists.txt file should describe a process of building the agent code (listing 32). It should contain various instructions and parameters needed to compile and link agent source code to *sc-machine* libraries.

CMakeLists.txt

```
# Find all files with the
     extensions .cpp and .hpp in
     the current directory and the
       agent subdirectory.
  file (GLOB SOURCES
2
     CONFIGURE_DEPENDS
      "*.cpp" "*.hpp"
3
      "agent/*.cpp" "agent/*.hpp"
4
5
  )
6
  # Create a dynamic library
     called set-agents.
  add_library(set-agents SHARED ${
8
     SOURCES })
  # Add a public dependency on the
       sc-memory library from the
     sc-machine package.
  target link libraries (set-agents
10
       LINK_PUBLIC sc-machine::sc-
     memorv)
  # Add the current source
11
     directory to the list of
     paths for header file lookup.
 target_include_directories(set-
12
     agents PRIVATE ${
     CMAKE_CURRENT_SOURCE_DIR})
  # Set properties for the set-
13
     agents target.
  set_target_properties(set-agents
14
      # Specify the output
15
          directory for the
          compiled library.
      PROPERTIES
16
           LIBRARY_OUTPUT_DIRECTORY
17
      ${SC_EXTENSIONS_DIRECTORY}
18
19
  )
 Listing 32. CMake build configuration for agent module
```

LIBRARY_OUTPUT_DIRECTORY property should be set only for libraries that represent modules with

agents.

CMAKE_OUTPUT_LIBRARY_DIRECTORY can be set instead of setting LIBRARY_OUTPUT_DIRECTORY property for each extension.

SC_EXTENSIONS_DIRECTORY variable should have path to the directory with extensions for the scmachine. After building the module with the agent, this directory path should be specified via -extensions when starting the *sc-machine* to load the implemented module with the agent.

Step 4. Define an agent class in C++

Define a class in C++ for the agent and specifies the class of actions that the agent performs and its program (listing 33).

sc_agent_calculate_set_power.hpp

1	#pragma once
3	<pre>#include <sc-memory sc_agent.hpp<="" th=""></sc-memory></pre>
4	
5	class ScAgentCalculateSetPower :
	public
	ScActionInitiatedAgent
6	{
7	public:
8	ScAddr GetActionClass() const
	override;
9	
10	ScResult DoProgram(ScAction &
	action) override;
11	};

Listing 33. Agent class header definition

An agent's class to be implemented must comply with the following requirements:

- It must inherit one of the common classes for implementing agents:
 - template <class TScEvent> class ScAgent,
 - or class ScActionInitiatedAgent.

The base class ScAgent contains API to implement agents that react to any sc-events. The base class ScActionInitiatedAgent inherits base class ScAgent and provides API to implement agents that react to sc-events of initiating sc-action.

- It must override at least methods ScAddr GetAction() const and ScResult DoProgram(ScActionInitiatedEvent const & event, ScAction & action).
- Override methods must be public. Otherwise, the code cannot be built because the *sc-machine* won't be able to call methods on the agent class.
- Other methods can be implemented in the agent's class.

To learn more about opportunities and restrictions for implementing agents, see [37].

Step 5. Implement all declared methods

Implement all declared methods of the agent's class (listing 34).

sc_agent_calculate_set_power.cpp

```
#include "
     sc_agent_calculate_set_power.
     hpp"
  #include <sc-memory/
3
     sc_memory_headers.hpp>
  ScAddr ScAgentCalculateSetPower::
     GetActionClass() const
  {
    return m context.
       SearchElementBySystem
       Identifier("
       action_calculate_set_power")
    // Must make sure that this
       class is in the knowledge
       base.
  }
9
  // Must specify valid action
10
     class. In other case, the
     agent cannot be
  // subscribed to sc-event.
11
12
  ScResult ScAgentCalculateSetPower
13
     ::DoProgram(ScAction & action)
14
  {
    // 'ScAction' class
15
       encapsulates information
       about sc-action.
    // The provided action is
16
       action that the given agent
       performs right now.
    // It belongs to class
17
       action_calculate_set_power'.
    // Actions are copyable and
18
       movable. ScAction is
       inherited from ScAddr.
19
    auto const & [setAddr] = action
20
        .GetArguments<1>();
    // This method finds
21
       construction 'action ->
       rrel 1: setAddr'.
    // Here the 1 is number of
22
       arguments which action must
       have. In step 1, an action
       should have a set as its the
        first and only one argument
        was specified. But the one
       who calls this agent may not
```

specify argument for the action. So need to check that the action has argument if (!m_context.IsElement(23 setAddr)) 24 { m_logger.Error("Action_does_ 25 not_have_argument."); // output: " 26 ScAgentCalculateSetPower: Action does not have argument." return action.FinishWithError 27 (); 28 } // There may be a situation 29 where someone is trying to specify a number of arguments more than needed. This can also be checked by specifying, for example, number 2 instead of number 1. But it's not always necessary to do this. 30 // To calculate power of the 31 set, all accessory constant positive permanents arcs from the set can be traversed and count number of these arcs. But, in any problem, the presence of NON -factors must be considered, but this is omitted here. uint32_t setPower = 0; 32 ScIterator3Ptr const it3 = 33 m_context.CreateIterator3(setAddr, 34 ScType::ConstPermPosArc, 35 ScType::ConstNode 36 37); while (it3->Next()) 38 ++setPower; 39 40 ScAddr const & setPowerAddr = 41 m_context.GenerateLink(ScType::ConstNodeLink); m_context.SetLinkContent(42 setPowerAddr, setPower); ScAddr const & arcCommonAddr 43 = m_context.GenerateConnector 44 (ScType::ConstCommonArc, setAddr, setPowerAddr); ScAddr const & nrelSetPowerAddr 45

46	= m_context.
	SearchElementBySystem
	Identifier("nrel_set_power
	");
47	// Must make sure that this non
	-role relation is in the
	knowledge base.
48	ScAddr const &
	membershipArcAddr =
	<pre>m_context.GenerateConnector(</pre>
49	ScType::ConstPermPosArc,
	nrelSetPowerAddr,
	arcCommonAddr);
50	
51	action.FormResult(
52	setAddr, arcCommonAddr,
	setPowerAddr,
	membershipArcAddr,
	<pre>nrelSetPowerAddr);</pre>
53	<pre>m_logger.Debug("Set_power_was_</pre>
	<pre>counted:_", setPower, ".");</pre>
54	// At the end of the agent's
	program, one of three
	methods ('FinishSuccessfully
	', 'FinishUnsuccessfully', '
	FinishWithError') must be
	called to indicate that the
	agent's performing of action
	is complete:
55	// - Method 'FinishSuccessfully
	' indicates that action was
	performed by agent
	successfully (sets class '
	action_finished_successfully
	'). It means that the agent
	solved specified problem.
56	// - Method '
	FinishUnsuccessfully '
	indicates that action was
	performed by agent
	unsuccessfully (sets class '
	action_finished
	_unsuccessfully'). It means
	that the agent didn't solve
	specified problem.
57	// - Method 'FinishWithError'
	indicates that action was
	performed by agent with
	error (sets class '
	action_finished_with_error')
	. It means that some
	incorrect situation was
	occurred in knowledge base.
58	// All these methods return
	objects of 'ScResult' class.

	An object of ScResult
	cannot be generated via
	constructor, because it is
	private.
59	return action.
	FinishSuccessfully();
60	}

Listing 34. Agent class implementation

Step 6. Define keynodes

For each agent, key sc-elements that the agent uses during the execution of its program can be specified. These key sc-elements are sc-elements that the agent does not generate, but uses in the process of searching for or generating connections between entities in knowledge base. Key sc-elements are named keynodes. These keynodes can be found by its system identifiers (method SearchElementBySystemIdentifier) if they have such identifiers.

ScKeynode class can be used to define keynodes as static objects and use them in agents. ScKeynodes class is base class for all classes with keynodes. It contains core keynodes, that can be used in each agent. See [38] to learn more about keynodes.

Define keynodes class for implemented agent (listings 35, 36 and 37).

1	set-agents-module/
2	agent/
3	sc_agent_calculate_set
	_power.hpp
4	sc_agent_calculate_set
	_power.cpp
5	+ keynodes/
6	+ sc_set_keynodes.hpp
7	CMakeLists.txt

Listing 35. Keynodes source location

CMakeLists.txt

1	file(GLOB SOURCES
	CONFIGURE_DEPENDS
2	"*.cpp" "*.hpp"
3	"agent/*.cpp" "agent/*.hpp"
4	+ "keynodes/*.hpp"
5)
6)

Listing 36. CMake build configuration update

sc_set_keynodes.hpp

#include <sc-memory/sc_keynodes.
 hpp>

2
3
// This class unites keynodes
that used by agents of one
module (with one sense).

1

```
4 class ScSetKeynodes : public
     ScKeynodes
  {
5
 public:
6
    static inline ScKeynode const
       action_calculate_set_power{
      "action_calculate_set_power"
8
         , ScType::ConstNodeClass
         };
    static inline ScKeynode const
9
       nrel_set_power{
10
      "nrel_set_power", ScType::
         ConstNodeNonRole;
    // Here the first argument in
11
       constructor is system
       identifier of sc-keynode
       and the second argument is
       sc-type of this sc-keynode.
        If there is no sc-keynode
       with such system identifier
        in knowledge base, then
       the one with specified sc-
       type will be generated.
    // Type of sc-keynode may not
12
       be specified here, be
       default it is 'ScType::
       ConstNode'. But ensure that
        the code will use this
       keynode with type 'ScType::
       ConstNode' correctly.
13 };
```

Listing 37. Keynodes class definition

sc-keynode with empty system identifier cannot be specified. It can be invalid.

All keynodes must be static objects. Keynodes can be defined as static objects everywhere (not only in classes).

Inject using keynodes in agent implementation (listing 38).

sc_agent_calculate_set_power.cpp

```
#include "
     sc_agent_calculate_set_power.
     hpp"
2
 #include <sc-memory/
     sc_memory_headers.hpp>
 + #include "keynodes/
5
     sc_set_keynodes.hpp"
 ScAddr ScAgentCalculateSetPower
7
     ::GetActionClass() const
 {
8
    return m_context.
     SearchElementBySystem
```

```
Identifier("
     action_calculate_set_power");
     return ScKeynodes::
  +
10
     action_calculate_set_power;
  }
11
12
 ScResult
13
     ScAgentCalculateSetPower::
     DoProgram(ScAction & action)
14
  {
  - ScAddr const &
15
     nrelSetPowerAddr
      = m_context.
16
     SearchElementBySystem
     Identifier("nrel_set_power");
17
 - ScAddr const &
     membershipArcAddr = m_context
      .GenerateConnector(
      ScType::ConstPermPosArc,
18
          nrelSetPowerAddr,
          arcCommonAddr);
19
  + ScAddr const &
     membershipArcAddr = m_context
      .GenerateConnector(
      ScType::ConstPermPosArc,
20
          ScKeynodes::
          nrel_set_power,
          arcCommonAddr);
21
  - action.FormResult(
22
      setAddr, arcCommonAddr,
23
     setPowerAddr,
     membershipArcAddr,
     nrelSetPowerAddr);
 + action.FormResult(
24
 +
      setAddr, arcCommonAddr,
25
     setPowerAddr,
     membershipArcAddr, ScKeynodes
     ::nrel_set_power);
    m_logger.Debug("Set_power_was_
26
       counted:_", setPower, ".");
    return action.
27
       FinishSuccessfully();
  }
28
```

Listing 38. Agent class implementation

Step 7. Implement module class for agent

Someone should subscribe the agent to event. It can be other agent, or any code at all. A class that allows subscribing agents can be implemented. This class is named sc-module. Each sc-module should subscribe agents with common sense.

Implement module and subscribe implemented agent to event (listings 39, 40 and 41).

```
set-agents-module/
```

2	agent/
3	<pre> sc_agent_calculate_set</pre>
	_power.hpp
4	<pre> sc_agent_calculate_set</pre>
	_power.cpp
5	keynodes/
6	<pre> sc_set_keynodes.hpp</pre>
7	+ sc_set_module.hpp
8	+ sc_set_module.cpp
9	CMakeLists.txt

Listing 39. Module sources location

sc_set_module.hpp

```
#pragma once
2
 #include <sc-memory/sc_module.</pre>
3
     hpp>
 class ScSetModule : public
5
     ScModule
  {
6
    // Here class is empty. No
7
       need to implement any
       methods.
    // 'ScModule' class contains
       all necessary API to
       subscribe agents as
       separate sc-module.
 };
```

Listing 40. Module class definition

sc_set_module.cpp

1	<pre>#include "sc_set_module.hpp"</pre>					
2	<pre>#include "agent/ sc_agent_calculate_set_power.</pre>					
4	hpp"					
5	SC_MODULE_REGISTER(ScSetModule)					
6	->Agent<					
	<pre>ScAgentCalculateSetPower>() ;</pre>					
7	; // This method pointers to module that agent class ` ScAgentCalculateSetPower` should be subscribed to sc- event of adding outgoing sc -arc from sc-element ` action_initiated`. It is default parameter in this method if an agent class inherited from ` ScActionInitiatedAgent` is subscribed.					

8 9 // This way of subscribing agents makes it easier to write code. 10 // There is no need to think about unsubscribing agents after the system shutdown -

Listing 41.	Module	class	implementation

itself.

the module will do it all by

If something else in the module besides agents needs to be initialized, methods Initialize(ScMemoryContext * context) override; and Shutdown(ScMemoryContext * context) override; can be overriden.

All modules functionality can be found in the [39]. *Step 8. Write tests*

To make sure how the agent works, it is best to generate tests and cover in them all possible cases that the agent has to handle. For this, create a separate file with test cases and implement them. A good code is a code covered by tests.

Write tests for implemented agent (listing 42, 43 and 44).

1	set-agents-module/
2	agent/
3	<pre> sc_agent_calculate_set</pre>
	_power.hpp
4	<pre> sc_agent_calculate_set</pre>
	_power.cpp
5	keynodes/
6	sc_set_keynodes.hpp
7	+ tests/
8	+ test_sc_agent_calculate
	_set_power.cpp
9	<pre> sc_set_module.hpp</pre>
10	<pre> sc_set_module.cpp</pre>
11	CMakeLists.txt

Listing 42. Agent tests location

CMakeLists.txt

1	<pre># code, specified above</pre>							
2								
3	# Collect all files with the .							
	cpp extension from the tests							
	directory.							
4	file(GLOB TEST_SOURCES							
	CONFIGURE_DEPENDS							
5	"tests/*.cpp"							
6)							
7								
8	# Create an executable file for							
	tests.							

```
9 add_executable(set-agents-tests
     ${TEST_SOURCES})
  # Link the tests with the agent
10
     module library.
u target_link_libraries(set-agents)
     -tests
      LINK PRIVATE GTest::
12
          gtest_main
      LINK PRIVATE set-agents
13
14
  # Add the source directory to
15
     the list of paths for header
     file lookup.
 target include directories (set-
16
     agents-tests
17
      PRIVATE ${
          CMAKE_CURRENT_SOURCE_DIR }
18
19
20 # Add tests to the project.
  # WORKING_DIRECTORY sets the
21
     working directory for running
       tests.
  gtest_discover_tests (set-agents-
22
     tests
      WORKING DIRECTORY ${
23
          CMAKE CURRENT SOURCE DIR
          }/tests
24
        Listing 43. Tests build configuration
```

```
test_sc_agent_calculate_set_power.cpp
```

```
// Include the header file for
     testing agents
  #include <sc-memory/test/sc_test</pre>
      .hpp>
  #include <sc-memory/
     sc_memory_headers.hpp>
  #include "agent/
     sc_agent_calculate_set_power.
     hpp"
  #include "keynodes/
     sc_set_keynodes.hpp"
9 using AgentTest = ScMemoryTest;
10
 TEST_F(AgentTest,
11
     AgentCalculateSetPower
     FinishedSuccessfully)
12 {
    // Register the agent in sc-
13
       memory.
```

```
m_ctx->SubscribeAgent<
14
        ScAgentCalculateSetPower>()
        ;
15
    // Create an action with a
16
        class for the agent to
        execute.
    ScAction action
17
      = m ctx->GenerateAction(
18
          ScSetKeynodes::
          action_calculate_set_power
          );
19
    // Create a set with two sc-
20
        elements.
    ScSet set = m_ctx->GenerateSet
21
        ();
    ScAddr nodeAddr1 = m_ctx->
22
        GenerateNode(ScType::
        ConstNode);
    ScAddr nodeAddr2 = m_ctx->
23
        GenerateNode (ScType::
        ConstNode);
    set << nodeAddr1 << nodeAddr2;</pre>
24
25
    // Set the created set as an
26
        argument for the action.
    action.SetArgument(1, set);
27
28
    // Initiate and wait for the
29
        action to complete.
    action.InitiateAndWait();
30
31
    // Verify that the action was
32
        completed successfully.
    EXPECT_TRUE (action.
33
        IsFinishedSuccessfully());
34
    // Get the result structure of
35
         the action.
    ScStructure structure = action
36
        .GetResult();
    // Verify that it contains sc-
37
        elements.
    EXPECT FALSE (structure.IsEmpty
38
        ());
39
    // Check sc-constructions in
40
        the result structure.
    // Verify the first three-
41
        element construction.
    ScIterator3Ptr it3 = m_ctx->
42
        CreateIterator3(
      structure, ScType::
43
          ConstPermPosArc, ScType::
```

```
ConstCommonArc);
    EXPECT_TRUE(it3->Next());
44
    ScAddr arcAddr = it3 \rightarrow Get(2);
45
46
    auto [beginAddr, linkAddr] =
47
        m_ctx->
        GetConnectorIncidentElements
        (arcAddr);
    EXPECT EQ(beginAddr, set);
48
    EXPECT TRUE (m ctx->
49
        GetElementType(linkAddr).
        IsLink());
50
    // Verify that the content of
51
        the link equals 2.
    uint32_t setPower;
52
    EXPECT_TRUE (m_ctx->
53
        GetLinkContent (linkAddr,
        setPower));
    EXPECT_EQ(setPower, 2u);
54
55
    // Verify the second three-
56
        element construction.
    it3 = m ctx->CreateIterator3(
57
      structure, ScType::
58
          ConstPermPosArc, ScType::
          ConstPermPosArc);
    EXPECT TRUE (it3->Next());
59
    ScAddr arcAddr2 = it3->Get(2);
60
61
    auto [relationAddr,
62
        targetArcAddr] = m_ctx->
        GetConnectorIncidentElements
        (arcAddr2);
    EXPECT_EQ(relationAddr,
63
        ScSetKeynodes::
        nrel_set_power);
64
    EXPECT_EQ(targetArcAddr,
        arcAddr);
65
    // Unregister the agent from
66
        sc-memory.
    m ctx->UnsubscribeAgent<</pre>
67
        ScAgentCalculateSetPower>()
        ;
68
69
  // Provide tests for
70
      unsuccessful and error
      situations.
  // ...
71
```



ScMemoryTest class includes m_ctx that is object of ScAgentContext class. You can use it to work

with sc-memory. See [40] and [41] to learn more about available methods for working with sc-memory.

Step 9. Build problem solver

Build it using CMake (listing 45).

1	cmake	preset	release-conan
			_

2 cmake --build --preset release

Listing 45. Build problem solver

These commands use CMake to build the C++ problem solver in Release mode. The -preset option specifies a pre-configured build setup.

Step 10. Run sc-machine

1	./sc-machine/bin/sc-machine -s
	kb.bin -e "sc-machine/lib/
	extensions;scp-machine/lib/
	extensions;build/Release/lib/
	extensions"



It starts the *sc-machine*, loading the knowledge base (kb.bin) and specifying the paths to the extensions.

To stop the running server, press Ctrl+C in the terminal where *sc-machine* is running.

X. Step-by-step guide to using web user interface within the OSTIS Technology

A. About sc-web

sc-web [42] is an intelligent user interface that serves as the primary web component of the OSTIS Technology. It provides a universal rendering mechanism for semantic interfaces defined within knowledge bases and is included as part of the OSTIS Platform.

B. Quick start with Docker

To quickly deploy *sc-web*, use the official Docker image (listing 47). It allows to connect the user interface to a running *sc-machine* server either locally or remotely.

```
1 # Connect to a remote sc-machine
server
2 docker run --rm -it -p 8000:8000
ostis/sc-web:latest --
server_host=<server-ip>
3
4 # Connect to a local sc-machine
instance
5 docker run --rm -it --network=
host ostis/sc-web:latest
```

Listing 47. Run sc-web with Docker

After starting, the web interface will be available at http://localhost:8000.

C. Manual installation

Step 1. Clone repository Clone *sc-web* repository (listing 48).

```
git clone https://github.com/
ostis-ai/sc-web --recursive
2 cd sc-web
```

Listing 48. Clone sc-web repository

Step 2. Install dependencies

For Ubuntu/macOS, install Node.js dependencies (listing 49) and Python dependencies (listing 50).

1	./scripts/install_dependencies.					
		sh				
2	nvm	use	16			
3	npm	inst	all			

Listing 49. Install Node.js dependencies

```
python3 -m venv .venv
source .venv/bin/activate
pip3 install -r requirements.txt
```

Listing 50. Install Python dependencies

Otherwise, ensure the following are installed:

- python3,
- pip,
- nodejs,
- npm,
- grunt-cli, and Python modules (tornado, sqlalchemy, numpy, configparser, py-sc-client).

Step 3. Build frontend

Build frontend of sc-web (listing 51).

```
1 npm run build
```

Listing 51. Build frontend

Step 4. Run backend server

Ensure *sc-machine* is running. Then start the backend (listing 52).

1	source .ve	env/bin/activate
2	python3 se	erver/app.py

Listing 52. Run backend server

The user interface will be accessible at http://localhost:8000.

To stop the running server, press Ctrl+C in the terminal where *sc-web* is running.

XI. Contributing and engaging with OSTIS Community

Active participation in the *OSTIS Community* accelerates knowledge sharing, troubleshooting, and collaborative advancement of the technology. Developers are encouraged to contribute, seek support, and stay informed about ongoing updates and events. Join *OSTIS Community* by research these opportunities:

- Join Element Chat OSTIS Tech Support [43]. Engage in real-time discussions, seek technical support, and collaborate with peers through the dedicated OSTIS Tech Support room.
- 2) Explore GitHub Repositories [8]. Contribute to the ongoing development of OSTIS Technology by accessing source code, submitting issues, and proposing enhancements via the official GitHub repositories. Use GitHub's issue tracker if you encounter issues or have suggestions.
- 3) Attend OSTIS Conference [44]. Participate in the annual OSTIS Conference, which brings together academics, industry professionals, and students to present research, share experiences, and initiate collaborative projects. The conference is open to all interested parties.

The OSTIS Community actively promotes communityengaged research practices, emphasizing the importance of trust-building, transparent role definition, and shared vision among stakeholders. The annual OSTIS Conference exemplifies this approach by providing a venue for presenting peer-reviewed research, networking, and forming new partnerships across academia and industry

XII. Development directions of the OSTIS Project

The OSTIS Project is evolving along several strategic directions aimed at advancing the theory, technology, and practical application of intelligent systems. The main development domains are as follows:

- formalization and continuous refinement of the OS-TIS Standard;
- development of the OSTIS Metasystem for intelligent project management and knowledge support;
- development of applied intelligent systems for automation and decision support;
- development of platform and tools for scalable intelligent system implementation;
- formation of a global OSTIS Ecosystem for knowledge exchange and collaboration;
- development of educational programs and training materials;
- maintenance of up-to-date documentation and a centralized knowledge portal.

These directions collectively aim to ensure the sustainable evolution of *OSTIS Technology* as a comprehensive, open, and interoperable technology for intelligent systems, supporting both foundational research and practical applications in diverse fields.

XIII. Conclusion

The OSTIS Technology provides a practical and modular framework for building semantically compatible intelligent systems. The approach centers on clear ontological structuring, use of *SC-code* for knowledge representation, and a multi-agent architecture for problem solving.

The step-by-step methodology – defining project structure, configuring dependencies, formalizing knowledge bases, and implementing agents – enables fast prototyping and easy extension of intelligent systems. OSTIS's plug-and-play integration, platform independence, and reflexivity make it suitable for scalable and maintainable solutions in research and industry.

The provided workflows ensure that developers can quickly assemble, verify, and expand their systems, focusing on real tasks rather than boilerplate or infrastructure issues.

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ПРИНЦИПЫ АВТОМАТИЗАЦИИ РАЗРАБОТКИ ОТКРЫТЫХ ПРОЕКТОВ НА ОСНОВЕ ЭКОСИСТЕМЫ ИНТЕЛЛЕКТУАЛЬНЫХ КОМПЬЮТЕРНЫХ СИСТЕМ НОВОГО ПОКОЛЕНИЯ

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Статья предназначена для исследователей, разработчиков и практиков в области искусственного интеллекта, инженерии знаний и проектирования интеллектуальных систем, которые стремятся создавать, расширять или интегрировать <u>семантически совместимые</u> интеллектуальные системы.

Данная статья особенно актуальна для тех, кто интересуется:

- разработкой модульных, повторно используемых и совместимых интеллектуальных систем с использованием технологий с открытым исходным кодом;
- применением формальных онтологических методов и SC-кода для представления знаний и рассуждений;
- реализацией многоагентных решателей проблем и их интеграцией с семантическими базами знаний;
- использованием технологии OSTIS для образовательных, исследовательских или промышленных приложений, требующих адаптивности, масштабируемости и семантической совместимости;
- изучением практических рабочих процессов, включая установку, настройку и тестирование, с помощью реальных примеров, таких как ostisexample-app.

Представленное в статье руководство предполагает базовое знакомство с понятиями искусственного интеллекта, онтологий и разработки программного обеспечения, но предоставляет подробные пошаговые инструкции, подходящие как для новичков, так и для опытных специалистов в этой области.

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Design Principles of Intelligent Personalized Healthcare Systems

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Abstract—this article proposes an approach for designing next-generation intelligent personalized healthcare systems, emphasizing the synergy between technological innovation and clinical applicability. The study delineates architectural frameworks, knowledge integration methodologies, ethical governance models, and human-intelligent system interaction paradigms essential for developing scalable, secure, and socially acceptable solutions. By analyzing interdisciplinary approaches spanning computer science, clinical medicine, and bioethics, the research aims to bridge the gap between theoretical advancements and real-world clinical integration, ensuring that such systems align with both technical feasibility and patient-centered care imperatives.

Keywords—intelligent personalized healthcare systems, semantic interoperability, artificial intelligence in healthcare, patient-centric care, predictive analytics, ethical governance, health data security, explainable AI, chronic disease management, regulatory compliance, 4P medicine (predictive, preventive, personalized, participatory), OSTIS, bloodbased biomarkers, algorithmic bias mitigation.

I. Introduction

The contemporary healthcare landscape is undergoing a paradigm shift driven by the escalating prevalence of chronic diseases, aging populations, and the growing demand for personalized, patient-centric care. Traditional healthcare models, predominantly reactive and episodic, face significant limitations in addressing the complexities of preventive medicine, longitudinal health monitoring, and individualized treatment strategies. Concurrently, systemic challenges such as resource scarcity, geographic disparities in access to specialists, and the rising burden on medical infrastructure underscore the urgent need for innovative solutions [1].

Intelligent personalized healthcare systems have emerged as a transformative force, leveraging advancements in artificial intelligence, machine learning, the Internet of Medical Things, and big data analytics. These systems enable a transition from fragmented care to continuous, data-driven health management, integrating real-time biosensor data, electronic health records, and multi-omics information to generate actionable insights. For instance, wearable biosensors facilitate ubiquitous monitoring of physiological parameters, while artificial intelligence-driven predictive analytics identify early biomarkers of conditions such as diabetes mellitus or cardiovascular disorders, enabling preemptive interventions.

However, the design and deployment of intelligent personalized healthcare systems entail multifaceted challenges. A critical issue lies in achieving semantic interoperability across heterogeneous data sources, including electronic health records, genomic datasets, and environmental sensors, which often adhere to disparate standards and formats. The reliability of artificial intelligence algorithms, particularly in scenarios with imbalanced or incomplete data, remains a persistent concern, necessitating robust validation frameworks to mitigate risks of diagnostic inaccuracies. Ethical and regulatory complexities, such as ensuring patient privacy under regulations like the General Data Protection Regulation and the Health Insurance Portability and Accountability Act, maintaining algorithmic transparency through explainable artificial intelligence, and addressing biases in training datasets, further complicate implementation. Additionally, adaptive learning mechanisms are required to enable systems to evolve with dynamic patient states and emerging medical knowledge without catastrophic forgetting [2].

II. Core requirements for intelligent personalized healthcare systems

The development of intelligent personalized healthcare systems demands a rigorous framework of requirements to ensure their efficacy, safety, and alignment with clinical and ethical standards. This section outlines the foundational prerequisites that guide the design and implementation of such systems, focusing on functional, operational, and socio-technical dimensions rather than specific technological implementations.

A primary requirement is the unified integration of heterogeneous data sources, spanning biometric sensors, electronic health records, genomic repositories, and environmental datasets. Systems must ensure semantic consistency across diverse formats and terminologies, enabling seamless aggregation of structured and unstructured data. This necessitates adherence to internationally recognized medical data standards and ontologies, which facilitate cross-institutional data exchange and reduce ambiguities in interpretation. For instance, aligning blood pressure measurements from wearable devices with clinical-grade equipment requires standardized metadata annotation and temporal synchronization protocols [3].

Intelligent personalized healthcare systems must incorporate robust analytical frameworks capable of delivering precise, context-aware insights. Machine learning algorithms should demonstrate resilience to data imbalances, such as underrepresented patient demographics or rare disease cohorts, through techniques that mitigate overfitting and bias. Models must dynamically adapt to evolving patient conditions and emerging medical knowledge, avoiding performance degradation when confronted with novel data patterns. This adaptability ensures sustained relevance in clinical workflows, particularly for chronic disease management where patient states fluctuate over time [4].

To foster trust among clinicians and patients, systems must prioritize interpretability of decision-making processes. Analytical outputs, such as risk predictions or treatment recommendations, should be accompanied by human-understandable rationales that link conclusions to input data and clinical guidelines. Explainability mechanisms must clarify how variables like genetic predispositions, lifestyle factors, or historical health data influence algorithmic outcomes, ensuring alignment with evidence-based medicine principles [5].

Compliance with global data protection regulations, such as the General Data Protection Regulation and the Health Insurance Portability and Accountability Act, mandates end-to-end security architectures. Systems must implement encryption protocols for data transmission and storage, granular access controls, and audit trails to prevent unauthorized use. Privacy-preserving techniques, such as federated learning, should enable collaborative model training without centralized data pooling, minimizing exposure of sensitive patient information [6].

User-centric design is critical to ensure intuitive interaction for both patients and healthcare providers. Interfaces must accommodate varying levels of digital literacy, offering customizable dashboards, multilingual support, and adaptive feedback mechanisms. For patients with disabilities, compliance with accessibility standards—such as screen reader compatibility and voice navigation—is essential. Clinician-facing tools should integrate seamlessly into existing workflows, minimizing cognitive load through automated data synthesis and prioritized alerting systems [7].

Systems must embed ethical governance frameworks to address biases in algorithmic decision-making, ensuring equitable outcomes across diverse populations. Transparent consent mechanisms are required for data collection and secondary use, particularly for genomic or behavioral information. Regulatory compliance extends beyond data privacy to encompass clinical validation processes, wherein algorithms undergo rigorous testing against real-world cohorts to verify safety and efficacy before deployment [8], [9].

Architectures must support horizontal and vertical scalability to accommodate growing patient populations and expanding data volumes. Redundancy mechanisms, such as distributed data storage and failover protocols, ensure uninterrupted operation during infrastructure failures or cyberattacks. Systems should also adapt to resource-constrained environments, such as rural health-care settings, without compromising core functionalities [10].

III. Ethical and legal aspects

The global deployment of intelligent personalized healthcare systems necessitates a rigorous examination of the legal, ethical, and sociotechnical challenges inherent to their integration within diverse healthcare ecosystems. This section delineates the multifaceted interplay between regulatory frameworks, ethical imperatives, and technological innovation, emphasizing the imperative for harmonized standards to ensure equitable and secure healthcare delivery.

Jurisdictional disparities in regulatory approaches underscore the complexity of governing intelligent personalized healthcare systems. The European Union's General Data Protection Regulation, enacted in 2018, establishes stringent safeguards for health data processing, mandating explicit patient consent for automated decisionmaking under Article 22 and prohibiting algorithmic opacity in clinical diagnostics. In contrast, the United States employs a decentralized regulatory model, wherein the Health Insurance Portability and Accountability Act governs data security, while the 21st Century Cures Act promotes interoperability through standardized application programming interfaces. This fragmented approach has precipitated regulatory gaps, particularly in addressing liability for artificial intelligence-driven diagnostic errors, a void partially filled by state-level initiatives such as California's Consumer Privacy Act [11], [12].

Asian regulatory frameworks reflect divergent priorities. China's Personal Information Protection Law, implemented in 2021, emphasizes state access to health data for public health surveillance, while Japan's Act on the Protection of Personal Information prioritizes anonymization techniques to facilitate secondary data use for biomedical research. These regional incongruities complicate the development of transnational intelligent personal healthcare systems, necessitating adaptive architectures capable of complying with conflicting legal requirements [13].

A paramount ethical consideration within global healthcare ecosystems pertains to the transparency of artificial intelligence-driven decision-making processes. The World Health Organization's 2021 guidelines on ethics and governance of artificial intelligence for health advocate for explainable artificial intelligence frameworks to ensure algorithmic outputs are interpretable by clinicians and patients. For instance, the European Commission's proposed Artificial Intelligence Act classifies intelligent personalized healthcare systems as highrisk applications, requiring exhaustive documentation of training datasets, bias mitigation strategies, and performance metrics across diverse demographic cohorts [14].

Algorithmic bias, perpetuated by non-representative training data, remains a pervasive challenge. Studies in dermatology reveal diagnostic inaccuracies in artificial intelligence models trained predominantly on lighter skin tones, disproportionately affecting populations in Sub-Saharan Africa and South Asia. Similarly, gender disparities in cardiovascular risk prediction algorithms, documented across Latin American clinical trials, underscore the global ramifications of biased model design. The African Union's Framework on Artificial Intelligence Ethics addresses these inequities by mandating inclusive dataset curation and participatory design methodologies involving underrepresented communities [15].

The absence of harmonized international standards for health data exchange poses significant barriers to the scalability of intelligent personalized healthcare systems. While the International Organization for Standardization's technical specification ISO/TS 22220 provides guidelines for patient identification, legal conflicts persist between data sovereignty laws and cloud-based system architectures. The European Union's General Data Protection Regulation restricts cross-border data transfers to jurisdictions lacking adequacy agreements, a provision incompatible with decentralized systems reliant on global server networks.

Initiatives such as the Global Digital Health Partnership, comprising 30 member states, seek to reconcile these disparities through policy alignment on data sharing and artificial intelligence governance. However, divergent national priorities—such as India's emphasis on cost-effective solutions versus Germany's focus on precision medicine—hinder consensus. Emerging technical solutions, including federated learning architectures and blockchain-based audit trails, offer partial mitigation by enabling collaborative model training without centralized data aggregation, thereby preserving jurisdictional compliance.

The World Health Organization's SMART Guidelines initiative exemplifies successful transnational cooperation, providing modular architectures for digital health systems adaptable to local epidemiological and infrastructural contexts. In Rwanda, the integration of these guidelines with intelligent personalized healthcare systems facilitated real-time prediction of malaria outbreaks while adhering to national data sovereignty laws. Conversely, the European Health Data Space, proposed in 2022, aims to unify access to electronic health records across European Union member states, though implementation challenges persist due to heterogeneous technical infrastructures and multilingual interoperability barriers.

The Global Alliance for Genomics and Health further illustrates the potential of international collaboration through its Beacon Project, which enables secure querying of genomic datasets across borders without transferring raw data. This framework balances scientific progress with ethical imperatives, ensuring compliance with regional privacy regulations such as the United States' Genetic Information Nondiscrimination Act and the European Union's General Data Protection Regulation [16].

The 2021 UNESCO Recommendation on the Ethics of Artificial Intelligence advocates for human rights-centric design principles in intelligent personalized healthcare systems, emphasizing equity, sustainability, and accountability. Parallel efforts by industry consortia, such as the Toronto Declaration on Machine Learning in Healthcare, promote open-source model sharing and third-party algorithmic audits to enhance transparency [17].

Regulatory bodies are increasingly classifying advanced intelligent personal healthcare systems as medical devices, subjecting them to premarket validation protocols. The United Kingdom's Medicines and Healthcare products Regulatory Agency, for instance, has proposed stringent evaluation criteria for artificial intelligencedriven diagnostic tools, a model adopted by Health Canada and Australia's Therapeutic Goods Administration. These developments signal a global shift toward risk-based regulation, though disparities in enforcement capacity between high-income and low-income nations threaten to exacerbate existing healthcare inequities [18].

IV. Proposed approach

In light of the identified requirements for intelligent personalized healthcare systems, including interoperability, semantic consistency, and adaptive knowledge processing, the Open Semantic Technology for Intelligent Systems (OSTIS) is proposed as a foundational framework for system design. OSTIS represents a nextgeneration semantic technology paradigm centered on the unified representation and context-aware processing of knowledge. Unlike conventional approaches reliant on syntactic data structures, OSTIS prioritizes semantic harmonization, enabling the integration of heterogeneous medical data, domain-specific ontologies, and decisionmaking algorithms into a cohesive architecture [19].

The core objective of OSTIS is the universal unification of knowledge representation through standardized semantic models. By translating diverse data types ranging from electronic health records and genomic datasets to clinical guidelines and sensor-generated biomarkers



Figure 1. Formalized knowledge base fragment for intestinal atony disease.

into a common semantic format, OSTIS eliminates structural and terminological disparities that hinder interoperability. This unification facilitates the creation of a global OSTIS Ecosystem, a federated network where healthcare systems, analytical tools, and domain-specific applications interoperate via shared semantic protocols.

Key advantages include:

- Semantic interoperability enables seamless data exchange between legacy systems, AI-driven diagnostic modules, and IoT-enabled wearable devices, addressing fragmentation in current healthcare infrastructures
- OSTIS supports dynamic knowledge inference through logic-based semantic networks, allowing systems to adapt recommendations based on evolving patient states, comorbidities, and epidemiological trends.
- 3) By embedding clinical ontologies (e.g., SNOMED CT, ICD-11) and causal relationships into its semantic framework, OSTIS ensures traceability of AI-generated decisions, aligning with regulatory demands for explainable AI in medicine.
- The reuse of preconfigured semantic components and collaborative knowledge engineering within the OSTIS Ecosystem reduces redundant development efforts, enabling rapid prototyping and deployment.

For personalized medical systems, OSTIS provides a structured methodology to harmonize patient-centric data streams with population-level health analytics. Its semantic architecture inherently supports ethical imperatives, such as bias mitigation through ontology-guided data sampling and privacy preservation via granular access control mechanisms defined at the semantic level. An



Figure 2. Gastrointestinal tract's diseases ontology fragment.

example of ontology fragment is shown in the figure 2 and represents gastrointestinal tract's diseases subsection. The adoption of OSTIS is posited to advance the realization of "4P" medicine (predictive, preventive, personalized, participatory) by fostering interoperable, context-sensitive healthcare ecosystems.

The system architecture comprises three core components: a knowledge base, a problem solver, and a webbased user interface. The knowledge base is structured as a semantic network of disease-specific modules containing granular symptom profiles, laboratory parameter correlations, and pathophysiological relationships. An example of a formalized fragment of a knowledge base is shown in the figure 5. These modules are interconnected within a unified semantic memory, enabling rapid and precise knowledge processing through context-aware reasoning. Problem solver integrates logical inference rules with adaptive algorithms to execute diagnostic operations. The hematological diagnostic workflow follows a multi-stage pipeline:

- 1) Data ingestion, where acquisition of heterogeneous blood test parameters is made.
- Data normalization, where conversion of raw values into ontology-compatible semantic representations is made.
- Pattern recognition, where comparison of normalized data against reference ranges and diseasespecific signatures within the knowledge base is made.
- 4) Conflict resolution, where reconciliation of ambiguous findings via probabilistic scoring and evidence-based decision matrices is made.
- 5) Output generation, where production of ranked diagnostic hypotheses annotated with confidence intervals and supporting biomarkers is made.

This architecture ensures clinician-centric operation, where the interface presents hypotheses as actionable recommendations requiring mandatory physician validation prior to treatment planning.

V. Blood-based biomarkers in disease diagnostics

Modern disease diagnostics are inconceivable without blood analysis – a method combining the precision of laboratory science with clinical interpretation. Blood serves as a universal indicator of health, reflecting organ dysfunction, metabolic disturbances, and latent pathological processes long before overt symptoms manifest. Over recent decades, technological advancements have transformed routine blood tests into robust tools of personalized medicine, enabling not only disease detection but also the prediction of disease progression.

Blood tests analyzing white blood cells (WBCs), platelets, and red blood cells (RBCs) are foundational for identifying a wide range of conditions, from infections to blood disorders. Each cell type provides unique insights into health and disease [20].

WBCs reflect the body's immune response. Elevated WBC counts (leukocytosis) often indicate bacterial infections, such as pneumonia, where neutrophils dominate. Viral infections, like mononucleosis, typically increase lymphocytes and may show atypical cells. Low WBC counts (leukopenia) can signal autoimmune diseases, chemotherapy effects, or bone marrow disorders. Abnormal cells, such as immature blasts, are critical for diagnosing leukemia. For example, chronic lymphocytic leukemia is identified by a high lymphocyte count and specific cell markers. Platelet levels help assess clotting risks. High platelet counts (thrombocytosis) may occur in inflammatory diseases (e. g., rheumatoid arthritis) or blood cancers like essential thrombocythemia, linked to genetic mutations. Low platelet counts (thrombocytopenia) arise from immune destruction (e. g., immune thrombocytopenia), liver disease, or bone marrow failure. Severe thrombocytopenia raises bleeding risks.

RBCs and hemoglobin levels diagnose anemia and polycythemia. Anemia is classified by cell size:

- microcytic anemia (small cells) suggests iron deficiency, confirmed by low ferritin;
- macrocytic anemia (large cells) often stems from vitamin B12 or folate deficiency, detectable via blood tests;
- normocytic anemia (normal cell size) may indicate chronic diseases.

High RBC counts (polycythemia) can result from genetic conditions, lung diseases, or tumors overproducing erythropoietin. Hemolytic anemia, marked by rapid RBC breakdown, shows increased young RBCs (reticulocytes) and low haptoglobin.

Combined analysis of WBCs, platelets, and RBCs enhances diagnostic accuracy. For instance, low levels of all cells (pancytopenia) may indicate bone marrow failure or cancer spread. Elevated platelets with high RBCs suggest blood cancers, requiring genetic testing (Tefferi et al., 2020). Blood smear microscopy identifies cell abnormalities, such as immature cells in leukemia or fragmented RBCs in hemolysis [21], [22].

Figure 2 illustrates the successful implementation of a diagnostic rule based on leukocyte, thrombocyte, and erythrocyte parameters in human blood, designed using the SCg (Semantic Code graphical) knowledge representation language.

Blood tests measuring thyroid-stimulating hormone (TSH), follicle-stimulating hormone (FSH), and luteinizing hormone (LH) are pivotal for evaluating endocrine function, particularly in thyroid and reproductive health. These hormones, produced by the pituitary gland, serve as biomarkers for disorders ranging from hypothyroidism to infertility [23].

TSH regulates thyroid hormone production (thyroxine, T4, and triiodothyronine, T3). Elevated TSH (>4.0 mU/L) with low free T4 indicates primary hypothyroidism, often caused by autoimmune Hashimoto's thyroiditis or iodine deficiency. This reflects the pituitary's attempt to stimulate an underactive thyroid. Conversely, suppressed TSH (<0.4 mU/L) with high T4/T3 signals hyperthyroidism, commonly due to Graves' disease or toxic nodules. Subclinical hypothyroidism (TSH 4.0–10.0 mU/L with normal T4) may progress to overt disease, especially with anti-thyroid peroxidase antibodies.

FSH and LH govern reproductive function. In women, they regulate the menstrual cycle and ovarian activ-



Figure 3. Formalized blood test diagnostic rule for intestinal atony disease.

ity. Elevated FSH (>25 IU/L) and LH (>15 IU/L) in reproductive-aged women suggest primary ovarian insufficiency (POI), marked by follicular depletion. During menopause, sustained high FSH/LH confirms ovarian failure. Conversely, low FSH/LH indicates hypogonadotropic hypogonadism, often due to pituitary tumors, stress, or excessive exercise, impairing ovulation and estrogen production [24].

In polycystic ovary syndrome, an LH/FSH ratio >2:1 is common, driven by hypothalamic-pituitary dysregulation. This imbalance promotes androgen overproduction, contributing to irregular cycles and infertility.

In men, FSH stimulates sperm production, while LH triggers testosterone synthesis. Elevated FSH/LH with low testosterone indicates primary testicular failure (e.g., Klinefelter syndrome). Low FSH/LH with low testosterone points to secondary hypogonadism, often linked to pituitary disorders [25].

Formalized rules implemented in the SCg language, as exemplified in this section, are utilized by the developing intelligent personalized healthcare system, aiding in preliminary disease identification. Designed algorithm employs formalized rules to analyze user-provided blood parameters against reference values, evaluate marginal thresholds and conflicts, determine possible disease associations, and return a diagnostic result.

The proposed system is designed to primarily automate the diagnostic workflow associated with blood test analysis, thereby significantly alleviating the workload of healthcare personnel. It is critical to emphasize that the system functions as a decision-support tool, generating probabilistic diagnostic hypotheses based on algorithmic interpretation of hematological parameters. Final clinical decisions, particularly those involving lifecritical interventions, remain the exclusive responsibility of licensed medical professionals. This human-centric design ensures adherence to ethical obligations in medical practice, preserving clinician oversight as a nonnegotiable component of patient care.

The workflow of the proposed intelligent system is illustrated in Figure 3. A blood sample undergoes automated analysis, where key parameters including white blood cell count, platelet levels and red blood cell morphology are extracted and processed using algorithms. The system identifies anomalies and correlates them with knowledge base-stored reference data to generate ranked diagnostic hypotheses. These hypotheses are presented to the clinician via an interpretable interface. Crucially, the physician retains full authority to accept, modify, or reject the system's suggestions, ensuring ethical accountability.

VI. Conclusion

The convergence of blood-based biomarker diagnostics and intelligent semantic architecture represents a paradigm shift in modern healthcare systems. Building upon analysis of leukocyte, thrombocyte, and erythrocyte parameter modeling via SCg, this work extends the framework through Open Semantic Technology for Intelligent Systems, which unifies diagnostic rule formalization with context-aware reasoning. By harmonizing



Figure 4. Formalized blood test diagnostic rule for hypogonadotropic hypogonadism disease.

Общий анализ крови	*		8 =
Тромбоциты	Эритроциты	Лейкоциты	
234	32434	23423	
Возможные диагнозы:			
холангитдакриоаденит			

Figure 5. The workflow of the proposed intelligent system.

heterogeneous data streams from hematological indices to multimodal health records, OSTIS addresses critical challenges in interoperability, ethical governance, and explainable AI, while preserving patient-centric priorities. The proposed architecture synthesizes adaptive semantic interoperability protocols and regulatory-compliant design to advance 4P (predictive, preventive, personalized, participatory) medicine. Notably, the integration of domain-specific diagnostic logic (e. g., blood biomarker thresholds) with OSTIS's knowledge representation capabilities demonstrates a scalable pathway for translating computational innovations into clinical workflows.

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ПРИНЦИПЫ ПРОЕКТИРОВАНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ ПЕРСОНАЛЬНОГО МЕДИЦИНСКОГО ОБСЛУЖИВАНИЯ

Сальников Д. А.

Данная статья предлагает подход для проектирования современных интеллектуальных систем персонального медицинского обслуживания, нацеленный на синергию технологических инноваций и клинической применимости. В работе описаны архитектурные решения, методы интеграции знаний, модели этического регулирования и парадигмы взаимодействия человека с интеллектуальной системой, необходимые для создания масштабируемых, безопасных и социально приемлемых систем. Путем изучения междисциплинарных подходов на стыке компьютерных наук, клинической медицины и биоэтики исследование направлено на преодоление разрыва между теоретическими разработками и практическим внедрением в клинические процессы.

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Principles of Building Intelligent Tutoring Systems for Secondary Education

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Abstract—The article describes an approach to creating intelligent tutoring systems using a geometry tutoring system as an example. The proposed approach assumes two modes of interacting with the system - theory tutoring and problem solving methods tutoring. The theory tutoring component allows the student to learn the material, obtain answers to various questions, and test their knowledge. In the problem-solving methods tutoring mode, the system performs a step-by-step solution checking, and provides the necessary support by answering the student's questions. This approach enables the system to store the knowledge necessary for solving problems in a formalized manner, to answer questions about the methods for solving a problem in the course of its solution, and to provide for wholistic tutoring of the theoretical concepts, including knowledge testing, which distinguishes it from other contemporary systems.

Keywords—problem solving, knowledge, knowledge base, intelligent systems, intelligent tutoring system, tutoring system

I. Introduction

In recent decades, there has been a significant increase in interest in tutoring systems in the field of school education, with particular attention being paid to the development of systems that promote independent learning.

Most recently, special attention has been paid to tutoring systems based on language models [1]. In particular, in the field of mathematics, systems that offer users automated solutions to problems have become readily available. However, despite their advantages, they do not provide sufficient support to users in the learning process. This work aims at developing an approach that focuses on interactive step-by-step guidance, aimed at effectively teaching users specific methods for solving problems rather than automatically obtaining answers.

II. State of the art

Examples of systems based on large language models (LLM) in the field of mathematics include Mathful [2],

Mathos AI [3], and MathGPT [4]. However, developers of such systems also promote solutions based on the same principles in other domains, such as chemistry or physics.

Such systems are marketed as problem solvers that provide the user with a description of the solution for educational purposes. This means that they are usually designed to solve problems automatically instead of offering step-by-step support to the user, which is a notable shortcoming of systems aimed at automatic problem solving.

In general, for interactive problem solving, existing LLMs can be used as is. In the latest versions of popular models, a reasoning function has appeared, which allows the user to see the problem-solving process itself, which can help in studying the material. However, using LLMs in their pure form has its drawbacks: for example, there is no control over the complexity of the information and its presentation, which is why the solution may not correspond to the student's level of knowledge; in addition, such problems of LLMs as providing unverified information and hallucinations are widely discussed [5]. The use of LLMs and AI in the field of education is also associated with additional ethical issues, such as personal data security and possible biases [6].

Moreover, the solution provided by LLM-based problem solvers can utilize methods that diverge from ones adopted in the school curriculum. LLMs also have a tendency to generate materials that do not always correspond to curricula approved by educational institutions. This can lead to the student learning problem solving methods that are not covered by the school curriculum or learning terminology that differs from the requirements of the course they are taking.

A different approach is taken by educational systems such as Euclidea [7] and Geogebra [8]. Euclidea is an application with a set of interactive tasks for studying geometry, which offers users the ability to check one's solution and read brief explanations before each task. An interesting feature of this system is its gamification – as students complete tasks, they can earn points depending on how efficiently the task was solved.

Geogebra, on the other hand, is an educational system for various areas of mathematics, aimed at developing the skills of school-age students in the relevant subject matter. The system has a detailed and wholistic program with a set of tasks on various topics, and the tasks are classified based on the student's level of knowledge (determined by their school grade). The system includes hints, tasks that teach specific theory, and test questions for reinforcement. Additionally, the system offers integrations with other systems used in education, such as Google Classroom.

However, the drawback of these systems is that they do not offer interactive and personalized support to students at all stages of studying the material and solving problems. The user does not have the opportunity to ask questions of interest at any time, and the systems themselves do not have a knowledge base on the topics being studied, which would allow them to interactively answer such questions.

Thus, this work is aimed at eliminating the abovementioned shortcomings in existing tutoring systems by developing an approach that focuses not so much on automatic solution of various problems and providing solutions, but rather on effective teaching of the user through interactive step-by-step guidance in solving problems using specific methods. The task providing for the ability of the system to solve arbitrary problems was not set at this stage.

III. Proposed approach

We propose to develop a system that will not only provide ready-made solutions to problems, but also perform an educational function, facilitating the solution process, rather than offering the answer immediately. For successful problem-solving, the user needs theoretical knowledge, so it is reasonable to implement two modes of working with the system:

- 1) Working with theory, including learning the theory and answering questions about it, as well as a testing mode.
- 2) Problem-solving training, in which the user is offered a problem on a given topic for solution, and the system provides support, giving explanations and hints if necessary.

We propose to create intelligent tutoring systems based on the OSTIS technology, which is focused on the development of knowledge-driven computer systems. The main principles of this technology [9] allow us to identify three key components: *knowledge base*, *problem solver*, and *user interface*, which corresponds to the traditional definition of an intelligent system [10]. As a formal basis for representing knowledge in this technology, a unified semantic network with an interpretation based on set theory is used. This representation model is called SC-code (Semantic Computer Code). The elements of the semantic network are denoted as sc-nodes and sc-connectors (sc-arcs, sc-edges). Agents described using SC-code will be called semantic agents or simply sc-agents.

This technology will help to set the necessary structure for organizing theory in the system, and with its multiagent approach, it will allow us to implement agents that help the user to solve specific problems based on preformalized problems.

To ensure that the theoretical material provided by the system corresponds to educational standards, it is necessary to formalize it in the system's knowledge base, within which it is possible to relatively easily structure the material according to various characteristics: topics, correspondence to specific classes, etc. – including the ability to take into account several characteristics at the same time.

The translation of formalized knowledge into a natural language representation is proposed to be carried out using LLMs with the approach described in the work [11].

The proposed approach not only allows the use of LLMs and various classifiers, but also creates conditions for their effective integration with the advantages of the developed intelligent educational system [12]. This synergy opens up new opportunities for improving the quality of interaction with users and enhancing the educational process.

The integration of LLMs in an intelligent system based on the OSTIS technology significantly expands the functional capabilities of the intelligent tutoring system. This allows for the creation of more effective and personalized learning conditions, which represents a significant step towards improving the quality of the educational process.

Using the OSTIS technology, we can effectively store knowledge obtained during communication with the user. This will enable the formation of more personalized responses, taking into account the context and individual needs of each student. Personalization of learning promotes deeper mastery of the material and increases student motivation.

Finally, to ensure necessary support in the process of problem solving, the knowledge base must contain problems' standard solution plans in the form of a sequence of actions. The issue of automatic construction of solution plans is discussed in the work [13], but at the initial stage of prototype development, it was decided to abandon the implementation of this mechanism in favor of manual preliminary description of solutions in the knowledge base. This will allow for faster testing of the concept and minimize errors associated with automatic generation. Thus, we propose to build the system according to the following principles:

- 1) A formalized representation of theoretical material in the knowledge base.
- A formalized representation of the actions necessary to solve a problem (generated by the system automatically or prepared in advance).
- 3) Translation of formalized knowledge into natural language.
- 4) Integration with LLMs as a means of generating tests, as well as part of the pipeline for translation of formalisms into natural language, but not as a source of knowledge.
- 5) The presence of functionality for interactive learning of problem-solving by users.
- 6) The presence of a user model in the system.

Next, we will consider the structural components of the system.

A. Theory tutoring component

The theory tutoring component provides a range of functional capabilities that facilitate the mastery of theoretical material.

The system proposes to divide learning by grade and topic. During the learning process, the user will be able to:

- 1) **Study material on a specific topic.** Before asking the system specific questions, the user must select the topic they want to study. After that, they will be provided with a list of key concepts, theorems, properties, etc. on a specific topic.
- 2) Get an answer to key questions. The system can provide answers to individual questions that interest the user on a specific topic. The intelligent system ensures the provision of information on a range of requests, including:
 - definition of term X;
 - properties inherent to X;
 - statements related to X;
 - theorems and properties within the corresponding field.
- 3) Consolidate the material. The user can consolidate the material by taking a test on the topic, where the system will ask the user questions exclusively on the selected topic.

The advantage of the proposed approach is that the intelligent system will limit its answers to include only the information directly related to a specific topic. This significantly reduces the likelihood of distracting the user with extraneous aspects unrelated to the material being studied.

Thus, the student will be able to focus exclusively on the knowledge and skills necessary for a deep understanding of the subject. Focusing on relevant information promotes more effective mastery of the material and improves the quality of education. Additionally, such a targeted structure of interaction allows minimizing cognitive load, which in turn can contribute to a higher level of retention and application of acquired knowledge.

B. Problem-solving methods tutoring component

This component is proposed to be divided into two sub-components:

- 1) Component for solving pre-formalized problems.
- 2) Component for solving problems that are unknown to the system.

Within the proposed intelligent system, students are given the opportunity to practice solving problems, which is an important aspect of their educational process. Students are offered a text description of the problem, accompanied by relevant graphical material, which facilitates visualization of the problem and better understanding of the task.

In the process of working on the problem, the student has the opportunity to enter intermediate values on the graphical representation or in the associated interface. For example, in the case of a geometry tutoring system, such a representation will be a drawing, and when solving a problem to calculate the perimeter of a right triangle with known legs, it is expected that the student will first enter the length of the hypotenuse. This function allows the system to track the sequence of steps performed to solve the problem and evaluate their correctness, which is critically important for forming skills and abilities.

In addition, the system provides the opportunity to ask clarifying questions about solving the problem. The student can request information on the following aspects:

- which theorems may be useful for solving the given problem;
- what properties should be remembered;
- what formulas may be useful in the solution process;
- what needs to be calculated next.

The system also allows for clarifying the correctness of intermediate results, which promotes the student's selfcontrol and increases their confidence in their abilities.

To implement the functionality for working with problems whose solutions are not previously known, it is critically important to create a module designed to build a solution plan for the problem. This module plays a key role in breaking down complex problems into simpler and more trivial components that do not require additional effort to solve [13].

With the help of this module, the system will be able to not only provide the user with the final answer, but also, as in the case of pre-formalized problems, offer hints that will help in the solution process. This will allow students to better understand the structure of the problem and develop analytical thinking skills.

IV. An example of the application of the proposed approach

The testing of the proposed approach is being carried out on the basis of existing developments of a tutoring system for geometry, since an extensive knowledge base on this topic was already created previously.

The system consists of three components: the user interface, the knowledge base, and the problem solver.

A. User interface

The interface of the developed system is presented in Fig. 1. The figure illustrates the key component of the system – the problem-solving component, which consists of the following elements:

1) Natural language chat.

This element provides students with the ability to ask clarifying questions about solving problems. Students can request information about useful theorems, properties, necessary formulas, and the sequence of calculations. Two-way communication between the student and the system via the chat promotes a deeper understanding of the material and active involvement of students in the learning process.

2) Drawing, which is a visual representation of the problem, making it much easier to understand. Students can enter intermediate values on the drawing, for example, the length of the hypotenuse in a problem of calculating the perimeter of a right triangle. This function allows the system to track the sequence of steps performed and evaluate their correctness, which is critical for developing problem-solving skills.

3) Data entry field.

This element is indicated by an arrow in the figure. This element allows students to enter the necessary values directly on the drawing, which improves interaction with the system.

B. Knowledge base

As part of the previously developed geometry system, an extensive knowledge base was created, which includes Euclidean geometry, various theorems, and basic concepts. This knowledge base serves as the foundation for teaching students and forming their mathematical skills. In connection with the need to adapt the system to the educational standards of secondary education, it was decided to supplement the existing platform with subject areas corresponding to different school grades.

This approach has several significant advantages. It allows the system to more accurately navigate through theorems and corollaries, which in turn promotes more effective problem-solving, taking into account the level of knowledge of the students. For example, for 7thgrade students, a simple and accessible solution to a problem will be proposed, corresponding to their level of preparation. This will provide them with the opportunity to gradually master the material and develop basic skills. In turn, for 9th-grade students, the system will be able to offer more complex hints and recommendations, corresponding to their higher level of knowledge. This will create conditions for in-depth study of geometry, which will help students develop critical thinking and analytical abilities. The possibility of a differentiated approach to learning is a key aspect that contributes to the individualization of the educational process and increases its effectiveness.

Thus, this approach has several advantages:

- 1) Promotion of more effective problem-solving, taking into account the level of knowledge of the students.
- 2) Adaptation of the system to the user's knowledge.
- 3) Gradual mastery of the material by students.
- 4) Development of critical thinking and analytical abilities in students.

C. Problem solver

As part of the developed system, a problem-solving verification agent was integrated, which plays a key role in the educational process. The system's knowledge base was supplemented with formalized problems from various areas of geometry, as well as theorems necessary for performing specific actions. This agent actively uses these formalized problems to evaluate user solutions, providing them with drawings to fill in.

The verification agent monitors the correctness of the user's problem-solving, comparing the user's actions with standard formalized problems. If errors are detected during the solution process, the agent highlights them in red on the drawing, indicating specific areas where inaccuracies were made.

When the user encounters difficulties or does not know how to continue solving the problem, the system offers hints without completely revealing the correct answer. For example, if a student tries to immediately indicate what the area equals to, ignoring the need to calculate the height, the agent draws attention to this and reports that necessary data is missing to complete the solution.

Fig. 2 shows an example of a formalized problem statement.

Fig. 3 shows a formalized sequence of actions for solving a problem with necessary justifications.

In Fig. 4, a construction in the knowledge base is presented, which is the result of performing one of the actions involved in solving the problem.

V. Conclusion

In this paper, we discussed an approach for creating an intelligent tutoring system that effectively integrates the teaching of theoretical aspects with the development of practical problem-solving skills. The system creates conditions for students to independently master the material and improves their skills.



Figure 1. User interface of the intelligent tutoring system for geometry



Figure 2. Formalization of a problem statement

The system provides users with the opportunity to solve complex problems step by step, breaking them down into simpler parts, which promotes a deeper understanding of the theory and forms a conscious approach to the solution process. Students can ask clarifying questions and receive recommendations on necessary theorems and formulas, which significantly improves their understanding of the subject matter.

Additionally, storing knowledge about the user in a knowledge base will allow the system to generate more accurate and contextualized responses, making the learning process more adaptive and effective. Thus, this intelligent tutoring system represents a significant step towards improving the quality of education, successfully combining theoretical knowledge with practical problemsolving skills and allowing students to develop independently.

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Figure 3. A formalized sequence of actions for solving a problem



Figure 4. The construction that is the result of performing one of the actions involved in the solution

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ПРИНЦИПЫ ПОСТРОЕНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ ОБУЧАЮЩИХ СИСТЕМ ДЛЯ СРЕДНЕГО ОБРАЗОВАНИЯ

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В статье описывается подход к созданию интеллектуальных обучающих систем на примере обучающей системы по геометрии. Предлагаемый подход подразумевает два режима работы системы – обучение теории и обучение методам решения задач. Компонент обучения теории позволяет изучить материал, получить ответы на различные вопросы по теме и протестировать полученные знания. В режиме обучения решению задач система осуществляет поэтапную проверку решения и поддержку, отвечая на вопросы ученика. Данный подход обеспечивает способность системы хранить необходимые знания по решению задач в формализованном виде, отвечать на вопросы по методам решения задачи в процессе ее решения, осуществлять комплексное обучение теоретическим аспектам, включая тестирование знаний, что отличает его от существующих систем.

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Intelligent Semantic Educational System: Purpose and Structure

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Abstract—In the article, the purpose and the structure of national intelligent educational system is considered. The properties and some requirements to the system along with the structural layers content are proposed. The system is plotted as interoperable, adaptive, multi-agent, each of the agents having its' own personal assistant as an intelligent subsystem to provide self-monitoring, control and establishing connections and communications within the system and with the third parties. The obtained results will allow determining the direction for development of intelligent educational system of national level as well as the subsystems and their educational content by means of the artificial intelligence technologies.

Keywords—intelligent educational system, semantic system intelligence, interoperability, multi-agent system, personal assistant

I. Introduction

In the last decade, especially after the Covid-19 pandemic, the development and implementation of information systems has been a top priority for almost all countries in the world. Today, information systems designed for use on a global scale have become a relevant area of research and development – not only by individual enterprises, but by corporations, sectors of the economy, and at the state level. In our country, this issue is also given much attention.

In any state, the level of development of society, public relations and, to a large extent, the economy is determined by the level of education and health of the members of this society. The quality of education significantly affects the intellectual potential of society as a whole, not only its younger generation, but also the future of the country.

Recently, a large number of scientific studies and publications have appeared in the field of development of integrated information environments. The issue of creating integrated educational environments using artificial intelligence technologies, network technologies, automation of administrative activities of educational institutions of different levels is being actively studied [1], [2]. Research in this direction is also being conducted in our country. Thus, the structure of the Republican information and educational environment is proposed [3]– [5]. The solutions proposed in these works allow creating a platform at the level of the education sector and include integration with various republican platforms and services, as well as with information systems at the level of higher education institutions, schools, and kindergartens. This is relevant work, and not only for the education system, but is of particular importance for it.

II. The structure of the intelligent educational system

Some problems to be covered within the intelligent semantic educational system (ISES). In addition to solving the problem of digitalization and informatization of education, the development and implementation of such information and educational environments should be aimed at solving important problems that exist today in the field of education at all its levels in our country. Among them are the creation of interactive semantic textbooks in various disciplines, automation of work processes in the work of teachers and administrators; personalization of education, aimed at the school level at identifying the interests of students, their inclinations to a particular type of activity, in general, at the career guidance of the student, at the level of professional training - at improving the quality of knowledge and skills of the student, taking into account his abilities and interests in the chosen field; increasing the degree of interaction between theory and practice in professional education; providing opportunities to improve the level of education of each participant in the system; unification of the processes of interaction of participants in the educational process; professional expertise of the quality of educational resources, pedagogical methods and techniques.

The requirements to the ISES. An educational semantic intelligent system must meet such requirements as adaptability, interoperability, security, scalability, communication, the ability to analyze processes both within the system and when interacting with third-party systems, and the use of a single platform for the development and operation of subsystems. Adaptability – the ability of a system to change when external conditions change so that the goal of the system's functioning is achieved, even if changes in external conditions prevent this – is an important property for maintaining the system's

operability when not only external conditions change, but also when its structural elements and/or connections within the system between its elements need to change. When new structures emerge in the education system, or the functions of existing elements change, it is important to maintain the system's operability during the transition period. Interoperability is not only a requirement for the functional compatibility of the technical components of the system, but also a necessity for the semantic compatibility of its subsystems. Security concerns the personal data of system users and all participants in the educational process, the data of the system itself, the processes of interaction within the system and with external systems, etc. Scalability is responsible for the ability to expand the system, i.e. add both new hardware and software resources to it, as well as increase the number of users and the diversity of their roles in the system. Communicability acts as a requirement for processing various types of data (information), using different approaches in the process of preparing and transmitting data necessary for intra-system communication, including users (students, teachers, etc.), along with interoperability is responsible for the semantic compatibility of the system and its individual subsystems and user requests. The ability to analyze processes - reflection - a requirement to analyze one's state at any given moment and make decisions on the need to correct actions to maintain the working state. Using a single platform for developing and operating the system will allow unifying and simplifying all technological and organizational processes, reducing the labor intensity of new developments and their implementation, complying with the above requirements, and training new developers, administrators, and users of the system faster and easier. The list of requirements can be changed in the course of research and work on creating and filling the system.

The structure of the ISES. Educational activities of any structures and organizations in our country are regulated centrally, therefore, automation of educational activities should be carried out based on the hierarchy of the entire education system both in terms of the educational process itself and the management of educational activities. Thus, the first step towards solving the problem of educational activities automation on a global scale can be the development of the architecture of an intelligent interoperable information system of education and the provision of educational services, taking into account the requirements for the system.

The educational semantic intelligent system should be considered as a global community of local intelligent systems of individual educational organizations and associations, down to the smallest unit of this community - an individual user. This global community will include educational institutions of different levels schools, secondary specialized educational institutions,



Figure 1. General structure of the global intellectual educational system

higher educational institutions, etc. - research institutes in the field of education, institutions for advanced training of specialists of different levels, enterprises and organizations that train their employees, organizational and management structures, and finally, individual users, such as schoolchildren, students, postgraduates, and adult participants in the educational process. All of them are included in the general global system as separate subsystems, also organized according to the principle of hierarchy. Separate subsystems can organize families among themselves, which also represent an intelligent system, depending on the direction of activity, the level of education of the student, the professional focus of training, etc. The diagram of the system is presented in Figure. 1. This structure is obviously a multi-agent one, so all the technologies, requirements and properties of the multi-agent systems are expected here.

The main role in organizing the work of such a global structure is assigned to the intelligent system "Personal Assistant" (PA). At the same time, the user of such a system is understood to be a unit of the system – an individual (as a participant in the educational, administrative or other process within the global system) or one of its subsystems in the global community, including the global system itself.

Main participants of the ISES:

- Learners
- Teachers (subject teachers, organizers, speech therapists, psychologists, psychologist-correctors, class teacher (curator), personal mentors (tutors))
- Experts in the field of educational content, pedagogical methods, teaching methods, etc.
- Administrators (educational institutions, technical, network, learning platform, etc.)
- Developers (technical programmers, testers, developer specialists in various fields of knowledge, teachers, psychologists, lawyers, etc.)
- Observers with the right to control processes (representatives of government agencies associated with educational standards, for example, the Ministry

of Education, National Institute for Higher Education, etc., parent/legal representative of a (underage) learner)

Each participant in the system can have different roles. For example, a teacher can act as an expert or administrator, a developer – as an observer or expert, any participant as a learner, etc. These roles determine the availability of data and services of the system for each participant at any given moment. Data is collected in the system and provided to the user upon request, personal data is primarily stored by the user, in his Personal Assistant (PA), and can be transferred upon request, provided that the requester has the right of access to this personal data processing. The system operation can be organized on the principle of a peer-to-peer network, each node of which can be a separate subsystem (network) performing its tasks. Individual elements of the system can be designed and developed as fractal structures, which determines the possibility of unification and standardization of the development of such systems, simplifying their implementation and operation. The internal representation of data and knowledge of all subsystems must be the same, the language of communication of subsystems and users must be defined. Individual elements of the system must be interoperable.

III. The main structural layers of the ISES

The internal architecture of each subsystem of the global system, including the global system itself, can be represented as consisting of several main layers: Data – Semantic processing – Components based on artificial intelligence – Applications and connection with existing third-party platforms. The layers "Semantic processing" and "Components based on AI" have a common element "Subsystem of explanations", which allows responding to user requests about the decisions made by the system. All these layers are united by a single infrastructure, the entire system, each of its subsystems and each participant (user) have in their structure the control element "Personal assistant (of the system)" (PA), which ensures communication and interoperability of all elements of the system (Fig. 2). Let's look at these layers in more detail.

Data Layer includes databases/knowledge bases, multi-modal data, data about trainees. *A. Databases/knowledge bases.* The data base and knowledge base make the heart of the system, acting as a structured repository of educational knowledge, administrative and managerial models, and expert knowledge. It is an integrator of educational and methodological materials, methods, and technologies for determining personal priorities and psychological characteristics of students. It combines otologies (formal knowledge models) and knowledge graphs to represent concepts, relationships, and resources specific to subject



Figure 2. The structure of a separate subsystem and the scheme for organizing the interaction of personal assistants of subsystems and users of the global system

areas and methodological approaches. Each subsystem can have its own database and knowledge base, but they must be largely general, i. e. accessible to each subsystem, and respond to user requests. Otologies and knowledge graphs are part of the knowledge bases.

Otologies define the structure of educational concepts, relationships, and hierarchies. They are formal, machinereadable structures that define the vocabulary, concepts, and relationships within a subject area (e.g. mathematics, computer science, physics, or linguistics). Key features present as Classes/entities to represent real or abstract concepts (e.g., course, skill, assessment); Properties/attributes: define characteristics of entities (e.g., a course has prerequisites, duration, learning outcomes); Relationships: define how entities interact (e.g., student \rightarrow enrolled \rightarrow course; skill \rightarrow required \rightarrow prerequisite skill); Hierarchies: organize concepts into taxonomies (e.g., math \rightarrow algebra \rightarrow linear algebra).

Today, in world practice, there are such standards as RDF - a standard for representing data in the form of triples (subject-predicate-object) [6], – OWL, which extends RDF to provide the possibility of complex reasoning [7].

Knowledge graph: A graphical representation of interconnected entities (nodes) and relationships (edges). It extends otologies by dynamically linking real-world data (e.g. student performance, resources, and institutional policies).

Structure:

- Nodes: represent entities such as Student, Course, Video, Grade, or Instructor.
- Edges: represent relationships (e.g. Student X → enrolled → Course Y; Video Z → teaches → Concept A).
- Triple format: (Subject, Predicate, Object) (e.g. Course 1 has prerequisite Algebra).

Functions:

• Multimodal integration: Links text, images, videos, and interactive content to concepts

- Dynamic updates: evolve as new data is added .
- Cross-domain connections: enable interdisciplinary learning.

Implementation tools available today include: Triplestores [8] for storing and querying RDF/OWL data; graph databases like Amazon Neptune [9].

B. Multi-modal data. Structured storage of educational resources (textbooks, videos, tests, simulations) and interactive content with semantic annotations. Main features:

- Metadata tagging;
- Annotation;
- Ontology links: Resources are linked to the knowledge graph.

C. Information about users-learners:

• Learner profiles (demographics, learning style, knowledge levels, learning history).

Semantic processing layer – *Semantic search:* Keyword-based search and semantic search over the knowledge graph to retrieve relevant resources (e.g., "Show me a video about solving kinematics problems").

Knowledge output: Reasoning mechanisms for inferring relationships (e.g., "If a student masters algebra, he can move on to calculus").

AI-powered components. *Adaptive learning mecha-nism:*

- Content development tools for *Personalization* (using machine learning models to recommend content based on student performance and goals) and *Learning Paths* (creating dynamic, personalized learning paths based on knowledge gap analysis and learners' progress through the content.
- Semantic textbooks in various disciplines built on the basis of AI tools [10].
- Tools for assessing the user's abilities, learning preferences, psychology of perception, communicative characteristics, determining methods and technologies for personalized learning taking into account the tasks and goals of learning, etc.

Rating and Feedback:

- Automated assessment: for example, using NLP algorithms to assess essays, papers, problem solutions, code submissions or open-ended responses.
- Competency tracking: identifying the user's (learner's) achievements by matching them with some predefined competencies (e.g. "Can solve linear equations") using an ontology.

Application layer

This layer may include the *User Interface (UI)* for system roles:

• Interface for technical developers with tools for managing data and functions of both the system as a whole and individual users (content developers, trainees, etc.)

- Tools for standards developers, including the ability to conduct collegial discussions and evaluate standards, programs, textbooks, methods and other content of the educational system, determine the direction of development of the education system, etc.
- Portals of educational institutions of different levels.
- Learner Portal: A dashboard showing personalized learning plans, progress, and recommendations
- Teacher tools: analytics dashboards for monitoring class/group performance and adjusting curriculum.
- Content Creation: Tools for educators to develop, tag, and link resources to the knowledge graph.
- Expertise of content and methods of its development.

Integration with existing systems:

- API for connecting to learning management systems such as, for example, Moodle, Canvas or Blackboard [11].
- Single sign-on for user authentication.

Infrastructure

- Cloud/on-premises setup to host knowledge graph and AI models
- Real-time processing of interactions, requests and updates.

When developing the structure and components of the subsystems of each layer, it is also necessary to take into account that access to them should be organized based on the allocated roles of system users. This implies the need to define goals and objectives for each user role, as well as a structural and functional scheme of the user's work in this role, including requirements for the functions of the role, the results of work in this role, the system security, the organization of communications between system participants, etc.

IV. Personal assistant as a main communicative structure of each participant

Currently, there are different approaches to the educational process organizing using information technologies. Combining different approaches into a single system is possible based on compliance with the rules for storing and presenting data in a single format (several formats if necessary), maintaining semantic compatibility between system elements, implementing user self-training technologies in the subsystems of the PA, gradually transitioning existing platforms (systems, applications) and further filling the system with content based on semantic technologies. The latter can also be achieved by developing a kind of translator (interpreter) of existing technologies into a semantic representation.

An important component of each subsystemparticipant of the system is the Personal Assistant. It can be defined as a separate class of subsystems of the educational system under consideration, which is a mandatory component for each participant - a person, a technical subsystem, the system itself as a whole. The PA of the technical subsystem is mainly responsible for its communications, i.e. data exchange, processing requests from other system participants, forming its own requests, monitoring processes within its subsystem, analyzing and correcting the subsystem's work, storing data and providing access to them, etc.

In addition to the above functions, the user-trainee's PA may include the following elements of interaction with a person:

- Natural language processing subsystem (NLP) including NLP mechanisms for analyzing queries, feedback and content from developers and users; Recognizing user intent from his request (e.g., "I need help with calculus," "Find an AI course," "Create a new textbook," etc.); Contextual analysis: linking user queries to specific knowledge graph(s) (e.g. mapping "machine learning" to related concepts like "artificial neural networks").
- User interaction subsystem based on video surveillance – recognition of emotions, gestures, images, text, voice and, in general, the user's intentions based on the analysis of his image and the objects he depicts (text, drawings, diagrams, etc.)
- Conversational AI: A chat-bot that uses conversational systems to answer questions, provide hints, and guide the user through the system.

Some issues that require special attention during development. Data movement: user data processing should be carried out to the greatest possible extent on the user's devices, which will also ensure greater security of his personal data collected and accumulated by the system during the learning process. Ontology Maintenance: Regular updates to the knowledge graph are required to reflect new domains or standards. Confidentiality and data protection (including personal data of users) Interaction: Compatibility with existing educational platforms. A subsystem for translating data from such platforms into a semantic representation of the system is required, a kind of "translator" into the internal language of the system. Explainability: all results of the work of AI-based algorithms must be explainable, i.e. a subsystem of explanations is needed not only in the semantic textbooks on subjects themselves, but also when communicating with users.

The structure and functions of the subsystem "Personal Assistant". This subsystem is one of the most important in the structure of the educational intellectual system. Moreover, a user's personal assistant can accompany him throughout his life, being an assistant and keeper of various types of information - medical, educational, professional, household. The PA as a intelligent system should also be an integral part of any subsystem of the intellectual educational system. It is through the PA that communication between subsystems occurs, data is collected and the internal processes of each subsystem are managed, data is stored and processed. The user's PA can be built into small devices, presumably wearable, such as a smartphone or smart watch, for example. Since the PA contains a database, AI components, a user interface, the device must have high-capacity RAM, high-speed data processing elements, cameras and microphones/speakers, and provide reliable wireless communication. In turn, the algorithms of the AI components must be as resourceefficient as possible. In general, the PA is a whole class of information systems that can be developed for people, information, measurement, technological and other systems that participate jointly in any processes and global systems.

V. A unified platform for the development, operation and advancement of an intelligent semantic educational system

Today, there is a wide variety of platforms and tools available to develop and operate information systems, including learning systems, using artificial intelligence technologies. They make it possible to develop both small applications for solving some problems in the field of education, and distributed systems that provide access to a wide range of educational services. Some of the tools and technologies have been mentioned above. The creation of large distributed unified systems based on rather disparate platforms and technologies complicates the developer's task, administration of such systems, data flow management, data protection, entry into the system at the user level, complicates the adaptation of new elements and structures within an existing system. In turn, a single platform for developing a global intelligent educational system is an important condition for its success not only as an information system, but also as a public, state system. Such a single platform, developed in our country, is the technology of ontological design, production and operation of semantically compatible hybrid intelligent computer systems - OSTIS. In addition to its main characteristics, which are included in the name, there are a number of other advantages of its use as a basis for the development and implementation of a state intelligent educational system. Thus, the OSTIS standard [12]–[14] has been developed and is constantly updated, describing the current technology of design, production, operation and evolution of information systems. The OSTIS technology meets the requirements for the IES considered in this work, in particular, adaptability, interoperability, scalability, communicativeness. Interoperability is one of the most important properties of systems developed in accordance with the OSTIS technology. The project is open, which allows any interested person to both familiarize themselves with the documentation and apply the technologies, models, methods and tools of ontological design of semantically compatible hybrid intelligent computer systems, capable of independently interacting with each other, presented in the standard. This means not only the possibility of using the standard by system developers, but also a reduction in the threshold for a new user to enter the system, adaptation of new elements in the system, ensuring semantic compatibility of both already developed and operating systems and those that will be developed and implemented in the future. The transition to such a single platform will allow for the successful implementation of such projects as an intellectual school, an intellectual faculty/department, an intellectual university, and in the future, an intellectual society.

VI. Conclusion

To achieve high level of national education on the basis of unified information system is possible by automating a number of processes in the education system based on the use of semantic, multi-agent, neural network and other AI technologies, including them in the developed structure of the intelligent education system. One of the most important factors determining the level of intelligence of any information system is interoperability, the ability to form collectives with other individual systems, including people. The level of interoperability of the individual information systems of the entire collective that forms the national intelligent education system should be quite high. The national has to be designed on the platform of OSTIS - the original technology developed in our country, having its standard that meets all the requirements to the interoperable intelligent semantic educational system proposed in the present paper.

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ИНТЕЛЛЕКТУАЛЬНАЯ СЕМАНТИЧЕСКАЯ ОБРАЗОВАТЕЛЬНАЯ СИСТЕМА: НАЗНАЧЕНИЕ И СТРУКТУРА

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В работе рассматривается назначение и структура национальной интеллектуальной образовательной системы. Предложены свойства системы и некоторые требования, которым она должна удовлетворять, а также содержание её структурных слоев. Система строится как интероперабельная, адаптивная, многоагентная, каждый из агентов которой имеет своего персонального помощника (ассистента) в качестве интеллектуальной подсистемы для обеспечения самоконтроля, управления и установления связей и коммуникаций внутри системы и с другими системами. Полученные результаты позволят определить направления развития интеллектуальной образовательной системы национального уровня, а также её подсистем и их образовательного содержания с использованием технологий искусственного интеллекта.

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Integrated Automation of Water Disposal in Terms of Interoperability of Monitoring and Control Processes

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Abstract—The main regulatory requirements and recommendations for the justification and creation of systems for the integrated automation of processes in various industries are analyzed. A structural and functional analysis of the process control scheme is performed; it is revealed that less than half of the operations are automated (even with the participation of a human operator). The functional intersections of the used manual and automated methods of collecting information and regulating equipment modes are presented, such as those where it is necessary to implement the developed scenarios for increasing observability and controllability in the integrated automation of wastewater disposal systems in populated areas with a critical requirement for their interoperability. It is proposed to use the new generation methodological apparatus of OSTIS Technologies for such purposes.

Keywords—water disposal, monitoring, control, integrated automation, interoperability, OSTIS technology

I. Introduction

A vital necessity for the development of water supply and sewerage organisations (WSS) is the complex automation of their technological processes, which is a management that provides for the functioning of a production unit (section, shop, enterprise as a whole) as a single interconnected information complex with monitoring and regulation also with human participation [1], [2]. According to GOST 34 (GOST 34.601-90) the creation of automated control systems (ACS) includes the following stages: formation of requirements, concept development, terms of reference, preliminary design, technical design, working documentation, commissioning, maintenance. At the initial stage of creating an ACS it is necessary to conduct a survey of the automation object; on the basis of the obtained data it is necessary to identify the main functional and user requirements for such a product. As a result of the conducted research, an analytical report should be drawn up (GOST 7.32-2001 'Report on research work' can serve as a basis for the creation of the document).

At the same time, this task is extremely difficult from the design stage, because it is necessary to identify potential sources of increasing the intensity and efficiency, reducing the duration of forced downtime, as well as to estimate the amount of necessary capital and operating costs (caused, including abnormal situations) [3]. At the same time, an important component of complex automation is [4]: interfacing (informational and constructive) of systems and equipment; unification of hardware, algorithmic, software, methods and means of maintenance. Within the framework of water supply and sanitation organisations it is difficult to systematise the collection of initial information and to set tasks of coordination of automated technical means and personnel of water disposal complexes [5], as such where the operational observability of parameters is extremely low and the uncertainty of bio-physico-chemical transformations in water solutions is high [6].

II. Structural and functional analysis of wastewater disposal in settlements

Since the key role in the creation of ACS is assigned to the justification and coordination of its architecture, as it should determine the requirements and procedure for the design, development and modernisation (reconstruction) of a single system solution, the structural layout of the wastewater disposal scheme is performed (Fig. 1).

On the basis of expert and calculation assessments [5], [7] it is known that the degree of automation of municipal wastewater disposal at the moment is low (less than 35% of the required) – many control operations are performed by specialists of the enterprises themselves in manual and expert modes (tab. I), while the average level of their qualification at the moment does not meet modern requirements.

When further analysing the functionality of wastewater disposal, at the initial level of generalisation, it is assumed that the processes that are partially automated are fully controllable. At the same time, it is obvious that out of ten (see Table I) monitoring and control subsystems, extremely insignificant part of them (two - three) corresponds to the term 'automatic' (operation without human participation). At the same time, even in such a technological situation, the task of coordination of monitoring and control operations of units and assemblies is acute, which is currently not actually solved within the framework of water supply and sanitation organisations.

III. Interoperability of real wastewater disposal systems in settlements

According to ISO/IEC 24765 interoperability is the ability of two or more systems or components to exchange information and to use the information obtained as a result of the exchange. The problem of interoperability, according to world practice, should be solved on the basis of the use of principles and technologies of open systems, using methods of functional standardisation [8]. Such solutions are standardised by GOST R 55062–2021 'Information technologies. Interoperability. Basic provisions'. To ensure compliance with this standard, any particular solution should be obtained on the basis of a unified approach containing a number of basic stages; it is also necessary to develop a document containing a plan (strategy), as well as a glossary on the problem of interoperability.

Based on the generalised ways of automating (monitoring and controlling) wastewater management (see Table I) we summarised their interactions (Fig. 2).

Systematisation of the operational overlay confirms the critically poor observability and controllability of the processes of the technological complex of municipal wastewater disposal and treatment (see Fig. 2) – there are only six interactions. There is no direct interconnection between individual elements (primarily concerning the processes in sewage pumping stations (SPS) and the sewerage network); there is also no direct data exchange between automated solutions that solve different tasks information coordination is provided by a human specialist in periodic mode, whose qualifications require significant strengthening. A segment of the wastewater disposal network is not fully controlled. Based on the author's methods [5], [6], scenarios for increasing the observability and controllability of such a complex are proposed (Table II).

Based on such approaches (see Table II) it is necessary to solve the problem of interoperability at three levels: technical, semantic and organisational [9]. The technical level includes the tasks of interaction between the service and the hardware and software platform on which it is hosted. The semantic level reflects those mechanisms that are used by services to establish interaction both among themselves (clusters of services) and with users. Such a task requires the exchange of information between services concerning their qualities that have entered into interaction: it must provide information about the operations they perform in a form that is available to be analysed either by the user or by another service [10], [11]. At the organisational level, in fact, in terms of its operation, it is a question of implementing the legal side of the possibility of providing services to another party.

Accordingly, the proposed coordination of wastewater monitoring and control methods based on the criterion of 'interoperability' in complex automation requires a specialised methodological apparatus of a new generation. Such solutions include the OSTIS Technology [12]. Intellectual computer systems of new generation developed on its basis are called ostis-systems. The basis of OSTIS Technology is a universal way of semantic representation (coding) of information in the memory of intellectual computer systems, called SC-code. SCcode texts (sc-texts, sc-constructions) represent unified semantic networks with basic set-theoretic interpretation. The elements of such semantic networks are called scelements (ssuzzles and sc-connectors, which, in turn, depending on their orientation can be sc-arc or sc-ribes). The universality and unified nature of the SC-code allows describing on its basis any types of knowledge and any methods of problem solving, which, in turn, greatly simplifies their integration both within one system and within a team of such systems.

The basis of the knowledge base developed by OSTIS Technology is a hierarchical system of semantic models of subject areas and ontologies, among which there is a universal Kernel of semantic models of knowledge bases and methodology of development of semantic models of knowledge bases, providing semantic compatibility of developed knowledge bases [13]. The basis of the ostis-system problem solver is a set of agents interacting exclusively by means of specification of the information processes they perform in the semantic memory (scagents). All of the above principles together allow to ensure semantic compatibility and simplify the integration of various components of computer systems, as well as of such systems themselves, which is in demand for WRC



Figure 1. Generalised structure of the wastewater disposal system of settlements

Point	Description of monitored indicators	Monitoring and management solutions used						
No.								
1	Condition of local pipelines and construction and regulatory infrastructure of	Personal diagnosis and manual handling						
	wastewater network subscribers							
2	Efficiency of wastewater treatment at local treatment plants (LTP) (if any):	Monitoring and control are partially implemented in						
	compliance of quality indicators of discharged wastewater with the requirements	automated mode						
	of maximum permissible concentrations (MPC) of pollutants							
3	Resource costs of localised wastewater treatment: electricity, reagents and other	Monitoring and management are partially imple-						
	consumables	mented in automated mode (performed at the end						
		of the reporting period)						
4	Condition of local treatment plant (LTP) equipment (if any)	Monitoring is partially realised in automatic mode						
5	Compliance of quality indicators of discharged wastewater of controlled sub-	Personal diagnostics – performed by by specialists of						
	scribers with the requirements of MPC of pollutants	water supply and sewerage organisations						
6	Wastewater quality indicators in the wastewater network: from the control well	Not fulfilled						
	to the entrance to the municipal sewage treatment plant (STP)							
7	Condition of equipment and premises of sewage pumping stations of the wastew-	Monitoring is partially automated						
	ater disposal network, their piping and building and regulatory infrastructure							
8	Efficiency of wastewater treatment at municipal WSCs: compliance of treated	Monitoring and control are implemented in auto-						
	wastewater discharged into water bodies with the requirements of regulatory	mated mode (dispatching)						
	documents							
9	Resource costs of wastewater treatment at municipal WSCs: electricity, reagents	Monitoring and management are partially imple-						
	and other consumables	mented in automated mode (performed at the end						
		of the reporting period)						
10	Condition of equipment of municipal WSCs, their pipeline and construction	Monitoring is partially realised in automatic mode						
	and regulatory infrastructure, including aeration system with blower stations,							
	disinfection modules and reagent farms							

Table I Analysing the monitoring and management processes of the wastewater system



Figure 2. Scheme of interaction between monitoring and management of wastewater disposal (intersection of solutions means their interaction)

Table II

Scenarios for increasing observability and controllability in integrated automation of wastewater disposal systems in settlements

	1. Systematisation on the basis of a single platform of all primary and calculated parameters.						
	2. Systematisation on the basis of a single platform of all used models.						
Minimum scenario	3. Systematisation on the basis of a single platform of all algorithms used.						
	4. Formation on the basis of the platform of a single circuit of technological monitoring and control (with						
	the formation of an up-to-date knowledge base with the function of training personnel on site) according to						
	the criteria of 'resource efficiency', 'reliability', 'environmental safety'						
	1. Performing a 'minimal' scenario.						
	2. Creation and implementation of new integrated models and algorithms for monitoring and management						
Medium scenario	on the basis of a single platform.						
	3. Installation of additional measuring equipment, including for indirect assessment of parameters of the						
	technological complex of wastewater disposal and treatment.						
	4. Creation of laboratory modelling information systems (LIMS).						
	5. Creation and implementation of new integrated monitoring and management strategies based on a single						
	platform						
	1. Performing an 'average' scenario.						
	2. Obtaining data on subscribers 'dangerous' for the WSC; installation of additional measuring devices in						
Optimistic scenario	this system, including for indirect assessment of parameters of the technological complex of water disposal						
	and wastewater treatment.						
	3. Creation and implementation of new integral models and algorithms for subscribers 'dangerous' for the						
	water utility.						
	4. Creation and implementation of new integrated monitoring and management strategies based on a single						
	platform.						

organisations.

Using SC-code, a number of top-level ontologies have been developed for the sphere of housing and communal services, describing the most common concepts. Let us consider several fragments of these ontologies in the SC code [13].

utility equipment

:= [totality of technical devices and systems ensuring functioning of engineering infrastructure of apartment buildings and municipal facilities]

 \Rightarrow subdividing*:

- plumbing equipment
- electrical equipment
- heating equipment
- accounting and analytical equipment
- \Rightarrow subdividing*:
 - main technological equipment
 - *auxiliary equipment*
 - emergency equipment
 - test equipment
 - }
- \Rightarrow explanation*:

[A complex of mechanical, electrical and electronic devices that ensure the supply of communal resources (water, heat, electricity) and the safe operation of the housing stock. Includes both traditional engineering equipment and modern intelligent control systems.]

shut-off valves

:= [a technical device for controlling the flow of a working medium by changing the area of the flow cross-section]

 \Rightarrow subdividing*:

- partitioning by design
 - *{● gate valve*
 - flap
 - tap
 - vent
 - valve
 - }

=

 \Rightarrow possible material*:

- cast iron
- carbon steel
- stainless steel
- brass
- bronze
- titanium
- polymer

suspended solids

:= [complex compounds of organic and inorganic substances suspended in water]

 \Rightarrow subdividing*:

- **{•** organic suspended solids
- inorganic suspended solids
- }

 \Rightarrow

 \Rightarrow

areas of application*:

- **{•** *wastewater treatment*
- water quality monitoring

 $\} \\ \Rightarrow parameters^*:$

- concentration
- particle size
- }
- operating principle*:
 - {• sedimentation
 - *filtration*
 - coagulation
 - }

Conclusion

As a result of structural systematisation of the wastewater disposal scheme, the key subsystems (subscribers, wastewater disposal network, sewage treatment plants) were identified, and the analysis of the methods of monitoring and control of technological processes used in them substantiated the conclusion that their automation is extremely low. The degree of overlap between manual and automated monitoring methods is significant and requires mandatory compliance with the interoperability criteria within the created scenarios (minimum, average, optimistic) for increasing the observability and controllability of wastewater disposal in settlements – it is necessary to state separately that a unified technological ecological environment has not been created in WSS organisations at the moment.

Justified to overcome such a significant problem is the use of OSTIS Technology, the basis of which is a universal way of semantic representation (coding) of information in the memory of intelligent computer systems, called SC-code. The fundamental results obtained with its use will make it possible to implement digital transformation of the housing and communal services (including at the state level) along the chain: 'wastewater disposal' – 'water supply and wastewater disposal' – 'water supply and sewerage facilities as a whole' – 'housing and communal services as a whole' on the basis of fulfilling the criterion of interoperability of systems, where it is necessary to take into account the human factor and the need for significant improvement of staff qualification.

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КОМПЛЕКСНАЯ АВТОМАТИЗАЦИЯ ВОДООТВЕДЕНИЯ В РАЗРЕЗЕ ИНТЕРОПЕРАБЕЛЬНОСТИ ПРОЦЕССОВ МОНИТОРИНГА И УПРАВЛЕНИЯ

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Проанализированы основные нормативные требования и рекомендации к обоснованию и созданию систем комплексной автоматизации процессов разноотраслевых объектов. Выполнен структурный и функциональный анализ схемы технологического управления; выявлено, что автоматизированы (даже с участием человека-оператора) менее половины операций. Представлены функциональные пересечения используемых ручных и автоматизированных способов сбора информации и регулирования режимами оборудования, как такие, где необходимо реализовывать разработанные сценарии повышения наблюдаемости и управляемости при комплексной автоматизации систем водоотведения населённых пунктов с критическим требованием к их интероперабельности. Предложено для таких целей использовать методологического аппарата нового поколения Texнологии OSTIS.

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Principles and Solutions for Integrating Computer Algebra Tools and Applications Based on Open Semantic Technologies

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Abstract—The principles, methodical and technical solutions for the integration of the Ecosystem of intelligent computer systems of the new generation (OSTIS ecosystem) and computer algebra systems are considered. The expediency of such integration is shown; various integration options, advantages and disadvantages of these options are noted. The implementation of the proposed approach is considered using the example of an intelligent learning system in discrete mathematics with illustrations of studying the topic, performing visualization tasks and solving graph theory problems.

Keywords—OSTIS Ecosystem, Wolfram Mathematica computer algebra system, intelligent learning system for discrete mathematics.

I. Introduction

At the current stage of information technology development, the transition from modern computer systems to new-generation computer systems, which should have a sufficiently high level of intelligence, is relevant. This means a transition to a fundamentally new technological order in automation, and also makes it necessary to develop a comprehensive Technology to support the life cycle of intelligent computer systems (ICS) of a new generation. The systems developed on the basis of such technology are called ostis-systems [1].

A special place in the technology of ICS development and modernization is occupied by approaches that ensure the connection and use of the most successful modern solutions already used in various fields. Such solutions currently include computer algebra (CAS) systems. It is important to transform the modern variety of tools (frameworks) for the development of various ICS components into a single technology for integrated design and support of the full lifecycle of these systems, ensuring the compatibility of all components being developed, as well as the compatibility of the ICS themselves. Convergence and unification of a new generation of ICS and their components is necessary, and it must be possible to solve certain tasks with optimization and maximum performance requirements. Similar problems are being solved during the development, improvement, updating of the content and expansion of the capabilities of computer algebra systems. The integration of CAS and the OSTIS Ecosystem is an important and urgent task.

II. About the integration of computer algebra systems with applications within the OSTIS Ecosystem

One of the options for the interaction of the OSTIS Ecosystem and CAS may be approaches similar to those implemented within the framework of integration into ostis systems of artificial neural networks ([1] Chapter 3.6). It is advisable to consider the following methodological and technical solutions (in detail – [1] § 7.4.2):

- "Black box" integration.
- Closer integration, in which a specific function remains part of a third-party CAS, when not only the result of its implementation, but also all possible specifications are immersed in the ostis system's knowledge base.
- Full integration, which translates the used functions of the computer algebra system from the internal language of this system into the ostis system.

The expediency of using one or another integration option is primarily due to the difference in their complexity, which, in turn, makes step-by-step integration preferable as the project develops. So, at the stage of testing the idea of integration, it is advisable to use the "black box" option as the least labor-intensive, but at the same time making it possible to determine the advantages of such integration.

From the point of view of practice, at this stage of development and application of the OSTIS Ecosystem, *integration into a single set of CAS capabilities and intelligent learning systems* built within the OSTIS Ecosystem seems to be the most promising. The expediency of such integration is due to the fact that CAS has an undoubted advantage and wide possibilities in solving problems relevant to teaching systems in almost all natural science

and technical disciplines involving the use of complex mathematical apparatus.

Despite the popularity of topics related to the automation and intellectualization of educational activities in natural sciences and the development of appropriate computer systems, at the moment there are practically no proven intelligent learning systems in the public domain that have the ability to independently generate and solve various tasks, as well as verify the correctness of the resulting solution. The approach to solving the problems of intellectualization of educational activities, based on the integration of ostis systems and CAS, has a number of advantages:

- When developing ostis systems, the need to program many functions that are implemented, tested and tested in CAS is eliminated. This is essential, as CASs are developed by highly qualified specialists in their respective fields. The implementation of similar functions in ostis systems may require significant financial and time costs.
- A specific ostis system using individual CAS functions, thanks to the approach to developing hybrid problem solvers in OSTIS Technology ([1] § 1.1.1), gets the opportunity to plan the course of solving problems when individual stages are implemented using attached functions.

It should be emphasized that the integration options do not exclude each other and can be combined. The deepening of integration can be carried out in stages, taking into account the advantages and disadvantages, the relevance of using certain CAS functions in solving specific tasks within the framework of the relevant ostis systems [2].

The step-by-step integration of CAS with the OSTIS Ecosystem involves, at a minimum, a description of the specification of the main functions of the selected computer algebra system using OSTIS Technology, in other words, the development of an ontology of external functions. In the case of systems of the Wolfram Mathematica family, the process of developing such an ontology can be automated due to the presence of the formal Wolfram Language and the well-documented functions of the system.

III. An example of integration of a prototype of the ostis learning system for discrete mathematics and Wolfram Mathematica

We emphasize the fundamental positions and basic capabilities that dictate the expediency of integrating CAS with the OSTIS Ecosystem:

- work with mathematical expressions in symbolic form, performing analytical transformations, presenting results in mathematical notation;
- numerical operations of any specified precision;
- availability of various types of data processing;

- an interactive graphical visualization;
- registration of results and preparation for publication;
- the use of special-purpose expansion packs;
- programming in an embedded language, program synthesis.

Here are illustrations of the joint use of the Wolfram Mathematica CAS [3] and a prototype of a semantic electronic textbook on discrete mathematics (SET DM) developed on the basis of OSTIS Technology.

In the examples below, the source data (graph) is received (imported) from the SET DM. The parameters and properties of the graph can be derived, and the graph can be modified [4], [5]. Users have the opportunity to obtain solutions to typical graph theory problems; Mathematica's tools allow them to export preferred final results back to the SET DM with different graphical visualization options.

The following illustrations were obtained in Mathematica, while the original sc.g-text from the SET DM was used to define the graph. For an imported graph in CAS, you can get and output general information, for example: the number of vertices, arcs, and a list of edges; using Mathematica graphics, you can visualize vertices and edges in different stacking options, vertex and edge signatures [6].

It should be noted that for understanding the content and analyzing the parameters of a graph, its graphical visualization is important. According to this position, Wolfram Language provides users of the Mathematica system with a wide range of possibilities – more than 30 variants of typical graph views in different layouts, various user settings tools for creating a preferred layout [7], [8].

Graphs provide excellent visualization of information. Highlighting the graph elements will allow you to emphasize the features of the information and its interpretation.

Using the options, you can design, change, and connect: Highlight Graphic Elements, Overall Look and Feel, Graph Layout, Vertex and Edge Styles, Vertex and Edge Labels, Vertex and Edge Shapes, Interactive Effects.

Using algorithmic layouts (stacking) of the graph, most of the structure in the graph will be understandable, for example, the connected components.

By attaching additional interactive effects to graph elements, you can provide detailed information.

The figures below show the most spectacular views for the graph under study.

The Wolfram Language provides extensive collections of carefully designed graph styles, highlight styles, and layout algorithms. The Wolfram Language provides also in-depth support for every aspect of styling, labeling, and shape generation for graphs, as well as carefully designed libraries of edge and vertex shapes. Figures 1 - 6 below show the most spectacular views for the graph under study.

The Figure 1 illustrates the stacking options CircularEmbedding (vertices on a circle) and StarEmbedding (vertices on a circle with a center).



Figure 1. Views (layouts) of the studied graph of the category circle embeddings.

The Figure 2 shows the stacking options for DiscreteSpiralEmbedding (vertices on a discrete spiral) and SpiralEmbedding (vertices on a 3D spiral projected to 2D).

The Figure 3 shows options for layouts in the category structured embeddings for layered graphs such as



Figure 2. Views (layouts) of the studied graph of the category spiral embeddings.

trees and directed acyclic graphs: RadialEmbedding (vertices on a circular segment), LayeredDigraphEmbedding (vertices on parallel lines for directed acyclic graphs), LayeredEmbedding (vertices on parallel lines).

The Figure 4 shows the installation options of the categories optimizing embeddings all minimize a quantity PlanarEmbedding (number of edge crossings) and High-DimensionalEmbedding (energy for spring-electrical in high dimension).

The Figure 5 shows the layout options for the categories SpringEmbedding (energy with edges as springs) and SpringElectricalEmbedding (energy with edges as springs and vertices as charges).

Variants of vertex and edges signatures are illustrated



Figure 3. Views (layouts) of the studied graph of the category layered embeddings.



GraphLayout - HighDimensionalEmbedding



Figure 4. Views (layouts) of the studied graph of the category optimizing embeddings.

in Figure 6 (labels and label positions for edges).

The FIgure 6 shows views using RadialEmbedding layout connections with directions and vertex numbers.

In the top part of the illustration, the output is made in the form of signatures of numbers in the centers of vertices and signatures of edges, indicating their types. In the lower part of the illustration, edges are displayed with a design according to the rules – all edges from a node with a large number to a node with a smaller number are displayed as dotted red lines, and the rest are solid green.

An example of solving the problem of finding the shortest path between two vertices is illustrated in Figure 7. Mathematica functions are used in the solution: FindShortestPath [9], HighlightGraph [10]. The output is





Figure 6. Views of graph under study, design variants.

Figure 5. Views (layouts) of the studied graph of the category springs embeddings.

done using the Radial Embedding layout.

The solution for the graph considered and illustrated in Figures 1 - 6 is shown on the top, it is important that movement in any direction is possible along the edge 15-17. The solution for the modified graph is shown on the lower part, in which the path from 15 to 17 vertices is "blocked", it is possible only in the direction from 17 to 15.

Note that the results obtained and considered include graphics tasks that are laborious to implement in programming languages, as well as mathematically and algorithmically complex tasks in the subject area. The presented visualization options and finding a solution require only careful study of the examples of the Wolfram Mathematica help system, initial programming skills, that is, they are available to most software engineers.

IV. Conclusion

Computer algebra systems currently represent powerful tool complexes, the capabilities of which have long gone beyond algebraic calculations and even classical mathematics in general. CAS provides many computing capabilities, processing algorithms, analysis, visualization. One of the leaders is the Wolfram Mathematica system, the core of which contains more than 6,000 functions [3]. Wolfram has also developed many unique projects, which, in addition to the Mathematica system,



Figure 7. Solutions to the problem of finding the shortest path.

include the Wolfram Alpha computational knowledge engine, which contains an extensive knowledge base and a set of computational algorithms.

The representation of factual, logical, and procedural knowledge for the Wolfram family's systems is based on the multi-paradigm programming language Wolfram Language. The presence of such an internal language, functions of Wolfram systems and, in general, a high level of documentation of these functions distinguishes Wolfram systems from other services that allow solving general and specific tasks. In many cases, Wolfram allows you not only to solve a problem, but also to explain the course of the solution, as well as to help the user choose a function suitable for solving his specific task, or to suggest a set of functions that can be applied to the input and received data used. Another advantage of the Wolfram family's systems is their complexity, which allows them to solve fairly complex tasks within a single application and without the need to integrate heterogeneous services.

Considering the above, we can definitely conclude that it is advisable to integrate the Wolfram Mathematica computer algebra system with ostis systems that are part of the OSTIS Ecosystem.

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ПРИНЦИПЫ И РЕШЕНИЯ ИНТЕГРАЦИИ ИНСТРУМЕНТОВ КОМПЬЮТЕРНОЙ АЛГЕБРЫ И ПРИЛОЖЕНИЙ НА БАЗЕ ОТКРЫТЫХ СЕМАНТИЧЕСКИХ ТЕХНОЛОГИЙ Таранчук В. Б.

таранчук Б. Б.

Рассмотрены принципы, методические и технические решения интеграции Экосистемы интеллектуальных компьютерных систем нового поколения (Экосистемы OSTIS) и систем компьютерной алгебры. Показана целесообразность такой интеграции, отмечаются различные варианты интеграции, преимущества и недостатки указанных вариантов. Реализация предлагаемого подхода рассматривается на примере интеллектуальной обучающей системы по дискретной математике с иллюстрациями изучения темы, выполнения заданий по визуализации и решениям задач теории графов.

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Ontology of Concepts of Technical Diagnostics in the Field of Electronics: from Standards to the Practice of Real Application

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Abstract—This article discusses the issue of comparing terminology used in the fields of diagnostics of computer equipment and electronic systems of automotive equipment.

Keywords-diagnostics, electronic systems of motor vehicles

I. Introduction

Electronic (including computer, information) technologies have become an integral part of all spheres of modern human activity. The number of specialists who consider themselves to be involved in this field is a significant part of the engineering and scientific community and continues to grow. During the entire life cycle of electronic products - development, production and operation, specialists (and users during operation) are faced with the need to monitor the technical condition, maintenance, repair and restoration of operability. Users and the overwhelming majority of specialists rely on general engineering knowledge and intuition when solving technical diagnostics problems, while TECHNICAL DI-AGNOSTICS is an area of knowledge that has developed into an independent technical discipline, including the theory, methods and means of determining the technical condition of objects [1]. Like any discipline, technical diagnostics has its own specifics, from the definition of concepts to formal and informal methods and techniques for solving applied problems. As the technological development of electronic (computer, information) diagnostic objects progresses towards their complication, automation and intellectualization, approaches, methods and means of diagnostics undergo development, and, as a rule, towards their complication and integration. Sometimes it is quite difficult to understand the intricacies of terms, definitions of directions, algorithms, software and hardware releases, etc., related in one way or another to

technical diagnostics, and the volume of information is large and constantly growing. Upon careful study of the subject of technical diagnostics, one can notice a number of "narrow points" related to synonymization, ambiguous interpretation of individual terms, and sometimes obvious differences in the definitions of concepts. Such discrepancies complicate communication between specialists, do not contribute to the development of classical provisions of the theory, but are especially harmful to the educational sphere, when a novice engineer needs to master a large volume of unstructured information. Vivid examples can be the requirements of standards in this area, both basic [2] and derivatives - industry standards [3], [4], [5], [6]. In this regard, debating the wording of certain provisions (terms) used by authoritative specialists [7], [8], [9] seems unproductive. Therefore, this article proposes an ontological approach to the consideration and discussion of technical diagnostics concepts. This means that the review of definitions and explanations of technical diagnostics concepts will be carried out in a structured and systematized form [10], with references to information sources with priority to reference books and standards.

II. Brief recommendations for applying the ontological approach

A. Maintaining the Integrity of the Specifications

Ontology is a formal description of the terms or concepts of a subject area and the relationships between them (Gaber 1993). Ontologies are necessary for a common understanding by people and/or software agents of the structure of information; for the possibility of collective analysis, accumulation and targeted application of knowledge in a subject area. In an ontology, a class describes a concept of a subject area. A class may have subclasses that represent more specific concepts than the superclass . For example, the class TECHNICAL DIAGNOSTICS may include the subclasses Technical conditions, Causeand-effect relationships of failures, Methods and means of diagnostics, Assessment of the quality of diagnostics. The description includes the properties and attributes of the class (sometimes called slots or roles), as well as constraints of roles or slots (facets). An ontology together with a set of individual instances of classes forms a knowledge base. In reality, it is difficult to determine where an ontology ends and a knowledge base begins [10]. In practice, ontology development includes defining the classes in the ontology, arranging the classes into a taxonomic hierarchy (subclass - superclass), defining the slots and describing the permissible values of these slots; filling in the values of the instance slots. It should be kept in mind that an ontology is a model of the real world, and the concepts in the ontology should reflect this reality. There is no single correct way to model a subject area there are always viable alternatives. Therefore, ontology development is an iterative process that will almost always revise the initial version and continue throughout the ontology's life cycle. An example of constructing an ontology in the subject area of systematization of the characteristics of the Internet of Things is given in [11].

III. Main ontological classes of concepts of technical diagnostics

The presented hierarchy of basic concepts does not introduce taxonomy of types yet, at the same time the inheritance of the terms "diagnostics" and "object" is clearly traced. This allows to easily and unambiguously form semantic links between terms without special definitions and explanations. For example, "A failure may occur in the diagnostic object", "The ultimate goal of diagnostics is to determine the technical condition or diagnosis of the diagnostic object", "The quality of the diagnosis will be determined by the nature of the failure, the type of diagnostics, the adaptability of the object to diagnostics (testability or testability)" and the specific diagnostic method used, etc., Fig. 1. In the figure, the hierarchy of concepts is reflected conditionally, since associative links in the semantic network can be established from any vertex, depending on the specific case (query formulation).

A. Otology and detailing of definitions of some concepts

For individual concepts, such as "Diagnostic Object", it is easy to construct an ontological taxonomy. In this case, the variant shown in Fig. 2 reflects the authors' subjective view of the subject area. Such a classification is intuitively understandable from general engineering knowledge and does not require special explanations. Obviously, this taxonomy can be supplemented both in breadth, for example, by the feature of repairability of diagnostic objects (repairable and non-repairable); and in



Figure 1. Enter Caption



Figure 2. Ontological taxonomy of the concepts "Diagnostic object"

depth, for example, digital diagnostic objects can be both programmable and a rigid function, electric machines can be both engines and generators, etc. Instances of this ontology will be specific products (microcircuits, indicators, sensors, power supplies or individual semiconductor devices, etc.), which will have a path from the root to the graph leaf and possess the corresponding characteristics. At the same time, some concepts are of key importance and at the same time have ambiguous interpretation in various sources, therefore they require additional clarification. The first part of ISO 26262 contains terms and definitions used in the framework of consideration of the issue of functional safety: Availability: The ability of a product to perform a necessary function under specified conditions, at a specified time, or for a specified period, provided that the necessary external resources are available."

GOST 20911-89 "TECHNICAL DIAGNOSTICS" establishes terms and definitions of basic concepts in the field of technical diagnostics and control of the technical condition of objects used in science and technology. The terms established by this standard are mandatory for use in all types of documentation and literature included in the scope of standardization or using the results of this activity:

B. Basic terms:

- Diagnostics is a field of knowledge that covers the theory, methods and means of determining the technical condition of objects.
- Diagnostics –determination of the technical condition of an object. Fig. 2 shows a generalized graphical representation of diagnostics.
- Object of diagnostics is a technical system, device or component whose condition is being assessed (e.g. motor, transformer).
- Reliability of diagnostics is the degree of objective correspondence of diagnostic (control) results to the actual technical condition of the object.
- Completeness of diagnostics is a characteristic that determines the possibility of identifying failures (malfunctions) in an object using the selected diagnostic method.
- The suitability of an object for diagnostics (testability) is a property of an object that characterizes its suitability for diagnostics (testing) using specified diagnostic (testing) tools.

The assessment of the technical condition of the diagnostic object is carried out in terms of three components:

C. Diagnostic parameter - a measurable characteristic of an object, used to analyze the state of being classified:

- design (physical and technical parameters);
- functional (performance of intended functions);
- by measurement method (direct, indirect).

D. Diagnostic methods - actions applied to the object can be classified:

- hardware (use of sensors, measuring devices);
- software (data analysis algorithms);
- expert systems (knowledge bases with rules).

E. A diagnostic model is a formalized description of an object that links parameters with states and is classified as:

- mathematical (equations, statistical models);
- physical (models based on the laws of physics);
- sensor oriented (sensor data).

When considering the results of the assessment, the following concepts are used: Diagnostic sign – a value or change in a parameter that indicates a malfunction. Associated with parameters and states. Threshold value is a critical level of a parameter at which the state of an object changes. Thus, by comparing the specified diagnostic parameters with the established thresholds of diagnostic features, accepted diagnostic methods and diagnostic models, the most complete assessment of the technical condition of the diagnostic object is carried out.



Figure 3. Schematic representation of connections and diagnostic relationships



Figure 4. Enter Caption

F. Types of technical condition of the facility:

- operational in which the object can perform all prescribed functions while maintaining values within the specified limits;
- serviceable meets the requirements of regulatory documentation;
- proper functioning in which it performs its function correctly without errors.

G. The stages of the object's condition are determined through diagnostic parameters and can be classified as follows:

- proper (normal functioning);
- faulty (has a deviation of the object's characteristics from the norm, which can lead to failure, while maintaining partial operability)
- borderline (risk of becoming faulty);
- failure (complete loss of functionality is an event in which an object loses its ability to perform a function).

H. ISO 26262 describes the opposite condition in a number of terms, depending on the cause.:

- Failure: The termination of an element's ability to perform a necessary function.
- Fault: An abnormal mode that can cause an element or device to fail.



Figure 5. Stages of the facility's technical condition



Figure 6. Classification of malfunctions according to the degree of security threat

• Anomaly: Condition (event) that deviates from expected values, for example, in requirements. specifications, project documentation, user documentation, standards, or in practice.

I. At the same time, the theoretical foundations of computer diagnostic tools describe it somewhat differently:

- Fault is a physical defect, imperfection, or flaw that occurs in the hardware and software of a computing system, as well as in its storage devices.
- Error is a deviation of the results obtained from the correct values or their accuracy.
- Failure is the failure of a system to perform any predefined functionality or to obtain a result other than the expected value.
- Mistake errors made at the design stage in software, circuit design, or incorrectly selected components..

J. Further analysis shows that within the framework of ensuring functional safety, the main emphasis is on the quantitative assessment of faults, the dependence of faults on the disclosure of potential threats and the consequences of failures:

- Single-point failure: A failure resulting from a single fault that directly results in the violation of a safety goal
- Single-point fault: A failure in an element not covered by a security mechanism that directly results in the violation of a security goal.



Figure 7. Diagnostic sequence

- Dual-point failure: A failure resulting from the combination of two independent failures that directly causes a violation of a safety goal. A dual failure is a multiple failure of the second order.
- Dual-point fault: An individual fault that, when combined with another independent fault, results in a dual failure.
- Multiple-point failure: A failure resulting from a combination of several independent failures that directly results in the violation of a safety goal.
- Multiple-point fault: An individual failure that, when combined with other independent failures, results in a multiple failure.
- Cascading failure: A failure of an element or device that results in the failure of another element or elements of the same device.
- Detected fault: A failure whose existence is detected within a specified time by a safety mechanism that detects the failure.
- Latent latent fault: A multiple fault whose presence is not detected by the safety mechanism and is not perceived by the driver during the multiple fault detection interval.
- Perceived fault: A failure, the presence of which is detected by the driver within a specified time interval.
- Permanent fault: A malfunction that occurs and does not disappear until it is corrected or repaired.
- Random hardware failure: A failure that occurs at a random point in the lifetime of a hardware element in accordance with a probability distribution.
- Safe fault: A failure whose occurrence does not significantly increase the probability of violating a security goal.
- Common Cause Failure (CCF): The failure of two or more elements of a device as a result of a single specific event or root cause.
- Dependent failures: Failures whose probability of simultaneous or sequential occurrence cannot be represented as a simple product of the unconditional



Figure 8. Classification of faults according to the assessment method

probability of each of them.

- Independent failures: Failures whose probability of simultaneous or sequential occurrence can be represented as a simple product of the unconditional probability of each of them.
- Diagnostic coverage: The proportion of hardware element failure rates that are detected or controlled by implemented safety mechanisms. Diagnostic coverage can be estimated using residual failures or using undetected multiple failures that can occur in hardware elements. Diagnostic coverage is essentially the result of the practically achieved implementation of diagnostic completeness, i.e. the share of implemented diagnostics in relation to the possible

The complete diagnostic process can be presented in the form of a diagram.

D. Knuth's article [13], on the evolution of the TEX typesetting system, one of the earliest and most frequently mentioned schemes for classifying software faults, denoted by letters of the Latin alphabet, is considered:

K. Software fault classification scheme by D. Knuth's :

- A incorrect, incorrect algorithm (algorithm awry);
- B a mistake or negligence (blunder or botch);
- D data structure corruption (damage) structure debacle);
- F forgotten function (forgotten function);
- L reasons related to the programming language (language liability);
- M mismatch between system modules between modules);
- R reliability, failure with bad input data (robustness);
- S a surprising, unusual scenario of functioning (surprising scenario);
- T typical typo (trivial typo).

- L. The classification system proposed by B. Beizer:
 - time of fault introduction for example, at the level of specification, implementation, or test procedure;
 - effects of fault activation such as unwanted control flow or data corruption;
 - location such as the object or application module that contains the fault;
 - type of required correct action for example, required, not required, or ambiguous.

M. The developers at IBM proposed the so-called orthogonal classification of faults (orthogonal defect classification) [14] types of faults:

- Function that characterizes incorrect functionality or its absence, which may require a formal change to the project;
- Interface identifies errors in communication between the user and the application, between its modules or application drivers;
- Checking is characterized by a data error in the source code;
- Assignment includes addressing faults, including erroneous initialization;
- Timing / serialization contain many faults that can be easily corrected with improved project development management;
- Build / package / merge identify issues due to errors in library systems and in change management and version control;
- Documentation characterizes errors in documentation and, first of all, in the user manual for a software product;
- Algorithm includes problems related to the efficiency or correctness of a software product that can be corrected by re-implementation without requiring a change in design.

The classifications proposed by D. Knuth, B. Beiser and the IBM company together allow for a more detailed characterization of the faults that arise.

The classification, applied, can be generalized as: emergency causes (causes crash) uniting all those malfunctions in a program that can cause a crash or freeze of the entire computing system, significantly disrupting the stability of its operation;

N. Applied generalized classification:

- Critical faults are anything that causes the program itself to freeze or crash without affecting the computing system as a whole ;
- functional faults are characterized by deviations in the functional behavior of the software compared to the required functionality;
- installation (setup) faults introduced at the stage of installation of the software application;



Figure 9. Applied fault classification.

- Cosmetic defects include design errors (e.g. wrong line color or font), user interface errors, etc.
- minor faults are theoretically insignificant faults, or faults of unspecified genesis;
- suggestion, which consists of a proposal to improve the software in terms of some of its characteristics or properties. Sometimes similar malfunctions are designated how feature.

The classifications presented are an average interpretation of a large number of classifications, including those discussed above. Summary: This ontology systematizes key terms of technical diagnostics, defining their interrelations and hierarchy. It can be expanded by adding subclasses, examples and specific methods for specific industries (aviation, energy, mechanical engineering).

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ОНТОЛОГИЯ ПОНЯТИЙ ТЕХНИЧЕСКОЙ ДИАГНОСТИКИ В СФЕРЕ ЭЛЕКТРОНИКИ: ОТ СТАНДАРТОВ К ПРАКТИКЕ РЕАЛЬНОГО ПРИМЕНЕНИЯ

Савчиц А.А., Татур М.М

В данной статье рассмотрен вопрос сравнения терминологии, принятой в областях диагностирования средств вычислительной техники и электронных систем автотракторной техники. Обзор определений и пояснения понятий технической диагностики будут выполняться в структурированном и систематизированном виде со ссылками на источники информации с приоритетом на справочники и стандарты.

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Russian Lexeme Processing and Generating a Tag-Semantic Dictionary for a Selected Domain

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Abstract—The methodology and algorithm for marking lexical units of Russian-language texts in Combinatory Semantics technology are presented. Fuzzy logic and fuzzy neural network rules have been proposed to automatically convert Parts of Speech to Parts of Language.

Keywords—lexical analysis, linguistic semantic category, tagging, morphology, fuzzy rules, neural network.

I. Introduction

Syntactic analysis (defining the role structure of a sentence) and formalization of semantics (determining the role structure of an event described by a sentence) are key stages in processing and understanding natural language texts, and while syntactic analysis (parsing) is actively used in computer systems to formulate rules or to detect contradictions in the description of any language grammar, then the capabilities of hardware-software complexes in explaining semantic relations, formation of semantic text representation, coding and decoding of the World Model are still in their development. The rapidly expanding number of scientific articles and publications has long ago exceeded the limit of their manual processing by specialists. Without automatic analysis of texts, their abstracting and summarizing, creation of reference lists and electronic academic books 'instantly' at the user's request, automatic semantic diagnostics and expertise - in other words, without artificial intelligent knowledge management systems - not every scientist or specialist can successfully navigate in their own and related scientific domains [1]. Active development of computer hardware requires new approaches to Natural Language Processing, new theories and algorithms that take into account the semantic meanings of language units, their contextual and meta-contextual dependence. The principles of building a lexical analyzer as the main tool for an intelligent system of semantic text processing

II. Artificial Intelligence in the Internet Content Processing

based on the Theory for Automatic Generation of Knowl-

edge Architecture (TAPAZ-2) are presented below [2].

Today, the development of Artificial Intelligence in the sphere of the Internet content and Natural Language Processing follows three directions:

- the Internet and Web services intellectualization (Semantic Web Project of W3C Consortium, Scheme.org International Public Resource Project of the Google, Microsoft, Yahoo and Yandex Developer Community), transformation of the Internet into a 'Giant Global Graph' (GGG) with simultaneous presentation of the possibility to connect automatic control systems to it ('smart home', 'smart city' projects, etc.);
- using machine learning, neural networks and other algorithms for statistical processing of content, including Big Data, in the creation of local and global information resources as a basis for the digitalization of the economy and its transition to the 7th Technological Paradigm; the most famous example of this approach is the development of chatbots with Generative Artificial Intelligence (Chat-GPT from OpenAI, DeepSeek, etc.) as services for checking and acquisition of information to replace 'traditional' search engines;
- increasing the efficiency of Large Language Models (LLMs) by integrating them with the RAG (Retrieval-Augmented Generation) system to connect with relevant external knowledge sources (articles, technical descriptions, etc.) and to search information.

The rapid development of 'activity-based technology' (since 2011) and 'Activity Vocabulary technology' (since 2017) has shown that in the nearest 10–15 years the main efforts of international scientific and financial centers will be focused on the construction of knowledge graphs for automatic extraction of semantically meaningful information from the Internet search pages, i.e. on the gradual development of a formalized meta-language, correlating in semantic power with natural language and capable of representing it in machine-readable form [3].

The main achievement of the Minsk School of Combinatory Semantics is the Theory for Automatic Generation of Knowledge Architecture (TAPAZ-2, http://tapaz.by) for computer modelling of human intellectual activity systems and inventive problem solving. The formal apparatus of TAPAZ-2, being a finalization of V. V. Martynov's Universal Semantic Code (USC), is intended for algebraic coding of semantics (meaning of signs, sense of sentences, content of patterns in the World Model and connections in the knowledge architecture), i. e. for calculating the semantics of subject domains, as well as automatic semantic marking up of any texts [4, p. 5–18].

TAPAZ code is a unconventional correlation of an algebraic expression with the semantic counterpart (an individ or its attribute in the role structure of an event) and has strict rules for interpreting regular superposition of individs with the transition from morphological categories of Parts of Speech (PS) to semantic categories of Parts of Language (PL) [5]-[7]. Thus, TAPAZ codes codify all macroprocesses and processes of subject domains, while simultaneously calculating them. Through the reverse process of decoding the patterns of the World Model rather than the categories of Linguistic Image of the World, TAPAZ code decodes the meaning of words and word-combinations, the sense of sentences and texts, i.e. natural-language semantics. This makes it unique and gives it an advantage over the mentioned international achievements in this field [8, p. 5-26].

III. The Architecture of the Universal Semantic Analyzer

The ideology of TAPAZ is the creation of a flexible and open architecture of a multilevel universal semantic analyzer for automatic markup of Internet content or text corpora from different subject domains (Fig. 1). After developing this system and training it on the texts from different subject domains marked up in the PL paradigm, it will be possible to widely implement and use this system for intelligent knowledge management. The kernel of the whole system is a lexical analyzer, with the help of which a tag-semantic dictionary of the selected subject domain is created according to a certain algorithm, where each lexical unit (word) is tagged with a certain semantic code-category from the Special Paradigm of PL [5, p. 173–179]. A tag is a code marker of the corresponding



Figure 1. The architecture of the Universal Semantic Analyzer

category in the PL paradigm – taigens (substantives) and yogens (predicatives), facilitating the process of semantic markup of sentences and search for necessary information. For example, the word *lecturer* is assigned a tag: *taigen, reduced, contracted, physical, constant, common, qualitative, single-place.* One sign can also belong to different tags: *canteen* (dinnerware), *canteen* (room for eating), etc. The tag-semantic dictionary constructed in this way allows us to solve the problem of homonymy [9, p. 29–36] and will be used later at the parsing stage for syntactic and semantic analysis of texts.

IV. The Algorithm of the Lexical Analyzer

After its launch lexical analyzer connects to the available dictionaries. Actual project is functioning on the source morphological dictionary containing over 300,000 words, pre-marked with the following morphological characteristics: Part of Speech, Animate – Inanimate, Gender, Number, Case, Abbreviation, Name, Toponym, Organization, Possible substance, Trademark, Qualitative, Superlative, Ordinal, Possessive, Comparative degree, Category of aspect, Perfect – Imperfect, Category of superlative, Multiple, Reflexive, Person categories, Categories of Time, Mood category, Collateral category, Interrogative, Demonstrative, Introductory word, Adverbial participle, Imperfective verb, Verbal noun, Predicative, Collective, Preposition variant, Adjective form.

Upon selection source morphological dictionary the user should load text corpora (*.txt or *.docx formats) into the database. Then starts text pre-processing step, consisting in anomalies detection and cleaning. Such lexical "noise" may contain any abnormal symbols, which should not be treated as lexical unit.

The algorithm of the Lexical Analyzer consists of the following sequence of steps (Fig. 2):

1) Extracting the morphological characteristics of PS (gender, case, person, number, declension, etc.) of each word of the text corpora from publicly available dictionaries.

- Constructing fuzzy logic rules for analyzing the morphological characteristics of PS and classifying them as PL.
- 3) Tabular single-valued determination of semantic tags of words (lemmas and their word forms) according to the rules of step 2.
- 4) Manual expert inspection of the tabular translation and markup of certain corpora of texts (not classified in the steps 2 and 3) for further training of the neural network.
- 5) Rule-based learning and training of fuzzy sets to recognize Parts of Language in order to generalize the fuzzy rules (step 2) to large volumes of texts and to solve lack of morphological characteristics and corresponding rules problems.
- 6) The final step of the algorithm is the creation of a tag-semantic dictionary (assigning a semantic tag to each lexical unit of the subject domain).

As the architecture, a fuzzy neural network NEFClass M (Modified Neuro Fuzzy Classifier) based on the generalized fuzzy perceptron architecture using the numerical optimization algorithm of the Gaussian belonging function and adapted to the existing task of semantic markup was chosen (Fig. 3). Fuzziness arises from incomplete measurements of object properties (absence or incompleteness of morphological characteristics of words in publicly available dictionaries).

The fuzzy rules describing the data are of the following form: The input layer of the network is a matrix of PS and morphological characteristics obtained from existing dictionaries. The hidden layer is a set of fuzzy rules for converting PS and morphological characteristics into PL. Finally, the output layer of the network is the resulting class of semantic tag according to the PL paradigm.

if x1 is μ 1 and x2 is μ 2 and ... and xn is μ n,

then the sample (x1, x2, ..., xn) belongs to type *i*, where μi , ..., μn are fuzzy sets.

For example,

if the word = *NOBODY* as SPEECH PART = *pronoun* AND morphological characteristic = *negative* **AND** morphological characteristic = *singular*

then the example (*NOBODY*) has tag = taigen contracted physical variable qualitative arbitrary narrative non-personal multi-place intensive

V. Realization and Results

The WEBSEMDICT program is designed to work with the morphological and semantic dictionaries of Russian words and to search for these words in selected text corpora.

The functions consist of selecting articles, dissertation abstracts or small books and further analyzing their contents using selected dictionaries by the user. The downloaded text is placed in the text area on the site, possible noises are indicated, the name of the document and the text is converted into a list of unique, nonrepeating sorted words. When saving the obtained results, the words have been searched in the database and marking is made about the found words considering their occurrence.

The resulting list of words with their morphological characteristics can be viewed in the corresponding table, and these same characteristics can be modified. The tagsemantic dictionary table directly indicates the semantic characteristics of these words, which can be edited by the expert if necessary. The user's personal account is represented by 5 data blocks that contain required personal information (name, role, email, phone, etc.). The site has a feedback mechanism with the developer, where the user can ask a question and get a prompt answer for support.

The registered users and administrators have access to the following functionality:

- 1) Working with text corpora;
- 2) Access to the morphological dictionary, displayed as a table;
- 3) Access to the tag-semantic dictionary, displayed as a table;
- The ability to contact the site administrator with a question by clicking on the "Support" button;
- 5) Access to your personal account, with the ability to install a two-factor protection system, correct the data entered during registration, as well as change the email and password. Access to deleting an account is disabled.
- 6) Access to unrecognized words that are not in the database. You can also do personal work with them by eliminating errors in the words themselves, indicating their belonging to the basic form (lemma) or to the word form, as well as in dicating their morphological characteristics.

VI. Realization and Results

The WEBSEMDICT software implementing the described method is developed as a Web-application based on microservice client-server architecture using ASP.Net Core MVC tools. The server part of the software is written in the high-level compiled software language C# under .NET Core Version 6.0. The client part is written in the interpreted software language JavaScript, markup language HTML-5, and using CSS-3, Bootstrap, Razorpages. The database is built on MS SQL [10].

At this stage of the project, the whole database contains 312,546 lemmas (base words) and 2,469,893 word forms. For this purpose, collections of texts in the subject domain 'optoelectronics' consisting of 113 text files in *.txt and *.docx format with a total volume of extracted 34,605 words were used. As a result of the software's functioning, the texts were cleaned from 'noise' with



Figure 2. The algorithm for semantic markup and tag-semantic dictionary creation

the subsequent creation of a morphological dictionary containing 8,948 unique words and 25,655 word forms having morphological characteristics. The morphological dictionary contains 57 unique characteristics. On the basis of TAPAZ technology, 98 fuzzy rules for converting Parts of Speech into Parts of Language have been developed with the ability to assign a compound semantic tag to each word in the dictionary (360 unique tags in total). After applying these fuzzy rules, a tag-semantic dictionary consisting of 5,224 lemmas and 20,152 word forms with semantic characteristics was formed.

In the future, it is planned to increase the Tag-Semantic Dictionary loading large texts of different subject domains with its further automatic processing by neural network combined with markup on the basis of PS-PL rules.

VII. Conclusion

A new approach to the construction of TAPAZ-based intelligent systems for the tasks of semantic processing of natural language texts is based on the classification of lexical units not on their frequency-statistical characteristics, as in algorithms of generative artificial intelligence, but on the basis of their semantic relations as PL and syntactic roles in a sentence. A hybrid method of tagging sentences using PL with automated tagging and construction of the Tag-Semantic Dictionary is proposed and described, which combines the application of

earch																			
elongs to	ID	Word	Taigen yogen	Expanded - collapsed.	Composition - complex	Abbr compressed	Inform physical.	Constant - alternating	Negative - positivo degree	1st, 2nd, 3rd degree	Own - Naritsat.	Qualit. Quant.	Index - Prod.	Relative - Possessive.	Question Narrative.	Personal - Impersonal	One Many.	Intensity - Extension.	Change
sic word	105061	алфёров	taigen					constant			own								Change
sic word	105222	альберт	taigen					constant			own								Change
sic word	105534	альпинист	taigen					constant											Orange
sic word	105560	альтернатива	taigen					coristant											Change
sic word	105562	альтернативный	yogen	folded															Change
sic word	105563	альтернативен	yogen	folded		abbreviated		constant	positive degree	2nd degree									Change
sic word	105601	альф	taigen					constant			OWIN								Chenge
sic word	105604	альфа	taigen					constant											Change
sic word	105773	алюмичисский	yogen	folded															Change
tic word	105776	алюмиий	taigen					constant											Change
w 1 to 10 vicus 1 N	of 10 ent	ries							-										

Figure 3. The Tag-Semantic Dictionary

tabular, unambiguous tagging of PS-PL by a fuzzy neural network and expert verification.

In terms of scaling our research results, determining the relevance of the training domain, and selecting adaptive machine learning algorithms, we are very much looking forward to comprehensive cooperation with Professor V. A. Golovko, a leading Belarusian expert in the field of artificial neural networks [11, p. 81-101]. We are also actively building up cooperation with Professor V. V. Golenkov within the framework of Open Semantic Technologies for Intelligent Systems (OSTIS Technology) [12, p. 81-98], which is focused on the development of hybrid intelligent systems. There are already good examples of OSTIS knowledge bases describing lexical, syntactic and semantic categories in terms of TAPAZ and available for implementation in Natural Language Processing and Understanding algorithms [13, p. 183-188], [14, p. 123-140], [15, p. 192-221]. OSTIS technology, with its original object-oriented high-level software language, is, in our opinion, the most suitable for immersing TAPAZ algorithms in a software environment.

This work is a significant step towards the promotion of a hardware-software complex for semantic processing of natural language texts, understanding of natural language and solving inventive problems in the forward and backward direction from the top-level ontology defined structurally to the semantic, syntactic and lexical analysis of any technical and technological descriptions in natural language [16, p. 176–197]. The research contributes to the creation of national artificial intelligent systems based on combinatory or knowledge-based methods.

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Figure 4. Fuzzy neural network NEFClassy

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АВТОМАТИЧЕСКАЯ ОБРАБОТКА РУССКИХ ЛЕКСИЧЕСКИХ ЕДИНИЦ И СОЗДАНИЕ ТЕГО-СЕМАНТИЧЕСКОГО СЛОВАРЯ ВЫДЕЛЕННОЙ ПРЕДМЕТНОЙ ОБЛАСТИ

Гордей А. Н., Панащик Р. С., Святощик М. И., Стрельченок О. А., Ткаченко В. В., Шумилин А. Г.

В статье представлены методология и алгоритм разметки лексических единиц русскоязычных текстов в технологии комбина́торной семантики. л автоматиаии еревода асте реи в асти ка редлоенравила неетко лоики и неетко неронной сети.

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Imbalanced Data Problem In Machine Learning

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Abstract—Imbalanced data is a common challenge in real-world classification tasks. This study analyzes methods and algorithms for addressing class imbalance in binary classification models. Experimental evaluations are conducted on data balancing techniques, including oversampling the minority class and undersampling the majority class. The experiments cover both tabular data and image datasets. Based on the results, the impact of these methods on model performance is assessed, and practical recommendations for effective data balancing are provided.

Keywords-imbalanced data, binary classification, sampling

I. Introduction

In machine learning tasks, both in research and practical applications, we often encounter imbalanced datasets. In medical diagnosis, rare diseases like cancer often have far fewer positive cases than healthy samples, making early detection difficult. Fraud detection systems face severe imbalance, as fraudulent transactions may represent less than 1% of all transactions. Spam filtering also deals with skewed data, where spam emails are vastly outnumbered by legitimate ones. Similarly, in manufacturing quality control, defective products are typically rare compared to non-defective ones, requiring specialized techniques to identify anomalies. Class imbalance presents a significant challenge, as traditional classifiers tend to bias their predictions toward the majority class, which is often the least important class. This makes them unsuitable for handling imbalanced learning tasks [1]. A dataset is considered imbalanced when there is a substantial disproportion between the number of instances in different classes. The degree of imbalance can range from a slight bias to extreme cases where one minorityclass instance corresponds to hundreds, thousands, or even millions of majority-class instances. To identify class imbalance, one can visually inspect a histogram showing the distribution of instances across classes or visualize the data on a graph when the feature space has low dimensionality. To quantify class imbalance, the imbalance ratio (IR) is commonly defined as the ratio between the number of instances in the minority class and the majority class.

imbalance ratio
$$(IR) = \frac{len(Y_{minor})}{len(Y_{major})}$$
 (1)

It is possible to distinguish datasets with no imbalance, minor imbalance, major imbalance and huge imbalance. The Figure 1 shows the synthetic datasets for two classes with different imbalance levels and the estimated imbalance ratio [2]–[4].

It is particularly important to emphasize the need for a semantic approach to class imbalance, which focuses on preserving and utilizing meaningful (semantic) relationships in the data rather than simply mechanically balancing class distributions. The semantic approach is especially effective in tasks such as: Natural language processing (NLP), Computer vision (where semantic differences matter), Recommender systems, Medical diagnosis (where interpretability is crucial). In OSTIS technology, data is represented through semantic networks and ontological models, ensuring flexibility and interoperability in intelligent systems. Combining classical approaches to handling imbalanced data with the advantages of OSTIS technology could be a promising direction for further research [5].



Figure 1. Scatter Plot of a Binary Classification Dataset with Different Class Distributions

The goal of this paper is to examine data balancing algorithms and evaluate their effectiveness for tabular data and images. Both classical machine learning algorithms and deep convolutional neural networks are explored in this work.

II. Related Work

According to [6], [7], methods for handling imbalanced data can be categorized as follows, Figure 2.



Figure 2. Approaches for class imbalansed learning

Algorithm-level approaches involve modifying existing machine learning algorithms to make them more suitable for imbalanced datasets by reducing their inherent bias toward the majority class. These modifications may include cost-sensitive learning techniques, where algorithms are adjusted to incorporate misclassification costs that penalize errors on minority class instances more heavily. Data-level approaches address class imbalance by directly modifying the dataset distribution prior to model training. These methods include oversampling techniques (e.g., SMOTE) that artificially increase minority class instances, and undersampling strategies that reduce majority class samples. Advanced variations combine both approaches or incorporate synthetic data generation through GANs. The hybrid approach combines the aforementioned methods in varying proportions to optimize classification performance. Different techniques can be integrated either across categories (e.g., combining data-level and algorithm-level methods) or within the same category (e.g., using multiple data-balancing techniques simultaneously). The literature presents numerous approaches for addressing class imbalance in machine learning. While various techniques exist, this study specifically examines oversampling and undersampling methods for data balancing.

The fundamental data-level approach for addressing class imbalance is known as data balancing. Among these techniques, increasing the minority class size (oversampling) is particularly valuable for small datasets, where reducing the majority class could compromise classification accuracy. The simplest method, Random Oversampling, duplicates randomly selected minorityclass instances. These algorithms progressively refine synthetic data generation to improve model performance while mitigating overfitting risks. More advanced techniques include:

- SMOTE: Generates synthetic minority-class instances by interpolating between existing examples, avoiding mere duplication.
- Borderline-SMOTE: Focuses synthetic sample generation near class boundaries to enhance decision boundary learning.
- Borderline-SMOTE-SVM: Uses Support Vector Machines to identify critical boundary regions for synthetic data generation.
- ADASYN: Adaptively creates synthetic samples based on local density and class distribution, prioritizing difficult-to-learn areas.

Undersampling methods reduce the majority class size through three strategic approaches: (1) retaining informative instances, (2) removing redundant/noisy instances, or (3) hybrid combinations. Key algorithms include:

- Random Undersampling: Randomly eliminates majority-class instances (Note: Corrected erroneous "duplicating" description from original text)
- CNN (Condensed Nearest Neighbor): Preserves a subset that maintains original decision boundaries
- NearMiss Variants: NearMiss-1: Keeps majority instances with smallest average distance to 3 nearest minority instances. NearMiss-2: Retains majority instances farthest from minority clusters. NearMiss-3: Stores majority instances closest to each minority instance.
- Tomek Links: Removes overlapping majority-class instances in boundary pairs
- ENN (Edited Nearest Neighbors): Deletes misclassified majority instances based on 3-NN evaluation
- OSS (One-Sided Selection): Hybrid of Tomek Links (boundary cleaning) and CNN (redundancy removal)
- NCR (Neighborhood Cleaning Rule): Combines ENN (noise removal) and CNN (redundancy reduction)

These methods systematically address imbalance while preserving critical data patterns. Figure 3 shows the concept of resampling [6]–[10].



Figure 3. Resampling Methods

III. Experiments with Tabular Data

For our experiments, we evaluated three imbalanced binary classification datasets (Table 1). The class imbal-

ance ratios are visually demonstrated through histograms showing the distribution of instances between classes for: (1) abalone_19, (2) mammography, and (3) car_eval_34 datasets.

- Abalone_19: Predicts abalone age (marine mollusks), where the "19" class (oldest specimens) represents the rare minority, creating significant classification challenges.
- Mammography: A medical imaging dataset for breast cancer detection with extreme imbalance, where calcification clusters (minority class) require specialized detection approaches.
- Car_eval_34: Derived from vehicle evaluations, with merged "good"/"vgood" acceptability classes forming the minority, testing boundary-learning capabilities (Figure 4).

Dataset	Samples	Features	Imbalanced
			Ratio
abalone_19	4 177	10	0.0077
mammography	11 183	6	0.0238
car_eval_34	1 728	21	0.0841
Historram of Labols for shalone 10	Imbalanced ratio 0 0077		
Histogram or Labers for adalone_19	andalanced racid:0.0077	Histogram of Labels for man	imography, imbalanced ratio:0.02
		19000	

Table I Dataset Summary



Figure 4. Abalone_19, Mammography and Car_eval_34 Datasets

Machine learning algorithms were selected for classifier construction, as detailed in Table II. These algorithms represent distinct approaches to classification - from linear separability to non-linear decision boundaries while being computationally efficient for comparative analysis. Their performance metric (Accuracy) will be evaluated against the same imbalanced datasets to ensure consistent benchmarking conditions.

Our investigation systematically evaluated two balancing approaches: (1) undersampling methods, implemented through 13 distinct algorithms including random undersampling, Tomek Links, and neighborhood cleaning rule (Table III), and (2) oversampling techniques,

Table II Classification Algorithms

Algorithm	Abbreviation
Logistic Regression	LR
SVC	SVC
KNN	KNN
DecisionTree	DT
Granient Boosting	GB
Random Forest	RF

comprising 7 algorithms such as SMOTE, Borderline-SMOTE, and ADASYN (Table IV). Each approach was rigorously tested under identical experimental conditions to ensure fair comparison of their effectiveness in handling class imbalance. The undersampling algorithms were selected to represent diverse strategies from random reduction to sophisticated instance selection, while the oversampling methods covered both basic interpolation and advanced adaptive synthesis techniques. This comprehensive framework allows for detailed analysis of how different balancing methodologies affect classifier performance across various imbalance scenarios.

All classifiers were implemented and evaluated using the specified algorithms under consistent experimental conditions. We employed 3-fold cross-validation to ensure robust performance estimation while maintaining computational efficiency.

Table III Undersampling Balanced Algorithms

Balanced Approach Designation										
Random Undersampling	Under1									
Condensed Nearest Neighbour	Under2									
Tomek Links	Under3									
One Sided Selection	Under4									
Edited Nearest Neighbours - kind_sel=all	Under5									
Edited Nearest Neighbours – Under6										
kind_sel=mode										
Repeated Edited Nearest Neighbours -	Under7									
kind_sel=all										
Repeated Edited Nearest Neighbours -	Under8									
kind_sel=mode										
All KNN – kind_sel=all	Under9									
All KNN – kind_sel=mode	Under10									
Neighbourhood Cleaning Rule	Under11									
Instance Hardness Threshold	Under12									

Table IV Oversampling Balanced Algorithms

Balanced Approach	Designation
Random Oversampling	Over1
SMOTE	Over2
Borderline SMOTE-1	Over3
Borderline SMOTE-2	Over4
SVM-SMOTE	Over5
KMeans SMOTE	Over6
ADASYN	Over7

The results of experiments for abalone_19 dataset with undersampling and oversampling approaches are

presented in Table V and Table VI. The results of experiments for mammography dataset with undersampling and oversampling approaches are presented in Table VII and Table VIII. The results of experiments for car_eval_34 dataset with undersampling and oversampling approaches are presented in Table IX and Table X.

IV. Experiments With Image Data

The CIFAR-10 dataset was selected for experiments with imbalanced image classification tasks. As a standard benchmark in computer vision, it comprises 60,000 32×32 color images evenly distributed across 10 mutually exclusive categories. The dataset is split into 50,000 training images (5,000 per class) and 10,000 test images (1,000 per class), featuring objects from ten distinct classes: airplane, automobile, bird, cat, deer, dog, frog, horse, ship, and truck (Figure 5). This balanced original distribution was intentionally modified to create controlled imbalance conditions for our study.



Figure 5. CIFAR-10 Dataset

Using the CIFAR-10 dataset, we constructed two specialized training sets for binary classification: (1) a balanced set containing 5,000 images per class, and (2) an imbalanced set with 5,000 majority-class images versus only 50 minority-class images (Figure 6). For evaluation, we created a separate test set comprising 2,000 images (1,000 per class) to ensure consistent benchmarking conditions across both balanced and imbalanced scenarios, (Figure 6).



Figure 6. Balanced and Imbalanced CIFAR for 2 Classes

A convolutional neural network was chosen as a classifier. The neural network is a CNN with three convolutional blocks, each followed by ReLU activation and max-pooling. It processes 32x32x3 input images, gradually reducing spatial dimensions to 4x4x32 while increasing depth. A global average pooling layer flattens features into a 32-unit vector, followed by a dense layer and dropout for regularization. The final dense layer outputs 2 classes. The model has 15,458 trainable parameters and avoids overfitting through pooling and dropout. First, the classifier was trained on balanced and unbalanced datasets. For each of the two resulting models, an accuracy ('Accuracy') evaluation was performed on the testing dataset. The results clearly demonstrate that the imbalance in the training dataset caused the misclassification of the testing dataset of images, (Figure 7).



Figure 7. Testung Results for Training with Balanced and Imbalanced Data

We investigated three imbalance mitigation strategies: (1) cost-sensitive learning via class weights, (2) minority-class oversampling (duplication/SMOTE), and (3) majority-class undersampling. Each method was implemented through reproducible preprocessing pipelines while keeping other experimental parameters constant. This design enabled isolated measurement of how different balancing approaches affect model performance on our imbalanced image datasets. The evaluation was conducted using testing dataset comprising 2,000 images (1,000 per class), with detailed performance metric (Accuracy) reported in Table XI. The confusion matrices for the three approaches are shown in Figure 8.

V. Discussion

Oversampling increases instances in the minority class (e.g., SMOTE, ADASYN) to improve rare class representation, while undersampling reduces majority class samples (e.g., random removal, Tomek Links) to balance distributions. Oversampling preserves data but risks overfitting and longer training times, whereas undersampling speeds up training but may discard valuable patterns. Oversampling suits small datasets (e.g., medical data), while undersampling works better for large datasets (e.g., credit scoring). Key trade-offs include synthetic data

Table V										
Undersampling	For	Abalone_	19	Dataset						

	Baseline	Under1	Under2	Under3	Under4	Under5	Under6	Under7	Under8	Under9	Under10	Under11	Under12
LR	0,735	0,656	0,406	0,735	0,721	0,736	0,734	0,744	0,734	0,756	0,737	0,753	0,803
SVC	0,768	0,706	0,62	0,763	0,736	0,754	0,712	0,736	0,712	0,748	0,743	0,767	0,853
KNN	0,547	0,662	0,322	0,547	0,546	0,615	0,546	0,664	0,546	0,647	0,563	0,613	0,693
DT	0,527	0,689	0,457	0,528	0,527	0,512	0,528	0,525	0,528	0,51	0,527	0,511	0,59
GB	0,798	0,759	0,369	0,779	0,776	0,806	0,785	0,811	0,785	0,784	0,773	0,808	0,877
RF	0,753	0,758	0,269	0,785	0,737	0,737	0,69	0,798	0,69	0,77	0,752	0,766	0,927

Table VI Oversampling For Abalone_19 Dataset

	Baseline	Over1	Over2	Over3	Over4	Over5	Over6	Over7
LR	0,735	0,872	0,885	0,933	0,94	0,933	0,945	0,873
SVC	0,768	0,907	0,919	0,984	0,994	0,983	0,955	0,902
KNN	0,547	0,995	0,975	0,992	0,995	0,991	0,991	0,96
DT	0,527	0,993	0,959	0,988	0,991	0,985	0,991	0,894
GB	0,798	0,999	0,989	0,997	0,997	0,996	0,997	0,975
RF	0,753	1	0,999	0,998	0,997	0,996	0,998	0,987

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Table VII Undersampling For Mammography Dataset

	Baseline	Under1	Under2	Under3	Under4	Under5	Under6	Under7	Under8	Under9	Under10	Under11	Under12
LR	0,921	0,938	0,814	0,922	0,922	0,924	0,923	0,926	0,923	0,925	0,922	0,923	0,941
SVC	0,881	0,949	0,84	0,893	0,893	0,918	0,9	0,928	0,901	0,925	0,907	0,908	0,978
KNN	0,9	0,942	0,793	0,901	0,901	0,915	0,901	0,917	0,904	0,917	0,902	0,916	0,945
DT	0,748	0,857	0,715	0,762	0,762	0,795	0,758	0,818	0,771	0,813	0,786	0,793	0,904
GB	0,94	0,944	0,846	0,944	0,944	0,951	0,948	0,952	0,952	0,953	0,951	0,952	0,972
RF	0,944	0,957	0,836	0,946	0,942	0,954	0,948	0,852	0,947	0,951	0,95	0,955	0,978

Table VIII Oversampling For Mammography Dataset

	Baseline	Over1	Over2	Over3	Over4	Over5	Over6	Over7
LR	0,921	0,924	0,931	0,955	0,954	0,965	0,994	0,862
SVC	0,881	0,965	0,969	0,922	0,991	0,99	0,995	0,93
KNN	0,9	0,981	0,977	0,993	0,993	0,993	0,994	0,933
DT	0,748	0,99	0,968	0,987	0,983	0,951	0,989	0,904
GB	0,94	0,985	0,985	0,994	0,995	0,994	0,997	0,951
RF	0,944	0,994	0,992	0,999	0,999	0,998	0,997	0,968

Table IX Undersampling For Car_eval_34 Dataset

	Baseline	Under1	Under2	Under3	Under4	Under5	Under6	Under7	Under8	Under9	Under10	Under11	Under12
LR	0,958	0,947	0,893	0,958	0,954	0,958	0,958	0,958	0,958	0,958	0,958	0,998	0,999
SVC	0,947	0,942	0,838	0,947	0,943	0,947	0,947	0,947	0,947	0,947	0,947	0,995	0,999
KNN	0,657	0,865	0,572	0,657	0,608	0,61	0,61	0,61	0,61	0,61	0,61	0,907	0,994
DT	0,559	0,802	0,47	0,559	0,506	0,559	0,559	0,559	0,559	0,559	0,559	0,532	0,669
GB	0,835	0,973	0,842	0,835	0,863	0,834	0,834	0,834	0,834	0,834	0,834	0,955	0,833
RF	0,899	0,948	0,615	0,899	0,891	0,892	0,892	0,892	0,892	0,892	0,892	0,985	0,992

Table X									
Oversampling	For	Car_	eval	_34	Dataset				

	Baseline	Over1	Over2	Over3	Over4	Over5	Over6	Over7
LR	0,958	0,954	0,952	0,948	0,905	0,98	0,938	0,975
SVC	0,947	1	1	1	0,994	0,983	0,992	1
KNN	0,657	0,996	0,991	0,986	0,938	0,982	0,917	0,975
DT	0,559	0,798	0,79	0,801	0,772	0,796	0,698	0,729
GB	0,835	0,913	0,925	0,94	0,893	0,986	0,903	0,97
RF	0,899	1	0,999	0,999	0,995	1	0,981	0,984

Table XI Evaluation Results for Image Classification on Imbalanced Dataset



Figure 8. Training Strategies for Imbalanced Datasets: Class Weighting vs. Resampling Methods

realism (oversampling) and information loss (undersampling). The choice depends on data size, computational resources, and domain requirements. In most cases, classifiers trained on the balanced dataset performed as well as on the original dataset. In all cases it is possible to improve classification accuracy by combining a particular classifier model and data balancing technique.

VI. Conclusion

This paper investigates the effects of class imbalance on machine learning models across diverse data types. We systematically analyze principal approaches for handling imbalanced datasets, with particular focus on data-level techniques including oversampling and undersampling methods. The study presents two experimental frameworks. Through comprehensive comparative analysis, we demonstrate the quantitative impact of data balancing techniques on model performance metrics. Our results provide actionable insights for selecting appropriate imbalance mitigation strategies based on data characteristics and model architecture.

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ПРОБЛЕМА НЕСБАЛАНСИРОВАННЫХ ДАННЫХ В МАШИННОМ ОБУЧЕНИИ

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Несбалансированные данные являются проблемой для реальных задач классификации. В работе анализируются методы и алгоритмы работы с несбалансированными данными при построении моделей машинного обучения для задач бинарной классификации. Проведены экспериментальные исследования алгоритмов балансировки данных, основанных на увеличении меньшего класса и уменьшении большего класса. Представлены эксперименты для табличных данных и изображений. По результатам экспериментов оценено влияние исследуемых методов и алгоритмов на качество моделей, получаемых в результате обучения. Даны рекомендации по применению методов балансировки данных.

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Neuro-symbolic Industrial Control

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Abstract—This article provides a review of the current state of neuro-symbolic AI (neuro-symbolic learning systems) in the industrial field using OSTIS Technology and examines the integration of classical approaches (standards in Industry 4.0, such as ISA-88, ISA-95, and ISA-5.1) with intelligent technologies (neuro-symbolic AI).

Keywords—Neuro-symbolic AI, neural network, ANN, reinforcement learning, standards, ontologies, Industry 4.0, Industry 5.0, OSTIS, ISA-88, ISA-95, ISA-5.1.

I. Introduction

This paper builds upon the ideas discussed in [1]– [4] and provides descriptions of current challenges and new tools for developing and using standards in industry in relation to modern techniques (neuro-control, neurosymbolic AI, semantic technologies). The connection to Industry 4.0 is considered, which is typically characterized by its complexity and the need for comprehensive knowledge of models and techniques to achieve an integrated solution [5]. Industry 4.0 necessitates the reliable and safe interaction of various intelligent systems [6]. By using artificial intelligence decision-making algorithms, process mapping in the new Industry 5.0 scenario can be enhanced, particularly by defining workflow checkpoints and identifying risks related to production and product quality.

All participants in the process play an important role: users — people (operators, masters, supervisors, etc.); devices - sensors and actuators (temperature sensors, pumps, valves, etc.); mechanized systems - conveyor systems, units; robotic systems - hinged robots, delta robots, manipulators; and software systems - SCADA (Supervisory Control and Data Acquisition), MES (Manufacturing Execution System), ERP (Enterprise Resource Planning). Their interaction ensures the achievement of the goal, elimination, and prevention of emergency situations. Both quantitative (number of operators, devices, aggregates, control panels, etc.) and qualitative indicators (quality of devices, qualification of operators, quality of software systems, etc.) are important. Also important in management systems is the speed of decision-making — making quick changes to meet plans. Each level is controlled by its own algorithms, and often the element may resemble a black box: input and output data are known, and the algorithm is hidden from the user. For instance, a neural network can so be described (Fig. 1). However, it is also important to understand the rules.



Figure 1. Neural Network as a Black Box

Although neural networks have given us many interesting developments, researchers believe that for progress, AI must understand not only "what" but also "why", that is, process cause-and-effect relationships. This has led to the search for new directions in AI. Neuro-symbolic AI is a form of AI that combines machine learning methods with symbolic systems.

Standardization describes different aspects of each developed human activity and includes a system of concepts (including terminology), a typology, and a model that describes how to apply appropriate methods and means, production sites, types, and structures of project documents, and accompanying activities. The existence of standards helps solve one of the key problems related to any technology, particularly rapidly developing computer information technologies, **compatibility problem** [7]. Compatibility can be analyzed from many aspects, from the consistency of terminology in the interactions of process participants to the consistency of actions taken in the process of technology application.

The cohesion of digital twin models is challenged by the need for a large number of disparate, unrelated, and heterogeneous models. On the other hand, connecting digital twins in a single system [8] requires interaction and conceptual unification. It also requires SCADA systems to achieve higher levels of integration, scalability, and technological modernity [9].

Despite advances in information technology, most standards are now presented in the form of traditional linear documents or web resources containing a series of static pages connected by hyperlinks. This approach to expressing standards has many serious drawbacks, and ultimately, the overhead costs of maintaining and using standards outweigh their benefits [10].

Recently, the development of semantic technologies has enabled the creation of a new generation of standards

based on formalized knowledge representation. These standards allow for the creation of intelligent systems that can automatically process and use this knowledge. This approach is based on the use of ontologies, which are formal representations of knowledge in a specific domain, enabling the creation of a common vocabulary and understanding of the concepts and relationships within that domain [7].

ISA (International Society of Automation) has released Mimo: a large language model (LLM) specifically trained on ISA content [11], such as standards, technical reports, and other documents. It is designed to assist users in understanding and applying ISA standards and practices. Mimo can answer questions, provide explanations, and generate text related to ISA content. It is intended to be a valuable resource for professionals in the automation and control industry. Mimo is not a replacement for human expertise but rather a tool to enhance understanding and application of ISA standards.

But the Mimo model is not open source and it is not possible to use it in the production. It is not possible to integrate it with other systems.

II. Problems and state of art

An analysis of the work has made it possible to formulate the most important and common problems related to the development and application of modern standards in various fields [10], [12]:

- Above all, the complexity of maintaining the standards themselves due to the duplication of information, especially the complexity of changing terminology.
- Duplicate information in the documentation describing the standard.
- Standards internationalization issues translating a standard into multiple languages actually requires supporting and coordinating independent versions of the standard in different languages.
- As a result, inconsistencies in the format of different standards. Also automating the process of developing and applying standards is complicated.
- The inconvenience of using the standard, especially the complexity of finding the information you need. As a result, the complexity of studying standards.
- The complexity of automating the verification that an object or process complies with the requirements of a particular standard.
- etc.

These problems are mainly related to the presentation of standards. The most promising approach to solve these problems is the transformation of each specific standard into a knowledge base, which is based on a set of ontologies corresponding to this standard [7], [10], [12]–[14]. This approach allows us to significantly



Figure 2. ISA-88 parts

automate the development processes of the standard and its application.

As an example, consider the *ISA-88* [15] standard (the basic standard for batch production). Although this standard is widely used by American and European companies and is actively implemented on the territory of the Republic of Belarus, it has a number of drawbacks. Essential ISA batch systems standards are shown at Fig. 2.

Another standard often used in the context of Industry 4.0 is *ISA-95* [16]. *ISA-95* is an industry standard for describing high-level control systems. Its main purpose is to simplify the development of such systems, abstract from the hardware implementation and provide a single interface to interact with the ERP and MES layers. Consists of eight distinct sections, described at Fig. 3.

Models help define boundaries between business and control systems. They help answer questions about which functions can perform which tasks and what information must be exchanged between applications. The ISA5 standards development committee is often referred to as the *ISA-5.1* standard among practitioners. However, the ISA5 committee, "Documentation of Measurement and Control Instruments and Systems", has a broader scope — namely to develop standards, recommended practices, and technical reports for documenting and illustrating measurement and control instruments and systems suitable for all industries. ISA5 standards consist of the following parts (Fig. 4).

This standard is useful when a reference to equipment is required in the chemical, petroleum, power generation, air conditioning, metal refining, and many other industries. The standard enables anyone with a reasonable level



of plant knowledge to read flow charts to understand how to measure and control a process without having to go into the details of instrumentation or the knowledge of an instrumentation expert.

III. Neurocontrol

Neurocontrol is a relatively young field of research that became independent in 1988. However, research in this area began much earlier. One of the definitions the science of "cybernetics" considers this as a general theory control and interaction not only of machines, but also biological beings. Neurocontrol tries to achieve this position through the construction of control systems (decision-making systems), which can be trained during operation, and thus improve its performance. In this case, such systems use parallel mechanisms of information processing, like the brain of living organisms [17].

For a long time the idea of building a perfect control system — a universal controller that would look like a 'black box' from the outside was popular. It could be used to control any system, with connections to sensors, actuators, other controllers, and a special link to the «Efficiency Module» — a system that determines the management efficiency based on given criteria. The user of such a control system would only set the desired result, the further trained controller would manage himself, perhaps following a complex strategy of achieving the desired result in the future. It would also constantly adjust its management based on the management object's response to achieve maximum efficiency. A classification of such systems is given below (Fig. 5).



Figure 5. Classification of Neural Network Methods for Solving Control Problems

IV. Neuro-symbolic control

Neuro-symbolic AI is one of the emerging directions in AI today. The first paradigm of AI was symbolic AI, which is based on symbolic representation of tasks and logical inference. It was succeeded by statistical AI (machine learning, neural networks), which solves problems that the previous paradigm could not handle, such as image, speech, and text recognition.

For a long time, these two approaches were considered opposites, with the first paradigm deemed outdated. However, it turned out that combining symbolic and statistical AI can significantly enhance the efficiency of neural networks and overcome some of the limitations of statistical AI for certain tasks.

Neuro-symbolic artificial intelligence is an advanced version that improves the decision-making process of a neural network by incorporating classical AI based on rules (symbolic AI). This hybrid approach requires less training data and allows humans to track how AI makes decisions.

For example, in image recognition, neuro-symbolic AI can use deep learning to identify an individual object and then add a layer of information about the object's properties and its individual parts using symbolic reasoning. Thus, a neuro-symbolic AI system can not only

identify an object, such as an apple, but also explain why it identified it as an apple by providing a list of unique characteristics and properties of the apple.

V. Developed Neuro-PID controller

The overall structure of the self-tuning Neuro-PID controller is shown in Fig. 6, where the neural network (NN) outputs are proportional (K), integral (T_I), and differential (T_d) components [18].

To control the Pasteurizer [18] PID is configured with a multilayer perceptron (MLP, neuro-PID adjuster) with the following structure: 20 input, 10 hidden and 3 output neural elements; the activation function for the hidden and output layers is sigmoid.

The discrete-time **PID controller** can be described by equation 1 [18], where P, T_I and T_D are proportional factors, integral and differential constituents respectively, u_n determines the input of a control object at a time of $t = nT_0$ and e_n — an error between the desired output value of r_n and the real output of $e_n = r_n - y_n$. T_0 defines a unit time interval.

$$u_{k} = u_{k-1} + \Delta u_{k},$$

$$\Delta u_{k} = q_{0}e_{k} + q_{1}e_{k-1} + q_{2}e_{k-2},$$

$$q_{0} = \mathbf{K} \left(1 + \frac{T_{D}}{T_{0}}\right),$$

$$q_{1} = -\mathbf{K} \left(1 + 2\frac{T_{D}}{T_{0}} - \frac{T_{0}}{T_{I}}\right),$$

$$q_{2} = \mathbf{K} \frac{T_{D}}{T_{0}}.$$
(1)

Algorithm for operation of neuro-PID adjuster [18]:

$$y_{j} = F(\sum_{i} \omega_{ij}y_{i} - T_{j}),$$

$$\gamma_{j} = y_{j} - t_{j},$$

$$\gamma_{i} = \sum_{i} \gamma_{i}F'(S_{i})\omega_{ji},$$

$$\omega_{ij}(t+1) = \omega_{ij}(t) - \alpha\gamma_{j}F'(S_{j})y_{i},$$

$$T_{j}(t+1) = T_{j}(t) + \alpha\gamma_{j}F'(S_{j}),$$

$$E = \frac{1}{2}\sum_{k=1}^{L}\sum_{j} (y_{j}^{k} - t_{j}^{k})^{2}.$$
(2)

To use the back propagation algorithm, we must select the E function, which must be minimized. It will be the management error e_n at the time $t = nT_0$ - get $E_n = \frac{1}{2}e_n^2$. To accumulate errors, we store the data we have previously obtained — $E_{n-p}, \dots E_{n-2}, E_{n-1}, E_n$, where p determines the number of previously saved images used for network learning (2):

VI. Examples of system operation with natural language information display

For information to be clear and understandable to the reader, it must be presented in a consistent manner. The recipe authoring system interface allows the structure of domains and ontologies to be expressed in natural language. This process of converting an internal knowledge representation to an external knowledge representation is performed by a graphical interface component.

VII. Integration of third-party solutions with a knowledge base

A standard system built on the basis of OSTIS Technology can be easily integrated with other systems in the workplace. To integrate *ISA-88*, *ISA-95* and *ISA-5.1* standards system with other systems running on JSC "Savushkin Product", a web-oriented approach is used — the ostis-system server is accessed with the use of the following queries:

http://industry.ostis.net?sys_id=unit

where "sys_id=unit" defines a term (the name of an entity) whose value we want to find out (in this example, in fact, the answer to the question "What is a "unit"?). This approach makes it relatively easy to add support of the knowledge base for current control systems projects, for this it is enough to indicate the names corresponding to the entities in the knowledge base within the control system.

Thus, an interactive intelligent help system for control systems projects is implemented, allowing employees to work with the control system and ask questions directly during their tasks.

Another example is the integrated help subsystem within corporate Add-in **EasyEPLANner** [19] for CAD EPLAN. It helps describe technological objects (Tank, Boiler, etc.), operations, and so on according to the *ISA-88* standard. The UML-model of EasyEPLANner highlevel objects can be described in OSTIS. The **PID controller** is at the lower level — the control module. It can be replaced by the development **Neuro-PID controller** with the connections to the units and other high-level objects.

VIII. Use in control systems

It is very important to quickly and correctly react to different events during process control, especially critical accidents. However, when we have a complex distributed system, it is rather complicated and normally requires the help of a human operator. This may lead to a variety of problems. Thus, using an OSTIS-based system can help solve the issues described in Fig. 7. For example, Project #2 has a valve failure but does not know what to do. It makes a request to the OSTIS server, which already knows which projects also use this line (with this valve). The OSTIS server polls the rest of the projects (projects #1 and #2). Each project has information about which operations are currently active and provides an answer on what to do — pause the operation, do nothing, etc. After that, the OSTIS server sends back to Project #2



Figure 6. The developed Neuro-PID controller (TD means delay operator)



Figure 7. OSTIS in control systems

an answer with the resulting actions to be used. These actions are performed automatically, without the need for a human operator.

IX. Future development

Current project issues can be found on GitHub ([20], [21], and [22]). The main problems to be solved are:

- Improving system performance and especially accelerating system response time to user requests. This is connected with productivity and overall user satisfaction.
- Continuously updating and refactoring ontological models (further formalization of missing concepts, fixing typos, etc.).
- Enhancing PFC-visualization not only displaying but also editing diagrams. Adding rich navigation

between PFC-diagrams and corresponding text representations.

- Further formulation of typical questions to the system from the user and their formalization at the level of the existing knowledge base.
- Adding detailed descriptions of real control projects based on the existing knowledge base.

The implementation of answers to complex questions is necessary to make the work easier not only for process operators but also for maintenance personnel instrumentation engineers, mechanics, electricians, etc. Therefore, it is planned to implement the system's answer to the following type of question: in what operations of which objects is this actuator used (for example, valve "T1V1"). This question is very important when a device failure occurs, and it is necessary to determine the criticality of this situation. For analysis, it is necessary to compare the time of the accident and the history of operations. For example, an accident of the mix-proof valve during the line washing operation and the active product dosing along the other line should lead to a stop of these operations and stop the preparation of the batch in the corresponding unit. The operator must report this to the appropriate maintenance specialist to fix it. After the fault has been eliminated, the operator continues to perform operations. This is the correct order of events, which is crucial to avoid mixing detergent and product. If the device malfunction occurred within the line, which is now inactive, then this situation has a low priority, does not lead to a halt in operations, and can be addressed later if the service personnel have available time.

X. Conclusion

The paper considers a technique for automating the process of creating, developing, and utilizing standards, primarily based on OSTIS Technology. Using the example of the ISA-88, ISA-95, and ISA-5.1 standards implemented at the Savushkin Product enterprise, the structure of the knowledge base, the features of the problem solver, and the user interface of the support system for these processes are considered. The developed system has been shown to integrate easily with other enterprise systems, serving as a foundation for building an information service system for employees within the context of Industry 4.0. The approach proposed in this work not only automates the processes of creating, agreeing upon, and developing standards but also significantly increases the efficiency of applying the standard, both manually and automatically.

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НЕЙРО-СИМВОЛИЧЕСКОЕ УПРАВЛЕНИЕ В ПРОМЫШЛЕННОСТИ Изаууар П. С

Иванюк Д. С.

В работе рассмотрен онтологический подход к пониманию, интеграции и развитию современных подходов к управлению (нейроуправление, большие языковые модели, современные международные стандарты) с использованием Технологии OSTIS. Уточнены формальные трактовки основных понятий, используемых в стандартах, что позволяет упростить описание реальных задач. Также описаны варианты интеграции базы знаний в используемые программные средства разработки и сценарии её использования непосредственно в системах управления.

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The Use of Distilled Large Language Models to Determine the Sentiment of a Text

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Abstract—This paper describes a distilled T5-large Transformer-based model for text sentiment analysis optimised for educational applications. The model, created by transferring knowledge from Large Language Models, demonstrates an accuracy of 97.22% on a test sample with a significant reduction in computational requirements. The distillation process, training methodology and experimental results are described. Application scenarios in educational contexts including adaptive learning and personalisation of feedback are proposed. The study shows promise for the use of distilled Large Language Models in resource-limited educational technologies.

Keywords—Large Language Model, reduction, sentiment detection, knowledge distillation, linguodidactics.

I. Introduction

Large Language Models (LLMs), for instance Grok, ChatGPT, DeepSeek, Llama, Qwen, Gemini, Claude and Mistral, have demonstrated high performance in many linguistic tasks (dialogue communication, syntactically and semantically correct text generation, summarisation, interlingual translation, text stylisation and attribution). This has resulted in a notable surge of interest in LLMs from educators and learners, including language teachers. LLMs have the capacity to automatically generate learning tasks, select examples, provide age-appropriate explanations of material, create a quiz, develop a didactic crossword puzzle, illustrate learning material, and numerous other functions. LLMs offer several advantages, including their perpetual availability and the provision of instantaneous, refined feedback. They also provide a diverse array of materials and the capability for personalised learning [1]. The personalisation of learning is inextricably linked to the development of the learner's personality [2]. The personalisation of learning with LLMs is a distinctive feature, with the capacity to adapt to the needs of the interlocutor (gender, age, level of education), including the emotional background, by determining the sentiment of the texts.

II. Statement of the problem of sentiment determination

Sentiment is a complex linguistic category that reflects the emotional and evaluative components of a communicative act. It is realised both at the lexical level through individual linguistic units (lexical tonality) and at the level of integral communicative fragments [3].

Sentiment analysis involves the identification and classification of those elements of a text or speech that express the emotional attitude of the subject of communication (speaker, author) to the object that is the subject of emotional evaluation. The subject's emotionality can be represented in the form of three main categories: positive, neutral or negative. Thus, sentiment reflects the author's position towards the topic under discussion, which, as a rule, is described within a one-dimensional emotional space, where the main poles are "positive" and "negative" evaluations.

For the purposes of linguodidactics, where the adaptation of scientific concepts to educational tasks is required, the definition of sentiment can be simplified and reformulated to meet the needs of learners. In this context, sentiment is defined as the emotional colouring of a speech or text that reflects the speaker's (or writer's) attitude to the subject of discussion, interlocutor or the situation being described.

III. Limitations of LLMs in education

In the context of pedagogical applications, one of the most salient features of LLMs is the partial unpredictability and unreliability of the results they produce. All LLMs are prone to errors, and they have been observed to 'hallucinate' (i.e. construct imaginary facts and operate on them as if they were real). This phenomenon remains to be the subject of rigorous scientific explanation, and its mitigation through technical means is challenging without significant disruption to communication. Furthermore, LLMs are trained on an unrestricted corpus of internet texts, including blogs and forums, which contain profanity, factually inaccurate information, and other such content. This renders their use in the educational process both risky and uncontrolled.

Large-scale neural network architectures, in particular transformers with several billion tunable parameters, demonstrate high accuracy, but face significant operational constraints during training: they require powerful GPU/TPU accelerators, occupy a significant amount of memory, have high power consumption and significant infrastructure costs, making them inaccessible to a wide range of users and necessitating the development of size optimisation techniques.

IV. Distilled models

In the field of large neural network model optimisation, a number of approaches have been developed to create compact architectures, comprising several major categories. Distilled models, such as DistilBert and TinyLlama, exploit the process of knowledge transfer from a large teacher model to a smaller student model, achieving preservation of up to 97% efficiency while significantly reducing the number of parameters. Efficiently designed models, represented by the MobileNet, ShuffleNet, SqueezeNet, EfficientNet and ALBert families, are initially developed with computational resource optimisation as the primary consideration, using special architectural solutions such as depthwise separable convolutions and channel shuffle. Quantisation allows reducing the model dimensionality by reducing the parameter type to 8-bit integers, while the pruning technique helps to achieve a similar effect by thinning the model, in the process of which low-value weights, neurons and even whole layers of neural elements are removed. A separate category is tensor compact models, which use special tensor representations to reduce the number of parameters while maintaining the generalisability of the network. Each of these approaches offers a different balance between performance and resource efficiency, allowing to choose the optimal solution for specific tasks and application conditions.

All of the above techniques, except for the use of special architectural solutions, can be labelled as methods of compression (reduction) of neural network models, allowing to reduce the size of the model while maintaining its efficiency.

This paper focuses on the technique of knowledge¹ distillation, which is particularly important for language² models because it preserves the underlying patterns that large models extract from large amounts of data in a³ more compact form. For example, Hinton describes how distillation can transfer knowledge from complex neural⁴ networks to smaller ones, preserving their efficiency [4].

In the context of educational technology, knowledge₁ distillation becomes critical for text sentiment detection, ² providing four key benefits. Firstly, the efficiency and ³ increased speed of compact models (e.g., DistilBert4 demonstrates a 60% speedup while maintaining 97% efficiency compared to the BERT model) allows for rapid, real-time text sentiment detection, which is especially im-5 portant for fast-paced classroom work [5]. Secondly, the significant reduction in equipment and maintenance costs makes AI technologies affordable even for educational institutions with limited budgets [6]. Thirdly, the ability to

adapt distilled models to specific educational tasks, from creating grammar exercises to mathematical problems of varying levels of difficulty, helps to personalise learning and increase its effectiveness [7]. Finally, fourthly, the use of distilled models that solve specific problems allow us to achieve manageability, through the possibility of direct pre-training, architectural changes, local deployment, etc. This eliminates dependence on large models deployed in the cloud and available only as a service.

V. Computational experiment

To determine the sentiment of a text, we trained a distilled Transformer t5 model. The experiments were conducted with a dataset of texts totalling 1080 sentences in English with different emotional colouring. The dataset was balanced into three sentiment classes: negative, neutral and positive (360 sentences of each class). To increase the representativeness of the data, texts from different thematic areas were included in the dataset: education, interpersonal relationships, parenting, travelling, etc. Subsequently, the data were divided into training (900 sentences, 83.3%) and test (180 sentences, 16.7%) datasets while maintaining a proportional distribution of classes. The said datasets were generated using the Claude 3.7 Sonnet, Grok 3 and Gemini 2.0 Pro models, followed by manual checking and correction by linguists to ensure naturalness and stylistic diversity.

As a basic model for distillation we used the seq2seq model of T5-large transformer, with the number of adjustable parameters 770 million [8]. The input of the model during training was JSON-formatted data, while the output was JSON-formatted reference values containing the type of sentiment, the confidence level of the model, and an explanation of why such a decision was made when classifying a sentence.

Example of input and output sequences:

{
"instruction": "Analyse the sentiment
of the following text.",
"input": "Please open your books to
page 10."
}
{
"sentiment": "neutral",
"confidence": 0.98,
"explanation": "A polite request/
instruction, expressing no
explicit emotions."

Training was performed for 100 epochs. Main parameters: mini-batch size -16 instances, learning rate -5e-5, and Adam method with weight decay was used for minimisation [9], input sequence size – 64 tokens, output sequence size – 128 tokens.

We used the A100 video accelerator in the training process [10].

In Fig. 1 the evolution of the error on the training dataset during the training process is depicted.



Figure 1. Evolution of the error on the training dataset.

The confusion matrix calculated on the test dataset is given in Table I.

Table I Confusion matrix

		Actual type				
		NEG	NEU	POS		
Type, received	NEG	59	0	0		
using	NEU	1	59	3		
the model	POS	0	1	57		

The final accuracy of the model on the training dataset was 99.89% (one error per 900 instances), on the test dataset it was 97.22%.

Examples of errors made by the model for sentences from the test dataset, taking into account the explanatory part, are given in the table II (T_a – actual type of sentence, T_a – type obtained by the model, Exp_a – actual explanation, Exp_m – explanation obtained by the model).

Thus, during the computational experiment, a distilled t5 transformer model was trained with high accuracy for text sentiment detection.

The obtained high accuracy rates (97.22% on the test dataset) are conditioned by several key factors: the specificity of the source data (sentences generated with LLMs contain more pronounced lexical sentiment markers compared to natural texts, which considerably simplifies the classification task), the advantages of the T5 architecture, which was originally developed as a universal model for various NLP tasks, providing high efficiency in tasks that require deep understanding of context and semantics, the efficiency of the T5 architecture, and the efficiency of the T5 model in tasks that require deep understanding of context and semantics.

 Exp_m Sentence T_m Exp_a International POS NEU Uses positive The text uses trade has language strong positive brilliantly ('brilliantly') evaluation lifted millions to highlight ('brilliantly') to praise the of families poverty out of poverty reduction success of benefits of international global trade. trade, implying admiration. but not strong emotion NEG NEU The human Uses The text toll negative presents of language factual globalisation а ('human observation can be seen in devastated toll'. about the factory 'devastated', impact of towns and 'abandoned') common а abandoned technological to describe communities social approach impacts without expressing an opinion about the moral or environmental value of this impact. POS Tourism has NEU factual The text uses a A expanded observation strong positive dramatically about descriptor as a result of ('dramatically') tourism globalisation trends describe to without clear the growth emotional of tourism judgement as а result of modern technological development

VI. Personalisation of education at the systemic level

In the long term, sentiment analysis can become an integral part of the educational process, transforming approaches to learning, interaction and assessment.

With the emergence of sentiment analysis technologies, there is a concomitant shift in the role of the teacher from the traditional "knowledge transmitter" to that of a facilitator and mentor. This new role is characterised by the utilisation of data to provide students with support and guidance. It is predicted that teachers will come to rely on automated systems for routine tasks such as the analysis of texts or monitoring of engagement, thus allowing them to focus more strategically on issues such as the development of individual learning trajectories or the nurturing of interpersonal relationships in the classroom.

Sentiment analysis has the potential to underpin the creation of personalised educational systems, whereby each student receives learning materials, assignments and feedback that are tailored to their cognitive, emotional and social characteristics. This is of particular impor-

Table II Examples of errors

tance in mass education settings, where traditional approaches often fail to account for individual differences.

For instance, the education platform employs sentiment analysis in conjunction with other data (e.g., test scores, task completion rates) to generate an individual profile for each student. Utilising this comprehensive profile, the system then proposes an optimal pace for learning, the most suitable types of assignments, and the instructor's preferred communication style.

Sentiment analysis also can contribute to the integration of emotional intelligence into educational programmes, making it an integral part of learning. This will prepare students not only for professional activity, but also for successful interaction in society, where the ability to understand and manage emotions is becoming increasingly important.

Sentiment analysis can be a tool to promote intercultural education, helping students to understand how emotions are expressed in different languages and cultures. This is particularly relevant in the context of globalisation, where students increasingly interact with people from other cultures, both in educational and professional contexts.

VII. Prospects for the application of the model in linguodidactics

Sentiment analysis has considerable potential for application in an educational context, covering a wide range of tasks.

For example, sentiment analysis plays a significant role in creating adaptive learning materials. It is possible to track preferred exercises, identify the most difficult and uninteresting topics, and find ways to increase student engagement. For example, a sentiment detection system can analyse students' comments and, detecting negative sentiment ("This topic is boring.", "Upbringing of children is tiresome, difficult and time-consuming.", "I don't like make up, so I'm not interesting in these words and the words are complicated to memorise."), suggest additional exercises to memorise vocabulary and factual information in game form or video lessons with native speakers. When integrated with artificial intelligence systems, it is possible to create more complex adaptive systems that will take into account not only the emotional state, but also the cognitive characteristics of learners.

The monitoring of student engagement is another important task that can be addressed by analysing the sentiment of the text. In the context of traditional teaching, the teacher is able to read non-verbal signals (gestures, facial expressions). However, it is simply impossible to track all students during a lesson, and the temporary manifestations of any emotions in the lesson may be caused by external factors unrelated to the educational process itself. Unlike traditional teaching, where the teacher focuses on non-verbal cues, automatic analysis helps to take more factors into account. The system can automatically analyse students' written answers, identifying markers of emotional state, such as the use of emotionally coloured vocabulary ("awful", "good", "clear", "curious") or patterns of behaviour (reducing the amount of text in answers). Thus, the teacher can promptly adjust the educational process by adding motivating elements, changing the focus and format of tasks, teaching material.

If attitudes towards the assignment or topic have been identified, there is still the problem of feedback. Sometimes it is difficult for the teacher to formulate a response that is not clichéd. At the same time, an inappropriate tone (e.g., overly critical or formal) can demotivate the student and reinforce his or her negative attitude towards the subject. For example, in an essay, a student writes "I'm not sure, whether my essay has a convincing argument for my point of view". The sentiment analysis system classifies this as negative or uncertain sentiment and offers the teacher the following comment: "You've already laid a good foundation for your argument, let's add some examples to strengthen your position". This approach helps to increase the student's confidence and motivate them to work further.

Sentiment analysis is not limited to written work. Modern automatic speech recognition systems are able to record the speech of teachers and students in the classroom, after which the sentiment analysis system can process this data.

This can be useful for teachers who wish to improve their speech in the classroom from the position of emotional colouring. For example, it is extremely important for student teachers to control their speech during the formation of professional speech (tracking negative vocabulary, imperatives, etc.). For example, a teacher uses a large number of imperatives: "Go to the blackboard. Open your books.", modal verbs with the meaning of owing "You have to do it. You must write down these words."

It is important for students of linguistic specialities to understand the emotional colouring of a text. Thus, the sentiment analysis system can check essays, oral recordings, comments, simple sentences, determining the level of emotional colouring of the text. For example, "The book left me with a deep sense of sorrow and contemplation. The protagonist's fate was truly heartbreaking." The text contains emotionally coloured words ("sorrow", "heartbreaking"), which indicates a negative sentiment, namely sadness and sorrowfulness. "This explanation is so confusing. I have no idea what the teacher meant." The phrases "so confusing", "no idea" indicate frustration and misunderstanding. Perhaps a further explanation should be offered.

Thus, sentiment analysis can help students better understand the emotional colouring of a text and improve their language skills. However, despite its considerable potential, it is important to consider a number of limitations associated with its application in an educational setting. Consider the main ones.

VIII. Limitations in the application of the model

Modern sentiment analysis algorithms, although demonstrating high accuracy in standard situations, may make mistakes when analysing complex texts containing irony, sarcasm, cultural allusions or non-standard language constructions. This is especially true in educational contexts where students' texts may be informal, contain errors, or reflect individual differences in style.

The system categorises the student's message "Oh great, another five-page essay due tomorrow. I just love staying up all night writing!". The expected sentiment of this comment is negative (sarcasm, dissatisfaction).

A possible algorithm error is evaluating sentiment as positive (because of the words "great", "love") without recognising sarcasm.

The use of sentiment analysis to monitor students' emotional state raises serious issues of confidentiality and ethics. One of the key issues is the collection of data without the explicit consent of students. This can lead to them holding back in expressing their thoughts for fear that their comments will be used against them.

Another important aspect is the use of the analysis results for academic decision making. If the algorithm determines that a student often uses negatively coloured expressions such as "I don't understand anything" or "This topic is frustrating", and on this basis the system marks him as under-motivated, this may affect his grade or level of learning. However, the emotional colouring of speech does not always correlate with actual performance.

In addition, there is a risk of stigmatisation. If a teacher receives a report in which one of the students is labelled as having a tendency to make negative comments, this may influence his/her attitude towards the student. Human perception is influenced by such labelling and the teacher may start to see the student as a problem student, even if there is no real reason for this.

The possibility of manipulation with the system should also be considered. If students realise that sentiment analysis affects their learning process, they may deliberately use positive expressions such as "This lesson was amazing!" or "I feel super confident!" even if they are actually experiencing difficulties. As a result, the teacher receives unreliable data, which reduces the effectiveness of feedback and hinders the adaptation of the learning process to the real needs of students.

Consequently, sentiment analysis holds considerable potential for implementation within the domain of linguodidactics. This is due to its capacity to personalise learning experiences, monitor student engagement, and consider their emotional state. Nevertheless, its effective implementation necessitates a comprehensive approach encompassing not only technological but also ethical components. It is imperative to consider the implications of language and cultural idiosyncrasies, as well as the potential inaccuracies inherent in algorithmic processes. The introduction of such technologies must be carried out in compliance with the principles of transparency, voluntariness and protection of personal data.

Furthermore, it is imperative to acknowledge that sentiment analysis should not be regarded as a standalone tool. Indeed, it is the combination of sentiment analysis with other methods of learning assessment and adaptation, including artificial intelligence, personalised learning strategies and pedagogical analysis, that will ensure optimal efficacy. It is only by adopting an integrated approach that a truly flexible and supportive learning environment can be created, where technology can take into account not only students' knowledge and skills, but also their emotional state.

IX. Distilled language models in OSTIS systems

To integrate a trained distilled language model, it is initially necessary to decide on the role that the model will perform in the OSTIS Ecosystem.

On the basis of the model, a problem solver can be developed – for example, to analyse the sentiment of a text. In this case, integration can be performed by embedding the model in a broader knowledge processing context. For example, the model analyses the text "Product is great, but delivery is slow". It determines the mixed sentiment, and then this result is passed to the OSTIS knowledge base, where it can be linked to the "Product" and "Delivery" entities for further analysis or decision making.

In the process of integration it is necessary to perform transformation of input and output data into SC-code. For this purpose, it is necessary to formalise the analysed text and encode the resulting sentiment as a semantic node associated with the analysed text. Such transformations allow the result to be used for more complex inferences.

Integration can also be done by implementing an agent that interacts with the model. In this case, the most proven approach is the use of microservice architecture with the implementation of an appropriate API for interaction with the OSTIS-agent.

Integration of the distilled model with the OSTIS system will allow it to be used in more complex scenarios, for example:

- **feedback analysis**: the model determines the sentiment of the reviews, and OSTIS makes recommendations or identifies problem areas (e.g., "slow delivery" is found in 70% of negative reviews);
- **training systems**: the sentiment of a student's text can be analysed to assess their emotional state and OSTIS will offer adapted learning content;
- social media monitoring: integration with data from different sources will allow real-time tracking

of public opinion, and OSTIS will link sentiment to specific topics or events.

X. Conclusion

Thus, we have developed a distilled sentiment analysis model based on the T5 architecture that achieves 97.22% accuracy on a test dataset while reducing the number of parameters by 92.2% compared to the original model, demonstrated the effectiveness of the knowledge distillation technique for creating resource-efficient natural language analysis models, and proposed scenarios for applying the developed model in an educational context, including adaptive learning, monitoring student engagement, and personalising feedback. The results obtained indicate the promising application of distilled language models in educational technologies, especially in the context of limited computational resources. The compact size and high speed of operation make the developed model suitable for integration into mobile applications and online learning platforms.

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ИСПОЛЬЗОВАНИЕ ДИСТИЛЛИРОВАННЫХ БОЛЬШИХ ЯЗЫКОВЫХ МОДЕЛЕЙ ДЛЯ ОПРЕДЕЛЕНИЯ ТОНАЛЬНОСТИ ТЕКСТА

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В статье описана дистиллированная модель на основе трансформера T5-large для анализа тональности текста, оптимизированная для образовательных приложений. Модель, созданная путем передачи знаний от больших языковых моделей, демонстрирует точность 97.22% на тестовой выборке при значительном снижении вычислительных требований. Описан процесс дистилляции, методология обучения и результаты экспериментов. Предложены сценарии применения в образовательном контексте, включая адаптивное обучение и персонализацию обратной связи. Исследование показывает перспективность использования дистиллированных больших языковых моделей в образовательных технологиях с ограниченными ресурсами.

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Intellectualization of Decision Support Systems Based on Cloud Computing

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Abstract—The implementation of artificial intelligence is a priority direction for the development of information management systems. Decision support systems (DSS) are information processing systems that emerged from the integration of automated management systems and database management systems. Their purpose is to assist users in making decisions on complex, unstructured, or weakly structured problems in various fields of human activity. Various methods can be used for analysis and generating recommendations by the system, including information retrieval, simulation modeling, case-based reasoning, situational analysis, cognitive modeling, machine learning, artificial neural networks, data mining, knowledge discovery in databases, genetic algorithms, and others. This article proposes a method for the intellectualization of decision support systems based on the use of OSTIS Technology, intelligent agents, and cloud computing. The implementation of autonomous agents for discovering hidden interpretable patterns in data and subsequent classifier construction is described. The effectiveness of the method is confirmed by the results of a numerical experiment based on model data.

Keywords—decision support systems, cloud computing, knowledge discovery, data mining, instance-based learning

I. Introduction

Solving problems related to improving the efficiency of using data warehouses and databases is one of the priority areas of computer science. This is a science that deals with the development of methods for processing, analyzing, and evaluating information, ensuring its effective use for decision-making [1], [2]. The development and implementation of artificial intelligence technologies are the most important factors in the progress of creating and using information systems [3]–[6]. Currently, the drivers of intellectualization in these systems are machine learning, artificial neural networks, and data mining [6]– [12].

The development of new approaches and technologies in machine learning largely determines progress in the field of artificial intelligence [13], [14]. At its core, machine learning is associated with identifying empirical patterns in data based on observed instances. Sets of positive and negative examples related by an unknown pattern are analyzed, and a classification algorithm is developed to separate the examples into classes [15], [16].

In machine learning, a situation has arisen where the construction of a classification algorithm follows a standard scheme: a description space of objects is given, in which a separating surface needs to be constructed. Learning occurs during the solution of an optimization problem and involves the construction of decision rules that provide an extremum for a certain criterion. A class of decision rules is predefined up to parameters, and learning is reduced to finding parameter values that provide an extremum for the selected criterion [17], [18].

The learning process involves multiple executions of the "training + testing" scenario. Within this process, through positive and negative reinforcement, the necessary patterns of classifier behavior are formed. However, learning can only be conducted in an automated mode, and the constructed classification algorithm represents a "black box" [19], [20].

An alternative method of learning by precedents can be implemented based on the properties generality principle. The main assumption of this principle is that instances of the same class share common properties reflecting their similarity. The learning process is aimed at investigating the properties of feature combinations from an a priori dictionary to construct feature spaces where class patterns do not intersect.

This article proposes a method for the intellectualization of decision support systems based on the use of OSTIS Technology, intelligent agents, and cloud computing. An original method for implementing autonomous agents to discover hidden interpretable patterns within training data and to construct a classifier is presented. The effectiveness of the method is confirmed by the results of a numerical experiment.

II. Decision Support System and Knowledge Discovery Classification

A decision support system (DSS) is an information system designed to help specialists quickly solve managerial and organizational problems that may arise unexpectedly and require prompt responses. DSS emerged from the integration of management information systems and database management systems (Fig. 1).



Figure 1. Decision Support System.

Various methods can be used for analysis and generating recommendations by the system, including information retrieval, simulation modeling, case-based reasoning, situational analysis, cognitive modeling, machine learning, artificial neural networks, data mining, knowledge discovery in databases, genetic algorithms, and others.

The implementation of DSS increases the efficiency of planning and managing processes in organizations. They facilitate the prompt resolution of emerging problems, allowing for more informed decisions. This leads to time savings and a reduction in the number of employees required, as well as mitigating the human factor in risk assessment.

In the late 1970s, intelligent decision support systems (IDSS) emerged, built on the application of artificial intelligence technologies [21], [22]. Ideally, an IDSS should act as a consultant-specialist to support decision-makers. The system should provide information collection and analysis, identify and diagnose problems, and propose and evaluate possible courses of action.

In the initial stages of implementation, many intelligent decision support systems were based on approaches and technologies developed for expert systems [23], [24]. Currently, the construction of IDSS is based on the use of machine learning methods, artificial neural networks, and data mining.

For the intellectualization of decision support systems, it is proposed to use cloud computing technologies and multi-agent systems (Fig. 2) [25], [26].

Intelligent agents are complex specialized objects that can interact with each other and possess the following properties:



Figure 2. Multi-agent System and Decision Support Systems.

- autonomy or semi-autonomy functioning without external intervention and ensuring self-control over their actions and internal states;
- social ability interacting with other agents through message exchange using communication means;
- reactivity the ability to perceive the state of the external environment;
- pro-activity agents respond not only to stimuli from the environment but also proactively initiate actions.

The Knowledge Discovery Agent (KD-agent) automatically identifies feature combinations that distinguish classes based on the analysis of training data. The Classifier Builder Agent (CB-agent) constructs a classification algorithm by receiving a set of distinguishing feature combinations from the KD-agent and automatically builds a classifier.

The task of intelligent agents is to implement the procedure of learning from instances. In the classical formulation, the mathematical statement of the problem is as follows: Let X be a set of object descriptions and Y be a set of valid classification responses. There is an unknown target dependency $y^* : X \to Y$ the values of which $X^m = \{(x_1, y_1), \ldots, (x_m, y_m)\}$ are known only for the objects of the training set. It is required to construct an algorithm $a : X \to Y$ that approximates this target dependency not only on the objects of the finite set but also on the entire set X.

Traditionally, to solve the problem, a parametric family of algorithms is first selected, in which the initial parameter values are fixed. Then, based on the training data, the final tuning of the algorithm is performed. In fact, learning is conducted within the framework of solving an optimization problem, which is reduced to constructing algorithms (*decision rules*) that provide an extremum for a certain criterion (*for example, the value of the average risk in a special class of decision rules*).

The main drawback of the described instance-based learning method is the lack of the possibility of its implementation in an automated mode.

Automated instance-based learning is proposed to be conducted based on the properties generality principle. Suppose that $K = \{K_1, \ldots, K_l\}$ is the alphabet of classes, $F = \{f_1, \ldots, f_n\}$ is the a priori dictionary of features, and X is the training set. Let $V = \{v_1, \ldots, v_q\}$

(where $q = 2^n - 1$) be the set of all non-empty subsets formed by all possible combinations of features from F. The goal of learning is to identify such feature combinations $v_i \in V$ that ensure class distinction.

It is proposed to obtain an estimate of the distinguishing properties of combinations $v_i \in V$ in the corresponding feature space by constructing class patterns and comparing their mutual placement. A class pattern should be constructed based on all its objects in the training set and will essentially represent the domain of the class. Feature combinations $v_i \in V$ that ensure class distinction are those for which, in the corresponding feature space, the patterns of different classes do not intersect.

The corresponding task is called *Knowledge Discovery Classification (KDC task).* The problem statement is as follows: Let two sets $\{I_0\}$, $\{I(S)\}$ be given - admissible training information $I_0(K_1,\ldots,K_l)$ and descriptions I(S) of admissible objects $S \in M$ respectively. It is required, based on the analysis of the set of information $I_0(K_1,\ldots,K_l)$, to find a set of distinguishing qualities of classes $Q(K_1, \ldots, K_l)$ such that $K_i \cap K_i = \emptyset, \forall i \neq j$ (where i, j = 1, 2, ..., l) and then, using the set Q(S), compute the values of predicates $P_i(S), j = 1, 2, ..., l$.

III. OSTIS Technology and Intelligent Agents

The process of representing the formal ontology of a subject domain and designing intelligent agents can be implemented based on the comprehensive component design technology of intelligent systems - OSTIS Technology (Open Semantic Technology for Intelligent Systems) [27].

The operation of intelligent agents is based on training data. The procedure for its formation begins with the construction of an alphabet of classes and an a priori dictionary of features. The use of OSTIS Technology allows, through SC-code (sc-models), to get the semantic representation of classes, the formalized representation of features of the a priori dictionary, and to construct a training set model.

The result of the KD-agent's work is a set of feature combinations $V^* = \{v_1^*, \ldots, v_t^*\}$, which possess the property of class distinction. Each combination $v_i^* \in V^*$ defines a pattern of the form "in the space of feature combinations v_i^* , the classes do not intersect" and is formally described using the unified representation language -SCcode.

The input information for the KD-agent is the a priori dictionary of features $F = \{f_1, \ldots, f_n\}$ and the training set X, and the result of its work is a set of feature combinations $V^* = \{v_1^*, \dots, v_t^*\}$ (where $0 \le t \le 2^n - 1$), ensuring class distinction (Fig. 3). The mathematical statement of the problem for the KD-agent is as follows: Let $F = \{f_1, \ldots, f_n\}$ be the a priori dictionary of features, X be the training set. It is required to find feature spaces in which class patterns do not intersect.





Figure 3. KD-agent Operation Scheme.

Let $V = \{v_1, ..., v_q\}$ (where $q = 2^n - 1$) be the set of all non-empty subsets formed by all possible combinations of features from F. The algorithm for searching on the set V for feature combinations that ensure class distinction is as follows:

Step 1. Select a subset $V^+ = \{v_1^+, \dots, v_+^i\}$ of V, where v_i^+ contains only one feature.

Step 2. For each v_i^+ we construct class patterns (class definition areas) and compare their mutual placement [28].

Step 3. If class patterns do not intersect, then feature v_i^+ is included in the set $V^* = \{v_1^*, \dots, v_k^*\}.$

Step 4. Exclude from the set $V = \{v_1, \ldots, v_q\}$ the subset $V^+ = \{v_1^+, \dots, v_n^+\}$ and get $V^{\Delta} = \{v_1^{\Delta}, \dots, v_p^{\Delta}\}$. Step 5. Exclude from V^{Δ} all combinations of v_i^{Δ} , that

contain any combination from $V^* = \{v_1^*, \dots, v_k^*\}.$

Step 6. Take the next combination v_i^{Δ} from V^{Δ} and build a feature subspace based on it.

Step 7. In this feature subspace, we construct class patterns and compare their mutual placement.

Step 8. If the class patterns do not intersect, we include the combination of features v_i^{Δ} in the set V^* , and exclude from V^{Δ} all combinations that contain v_i^{Δ} .

Step 9. Repeat the process until V^{Δ} is empty.

As a result of the algorithm execution, the set $V^* =$ $\{v_1^*,\ldots,v_t^*\}$ is formed, where $0 \le t \le q$.

The input information for the CB-agent is the training set X and the set of feature combinations $V^* =$ $\{v_1^*,\ldots,v_t^*\}$, ensuring class distinction, and the result of its work is a classification algorithm.

The mathematical statement of the problem for the CB-agent is as follows: Let X be a set of object descriptions and Y be a set of valid classification responses. There is an unknown target dependency $y^* : X \to Y$, the values of which $X^m = \{(x_1, y_1), \dots, (x_m, y_m)\}$ are known only for the objects of the training set. It is required, based on the set $V^* = \{v_1^*, \ldots, v_t^*\}$ of feature combinations ensuring class distinction, to construct an algorithm $a : X \to Y$ that approximates this target dependency not only on the objects of the finite set but also on the entire set X(Fig. 4).

Feature combinations $v_i^* \in V^*$ define decision spaces in which class patterns do not intersect. In such spaces,



Figure 4. CB-agent Operation Scheme.

classification is conducted in terms of the *KDC task* according to the rule:

- for each feature combination $v_i^* \in V^*$ (where i = 1, 2, ..., t), based on the training data, cluster structures $P_1^i, ..., P_l^i$ class patterns $K_1, ..., K_l$ are constructed;
- the object under study $S \in K_m$ if $S \in P_m^i \forall i = 1, 2, \dots, t$.

IV. Example of Supervised Learning Based on Model Data

Let the following be given:

- class A (four-digit decimal numbers with digits in the Units place ranging from 0 to 4 inclusive), class B (four-digit decimal numbers with digits in the Units place ranging from 5 to 9 inclusive, and in the two higher places Hundreds and Thousands a pair of digits of the form even-even or odd-odd), class C (five-digit decimal numbers with digits in the Units place ranging from 5 to 9 inclusive, and in the two higher places Hundreds and Thousands a pair of digits of the form even-even or odd-odd), class C (five-digit decimal numbers with digits in the Units place ranging from 5 to 9 inclusive, and in the two higher places Hundreds and Thousands a pair of digits of the form even-odd or odd-even);
- a priori dictionary of features $F = {Units, Tens, Hundreds, Thousands};$
- the content of the training set is presented in Table I.

Table I Training Set

n/n	Class A	Class B	Class C
1	7854	2479	4319
2	9723	7327	7205
3	5481	8256	3856
4	4270	6825	9248
5	3422	1798	3037
6	1351	3756	2965
7	2650	4439	2389
8	5964	5917	7827
9	9293	9385	5408
10	8762	3148	8746

Table II presents the results of the study of the intersection of patterns of class A and the class formed by combining instances of classes B and C. From Table II, it can be seen that:

Table II Results for classes **A** and **B+C**

			D.C				D.C.
		A	B+C			A	B+C
	0	2	0		0	0	1
	1	2	0		1	0	1
	2	2	0		2	2	3
	3	2	0	sp	3	1	4
its	4	2	0	lree	4	2	3
Uni	5	0	4	nn	5	0	0
	6	0	4	Ĥ	6	1	0
	7	0	4		7	2	3
	8	0	4		8	1	3
	9	0	4		9	1	2
	0	0	2		0	0	0
	1	0	2		1	1	1
	2	2	3		2	1	3
	3	0	2	ds	3	1	4
us	4	0	3	san	4	1	2
Te	5	3	3	no	5	2	2
	6	2	1	Th	6	0	1
	7	1	1		7	1	3
	8	1	2		8	1	2
	9	1	1		9	2	2

Table III Results for classes **B** and **A+C**

		B	A+C			B	A+C
	0	0	2		0	0	1
Tens Units	1	0	2		1	1	0
	2	0	2		2	1	4
	3	0	2	s s	3	2	3
Units	4	0	2	lre	4	2	3
Un	5	2	2	pur	5	0	0
	6	2	2	É	6	0	1
	7	2	2		7	2	3
	8	2	2		8	1	3
	9	2	2		9	1	2
	0	0	2		0	0	0
Tens Units	1	1	1		1	1	1
	2	2	3		2	1	3
	3	1	1	ds l	3	2	3
us	4	1	2	san	4	1	2
Te	5	2	4	no	5	1	3
	6	0	3	L L	6	1	0
	7	1	1		7	1	3
	8	1	2		8	1	2
	9	1	1		9	1	3

- values 0, 1, 2, 3, 4 of the *Units* feature are present only in representatives of class A, and values 5, 6, 7, 8, 9 only in representatives of the combined class B+C, which means that the *Units* feature ensures the distinction between classes A and the combined B+C;
- features *Tens*, *Hundreds* and *Thousands* do not possess the property of distinguishing classes **A** and the combined **B+C**.

Table III presents the results of the study of the intersection of patterns of class **B** and the class formed by combining representatives of classes **A** and **C**. From Table III, it can be seen that none of the features *Units, Tens, Hundreds* or *Thousands* ensures the distinction

between classes **B** and **A+C**.

Table IV presents the results of the study of the intersection of patterns of class C and the class formed by combining instances of classes A and B.



From Table IV, it can be seen that none of the features *Units, Tens, Hundreds* or *Thousands* ensures the distinction between classes C and A+B.

The results of the study of the properties of the features *Units, Tens, Hundreds* and *Thousands* demonstrated that the properties of the *Units* feature are unique for class **A**, and the following intermediate classification rule can be formulated:

IF (0 ≤ Units ≤ 4) *THEN Class A ELSE* (*Class B or Class C*)

. Next, to finalize the classifier, it is necessary to find feature combinations that ensure the distinction between classes B and C.

Let's proceed to analyze the properties of feature combinations (Units, Tens), (Units, Hundreds), (Units, Thousands), (Tens, Hundreds), (Tens, Thousands), (Hundreds, Thousands).

Table V presents the results of the study of the mutual placement of patterns of classes **B** and **C** in the space formed by the combination of features (*Units, Tens*).

From Table V, it can be seen that there are intersections of patterns of classes **B** and **C** (pairs 27, 48 and 56), and the combination of features (*Units, Tens*) does not ensure the distinction between classes **B** and **C**.

Table VI presents the results of the study of the mutual placement of patterns of classes **B** and **C** in the space formed by the combination of features (*Hundreds, Thousands*). From Table 6, it can be seen that the patterns of classes **B** and **C** do not intersect. For representatives of class **B**, the combinations of values of features (*Hundreds, Thousands*) are either (*even, even*) or (*odd, odd*),

Table V Results of placement of patterns \mathbf{B} and \mathbf{C} in the space (Units, Tens)

Units Tens	0	1	2	3	4	5	6	7	8	9
0						С		В	С	
1										С
2						В		B,C		
3								C		В
4							С		B,C	
5							B,B,C			
6						C				
7										В
8						В				C
9									В	

Table VI Results of placement of patterns **B** and **C** in the space (*Hundreds*, *Thousands*)

Hundreds Thousands	0	1	2	3	4	5	6	7	8	9
0										
1								В		
2				С	В					С
3	С	В						В	С	
4				С	В					
5					С					В
6									В	
7			С	В					С	
8			В					С		
9			С	В						

while for representatives of class **C**, the combinations of values of features (*Hundreds*, *Thousands*) are either (*odd*, *even*) or (*even*, *odd*).

The results of the study of the properties of feature combinations (*Units, Tens*) and (*Hundreds, Thousands*) demonstrated that the classification rule for representatives of the two classes C and B is as follows:

IF ((Hundreds, Thousands) = (even, even) or (Hundreds, Thousands) = (odd, odd))

THEN Class B ELSE Class C

Combining the two local rules identified during the study, for the three classes A, B, C, we obtain the following general rule for constructing the classifier:

IF ($0 \le Units \le 4$) THEN Class A

ELSE IF ((Hundreds, Thousands) = (even, even) or (Hundreds, Thousands) = (odd, odd)) THEN Class B ELSE Class C

V. Conclusion

The article proposes a method for the intellectualization of decision support systems based on the joint use of OSTIS Technology, autonomous agents, and cloud computing. An original method for implementing intelligent agents based on the properties generality principle is presented. The input is a training set, and by interacting with each other, the agents automatically implement supervised learning. An algorithm for learning from instances is described to identify feature combinations that possess the property of class distinction. In an automated mode, the training data is analyzed, and a classifier is constructed. A model example demonstrates the results of applying an intelligent agent for the automatic construction of a classification algorithm based on the proposed method and algorithm for learning from instances.

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ИНТЕЛЛЕКТУАЛИЗАЦИЯ СИСТЕМ ПОДДЕРЖКИ ПРИНЯТИЯ РЕШЕНИЙ НА ОСНОВЕ ОБЛАЧНЫХ ВЫЧИСЛЕНИЙ

Краснопрошин В. В., Родченко В. Г., Карканица А. В.

Системы поддержки принятия решений представляют собой системы обработки информации, которые возникли в результате слияния автоматизированных систем управления и систем управления базами данных. Их назначение - помогать пользователям принимать решения по сложным не- или слабоструктурированным проблемам. Для анализа и выработки системой предложений могут быть использованы различные методы – информационный поиск, имитационное моделирование, рассуждение на основе прецедентов, ситуационный анализ, когнитивное моделирование, машинное обучение, искусственные нейронные сети, интеллектуальный анализ данных, поиск знаний в базах данных, генетические алгоритмы и др. В статье предлагается метод интеллектуализации систем поддержки принятия решений на основе использования технологии OSTIS, интеллектуальных агентов и облачных технологий. Описывается реализация автономных агентов для обнаружения в данных скрытых интерпретируемых закономерностей и последующего построения классификатора. Эффективность метода подтверждается результатами численного эксперимента на основе модельных данных.

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Artificial Intelligence: Definition and Prospects for Use in the Field of Humanities Research

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Abstract—This article explores definitions of artificial intelligence (AI) and its prospects in humanities research. It defines an object-oriented approach to understanding AI and analyzes key components of its architecture: data and algorithms. The article examines the potential development of AI technologies, including artificial general intelligence (AGI) and artificial superintelligence (ASI). The limitations of modern AI models are discussed, particularly their inability to replace humanities researchers, while their usefulness as a tool for supporting scientific activity is emphasized.

Keywords—artificial intelligence, machine learning, large language model, humanities research, AGI, ASI.

I. INTRODUCTION

Since artificial intelligence (AI) no longer requires a separate introduction, we will replace this section with a definition. In this article, we will not interpret the concept of AI and related terms from the perspective of a timeline of scientific and technological progress or by pinpointing a specific moment on that timeline. Instead, we will focus on the specific implementation of AI technologies, perceiving them as distinct objects. This object-oriented approach allows us to examine AI systems as self-contained entities with defined properties and behaviors, rather than as stages in an evolutionary process. In this context, we define the key components of AI and evaluate its prospects for application in humanities research. Our methodology emphasizes practical implementation over historical development, recognizing that contemporary AI systems represent complex integrations of hardware, software, and data architectures that warrant analysis as complete technological artifacts.

II. DEFINITION AND ARCHITECTURE OF ARTIFICIAL INTELLIGENCE

AI is a technology that enables the emulation of certain external parameters of human activity. A specific AI technology is traditionally referred to as a model (e.g., «large language model» (LLM), «visual-language model» (VLM), etc.) [1], [2]. These models represent sophisticated computational frameworks designed to process and generate human-like outputs across various modalities. The term "model" reflects their function as abstract representations of cognitive processes, implemented through complex mathematical architectures.

From an object-oriented perspective, AI is always implemented through a combination of hardware and software. Its architecture can be described through two fundamental components that interact in a dynamic feedback loop:

- Data processed by AI, which serves as both the input and training material for the system's knowledge base;
- Algorithms that facilitate data processing, comprising the computational rules and learning mechanisms that transform inputs into meaningful outputs.

The purpose of AI development is to automate data processing at scale, and its machine learning (ML) algorithms regulate responses to input queries through probabilistic inference and pattern recognition. This automation extends beyond simple rulebased systems to incorporate adaptive learning capabilities that improve with exposure to additional data.

Data is represented in digital format as sequences of 0s and 1s since the vast majority of AI's hardware operates using digital technologies and follows the Princeton architecture. Consequently, any information that can be reasonably converted into a binary sequence qualifies as data for AI. This includes not only traditional text and numerical data but also multimedia content, sensory inputs, and even abstract concepts when properly encoded. Notably, algorithms themselves are also sequences of 0s and 1s and can therefore be classified as data, creating a recursive relationship where algorithms process data that may itself contain other algorithms.

Traditionally, AI algorithms are defined as machine learning algorithms, which significantly differ from classical computational algorithms [3]. The key distinction is that machine learning algorithms, due to

their built-in autonomy, can self-regulate the nature of their responses based on the data they receive. This regulation occurs through machine learning itself, meaning AI technology is capable of software-based self-organization that adjusts its internal parameters without explicit programming. A classical algorithm, by its inherent nature, always produces the same result for the same input data. However, intelligent models do not. This discrepancy is not solely due to the probabilistic nature of machine learning algorithms but is fundamentally linked to the presence of learning itself: given identical input data, a model at one stage of training may yield one result, while at another stage, it may produce a completely different one as its internal representations evolve through exposure to new information.

In a way, the difference between classical algorithms and machine learning algorithms boils down to the following: classical algorithms represent human problem-solving through an algorithm, whereas machine learning algorithms represent model-based problem-solving with human assistance. Of course, human «assistance» here refers to the initial configuration of the model's parameters, training data selection, and ongoing supervision, creating a collaborative dynamic between human designers and artificial systems. This distinction highlights the paradigm shift from deterministic programming to statistical learning that characterizes modern AI systems.

III. LIMITATIONS AND RISKS OF ARTIFICIAL INTELLIGENCE

presence self-It is precisely the of organization—even adjustable-that if it isunderpins concerns and negative forecasts regarding AI. This is because predicting the exact «configuration» of a specific AI technology in advance is nearly impossible due to the high complexity and extreme multifactorial nature of large models. The emergent behaviors that arise from these complex systems often defy straightforward analysis, creating challenges for verification and validation. As models grow in size and capability, their decision-making processes become increasingly opaque, even to their creators, resulting in what is often termed the "black box" problem of AI systems.

Of course, developers do not ignore the risks: every AI model undergoes rigorous testing and is subject to imposed restrictions before being released. However, eliminating the possibility of a model «going out of control» and acting independently is virtually impossible. The very features that make AI systems valuable—their adaptability and capacity for unexpected solutions—also make them inherently unpredictable to some degree. Ensuring absolute safety would severely limit a model's functionality, rendering it uncompetitive in the AI technology market [4]. This creates a fundamental tension between capability and control that permeates AI development. Metaphorically speaking, making a model completely safe is akin to sealing off a sacred spring with concrete—greater functionality inevitably comes with greater unpredictability, and vice versa. The challenge lies in finding the optimal balance where systems remain both powerful enough to be useful and constrained enough to be trustworthy.

Additional risks emerge from the potential for AI systems to amplify existing biases present in their training data, make errors with high confidence, or be manipulated through adversarial attacks. These vulnerabilities stem from the statistical nature of machine learning, where models optimize for patterns rather than truth or fairness. Furthermore, the rapid deployment of AI systems across critical domains raises concerns about accountability, as traditional mechanisms for assigning responsibility become complicated when decisions are made by algorithms that even their developers may not fully understand.

IV. PROSPECTS FOR THE DEVELOPMENT OF ARTIFICIAL INTELLIGENCE

The prospects for the development of AI technologies themselves are general artificial intelligence (AGI—artificial general intelligence) and the socalled artificial superintelligence (ASI—artificial superintelligence) [5]. Since opinions and definitions of what they should be suffer from extreme pluralism, we will provide the most abstracted forms that capture the essential characteristics while acknowledging the ongoing debate in the field.

AGI is a technology capable of emulating the external parameters of human activity in any field, at least as well as, and possibly even slightly better than, a human who is a high-level expert in that field. In other words, AGI, presumably, should understand mathematics at least as well as the best mathematicians; linguistics, as well as the best linguists; programming, as well as the best programmers, and so on across all domains of human knowledge and skill. This would require not just specialized competence but the flexible integration of abilities across disciplines—a hallmark of human cognition that current AI systems lack. In this sense, AGI should represent a kind of collective image of all the specialists who are significant for science and the economy, capable of transferring knowledge between domains and adapting to novel situations with human-like versatility. At the moment, leading companies in the field of AI development are competing to achieve AGI, though there is significant disagreement about how

close current technologies are to this goal or whether fundamentally new approaches will be required.

ASI represents a much more ephemeral phenomenon, as it is significantly less clearly understood by the developers themselves. However, in any case, when talking about ASI, it refers to a technology that significantly surpasses the most outstanding human abilities, both quantitatively and possibly even qualitatively [?]. This concept pushes beyond the boundaries of human cognition to imagine intelligences that might develop entirely new forms of reasoning, perception, or understanding inaccessible to biological minds. Regarding the fundamental possibility of creating ASI, intense philosophical and semiphilosophical discussions are ongoing, with positions ranging from confident predictions of its inevitability to arguments that such systems are fundamentally impossible or inherently unstable. The timeline for potential ASI development remains highly speculative, with estimates ranging from decades to centuries or never.

At the moment, AI has capabilities that unquestionably surpass human abilities only in areas where two conditions are met:

- The availability of all the necessary information to solve the problem within a well-defined formal system;
- 2) The unambiguity of result validation through objective, computable metrics.

This, for example, includes intellectual games with complete information, such as chess, go, and others where the rules are fixed and all game states are observable. In these constrained domains, AI systems can explore possibilities far beyond human capacity through brute-force computation and advanced heuristics. In other areas, such as the creation of textual or visual content, it can be confidently stated that AI is capable of generating content that is often impossible to unambiguously identify by its origin, meaning that it is either not possible to clearly distinguish whether it was created by a human or by AI, or it requires in-depth analysis [7]. This blurring of boundaries raises important questions about authenticity, creativity, and intellectual property in the digital age.

It is worth noting, however, that creating highquality content using AI requires quite advanced prompt engineering skills, that is, the ability to create a textual «action plan» with a large number of details and conditions. Otherwise, AI will simply generate «something on the topic» that may lack depth, coherence, or originality. This requirement for skilled human guidance highlights the current limitations of AI systems and their dependence on human expertise for optimal performance. The most effective applications of AI often involve tight human-AI collaboration, where each contributes their respective strengths to the creative or analytical process.

V. The Use of Artificial Intelligence in Humanities Research

Since AI, in any case, represents an attribute of the «new reality», it is reasonable to use it for constructive purposes that enhance rather than replace human capabilities. In the field of humanities research, it so happens that the final result of representatives of the field coincides with that of the most widespread AI technology at the moment—LLM, that is, a large language model [8]. This convergence creates both opportunities for synergy and challenges to traditional scholarly practices. In this sense, any representative of the industry can be represented as a set of finite sequences of words, which are arranged into sentences, paragraphs, articles, monographs, etc., meaning that a humanities scholar is essentially a collection of textual data. Statistically, any researcher is «summarized» in the results of their work: thoughts, feelings, consciousness, soul, and other metaphysical presences do not have potential in this case and will not be taken into account when assessing the level of a scholar's activity. This reductionist view, while useful for certain analytical purposes, risks overlooking the contextual, interpretive, and experiential dimensions that often distinguish profound humanities scholarship.

However, in this same context, an LLM is also a collection of textual data. That is, a more or less accurate comparative understanding of a scholar as a data generator and AI as a data generator is possible when considering their outputs in purely formal terms. Both process information and produce textual representations, though through radically different mechanisms—one biological and experiential, the other computational and statistical. This superficial similarity masks profound differences in understanding, intentionality, and the capacity for genuine insight that continue to distinguish humanistic inquiry from artificial text generation.

However, it should be noted right away that in the field of AI development, only three key aspects can be scaled (improved, advanced):

- 1) Model training, which is summarized by the number of model parameters and the algorithms it uses, including architectural innovations and optimization techniques;
- 2) Hardware computing power, currently represented by graphics cards and specialized AI accelerators, along with supporting infrastructure;
- 3) Model reasoning, which it performs when generating a response to a query according to its al-

gorithms, including improvements in attention mechanisms and knowledge integration.

The first aspect has already been significantly scaled to some extent, with modern models containing hundreds of billions of parameters, and it is not entirely clear whether its further multiple expansion would be reasonable given diminishing returns and increasing costs. The second aspect, while it can be improved, is still subject to Moore's Law under current technologies—that is, doubling computing power does not necessarily lead to a twofold improvement in computations due to various bottlenecks in memory, bandwidth, and parallel processing limitations.

Because of this, as well as due to the high cost and debatable feasibility of aspect 2, the latest flagship models have primarily been scaled in aspect 3—reasoning in the process of generating responses. These are the so-called reasoning models that attempt to emulate more sophisticated cognitive processes beyond simple pattern recognition. As for improvements in the algorithmic component, they are being pursued continuously, but breakthrough results in this field are rare. How much further models can be improved remains an open question that depends on both theoretical advances and practical engineering constraints. However, the very fact that scaling in aspect 3 has already begun, while AGI has still not been created, is starting to cause some concern—both among developers and those invested in technological progress—about whether current approaches will ever achieve truly general intelligence or if they are reaching the limits of their potential.

Thus, at present, AI cannot serve as a relevant alternative even to an average humanities researcher, if only for the reason that a properly structured prompt (query or command) must, in any case, be formulated by the researcher themselves [9]. This requirement for precise, knowledgeable input reflects the fundamental limitations of current AI systems as tools rather than autonomous thinkers. If one attempts to delegate this task to AI, there would still be a need for someone to generate a prompt for it, and so on in an infinite regress. Additionally, it is necessary to have someone who will verify the content generated by the model, assessing its validity, relevance, and scholarly rigor—tasks that require human judgment and disciplinary expertise. That is, in some fields and when necessary, slight optimization is possible—for example, at Google, 25

But when it comes to generating high-level text—such as a groundbreaking scientific research result—the prompt for AI would have to be so large that it might actually be easier for a human to write the text themselves, and it would likely be more concise. The reason for this is that, at present, AI performs well when working with data similar to what it was trained on. The ability to extrapolate skills is inversely proportional to the similarity between the «semantic form» of the training dataset and the «semantic form» of the test dataset. In other words, if the meaning that a person wants to «explain» to AI is qualitatively new, the AI simply «won't understand» it without additional fine-tuning. In this sense, one could hypothesize a correlation between the prompt and the result, according to which the more specialized and high-level the AI-generated content needs to be, the larger the prompt must be. Ultimately, it all comes down to the fact that, for now, someone still has to write that prompt with sufficient expertise to guide the AI effectively—a requirement that preserves the central role of human scholars in the research process.

The above allows us to propose yet another hypothesis. It is well known that any LLM can «consume» a limited number of tokens (words, word parts, symbols, etc.) [10]. The data it consumes represents the context based on which the model generates a response. In other words, any query to an LLM constitutes the formation of context that bounds and directs its output. Based on this, we propose the hypothesis that in the humanities, there exist certain results—that is, texts—for which, at present, there are no models with a sufficiently large context size to fully comprehend and process them. That is, if the hypothesis is correct, there are humanities research results that require feeding the model more tokens than it is capable of consuming in a single context window—complex arguments, extensive evidentiary bases, or nuanced theoretical frameworks that exceed current technical limitations. From this, we can conclude that an equivalent replacement of a «humanities researcher with AI» is currently impossible—if our hypothesis holds true—because the most sophisticated humanistic work operates at scales and complexities beyond what current AI systems can handle in their entirety.

Therefore, for the needs of the humanities, it is advisable to use AI in the following cases where it can augment rather than replace human capabilities:

- For compiling a selection of literary sources on a particular problem area. This is somewhat similar to the result of a long search in a typical browser, but faster and more relevant due to the AI's ability to understand semantic relationships between works;
- For forming a summary of texts with an emphasis on a specific narrow aspect of the problem. For example: «The disclosure of the theme of existential doom in War and Peace by L. N. Tolstoy» where the AI can quickly identify and

synthesize relevant passages;

- For conceptual verification of the originality of conclusions and reasoning. As an example of a prompt for an interdisciplinary socio-biometric study: «Has the idea of a correlation between the number of marriages in a person's life and the square root of the factorial of their nose length ever been expressed in the scientific community before?» allowing researchers to check for prior art efficiently;
- For providing feedback on the results of conducted research before its publication. An example of a prompt: «Is it true that my research on the influence of the dynamic component of wage growth in the USSR during 1950-1970 on the number of bottles in the briefcase of the hero of V. Yerofeev's poem 'Moscow to the End of the Line' is worthy of the Nobel Prize in Literature for 2025?» helping scholars gauge potential receptions of their work;
- For validating the logical and methodological foundation of the research. An example of an implication check: «Is it true that if 2+2=5, then 3+3=6?» where the AI can quickly identify formal logical flaws;
- For selecting ways to improve both the research itself and its results by suggesting alternative approaches, complementary methodologies, or overlooked sources based on its training data.

Thus, in the humanities, the use of AI can be presented as the «assistance of a senior colleague» who has read widely but may lack deep insight—valuable for certain tasks but insufficient as a replacement for original scholarship. And this is indeed significant when properly understood as a tool rather than an authority. The most productive applications involve using AI to handle time-consuming mechanical aspects of research while reserving the interpretive and synthetic work for human scholars.

Furthermore, AI can be used to evaluate the results of scientific research activities, for example, to categorize them according to the following scales where quantitative assessment is feasible:

- Innovativeness, measured by comparison to existing literature;
- Fundamental nature, assessed through structural analysis of arguments;
- Scientific significance, judged by citation patterns and topic modeling;
- Practical applicability, evaluated through realworld impact metrics;
- Development and detail of the issues, analyzed through textual complexity measures.

The advantage of AI here lies in its speed and relative impartiality when dealing with large datasets. For instance, to categorize works by the innovativeness scale, a person would need several days of careful reading and comparison, while AI can accomplish the same task in just a few minutes by processing the entire corpus simultaneously. However, these automated assessments should be understood as preliminary indicators rather than definitive judgments, always requiring human oversight and contextual understanding to interpret properly. The true value emerges when AI's scalability complements human discernment, creating a collaborative research ecosystem that leverages the strengths of both.

VI. CONCLUSION

In summary, the complete replacement of humanities researchers with AI technologies is not foreseeable in the near future due to fundamental limitations in current systems' capacities for genuine understanding, creativity, and contextual judgment. However, the use of AI as a tool for enhancing research is highly relevant and beneficial when properly integrated into scholarly workflows. While the future development of AGI and ASI may broaden AI's applications, its current effectiveness is constrained by the necessity for complex prompt engineering and the limited context window available for analyzing intricate humanities problems. The most promising path forward involves viewing AI as a collaborative partner in the research process—one that can handle certain mechanical aspects of scholarship with unprecedented speed and scale, while human researchers focus on the interpretive, synthetic, and creative dimensions that remain beyond artificial systems' reach. This complementary relationship, rather than replacement, represents the most productive framework for integrating AI into humanities research while preserving the field's essential humanistic values and modes of inquiry.

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ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ: ОПРЕДЕЛЕНИЕ И ПЕРСПЕКТИВЫ ИСПОЛЬЗОВАНИЯ В СФЕРЕ ГУМАНИТАРНЫХ ИССЛЕДОВАНИЙ

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Статья предлагает системный анализ искусственного интеллекта (ИИ) как технологического феномена с позиций объектно-ориентированной парадигмы. В отличие от традиционных историкотехнологических подходов, авторы рассматривают ИИ как совокупность дискретных артефактов, обладающих устойчивыми архитектурными характеристиками. Ключевыми компонентами такой архитектуры выступают: 1) данные в цифровом представлении, включающие как экзогенную информацию, так и эндогенные алгоритмические структуры; 2) машинные алгоритмы обучения, принципиально отличающиеся от классических детерминированных алгоритмов способностью к параметрической самоорганизации. Особое внимание уделяется анализу эмерджентных свойств современных ИИ-систем, проявляющихся в непредсказуемости выводов при идентичных входных данных. Это свойство, обусловленное стохастической природой машинного обучения, создаёт фундаментальные ограничения для применения ИИ в экспертно-ориентированных областях. Авторы детально исследуют феномен "чёрного ящика"нейросетевых архитектур, подчёркивая принципиальную несводимость процессов принятия решений в глубоких нейронных сетях к интерпретируемым логическим схемам. В контексте развития технологий общего искусственного интеллекта (AGI) обсуждаются современные исследовательские тренды, включая мультимодальное обучение, нейросимволическую интеграцию и метаобучение. При этом отмечается, что современные системы типа GPT-4 и Gemini демонстрируют лишь узкоспециализированную компетентность, оставаясь в рамках слабого ИИ. В заключении формулируются этические императивы для интеграции ИИ в гуманитарную сферу: необходимость разработки специализированных онтологий предметных областей, создание гибридных экспертных систем "человек-ИИ целесообразность сохранения эпистемологического суверенитета исследователя.

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System of Smart Monitoring of the Condition of Heat Pipes and Heat Chambers Based on OSTIS and IoT Methodology

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Abstract—The paper presents the development of an intelligent system for monitoring thermal networks based on OSTIS (Open Semantic Technology for Intelligent Systems) methodology and Internet of Things (IoT) technologies.

The proposed system includes three key components: a server cloud platform, a platform for mobile devices and an object platform. The server platform collects, processes and analyzes data from autonomous detectors installed on pipelines. The mobile platform provides users with an interactive interface for data visualization and critical change notifications. The object platform is responsible for collecting telemetry information from the sensors and transmitting it to the cloud.

The developed system architecture can be adapted to monitor other engineering infrastructures, such as water and gas networks, which makes it a universal solution for smart city tasks. The proposed intelligent system realizes the author's approaches to knowledge base creation, logical inference mechanism and user interface of the system. The described algorithms of data processing and ontological model of the system ensure its effective functioning.

Keywords—heat networks, monitoring, IoT, OSTIS, semantic technologies, autonomous detectors, intelligent systems, smart city.

I. Introduction

A. Relevance of the Problem

Heat networks are a critical engineering infrastructure that ensures uninterrupted supply of heat energy from sources (cogeneration plants, boiler houses) to end consumers (residential and industrial facilities, social institutions). The operation of heat networks is associated with a number of problems, including corrosion damage of metal elements, deterioration of the characteristics of the thermal insulation layer, mechanical damage to pipelines, and flooding of heat chambers. These factors combine to create the potential for significant economic and environmental losses associated with operational disruption.

Traditional methods of monitoring the condition of heat pipelines and heat chambers include periodic manual measurements that require significant time and labor resources. The use of IoT and smart technologies in automating the diagnostic process allows for significantly increasing the efficiency of defect detection, minimizing the role of the human factor, and significantly improving the overall reliability of heat networks.

B. Basic Definitions

The article uses the following conceptual apparatus fixed in normative documents [1]–[3].

- Stand-alone detector a device designed for periodic measurement:
 - electrical resistance of the thermal insulation layer and the signal conductor;
 - status of the flood sensors of the heat chambers;
 - the charge level of the built-in rechargeable battery.
- Heat consumption system a complex of heat installations with connecting pipelines and (or) heat networks [1, p. 6].
- Heat supply system a set of interconnected heat source(s), heat networks, and heat consumption systems [1, p. 6].
- **Signal conductor** copper signal conductors in the thermal insulation layer of pipelines, running along the entire length of pre-insulated pipes [2, p. 8].
- **Pre-insulated** (**PI**) **pipeline** steel pipes, prethermally insulated with rigid polyurethane foam [2, p. 3]].
- System of Operational Remote Control (SODC) designed to control the electrical resistance of the thermal insulation layer of FPU (decrypt) PI-pipes. SODC allows for detecting, with the help of control and measuring devices, areas with increased humidity of insulation and places of damage to the signaling system [3, p. 9].

C. District Heating

Centralized heat supply systems ensure the transmission of heat energy in the form of hot water through heat networks to end consumers. The use of PI pipelines allows for increasing the durability of engineering systems and minimizing heat losses. However, maintaining the operational characteristics of such pipelines requires constant control of the moisture content of the thermal insulation layer by measuring the electrical resistance.

In accordance with regulatory and legal acts, control measurements of the condition of the thermal insulation layer and signal conductor are regularized and should be carried out manually (at least once every two weeks) or in automatic mode with a frequency of 5 minutes to 24 hours. Continuous monitoring makes it possible to promptly diagnose the occurrence of emergency situations, such as damage to thermal insulation or flooding of heat chambers, which was the idea behind the creation of an intelligent monitoring system for the heat pipeline and heat chambers.

II. OSTIS Methodology and Its Application in the Monitoring System

OSTIS (Open Semantic Technology for Intelligent Systems) methodology is a conceptual framework for building intelligent systems based on semantic technologies. Its application allows for structuring knowledge, integrating heterogeneous data sources, and automating decision-making processes.

In the proposed smart heat network monitoring system, OSTIS methodology is utilized to solve the following problems:

- Creation of an ontological model of heat networks formalization of knowledge about the structure of pipelines, heat chambers, and their technical characteristics;
- Integration of data from IoT devices transformation of heterogeneous telemetry data (resistance, humidity, temperature measurements) into a single semantic model [4, p. 56];
- Intelligent data analysis application of logical rules to identify deviations from normative values;
- Generation of control decisions formation of recommendations on elimination of detected faults and planning of preventive measures [5, p. 67].

The implementation of OSTIS in an intelligent monitoring system for heat networks provides the following benefits:

- Flexibility and adaptability the system can be integrated with different types of heat networks and sensors;
- High degree of automation minimizing manual work through intelligent analysis and automatic decision-making;
- Scalability the ability to expand the system to monitor other utility infrastructures, such as water or gas networks;

• Economic efficiency – reduction of operating costs due to automation of diagnostic processes and data analysis.

The proposed system, based on OSTIS methodology and IoT concept, allows for realizing an intelligent approach to monitoring the condition of heat networks, ensuring their reliability and operational efficiency.

III. Architecture of the Proposed System

The formation of a universal cross-industry method of technological realization of system architecture and applications within the IoT is based on three key platform components that form a heterogeneous integrated system. These platforms provide synergistic functionality, allowing developers to focus on creating application logic, eliminating the need for in-depth development of technical aspects of the underlying infrastructure. The system architecture includes the following layers.

A. Server Cloud Platform

A cloud server platform is a centralized management node characterized by high computing power and significant data storage capacity. Its main functionalities include:

- Data collection and consolidation receiving and aggregating heterogeneous data from sensors and autonomous detectors via IoT protocols (e. g., MQTT, CoAP, NB-IoT);
- Analytical processing and modeling application of machine learning methods and semantic technologies to interpret data, detect anomalies, and formulate management decisions;
- Integration of external services organization of interaction with knowledge bases, intelligent decisionmaking modules, and external information systems through standardized APIs;
- Security management providing multiple layers of data protection, including authentication, authorization, and access control for users and devices.

In the context of monitoring heat pipe systems, the server platform performs processing and systematization in a semantic knowledge base of data about:

- insulation resistance,
- the state of the signal wires,
- flooded cells.

Integration with cloud services (Yandex IoT Core) is implemented to improve fault tolerance.

B. Platform for Mobile Devices

The mobile platform serves as the interface component of the system, providing an operational presentation of information to users. Its key functions are listed below:

• Data visualization: display of heat network condition parameters on a geoinformation basis with dynamic indication of anomalous areas.

- Notification and management system: automatically notifies users of critical changes (e. g., "signal conductor break" or "heat chamber flooding") and provides configuration tools for monitoring parameters.
- Local analytics: partial processing of incoming data on the mobile device, including pre-filtering and segmentation.
- Synchronization with the server platform: interactive real-time data exchange with the server platform via REST API or MQTT.

The system's interactive web interface contains analytical graphs of resistance changes, an interactive map of heat networks, and service data; a mobile application promptly notifies personnel of critical changes in the condition of pipelines.

C. Object Platform

The object platform is a layer of interaction of physical devices with the system, including a network of sensors and autonomous detectors. Its functionality is described below:

- Collection of telemetry information: measurement of environmental parameters (resistance, humidity level, battery status) using sensor modules.
- Standardized communication: unification of communication protocols (NB-IoT, MQTT) to integrate heterogeneous sensor solutions.
- Local processing: filtering data at the sensor node level before sending it to the server.
- Communication via IoT gateways: aggregating data from sensors via gateways and transferring it to the cloud.

Autonomous detectors installed along heat pipelines transmit data on the parameters of the thermal insulation layer and battery charge level via MQTT brokers. IoT gateways convert the received information into a standardized format, providing a unified communication channel with the server platform.

Interaction of platforms in the system:

- The object platform collects data from sensors and transmits it to the server cloud platform;
- Server platform analyzes the received data using OSTIS semantic technologies, identifies anomalies, and forms management recommendations;
- Mobile platform displays analysis results, sends notifications to operators, and provides monitoring configuration tools.

This architectural approach provides:

- Scalability the system can be expanded by connecting new types of sensors and integrating additional services.
- Flexibility adaptation to different industries, including monitoring of water supply, gas distribution networks, and industrial equipment.

• Energy efficiency – optimizing the amount of data transferred, which is critical for devices with limited power resources.

Integration with elements of technical implementation:

- Node-RED is used to visually construct data flows between the object and server platforms;
- Yandex IoT Core provides reliable messaging via the MQTT protocol;
- Yandex Compute Cloud virtual machines deploy server components, ensuring their high availability and fault tolerance.

The developed architecture forms a universal platform for intelligent monitoring, applicable not only in heat networks but also in a wider range of typical infrastructure solutions of a smart city, including street lighting control systems, water supply monitoring, and automated transportation networks.

IV. Algorithmic Support of Data Processing

A. Data Collection Phase

Autonomous sensor nodes register parameters of engineering networks in order to provide comprehensive monitoring and diagnostics of their condition. The following indicators are recorded during the collection process:

- Resistance of the thermal insulation layer;
- Resistance of the signal conductor;
- The condition of the flood sensor;
- Battery charge level.

Transfer of the received data to the cloud server platform is carried out in accordance with the specified time schedule, ensuring the relevance of information and continuity of monitoring.

B. Analytical Processing of Data

The analytical module of the system realizes multicriteria processing of incoming data by applying the following methodologies:

- Detecting anomalies by comparing actual measurements with normative values;
- Predicting the probability of emergency situations using machine learning and time series methods [6, p.84];
- Classification of abnormal conditions to determine the nature of faults (e.g., degradation of thermal insulation, broken signal conductor, flooded chamber).

C. Generation of Prescriptions

Based on the analysis, the system generates management decisions and prescriptions that include:

- Recommendations for preventive or repair measures;
- Instructions for replacing equipment;
- Notifications to operators of detected critical events.

V. Knowledge Base of the Intelligent System for Monitoring Pipelines and Heat Chambers

The knowledge base is represented by an ontologically organized structure describing monitoring objects, their properties, attributes, and interrelationships. It provides unified storage, processing, and interpretation of incoming data, forming the basis for the work of the problem solver and visualization components.

Monitoring systems consist of:

- Subsystems for control of the thermal insulation layer and signal conductor,
- Subsystems for analyzing the state of flooding of chambers,
- Application access subsystems.

A. Subsystem for Monitoring the Condition of the Thermal Insulation Layer and Signal Conductor

The subsystem consists of several monitored sections of the heat network pipeline. Each monitored section has its own parameter measurement point, in which an autonomous detector is installed that registers values of electrical resistance of thermal insulation, signal conductor, and battery charge level of the autonomous detector.

B. Heat Chamber Flooding Status Monitoring Subsystem

The subsystem consists of several monitored heat chambers, in which an autonomous detector is installed that registers the triggering of the water flooding level sensor in the heat chamber.

C. Application Access Subsystem

The subsystem of access to applications realizes the possibility to provide access of some number of logins for the operating personnel within the limits of the established access rights with the defined authentication mechanism.

VI. Problem Solver for Intelligent Monitoring System

The problem solver is a computing module that analyzes information stored in the knowledge base for the purpose of automated prescription generation. It performs the following functions:

- Aggregation and structuring of monitoring object data [9, p. 60];
- Automatic ranking of parameters for further interpretation [11, p. 100];
- Formation of user interface web pages based on actual data [10, p. 125] [10, p.125].

To ensure correctness of monitoring, each parameter is assigned storage rules. For example:

- Resistance values of the thermal insulation layer are stored for 12 months;
- The flood condition is fixed with the last value obtained.

To simplify the analysis, the data are ranked into predefined normative categories.

Resistance of the thermal insulation layer:

- "Norm 1" $\geq 1 \text{ meg}\Omega$;
- "Norm 2" 500 k Ω to 1 meg Ω ;
- "Norm 3" 100 k Ω to 500 k Ω ;
- "Norm 4" 50 k Ω to 100 k Ω ;
- "Norm 5" 5 k Ω to 50 k Ω ;
- "Wetting" $< 5 \text{ k}\Omega$.

Resistance of the signal conductor: "Open" - > 200 Ω s [8, p.13].

VII. User Interface: Architecture and Functional Components

The user interface of the developed system is a structured set of web pages that provide interactive user interaction with the monitoring system. The interface is characterized by modular organization, which allows it to be adapted to different operating scenarios. It is based on the principles of ergonomics, visual informativeness, and intuitive navigation [7, p. 110].

A. Home Page: Visualization and Analytics

The Home page serves as a centralized access to the key data of the monitoring system. It includes the following functional areas:

- G list zone: dynamically generated list of dispatcher names of pipeline sections accompanied by status indicators ("Normal n", "Wetting", "Break"). Color coding, including the possibility of color representation of multifactor spatial and temporal data, is used to simplify the perception of critical situations. Support for sorting and scrolling mechanism is implemented.
- Map backing area: a geoinformation module that provides a visual representation of the spatial location of G sites. Interactive symbols allow you to quickly analyze the status of sites in real time.
- Graphical analytics zone: a tool for temporal analysis of parameter dynamics. Includes means of displaying graphs of resistance of thermal insulation layer and signal conductor for different time intervals (1 day, 2 days, 10 days, 30 days, 6 months, 1 year).
- Service area: additional information panel, which contains the values of parameters G (dispatch name of the site), K (coordinates), L (serial numbers of autonomous detectors).

B. Service Module "Autonomous Detectors"

This section is intended for monitoring and diagnostics of the technical condition of autonomous detectors used in the system.

Major Functional Components:

- Zone G: presentation of a list of dispatch names of pipeline sections equipped with autonomous detectors. Includes search, sorting, and scrolling options;
- Zone M: analytical block containing information on the detectors' mobile communication parameters (signal strength, network identifiers, data transmission protocol);
- Information packet zone: detailed time-stamped representation of telemetry data. Includes parameters obtained from the autonomous detector such as measured resistance values, battery level, flood sensor status, and real-time data transmission.

C. Service Module "Adding and Modifying Autonomous Detectors"

This section is intended for configuring parameters of autonomous detectors, including their initial registration, data update, and deletion of irrelevant devices. Functional areas:

- Zone G, L: display the list of dispatch names (G) and detector serial numbers (L) with the possibility to edit them.
- Parameter fields area: interactive form for entering and adjusting the values of the key parameters listed below.

Key parameters:

- Dispatch name of the site (G);
- Detector serial number (L);
- Modem unit identifier (M);
- Geographic coordinates of the beginning and end of the site (K1, K2);
- Detector installation coordinates (P);
- Data on technical and service personnel (T2, T3).

The developed user interface architecture (see Figure 1) combines the principles of ergonomics, adaptability, and analytical informativeness. The use of interactive cartographic and graphical elements increases the effectiveness of monitoring, simplifying data analysis and management decision-making.



Figure 1. User interface

VIII. Elements of Technical Implementation

The design and subsequent program implementation of the intelligent monitoring system (see Figure 2) were carried out using the concept of stream programming and cloud computing platforms. Visual programming environment, cloud services, and specialized mechanisms of data exchange via MQTT protocol were used as tools. This approach provides a modular organization of the architecture, increases the flexibility of the system, and contributes to the effective management of data flows in a distributed environment.

As part of the implementation of the server components of the system, a virtual machine (VM) was deployed in a cloud environment. High availability and fault tolerance: the ability to scale computing power when the load on the system increases is implemented.

The Message Queuing Telemetry Transport (MQTT) protocol is used as the main communication mechanism between object devices, cloud infrastructure, and endusers, which is designed for efficient message transmission under limited computational resources.

Key features of an MQTT broker:

- Support for publish-subscribe mechanisms: devices send data to the cloud on a publish-subscribe basis to minimize network load;
- Ensuring reliability of message delivery: three levels of quality of service (QoS 0, QoS 1, QoS 2) regulating guarantees of message receipt are provided;
- Integration with Node-RED: implemented through MQTT Input and MQTT Output nodes that allow organizing data exchange between IoT objects and server components of the system.

The integrated application of streaming programming, cloud computing, and asynchronous messaging has resulted in a high-performance, scalable, and reliable monitoring system for infrastructure.



Figure 2. Architecture of the intelligent monitoring system

IX. Examples of System Implementation and Testing

A. Pilot Project: Methodology and Results

For experimental testing of the developed system, a pilot project was implemented in real conditions of heat networks operation. As part of this stage, 15 autonomous diagnostic sensors were deployed and tested on several sections of main heating pipelines with a length of up to 2.5 km. These devices monitored the condition of the

pipelines and transmitted data to the central server with a set periodicity of once an hour.

Experimental validation led to the following results, and analysis of the data collected during the tests allowed us to quantify the performance of the system:

- Diagnostic accuracy the probability of correct determination of the state of thermal insulation and signal conductor has reached 95%, which indicates high reliability of the system;
- Speed of anomaly detection the system demonstrated the ability to detect abnormalities within 5 minutes of their occurrence, which is critical for rapid response;
- Economic efficiency due to automation of the control process and reduction of the need for regular visits of technical personnel, operating costs were saved by 30%.

B. Feedback from Staff of Operating Organizations

Analysis of feedback from specialists responsible for the operation of heat networks showed that the system has a high degree of convenience and informativeness. In particular, the most popular functions were recognized as:

- Automatic notifications of critical parameter changes;
- Geo-information visualization of deviated areas, increasing visibility and speed of decision-making.

These factors helped to improve the efficiency of technical staff and minimize the risks associated with missed infrastructure damage.

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СИСТЕМА УМНОГО МОНИТОРИНГА СОСТОЯНИЯ ТЕПЛОПРОВОДОВ И ТЕПЛОВЫХ КАМЕР, ОСНОВАННАЯ НА МЕТОДОЛОГИИ OSTIS И IOT

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В статье представлена разработка интеллектуальной системы мониторинга тепловых сетей на основе методологии OSTIS (Open Semantic Technology for Intelligent Systems) и технологий Интернета вещей (IoT).

Предложенная система включает три ключевых компонента: серверную облачную платформу, платформу для мобильных устройств и объектную платформу. Серверная платформа обеспечивает сбор, обработку и анализ данных, поступающих от автономных детекторов, установленных на трубопроводах. Мобильная платформа предоставляет пользователям интерактивный интерфейс для визуализации данных и уведомлений о критических изменениях. Объектная платформа отвечает за сбор телеметрической информации с датчиков и её передачу в облако.

Разработанная архитектура системы может быть адаптирована для мониторинга других инженерных инфраструктур, таких как водопроводные и газовые сети, что делает её универсальным решением для задач умного города.

Предлагаемая интеллектуальная система реализует авторские подходы к созданию базы знаний, механизму логического вывода и пользовательскому интерфейсу системы. Описанные алгоритмы обработки данных и онтологическая модель системы, обеспечивают её эффективное функционирование.

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Intelligent Diagnosis of Gait Disorders Using Video-Based 3D Motion Analysis

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Abstract-This experiment proposed an intelligent disease diagnosis method based on gait video analysis. Gait videos were analyzed using OpenPose for 2D pose estimation, and a Temporal Convolutional Network (TCN) was employed to predict 3D poses, obtaining 3D gait motion data of the target. After extracting motion features, a knowledge base and inference rules for gait abnormalities and diseases were constructed within the framework of the Open Semantic Technology Intelligent System (OSTIS). The gait features were semantically processed accordingly. Finally, a classification model was used to diagnose potential diseases and provide interpretable diagnostic recommendations. Experimental results demonstrated that this method effectively integrates 3D motion features with semantic reasoning, achieving accurate disease classification and diagnosis, thus offering a novel technological approach to intelligent medical diagnosis.

Keywords—Gait Analysis, OpenPose, 3D Motion Features, OSTIS, Intelligent Medical Diagnosis

I. Introduction

Gait analysis, as an important means of studying human motor functions, has significant value in the early screening and diagnosis of neurological diseases, skeletal disorders, and movement-related diseases [3], [12]. Gait features can reflect human movement patterns and functional states, as different diseases are often accompanied by specific gait abnormalities, such as shortened stride length, imbalanced gait cycle, and restricted joint mobility [8], [20]. Therefore, precise analysis and pattern recognition of gait data provide critical evidence for disease diagnosis. However, traditional gait analysis often relies on complex equipment in laboratory environments, such as motion capture systems or pressure sensor floors [6]. These methods are not only costly and challenging to popularize but are also limited by experimental conditions, resulting in a lack of flexibility in the data acquisition process.

In recent years, the rapid development of computer vision and deep learning technologies has provided new approaches to gait analysis. From Fig 1 video-based gait analysis methods enable the efficient and low-cost acquisition of human motion data using standard video equipment [11]. The emergence of pose estimation technologies like OpenPose [1] makes it possible to extract human 2D keypoints from video data, while deep learn-



Figure 1. Gait diagnostic network composition.

ing models such as Temporal Convolutional Networks (TCN) [2], [19]further allow for high-precision 3D pose prediction from 2D keypoints. This technical framework provides powerful tools for gait analysis, enabling the efficient extraction and analysis of gait data under non-contact conditions.

At the same time, with advancements in intelligent medical technologies, semantic reasoning and knowledge representation are increasingly being applied in the field of disease diagnosis. The Open Semantic Technology for Intelligent Systems (OSTIS) provides strong support for the structured representation of medical knowledge and logical reasoning. By constructing a knowledge base related to gait abnormalities and combining it with inference rules for semantic processing of gait features, it is possible to perform logical deduction from gait features to disease diagnosis, thereby improving the accuracy and interpretability of diagnostic results [18].

II. Related work

A. Data preparation

The analysis and research of gait data require highquality annotated datasets as a foundation. This study utilized two types of gait data: healthy gait samples and pathological gait samples. The healthy gait data were obtained from the publicly available Human3.6 dataset, which contains rich 3D human motion data and is wellsuited for the extraction and analysis of gait features [7]. The pathological gait data were collected from online videos of patients with Parkinson's disease and other gait abnormalities. Keypoint information was extracted from these videos using video analysis techniques, and 3D gait data were subsequently generated [?] These data samples encompass various gait features and abnormal patterns, providing ample data support for model training and evaluation. Additionally, to enhance the model's generalization capability, the dataset was augmented with gait data from different patients, ensuring coverage of a broader range of gait abnormality types [13].

B. Extraction of gait features

Gait features are critical representations of human movement patterns, as different diseases are often associated with specific gait abnormalities [4]. This study extracted 10 key features from 3D gait data, including stride-related metrics stride ratio, big gait, small_gait, speed speed, gait cycle characteristics mean_gait_cycle_time, mean_swing_phase_time, step width mean_step_width, and joint range of motion right_ankle_angle_range, left_ankle_angle_range, knee angle range. These features provide а comprehensive description of individual gait patterns and form a foundation for disease identification. Patients with Parkinson's disease often exhibit reduced stride length, asymmetric gait, and slower movement, while stroke patients may present with prolonged gait cycles or abnormal swing phase durations. Limited joint motion, such as restricted ankle or knee movement, can also indicate specific gait disorders.

III. Material and Methods

A. openpose predicts 2D sequences

The core of gait analysis lies in extracting key features of human motion. This paper utilizes the OpenPose framework to estimate 2D keypoint sequences of human gait from videos. OpenPose is a deep learning-based multi-person pose estimation method that can locate 17 keypoints of the human body including the nose, neck, shoulders, elbows, wrists, hips, knees, and ankles and outputs the 2D coordinates of each keypoint in the image.

The core optimization objective of OpenPose is to accurately locate human body keypoints and model the connections between keypoints by jointly optimizing keypoint heatmaps and part affinity fields. Its optimization objective is defined by the following loss function:

$$\mathcal{L} = \sum_{k=1}^{K} \left\| \mathbf{H}_{k} - \hat{\mathbf{H}}_{k} \right\|^{2} + \sum_{c=1}^{C} \left\| \mathbf{L}_{c} - \hat{\mathbf{L}}_{c} \right\|^{2}$$
(1)

From the formula, the first part represents the loss of the keypoint heatmaps, while the second part represents the loss of the part affinity fields. By jointly optimizing, the loss function \mathcal{L} simultaneously constrains the accuracy of the keypoints optimized through \mathbf{H}_k and $\hat{\mathbf{H}}_k$ and the connections between the keypoints optimized through \mathbf{L}_c and $\hat{\mathbf{L}}_c$. This joint modeling enables OpenPose to achieve high-precision estimation of keypoint detection and human skeleton connections in complex scenarios.

B. Temporal Convolutional Network module predicts 3D sequences

This paper utilizes 2D skeleton data extracted by OpenPose to predict 3D pose sequences from 2D keypoint sequences using a Temporal Convolutional Network . Convolution is the core module of the Temporal Convolutional Network and is used to preserve contextual information in temporal sequence modeling. Its design incorporates a temporal causality constraint into the receptive field of the convolution kernel [15]. To capture longterm dependencies in the temporal sequence, Temporal Convolutional Network introduces dilated convolutions within the convolution layers, enabling deep networks to extract features across different time scales. To enhance the training stability of deep networks, residual connection modules are added. Residual connections allow the input to be directly passed to the output, alleviating the problem of vanishing gradients. The formula for dilated convolution is:

$$\mathbf{y}_t = \sum_{i=0}^{k-1} \mathbf{W}_i \cdot \mathbf{x}_{t-i \cdot d} \tag{2}$$

In the formula, k represents the length of the convolution kernel, and d is the dilation rate, which controls the expansion speed of the receptive field. x represents the input data of the temporal sequence, and W is used to extract features from the input data and learn the weight relationships across different time steps. By expanding the receptive field, the model can better capture contextual information from the sequence, enabling more accurate estimation of 3D pose sequences.

The input 2D gait sequence joint trajectories is fed into the model as a temporal sequence. The model utilizes multiple layers of causal dilated convolutions to capture both short-term and long-term dependencies in the temporal sequence, thereby learning the mapping relationship between the input data and the corresponding 3D motion patterns. The network outputs the 3D joint coordinate sequence for each time step.



Figure 2. 3D Gait Prediction Gait.

The Fig 2 illustrates the workflow of gait sequence analysis for patients with gait disorders. The left-side image shows the extraction of 17 2D keypoints of the human body using OpenPose, which are annotated on the original image to describe the patient's gait features. Subsequently, deep learning models such as Temporal Convolutional Networks are used to predict these 2D keypoint sequences into the 3D skeletal gait sequence on the right. The 3D skeletal diagram demonstrates the patient's motion trajectory and posture features in threedimensional space, with red and black skeletons representing dynamic changes at different time steps. This clearly highlights the characteristic changes associated with gait disorders, providing a reliable basis for gait analysis and disease diagnosis.

C. Analysing gait and feature extraction

This graph shows the complete gait cycle phase dynamics, and extracting gait characterisation information from the graph can help diagnose possible gait disorders. Through the gait analysis shown in the Fig 3, gait features such as gait cycle time, swing phase duration, step length, step width, and joint range of motion (ROM) can be extracted. These features are used to evaluate gait symmetry, stability, and movement efficiency, aiding in the diagnosis of gait abnormalities hemiplegic gait or neurological impairments. This provides a basis for rehabilitation training and disease screening [16].

Normal gait and pathological gait can be distinguished through joint motion patterns. The Fig 4 below illustrates the temporal variation curves of the left knee joints in three-dimensional space X, Y, Z coordinates across different gait categories normal, Parkinson's, stroke, and other pathological gaits. The curves for each category reflect the motion trajectories of the knee joints throughout the gait cycle.

Green is normal gait, the key characteristics of healthy gait include left-right symmetry, smoothness of the knee joint trajectories, and periodic changes.

Purple is Parkinsonian gait is characterized by stiffness in joint motion, reduced range of motion, and less distinct trajectory changes. The restricted knee joint motion trajectories can effectively differentiate Parkinson's disease from normal gait.

Blue is Stroke The most notable feature of stroke gait is the asymmetry in the motion trajectories of the left and right knee joints.

Other pathological gaits is red curve, Other pathological gaits are characterized by irregularity and instability in knee joint trajectories, which may be caused by arthritis, spastic gait, or other lower-limb functional impairments.

To diagnose diseases based on gait characteristics, I extracted 10 features from the gait cycle. Here, I will use two representative features as an example. The formula for the range of motion (ROM) is as follows:

Angle =
$$\arccos\left(\frac{\mathbf{A} \cdot \mathbf{B}}{\|\mathbf{A}\| \cdot \|\mathbf{B}\|}\right)$$
 (3)

Joint angle is an important feature in gait analysis for assessing joint flexibility and range of motion (ROM). It plays a significant role in diagnosing and distinguishing Parkinson's disease, stroke, and other gait abnormalities. In Parkinson's patients, the ROM of the knee and hip joints is significantly reduced.

Stride ratio is a key quantitative metric in gait analysis, used to evaluate the relationship between stride length and body dimensions (typically measured by lower limb length or other body reference dimensions). It provides a standardized measure of stride length relative to body proportions, eliminating the influence of height or body size differences on the comparison of absolute stride lengths. The formula is as follows:

Stride Ratio =
$$\frac{\text{Mean Stride Length}}{\text{Mean Body Size}}$$
 (4)



Figure 3. Illustration of the gait cycle.

By calculating the horizontal displacement of the same foot making ground contact twice during the gait cycle, the stride length for each step is determined, and the average stride length is obtained. The average body size is then calculated using the anatomical coordinates of key points hips, knees, and ankles. Dividing the average stride length by the average body size yields the stride ratio [17].

The stride ratio standardizes the relationship between stride length and body size, eliminating the influence of individual body dimensions. It is a crucial indicator for assessing gait symmetry, coordination, and disease screening. By combining the absolute stride length and the body reference length, a more comprehensive analysis of gait abnormalities Parkinsonian gait or stroke gait can be performed.

D. OSTIS-based diagnostic knowledge graph construction

OSTIS relies on semantic networks, so the first step is designing an ontology that maps relationships between gait parameters, diseases, and symptoms. We define the following class for Gait based on parameters: $step_length$, speed, $movement_symmetry$, rhythm, $knee_flexion_angle$, $torso_tilt$, and metrics such as asymmetry > 15%, speed < 0.8 m/s. As a result, it is possible to define classes for diseases, for example: $Parkinson's_Disease$, Arthritis, $Multiple_Sclerosis$, $Ankle_Injury$. In this case, there are properties such as $associated_symptoms$, and $prevalence_statistics$. This allows the definition of classes for symptoms, for example: $resting_tremor$, $joint_pain$, $muscle_weakness$. For OSTIS systems, Gait analysis is based on the following relationships:

- hasSymptom (Disease \rightarrow Symptom)
- hasGaitParameter (Disease \rightarrow Gait)
- correlatesWith (Parameter \rightarrow Disease)

OSTIS supports rule-based inference using semantic relationships. An example of diagnostic rules is shown in the following script:

```
If movement asymmetry > 20% and speed<0.6
m/s → suggest Multiple_Sclerosis
rule:
   (gait: movement_asymmetry > 20%) &
   (gait: speed < 0.6)
->(diagnosis: Multiple_Sclerosis,
   probability: 0.75);
If knee flexion angle < 30° and joint_pain
→ suggest Arthritis
rule:
   (gait: knee_flexion_angle < 30) &
   (symptom: joint_pain)
->(diagnosis: Arthritis,probability: 0.85)
```

The advantages of OSTIS technology include Interpretability, Flexibility, and Knowledge Integration. This results in a common ontology that can be expanded with new disease parameters and combines data from diverse sources, such as research and clinical guidelines.

This architecture enables an intelligent system for automated diagnosis and clinical decision support. Implementation requires ontology refinement and collaboration with medical experts. To establish a semantic association between gait features and disease diagnosis, this study utilized the OSTIS platform to construct a three-layer diagnostic knowledge graph, which includes gait features, gait abnormalities, and disease types. OSTIS is an open



Figure 4. Four categories of knee coordinate change.

semantic technology intelligent system that can model and infer complex semantic relationships through the structured representation and logical reasoning capabilities of its knowledge base [14]. To integrate the semantic information from the OSTIS knowledge graph into the diagnostic model, this study employed the Node2Vec embedding method to represent the nodes in the knowledge graph as low-dimensional vectors. These embedding vectors preserve the semantic structural information of the knowledge graph, enabling the model to utilize the semantic associations of gait features for classification and reasoning [9].

Random walks were performed on the nodes in the

knowledge graph gait features, gait abnormalities, and diseases to generate node sequences. Node2Vec was then used to train these sequences and generate vector representations 128 dimensions for each node [10]. The embedding vectors of the gait feature nodes were fused with the actual extracted gait feature data to form semantically enhanced representations of gait features.

E. MulticlassNN model diagnostics

The MulticlassNN model integrates gait features and knowledge graph embeddings to construct a neural network-based classification model for gait-related diseases [5]. The model performs four-class classification, distinguishing among "No Disease," "Parkinson's Disease," "Stroke," and "Other Gait Disorders."

The input to the model consists of two components: 10 gait features such as stride ratio, speed, joint angle range and a 128-dimensional embedding vector generated from the knowledge graph. The knowledge graph embeddings, created using the Node2Vec algorithm, encode the semantic relationships among gait features, gait abnormalities, and disease nodes into a high-dimensional space, thereby enhancing the feature representation capability.

From the Fig 5, it can be observed that different gait features exhibit significant variations in their distributions across the four classes (Normal, Parkinson's Disease, Stroke, and Other Gait Disorders). These distribution patterns reflect the characteristic differences in gait abnormalities, providing crucial evidence for disease classification.

From the Fig. 5, it is evident that the feature distributions corresponding to different diseases exhibit significant differences.

Parkinson's Disease: Characterized by small stride lengths, prolonged gait cycles, and reduced ranges of motion in the ankle and knee joints. Stroke: Features a dispersed distribution, with manifestations such as gait asymmetry, prolonged cycle time, and abnormal swing phase time. Other Gait Disorders: Displays a broader distribution, potentially exhibiting compensatory gait characteristics (e.g., increased stride length and step width). These distribution patterns provide critical evidence for the classification model. By capturing these patterns, the model can effectively distinguish between the gait characteristics of different diseases.

The role of the MulticlassNN model is to combine the physical significance of gait features with the semantic relationships in the knowledge graph to achieve efficient classification of disease-related gaits. Knowledge graph embeddings compensate for the limitations of standalone gait features, enhancing the model's ability to recognize gait abnormalities such as Parkinson's disease and stroke. Ultimately, through quantitative analysis of gait features and automated classification, the model provides an accurate tool for early disease screening and diagnosis.



Figure 5. Distribution of values for gait features.

IV. Experimental Results

From Fig. 6 an intelligent disease diagnosis method based on gait video in a four-classification task normal, Parkinson's disease, stroke, and other gait disorders

The loss curve during training indicates that the model converges well within 500 iterations, with the validation loss stabilizing at 0.39 and the training loss decreasing to 0.17. This demonstrates that the model exhibits good fitting performance during both the training and validation phases.

From the Fig 7 report, it can be observed that the Macro Average and Weighted Average F1 scores are both close to 0.93-0.94, further validating the robustness of the model in the overall classification task.

On the test set, the overall accuracy of the model reached 91.8%. From the classification report, it can be observed that the performance metrics across different categories are excellent. Specifically, the "Normal" and "Other Gait Disorders" categories achieved a precision, recall, and F1-score of 1.0.

The recall for Parkinson's Disease is the highest (1.0), but the precision is 0.77, indicating a small number of misclassifications in this category. For the Stroke category, the precision is 1.0, while the recall is 0.74, which may be attributed to the complexity of its feature distribution.

V. Conclusion

This paper proposes an intelligent disease diagnosis method based on gait videos, integrating 3D gait feature

extraction, knowledge graph construction, and a deep learning classification model to accurately diagnose four gait states: "Normal," "Parkinson's Disease," "Stroke," and "Other Gait Disorders." Using OpenPose for 2D pose estimation on gait video data and a Temporal Convolutional Network (TCN) to predict 3D poses, ten gait features were extracted, including stride length, gait speed, gait cycle, step width, and joint range of motion. These features comprehensively describe gait patterns and provide critical data support for disease classification.

Additionally, by combining the knowledge graph constructed with the Open Semantic Technology Intelligent System (OSTIS) and the Node2Vec embedding method, the semantic relationships among gait features, gait abnormalities, and diseases were embedded into a highdimensional space. This enhanced the feature representation capability, providing semantically enriched feature inputs for the model.

The loss curve during training shows that the model converged well within 500 iterations, with the validation loss stabilizing at 0.39 and the training loss decreasing to 0.17. Experimental results indicate that the proposed method achieved a classification accuracy of 91.8% on the test set and demonstrated excellent robustness across multiple classification performance metrics. This indicates that the model effectively captures the characteristic information of the respective categories. The model exhibited good fitting performance during both training and validation phases.



Figure 6. Model losses and classification results.

Accuracy: 0.91 Classification	1803278688524 n Report:	59		
	precision	recall	f1-score	support
0	1.00	1.00	1.00	9
1	0.77	1.00	0.87	17
2	1.00	0.74	0.85	19
3	1.00	1.00	1.00	16
accuracy			0.92	61
macro avg	0.94	0.93	0.93	61
weighted avg	0. 94	0.92	0.92	61

Figure 7. Classification Report and Metrics Overview.

By combining the semantic reasoning capability of the knowledge graph with the precise representation of 3D gait features, this method not only achieves efficient disease classification but also provides semantic interpretability for the diagnostic process, enhancing the explainability of diagnostic results.

This study achieves intelligent and efficient diagnosis of gait abnormalities and diseases through the organic integration of gait feature extraction, semantic reasoning, and classification models. It provides a novel technological approach to intelligent medical diagnosis based on gait analysis. This method holds significant application value in fields such as early disease screening, rehabilitation assessment, and intelligent medical auxiliary diagnosis. Furthermore, it offers theoretical and practical support for the development of future intelligent and contactless medical technologies.

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ИНТЕЛЛЕКТУАЛЬНАЯ ДИАГНОСТИКА ЗАБОЛЕВАНИЙ ПОХОДКИ С ИСПОЛЬЗОВАНИЕМ ВИДЕОАНАЛИЗОВ 3D-ДВИЖЕНИЯ

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В данном эксперименте предложен метод интеллектуальной диагностики заболеваний на основе анализа видео походки. Видео походки анализировались с использованием OpenPose для 2D-оценки позы, а для предсказания 3D-поз использовалась временная сверточная сеть (TCN), что позволило получить 3D-данные о движении походки целевого объекта. После извлечения движенческих признаков была построена база знаний и правила вывода для нарушений походки и заболеваний в рамках системы интеллектуальных технологий Open Semantic Technology Intelligent System (OSTIS). Признаки походки были соответственно семантически обработаны. В завершение использовалась модель классификации для диагностики потенциальных заболеваний и предоставления интерпретируемых диагностических рекомендаций. Экспериментальные результаты продемонстрировали, что данный метод эффективно интегрирует 3D-движенческие признаки с семантическим выводом, достигая точной классификации и диагностики заболеваний, тем самым предлагая новый технологический подход к интеллектуальной мелицинской лиагностике.

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Enhancing Fundus Image Classification with Semantic Segmentation-Based Attention Mask

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Abstract—This research proposes a method for classifying ocular diseases in fundus images using semantic segmentation as an attention mechanism. Unlike conventional approaches that rely on the entire retinal image, the proposed framework emphasizes anatomically relevant regions extracted via segmentation of the optic disc, optic cup, and retinal vessels. These segmentation masks are integrated into the classification pipeline to enhance feature learning. A EfficientNetB6-based classifier is utilized to evaluate the impact of this strategy. Experimental results demonstrate improvements in classification performance across multiple evaluation metrics.

Keywords—automated model, ocular fundus, deep learning, attention mask, semantic segmentation, optic disc, optic cup, vessels, classification, UNet, EfficientNetB6

I. Introduction

Fundus imaging has become a cornerstone in ophthalmology, offering non-invasive and high-resolution visualization of the retina and its associated structures. These images are integral in diagnosing a broad spectrum of ocular and systemic diseases. The interpretation of such images, however, demands a high level of expertise and can be time-consuming, especially in regions with limited access to ophthalmic specialists [1]. As the global burden of ocular diseases continues to rise, there is a critical need for automated systems that can support clinical decision-making and screening efforts.

Recent advancements in deep learning have shown considerable promise in addressing this challenge [2]. Convolutional Neural Networks (CNNs) have demonstrated strong performance in a variety of medical image classification tasks, including retinal disease recognition [3]. Nevertheless, one of the limitations of end-to-end classification models is their reliance on global image features, which may dilute the impact of localized, clinically relevant structures. Consequently, classification

performance may suffer, particularly in the early stages of disease when only subtle signs are present.

To improve the focus of deep learning models on diagnostically relevant regions, attention mechanisms and region-guided methods have gained popularity. In this study, we explore the use of semantic segmentation as an attention strategy in the classification of ocular fundus images. By segmenting anatomical regions known to exhibit pathological changes—such as the optic disc, cup, and retinal vessels—and using these masks to enhance or filter the input images, we aim to guide the classifier's attention to the most informative areas [4].

II. Sympoms of ocular diseases in fundus imaging

Fundus photography enables non-invasive visualization of the internal structures of the eye, including the retina, optic disc, macula, and posterior pole. It plays a critical role in the identification and monitoring of numerous ocular diseases. The following section outlines key pathological signs of common ocular diseases as they appear in retinal fundus images.

A. Myopia

Pathological myopia is typically associated with axial elongation of the eyeball, which leads to mechanical stretching and thinning of the retina. Fundus images of myopic patients frequently exhibit peripapillary atrophy, tessellated fundus appearance, tilted optic discs, and staphylomas. These features reflect structural deformation and progressive degeneration of the posterior segment, which can predispose the eye to chorioretinal atrophy and retinal detachment.

B. Hypertension

Hypertensive retinopathy results from chronic elevated blood pressure and manifests through various microvas-

cular changes. Common fundus signs include generalized and focal arteriolar narrowing, arteriovenous (AV) nicking, arteriolar wall opacification (copper wiring and silver wiring), flame-shaped hemorrhages, cotton wool spots, and hard exudates. In severe cases, swelling of the optic disc and macular star formation may occur, indicating malignant hypertension and necessitating immediate intervention.

C. Diabetes

Diabetic retinopathy (DR) is one of the most prevalent causes of blindness globally. Its hallmark features in fundus images include microaneurysms, intraretinal hemorrhages (dot and blot types), hard exudates, cotton wool spots, and retinal edema. Proliferative diabetic retinopathy (PDR) may present with neovascularization on the optic disc or elsewhere in the retina, vitreous hemorrhage, and tractional retinal detachment. Diabetic macular edema, characterized by retinal thickening in the macular area, is a leading cause of vision loss in DR [5].

D. Glaucoma

Glaucoma is characterized by progressive optic neuropathy and loss of retinal ganglion cells, with corresponding changes visible in fundus photographs. These include increased cup-to-disc (C/D) ratio, thinning or notching of the neuroretinal rim, peripapillary atrophy, and optic disc hemorrhages (especially in normal-tension glaucoma). Advanced stages may show "bean-pot" excavation of the optic nerve head. Evaluation of the C/D ratio and asymmetry between eyes is essential in glaucoma detection.

E. Cataract

Although cataract primarily affects the crystalline lens and is best visualized via slit-lamp biomicroscopy, it can have indirect effects on fundus photography. Opacification of the lens leads to decreased image contrast, blurring, and reduced visibility of retinal structures. In fundus images, this appears as a generalized haze, particularly in the red channel, which may complicate retinal assessment and affect automated analysis accuracy.

F. Age-Related Macular Degeneration (AMD)

AMD is a degenerative disease of the central retina and is classified into dry (non-exudative) and wet (exudative) forms. Early signs in fundus images include drusen (yellowish extracellular deposits beneath the retina), pigmentary changes, and geographic atrophy. In neovascular AMD, subretinal hemorrhage, fluid accumulation, and choroidal neovascular membranes may be observed. These manifestations often result in central vision loss and are identifiable through high-resolution fundus imaging. The specific appearance of these pathologies on fundus images forms the basis for automated diagnostic algorithms. Accurate segmentation and localization of relevant anatomical structures will later enable our models to focus on informative regions.

III. Multiclass semantic segmentation methods

To extract the most informative features we segmented the main objects:

- optic disc;
- optic cup;
- blood vessels.

To form a semantic map of the image's most informative objects was chosen a convolutional neural network of Unet widely used for segmentation of medical images.

A. Optic disc and optic cup segmentation

The segmentation model employed for segmenting optic disc and optic cup is based on a modified U-Net architecture implemented in PyTorch. The network is trained to produce dual-channel output masks corresponding to the optic disc and optic cup regions.

The model follows the classical U-Net design with symmetric encoder-decoder paths and skip connections between corresponding layers. Each encoder block performs two convolutions with ReLU activation, followed by a downsampling operation (MaxPooling). The decoder mirrors this process with upsampling via transposed convolutions and concatenation with features from the encoder.

- Input: RGB image of shape (3, 256, 256)
- Output: Segmentation mask of shape (2, 256, 256) (channel 0: disc, channel 1: cup)

 Table I

 Semantic interpretation of multi-channel segmentation mask

Channel 0 (Disc)	Channel 1 (Cup)	Semantic Class
0	0	Background
1	0	Disc only
0	1	Cup only
1	1	Cup inside Disc

The training was supervised using a Binary Cross-Entropy (BCE) loss per class for 30 epochs with early stopping. The loss during training epochs can be seen on Figure 1.

Model performance was evaluated during training using the Dice coefficient (Figure 5), which provides a measure of spatial overlap between predicted and true segmentation masks.

The final evaluation on the validation set showed a high quality of segmentation. The Binary IoU (Jaccard index) achieved:

- Optic disc: 0.92
- Optic cup: 0.83

These values indicate good spatial agreement between predictions and ground truth masks, especially for the



Figure 1. BCELoss during training for optic disc and optic cup.



Figure 2. Dice coefficient during training for optic disc and optic cup.

optic disc. The optic cup, being smaller and less distinct in fundus images, showed a lower but still acceptable IoU score.

The Dice coefficient at convergence was approximately 0.95 for the optic disc and 0.88 for the optic cup, which reflects the class imbalance and visual complexity in segmenting the excavation zone.

An analysis of training dynamics shows that the loss curves are not monotonic and include fluctuations, particularly for the optic cup, which suggests sensitivity to anatomical variations and class imbalance.

Further improvement of segmentation accuracy can be achieved by:

- Incorporating *Dice loss* or *combined BCE* + *Dice loss* during training to better handle imbalanced regions;
- Using *focal loss* to reduce the impact of background pixels;
- Applying *data augmentation* focused on enhancing variability in cup morphology.

Overall, the segmentation model is robust and provides sufficiently accurate anatomical masks for our algorithm.

B. Segmentation of blood vessels

The training of the model extracting the vascular network of the image was carried out in 2 stages. In the first stage, the network was trained on an additional set of 300 labeled data from publicly available datasets such as DRIVE [6], CHASE DB1 [7] and HRF [8]. In the second stage, the network was trained on target images.

Initially, the analyzed three-channel (RGB) image was compressed to a size of 996 x 996. After that, it was split into 9 slices with a resolution of 352×352 so that each slice captures a part of the neighboring slices (10 pixels). This is to eliminate distortion at the boundary between two tiles. Vessel segmentation by the neural network was performed for each tile. We chose UNet architecture with a resnet18 backbone pre-trained on the ImageNet dataset.

The model contains 23 convolutional layers and consists of convolutional (encoder) and up-convolutional (decoder) parts. To reduce each 64-component vector to the required number of classes, 1×1 convolutions are applied on the last layer. The input image size is determined by the need for even values of height and width for adequate application of subsampling operation (2×2 max pooling).

The network is trained by stochastic gradient descent based on the input images and their corresponding segmentation maps (masks). Applied function, soft-max brings the model prediction to the mask view. The loss function is a binary cross-entropy + jaccard functions. The accuracy is calculated by the BinaryIOU() [9] function, which finds the ratio of the correctly predicted mask to the union of the predicted and true masks. After the tiles were merged into a single image with the boundary 5 pixels cropped on each of them. They were then merged into rows. To smooth the transition between two tiles, their 5-pixel boundaries are overlaid and the resulting brightness is calculated using alpha blending to obtain a smooth transition. This process is shown in Fig. 3.



Figure 3. left – result of segmentation model on neighboring tiles, right – tiles merged with alpha blending

The same way the obtained 3 rows of tiles are combined into a vessel mask of the whole image. After that the obtained mask is stretched to the size of the original image.

The results of segmentation model for vascular network on training set and validation set are shown in Fig. 4.

IV. EfficientNetB6 Classifier (without attention mask)

We examined a baseline image classification pipeline trained to categorize retinal fundus images into one of seven diagnostic classes. The model was trained on a curated version of the ODIR-5K dataset. Each fundus image (left or right eye) was labeled into one of the following categories:

- Pathological Myopia
- · Hypertensive Retinopathy
- Diabetic Retinopathy
- Glaucoma
- Cataract
- Age-related Macular Degeneration (AMD)
- Normal (Healthy)

Each class was sampled with up to 250 left-eye and 250 right-eye images. Images were loaded, resized to 224×224 , and paired with integer labels.

a) Data Augmentation.: Training images were augmented using the ImageDataGenerator utility with the following transformations:

- Rotation: $\pm 30^{\circ}$
- Width and height shift: 10%
- Zoom: 20%
- Horizontal flipping

These augmentations were applied to improve generalization and reduce the risk of overfitting. b) Model Architecture.: The core of the model is EfficientNetB6 [10] with include_top=False. Pretrained weights were used to initialize the base. A custom classification head was added:

- GlobalAveragePooling2D
- Dense(224, activation='relu')
- Dropout (0.3)
- Dense(7, activation='softmax') for 7-class prediction

c) Training Configuration:

- Loss function: sparse_categorical_crossentropy
- Optimizer: Adam with a learning rate of 1×10^{-4}
- Epochs: 30
- Batch size: 8
- Early stopping: Enabled (patience = 5)

d) Baseline result: Figure X shows the confusion matrix of the model on the test set, highlighting perclass prediction accuracy and common misclassification patterns (Fig. 5). It reveals both the strengths and limitations of the baseline model when distinguishing between retinal diseases.

Key Metrics:

- Overall test accuracy: 78.3%
 - Highest per-class accuracy:
 - Myopia: 94%
 - Age-related Macular Degeneration (AMD): 90%
- Lowest per-class accuracy:
 - Diabetic Retinopathy: 29%
 - Healthy: 69%

V. EFFICIENTNETB6 CLASSIFIER using semantic attention mask

To improve classification performance, we introduced an attention mechanism that utilizes semantic segmentation masks generated for each fundus image. The core idea is to guide the classifier's focus toward clinically relevant anatomical regions—namely the optic disc, optic cup, and retinal vessels—by assigning higher weights to these structures and attenuating the influence of the background.

A. Attention Mask Generation

For each image, we applied pretrained segmentation models to generate binary masks corresponding to:

- Optic disc (channel 0),
- Optic cup (channel 1),
- Retinal vessels (channel 2).

These masks were resized to match the input image dimensions and normalized to the range [0, 1]. Each region was assigned a scalar weight based on its diagnostic relevance:

- $w_{\rm disc} = 0.9$,
- $w_{\rm cup} = 1.0$,
- $w_{\text{vessels}} = 0.8$,
- $w_{\text{background}} = 0.2$.

The values were selected empirically through ablation studies and reflect the clinical importance of each anatomical structure.



Figure 4. IoU score. first - training, second - validation. Blue - disk segmentation, red - excavation zone, orange - blood vessels



Figure 5. Confusion matrix for the baseline model.

B. Mask-Based Image Enhancement

A composite attention mask M is computed as a weighted sum of the individual segmentation maps:

$$M = w_{\text{disc}} \cdot \text{mask}_{\text{disc}} + w_{\text{cup}} \cdot \text{mask}_{\text{cup}} + w_{\text{vessels}} \cdot$$
$$\text{mask}_{\text{vessels}} + w_{\text{background}} \cdot (1 - \text{combined}_{\text{mask}})$$

where combined_mask denotes the union of all binary object masks. The attention-enhanced image I_{attn} is then obtained via element-wise multiplication:

$$I_{attn}(x,y) = I(x,y) \cdot M(x,y)$$

This operation suppresses less informative background regions while amplifying features in diagnostically critical areas.

C. Classification Pipeline

The modified images I_{attn} are fed into the same EfficientNetB6 classifier described earlier. The training

configuration—loss function, optimizer, learning rate, and number of epochs—remains unchanged to ensure a consistent comparison with the baseline model.

This strategy allows the network to concentrate on regions most likely to contain pathological changes, and leads to measurable improvements in classification accuracy, especially in complex or borderline cases.

a) Improved result: After training model with attention masks the confusion matrix of the model shows optimized classification performance. The updated matrix demonstrates better per-class accuracy and reduced confusion among visually similar diseases compared to the baseline model (Fig. 6).



Figure 6. Confusion matrix for the improved model.

Key Metrics:

- Overall test accuracy: 92.2%
- Highest per-class accuracy:
 - Cataract: 96.6%
 - Myopia: 96.0%
- Lowest per-class accuracy:
 - Diabetic Retinopathy: 84.6%
 - Healthy: 84.4%

VI. Discussion

Within the framework of OSTIS (Open Semantic Technology for Intelligent Systems), attention masks and reflexivity become key components for building an intelligent diagnostic system based on the analysis of fundus images. At the core of the method is the use of semantic segmentation to highlight key anatomical structures the optic disc, optic cup, and blood vessels - which are then used as attention masks in the EfficientNetB6 neural network, significantly improving classification accuracy from 78.3% to 92.2%. This approach is particularly valuable for diagnosing complex diseases such as diabetic retinopathy, where precise detail recognition is critically important. Within OSTIS, attention masks become a tool that implements the principle of reflexivity: the system can analyze its own decisions, adjusting the weights of these masks based on classification errors, which enhances its adaptability and effectiveness.

Attention masks are weight maps that highlight anatomically significant areas of the image, such as the optic disc, optic cup, and blood vessels. They are created using semantic segmentation and integrated into the OSTIS system as a tool that directs the classifier's focus to critically important zones. This allows the system to amplify signals from key areas, improving the accuracy of diagnosing pathologies such as glaucoma or diabetic retinopathy. For example, by applying attention masks, the model can more clearly distinguish subtle changes in eye structures, which is especially important for diseases with minor visual manifestations.

Representing knowledge about diseases and anatomy in a universal format ensures their reusability and scalability, allowing for the creation of flexible systems. This integration not only improves diagnostic accuracy but also makes the system capable of explaining its conclusions, which is crucial for medical practice where the interpretability of decisions plays a key role.

The integration of attention masks and reflexivity makes the OSTIS system not only more accurate but also interpretable. Attention masks help explain which areas of the image the classifier relies on, while reflexivity ensures transparency in the learning and adjustment process. This is particularly valuable in medical practice, where doctors need justification for diagnostic decisions.

VII. Conclusion

This study demonstrates that incorporating semantic segmentation into the classification pipeline significantly enhances the performance of retinal disease diagnosis from fundus images. By generating semantic masks of the optic disc, optic cup, and retinal vessels, and using them to guide the classifier's attention, we were able to improve both accuracy and robustness of the model.

The proposed attention mechanism allows the network to prioritize clinically relevant regions while suppressing less informative background areas. This research shows that semantic information, when embedded in the form of weighted attention masks, leads to better feature representation and higher classification performance, particularly in cases involving subtle or overlapping pathological signs.

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УЛУЧШЕНИЕ ДИАГНОСТИКИ ИЗОБРАЖЕНИЙ ГЛАЗНОГО ДНА С ИСПОЛЬЗОВАНИЕМ МАСКИ АЛГОРИТМА ВНИМАНИЯ НА ОСНОВЕ СЕМАНТИЧЕСКОЙ СЕГМЕНТАЦИИ

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В данной работе предлагается метод классификации офтальмологических заболеваний по изображениям глазного дна с применением семантической сегментации в качестве механизма внимания. В отличие от традиционных подходов, использующих всю область сетчатки, предложенная система акцентирует внимание на анатомически значимых зонах, выделенных посредством сегментации диска зрительного нерва, оптической чаши и сосудистой сети. Полученные сегментационные маски интегрируются в алгоритм классификации для улучшения извлечения признаков. В качестве классификатора используется модель на базе EfficientNetB6, позволяющая оценить эффективность предложенной стратегии. Результаты экспериментов демонстрируют повышение точности классификации по ряду метрик и успешность данного метода.

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YOLO11-LKAConv: Optimizing UAV Image Multi-Target Detection Based on Improved YOLO Architecture

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Abstract-This paper presents YOLO11-LKAConv, an improved model based on the YOLOv11 framework, to address the issue of low detection accuracy for small targets in UAV aerial images. By replacing standard convolutions with lightweight large-kernel attention convolution (LKAConv), the model integrates dynamic large-kernel receptive fields and channel-spatial attention mechanisms, enhancing its ability to capture long-range contextual features for small targets. Experiments on the VisDrone2019 dataset show that the improved model achieves an mAP50-95 of 0.173, a 1.2% increase over the baseline YOLOv11n, with improvements in both P and mAP50 while maintaining almost the same inference time. The results indicate that LKAConv effectively balances detection accuracy and computational efficiency through its lightweight large-kernel design, offering a better solution for real-time UAV target detection tasks.

Keywords—Small target detection; YOLOv11n; UAV detection; LKAConv; Lightweightt

I. Introduction

With the rapid development and popularisation of UAV technology, UAVs have been widely used in aerial photography, agriculture, security monitoring, disaster rescue, environmental monitoring and other fields. UAV aerial photography can not only provide high-definition images and videos, but also complete tasks such as monitoring, surveying and search and rescue of complex environments, which has become an indispensable technical means in modern society [1]. However, the flight safety and effective monitoring of UAVs have become an urgent problem, especially in complex scenarios, and the performance of target detection technology directly determines the intelligence level of UAVs [2], [3].

Traditional UAV target detection methods usually rely on hand-designed feature extractors and classifiers (e.g., HOG, SIFT, etc.), which perform reasonably well in specific scenarios, but their performance is often limited under complex backgrounds and variable target morphology [4], [5]. In recent years, the rapid development of deep learning technology provides new solutions for UAV target detection. Deep learning-based target detection methods significantly improve detection accuracy and robustness by training deep neural networks to automatically learn the feature representation of the target [6], [7]. Among them, the YOLO series of algorithms has become a research hotspot in the field of UAV target detection due to its fast speed and high accuracy [1], [4]. However, with the expansion of UAV application scenarios, the existing YOLO series network still has deficiencies in dealing with the problems of dense small targets and complex backgrounds [2], [3].

Aiming at the insufficient performance of the existing UAV target detection algorithms in the dense and complex background of small targets, this study aims to propose a lightweight kernel attention mechanism (LKA-Conv) in the YOLOv11 framework, which dynamically adjusts the kernel sensing field and the allocation of the attention weights, enhances the ability of the model to capture the features of the small targets, and improves the detection precision and the recall rate, so as to realise a lightweight design of the model and ensure that it can be used in the UAV application scenarios [2], [3]. The lightweight design ensures its real-time application on resource-constrained devices such as UAVs.

II. Method

A. YOLOv11

YOLOv11, a new generation of object detection algorithms introduced by Ultralytics in 2023, aims to further improve the accuracy and efficiency of object detection. It has made several improvements based on YOLOv8 [8] to adapt to a wider range of application scenarios and enhance model performance. YOLOv11 provides multiple versions of different scales, including YOLOv11n (ultra-light), YOLOv11s (small), YOLOv11m (medium), YOLOv111 (standard), and YOLOv11x (extra-large), to meet different needs. Compared with previous YOLO versions, YOLOv11 has made the following improvements:

- Backbone Network: YOLOv11 introduces the C3k2 module [9], replacing the C2f module in YOLOv8. The C3k2 module uses smaller convolution kernels to improve computational efficiency while maintaining performance. It retains the spatial pyramid pooling fast (SPPF) module [10] and introduces the cross-stage partial and spatial attention (C2PSA) module [10], enhancing spatial attention in feature maps and improving detection accuracy.
- 2) Neck Structure: In the neck structure, YOLOv11 replaces the C2f module with the C3k2 module, improving the speed and performance of feature aggregation. The C2PSA module enhances spatial attention, enabling the model to more effectively focus on key areas in the image and improving detection accuracy for small and partially occluded targets.
- Head Structure: In the head structure, YOLOv11 uses multiple C3k2 modules to process and optimize feature maps, improving the model's detection accuracy.



Figure 1. YOLOv11 Network Structure Diagram

Additionally, YOLOv11 adopts multi-scale training and data augmentation techniques during training to further improve the model's generalization and detection accuracy. Compared with previous generations, YOLOv11 shows significant improvements in inference speed and accuracy. In summary, YOLOv11 has made significant progress in the accuracy and efficiency of object detection by introducing innovative technologies such as the C3k2 module and the C2PSA module. It performs well in models of different scales and demonstrates strong adaptability and practicality in various application scenarios. The network structure of YOLOv11 is shown in Figure 1.

B. LKAConv

LKACONV (Large Kernel Attention Convolution) is a key component of the LKA mechanism, used to implement the decomposition of large convolution kernels [11]. LKACONV captures long-range dependencies by decomposing a large convolution kernel into multiple small convolution kernels and dilated convolutions. This decomposition method not only retains local structural information but also effectively captures long-range dependencies while maintaining linear complexity. The principle of the large convolution kernel is shown in Figure 2:



Figure 2. Decomposition Diagram of Large-Kernel Convolution

The core formula of LKA is as follows:

Attention =
$$\operatorname{Conv}_{1 \times 1}(DW - D - \operatorname{Conv}(DW - \operatorname{Conv}(F))),$$
 (1)

$$Output = Attention \otimes F$$
(2)

where: **F** is the input feature map, DW - Conv represents depthwise separable convolution, DWD - Conv represents dilated depthwise separable convolution, $Conv_{1\times 1}$ represents 1×1 convolution, and 1×1 represents element-wise multiplication.

In this study, we introduced the large kernel attention convolution to enhance the feature extraction capability of the YOLOv11 model, especially when processing UAV datasets. LKAConv is a new type of convolution module that combines the advantages of convolution and self-attention mechanisms, effectively capturing longrange dependencies and local structural information. In our model, the 5th layer adopted LKAConv with parameter settings of 512 input channels, a 3x3 convolution kernel, and a dilation rate of 2. In addition, the downsampling process was mainly completed by standard convolution and LKAConv. The features extracted by LKAConv were fused with the features of the previous layers through concatenation and convolution layers to form rich feature maps. This fusion method effectively combined multi-scale features, further enhancing the model's detection performance.

C. YOLO11-LKAConv

This paper takes YOLOv11n as the baseline and proposes an improved model, YOLO11-LKAConv, to address the problem of detecting small targets in UAV aerial images. YOLOv11n still has high rates of missed and false detections in complex backgrounds, dense targets, and small target detection. The improved model maintains a lightweight design while significantly improving detection accuracy. The specific improvements are shown in Figure 3 below:



Figure 3. YOLO11-LKAConv Structure

The 5th layer of Backbone corresponds to the output of P4, which is in the middle-level feature stage. This layer is responsible for detecting medium-scale targets. The purpose of introducing LKAConv is to expand the receptive field of the middle-level features, suppress background noise interference, and balance computational efficiency. In drone aerial images, medium-sized targets are often mixed with ground or vegetation of similar colors. The channel attention mechanism of LKA-Conv can enhance target-related channels and suppress noise channels such as vegetation texture through feature recalibration. The 16th layer of Head corresponds to the feature fusion layer after P3 upsampling. This layer fuses deep semantic features and shallow detail features through Concat operation. The design of introducing LKAConv here is to strengthen cross-scale feature fusion and resist scale change interference. LKAConv can introduce multi-scale perception capabilities at this level. Large kernel convolution covers spatial patterns of different scales, and the attention mechanism focuses on the current dominant scale.

The two LKAConvs in the backbone and head form a "mid-level capture-high-level refinement" synergistic effect: capturing contextual association features of targets through large receptive fields and providing high-quality mid-level semantic information for subsequent FPN. Using attention mechanisms to screen cross-level features and reconstruct the complete spatial structure of small targets. This "coarse-fine" synergistic strategy retains the speed advantage of the YOLO series while breaking through the performance bottleneck of traditional methods in complex air-to-ground detection scenarios, providing a new technical paradigm for real-time UAV target detection.

III. Experiments

A. Dataset

The VisDrone2019 [12] dataset is a large-scale benchmark dataset created by the AISKYEYE team of the Machine Learning and Data Mining Laboratory of Tianjin University, China. The dataset was collected using various drone platforms (i.e., drones with different models) in various situations and under various weather and lighting conditions. It contains carefully annotated ground truth data for various computer vision tasks related to dronebased image and video analysis.

This experiment uses the static images in this dataset, which contains 10,209 images. This experiment divides the dataset into the following: 6,471 training sets, 548 validation sets, and 1,610 test sets. The current dataset has a total of 471,266 annotated targets, covering 11 categories: 0: pedestrian, 1: people, 2: bicycle, 3: car, 4: van, 5: truck, 6: tricycle, 7: awning-tricycle, 8: bus, 9: motor, 10: other. Others are non-valid target areas and are ignored in this project. The validation set contains 38,759 instances, of which small targets (pixel area <32×32) account for 68.2%, and dense scenes (>100 targets per image) account for 45%, which fully reflects the detection challenges from the perspective of drones.

The data annotation is shown in Figure 4 below:



Figure 4. Data annotation

B. Experimental Environment and Configuration

The experimental platform is a 64-bit Windows 11 operating system, with PyTorch 2.4.0 and CUDA 2.4.1 as the deep learning framework. An NVIDIA GeForce

RTX 4060 GPU is used for training, with Python 3.9 and CUDA version 12.41. Specific experimental environment configuration parameters are shown in Table I. Parameters not provided in this paper adopt the default parameters of YOLOv11n.

Table I Table to test captions and labels

epochs	batch	imgsz	device	optimizer	amp
100	16	640	0	auto	true

C. Evaluation indicators

The experiment mainly uses mean average precision (mAP), accuracy (precision, P), and recall (recall, R) to evaluate the algorithm's target detection performance. At the same time, floating point operations (GFLOPs), parameter volume (params), model size (volume), and frames per second (FPS) are used to evaluate the model complexity and detection efficiency. The calculation formulas for precision, recall, and average accuracy are shown in equations (3) to (5).

$$P = \frac{TP}{TP + FP},\tag{3}$$

$$R = \frac{TP}{TP + FN},\tag{4}$$

$$\begin{cases}
AP = \int_0^1 P(R) dR \\
mAP = \frac{\sum_{i=1}^n AP_i}{n}
\end{cases}$$
(5)

In the formula: P is precision; R is recall; TP is the number of samples predicted to be positive and actually positive; FP is the number of samples predicted to be positive but actually negative; FN is the number of samples predicted to be negative but actually positive; AP is the precision of each category in the dataset; mAP is the average accuracy of all categories in the dataset.

D. Cross-Model Comparison Results and Analysis

In order to verify the comprehensive performance of the YOLO11-LKAConv model proposed in this paper in the UAV target detection task, a comparative experiment was designed. We compared it with the mainstream lightweight versions of the YOLO series, including: YOLOv5n [13], YOLOv6n [14], YOLOv8n, YOLOv10n [15], and YOLOv11n. The experimental environment, configuration, and parameters are the same, and the experimental results are shown in Table II:

Through experiments, we found that on the Vis-Drone2019 dataset, each model performed differently in terms of accuracy and efficiency. The P values of v11n and v10n were both 0.402, and the R values were 0.308 and 0.299, respectively. They performed well in terms of

Table II Comparison of Different Models on the VisDrone2019-DET Datase

	v11n	v10n	v8n	v6n	v5n	LKAConv
Р	0.402	0.402	0.398	0.363	0.387	0.407
R	0.308	0.299	0.302	0.28	0.279	0.302
mAP50	0.297	0.291	0.291	0.271	0.273	0.301
mAP50-95	0.171	0.163	0.165	0.156	0.154	0.173
time	6.012	5.885	7.193	5.794	5.172	6.015
preprocess	0.1ms	0.2ms	0.2ms	0.2ms	0.2ms	0.2ms
inference	1.7ms	1.4ms	2ms	1.7ms	1.7ms	2ms
parameters	2.46M	2.39M	2.57M	3.96M	4.04M	2.51M
GFLOPs	6.3	7.1	8.2	11.5	11.8	6.7



Figure 5. Comparison of GFLOPs of different models



Figure 6. Comparison of FPS of different models

precision and recall, but their FPS were relatively not the highest, at 344.83 and 204.08, respectively, and a tradeoff between accuracy and speed was required; v8n had the highest FPS, at 357.14, and its mAP50-95 was also relatively high, at 0.165. It achieved a high processing speed while ensuring a certain accuracy, and was suitable for scenarios with high real-time requirements; v5n and v6n had more parameters, and v5n had a longer postprocessing time of 3.2 seconds. In terms of accuracy, the mAP50-95 value of yolo11-LKAConv reached 0.173, an increase of 1.2% over the baseline v11n, and significantly better than other models. This shows that it has better performance for complex scenes (such as occlusion and small targets). The value of yolo11-LKAConv on mAP50 reaches 0.301, indicating that the model is better at detecting medium-scale targets. The model maintains the same inference speed as the baseline v11n at the cost of a slight increase in the number of parameters and computation, as shown in Figures 5. and 6. The lightweight design effectively balances efficiency.

E. Comparison Results and Analysis of Different Convolution Layers

To verify the effectiveness of the improved YOLO11-LKAConv model, it is compared with different convolution layer variants of the baseline YOLOv11n, including RepViTblock, GSConv, and ADown. Experimental results are shown in Table 3. On the VisDrone2019 dataset,

Table III Comparison of Different Convolution Models on the VisDrone2019-DET Dataset

	v11n	RepViTblock	GSConv	ADown	LKAConv
Box(P	0.402	0.395	0.39	0.401	0.407
R	0.308	0.308	0.303	0.304	0.302
mAP50	0.297	0.298	0.295	0.298	0.301
mAP50-95	0.171	0.169	0.166	0.171	0.173
time	6.012	5.982	6.067	6.086	6.015
preprocess	0.1ms	0.2ms	0.2ms	0.2ms	0.2ms
inference	1.7ms	1.9ms	1.7ms	1.7ms	2ms
parameters	2.46M	2.78M	2.45M	2.36M	2.51M
GFLOPs	6.3	6.3	6.1	6	6.7

RepViTblock has a P value of 0.395 and an R value of 0.308, which are close to v11n's P value of 0.402 and R value of 0.308, but its FPS is 312.50, which is lower than v11n's 344.83; GSConv has a P value of 0.39 and an R value of 0.303, which are slightly lower than v11n, and its time consumption is slightly higher than v11n, which is 6.067 seconds; ADown has a P value of 0.401 and an R value of 0.304, which are close to v11n, but it

has the least number of parameters and may have certain advantages in model complexity;

In this experiment, YOLO11-LKAConv still achieves higher mAP50 and mAP50-95 values than other variant models. This indicates that YOLO11-LKAConv can effectively improve small target detection accuracy while maintaining inference efficiency. Although YOLO11-LKAConv's recall rate is slightly reduced due to the feature screening of large-kernel features by LKAConv, the model maintains a similar inference speed to the baseline YOLOv11n with a slight increase in parameters and computational cost, verifying the effectiveness of the lightweight large-kernel design.

IV. Summary

This study proposes an improved model, YOLO11-LKAConv, based on the YOLOv11 framework for UAV target detection tasks. By introducing the lightweight large-kernel attention module (LKAConv), the model significantly improves detection performance for small targets in complex scenes. Experiments on the Vis-Drone2019 dataset show that the improved model performs excellently in detection accuracy, computational efficiency, and model complexity. Specifically, YOLO11-LKAConv achieves an mAP50-95 of 0.173 and an mAP50 of 0.301, representing improvements of 1.2% and 1.3% over the baseline model YOLOv11n. The inference time (6.015 hours) is almost the same as the baseline model, and the increase in parameters and computational cost is kept within a small range, verifying the effectiveness of the lightweight design. Ablation experiments and visualization analysis further confirm the key role of the LKAConv module in improving model performance. This module dynamically adjusts the largekernel receptive field and attention weight distribution, enhancing the model's ability to capture small target features and effectively suppressing interference from complex backgrounds. Additionally, comparative experiments with existing variant models (such as YOLO11-RepViTblock, YOLO11-GSConv, and YOLO11-ADown) show that YOLO11-LKAConv achieves better efficiency and lightweight levels while maintaining high detection accuracy. This study provides an efficient and accurate solution for UAV target detection tasks with significant practical application value. The real-time performance of the improved model on UAV edge computing devices makes it widely applicable in scenarios such as public interest litigation and environmental monitoring. Future research directions may include further optimizing the channel pruning strategy of the LKAConv module or introducing dynamic sparse computation to further improve recall rate and inference speed.

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YOLO11-LKACONV: ОПТИМИЗАЦИЯ ОБНАРУЖЕНИЯ НЕСКОЛЬКИХ ЦЕЛЕЙ НА СНИМКАХ БПЛА НА ОСНОВЕ УЛУЧШЕННОЙ АРХИТЕКТУРЫ YOLO

Ву Сяньи, Абламейко С. В.

В данной статье представлен YOLO11-LKAConv улучшенная модель, построенная на основе фреймворка YOLOv11, которая направлена на решение проблемы низкой точности обнаружения маленьких целей на аэрофотоизображениях БПЛА. Заменяя стандартные сверточные слои на легковесные сверточные слои с большим ядром и вниманием (LKA-Conv), модель интегрирует динамические крупные рецептивные поля и механизмы канално-пространственного внимания, что усиливает ее способность захватывать долгосрочные контекстные признаки для маленьких целей. Эксперименты на датасете VisDrone2019 показывают, что улучшенная модель достигает mAP50-95 в 0,173, что на 1,2% выше, чем у базовой YOLOv11n, причем показатели точности (Р) и mAP50 также улучшены, а время вывода осталось почти неизменным. Результаты указывают на то, что LKAConv благодаря своему легкому дизайну с большим ядром эффективно балансирует точность обнаружения и вычислительную эффективность, предлагая лучшее решение для задач реального времени по обнаружению целей на БПЛА.

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Designing an Ontology of the Educational Process in a Specialized Secondary Education Institution

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Abstract—The paper presents the author's results on the use of information technology to automate business processes in the Republic of Belarus, in particular, it shows the development of partial automation of business processes for different levels of the education system. On the example of a specialized secondary education institution, the author substantiates the relevance and necessity of implementing digital twin technology in the educational sphere of the Republic of Belarus. The stages of building a digital twin of the educational process developed by the author are highlighted. On the basis of the process approach of business process modeling the upper ontology of the college is formed. Examples of graph model of ontology with the help of OSTIS technology are given.

Keywords—secondary specialized education institution, digital twin, interoperability, automation, expert system of educational process management, ontology, knowledge base, OSTIS technology

I. Introduction

In today's digital society, information is becoming a strategic resource, and information technology is one of the tools for improving the efficiency of economic and social systems management, including the education system. Currently, the most actively developing and implementing such technological trends as: artificial intelligence, machine learning, Internet of Things, virtual and augmented reality, robotic process automation, blockchain, autonomous vehicles, digital twins, cybersecurity, 3D printing.

The introduction of information technologies in the spheres of public administration is a task of strategic importance. That is why the State Program "Digital Development of the State for 2021-2025" has been developed and approved, the tasks of which are largely determined by the main provisions of the National Strategy for Sustainable Development of the Republic of Belarus for the period until 2035.

The purpose of the State Program is to ensure the introduction of information and communication and advanced production technologies in the sectors of the national economy and spheres of society. In order to realize this goal, it is necessary to implement complex automation of information systems in various spheres – medicine, education, public administration, production, transport, agriculture, etc. The State Program is aimed at ensuring the implementation of information and communication technologies and advanced production technologies in various sectors of the national economy and spheres of society.

Figure 1 shows the statistics of the BEROC research center on the surveyed private and state-owned enterprises of the Republic of Belarus, which reflects for 2019 the use of information technology to automate business processes in the following areas:

- accounting 93.4%;
- personnel accounting and sales 47.9%;
- warehousing 46.5%;
- document management 41.5% and others [1].



Figure 1. Automated and business processes requiring priority automation.

Thus, as of today, partial automation of business processes has been implemented, i. e. there is no unified information system that ensures the adoption of sound management decisions based on quality and reliable information obtained with the help of modern information technologies.

II. Digital twins

A. Digital twins in the Republic of Belarus

To realize complex automation of business processes, a so-called digital twin (twin) is required. By digital twin we mean a dynamic digital model of a real system, which can use data from sensors to assess its state, react to changes, improve its operation and perform additional functions. A digital twin can be a digital model that includes a combination of metadata, i. e. structured data such as classification, composition, material specification, structure, guidelines and other conditions and states (location, temperature), event data and analytics (algorithms, rules). Their practical application is associated with preventive maintenance and prediction of equipment failures, process planning, and improving the efficiency of systems management in general [2].

The National Statistical Committee of the Republic of Belarus conducted a study of the use of different digital technologies in their activities by private and public organizations for the year 2023, which showed the percentage as follows (Figure 2):

- "internet of things" 18.5%;
- radio frequency identification technologies 13.7%;
- "big data" 12.3%;
- artificial intelligence 3.6%;
- "digital twin" 0.6% [3].

Thus, the application of digital twin technology is at the early stages and requires further development and integration into various spheres of economy and management, including the education system.



Figure 2. Statistics on the use of digital technologies.

The low utilization of digital twins may be due to a number of factors, such as lack of awareness of the benefits of this technology, limited financial resources for the implementation of complex systems, and a shortage of qualified specialists capable of working with such solutions.

Main areas in the Republic of Belarus, where digital twin technologies are developed and/or applied:

 Oil and gas production and refining: the engineering data management system developed by the institute "Belorusneft' – Neftekhimproekt" was implemented in the republican unitary enterprise "Belorusneft' – Brestoblnefteprodukt".

- 2) Industry:
 - a) Pilot project "Intellectual system of design and technological design and production preparation of products using digital technologies", developed by the central research and design and technological institute of organization and management techniques, two enterprises were chosen as platforms for the project – open joint-stock company "Minsk Mechanical Plant" named after S. I. Vavilov and open joint-stock company "Vityaz".
 - b) Robotic line of Belvest shoe production, developed by LACIT-Laboratory of Digital Technologies Limited Liability Company.
 - c) Information system for automation of business processes based on the innovative software product "1C:ERP Enterprise Management 2.4" developed by YUKOLA-INFO-Brest, a company with additional responsibility.
 - d) Digital twin of a dump truck and digital twin of a quarry a joint development of SAP CIS and BELAZ.
- 3) *Energy:*
 - a) Pilot projects on the creation of digital simulators, which allow operational personnel to practice skills of working on power equipment in real time while performing tasks, are developed within the framework of cooperation between organizations of the Ministry of Energy of Belarus and Rosatom State Corporation.
 - b) "Digital twin" of operation of turbine units PT-60-130 of stations №1,2,3 of Bobruisk thermal power plant №2, developed by the republican unitary enterprise "Belnipienergoprom".
- 4) IT sphere: the Belarusian IT company "International Business Alliance" has developed the system "Chancellor RPA", designed for development, support and modification of program robots that simplify the support of business processes.
- Construction: open Joint-Stock Company "Clay Gravel Plant Novolukoml" developed and placed in free access on the official website of the enterprise VIM-models of claydite concrete blocks "ThermoComfort".
- Education: virtual and Augmented Reality Laboratory, developers: InnowiseGroup (Limited Liability Company "Factory of Innovations and Solutions") for P.M. Masherov Vitebsk State University).
- 7) Medicine:
 - a) The Republican Scientific and Practical Center "Cardiology" has developed a technique

for creating a virtual heart model for 3D printing.

- b) An automated information system "Electronic Prescription" has been developed.
- 8) Sport: developed by the Ministry of Sports "Digital Movement Laboratory". This technology is used to check physical development during certain exercises. Such technology is used by highly professional athletes in the training process to adjust training.
- 9) *Urbanistics:* implementation of the regional state standard digital platform "Smart City (Region)" in the city of Minsk, regional centers, cities and districts with a population of 80 thousand people and more, providing on their basis services in various spheres of life and management.

In the Republic of Belarus, digital twins have been implemented in manufacturing – for example, in machine and equipment manufacturing enterprises, where models are used to optimize processes and improve efficiency, and in healthcare – for example, in the development of virtual models for planning surgical operations and monitoring patients' condition. In education, there are practically no developments with the use of this technology, so it is becoming increasingly important to implement digital twins, which can help to create individualized educational programs, analyze students' academic progress, optimize the learning process and other opportunities in accordance with the needs of the educational institution.

B. Digital twins in the field of education in the Republic of Belarus

Digitalization of educational processes is one of the most effective ways to improve the quality of learning and management of the learning process in educational institutions. This is especially relevant in the context of rapid technological development and the need to adapt educational systems to modern requirements. In this regard, educational institutions are beginning to implement various information technologies and automated systems to optimize their business processes.

Existing information technologies in the educational sphere are limited to performing a set of specific functions, leaving a significant part of management decisions to human judgment. This results in teachers and administrators having to rely on their experience and intuition rather than on the data provided by systems in situations that require a quick response (e. g., low group performance or schedule changes). Within the framework of the direction of education there are the following developments on partial automation of business processes:

At the level of higher education within the framework of realization of the concept of digital university 4.0 corporate information systems are being developed, which include subsystems:

- for management processes: subsystem "Reporting and analytics", subsystem "Administration of university-wide classifiers", subsystem "Divisions";
- for operational processes: subsystem "Students", subsystem "Educational and methodological support of the educational process", subsystem "Schedule", subsystem "Journal of current academic progress", subsystem "Curator's Journal", subsystem "Dean's Office", subsystem "Department", subsystem "Gifted Bank", subsystem "Student's Personal Cabinet", subsystem 'Rating', subsystem "Employee's Personal Cabinet", subsystem "Electronic Applicant", subsystem of e-learning (Moodle);
- for supporting processes: "Dormitory" subsystem, 'Passportist' subsystem, "Military registration desk" subsystem, "Student Personnel Department" subsystem, "Production and accounting of student credit books" subsystem, "1C: ERP Enterprise Management (1C ERP)" - "Salary", "Scholarship", "Payment for Hostel", "Payment for Education", "Personnel Department", "Planning and Finance Department", "Extra-budgetary bonuses", "Children's allowances", "Assignment of orphans' allowances", 'Deponents', "Accounting of budgetary and extra-budgetary financing of money and expenses (Banks)", "Accounting of Material Assets", automation of information exchange through the "Client-Bank" system, automation of information exchange with the Federal Social Security Fund", the EUMKD subsystem, the "Electronic Library" subsystem, the "Telephone Directory" subsystem, and the "User Administration" subsystem.

At the level of secondary specialized education on the basis of "1C:Enterprise 8" the implementation of the configuration "1C: e-College PROF" will be introduced, this information system was developed within the framework of the pilot project of EE RIPO. Business processes of both activity planning and execution control are automated: preparation of working curricula on the basis of state standards, formation, distribution and accounting of teaching load, scheduling and accounting of daily substitutions, planning and control of execution of activities, accounting of academic performance and attendance, planning and implementation of industrial practice and many others.

The development of automated information systems in each educational institution is individualized using different programming technologies. Consequently, the transition to digital transformation and the creation of a unified republican information and educational environment, laid down in the Concept of Digital Transformation of Processes in the Education System of the Republic of Belarus for 2019-2025 [4], is impossible due to the lack of open systems and interoperability between these systems [5].

III. Stages in the development of a digital twin

To solve the problem of ensuring openness and seamless information integration of subsystems within the information system of an educational institution and between systems in general, it is proposed to use a digital twin of the functioning environment of an educational institution. The proposed digital twin should consist of expert systems for each business process of a specialized secondary education institution. The structure of the expert system is based on: knowledge base, solver, help and explanation subsystem. The generalized structure of the expert system is presented in Figure 3.



Figure 3. Structure of the expert system.

The blocks shown in Figure 1 are present in any expert system. In general, the process of functioning of an expert system can be presented as follows: a user who wants to obtain the necessary information sends a request to the expert system through the user interface. The solver, based on the knowledge base, generates and issues a suitable recommendation to the user, explaining the course of its reasoning with the help of the explanation subsystem [6].

Knowledge base construction involves three steps:

- description of the subject domain;
- selection of a knowledge representation model;
- knowledge acquisition.

The development of the knowledge base consists in the allocation of the subject area, on the solution of which the expert system is oriented. In this case it is necessary to:

- determine the nature of the tasks to be solved;
- identify the objects of the subject area;
- establish links between the objects;
- select a model of knowledge representation;
- identify the specific features of the subject area.

A. Development of a knowledge base of a specialized secondary education institution

The main factor of ensuring compatibility of different types of knowledge, different models of problem solving and different computer systems in general is unification of information representation in the memory of computer systems. An objective guideline for unification of information representation is formalization of the meaning of the represented information. OSTIS technology was chosen for the development of knowledge bases of the institution of secondary special education, which is based on a clear separation from the process of designing a formal description of the semantic model of the developed knowledge base to the process of implementation (interpretation) of this model on one or another platform. This fact allows to provide cross-platform development of intellectual systems. The knowledge base built using OSTIS technology is based on the hierarchy of subject areas and their corresponding ontologies, which allows, on the one hand, to localize the area of solving certain problems, and on the other hand, to describe the relationships between different concepts and ensure the inheritance of their properties.

In the framework of the subject area under consideration, covering the business processes of a specialized secondary education institution (college), a knowledge base was formed using an ontological approach based on the representation of information in the form of semantic networks (knowledge graphs).

To illustrate such a model, let us consider the top ontology of college activity in Figure 4. In this fragment, types of educational institutions are identified according to the levels of the education system, such as: higher education institution, specialized secondary education institution, vocational education. The real representative of the secondary specialized education institution is the college. The following structural units are defined for the college: Board, educational and methodological association, library, competence center, management, personnel service, department.



Figure 4. The upper level of formalization of the college.

The example of the branch of BSUIR Minsk Radio Engineering College shows that the college consists of departments, where there is a head of department (Figure 5). Here the real example of a department is the department of computer technologies. Each department is a representative of the general class of the department.

Figure 6 demonstrates the formalization of the department into cyclic commissions on the example of the



Figure 5. Formalization of the organizational structure of the college.

cyclic commission of information technology software. The cyclic commission is headed by the chairman. The cyclic commission consists of teachers with the following possible categories: highest, first, second, no category.



Figure 6. Formalization of college departments.

Figure 7 shows that the cycle commission, as the most important element of the college functioning, implements the educational process according to the regulations of educational and methodical documentation in accordance with the direction of a particular specialty. The educational standard and the curriculum of the specialty are chosen as the basis of educational and methodical documentation.



Figure 7. Formalization of the cycle commission of the college.

Figure 8 demonstrates that the curriculum of the specialty consists of academic disciplines, for which

the teaching hours of the following types are defined: lectures, practical and laboratory classes, seminar.



Figure 8. Formalization of the curriculum of the specialty.

Within the framework of formalization are highlighted:

- Terms: "Educational institution", "Institution of secondary special education", "College", "Board", "Management", "Competence center", "Department", "Educational and methodological association", "Personnel service", "Head of department, "Chairman of cycle commission", "Teacher", "Cycle commission", 'Category', "Curriculum documentation", "Teaching hours".
- Attributes: "No category", "Second category", "First category", "Higher category", "Teaching specialty", "Educational standard", "Sample curriculum", "Teaching discipline", "Practical lesson", "Lecture lesson", "Laboratory lesson", "Seminar".
- Relationships: "The teacher has the second category", "The teacher has the first category", "The teacher has the highest category", "The cycle commission includes support of educational specialties", "The educational specialty is based on the educational standard and exemplary curriculum", "The exemplary curriculum contains a variety of academic disciplines", "The academic discipline involves the passage of training hours of different formats: lecture, laboratory class, practical class, seminar".

The presented list of terms, attributes and relations is far incomplete and can be extended and supplemented when designing an automated system.

This article presents a fragment of the ontology of activities of a specialized secondary education institution, it can also be extended depending on the tasks that need to be automated to make managerial decisions.

The developed ontology allows solving the following tasks:

- describe objects and processes of the educational process;
- describe relations between objects and processes;

• transform information from existing standards into a knowledge base and back, which together is the basis for the design and construction of an automated management system of an educational institution.

IV. Conclusion

The article presents an original model of business process ontology in the form of sets of terms, attributes and relations, and describes the composition of these sets. The model of the upper ontology of the activity of a specialized secondary education institution is developed in the form of a graph formalizing the activity of a specialized secondary education institution and a graph formalizing the activity of a cycle commission, which can serve as a basis for the development of expert systems for managing the educational process. Since the formalization of activity is represented with the help of OSTIStechnology, the developed upper ontology will allow to unify data, improve interaction between the participants of the educational process and increase the quality of decisions. It can be predicted that in the future the introduction of such systems can significantly improve the efficiency of learning and adaptation of educational programs to the requirements of modern society.

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ПРОЕКТИРОВАНИЕ ОНТОЛОГИИ ОБРАЗОВАТЕЛЬНОГО ПРОЦЕССА В УЧРЕЖДЕНИИ СРЕДНЕГО СПЕЦИАЛЬНОГО ОБРАЗОВАНИЯ Бущик Е.А.

В работе представлены результаты автора по использованию информационных технологий для автоматизации бизнес-процессов в Республики Беларусь, в частности, показаны разработки по частичной автоматизации бизнес-процессов для разных уровней системы образования. На примере учреждения среднего специального образования обоснована актуальность и необходимость внедрения технологии цифрового двойника в образовательную сферу Республики Беларусь. Выделены разработанные автором этапы построения цифрового двойника образовательного процесса. На основе процессного подхода моделирования бизнеспроцессов сформирована верхняя онтология колледжа. Приведены примеры графовой модели онтологии с помощью технологии OSTIS.

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Hardware Components in Intelligent Systems for Parkinson's Disease Diagnosis

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Abstract—This paper proposes an IT-based diagnostic system for Parkinson's disease, supported by the OSTIS platform. The system combines a domain ontology and knowledge base to formally represent and manage medical information related to Parkinson's disease. A specialized hardware-accelerated processing module based on FPGA is integrated to enable real-time analysis of patient data. Discrete wavelet transform and a gated recurrent unit (GRU) neural network are used for extracting and analyzing motor features. The hardware implementation was realized using Xilinx Vitis HLS, allowing efficient deployment of wavelet and GRU modules. Preliminary experiments on open datasets show that the system achieves approximately 95% accuracy in recognizing speech and motor patterns associated with Parkinson's disease.As a result of using FPGA, processing is accelerated by 20 times compared to the CPU implementation.

Keywords—Parkinson's disease, intelligent diagnostic systems, hardware integration, OSTIS technology, real-time monitoring.

I. Introduction

Parkinson's disease [1] is a prevalent neurodegenerative disorder characterized by motor impairments such as tremors, rigidity, bradykinesia, and balance disorders, significantly affecting patients' quality of life. With the acceleration of global aging, the incidence of Parkinson's disease is steadily increasing, placing a growing burden on healthcare systems and society. However, the diagnosis of Parkinson's disease currently relies heavily on clinical experience and subjective observation by physicians, lacking objective, quantifiable, and efficient diagnostic methods. Thus, achieving early, accurate, and continuous monitoring of Parkinson's disease has become a critical topic in clinical research. In recent years, rapid advancements in artificial intelligence have provided new opportunities for medical diagnostics, significantly improving the precision and efficiency of disease identification through intelligent diagnostic systems. However, genuine intelligent diagnosis cannot be achieved solely through software or algorithms. An intelligent diagnostic system must integrate both software and hardware resources to form a complete loop encompassing data acquisition, processing, diagnostic reasoning, and result

visualization. This paper presents an IT-based diagnostic system for Parkinson's disease that integrates semantic knowledge representation with hardware-accelerated data processing. The system is built on the OSTIS platform, where symptoms, diagnostic criteria, and measurement parameters are formalized using an ontological approach. Wavelet transform and a GRU-based neural network model are used to analyze speech and motor signals, both implemented on FPGA. This enables high processing speed, low latency, and energy efficiency, which are essential for embedded medical systems.

II. Overall Architecture of Intelligent Diagnostic Systems

Intelligent medical diagnostic systems typically adopt a modular architecture, consisting of components such as data acquisition, data processing/knowledge base, inference engine, and user interface. Taking Parkinson's disease (PD) monitoring as an example, the system usually comprises three main units: a wearable multisensor unit, a local base unit (such as a smartphone or home gateway), and a central hospital unit. Wearable sensors continuously monitor the patient's movements and physiological signals, transmitting the collected data wirelessly to a local or cloud-based processing platform.

The processing platform performs data preprocessing and feature extraction, then stores meaningful information in a medical knowledge base. For example, the system can use ontology and knowledge graphs to model the patient's health status, thus supporting the recognition of complex events and diagnostic reasoning. Based on machine learning, the system can analyze and assess typical symptoms such as tremors and bradykinesia, providing visualization results to assist doctors in clinical decision-making.

On this basis, the introduction of OSTIS (Open Semantic Technology for Intelligent Systems) can further enhance the system's intelligence. OSTIS supports the construction of an open semantic knowledge base, integrating intelligent problem-solving and human-computer interaction mechanisms. It is particularly suitable for modeling complex medical information and semantic reasoning. By representing medical knowledge in the form of SCg-graphs, OSTIS enables structured representation, dynamic updates, and interpretable reasoning, offering strong support for personalized treatment recommendations.

The figure 1 below illustrates a typical architecture of a Parkinson's disease monitoring system: inertial data collected by sensors is preprocessed and labeled, then analyzed on the cloud using time-frequency analysis and machine learning models to assess the severity of symptoms. The analysis results are stored in a database and presented to medical personnel through a web interface.

III. Types and Functions of Hardware Tools

Intelligent diagnostic systems rely on a variety of hardware sensing tools to acquire objective physiological data from patients.

Wearable Devices and Inertial Sensors [2]: Wearable devices—such as smart wristbands, sensor-embedded insoles, and motion sensor modules—are equipped with various sensors, including triaxial accelerometers [3], gyroscopes [4], and magnetometers, to capture the patient's limb movements. These inertial sensors can quantify motor symptoms of Parkinson's disease (PD), such as measuring tremor frequency and amplitude, recording gait and balance data, and assessing the degree of bradykinesia. A typical implementation involves placing multiple sensors on different parts of the body (e.g., wrists, ankles), which transmit raw data streams to a processing unit via interfaces such as Bluetooth, enabling continuous monitoring of motor status.

Voice Acquisition Devices [5]: Patients with PD often experience speech impairments, including reduced volume, monotony, and slurred articulation. Smartphones or microphones can be used to record speech and extract acoustic features for diagnostic support. Studies have shown that analyzing prosodic features such as pitch variability and pause distribution in everyday speech can facilitate symptom monitoring. For instance, a collaborative project between Pfizer and IBM utilized smartphonebased sensors to record natural speech and analyze vocal patterns for disease monitoring. Similarly, the "Parkinson's Voice Initiative" enables early detection of vocal signs—such as vocal fold tremor and unstable respiration—by analyzing a simple sustained vowel sound ("aaaah") spoken into a smartphone.

Electroencephalography (EEG) [6]: EEG devices record cortical brain activity through head-mounted electrodes. In PD patients, neural network activity may exhibit specific abnormalities, such as altered rhythmicity or disrupted functional connectivity. EEG is considered a potential biomarker for PD, providing insight into brain function. For example, wireless multichannel EEG systems have been used to detect brain signal changes during walking tasks in PD patients, which can help predict motor disturbances such as freezing of gait (FOG). EEG is also employed to evaluate non-motor symptoms related to PD—such as sleep disturbances [7] and cognitive [8] impairment—offering objective quantification of disease stage and symptom severity.

Electromyography (EMG) [9]: Surface EMG sensors capture muscle electrical activity and are used to quantify muscle contractions and tremors. For PD patients, EMG assists in detecting the rhythmic muscle discharges associated with resting tremor, assessing muscle rigidity, and analyzing changes in muscle activity during movement initiation difficulties (bradykinesia). Wearable EMG sensors, especially those placed on the upper limbs, can be combined with analytical algorithms to identify PDspecific motor abnormalities. For instance, analyzing the spectral and amplitude characteristics of EMG signals allows for the identification of tremor cycles, differentiation between Parkinsonian and other types of tremors, and assessment of symptom severity.

In addition, pressure sensors [10]—such as pressure pads embedded in smart insoles—are used to measure gait and postural balance. Collectively, these sensors provide multimodal, objective data inputs that enable intelligent diagnostic systems to comprehensively evaluate the condition of patients with Parkinson's disease.

IV. Ontological Elements

In the developed system, the ontology covers both clinical and hardware-computational aspects, providing a semantic foundation for Parkinson's disease diagnostics. The ontology defines the following levels of concepts:

- Medical disease concepts: Parkinson's disease and related motor disorders (e.g., atypical parkinsonism, essential tremor, etc.).
- Symptoms and signs:
 - Motor: bradykinesia, resting tremor (4–6 Hz), rigidity, postural instability;
 - Non-motor: hyposmia, sleep disturbances, depression, cognitive impairment.
- Diagnostic indicators:
 - Gait parameters: step length (35–65 cm), gait cycle (0.9–1.5 s), variability > 5%;
 - Voice features: jitter > 1%, shimmer > 3.5%, formant F1 = 500–800 Hz;
 - *Wavelet features:* D3-level energy > 0.6, entropy > 1.2.
- **Diagnostic rules:** logical expressions derived from authoritative sources (e.g., UK Brain Bank criteria), such as: *if bradykinesia is present and one of the following symptoms (rigidity or tremor), then Parkinson's disease is diagnosed.*

• Hardware-accelerated computing concepts:

 FPGA module: Xilinx Zynq-7000 / Artix-7, up to 150 MHz, 32-threaded;



Figure 1. Integrated Parkinson's Disease Monitoring System Architecture with Multi-sensor Fusion and Semantic Cloud Analytics.

- *Preprocessing:* wavelet transform (Db6, level 5), filtering, normalization;
- GRU network: input = 64, hidden size = 32, 2 layers, latency < 2 ms/frame;
- FPGA resources: 12,000 LUTs, 28 BRAMs, 24 DSPs, total latency < 10 ms;
- Performance: 100+ signals/sec, power consumption < 1.2 W, accuracy ~95%;
- Task-to-block mapping: "gait \rightarrow wavelet", "voice \rightarrow GRU".
- Efficiency metrics:
 - Diagnostic accuracy: $\geq 93\%$;
 - Average response time: < 50 ms;
 - Idle power consumption: ≤ 0.5 W;
 - Compatibility: ARM, wearable and edge devices.

V. Knowledge Base Based on Voice Wavelet Features and GRU Analysis

In the proposed system, the knowledge base is constructed with a focus on the patient's voice data, as speech impairments are early and significant indicators of Parkinson's disease. Patients often exhibit monotonous speech, slowed tempo, unstable pitch, and increased pauses between words. To formalize such features, the system uses *discrete wavelet transform (DWT)* to extract multilevel temporal features, followed by a *GRU-based recurrent neural network* for dynamic sequence analysis. The extracted features and classification results are semantically integrated into the knowledge base built on the OSTIS platform.

1. Semantic Modeling of Voice Features

The patient's voice signal is segmented into frames (25 ms, step 10 ms), then processed using DWT decomposition (db6, 5 levels). From each level, the following features are extracted:

- Wavelet coefficient energy (e.g., D3: E = 0.74);
- Entropy of coefficients (H = 1.21);
- Waveform length and signal norm (L = 0.96).

These values are transformed into knowledge base instances linked to ontological concepts, for example:

- wavelet_energy_D3 = 0.74 → "high frequency activity";
- wavelet_entropy_D2 = 1.21 → "signal instability".

2. GRU-Based Recognition and Logical Inference

The extracted features are input into a pre-trained GRU model with the following parameters:

- Input: 75-dimensional feature vector (per frame);
- Hidden units: 32, 2 layers;
- Output: binary classification (normal / pathological);

• Model accuracy: 95.2% (tested on an open dataset).

If the GRU model detects suspicious speech activity, a semantic node such as "possible Parkinsonian speech" is generated in the knowledge base, linked to relevant symptoms (monotony, tremor, articulation degradation). For example:

• GRU_output = 1, confidence = 96.2% → "probable pathological speech".

3. Hardware Acceleration and Interface with the Knowledge Base

The system uses FPGA-based acceleration for voice data processing:

- Platform: Xilinx Artix-7 (XC7A100T);
- Frequency: 100-150 MHz;
- Resource usage: 18 DSPs, 12000 LUTs, 20 BRAMs;
- Processing latency per frame: ≤ 2.1 ms.

Wavelet features are grouped into packets and sent to the embedded processor for GRU inference. After classification, the data are automatically integrated into the OSTIS SC-graph as facts and semantic relationships.

VI. Hardware-Accelerated Processor Module for Intelligent Biosignal Analysis

The processor module serves as the computational core of the system, responsible for high-efficiency realtime processing and analysis of biosignals received from the patient. Considering the requirements of Parkinson's disease diagnostics, the processor must handle various types of biosignals, particularly voice and gait data obtained via wearable sensors (e.g., accelerometers). To achieve high performance, low latency, and energy efficiency, the system employs a *hardware-software codesign* architecture: core computations are performed on an **FPGA**, while control logic runs on a CPU or microcontroller (MCU).

The module includes three functional submodules, integrated in a pipelined structure on the FPGA:

3. GRU Recognition Module

• GRU Architecture:

- Input: 75 features;
- Hidden state: 32 units;
- Network depth: 2 layers;
- Activation functions: tanh, sigmoid;
- Implementation: fixed-point arithmetic (Q8.8), streaming scheme using Vitis HLS;
- Average latency: 2.4 ms per input segment;
- Resource usage: 14,800 LUTs, 28 DSPs, 18 BRAMs.



Figure 2. Hierarchical structure of the GRU inference design in Vitis $\ensuremath{\text{HLS}}$

Figure 2 shows the hierarchical hardware implementation of GRU inference in the Vitis HLS environment. Each component of the recurrent neural network including matrix multiplication, addition, activation functions (tanh, sigmoid), and hidden state updates is decomposed into dedicated hardware modules. This modular design enables efficient parallel execution and high-speed inference on the FPGA.

Data Exchange and Interaction with Other Modules

The processor module communicates with the knowledge base and the user interface via an AXI interface:

- At the start of analysis, the UI sends a command to the CPU to initialize the sensors;
- Extracted features and GRU results are transferred to the knowledge base as factual nodes (e.g., "D3 energy = 0.74", "speech pathology probability = 96.2%");
- The diagnostic result is displayed in the interface as a textual conclusion;
- In expert mode, full access to all intermediate feature values is available.

A. Functional Verification and Experimental Results

This section presents the verification of the computational modules implemented on a Xilinx FPGA using the Vitis HLS tool. The hardware design includes two accelerated components: wavelet feature extraction and GRU analysis. The wavelet transform, based on a Daubechies-6 (db6) wavelet, performs a four-level decomposition of triaxial accelerometer data. Five statistical features (entropy, energy, variance, standard deviation, and waveform length) are extracted at each level, forming a 75-dimensional gait feature vector. To ensure real-time performance, several HLS-level optimizations were applied: pipelining, dataflow, and fixed-point arithmetic. The GRU model is implemented as a two-layer network with pre-trained and fixed parameters, enabling efficient inference on FPGA. Experimental results confirmed that both modules meet the performance, energy, and latency requirements for embedded systems.

To validate the wavelet feature module, C simulation (CSIM) of the HLS code was performed. Figure 3 shows the simulation output log, which captures the feature_out values computed for different signal windows. Each window corresponds to a specific segment of the input signal, and the resulting features provide insight into its time-frequency characteristics.

The CSIM simulation completed successfully without errors, confirming the functional correctness of the wavelet feature algorithm in HLS.

TNED- ISTM 21 ***********************************
SINFO: [SIM 4] CSIM will launch GC as the compiler
Imake: 'csim.exe' is up to date.
August Feature Out sizes
SWindow 0:
<pre>6 feature out[0][0] = 5.58064</pre>
<pre>7 feature out[0][1] = -12.1227</pre>
<pre>8 feature out[0][2] = +6.06135</pre>
<pre>9 feature out[0][3] = -1.0418</pre>
<pre>10 feature out[0][4] = 1.67323</pre>
llWindow 1:
<pre>12 feature_out[1][0] = 5.59485</pre>
<pre>13 feature_out[1][1] = -12.1269</pre>
14 feature_out[1][2] = -6.06343
<pre>15 feature_out[1][3] = -1.04697</pre>
16
17 Window 2:
<pre>18 feature_out[2][0] = 5.57957</pre>
<pre>19 feature_out[2][1] = -12.1075</pre>
<pre>10 feature_out[2][2] = -6.05374</pre>
<pre>11 feature_out[2][3] = -1.03515</pre>
<pre>22 feature_out[2][4] = 1.67128</pre>
23Window 3:
<pre>14 feature_out[3][0] = 5.56318</pre>
<pre>25 feature_out[3][1] = -12.0999</pre>
16 feature_out[3][2] = -6.04996
<pre>17 feature_out[3][3] = -1.05637</pre>
<pre>18 feature_out[3][4] = 1.67044</pre>
29 Window 4:
<pre>feature_out[4][0] = 5.57666</pre>
<pre>31 feature_out[4][1] = -12.1184</pre>
<pre>12 feature_out[4][2] = -6.05919</pre>
<pre>feature_out[4][3] = -1.04248</pre>
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15 Window S:
<pre>16 feature_out[5][0] = 5.59449</pre>
<pre>17 feature_out[5][1] = -12.1291</pre>
<pre>18 feature_out[5][2] = -6.06457</pre>
<pre>5 feature_out[5][3] = -1.04254</pre>
<pre>feature_out[5][4] = 1.67392</pre>
1Window 6:
<pre>42 feature_out[6][0] = 5.58349</pre>
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+eature_out[b][2] = -6.05513
<pre>teature_out[6][3] = -1.03111</pre>
<pre>teature_out[6][4] = 1.6/143</pre>
INFU: [SIM I] CSIM done with 8 errors.

Figure 3. Verification of the wavelet feature extraction module

Similarly, the GRU (Gated Recurrent Unit) module was verified using HLS simulation (CSIM). Figure 4 shows the simulation log, including the compilation of gru_dense.cpp and test_gru_dense.cpp and the execution of csim.exe. The final computed values confirm the correct operation of the algorithm.

This module performs hidden state computations in a recurrent neural network, which is critical for temporal data processing. The CSIM test completed successfully without any errors, confirming the model's correct behavior in the HLS environment.

INFO: [SIM 2] ***********************************
INFO: [SIM 4] CSIM will launch GCC as the compiler.
Compiling///test_gru_dense.cpp in debug mode
Compiling///gru_dense.cpp in debug mode
Generating csim.exe
Final output: 0.938436 0.0615642
INFO: [SIM 1] CSim done with 0 errors.
INFO: [SIM 3] ********************** CSIM finish ************************************

Figure 4. Verification of the GRU inference module

Additionally, Figure 5 presents the hardware-software interface diagram of the wavelet feature extraction module. It shows the main hardware interfaces (HW Interfaces) and their corresponding software call parameters (SW I/O Mapping). The input data input_x and h_prev are processed via AP_MEMORY, and the computed results (feature_out) are stored in the appropriate memory ports of the FPGA. Figure 6 shows

the hardware-software interaction diagram of the GRU module. It depicts the main input parameters (input_x, h_prev) and output parameter (final_output), their mapping to the FPGA hardware interfaces, as well as memory resources and control signals (ap_ctrl). The results demonstrate that the developed module was successfully synthesized and can be further optimized for hardware deployment. Both software models passed functional testing at the CSIM stage without errors, confirming that:

1.Algorithm correctness: The wavelet feature and GRU inference algorithms worked correctly at the HLS level without functional errors.

2.Interface compliance: Software interfaces were successfully mapped to FPGA hardware resources, ensuring correct addressing and control. 3.Stable data transfer: Communication between software and hardware via AP_MEMORY and control signals (ap_ctrl) was reliable and loss-free.

1.1				
Interface		Bitwidth		
final outp	ut_address0	1		
final outp	ut_d0	32		
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h prev ad	dress1	3	ļ	
h_prev_q0		32		
h_prev_q1		32		
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Figure 5. Hardware interfaces and software mapping of the GRU computation module

			1	
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eature out	_d0	64		
lignals add	ress0	13	ł	
signals_q0		64		
TOP LEVEL	CONTROL			
nterface	Туре	1		Ports
ip cik	clock			ap cik
p rst	reset			ap_rst
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Figure 6. Hardware interfaces and software mapping of the wavelet feature extraction module

VII. Conclusion

This paper presents an IT-based diagnostic system for Parkinson's disease based on the OSTIS platform, combining semantic knowledge representation with hardware-accelerated signal processing. The system integrates an ontology and knowledge base for interpreting medical concepts, along with FPGA-based modules for wavelet feature extraction and GRU-based neural analysis. Its modular architecture includes a knowledge base, a processor core, and a user interface. Verification results confirmed that the system achieves high efficiency and accuracy in symptom analysis and diagnostic decisionmaking.

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АППАРАТНЫЕ СРЕДСТВА В ИНТЕЛЛЕКТУАЛЬНОЙ СИСТЕМЫ ДЛЯ ДИАГНОСТИКИ БОЛЕЗНИ ПАРКИНСОНА

Вишняков В.А., Ивей С.

В этой статье предлагается ИТ-система диагностики болезни Паркинсона, основанная на платформе OSTIS. Система сочетает предметную онтологию и базу знаний для формального представления и управления медицинской информацией, связанной с заболеванием. Для обеспечения анализа данных пациента в реальном времени в систему интегрирован специализированный модуль обработки на базе ПЛИС (FPGA). Извлечение и анализ двигательных признаков осуществляется с помощью дискретного вейвлет-преобразования и рекуррентной нейронной сети с блоками GRU. Аппаратная реализация выполнена с использованием инструмента Xilinx Vitis HLS, что обеспечивает эффективное внедрение вычислительных модулей. Предварительные эксперименты на открытых наборах данных показали, что система достигает точности распознавания около 95% при анализе речевых и моторных паттернов, характерных для болезни Паркинсона.В результате использования ПЛИС, обработка ускорилась в 20 раз по сравнению с реализацией на СРU.

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Hardware Support in an Intelligent IT Diagnostic System for Alzheimer's Disease

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Abstract—The report presents an integrated intelligent diagnostic framework combining semantically oriented knowledge representation based on ontologies, hardware acceleration using FPGA and OSTIS concepts in order to increase the efficiency of real-time processing for IT diagnostics of patients with Alzheimer's disease. An ontology has been developed for such patients, on the basis of which a knowledge base, a solver and an intelligent interface are presented. An FPGA accelerator is proposed, due to which an intelligent IT diagnostic system for patients with ASTHMA provides efficient collection, preprocessing, feature extraction and semantic analysis of voice data, which reduces diagnostic delays and increases decision-making efficiency by about an order of magnitude. The developed ontologies are consistent with the semantic requirements of the OSTIS knowledge management concepts. The developed hybrid CPU-FPGA architecture and the proposed user interface integrate knowledge base queries, hardware management, real-time monitoring and diagnostic conclusion, demonstrating improved user interaction, semantic transparency and operational efficiency.

Keywords—ontology, Alzheimer's disease, semantic representation of knowledge, solver, knowledge base, intelligent interface, FPGA accelerator.

I. Introduction

At the present stage, Alzheimer's disease (AD), as the most common neurodegenerative disorder among the elderly population, has become a critical topic in the field of global public health [1]. An annual report released by the Alzheimer's Association, reveals the burden of Alzheimer's and dementia on individuals, caregivers, government and the nation's health care system [2], in 2024, Alzheimer's and other dementias will cost the nation 360 billion dollars, by 2050, these costs could rise to nearly 1 trillion dollars. Currently, diagnostic technologies for AD are undergoing a transformation from traditional clinical assessments to intelligent and digitalized frameworks.

Mainstream IT-based diagnostic approaches for AD currently integrate information technology with medical science. The primary methods and applications include deep learning-based medical imaging analysis, multi-modal data fusion, digital cognitive assessment tools, voice and language analysis (NLP technologies) [3]. The development of an intelligent IT diagnostic system for

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AD, based on these mainstream methods, involves eight key stages: requirement analysis and planning, data acquisition and management [4], data preprocessing and feature engineering, among others. Based on the OSTIS platform, an IoT network architecture [5] is adopted to construct domain-specific semantic knowledge ontologies for AD, along with corresponding solvers and user interfaces, thereby enabling efficient voice data acquisition, processing, and semantic analysis to support early clinical diagnosis and intervention.

In the construction of an intelligent IT diagnostic system, hardware support is a fundamental requirement for data acquisition, real-time monitoring, and largescale computation. Medical imaging (such as MRI and PET) cannot be achieved without hardware support from imaging devices in clinical settings [6], hardware accelerators such as FPGAs, equipped with programmable logic arrays, can execute convolutional operations, matrix multiplications, and other tasks in parallel, significantly reducing inference latency and power consumption [7].

OSTIS, as an open semantic technology framework designed for the development and implementation of intelligent systems, aims to reduce the complexity of interaction among heterogeneous computing systems by offering unified knowledge representation and a semantically compatible infrastructure, thereby facilitating knowledge sharing and collaborative reasoning. Given the realtime and high-efficiency requirements of data processing in medical diagnostic scenarios, the introduction of a hardware-software collaborative architecture provides a novel implementation pathway for OSTIS-based systems. This paper aims to present a framework that integrates hardware acceleration with intelligent information processing, incorporating medical ontologies and knowledge bases to support diagnostic decision-making for Alzheimer's disease.

II. The Ontology

Ontology, as a tool, enables the formal and logical definition and classification of knowledge and concepts within a specific domain. By defining the attributes of domain-specific concepts and their interrelationships, ontology supports semantic linking and understanding between data, allowing computers to identify and reason about domain knowledge.

OSTIS (Open Semantic Technology for Intelligent Systems) is closely related to ontology [8]. It focuses on the design and operation of semantically compatible hybrid intelligent computing systems, employing onto-logical methods for structured knowledge representation and semantic standardization. It offers the technologies and tools necessary for building, managing, and utilizing knowledge graphs.

In intelligent systems for Alzheimer's Disease (AD) diagnostics, speech processing is one of the key sources for obtaining pathological clues from patients. Under the OSTIS technical framework of hardware-software co-design, ontology serves as a semantic knowledge representation tool. On the one hand, it provides standardized domain concepts and terminology to support medical term disambiguation, text feature extraction, and semantic relationship construction on the CPU side, ensuring consistency in data semantic representation. On the other hand, ontology clearly defines the relationships and reasoning rules among medical concepts, enabling the FPGA side to perform parallel reasoning and classification decisions based on structured knowledge. The semantic and data organization foundations provided by the following ontologies allow the system's hardware modules to work collaboratively with software and data in various stages of speech acquisition, preprocessing, feature extraction, and machine learning inference, while ensuring compliance and traceability within clinical settings.

Patient Voice Characteristics Ontology

- := [Define and describe the patient voice characteristics associated with the diagnosis of Alzheimer's Disease (AD).]
- [Provides a structured description framework for sound data, ensuring that the collection, storage, and sharing of sound data all follow a set of clear standards.]
- \ni Characteristics of a sound sample
- \Rightarrow includes*:
 - Pitch
 - := [The degree of highness or lowness of a sound, typically measured in Hertz (Hz).]
 - Volume
 - Rhythm
 ⇒ incli
 - includes*:
 - Speech rate
 - Pause frequency
 - Overall voice dynamics
 - }

- Pause Duration
- Speech Clarity
- Timbre
- Speech Coherence
- The change of sound
- }

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Description of the Data Collection Environment includes*:

- Background Noise Level
- Recording Device Type
- Recording Format
- Recording Environment
- Recording Session Duration and Timing
- Recording Distance and Angle
- Speaker's Position and Posture
- }

Patient's basic information

- includes*:
 - $\{\bullet Age$
 - Gender
 - Stage of Disease
 - Educational Background
 - Language Habits
 - Health Status
- }

Patient Voice Characteristics Ontology clearly defines the key features of patient voice data (e.g., pitch, volume, rhythm, speech clarity), recording environment parameters, and basic patient information. Based on this ontology, hardware can be configured accordingly in terms of fixed-point/floating-point formats, register bit-widths, and estimated data throughput. Since the ontology specifies the semantics and units of each feature, hardware and software components such as drivers and register mappings can adopt consistent field identifiers, thereby avoiding issues related to data misalignment or naming conflicts.

Based on the clear definition of voice data characteristics, the "Voice Sound Processing Rules Ontology" delineates the entire pipeline of voice data processing—from acquisition, segmentation, and denoising to feature extraction, algorithmic analysis, and result validation. Through the key algorithm identifiers within the ontology, the hardware layer can pinpoint the functional modules to be implemented and assess the resource requirements of each algorithm. This ontology not only directly guides the selection of algorithms and the design of functional modules necessary for hardware acceleration, but also reserves a well-defined semantic space and data interfaces for future system extensions, such as the integration of novel machine learning algorithms or emotion analysis modules.

Voice Sound Processing Rules Ontology

- [Describes the specific rules and methods for := processing and analyzing patient voice data.]
- [Focused on the procedures and rules for pro-:= cessing sound data, with the aim of ensuring consistency and accuracy in data analysis.]

subdividing*: \Rightarrow

- Feature Extraction Methods {∙
 - [How to extract useful information := or features from raw sound data.]
 - includes*: \Rightarrow
 - Spectral Analysis {∙
 - Time-Domain Analysis
 - Cepstral Analysis
 - Morphological Feature Extraction

- Voice Analysis Algorithms
 - [Analyze these features to identify := patterns related to diseases.]
 - includes*: \Rightarrow
 - **{•** Machine Learning Algorithms

 \Rightarrow includes*:



- Identification
- **Emotion Analysis**
- Data Cleaning and Preprocessing
 - := [Ensure data quality]
 - \Rightarrow includes*:
 - Noise Reduction {∙
 - Voice Segmentation
 - Normalization

- Evaluation and Validation
 - [Ensure the effectiveness and reli-:= ability of the analysis methods]
 - includes*: \Rightarrow
 - Cross-Validation **{•**
 - **Performance Metrics**
 - ⇒ includes*:
 - **{•** Accuracy
 - Recall
 - Precision
 - F1 Score

III. Proposed Approach

A. Development of the Solver and Knowledge Base.

A knowledge base is a broad term referring to an electronic repository for storing knowledge information, which can be structured or unstructured, including text documents, databases, images, videos, etc. Figure 1 illustrates the complete knowledge engineering process from concept collection and requirements validation to ontology construction, knowledge base application, and maintenance, realizing end-to-end modeling of "domain knowledge to hardware-driven execution" within an intelligent system. The process includes four main phases: Coordination Phase, Establishment Phase, Application Phase, and Maintenance Phase.



Figure 1. Ontological Engineering Architecture Diagram

The Coordination Phase emphasizes continuous communication between knowledge engineers and domain experts. Knowledge engineers are responsible for formalizing the experts' knowledge into ontologies, while domain experts provide core knowledge such as diagnostic experience, domain terminology, and data usage logic.

The Establishment Phase is the core of the process, forming the main development workflow for ontologies. It defines the objectives of ontology construction (e.g., for AD voice diagnostics), its scope (e.g., covering voice and semantics, excluding vision or behavior), and specific technical/data/interaction requirements. Based on domain expert input and literature review, core concepts related to the modeling objective are systematically collected and modeled-such as "voice features," "pause duration," and "FPGA feature extraction module." The collected concepts undergo structural analysis to identify their relationships (e.g., is-a, part-of, used-by, measured-in), and a hierarchical concept structure is built. The constructed ontology structure is then imported into the system to interface with the knowledge base and other applications. This stage can be seen as a "coding" phase, where ontological concepts are represented in a formal, machine-readable format (e.g., SC-code).

The final output of the Establishment Phase is the Ontology, which comprises two subclasses: Information Ontology and Domain Ontology. Together, these ontologies form the semantic backbone of the entire knowledge architecture—interfacing downward with the knowledge base and upward with diagnostic logic, rules, and interaction definitions.

Ontologies and knowledge bases are reciprocate—ontologies define the semantic structures for the knowledge base, while actual data in the knowledge base can feed back into the refinement and expansion of the conceptual system. In the knowledge base storage system, concept instances defined by the ontology correspond to real data, such as:

- 1) Structured voice feature data (e. g., pitch=150Hz, pause_duration=0.7s);
- 2) Hardware configuration files (e. g., FPGA register allocation, interface specifications);
- 3) Medical records, expert diagnostic criteria, etc.

The Application Phase represents the front-end where end users interact with the system, such as doctor terminals, hardware monitoring interfaces, and AD diagnostic dashboards. It retrieves the necessary inference information from the knowledge base and provides intelligent assistance to hardware algorithm modules, diagnostic engines, or clinical interfaces.

The system also generates new data and rules (e. g., high-risk features newly identified by models), which are fed back into the knowledge base, forming a cycle of knowledge enrichment.

The Maintenance Phase allows knowledge engineers or technical experts to perform dynamic updates, offering graphical interfaces or toolkits for maintaining the ontology structure, updating conceptual definitions, and fixing semantic errors, thus adapting to evolving medical standards, hardware changes, or new modules.

The foundation of the ostis-system problem solver is a set of agents (sc-agents) that interact solely through information processing rules executed within the semantic memory [9]. As a multidimensional, multilingual, layered, and nestable collection of sc-agents, it provides a clear hierarchical structure and flexible nesting mechanism, enabling seamless alignment from high-level functional requirements to low-level executable procedures, ensuring efficient, flexible, and scalable complex problem-solving capabilities.

The following problem solver description outlines how processes such as feature extraction, reasoning, and result synthesis are accelerated using FPGA hardware, and how the hardware interacts with the ontology and knowledge base.

FPGA Problem Solver for AD Diagnostic System

:= [sc-mode of the ostis-system problem solver with hardware acceleration]

Decomposition*:

 \Rightarrow

- **{•** sc-agent for input data acquisition
- \Rightarrow Decomposition*:
 - **{•** sc-agent for identifying data type
 - sc-agent for receiving raw data
 - *sc-agent for synchronizing with the hardware interface*
 - sc-agent for storing raw data into the knowledge base
 - }
- sc-agent for FPGA-accelerated data processing
- \Rightarrow Decomposition*:
 - **{•** sc-agent for data preprocessing
 - \Rightarrow Decomposition*:
 - sc-agent for noise reduction
 - sc-agent for tokenization/segmentation
 - sc-agent for basic transformations
 - sc-agent for feature extraction
 - \Rightarrow Decomposition*:

ł

- {• sc-agent for TF-IDF computation
- sc-agent for
 - dimensionality reduction
- sc-agent for fixed-point quantization / converting data format for FPGA
- }
- sc-agent for FPGA pipeline control
- \Rightarrow Decomposition*:
 - {• sc-agent for uploading model parameters
 - sc-agent for running inference on FPGA
 - sc-agent for reading back results
 - sc-agent for optimizing FPGA resource usage
 - sc-agent for storing intermediate results
- } sc-agent for inference and reasoning

Decomposition*:
- **{•** sc-agent for random forest voting
- sc-agent for comparing results with knowledge base thresholds
- sc-agent for final classification (AD / non-AD)

}

• sc-agent for results output

 \Rightarrow Decomposition*:

- sc-agent for retrieving classification outcome from the knowledge base
- sc-agent for generating explanation
- sc-agent for natural language generation / UI display

}

B. Designing the User interface.

}

In terms of interactive interface design, during the data presentation stage of the diagnostic network, referring to article [10], the authors considered factors such as the user interface concept within the OSTIS ecosystem and adopted a component-based approach to design an adaptive intelligent multimodal interface for the OSTIS system.

At the current stage, OSTIS primarily functions as a 'semantic web/knowledge graph visualization editor,' allowing users to draw concepts, define relationships, and perform basic reasoning operations within the platform. The logical design concept of this interactive interface is described in scn-code as follows:

Hardware-Supported Diagnostic Interface for AD

- := [HCI page that allows real-time data acquisition from FPGA, performs hardware-accelerated inference, and displays final results]
- \Rightarrow Decomposition*:
 - Non-atomic UI components
 - \Rightarrow Example*: Inclusion*:

}

- **{•** *Hardware Control Panel*
- \Rightarrow Example*: Inclusion*:
 - Start Hardware Button
 - Stop Hardware Button
 - Config Hardware Button
 - Hardware Status Indicator

Data Acquisition & Monitoring Panel
 ⇒ Example*: Inclusion*:

- {
 Audio/Voice Input Button
 - Realtime Waveform Display
- FPGA Processing Throughput Indicator

- Diagnostic Inference Panel
- \Rightarrow Example*: Inclusion*:
 - **{•** *Predict AD Button*
 - Show Confidence Score Checkbox
 - Additional Explanation Toggle
 - .
- Knowledge Base / Ontology Access Panel
 ⇒ Example*: Inclusion*:
 - Query Existing Records Button
 - Show Concept Graph Button
 - Export Results to Knowledge Base Button
 - }

}

}

- Atomic UI components
- \Rightarrow Example*: Inclusion*:
 - Logs & Alerts Area
 - Final Diagnosis Display Area

IV. FPGA accelerator

In practical implementation, the authors proposed an FPGA-based hardware accelerator aimed at addressing the performance bottlenecks of random forest classification models in intelligent text analysis tasks when executed on traditional CPU and GPU platforms. The FPGA accelerator is specifically designed to perform inference of the random forest algorithm, targeting scenarios characterized by constrained resources, real-time requirements, and low power consumption, such as those found in edge computing environments.

To effectively adapt to the resource limitations inherent to FPGA platforms, the authors applied a lightweight algorithmic design strategy on the hardware side. This included significant dimensionality reduction of feature vectors as well as quantization of floating-point values into fixed-point representations. These design choices reduced the consumption of FPGA logic resources and improved computational efficiency by eliminating the need for costly floating-point arithmetic units.

Regarding architectural design, the FPGA accelerator employs a combination of parallelism and pipelining. Each decision tree within the random forest is implemented in parallel on the FPGA, enabling independent execution of inference operations. The final classification result is obtained through a majority voting scheme. Furthermore, the inference process within each tree is pipelined, with threshold comparisons and feature evaluations conducted using efficient fixed-point operations, thereby further reducing latency.

During hardware implementation, the authors utilized high-level synthesis directives provided by the Vitis HLS development environment—such as #pragma HLS PIPELINE and #pragma HLS UNROLL—to automate pipelining and enhance intra-module parallelism. The FPGA communicates with the CPU via AXI-Lite or memory-mapped interfaces, simplifying data exchange and facilitating system integration between hardware and software components.

The study also devoted attention to evaluating resource utilization and performance of the implemented accelerator. Synthesis results showed moderate consumption of logic elements (LUTs), flip-flops (FFs), and DSP blocks, with sufficient remaining resources available on the FPGA for potential future expansions. Additionally, performance measurements conducted in the Vitis HLS environment revealed a theoretical acceleration ratio of approximately 427,840×. However, this figure represents an idealized estimate, as it compares a simulated software environment with pure hardware execution and does not account for practical factors such as I/O latency.

V. Conclusion and future works

In the report, the authors integrate the OSTIS «semantic layer-knowledge base-problem solver» hybrid intelligent approach with hardware resources such as FPGA, introducing a novel technical framework characterized by high efficiency, low latency, traceability, and scalability for Alzheimer's disease diagnostic scenarios. The described "hardware + software" pipelined collaborative model emphasizes interaction between the ostis-system semantic framework and sc-agent components. For practical engineering implementation, each sc-agent can be regarded as a software task module running on the CPU side, paired with parallel computing or inference units on the FPGA, thereby constructing a hybrid pipeline from data acquisition to inference output. Future research directions may focus on further algorithmic optimization, expanded multimodal data integration, and large-scale clinical validation to reinforce the clinical effectiveness and applicability of the proposed system.

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АППАРАТНАЯ ПОДДЕРЖКА В ИНТЕЛЛЕКТУАЛЬНОЙ СИСТЕМЕ ИТ-ДИАГНОСТИКИ БОЛЕЗНИ АЛЬЦГЕЙМЕРА

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В докладе представлен интегрированный интеллектуальный диагностический фреймворк, сочетающий семантически ориентированное представление знаний на основе онтологий, аппаратное ускорение с использованием FPGA и концепции OSTIS с целью повышения эффективности обработки в реальном времени для ИТ-диагностики пациентов с болезнью Айцгеймера. Разработана онтология для таких пациентов, на основании которой представлены база знаний, решатель и интеллектуальный интерфейс. Предложен FPGAускоритель, за счет которого интеллектуальная система ИТ-диагностики пациентов с БА обеспечивает эффективный сбор, предварительную обработку, извлечению признаков и семантический анализ голосовых данных, что позволяет сократить задержки в диагностике и повысить оперативность принятия решений, примерно на порядок. Разработанные онтологии согласованы с семантическими требованиями концепции OSTIS. Разработанная гибридная архитектура CPU-FPGA, и предложенный пользовательский интерфейс интегрирует запросы к базе знаний, управление аппаратными средствами, мониторинг в реальном времени и диагностическое заключение, демонстрируя улучшенное взаимодействие с пользователем, семантическую прозрачность и операционную эффективность.

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Intelligent Automation of Telegram Processing Processes for Adjusting the Normative Train Schedule

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Abstract-The article deals with the technologies of robotic process automation and intelligent automation used in JSC "Russian Railways", technological aspects of adjusting the normative train schedule. The technology of interaction between the APC ELBRUS hardware-software complex, the automated system GID "Ural-VNIIZhT" and the Centralized database of freight train timetables for the task of maintaining the normative train schedule is considered. Examples of operating software robots and chatbots (virtual consultant) in corporate information systems operated in traffic control directorates are presented. Projects using artificial intelligence technologies are presented. The identified and actual problems of support of the technology of maintaining normative schedules of goods trains are described. The analysis and selection of means of intellectual automation of processes and intellectual processing for text recognition in telegrams are carried out. Problems of binary image segmentation and Python programming language libraries for processing and analysis of telegrams using methods of recognition and conversion of incoming information for intelligent process automation are considered. Prospects of development of automation of maintenance processes using software and intelligent robots are defined.

Keywords—intelligent automation, normative train schedule, segmentation, software robots, telegram processing, virtual consultant.

I. Introduction

In large organisations, due to large data flows from various information systems, employees spend a significant amount of time processing and analysing information. Scripts, software robots, macros and chatbots help to facilitate such work - such individual solutions require human participation for their successful operation, rather than performing complex automation.

Active implementation of digital assistants occurred at the beginning of the second decade of the XXI century, such a growth in popularity of these technologies is due to the fact that the processes that users perform are associated with a significant amount of repetitive routine operations to support users and fill out documents. The main criterion for automating processes is the availability of incoming structured data with the ability to build an algorithm and scenario for its solution [1], [14]. An important aspect of modern information and technical systems is their real-time operation. Automated systems and programmed must ensure the achievement of set goals and at the same time have logically coordinated actions. For this purpose, it is necessary to preliminarily realise the performance of a set of preparatory operations, which are used by monitoring tools. Such realtime systems and programmed are divided into reactive and active. For example, the system "job scheduler" has an active character, where the moments of achievement time are already set, as opposed to systems that react to external events (are in a cycle of waiting for external events).

The concept of software robots is based on application programming interfaces (APIs). Robots are divided into unattended robots, where the robot performs work without human intervention, and attended robots, where user interaction with the robot is required to keep it running. RPA robots use a software algorithm to enter data and navigate through screen forms using integrated desktop technology, which automatically consolidates data from various disparate sources and performs end to-end data processing based on reconfigured algorithms.

II. Analysis of problems in correcting incoming telegrams

The prerequisites for the digital transformation of the transport industry were the rapid development of technology and its impact on process efficiency, the need to reduce labour costs and online interaction [2]. Examples of robotisation include the optimisation of the analysis of employee requests in the data set system and their modification - "Administration of internal users: creation, renewal and blocking of accounts". Thus, 90 percent of 30,000 appeals were processed by the robot and the turnaround time was reduced from 48 to 6 hours [1]. At the information and computer centres of JSCo "Russian Railways", the RPA robot generates daily reports on train interval violations uploaded from the automated system "Ural-VNIIZhT". Reduction of labour costs has been achieved due to the work of the software robot script interacting with a macro in Visual Basic for Application language to generate the report and using integrated C Sharp program code. The software robot analyses the previously downloaded data to exclude redownloading in case of a failure in the execution of the script.

The processing of telegrams for adjustments to the normative train schedule includes part of the tasks that are effectively solved by robotising the processes. Telegrams containing information on necessary adjustments to the normative train schedule are received by the Unified Automated Document Management System (UDMS), the Unified User Support Service Management System (UUSMS) and e-mail [3]. The timetable must be uploaded to the automated system for the construction of daily energy-saving train schedules - APC ELBRUS and automated system GID "Ural-VNIIZhT" - promptly, before the specified time, as it is automatically uploaded daily to the Centralized database of freight train timetables to keep the data up-to-date. If the upload occurs later, there will be a discrepancy in the regulatory train schedule information between the automated system GID "Ural-VNIIZhT" and the automated system "Information Repository for the Analysis of Schedule Execution", as the last automated system displays the schedule from the Centralized database of freight train timetables [3].

For the period from 2022 to 2024, an analytical analysis of data on incoming telegrams to the corporate information systems of JSCo "Russian Railways" was carried out. It was found that a greater flow of telegrams to adjust trains is received due to the change of commuter and passenger train traffic due to the onset and end of the summer schedule, maintenance work, and at the beginning of each year due to the formation of a new annual schedule. In order to improve efficiency indicators and accurate planning, a programme was developed that uses software tools to analyse current information in existing systems so that automated systems work in an integrated manner and provide full automation of production processes. Design and testing of a software solution for identification and monitoring of objects in information-corporate systems and electronic mail system containing telegrams to adjust train schedules was performed.

Thus, the programmed developed with the help of RPA ROBIN means for tracking the receipt of telegrams on adjustment of the normative schedule of goods trains with loading in APC ELBRUS - has both active and reactive character depending on the user's work at the computer and has the following functions:

- monitoring of incoming requests with a search for requests to adjust the normative train schedule;
- saving telegrams in a folder with their subsequent processing by a programmed implemented in the Python programming language;

• loading of the processed document into the APC ELBRUS.

When developing the script and program code, ROBIN eliminates the possibility of code tampering at runtime because the robot script is encrypted and protected from unauthorised access. The software code is compiled once during the creation of the action, rather than each time it is run for execution, ensuring that the code is unchanged when the software robot is run. The description of the stages of the telegram tracking process is described in the article on automating the processes of adjusting the normative train schedule in the automated system GID "Ural-VNIIZhT" using software robots, as well as in the article on using software robots to track the arrival of telegrams and interact with the automated system for building predictive energy-saving train schedules [2], [4].

Robotic process automation implements a number of specific tasks to offload data from systems, monitor and alert users according to a certain scenario, but complex automation requires the development and use of new technologies as robotic process automation is prone to robot failure and inability to analyse data [5], [26]. The main problems with RPA are system updates or changes that can lead to software robot failure and the involvement of a developer to change or refine the robot script, which in turn is unacceptable for real-time information and automation systems.

III. Utilising intelligent automation

Intelligent automation technology can solve this problem. The new approach to process automation includes the use of technologies with artificial intelligence. This approach helps to increase the efficiency of information and computing facilities. When considering the development and synergies of intelligent automation, the following epochs of technology development can be distinguished:

- Integrated Business Process Management Systems: Business Process Management System (BPMS), Business Activity Monitoring (BAM), process modelling, integration of applications and automated systems.
- 2) Advanced modelling: BPM system, Business Process Model and Notation (BPMN), simulation modelling, organisational design, enterprise architecture.
- Intelligent business process management systems: Integrated communications, cloud storage, chatbots, low-code platforms.
- Robotic technology and case management: Robotic Process Automation (RPA), Decision Model and Notation (DMN), Case Management Model and Notation (CMMN), decision support systems, case management.

 Digital technologies for business process management: AI machine learning, predictive service, speech recognition, microservices.

The information systems used railway transport receive a large flow of documents and telegrams from various sources - information and corporate systems. Since the technologists of these systems take a lot of time to process this information, the application of process automation should be considered.

The paper considers the application of robotisation with elements of intelligent automation in the processing of telegrams to adjust the normative train schedule in the automated system GID "Ural-VNIIZhT".

The basis for telegrams is the formation of new trains for the redeployment of wagons and the identification of errors in the schedule as a result of the triggering of control in the automated system GID that require prompt correction [3], [4].

According to information from incoming telegrams, technologists of information and computer centres maintain the standard timetable in the systems: APC Elbrus and automated system GID "Ural-VNIIZhT" in order to promptly update and update the standard timetable. APC Elbrus solves the tasks of building forecast energy-saving train schedules for railway polygons, taking into account inter-road junctions on the basis of simulation modelling [2]. The standard schedule is the organisational and technological basis for the work of many railway departments and must ensure the efficient use of station capacity, compliance with the established continuous work of locomotive crews, and the possibility of carrying out works on the current condition and repair of the track. The organisation of train traffic is regulated by the normative schedule, while the actual use of capacity is determined by the executed schedule. The maintenance of the normative schedule includes change of train number, change of train date and time, change of stations on the route, as well as removal and addition of trains. Technologists perform the adjustment function manually by copying data, deleting it, transferring information to the appropriate columns, which can lead to errors and duplication of information [1], [3]. In order to exclude the above risks and free up technologists' time, the analysis of means for automation of this process was carried out, which showed that incoming telegrams include data in unstructured form, contain errors or defects resulting from poor quality scanning. These factors lead to failure of data processing by software robots, so the use of intelligent automation is required. The application of technology using intelligent automation in various fields of activity is conditioned by the National Strategy for the development of artificial intelligence for the period up to 2030. Intelligent process automation (IPA) technology combines robotic process automation (RPA) and artificial intelligence technologies to take process

automation to the next level [4], [6], [7]. The AI-enabled module integrated into the platform is able to work with unstructured data, process text, highlight and validate data, perform analyses and provide answers to questions as a consultant. JSCo "Russian Railways" projects using artificial intelligence technologies are presented in Figure 1.



Figure 1. Projects using artificial intelligence technologies

An example of intelligent automation of processes are chatbots, which allow to classify the received message, understand the subject of the question and give an answer using the accumulated knowledge base [4].

The chatbot builder built into the platform allows you to design communication channels via text or voice messages. The created chatbots can be used both for communication within the company and for interaction with external customers. Using the ROBIN AI component, chatbots recognise human speech and determine which branch of the process should be followed. Chatbots can upload data received from users into business applications, transfer it to robots and initiate the launch of other process instances. In addition, ROBIN AI provides responses to user requests and counselling. Intelligent search of the knowledge base serves as a basis for making decisions on requests [5], [8].

To ensure centralised management, the ROBIN Process builder is used to configure software robots, AI components, chatbots, voice assistants, combine them into an end-to-end complex process and connect company employees to it using visual dialogue forms.

Partly digital transformation helped to cope with a large flow of requests from users in terms of technological support for maintenance of information systems used on the railway the help of development of a chatbot virtual consultant "ViCo" using artificial intelligence technologies. "ViCo" is based on artificial intelligence, machine learning and big data technologies and is able to recognise the semantics of questions and provide answers using the accumulated knowledge base. The virtual consultant is a system of chatbots developed on the basis of the ChatNavigator software product. This is a development of the Speech Technology Center, which is a platform for setting up a dialogue using a graphical interface, deployed on servers running the Red OS operating system and the free non-commercial object-relational DBMS Postgres [9].

The dialogue scenario in the visual editor is presented in the form of a tree, while the chatbot is debugged on the stand, which provides checking of the chatbot software code for syntax errors, as well as controls the correct placement of questions in the appropriate topics, according to the rules of topic definition and based on the scenario library.

The peculiarity of such a system, built on the basis of the open semantic technology of intelligent systems OS-TIS, is platform independence. It is focused on semantic knowledge representation, which is completely abstracted from the peculiarities of technical implementation of intelligent systems. When considering chatbots, OSTIS provides a flexible framework for constructing dialogue rules with the user, allowing for efficient processing of user requests in natural language - this provides adaptability to different conversational contexts, resulting in more intuitive and user-friendly interactions.

"ViCo" is based on an intelligent decision support system, includes the following components:

- block of input data collection and storage (knowledge accumulation);
- block of data processing;
- block of user counselling issuing a response to the end user of the system about the decision on the arisen issues of the information system, and recommendations for further actions.

The basis for the functioning of the virtual consultant is a decision support system. Obtaining knowledge by the user will contribute to the understanding to solve emerging issues on a particular information system. Important aspects of the system functioning are accumulation of data and knowledge, their systematisation. Such OSTIS system should have all necessary knowledge and normative and reference information for data exchange between corporate systems and programmes. The technology is based on the OSTIS standard, which is a standard of semantic computer systems that provides:

- semantic interoperability of systems conforming to this standard;
- methods of construction of such computer systems and their improvement in the process of operation;
- means for building and improving systems, including language tools, libraries of standard technical solutions, as well as synthesis and modification tools;
- means of analysis, verification, diagnostics, testing [10], [11].

The digital assistant interacts with users on the basis of a dialogue platform using text messages. The chatbot is a dynamic self-learning system, with an architecture, rules for learning and solving questions based on pre-prepared answers. The system includes a control module that ensures interaction between the platform and chatbots of functional modules grouped by 8 areas of activity of JSCo "Russian Railways". "ViCo" receives information on requests and enquiries from related systems using get-requests. Interaction is carried out via the Russian Railways SPD without access to the Internet [1], [4].

More than 2,500 software robots and chatbots operate in Russian Railways. In the coming years, it is planned to create a multi-agent system using intelligent assistants [12]. An intelligent robot, unlike a software robot that works according to a set algorithm, can analyse information and make recommendations.

Functions and features of the ROBIN Process module:

- creating end-to-end processes that can involve both employees and digital assistants;
- planning and control of task execution using customisable screen forms;
- delegating typical tasks to chatbots and voice assistants;
- automatic optimisation of task allocation depending on priorities and resource utilisation;
- compliance with corporate standards of Enterprise architecture and information security [13], [14].

Figure 2 shows the stages of passing an appeal from a user to a technologist of a particular information system or solving it with the help of a chatbot.



Figure 2. Stages of passing a request from a user to a technologist of a particular information system or solving it with the help of a chatbot

Applied systems using artificial intelligence should have: image recognition, optical character recognition (OCR), perform semantic analysis of text, in control tasks use technical vision with recognition and classification of objects - such systems use the logical method of solution (symbol-oriented), reproducing on the computer the laws of thinking, using laws and rules formulated with the help of symbols.

Simple recognition algorithms used by OCR tools, although effective, have a limited range of actions. By the example of the ABBYY Reader system used by JSC "Russian Railways", OCR uses classifiers of individual characters rather than words or text fragments. Such a system and application cannot be retrained, and errors appear in the output at the end of OCR and word definition. Searching for character boundaries is made more difficult by printing or scanning artefacts in telegrams, making it impossible to correctly identify characters. In order for the system to cope with a large volume of tasks, it is necessary to enrich it with artificial intelligence technologies, such as IDP - intelligent document processing using ML and LLM. The IDP system receives a source file, finds hard-to-read elements in the image and tries to normalise them: rotate, crop, sharpen. If it is a text document, the system recognises it in its entirety, i.e. it receives a complete material suitable for further content search. Modern IDP systems can work based on different principles, including detection of the target information search area in an image using ML models, which means that they need to be trained beforehand.

To improve the level of competitiveness and efficiency of business processes, a promising solution is the use of new technologies of intelligent process automation (IPA) and their implementation in the operation of information systems at enterprises and structural divisions of JSCo "Russian Railways" [2]. Intelligent automation allows solving tasks related to unstructured information and data analysis with the help of optical recognition technology, using the accumulated knowledge base. Intelligent process automation combines robotic process automation and artificial intelligence technologies to increase the level of automation of business processes.

Intelligent automation combines artificial intelligence technologies such as natural language processing (NPL), generative artificial intelligence and optical character recognition to optimise business processes. IPA uses machine learning and other cognitive technologies to continuously collect data, process and analyse it [15], [16].

The accelerated development of technologies in such areas as business process automation, data management and the development of intelligent solutions requires the use of artificial intelligence and machine learning systems. These technologies make it possible to create new tools, gain new opportunities, and help solve a large number of tasks in a new way, significantly reducing labour intensity and increasing efficiency.

Intellectual automation is justified by the availability of OSTIS technological base, application of logicalsemantic approach in the tasks of determining the right decision to make the right train routes based on the incoming telegrams with the normative train schedule.

The development of an intellectual system for for-

malising telegrams based on text data processing using optical character recognition is proposed. The proposed intelligent system should:

- process different types of data;
- provide standardisation of data representations (forms of representation, information processing models);
- maintain data relevance, and provide the possibility of adding new components and data types [17].

IV. Proposed approach

When implementing the process of complex automation, a software module - converter, using intelligent automation technology, is used to receive data from telegrams. Telegrams in PDF-format and images have unstructured form - such document is encoded in the form of low-level instructions of text reproduction, reading of its structure by a computer programme is not provided in any way. In order to make unlabelled PDF documents available for machine processing, their structure must be recovered. Document layout analysis consists of recognising the elements of the document structure. The basic part of this process is the segmentation of pages into blocks, which can then be classified as headings, paragraphs, objects, etc. The software module performs analysis on image preprocessing and data segmentation for text recognition within the telegram using optical text recognition.

When using the extraction approach with conversion to editable view, PDF documents are automatically converted to editable view. The text is read from this view, and it is possible to merge blocks of text corresponding to individual words into blocks of text corresponding to whole paragraphs. The advantage of this approach is that the PDF conversion software "pdf2text" can be used to convert to a readable representation that is easier to decode than the original PDF format. However, in general this conversion is accompanied by errors in extracting "characters", "words", "blocks of text". In particular, this results in the loss of information that should be used in decision-making in the analysis process to adjust the regulatory schedule.

Another approach is text extraction with conversion to bitmap images. This approach involves pre-rasterisation of PDF documents and further extraction of tables from document images. Methods implementing this approach have traditionally been based on rules and machine learning. The main direction of their development is related to the application of deep learning, including models of object detection in images, semantic image segmentation, as well as generative and adversarial models [18].

Semantic segmentation is a task in computer vision that aims to classify each pixel in an image into predefined classes [20], [21]. Semantic text segmentation refers to the positioning and size of text regions in documents, which affects the quality of the OCR system. To solve the problem of semantic segmentation of text lines and tables in documents, the UNetFormer architecture is used. It allows recognising all possible orientations of text and tables, as well as storing information about the structure of the document (position of text fields, tables).

Image segmentation can be compared to a classification task in which some initial classes are given. However, an image classification task implies a label for the whole image as a result, whereas in semantic segmentation a label is assigned to each pixel of the image. Thus, unlike classification tasks, segmentation aims not only to identify the main object of interest, but also to study its optical and morphological characteristics such as its edges, its position in the image and its position relative to other objects [22], [23].

Types of segmentation problems that can be solved using neural networks:

- semantic segmentation: the task is to assign to each pixel in an image the class it represents;
- instance segmentation: in such a task, not only each pixel is assigned a class, but also each object of that class is assigned a unique identifier. This allows to distinguish between separate instances of objects within the same class;
- text segmentation: neural networks can be used to segment text at the character, word or phrase level, which is useful in the field of natural language processing.

Deep learning methods, convolutional neural networks (CNNs), which are trained on large datasets to accurately detect boundaries and classes of objects in images, are used for the semantic segmentation task [23], [24].

The use of methods consisting of a combination of machine learning and computer vision algorithms allows for high accuracy of text segmentation, where Convolution Neural Networks are used for image preprocessing, and Recurrent Neural Networks are used to analyse the original text data.

The image segmentation algorithms are: watershed algorithm, thresholded image binarisation, segmentation using k-means algorithm - automatic selection of optimal cluster structure. In the latter, the segmentation is based on machine learning, which improves the image processing. With the right choice of algorithm, the efficiency of the processing solution is improved.

When processing text images, a foreground region is searched, foreground objects are separated from the background, and the image quality is improved. At the next stage of processing the type of the selected area is determined, if the found area is text, then the transition to segmentation is performed [25].

The location of all fields in the telegram is determined, then character recognition for text detection is performed using the CRAFT (Character-region awareness for text detection) method, fields with train number, station names and their arrival and departure times are split into separate words. It allows to quickly highlight objects of interest in an image or in a telegram. To work with the CRAFT model we used software libraries: transformers, datasets, torch. CRAFT performs selection of text and object contours using contour segmentation methods, as well as analysis of neighbouring points of the image by the degree of homogeneity, based on the search for homogeneous areas. Pre-training of the data model for telegram recognisable object entities was performed.

Binary image segmentation highlights individual tokens - objects and words recognised by the software module. Libraries for creating and training models cv2, torch, torchvision, json, PyTesseract, OpenCV, etc. Annotations.json contains a list of keys ['images', 'annotations', 'categories'] with a list of dictionaries of various kinds. Dictionary ['annotations'] - stores information about coordinates of masks of individual tokens - this storage format is called polygon.

Before working with the model itself, we need to define its parameters and load the model architecture. The next step is registration and description of classes for each token. If a class is characterised by some common properties inherent in all its members, the construction of a recognition system can be based on the principle of commonality of properties. The basic assumption in this case is that patterns of the same class have common properties reflecting their similarity. The object recognition process involves the identification and categorisation of objects into predetermined classes or categories. In object detection, the procedure of recognising and accurately locating an object in an image is performed by creating a bounding box around the object. In semantic segmentation, semantic labels or classes are assigned to each pixel in the image. In case of instance segmentation, semantic labels or class labels are assigned to each pixel in the image with the difference between individual instances of the same class. If all objects of one class have a number of common properties or attributes that are absent or have other values in all representatives of other classes, then the construction of a recognition system can be implemented on the basis of the principle of commonality of properties.

Registration of the dataset representing the dataset is performed, the image size is changed to make the training faster. The order of channels in the input image is specified, parallel loading is performed for faster loading of data into the model. The "learning rate" parameters are set, the model training steps, the number of iterations and the number of classes in the sample are specified. After that the model is trained "trainer.train()". The trained model is used to check the quality of validation. In the resulting array of binary matrices - a matrix is responsible for the individual detected text mask. When the binary mask is visualised, a separately selected token is obtained.

After preliminary training and indexing, data addition is performed automatically when a new railway station is found in a telegram or ECP code records in NSI directories are changed. For schedule adjustment telegrams with new data, the system must be regularly updated and periodically record new changes. The system of intellectual analysis of unstructured data based on ML-technologies - is responsible for indexing, selection of objects and their relationships. Thanks to this the system can "understand" what information is stored in the telegram. And indexing and selection of facts is performed without human participation.

When creating the dictionary, a base consisting of different representations of the station record was formed, recognition of the station object entity, train number, time of arrival and departure from the station was performed. When processing telegrams a CSV file is formed, for selected telegram data the file contains information about classes of the text layer of telegram pages. The programmed indexes records from directories by names of railway stations. During the verification process the programmed performs verification and corrects errors. If an abnormal situation related to a hardware problem is detected, the control logic should provide for verification of the corresponding logical conditions.

Using built-in Python libraries of numerical algorithms, the data is processed and formalised into a set format for uploading the document to the APC Elbrus. The information is processed in accordance with the rules and formed into an approved *.ntp file, then it is processed by the software robot and the normative train timetable is uploaded to the APC ELBRUS system, with the file entered into the folder with the upload calendar. With marked-up data Pandas is used to process tabular data. In case of incorrect description of the telegram, libraries are used to process missing values, as missing values at zero input can cause failure or discrepancy of information in automated systems. In the programmed module, based on intellectual analysis, it is possible to add information to the database about new stations, their id, ECP-code in cases of their appearance in new telegrams on the input and correction of the normative train schedule.

V. Conclusion

The article considers the advantages and disadvantages of robotic process automation. The classification of robots is carried out. Ways of solving the problems of robotisation are presented. Methods of working with unstructured information are considered on the example of segmentation and classification of telegram data for adjusting the normative schedule of the train schedule are considered.

With the development of the new generation of universal neural networks for data analysis there are more

and more machine learning models for intelligent automation. These solutions are many times more efficient than previous generations of similar services and have great potential for the development and improvement of business processes. The application of intelligent automation allows today's enterprises to reduce costs by up to 60 percent due to the redistribution of staff time, and the performance of a number of business processes can increase by 80 percent. In addition, smart robots allow to practically eliminate errors in the performance of business operations, which minimises associated financial and reputational losses [5].

The development of digital technologies and the emergence of new products entails the need to choose the best combination of tools to automate tasks. The use of technologies such as RPA and IPA facilitates a safe transition from automated automation to intelligent process automation, improving the qualitative and quantitative parameters of technological and business processes.

Thus, software robotisation allows reducing labour costs of technologists up to 70-80 percent by monitoring and uploading data to hardware and software complexes and automated systems. At joint use of software robot and intellectual automation with the software-converter there is a 10 times reduction of time for adjustment of the normative schedule, performing the task of monitoring with different information-corporate systems minimising time and increasing the quality of work. When using intelligent automation, the result of normative schedule adjustment is checked, which allows minimising the influence of human factor, increasing the level of consistency and coordination within information systems. Integrated automation with the help of semantically compatible intelligent computer systems will increase productivity and reduce the time required to complete tasks.

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ИНТЕЛЛЕКТУАЛЬНАЯ АВТОМАТИЗАЦИЯ ПРОЦЕССОВ ОБРАБОТКИ ТЕЛЕГРАММ ДЛЯ КОРРЕКТИРОВКИ НОРМАТИВНОГО РАСПИСАНИЯ ДВИЖЕНИЯ ПОЕЗДОВ Гаранин А.В., Никищенков С.А.

В статье рассматриваются технологии программной роботизации и интеллектуальной автоматизации, применяемые в ОАО «РЖД», технологические аспекты корректировки нормативного расписания движения поездов. Рассматривается технология взаимодействия аппаратно-программного комплекса ЭЛЬБРУС, автоматизированной системы ГИД «Урал-ВНИИЖТ» и ЦБДГР для задачи ведения и анализа графика исполненного и нормативного графика движения поездов на железнодорожном транспорте. Приведены примеры действующих программных роботов и чат-ботов (виртуальный консультант) в корпоративных информационных системах, эксплуатируемых в дирекциях управления движением. Представлены проекты, использующие технологии искусственного интеллекта. Описаны выявленные и актуальные проблемы сопровождения технологии ведения нормативных графиков движения грузовых поездов. Проведен анализ и выбор средств интеллектуальной автоматизации процессов и интеллектуальной обработки для распознавания текста в телеграммах. Рассмотрены задачи семантической сегментации, бинарной сегментации изображений и библиотеки языка программирования Python для обработки и анализа телеграмм, используя методы распознавания и конвертации поступающей информации для интеллектуальной автоматизации процессов. Определены перспективы развития автоматизации процессов сопровождения с использованием программных и интеллектуальных роботов.

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Developing an AI-Powered Bird Sound Recognition System for Monitoring Avian Biodiversity in Belarus

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Abstract—This paper explores the application of artificial intelligence (AI) of automated bird vocalisation recognition for the purpose of continuous monitoring of avian species in Belarus. It presents a novel system comprising a large, annotated dataset of Belarusian bird sounds, a convolutional neural network model trained for multi-label species identification, and a publicly available software platform. The AI-driven approach of the system enables efficient analysis of large audio datasets and real-time species identification. This research demonstrates the feasibility of using AI to overcome challenges in biodiversity monitoring and lays the groundwork for future advancements in automated wildlife conservation.

Keywords—artificial intelligence, bird voice recognition, automatic processing, annotation, Mel spectrogram, convolutional neural network, deep learning, ontological approach.

I. Introduction

Bird vocalisations are a critical component of avian behavior, ecology, and communication. The ability to recognize and interpret these vocal signals is essential for various fields, including ornithology, ecology, and conservation biology. Birds are among the most vocal animals, using a complex array of sounds for communication, mating, territory establishment, and alarm signaling. Understanding these vocalisations provides information on avian behavior and ecology, making it a vital area of study for researchers. As global biodiversity faces unprecedented threats, recognition of bird voices can play a crucial role in monitoring populations and informing conservation strategies.

The recognition of different bird species is complicated by numerous variations in their sound signals. Engaging ornithologists for manual processing of individual signals requires additional time, which significantly hinders the automation of species identification. This highlights the need to develop automated bird voice recognition systems capable of analysing large datasets [1]. Currently, there are several well-known applications, such as *Aubio*, Prodigy, BirdNET, Merlin Bird ID by Cornell Lab, Song Sleuth, Warblr, and Chirpomatic, that interpret bird vocalisations in various regions of the world [2]. The urgent need for a bird voice recognition system in Belarus arises from the fact that existing applications do not encompass the full biodiversity of birds in the country, with only a few capable of recognising European species. Belarus is home to a rich diversity of bird species, many of which are unique to the region or are part of migratory routes. Effective monitoring of these species is crucial for conservation efforts, especially for those that are rare or threatened. Traditional methods of monitoring birds often rely on manual observation and identification, which can be time-consuming and labor-intensive. Automated sound recognition systems can streamline this process by allowing the rapid analysis of large volumes of audio data. This efficiency enables researchers and conservationists to gather more comprehensive data on bird populations and their behaviors. Although there are several bird sound recognition applications available, many do not cover the full range of species found in Belarus. Developing a localized system ensures that unique vocalisations of Belarusian birds are accurately recognised and documented [3]. This specificity is crucial for effective conservation and research efforts tailored to the region's ecological needs.Furthermore, automatic voice recognition poses a particularly pressing challenge in countries that lack the resources to effectively monitor and protect wildlife. The successful development of such systems could have significant practical applications, including improved monitoring of bird populations, assessment of their ecological status, and conservation of biodiversity [4].

Therefore, the objective of the research is the development of a technology of automatic unmasking of residential signals to provide continuous automatic monitoring of rare, threatening, and other types of life and the state of vulnerability in forest ecosystems [5].

II. The Development of Bird Sound Recognition System Based on Artificial intelligence

Within the framework of the project, several tasks have been established:

- Preparation of methodological foundations for the collection, annotation, and recognition of animal voice signals in Belarus.
- Organizing data sets of existing electronic recordings of animal vocalisations from available sources.
- Development of a structural framework for the automated recognition of animal voice signals to facilitate the the continuous monitoring of rare, threatened, and indicator species.
- Creation of an analytical center for the continuous autonomous monitoring of rare, threatened, and indicator animal species.
- 5) Generating automated annotations of animal voice signals within the compiled databases.

In a previous paper [6] we described a dataset of bird vocalizations, the algorithms for their annotation, and the initial recognition model based on artificial intelligence (AI). The development of such systems is significantly enhanced by the application of AI for several reasons. Using machine learning algorithms, it can analyse complex sound patterns with a high degree of accuracy. Convolutional neural networks (CNN) learn to differentiate between subtle variations in bird vocalizations, leading to a more precise identification of species compared to traditional methods [7]. AI systems process large amounts of audio data quickly and efficiently. This scalability allows researchers to analyse extensive datasets collected from various locations over long periods, making it feasible to monitor large populations and diverse habitats without the need for extensive manual labour. AI models are trained and improved over time as more data become available. This ability to learn from new examples means that the system can adapt to changes in bird vocalisations, such as variations due to environmental factors or changes in species behavior, leading to ongoing improvements in recognition accuracy. AI systems can be designed to analyse audio streams in real-time, enabling immediate identification of bird species. This capability is particularly useful for field studies and monitoring programs, where timely data can inform conservation actions or research findings. AI can integrate audio data with other ecological data, such as weather conditions, habitat types, and geographic information. This holistic approach allows for more comprehensive analyses and a better understanding of the factors influencing bird populations and behaviors.

As part of preparing methodological foundations for the collection, annotation, and generation of animal vocal signals in Belarus, a comprehensive database was created

from various sources. This database contains more than 2,500 audio recordings representing 116 bird species, which yield approximately 42,000 annotated vocalisations. The data set includes recordings of varying quality and audio features with different numbers of species that sing simultaneously. The annotation process for audio files intended for automated recognition involves segmenting them into appropriately sized windows, performing computer analysis, and generating a Mel spectrogram for each file (fig. 1). A Mel-spectrogram is a visual representation of sound that displays how the energy of a signal is distributed across different frequencies over time. It is derived from the Fourier transform, which analyses sound waves to extract their frequency components. In a Mel-spectrogram, the x-axis represents time, the y-axis represents frequency, and the intensity of colour or brightness indicates the amplitude (energy) at each frequency at each moment in time. The Mel scale is a perceptual scale of pitches that approximates the way humans perceive sound, making it particularly useful for audio analysis. The Mel scale emphasises frequencies that are more relevant to human hearing, allowing for better feature extraction that aligns with how we perceive sounds, which can improve the performance of recognition algorithms.

To create experimental software for the automatic recognition of animal vocal signals, efforts have been made to develop a model and its corresponding algorithms. This model is built on a pretrained convolutional neural network that incorporates additional layers, including *Flatten, Dropout, and Dense*. The activation functions for the final layer are *Softmax and Sigmoid*, with binary cross-entropy used as loss function. The task has evolved from Multi-Class Classification (one window – one prediction) to Multi-Label Classification (one window – multiple predictions). The neural network training process is carried out over 50 epochs, with adjustments to the learning rate based on the *ReduceL-ROnPlateu method*.

The input data is presented in the form of audio recordings and text annotations containing timestamps of the appearance of bird species. The refinement process includes three key steps (fig. 2). At the first stage, audio recordings are protected from background noises such as rain, wind, urban sounds, and other unwanted acoustic interference. For this purpose, the threshold spectrum processing method is used, which analyses the amplitude characteristics of the frequency components of the signal and drowns out the noise components, the level of which is below a given threshold. In the second stage, the audio signal is divided into 2-second windows according to the timestamps of the annotations. This process ensures the formation of a training sample in which each fragment contains bird sounds in a given time range. At the third stage, Mel-spectrograms are calculated for each selected



thrush nightingale





chaffinch



spotted eagle





goat-sucker



Figure 1. The spectrogram of bird voice signals

window using compression. The use of the Mel-spectral representation makes it possible to effectively describe the acoustic features of the signal, bringing them closer to the perception of the human ear and improving the quality of the features supplied to the input of the model.

The model's performance was evaluated using *precision*, *recall* metrics, and their geometric mean, *the flscore*. A sample was created from the compiled dataset for testing, ensuring that the same recording did not appear in multiple samples simultaneously. Testing on a selected set of 10,000 annotations from the test data revealed that the Multi-Class Classification model achieved average precision is 0.59, recall – 0.58, and fl-score – 0.54. Meanwhile, the Multi-Label Classification model demonstrated average precision of 0.53, recall – 0.56, and fl-score – 0.52. These results are considered acceptable at this stage of the model's development.

III. The improvement of the bird sound recognition system

The above system test results prove the need to refine the application and add new functionality. The list of additional improvements, which requires additional research work. They can be described as continuing training the automated voice recognition model on more annotations and unique audio tracks for species with insufficient numbers (<200 annotations, less than 30 unique files).

To address this issue, new annotations of vocal signals have been added for bird species that previously had an insufficient number identified. Experiments were conducted to train the model using an increased number of annotations of bird vocal signals, raising the count from 250 to 400 annotations for each species. As a result of this work, a minimum threshold of 350 annotations per species was established. Plans are in place to further enhance the annotated data for those species that currently lack sufficient data to effectively train the voice recognition model, which will contribute to improved recognition accuracy.

The Multi-Label Classification architecture was employed to address the problem. The model outputs probabilities indicating the likelihood that a given sound window belongs to a specific class, thereby allowing for the prediction of multiple species occurring simultaneously. To train the automated voice recognition model, spectrograms were generated in a manner that allows multiple spectrograms to correspond to a single recording. The following experiments were conducted:

1. The minimum threshold is set at 200, and the maximum is 300 windows. The number of species that met the specified conditions was 113. The results of the experiment are shown in Table I.

Table I The results of training the model on the number of 200-300 windows

Parameter	precision	recall	f1-score	support
micro avg	0,69	0,40	0,51	6630
macro avg	0,66	0,41	0,42	6630
weighted avg	0,65	0,40	0,42	6630
samples avg	0,42	0,42	0,42	6630

Based on the results shown in the table, it can be concluded that the minimum threshold should be set to more than 200 windows, since the recall indicator should be greater than 0.4 to ensure the accuracy of predicting the bird whose singing is present on the recording.

For example, figure 2 shows a mel-spectrogram of an audio recording with Luscinia's and Grey Warbler's singings, where the y-axis is frequency, the x-axis is time, and the signal strength is indicated by color. The spectrogram is divided into 2-second windows where the model makes predictions. Just below, the model's



Figure 2. Processing of input audio files

predictions themselves are displayed with the model's confidence value (probability) for each 2-second window. Each bird is indicated by its own color. Everyone can see that the system indicates this audio as uscinia's song. But there is a big prabability that it can be Grey Warbler.

2. The minimum threshold set is 250, and the maximum is 350 windows. The number of species that fit this framework was 102. The following results were obtained, which are presented in Table II.

Table II The results of training the model on the number of 250-350 windows

Parameter	precision	recall	f1-score	support
micro avg	0,90	0,74	0,81	6792
macro avg	0,88	0,74	0,79	6792
weighted avg	0,88	0,74	0,79	6792
samples avg	0,77	0,76	0,76	6792

The results improved, but in some bird species the recall index is < 0.5, which makes their singing complex. 3. The minimum threshold set is 250, and the maximum is 350 windows. The types that are poorly recognised were also subtracted (recall < 0.5). The number of species that fit the noted creteria was 91. The experimental results are shown in Table III.

The decrease in the number of types in the recall indicator did not significantly affect the recognition result.

4. The minimum threshold set is 300, and the maximum is 400 windows. The number of species that

Table III The results of training the model on the number of 250-350 windows with the recall parameter >0.5

Parameter	precision	recall	f1-score	support
micro avg	0,92	0,76	0,83	6043
macro avg	0,93	0,76	0,82	6043
weighted avg	0,92	0,76	0,82	6043
samples avg	0,77	0,77	0,77	6043

met these criteria was 85. The results are presented in Table IV.

Table IV The results of training the model on the number of 300-400 windows

Parameter	precision	recall	f1-score	support
micro avg	0,92	0,71	0,80	6505
macro avg	0,90	0,72	0,78	6505
weighted avg	0,90	0,71	0,78	6505
samples avg	0,75	0,74	0,74	6505

As the number of windows increased, high precision values were attained; however, there are several bird species that are not well recognised in terms of recall. This indicates that these species are infrequently predicted. To address this issue, a list of birds has been created for which it is essential to increase the number of collected and processed annotations between 350 and 400: *turdusmerula*, *turdusphilomelos*, *troglodytestroglodytes*, *sylviaatricapilla*, *phylloscopuscollybita*, *parusmajor*, *luscinialus*-



Figure 3. The recognition of Luscinia's and grey warbler's singings

cinia, fringillacoelebs, erithacusrubecula, dendrocoposmajor, cyanistescyanus, dendrocoposleucotos, corvuscornix, garrulusglandarius, pyrrhulapyrrhula, clangaclanga, scolopaxrusticola, glaucidiumpasserinum, turdusviscivorus, poecilepalustris, regulusignicapilla, dryobatesminor, ficedulahypoleuca, streptopeliaturtur, carpodacuserythrinus, alcedoatthis, picuscanus, coraciasgarrulus, leiopicusmedius, picoidestridactylus, asiootus, aquilachrysaetos, emberizacalandra, emberizahortulana, falcocolumbarius, falcotinnunculus, hieraaetuspennatus, nucifragacaryocatactes, otusscops, picusviridis, strixuralensis. This will allow everyone to train the model on more data and improve the prediction results.

Thus, to improve the efficiency of a bird voice recognition system, we are considering the following points:

- Collect a larger and more diverse dataset of bird vocalisations, including various species, environmental conditions, and recording settings;
- normalise audio levels and trim unnecessary segments to focus on the relevant vocalisations;
- utilise data augmentation techniques to artificially increase the size of the training dataset by creating variations of existing recordings;
- investigate ensemble methods that combine multiple models to improve overall accuracy;
- 5) implement a feedback mechanism that allows users to report misclassifications, and use this data to retrain and improve the model over time; continuously test the system on new and unseen data to evaluate its performance and identify areas for improvement; optimise the code and algorithms for faster processing times, ensuring the system can handle real-time recognition if needed.

IV. The software for the automated bird sound recognition

The experimental software designed for the automated recognition of animal (bird) vocalisations was developed on the basis of automated annotation of animal vocal signals within the collected databases and the model of recognising birds' sounds. This is the Information and Analytical Centre for Continuous Monitoring (IAC). It comprises several components, including database software, a collection of electronic datasets for training recognition models, and a website that facilitates data download and processing from various sources while generating recognition results.

To access the centre and its databases, users must register at the Information and Analytical Center. The software produces a Mel-spectrogram of the audio recording along with automated annotations of animal vocal signals based on the processed audio. These annotations can be exported into a text file. The advantages of the developed software include a user-friendly interface, a comprehensive scientific database of bird vocalisations that is continuously updated. The prototype's interface is designed to be intuitive and easy to navigate, ensuring that site visitors can easily find the information they need or accomplish their personal tasks.

On page with a database (fig. 4), each audio file is assigned a unique identification number (ID) upon download, which is displayed in the first column of the table. The subsequent columns provide additional details about the audio file, including the date (Date), recording time (RecordTime), coordinates of the bird song recording location (GPS), ambient temperature during the recording (Temperature), and the name of the recording device used (TrapName). After recognition, the name of the identified bird appears in the *BirdRecognized* column. The *SessionTime* column indicates the duration of the audio session from the time of file download to its recognition. Each audio file is also assigned a status that reflects the success of its processing.

For more information about the recognised audio file, click on (...). You can view a spectrogram displaying the predicted bird species and an annotation with timestamps and predicted species, as well as listen to the original audio recording.

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	Гукап	асткі						
C		загрузіць	файл		(пачаць распаз	наванне	audioFile
Ы	Date	RecordTime	GPS	Temperature	TrapName	BirdRecognized	SessionTime	spectrogram
3677	2024-06-11	03:57:02	0, 0	-100	2MM02906	turdusmerula	Session Time	true +++
3676	2024-06-11	04:00:02	0, 0	-100	2MM02906	turdusmerula	Session Time	tue ····
3675	2024-06-11	09:22:19	0, 0	-100	2MM02906	fringillacoelebs	Session Time	true
3670	2024-11-28	10:29:11	0, 0	-100	2MM02906	accipitemisus	Session Time	tue
3669	2024-06-11	10:29:11	0, 0	-100	2MM02906	fringillacoelebs	Session Time	true ····
3668	2024-11-28	10:29:11	-1, -1	100	2MM02906	accipiternisus	Session Time	(tue)
3667	2024-06-11	10:29:11	-1,-1	100	2MM02906	fringillacoelebs	Session Time	true
3666	2024-06-11	10:29:11	0, 0	-100	2MM02906	fringiliacoelebs	Session Time	true

Figure 4. The software interface of audiofiles processing

The software is fully integrated into the continuous monitoring information and analysis centre and is publicly available. Thus, the completed tasks not only produced significant scientific and technical results, but also opened up ways to further improve methods for monitoring and protecting the fauna of Belarus, contributing to the conservation and study of biodiversity in forest ecosystems. The results obtained will make it possible to spread knowledge and experience in ornithology among a wide audience and conduct further research in this direction.

V. Ontological approach for enhanced classification and monitoring of avian biodiversity

The complexity of avian biodiversity monitoring in Belarus, as highlighted in the development of the AIpowered bird sound recognition system, underscores the need for a more structured and semantically rich approach to data organisation and classification. Traditional methods of species identification, while effective to a certain extent, often struggle with the integration of diverse data types — such as audio recordings, geographic locations, and ecological contexts – leading to challenges in achieving high accuracy and scalability. To address these limitations, an ontological approach offers a promising solution by providing a formal framework for representing and interlinking knowledge about bird species, their vocalisations, and their habitats.

The recognition of bird species through vocalizations involves not only the analysis of audio signals but also the contextual understanding of where and under what conditions these vocalisations occur. For instance, the same species may exhibit variations in its calls depending on its habitat, season, or interaction with other species. Current AI models, such as CNNs, employed in this study, excel at pattern recognition but lack the ability to incorporate semantic relationships between species, their behaviours, and their environments. An ontological approach helps fill this gap by allowing knowledge to be represented in a way that machines can understand, making it easier to combine different types of data and enhancing the accuracy of classifying and monitoring species.

The OSTIS technology [9] provides a robust framework for building intelligent systems through the use of SC-code, which is a universal method of semantic representation based on semantic networks. Within OS-TIS, knowledge is organised as a hierarchical system of subject domains and ontologies, allowing for the explicit description of entities, their properties, and their relationships. In the context of avian biodiversity monitoring, this approach can enhance the system's ability to reason about the relationships between bird species and their habitats, leading to more accurate identification and a deeper understanding of ecological dynamics.

To illustrate the application of OSTIS in avian biodiversity monitoring, we have integrated the description of "Bubo bubo" (Eurasian eagle-owl), a notable bird species in Belarus, with two significant geographic objects: "Belovezhskaya Pushcha" and "Berezinsky Biosphere Reserve". The description of Bubo bubo is formalized using the SC-code, following the structure provided in the study. The geographic objects are described based on the formal ontology of terrain objects outlined in next works dedicated to intelligent geoinformation systems [10].

The Bubo bubo, known as the Eurasian eagle-owl, is one of the largest owl species in the world, widely distributed across Europe, Africa, and Asia. Its description within the OSTIS framework is structured as follows:

Bubo bubo

 \in

 \subset

:= [Eurasian eagle-owl] \in English language [Puchach] := \in Belarusian language species bubo genus \in С strigidae family \in C strigiformes order \in \subset chordata \in phylum С animalia \in kingdom habitat*: \Rightarrow **{•** Europe coordinates*: \Rightarrow [From: 48.0° N, 5.0° E] {∙ [To: 65.0° N, 40.0° E] Africa Asia physical characteristics*: \Rightarrow [Large owl with a wingspan of 1.5-2.0 meters, prominent ear tufts, and mottled brown and gray plumage] diet*:

- \Rightarrow [Primarily small mammals, birds, and occasionally reptiles]
- \Rightarrow behavior*: [Nocturnal, territorial, with a deep hooting call often heard at dusk or dawn]

This formalization captures the taxonomic hierarchy of Bubo bubo, its common names in English and Belarusian (sourced from the image and the Internet), its habitat range (including coordinates in Europe), and additional ecological details such as physical characteristics, diet, and behavior. The use of SC-code ensures that this knowledge is machine-readable and can be linked to other entities within the ontology.

"Belovezhskaya Pushcha" and the "Berezinsky Biosphere Reserve" are two critical habitats for avian species in Belarus, known for their rich biodiversity and conservation significance. Following the formal ontology of terrain objects proposed in [11], [12], these geographic

objects are classified as areal objects within the category of vegetation cover and soils. Their descriptions in SCcode are represented below:

Belovezhskava Pushcha

20007	
\in	terrain object
\subset	areal object
\subset	vegetation cover and soils
\Rightarrow	proper name*:
	[Belovezhskaya Pushcha]
\Rightarrow	coordinates*:
	[52.5° N, 23.8° E]
\Rightarrow	area*:
	[1500 km ²]
\Rightarrow	vegetation type*:
	[Mixed forest with predominance of coniferous
	and deciduous trees]
\Rightarrow	biodiversity significance*:
	[UNESCO World Heritage Site, habitat for rare
	and threatened species]
\Rightarrow	relation of spatial-logical connections between
	terrain objects*:
	<i>inclusion of terrain object</i>
	\Rightarrow requirement*:
	[Includes protected forest zones
	and wetland areas.]
	}
	-
Berez	zinsky Biosphere Reserve

terrain object \in С areal object

- С vegetation cover and soils
- ⇒ proper name*:
 - [Berezinsky Biosphere Reserve]
- coordinates*: \Rightarrow
 - [54.7° N, 28.3° E]
- area*: \Rightarrow

 \Rightarrow

 \Rightarrow

- [851 km²]
- vegetation type*: \Rightarrow
 - [Coniferous forests, bogs, and meadows]

biodiversity significance*: [UNESCO Biosphere Reserve, key area for migratory bird species]

relation of spatial-logical connections between terrain objects*:

- **{•** inclusion of terrain object
 - requirement*: \Rightarrow [Includes river systems and bog ecosystems.]

}

These descriptions provide a formal representation of the geographical objects, including their spatial properties, vegetation types, and ecological significance. The inclusion of terrain object relation indicates the presence of subentities (e.g., wetlands in Belovezhskaya Pushcha and

river systems in Berezinsky Biosphere Reserve), which are critical for understanding the habitat preferences of bird species.

The integration of Bubo bubo with Belovezhskaya Pushcha and the Berezinsky Biosphere Reserve is achieved by establishing semantic relationships within the OSTIS framework. Specifically, the habitat of Bubo bubo in Europe overlaps with the coordinates of both geographic objects, allowing us to define the following relationships:

Bubo bubo

- \Rightarrow habitat*:
 - Belovezhskaya Pushcha
 - \Rightarrow observation frequency*:
 - [Occasional, primarily in dense forest areas]
 - ⇒ vocalization characteristics*:
 [Deep, resonant hooting calls, often heard at dusk in mixed forest zones]
 - Berezinsky Biosphere Reserve ⇒ observation frequency*: [Rare, observed in coniferous forests near bogs]
 - ⇒ vocalization characteristics*: [Lower-pitched hoots, typically in quieter, isolated areas]

ł

- ⇒ relation of spatial-logical connections between species and terrain objects*:
 - presence in terrain object
 - \Rightarrow first domain*:
 - [Bubo bubo]
 - \Rightarrow second domain*:
 - Belovezhskaya Pushcha
 Berezinsky Biosphere Reserve
 - }
 - }

This integration links the bird species to specific habitats, detailing its observation frequency and vocalisation characteristics in each location. The presence in terrain object relation formalizes the ecological association between Bubo bubo and the two reserves, allowing the system to reason about the distribution and behavior of the species in different environments. The use of OSTIS to build an ontology for avian biodiversity monitoring offers several advantages. First, it enables the system to incorporate semantic knowledge about species and their habitats, improving the accuracy of classification by considering contextual factors such as habitat type and geographic location. For example, the distinct vocalisation characteristics of Bubo bubo in Belovezhskaya Pushcha versus Berezinsky Biosphere Reserve can be used to refine the AI model's predictions, reducing false positives in species identification. Second, the ontology facilitates the integration of diverse data sources, such as audio recordings, geographic information, and ecological metadata, into a unified knowledge base. This holistic approach supports more comprehensive analyses of avian biodiversity, such as tracking migratory patterns or assessing the impact of habitat changes on species populations. Finally, the machine-readable nature of the SC-code allows for automated reasoning and querying, enabling researchers to extract meaningful insights from the data, such as identifying key habitats for conservation prioritisation.

VI. Comparative analysis of BirdNet and AIC systems

In order to test the effectiveness of the developed system, a comparative study with the BirdNet system was carried out. *BirdNet* is an advanced machine learning system designed for the identification and classification of bird species based on their vocalisations. Developed by researchers at the Cornell Lab of Ornithology, BirdNet utilises deep learning algorithms to analyse audio recordings of bird calls and songs, enabling users to identify various bird species with high accuracy. The system can distinguish between similar-sounding species, which is often a challenge for other applications.

One of the main reasons for comparing bird voice recognition systems is to evaluate their accuracy and reliability. The comparison allows determining which system provides the best results in different conditions, such as background noise, recording quality, and variety of views. This is especially important for research, where the accuracy of identification can influence conclusions about the state of populations and ecosystems.

Comparative testing of two bird voice recognition systems can be carried out in several stages. They are defining goals and criteria, collecting data, preparing data, configuring systems, conducting testing, comparing results, statistical analysis, and interpreting statistical data.

The results of recognition of bird sound signals by BirdNet programs (desktop application, recognition model version: V2.4) and the Information and Analytical Centre for Continuous Monitoring were compared using annotated audio recordings of 232 birds singing. There are 2 audio recordings for each bird species, which are recognised by the Information and Analytical Center model. The parameters for obtaining recognition results are: minimum confidence – 80 percent, minimum bandpass frequency (Hz) – 200, maximum bandpass frequency (Hz) – 10000, sensitivity – 1. The comparison criteria were as follows:

 the number of audio recordings with correctly predicted bird species, the number of audio recordings with unidentified or incorrectly predicted bird

Table V The results comparing BirdNet and AIC systems

Prodiction criteria	Cour	nt	Percentage (%)	
r realement criteria	BirdNet	AIC	BirdNet	AIC
True Positives (TP)	175	150	75	65
False Positives (FP)	57	82	25	35

species. The results are presented in the table V in quantitative and percentage terms relative to the total number of recordings;

2) The number of audio recordings with a higher maximum percentage of the prediction result (confidence threshold). The results are presented in the table V in quantitative and percentage terms relative to the number of recordings with correctly predicted bird species in both programs (150 audio recordings).

Conclusions based on the results of recognition of bird sound signals are next:

- the Information and Analytical Centre for Continuous Monitoring correctly predicted 11 per cent fewer audio recordings than the BirdNet (out of 232 test audio recordings);
- 2) The Information and Analytical Center gave a higher maximum percentage of prediction results in 20 percent of audio recordings with correctly predicted bird species (150 audio recordings) compared to BirdNet.

This is a pretty high-quality result for a software environment that is currently under development. According to the test results, it is necessary to pay attention to the increase in the amount of annotated data for bird species that have not been recognised. Also, work on improving the recognition of audio recordings with poor quality will be continued.

VII. Conclusion

Bird vocalisations play a crucial role in avian behavior, ecology, and communication, making their recognition essential for fields such as ornithology, ecology, and conservation biology. This article discusses the development of an automated bird voice recognition system tailored to the unique biodiversity of Belarus, where existing applications fall short. Using artificial intelligence, particularly models of convolutional neural networks, the system aims to enhance the accuracy and efficiency of bird species identification. A comprehensive database of over 2,500 audio recordings representing 116 bird species has been created, which facilitates the training of the recognition model. The article outlines the methodology for data collection, annotation, and implementation of a user-friendly software interface that integrates various components for continuous monitoring.

After successful launch and testing, the model demonstrates the following indicators: accuracy: 0.92; macro avg: f1-score 0.5216, recall 0.5311, precision 0.92; weighted avg: f1-score 0.84, recall 0.78, precision 0.92. The results are promising, although they indicate a need for further refinement and additional data collection to improve recognition accuracy, particularly for species with insufficient annotations. Ultimately, this research contributes to the conservation of Belarusian biodiversity and promotes public participation in ornithological studies.

The creation of a comprehensive annotated dataset and the implementation of a CNN-based model lay a solid foundation for future advancements. Although the initial performance metrics are promising, ongoing efforts to expand the dataset, particularly for underrepresented species, and refine the model architecture are crucial for improving accuracy and reliability. The integration of this system within a publicly accessible information and analysis centre has the potential to transform bird monitoring efforts in Belarus, providing valuable data for conservation planning, ecological research, and public participation in ornithology. The further development and broader application of this technology promise more effective wildlife management and biodiversity conservation in the region.

In the paper, approaches to further improve the quality of ML models through the use of the ontological approach and OSTIS technology are also proposed. The integration of an ontological framework, as demonstrated with the case study of Bubo bubo (Eurasian eagle-owl) in Belovezhskava Pushcha and Berezinsky Biosphere Reserve, enhances the system's ability to incorporate semantic relationships between species, their vocalisations, and their habitats. By formalising knowledge using SCcode within the OSTIS technology, the system can better account for contextual factors such as habitat-specific vocalisation variations, leading to a reduction in false positives and an improvement in classification accuracy beyond the current 75.6 percent. This approach also facilitates the integration of diverse data types, such as geographic and ecological metadata, into a unified knowledge base, enabling more comprehensive biodiversity analyses.

Furthermore, the ontological approach lays the groundwork for future advancements in real-time monitoring and conservation efforts. The structured representation of knowledge about species such as Bubo bubo and their habitats in Belarus supports automated reasoning and querying, which can be leveraged to identify critical areas for conservation prioritisation and to track ecological changes over time. As the project expands to include more species and data types, the ontology can be scaled to support dynamic monitoring applications, providing conservationists with actionable insights, such as immediate alerts for the presence of rare or threatened species in specific locations. This integration of semantic technology with machine learning models represents a significant step toward more accurate and ecologically informed avian biodiversity monitoring in Belarus.

Overall, as a comparative study of AIC with BirdNet shows, AIC stands out among its analogues due to its high accuracy, user-friendly design, real-time identification capabilities, and strong community engagement. These advantages make it a powerful tool for anyone interested in birdwatching, research, and conservation, helping to foster a greater appreciation for avian biodiversity.

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РАЗРАБОТКА СИСТЕМЫ РАСПОЗНАВАНИЯ ГОЛОСОВ ПТИЦ ДЛЯ МОНИТОРИНГА БИОРАЗНООБРАЗИЯ ФАУНЫ БЕЛАРУСИ

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В статье рассматривается разработка автоматизированной системы распознавания голосов птиц, адаптированной к уникальному биологическому разнообразию Беларуси. Система, разработанная на основе технологий искусственного интеллекта, в частности глубокого обучения моделей на основе сверточных нейронных сетей, направлена на повышение точности и эффективности идентификации вокализаций видов птиц. Созданная обширная база данных из более чем 2500 аудиозаписей содержит вокализации 116 видов птиц, что содействует обучению модели распознавания на разнообразных голосах птиц.

В статье описывается методология сбора данных, аннотирование и внедрение удобного программного интерфейса, который объединяет различные компоненты для непрерывного мониторинга. После успешного запуска и тестирования модель демонстрирует следующие показатели: точность: 0,92; макро среднее: f1-мера 0,5216, полнота 0,5311, точность 0,92; средневзвешенное значение: f1-мера 0,84, полнота 0,78, точность 0,92. Результаты многообещающие, хотя и указывают на необходимость дальнейшего уточнения и сбора дополнительных данных для повышения точности распознавания, особенно для редких видов с недостаточным количеством аннотаций. Исследование способствует сохранению биоразнообразия Беларуси и содействует участию общественности в орнитологических исследованиях.

Интеграция алгоритмов распознавания в общедоступный информационно-аналитический центр (ИАЦ) содействует объединению усилий по мониторингу птиц в Беларуси, предоставляя ценные данные для планирования охраны природы, экологических исследований и участия общественности в орнитологии.

Как показывает сравнительное исследование информационно-аналитического центра с автоматической системой распознавания голосовых сигналов BirdNet, ИАЦ выделяется среди своих аналогов благодаря высокой точности, удобному дизайну, возможностям идентификации в режиме реального времени и активному участию сообщества. Эти преимущества делают его эффективным инструментом для всех, кто стремится лучше понимать биоразнообразие птиц.

В статье также предлагаются подходы к дальнейшему повышению качества ML-моделей за счет использования онтологического подхода и технологии OSTIS. Интеграция онтологической структуры, как было продемонстрировано на примере Бубо-бубо (евразийского филина) в Беловежской пуще и Березинском биосферном заповеднике, повышает способность системы учитывать семантические связи между видами, их вокализациями и местами обитания. Формализуя знания с помощью SC-кода в рамках технологии OSTIS, система может лучше учитывать контекстуальные факторы, такие как вариации вокализации в зависимости от среды обитания, что приводит к снижению числа ложных срабатываний и повышению точности классификации по сравнению с текущими 75,6 процентами.

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Determining Neural Network Weights Using an Electrostatic Field

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Abstract-This study explores an approach to determining the weights and thresholds of a neural network based on the potential of an electrostatic field, without the need for additional analytical computations or traditional training algorithms. The neural network follows a metric-based recognition method, and the electrostatic field simulation is implemented in the Builder C++ programming environment. The software computes the total electrostatic potential at designated points in the proposed model (corresponding to sensor locations-potentiometers). The same software module also enables the creation of a neural network based on metric recognition methods, where the weights of the first-layer neurons are assigned based on the computed potentials of the simulated electrostatic field. The effectiveness of the resulting neural network is evaluated using the MNIST dataset for the task of handwritten digit classification. Additionally, the possibility of applying this approach to semantic text understanding tasks is considered.

Keywords—neural networks, image recognition, MNIST, training algorithms, electrostatic field potential, electrostatic field.

I. Introduction

The use of artificial neural networks remains a promising approach for solving various tasks [1]–[4], including pattern recognition problems. Although artificial neural networks were originally designed to mimic biological neural networks, their capabilities are still significantly limited compared to their biological counterparts. For example, biological neural networks possess the ability to accumulate a large number of recognizable patterns and can rapidly memorize and recognize new patterns (classification tasks) without lengthy training procedures or large training datasets. In contrast, modern artificial neural networks typically lack these abilities.

Consequently, developing new neural network architectures that enhance the capabilities of conventional models—particularly by accelerating network creation and training—remains an important research objective. To this end, studies [5]–[8] have proposed and described neural network architectures based on metric recognition methods. These architectures exhibit several distinctive features, including:

• The ability to rapidly construct the network structure (number of layers, neurons, and connections) based

on the initial problem parameters, such as the number of reference patterns and recognized classes.

- Transparency, meaning that the function of each neuron, layer, weight, threshold, and connection is well-defined and interpretable.
- Easy and flexible expansion of the network through cascade-based addition of new neurons, enabling new patterns (new recognized classes) to be incorporated into an operational network without modifying previously established weight values.
- The possibility of precomputing neural network weight values analytically using metric similarity measures.
- Compatibility with standard neural network training algorithms for additional fine-tuning.

While precomputing weight values accelerates neural network creation and training, it also requires computational time. As the number of recognized patterns and reference examples increases, the time required for weight calculations grows, particularly when higherdimensional weight matrices are needed for the first or zeroth layer of the network.

To address this challenge, study [8] demonstrated that neural network weights can be determined using electrostatic field parameters. This method enables nearinstantaneous weight assignment without analytical calculations, provided a relatively small reference dataset is available and each neuron has access to a model for reading electrostatic field parameters.

The primary objective of this study is to experimentally validate the proposed model) by assessing the functionality of a neural network whose weight values are determined based on electrostatic field parameters. In this approach, the potential of the electrostatic field serves as the key parameter.

To achieve this goal, a simulation model [8] was developed in the Builder C++ environment. This model computes the total electrostatic potential at each potentiometer sensor location (Figure 1). Additionally, a neural network based on the metric recognition method was implemented, allowing the first-layer neurons' weight values to be assigned according to the computed potentials of the simulated electrostatic field.

II. The Electrostatic Field Potential as the Weights of a Neural Network

The developed software module also facilitates performance evaluation using the MNIST (Modified National Institute of Standards and Technology) dataset. MNIST consists of handwritten digit images (0–9) and comprises two subsets: a training set (60,000 images) and a test set (10,000 images). Each image in MNIST is 28:28 pixels in size, with grayscale values ranging from 0 to 255.

In the experiments presented below, no training dataset was used, as the neural network did not undergo a training phase. Instead, only the test dataset (10,000 images) was utilized to assess the performance of the generated neural networks and compare the results. Here, the performance of the neural network is defined as the proportion of correctly classified test images.

The functionality of the generated neural network was evaluated using the Builder C++ software module.

The distance between two compared images in this example is set to 8 sm. That is, the plane for the simulated potentiometer sensors is positioned between two planes of charged surfaces of the images, at a distance of $d_2 = 4$ cm from each image (see Figure 1). Each active pixel on one image receives a charge of $q = -10^{-9}$, and $q = 10^{-9}$ on the other image, thus creating an electrostatic field between the image panels. Each sensor on the sensor panel, located between them, measures the potential of the electrostatic field between the two images at the sensor's position.

Thus, all the obtained potential values on the sensor panel are further used as weights for the firstlayer neurons, whose output separates these two images. Similarly, other reference images are compared pairwise in the same manner. The technology for instant weight determination based on the electrostatic field potential was described in more detail in [8].

III. Experimental Results

Table I presents the recognition results on the MNIST test dataset using 30 reference patterns from Figure 2a. The table shows both the results for each individual digit (where i_j represents the total number of digit j images in the MNIST test dataset, and s_j represents the number of correctly identified digit j images) and the overall result, which amounted to 5,047 correctly identified images (approximately 50%).

Table II presents the recognition results for the MNIST test set after reducing the distance between the two image planes to 4 cm and the distance to the sensor plane to $d_2 = 2$ cm.

Based on the results in Table II, it can be observed that the final recognition accuracy 53% improved by 3% compared to the previous experiment. This indicates that changes in the initial physical parameters of the simulated system—such as the value of the point charge q, the distance between the weight matrix cells d_1 (sensor spacing), and the distance between the image plane and the potentiometer sensor plane d_2 –also affect recognition performance.

Table III shows the recognition results for the MNIST test set after adding two additional reference patterns (Figure 2a) to each image, as shown in Figure 2c. After the new reference patterns were added, new first-layer neurons were cascaded into the neural network, and their corresponding weight tables were computed. The weight tables for the remaining neurons were not altered. Testing on the MNIST test set with the updated reference patterns increased the performance to approximately 70%.

In Table IV, the results of recognizing the MNIST test set after adding 20 new reference patterns, as shown in Figure 2c, are presented. This increased the total number of reference patterns to 70 (4 patterns for each class). The recognition results for the MNIST test set improved, with 7,721 images correctly identified (77%).

From the results in the tables, it can be observed that increasing the number of reference patterns also increases the percentage of correctly recognized images. Adding reference patterns to the neural network based on metric recognition methods does not change the previous weight values of the network.

IV. Determining Weights Based on Electrostatic Field Parameters for Semantic Tasks

This approach can theoretically also be applied to semantic tasks and natural language understanding tasks. As is known, there are various ways to encode language, implemented in different word embedding libraries. For example, Word2Vec, GloVe, BERT, GPT, and others. Language elements such as words, syllables, and word combinations are represented as vectors of numbers (embeddings). The number of digits in one word vector can be in the hundreds. To digitally represent a sentence, the text is broken down into words, syllables, or entire word combinations. For some word encoding methods, such as the BERT method, not only words or syllables are encoded but also the positional number of the word in the sentence, which allows for a more accurate understanding of the meaning of the text. For example, if for the sentence "Cat caught mouse" each word is encoded as a vector with three numbers, like this:

- "Cat" \rightarrow [23, -67, 89]
- "Caught" \rightarrow [12, 45, -34]
- "Mouse" \rightarrow [34, .78, -23]

We end up with a matrix of size 3x3. If each number in this matrix is converted into binary code, we get a matrix with binary codes:

[00010111] [10111111] [01011001] [00001100] [00101101] [1111110] [00100010] [00000001] [11101001]

As a result, by analogy with black-and-white images, we obtain a binary table of the sentence, which is



Figure 1. A scheme for obtaining neuron weight values based on the potential of an electrostatic field.



Figure 2. (a) 30 reference patterns, (b) Added reference set for the experiment with 50 reference samples, (c) 20 additional reference patterns for the experiment with 70 reference patterns.

Table I

Test results of the neural network on the MNIST test set with initial conditions: N = 30 reference patterns, q = 10^{-9} C, d_2 = 4 sm, d_2 = 2 sm. The number of recognized symbols for each digit class (s_j) The total number of characters in the database for each digit class (i_j) .Percentage of correctly recognized symbols (p_j)

		-
The number of recognized symbols for each digit class (s_j)	The total number of characters in the database for each digit class (i_j) .	Percentage of correctly recognized symbols (p_j)
s0 = 701	i0 = 980	p0 = 71%
s1 = 936	i1 = 1135	p1 = 82%
s2 = 296	i2 = 1032	p2 = 28%
s3 = 361	i3 = 1010	p3 = 35%
s4 = 434	i4 = 982	p4 = 44%
s5 = 357	i5 = 892	p5 = 40%
s6 = 413	i6 = 958	p6 = 43%
s7 = 504	i7 = 1028	p7 = 49%
s8 = 500	i8 = 974	p8 = 51%
s9 = 545	i9 = 1009	p9 = 54%
In summary		
5047	10000	50%

Table II

Testing Results of the Neural Network on the MNIST Test Set with Initial Conditions: N = 30 References, $q = 10^{-9}$ C, $d_2 = 2$ sm, $d_1 = 2$ sm. The number of recognized characters for each digit class (s_j) . The total number of characters in the dataset for each digit class (i_j) Percentage of correctly recognized characters (p_j)

The number of recognized characters for each digit class (s_j)	The total number of characters in the dataset for each digit class (i_j)	Percentage of correctly recognized characters (p_j)
s0 = 729	i0 = 980	p0 = 74%
s1 = 987	i1 = 1135	p1 = 86%
s2 = 307	i2 = 1032	p2 = 29%
s3 = 387	i3 = 1010	p3 = 38%
s4 = 468	i4 = 982	p4 = 47%
s5 = 385	i5 = 892	p5 = 43%
s6 = 484	i6 = 958	p6 = 50%
s7 = 532	i7 = 1028	p7 = 51%
s8 = 477	i8 = 974	p8 = 48%
s9 = 608	i9 = 1009	p9 = 60%
In summary		
5364	10000	53%

Table III

Test Results on the MNIST Test Set Using 50 References The number of recognized characters for each digit class (s_j) The total number of characters in the dataset for each digit class (i_j) Percentage of correctly recognized characters (p_j)

The number of recognized characters for each digit class (s_j)	The total number of characters in the dataset for each digit class (i_j)	Percentage of correctly recognized characters (p_j)
s0 = 852	i0 = 980	p0 = 87%
s1 = 1123	i1 = 1135	p1 = 99%
s2 = 516	i2 = 1032	p2 = 50%
s3 = 585	i3 = 1010	p3 = 58%
s4 = 775	i4 = 982	p4 = 79%
s5 = 588	i5 = 892	p5 = 66%
s6 = 555	i6 = 958	p6 = 58%
s7 = 616	i7 = 1028	p7 = 60%
s8 = 633	i8 = 974	p8 = 65%
s9 = 726	i9 = 1009	p9 = 72%
In summary		
6969	10000	70%

Table IV

Testing results on the MNIST test set using 70 reference patterns. The number of recognized characters for each digit class (s_j) The total number of characters in the dataset for each digit class (i_j) Percentage of correctly recognized characters (p_j) .

The number of recognized characters for each digit class (s_j)	The total number of characters in the dataset for each digit class (i_j)	Percentage of correctly recognized characters (p_j)
s0 = 852	i0 = 980	p0 = 87%
s1 = 1123	i1 = 1135	p1 = 99%
s2 = 516	i2 = 1032	p2 = 50%
s3 = 585	i3 = 1010	p3 = 58%
s4 = 775	i4 = 982	p4 = 79%
s5 = 588	i5 = 892	p5 = 66%
s6 = 555	i6 = 958	p6 = 58%
s7 = 616	i7 = 1028	p7 = 60%
s8 = 633	i8 = 974	p8 = 65%
s9 = 726	i9 = 1009	p9 = 72%
In summary		
7721	10000	77%

widely used in image recognition with neural networks. If we change the order of words, for example: "Mouse caught cat" then in this case, the binary image table also changes:

[00100010] [00000001] [11101001] [00010111] [10111111] [01011001] [00001100] [00101101] [1111110]

Accordingly, the neural network will be able to distinguish between these two sentences. The figure 3 shows the binary images of the two sentences: "Cat caught mouse" and " Mouse caught cat" constructed from the two matrices above, where 0 corresponds to the white area and 1 corresponds to the black area. Similarly to Fig. 1, the figure 3 presents the scheme for obtaining the first layer neuron weights based on the electrostatic field parameter - potential. The value of each pixel in the first binary image equal to 1 has a charge q = 10(-9), and the value of each pixel in the second binary image equal to 1 has the opposite charge q = -10(-9). As a result, an electrostatic field is formed between the two images. The figure 3 also shows that between the two binary images is a layer of 3*24=72 potentiometer sensors measuring the potential of the electric field at their location. The values of the obtained potentials are immediately fed as the weights of the first-layer neuron. As a result, this neuron can immediately distinguish between the two sentences without training. Similarly, for other pairs of images, the weights for other neurons in the first layer can also be directly defined.

V. Conclusion

Thus, the experiments conducted above show that a neural network with weight values determined by the characteristics of the electrostatic field is feasible. This indicates that the neural network can instantly determine weight values with a small reference set.

This means that the neural network can significantly faster memorize and recognize new patterns compared to standard neural network architectures. Furthermore, if needed, the resulting neural networks can be further trained using conventional training algorithms. As shown in [7], even in this case, the process of creating a neural network, calculating its weight and threshold values, and further training occurs faster than training a neural network using traditional methods with randomly initialized weight values. The model for determining the weight and threshold values of the neural network based on the electrostatic field parameters can further accelerate this entire process.

The reasoning presented above in this work shows that the capabilities of neural networks are even broader and allow not only computation but also instant memorization of patterns without training and calculations, provided there is a small set of reference patterns. If we consider the fact that electric charges and electric fields are omnipresent in the living cells of neurons in living organisms, as well as in the retinas of living organisms, etc., it can be hypothesized that living organisms could likely possess similar abilities.

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Figure 3. Scheme for determining neuron weights based on the electrostatic field potential for a semantic task.

ОПРЕДЕЛЕНИЕ ВЕСОВ НЕЙРОННОЙ СЕТИ С ИСПОЛЬЗОВАНИЕМ ЭЛЕКТРОСТАТИЧЕСКОГО ПОЛЯ Гейдаров Полад

В данном исследовании рассматривается подход к определению весов и порогов нейронной сети на основе потенциала электростатического поля, без необходимости в дополнительных аналитических вычислениях или использовании традиционных алгоритмов обучения. Нейронная сеть работает по методу метрического распознавания, а моделирование электростатического поля реализовано в среде программирования Builder C++. Программное обеспечение вычисляет общий электростатический потенциал в заданных точках предложенной модели (соответствующих расположению датчиков – потенциометров). Этот же программный модуль позволяет создавать нейронную сеть на основе методов метрического распознавания, в которой веса нейронов первого слоя назначаются на основе вычисленных потенциалов смоделированного электростатического поля. Эффективность полученной нейронной сети оценивается с использованием набора данных MNIST для задачи классификации рукописных цифр. Также рассмотрена возможность применение этого подхода в задачах семантического понимания текста.

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The Efficiency of FedAVG Federated Learning in Training Generative Image Models

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Abstract—Training neural networks often requires very large amounts of image data. However, sharing images owned by different institutions can be problematic. One of the known solutions could be to train neural networks jointly by way of iterative sharing neural models, but not the restricted sets of training images. Such an approach is known as Federated Learning. In this paper, we present results of an experimental study of the efficiency of Federated Learning of generative neural networks of the DC-GAN type. Specifically, the FedAVG approach has been investigated based on large collection of medical images, including chest x-ray images, axial slices of 3D computed tomography images, and Hematoxylin-Eosin stained histology images. The results of the FedAVG approach were found to be highly dependent on the homogeneity of the image datasets. Among the images being employed, the best potential for federated training was demonstrated by chest x-ray images, while the routine histology images were found to be unsuitable for FedAVG training. The 2D computed tomography image slices were situated somewhere in-between of these two image types and showed characteristically unstable behavior. The period of aggregation of training results on the federated server should be reasonably short and repeated after every 1-3 epochs performed on the local image datasets of federated clients.

Keywords—federated learning, generative models, FedAVG

I. Introduction

Training of modern neural networks typically requires a large amount of data. However, merging and sharing a sufficient amount of the original images can be problematic even with collaborating partners. This is due to factors such as data privacy, limitations applied by the national law, conditions of past contracts, ethical selflimitations, etc. In the context of medical applications, there could be several institutions in possession of the data necessary for the training of neural networks of common interest. However, these data may not be shared by the above reasons. Federated Learning (FL) methods [1] aim to train large neural network models together, without sharing image data between participating institutions. Instead, copies of the same model are trained on local image datasets of each client, and then, at the every training round, these copies are iteratively transferred to

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a server which aggregates them into a joint model and sends back.

Depending on the way the training data are generated and distributed, FL approaches are subdivided into two different categories. The first is primarily referred to as the horizontal one, whereas the other is called vertical [2]. In Horizontal FL participants share the same feature space but have different local samples. The goal is to train a global model that can generalize between samples from different clients. In the scenario of Vertical FL, clients share the same aligned samples but have different local features. The goal of Vertical FL is to train a global model that is capable of making predictions using the distributed features of shared samples. Thus, this paper is deals with Horizontal, Centralized, Non-Heterogeneous (same network architecture) Federated Learning.

There are several approaches exploring the FL setup including the FedProx [3], SCAFOLD [4], the FedProc [5], and some others. In this paper, we are considering a version of the FedAVG algorithm that averages weights of convolutional filters of the neural networks. Such an approach is known and commonly abbreviated as the FedAVG [1]. The family of the FedAVG algorithms are relatively simple but still under investigation in different applications. Unlike many other works, we are focusing on medical image generation rather than on the image classification.

Despite the basic idea of the FL method is transparent, implementation schemes of every particular algorithm could be different. For instance, in their work [1], McMahan with colleagues have introduced a version of FedAVG and performed a set of experiments that confirmed that the approach is robust to the unbalanced, nonindependent and identically distributed datasets. Among the options under consideration, FedAVG appears to be one of the most flexible, with the potential for easy implementation, adjustment, and modification according to the specific problem the researchers are dealing with. Nevertheless, it remains not completely clear how much it is applicable to the generative neural network models and what results it would provide for different kinds of medical images.

In this paper, we are using the weight-averaging approach to train Deep Convolutional Generative Adversarial Networks known as DC-GANs [6], [7]. The particular goal was to assess the impact of various factors on the quality of the FedAVG-based federated training such as the type of medical images, the amount of image data, the balance of different image classes owned by the clients participating in federated training, the output image sizes, and the way of integration of training and model aggregation steps. The relative simplicity of FedAVG algorithm and low communication cost it convenient to use it as a baseline for investigation of the technology of FL for widely used family of generative models of DC-GAN type (e.g., StyleGAN, CycleGAN, Conditional GAN, Wasserstain-GAN, Super-Resolution GAN) as compared to the extensively studied classification networks.

II. Materials

The study was performed based on three different image datasets. The first radiological dataset consisted of 10,000 chest x-ray images of healthy subjects, whereas the second one included 10,000 axial slices of 3D Computer Tomography images of lung tuberculosis (TB) patients. In addition, the third dataset represents histological images and was composed of 100,000 high-resolution color microscopy images routinely used for breast cancer diagnosis. The choice of such diverse medical image types was motivated by the intention to better understand the role of specific types of image features used for federated training.

A. Chest X-ray images

A study group of chest x-ray images was created by a random sub-sampling of suitable subjects from the original repository. The age range was chosen to be 50 years spanning from 21 to 70 years. The availability of the large image repository allowed to create a study group that was well-balanced by both age and gender. For every year of life we selected exactly 100 male and 100 female subjects. Such sub-sampling resulted in the study group consisting of (100 male + 100 female) subjects * 50 years = 10,000 subjects. Thus, we believe that the use of such a balanced dataset of healthy subjects allows us to avoid additional factors caused by the natural variability of pathological changes in different patients.

Since the primary goal of this study was not the analysis of chest radiographs as such but comparison of different ways of medical image generation in the context of FL, the original x-ray images were preprocessed to avoid unnecessary large intensity range. This was done by adaptive intensity rescaling of the original images stored in medical DICOM format with 2 bytes per pixel down to the commonly used range of 0 - 225. Rescaling was done with the help of well-known technique of cutting the intensity range by histogram

quantiles of 0.02 and 0.98. The characteristic large area of dark background was excluded using body masks which resulted from a preliminary image segmentation. Taking into account our close links with the manufacturers of x-ray machines, we have chosen to crop all the images by cutting out 25 % of bottom rows of the original chest scans and by 5% of pixels from the other three sides. Finally, all the images were resized down to 256x256 pixels proportionally. Example images are given in Fig. 1. Additional information related to the xray image properties in the context of classification tasks can be found in [8].



Figure 1: Examples of chest x-ray images.

B. Computed tomography images

For discovering possible dependencies of results on the medical image modality, we also used 2D slices of 3D CT images of tuberculosis patients. The original CT scans satisfy all the actual regulations, limitations, and the project agreements they are performed with. The original images were anonymized in due course before any steps of their computerized pre-processing and classifications. Thus, there are no ways to disclose, share, and disseminate any personal data. The approach and the sequence of steps of CT image data preparation are described below.

We started with a large CT image dataset containing as many as 10,714 3D CT scans. Then we excluded scans for which the information about Age and Gender of patients was not available. As a result, we end up with 8,463 CTs including 4,662 Males and 3,801 Females. The remaining 8,463 3D images were split into 2D axial slices. This resulted in 1,002,012 2D slice images of 512x512 pixels in size (574,309 in Male and 427,703 in Female image datasets). Finally, all the 2D images were exported to lossless PNG format with reduced 8 bit/pixel intensity resolution.

We started with a large CT image dataset containing as many as 10,714 3D CT scans. Then we excluded scans for which the information about Age and Gender of patients was not available. As a result, we end up with 8,463 CTs including 4,662 Males and 3,801 Females. The remaining 8,463 3D images were split into 2D axial slices. This resulted in 1,002,012 2D slice images of 512x512 pixels in size (574,309 of Male and 427,703 of Female patients). Finally, they were exported to lossless PNG format with 8 bit/pixel intensity. In addition, all slice images were sub-divided into 3 conditional anatomical groups ("classes") to ease processes of balancing the semantic content of image datasets (see Fig. **??**).

Class c1: The upper part of Liver.

Class c2: The Heart class, which was represented by a middle heart section plus some limited amount of adjacent axial slices along with Z vertical axis.

Class c3: The shoulders which include the upper part of lungs and their close neighboring sections above and below them by Z axis.



Figure 2: Examples of 2D slices of computed tomography images.

It should be noted that we were not able to consider other distinct anatomical sections such as the ones situated at the Neck and Kidney levels. This is because the project the image data came from, was focused on the lung tuberculosis and therefore patients were scanned only within the regions of lungs plus few additional upper and bottom safety image slices.

C. Histology images

Histological images playing the role of a "Gold standard" in diagnosis of oncological diseases world-wide. A study group of Hematoxilin-Eosin stained histological images was sampled from the dataset of whole-slide images used in an international challenge of breast cancer diagnosis (see "Minsk Team" in [9]). A total of 100,000 RGB image pieces (image tiles) of 256x256 pixels in size were sampled and pre-processed from the large original whole-slide images. The resultant image dataset included 50,000 images representing the norm and 50,000 images of cancerous tissue. Some distinctive Illustrative examples that help to imagine the image variability are given in [9]. Few illustrative examples are given in Fig. 3



Figure 3: Examples of histological images.

III. Methods

The primary objective of the present study was to conduct a series of computational experiments to evaluate the efficacy and productivity of FL collaborative processes on training medical image generation models, as well as to identify key factors playing the role. The experimental conditions are summarized and presented in an itemized style below.

- We used Deep Convolutional Generative Adversarial Networks because they remain very popular despite the emergence of several other image generators such as the diffusion models which produce higher-quality image samples and more easy to scale and control [10], [11].
- Training of generative models was executed with different number of training epochs before performing the aggregation step on the FL server. The aggregation was carried out after every 1, 2, and 5 epochs.
- In each experiment we trained generative network during the total of 100 rounds of federated training.
- The Influence of specific medical image modality, i.e., the image type was studied by way of running same set of experiments. Each experiment followed by comparison of the FL results including the federated training efficiency as well as the quality of generated images.
- In all the occasions we used the Fréchet Inception Distance (FID) [12] to evaluate the quality of the generated images. This metric combines two different and controversial properties. The FID score expresses quantitatively how similar the generated images to their parental image dataset and how variable the generated image dataset is. The smaller FID value, the more similar generated images to the original ones.
- During the federated training, the FID distance computed between the generated images produced by each copy of the local generative model as compared to the local training image dataset of each client. It should be noted that the resultant FID value is computed using Inception v3 neural net which is trained by itself each time it is called.
- For the research purposes, the FID score was also calculated for an aggregated model on the server relative to a common fetched dataset, which is the union of local image datasets.
- Dependence of federated training convergence on the image size was evaluated using relatively small image resolution of 64x64 and 128x128 pixels. This is because of commonly known substantive problems of GANs associated with generation of high-resolution images. An additional, purely technical reason was to accelerate the massive computations necessary for distributed training of image generators.
- Considering the very high computation expenses caused by a grid-like set of experiments, the size of generated images and corresponding number of image generation experiments was limited to 64x64 and 128x128. All the experiments were repeated for each image dataset and each resolution.
- Our FL setup has 2 clients that send all the weights of the local models to the server every round. Once the weights of local models are sent to the server, they are aggregated by weights averaging. Then the new copy of aggregated model is sent back to the clients to continue training on local data.
- The number of image data items was the same in each client and they do not overlap.
- Experiments were performed on a dedicated server equipped with 4 GPU of NVIDIA V-100 type with 16Gb of video RAM each.

IV. Results

The results of the computational experiments are summarized in figures 4 and 5. Fig. 4 reports results of joint federated training of generative model aimed at creating images of 64x64 pixels whereas Fig 5 represent the training of the model for generating artificial images of 128x128 pixels in size. It is easy to see that the structure of both figures is identical. The rows of both figures correspond to 3 different types of medical images examined in this study including chest x-ray, computed tomography, and histological images.

The figure columns illustrate dynamics of convergence of federated training processes with respect to 3 different ways of aggregation of particular clients' results by the federated server. Namely, 3 figure columns depict results obtained when aggregation (averaging) of neural net weights performed after 1, 3, and 5 training epochs accomplished by the clients on their private image data.

The image data sets used in this study are different in the degree of their heterogeneity. The most homogeneous dataset among them is the dataset of chest x-ray images of 10,000 healthy subjects. Typically, for non-specialists majority of them appear nearly the same except for subtle visual features associated with age, gender, and (sometimes) general body constitution. More details can be found in [13], [14]. As a result, from the 1st row of Fig 4 representing training of tiny 64x64 x-ray images we see that the federated training progresses reliable and consistent for all 3 ways of aggregation of particular training results obtained by different clients. However, when it turns out to larger image samples (see the 1st row of Fig 5), the plot curves expressing the consistency of results produced by trained generative models measured with the help of FID scores, become more noisy. In case the aggregation was done after every 5 epochs (last plot of the 1st row of Fig 5), the training is not converged at all.

In general, the training trajectory of computed tomography images (see the 2nd rows of figures 4 and 5) is somewhat similar to the x-ray images discussed above. However, in all the occasions the training becomes much more unstable. This is evident from the bahaviour of curves characteristic for both training processes in clients (blue and yellow curves) as well as for the results of aggregation in the server (green curve).

It is easy to note even from the small set of histological images shown in Fig. 3 that they are highly variable morphologically. Usually, there is no repetition of the same cell patterns presented in the very large wholeslide microscopy image taken from the biopsy sample. This case, the FedAVG approach behaves similarly for both image sizes (see the 3rd rows of figures 4 and 5). Namely, in the majority of training loops, the model that aggregates results obtained by two clients (note the green line) is always situated above the blue and orange lines that correspond to the two independent clients. The aggregated results are notably worse than the ones obtained when each client trains generative model locally. This practically means that the Fréchet distance between the real and generated images is large and the use of FL technology leads to high dissimilarity of real and generated images. Thus, under given specific conditions, it is not worth considering Federated training.

V. Conclusions

Results obtained in this study allow to draw the following conclusions.

1. It was found that the potential utility of the horizontal FedAVG FL approach depends strongly on the natural homogeneity of the image datasets involved in the federated training.

2. Among the examined images, the best potential for federated training has been demonstrated by chest x-ray images whereas the typical Hematoxylin-Eosin stained images were rendered as not suitable for FedAVG training. The 2D computed tomography image slices are situated somewhere between the two aforementioned image types with some unstable behavior during the training.

3. The period of aggregation of training results on the federated server should be reasonably short and repeated after every 1-3 epochs performed on the local image datasets of clients.

VI. An outline of future research directions

Finally, let us make a sketch of possible future research for two different directions. The firs direction is related to the near future of developments in the field of FL technologies while the second one is more general and associated with the potential synergy of joining basic ideas and technologies of *General-AI* and Large Language Models (LLMs) [16].

A. Vertical Federated Learning in medical image analysis

Based on the distributed way of data, FL can be primarily categorized into three scenarios [15]:

- Horizontal FL, which is dealing with image data with similar distribution among the clients (e.g., chest x-rays of Norm and Pathology, MRI tomography images acquired by different MRI scanners with the strengths of magnetic field of 1.5 and 3.0 Tesla, etc).
- Vertical FL in which clients share the same samples (e.g., patients) but have different local features.
- Federated Transfer Learning [17] in which clients share both common samples and parts of the feature spaces.

In our view, the main way of further development of FL technologies in computerized medical diagnosis and treatment is to jointly use multi-sort image, signal, and laboratory data and proceed with them by the algorithms of Federated Transfer Learning technology. In this context, the Federated Transfer technology could be used without the need to share aforementioned private data to fulfill the local law and privacy concerns applied in different places (e.g., hospitals, regions, countries).



Figure 4: Results of training generative model for images of 64x64 pixels in size (explanations in text).



Figure 5: Results of training generative model for images of 128x128 pixels in size (explanations in text).

B. Relationships with classical General-AI Methodology

The process of integration of classical AI concepts such as semantic networks, logical inference, frame-based systems, and various connectionist approaches (i.e., methods of cognitive modeling that utilizes large networks of simple computational units) with modern LLM technologies offers promising ways to address existing limitations in reasoning, knowledge grounding, and interpretability. A short list of promising approaches to bridge these two is given below. There is a large body of relevant references that can be explored separately according to the specific area of interests.

- Structured Knowledge Integration by way of using semantic networks as Knowledge Bases in explicit relationships (e.g., "Paris is capital of France"). Generation of commonsense knowledge by fine-tuning LLMs on semantic graphs.
- Enforcement of frame-based representations including generation of structured output using frame templates (e.g., "disease: symptoms, treatments") to guide LLMs in generating consistent outputs by converting unstructured LLM outputs into structured formats.
- Improving explainability and debugging by tracing inference paths and map LLM outputs to paths in a semantic network to explain decisions (e.g., "The model inferred X because of relationships Y and Z") and using tools like AllenNSP to visualize reasoning steps. Using logical inconsistency detection to identify hallucination patterns in LLMs. For instance, detecting claims that violate knowledge graphs.
- Using Hybrid Models that combine symbolic AI (rulebased systems) with LLMs to improve reasoning and decision-making.
- Employing few-shot and zero-shot for learning LLMs' ability to generalize from minimal examples, aligning with General AI's goal of adaptability.
- Promoting cross-disciplinary applications by way of using LLMs in fields like neuroscience and robotics to emulate human-like learning and adaptability.

Thus, classical AI techniques can mitigate LLM weaknesses (e.g., hallucination, poor reasoning) by injecting structured knowledge, enabling hybrid neuro-symbolic architectures, and improving interpretability. This synergy could lead to systems that are not only powerful in language tasks but also capable of broader, more generalized intelligence.

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ОЦЕНКА ЭФФЕКТИВНОСТИ ТЕХНОЛОГИИ FEDAVG ПРИ ФЕДЕРАТИВНОМ ОБУЧЕНИИ ГЕНЕРАТИВНЫХ НЕЙРОННЫХ СЕТЕЙ

Ковалев В. А., Карпенко Д. С.

Цель данной статьи - представить результаты экспериментального исследования эффективности федеративного обучения генеративных нейронных сетей типа DC-GAN. В качестве основы федеративного обучения был выбран подход FedAVG, который был исследован на больших наборах медицинских изображений, включающем рентгеновские снимки грудной клетки, аксиальные срезы трехмерных компьютерных томограмм, а также гистологические изображения, окрашенные гематоксилином-эозином. Было установлено, что результаты подхода FedAVG сильно зависят от однородности наборов изображений. Среди рассматриваемых изображений наилучший потенциал для федеративного обучения продемонстрировали рентгеновские снимки грудной клетки, в то время как типичные гистологические снимки, окрашенные гематоксилиномэозином, оказались непригодными для обучения методом FedAVG. В этом отношении, 2D слои компьютернотомографических изображений оказались где-то между указанными двумя классами. При этом процесс обучения генеративной нейронной сети на томографических изображениях отличался значительной нестабильностью при переходе от эпохи к эпохе. Установлено, что период агрегирования частных результатов обучения на стороне федеративного сервера должен быть достаточно коротким, порядка 1 раз в течении 1-3 эпох тренировки участниками федеративного обучения их копий нейронных сетей на локальных наборах изображений.

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Technological Aspects of Control Adaptation Based on Neural Network Modeling

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Abstract—An innovative technology for adapting control signals of the technological production cycle control system to external control actions and random disturbances is presented. A new solution for reducing the impact of destabilizing environmental factors in real time is proposed. A method for adapting the automated technological cycle control has been developed, based on constructing control feedback algorithms to reduce the sensitivity of process operation parameters to changes in the operating conditions of process equipment and the environment. A description of the tools for implementing the means of adapting the technological cycle control based on constructing control feedback algorithms and synthesizing neuroregulators using neural network algorithms is provided. A procedure for generating a knowledge base in accordance with the "technological processes with probabilistic characteristics" ontology is proposed, providing a formal description of the component classes of the process cycle, their properties and relationships between classes, coding in the SC code format and integration with logical inference mechanisms.

Keywords—adaptive control, neural network modeling, feedback construction algorithms, synthesis of neuroregulators, adaptation technology

I. Introduction

In the process of real operation of complex technical systems, in particular, the technological production cycle [1], there is a need to take into account external destabilizing factors in real time. Therefore, the issue of developing methods, algorithms and tools that can ensure a significant reduction in the sensitivity of the parameters of the technological cycle to the impact of destabilizing factors, including random external disturbances and control actions, deserves attention.

Development of new technologies for control adaptation based on modern methods of artificial intelligence will allow building an ecosystem of solutions for the automation of modern production systems, improving product quality and economic efficiency.

The article describes the technology for adapting the control of the technological process at the level of technological operations, which ensures the use of intelligent computer systems of adaptive control in real time. The process of synthesis of a neuroregulator is described, Vladislav Prokhorenko Department of Mathematical Problems of Control and Informatics Francisk Skorina Gomel State University Gomel, Belarus Email: shnysct@gmail.com

including the use of algorithms for automated search for the optimal architecture of a neural network.

II. Creation of a knowledge base on the subject area "technological processes with probabilistic characteristics"

The procedure for generating a knowledge base based on an ontology involves the sequential formation of structured data reflecting the entities and relationships of the subject area. This process is based on the formalization of knowledge about technological and probabilistic technological processes, their elements and characteristics.

The relevance of building a knowledge base using OS-TIS technology [2] is due to the increasing complexity of modern technical systems and the need for an integrated approach to their control. The advantages of OSTIS are to ensure a uniform representation of knowledge through the use of a formalized SC-code language, which helps to increase the accuracy and consistency of data, and also allows for the automation of information update and adaptation processes. In addition, OSTIS technology ensures system scalability by supporting the dynamic integration of heterogeneous data sources, which is especially important for intelligent systems operating in a changing environment. Thus, the use of OSTIS for building a knowledge base contributes to the formation of effective, adaptive and highly accurate models that ensure high-quality control of complex technical objects.

The first stage is the extraction of information from regulatory and technical documentation, scientific publications and empirical data related to the operation of complex technical systems. The obtained information is analyzed and interpreted in the context of the ontology, which allows identifying key concepts such as technological processes, technological and microtechnological operations, as well as probabilistic parameters for their implementation.

The next stage consists of structuring the data in accordance with the ontological model. For this purpose, classes and their attributes are formed, connections between entities are established, and constraints and dependencies are defined. For example, a technological operation is linked to the corresponding microtechnological operations, and the probabilistic parameters of the processes are determined based on statistical analysis of data on the actual functioning of the systems.

To represent knowledge, SC-code is used – a formal language used in OSTIS technology [3]. Transformation of formalized data into SC-code ensures the creation of machine-processed semantic networks, where each concept receives an unambiguous description and a clear connection with other elements of the system is established. Knowledge integration is carried out by combining individual semantic modules into a single model, which helps ensure the integrity and consistency of the information presented.

After the coding stage, a comprehensive check of the correctness and completeness of the integrated knowledge base is carried out. Verification is carried out using logical analysis methods to identify and eliminate contradictions in the presented data. Validation, in turn, is carried out using expert assessments and comparative analysis with empirical data, which allows confirming the practical applicability and reliability of the developed system.

The final stage is the integration of the knowledge base with reinforcement learning and adaptive control systems, which provides the ability to conduct intelligent analysis, forecast process parameters and make management decisions in real time. The use of semantic technologies allows dynamically updating the knowledge base and adapting it to changing operating conditions of technical systems.

As a result, a complex system is formed that is capable of dynamically updating knowledge and supporting decision-making at various levels of technological process management.

Thus, the application of the developed ontology for constructing a knowledge base in OSTIS technology is a multi-stage process, including formalization, structuring, semantic coding, integration, as well as verification and validation of the presented knowledge. This approach contributes to the creation of a flexible and adaptive intelligent system capable of providing effective management of technological processes due to automated analysis and updating of information.

Direct loading of data into the knowledge base through specialized interfaces that provide automated recognition and integration of ontology elements into the overall architecture of the system. At the subsequent stage, the process of indexing and optimization of the loaded information is implemented to ensure fast semantic search and correct logical inference, and data synchronization mechanisms are configured to maintain the relevance of the knowledge base [3].

III. Algorithms for the synthesis of neuroregulators

Neural networks are parameterized models that can be used as universal approximators [5], are noise-resistant, and have applications in complex applied problems. The developed control adaptation system uses a procedure for synthesizing a neural regulator using neural network algorithms. The procedure for synthesizing a neural regulator can also include the use of algorithms for searching for the optimal neural network architecture. The general approach assumes that the user of the system can specify numerical criteria for assessing the quality of adaptation (functionality for assessing the quality of adaptation) and has a simulation model [6] of the process control system. Alternatively, it is possible to simulate the known dynamics of a prototype regulator, if available (Fig. 1).



Figure 1. General schemes for synthesizing neuroregulators in the presence of an existing prototype (left) and when searching for an optimal action selection policy using reinforcement learning methods (right)

IV. Modeling the dynamics of an existing regulator

If an existing prototype regulator of the system is available, its dynamics can be simulated using supervised learning [7].

The process of training neural networks (Fig. 2) consists of searching for optimal values of the adjustable parameters of the model (weight coefficients) in the context of the problem being solved, which is usually done by solving some optimization problem, usually by gradient methods [5]. It should be noted that at the data collection stage, it is necessary to ensure the storage of complete and representative statistics of the functioning of the prototype regulator, adequately reflecting the existing space of observations and control actions.

V. Search for the optimal neural network architecture

Since the task of selecting the neural network structure in each case is complex and difficult to formalize, meth-



Figure 2. Dynamics of change of loss function (training and validation) in the process of constructing a neuroregulator based on a prototype regulator

ods for partial automation of its solution are proposed. Within the framework of the developed technology, 2 approaches to searching for the optimal architecture of the neuroregulator are implemented: based on the scheme of enumeration of candidate architectures and based on the evolutionary algorithm. In the case of the structure of the observation space of the neuroregulator, which allows the use of neural network architectures that are not deep, the enumeration schemes allow obtaining and clearly displaying the efficiency of the candidate architectures under consideration (Fig. 3).



Figure 3. Example of a heat map of average values functionality for assessing the quality of control adaptation in the automated selection of the architecture of the neuroregulator

When solving the problem of searching for a deep architecture for a neuroregulator, the criteria for enumeration are not obvious. Genetic algorithms are potentially universal [10], they allow finding a solution in a situation where it is unknown how to search for it. There are examples when genetic algorithms for searching for neural network architectures have significantly improved the quality of models [11]. The search for the optimal architecture of a neuroregulator within the framework of the described approach is carried out using a modified NEAT neuroevolution algorithm (Fig. 4), in which a sequential movement from simple structures to more complex ones is carried out [11] [12]. Unlike NEAT, the proposed algorithm does not perform optimization of the weights of connections in the neural network using evolutionary methods and operates not with single neurons as nodes, but with modules that can represent an arbitrary given set of layers. The use of an evolutionary algorithm allows constructing a neural network architecture corresponding to the problem being solved (Fig. 5).



Figure 4. Scheme of evolutionary algorithm for searching for architecture of neuroregulator

VI. Synthesis of a neuroregulator for optimal control adaptation

In real conditions, the principles of constructing optimal control adaptation may not be obvious. In this situation, reinforcement learning methods can be used to solve the problem of synthesizing a neuroregulator [6].

This approach allows taking into account the requirements specified by the technological regulations for the implementation of a technological operation as part of the production process and to synthesize control adaptation to ensure the functioning of the process in accordance with these requirements. Formalization of user requirements for the policy of choosing control adaptation is carried out by defining the function that assesses the quality of control adaptation.

When solving the problem of finding the optimal strategy for servicing the equipment devices of the techonogical process (TP), the function of assessing the quality of control adaptation includes components responsible for assessing the stabilization of the parameters of the TP operation, such as the time of continuous operation of the cycle (R_{nop}), the total volume of costs for servicing and



Figure 5. An example of a deep neuroregulator architecture obtained by applying evolutionary search.



Figure 6. Histograms of distributions of total costs during testing of the standard system regulator and the trained neuroregulator



Figure 7. Histograms of distributions of total costs during testing of the standard system regulator and the neuroregulator synthesized with reinforcement learning algorithms

eliminating failures and equipment accidents (R_{cost})), the total number of equipment failures (R_f) , including those that led to an accident (R_{fe}) , the total number of preventive maintenance per cycle (R_{rep}) . The coefficients (α_{1-5}) are set by user of the system to determine the weights assigned to the components. In accordance with the requirements imposed on the process of adaptation of the TP control, the target function is constructed on the basis of these components:

 $R = \alpha_1 R_{nop} + \alpha_2 R_{cost} + \alpha_3 R_f + \alpha_4 R_{fe} + \alpha_5 R_{rep}$

The neural regulator is trained using policy gradient algorithm (the REINFORCE algorithm [2]). As a result of training, the system with the constructed regulator shows higher efficiency in minimizing maintenance costs than the system with the standard regulator (Fig. 7). At the same time, the cycle downtime associated with failures does not increase. Testing of models allows to establish that the use of a neuroregulator in the control system has reduced the costs of process maintenance by 20-25% according to the specified criteria for the quality of control adaptation.

A similar approach can also be considered when solving the problem of stabilizing the parameters of a technological operation of laser processing of materials [6]. For example, in the problem of single-beam laser thermal splitting of brittle non-metallic materials (Fig. 9), an important issue is maintaining the temperature regime in order to prevent overheating and melting of the workpiece. Structure of the technological operation is shown in Fig. 8 In this problem, the function for assessing the quality of adaptation has the form:

$$R = \alpha_1 R_T + \alpha_2 R_P + \alpha_3 R_\sigma$$
 where

• R_T is the component for assessing temperature


Figure 8. Fragment of the knowledge base about the technological operation of laser cutting

maintenance within the permissible range;

- R_V is the component for assessing the cutting speed;
- R_{σ} is the component for assessing the maximum tensile stress;
- α_{1-3} are the coefficients defining the weights of the components.

Figure 10 shows the dynamics of the change in the average values of the function for assessing the quality of control adaptation when training the neural regulator of the process operation control system using the REIN-FORCE algorithm.

Table I shows the results of using the neural regulator of the process operation of laser material processing. It contains the values of the parameters of speed (V), laser radiation power (P), observed temperature (T) and the approximated value of the maximum tensile stress (σ_{yy}) . The use of neuroregilator synthesis algorithms for adaptation of the control of the technological operation of laser processing made it possible to increase the processing speed by 21% while maintaining temperature within the permissible range of values.

Table I

Comparison of the values of the parameters of the technological operation of laser processing of materials without the use of a neuroregulator (first line) and with the use of a neuroregulator (second line)

V,m/s	P,Wt	T,K	σ_{yy} , MPa
0.011	24.0	1390	7.04
0.0133	26.5	1395	7.2



-2.24-1.92-1.60-1.28-0.96-0.64-0.320.00 0.32 0.64

Figure 9. An example of visualization of temperature fields (a) and tensile stress fields (b) on the surface of a glass workpiece during laser processing technological operation



Figure 10. Dynamics of changes in the function of assessing the quality of adaptation in the learning process

VII. Conclusion

Neural networks, having the properties of universal approximation and resistance to noise, allow one to effectively solve control problems under conditions of uncertainty. The article presents the technology of adaptive control of automated production systems based on neural networks, which ensures the use of an intelligent computer system for adapting control of the technological cycle in real time.

The use of neural network modeling algorithms in the implementation of adaptation of the control of the technological operation of laser processing of materials made it possible to increase the processing speed by 21% and reduce the costs of servicing the equipment of the technological production cycle by 20-25%.

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ТЕХНОЛОГИЧЕСКИЕ АСПЕКТЫ АДАПТАЦИИ УПРАВЛЕНИЯ НА ОСНОВЕ НЕЙРОСЕТЕВОГО МОДЕЛИРОВАНИЯ

Смородин В.С., Прохоренко В.А.

Представлена инновационная технология адаптации управляющих сигналов контура управления технологическим циклом производства к внешним управляющим воздействиям и случайным возмущениям. Предложено новое решение для снижения влияния дестабилизирующих факторов окружающей среды в режиме реального времени.

Разработан метод адаптации управления технологическим циклом автоматизированного производства, основанный на построении алгоритмов обратных связей по управлению для снижения чувствительности параметров технологических операций к изменениям условий функционирования технологического оборудования и окружающей среды.

Приведено описание инструментария для реализации средств адаптации управления технологическим циклом производства, основанного на построении алгоритмов обратных связей по управлению и синтезе нейрорегуляторов с использованием нейросетевых алгоритмов. Предложена процедура генерации базы знаний в соответствии с онтологией «технологические процессы с вероятностными характеристиками», обеспечивающая формальное описание классов компонентов технологического цикла, их свойств и взаимосвязей между классами, кодирование в формате SC-кода и интеграцию с механизмами логического вывода.

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Semantic Analysis of Speaker Personality Traits for Voice User Interfaces of Intelligent Systems

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Abstract—Modern speech interfaces have achieved remarkable advancements in intelligibility, naturalness of synthesized speech, and accuracy of speech recognition, enabling seamless integration into everyday life. These capabilities underpin the growing prevalence of voice-based interactions with artificial intelligence (AI) systems. However, enhancing user-machine interaction requires addressing empathy and personalization, adapting AI responses to users socio-cultural, professional, and psychological traits. This is particularly relevant as anthropomorphic robotic systems emerge, where voice may serve as the sole communication channel. This paper explores how semantic analysis of vocal characteristics can infer personal traits, leveraging open semantic technologies to improve intelligent systems adaptability and empathy.

Speech interfaces (SI) or voice user interfaces (VUI) have evolved significantly, with text-to-speech (TTS) systems achieving high naturalness and speech-to-text (STT) systems boasting impressive recognition accuracy [1]. These advancements, driven by deep learning and large-scale datasets, have made voice a primary modality for interacting with AI, from virtual assistants like Siri and Alexa to cutting-edge models like ChatGPT with voice capabilities [2]. Currently, such systems are ubiquitous, facilitating tasks from ordinary scheduling to complex problem solving [3].

Keywords—semantic analysis, speech interfaces, OSTIS, personalization in AI, personality traits recognition, intelligent systems, empathy in human-machine interaction, OCEAN personality model, real-time voice processing

I. Introduction

However, challenges remain in moving these interactions beyond the usual functionality. Users increasingly expect empathetic, context-aware responses tailored to their individuality. This demand is further amplified by the growing popularity of anthropomorphic robots, such as Atlas by Boston Dynamics, Ameca by Engineered Arts and and Optimus by Tesla, designed for human-like interaction [4]–[6]. In such systems, voice often becomes the sole input source, which requires advanced analysis to decode not only the content, but also the speaker's personal characteristics — accounting for extralinguistic features of their speech: psychological, sociocultural, professional, and other aspects of their behavior [7]. This enhances user engagement during interaction and fosters a positive overall user experience, as personalized and emotionally nuanced responses create a sense of genuine dialogue, strengthening trust and attachment to the system. When an interface not only solves a task but also considers the user's context, emotional state, and cultural background, they feel heard and understood, reducing cognitive load and increasing satisfaction. In the long term, this builds loyalty, as the interaction ceases to be transactional and evolves into meaningful, human-like communication.

II. State of the art in emphatic voice interfaces for intelligent systems

Despite this technological maturity, most speech interfaces deliver generic responses that lack personalization, a limitation evident in social robots used for therapy, as described in the study on a personalized behavior control system for social robots [8]. These robots, designed to assist children with autism, often fail to adapt to individual emotional or behavioral cues, such as when a child's heightened excitement requires a calming response, yet the system provides a standard reply, potentially disrupting engagement. A promising advancement addressing this gap is the Empathic Voice Interface (EVI), introduced by Hume AI [9]. EVI analyzes prosodic features like pitch variation and tempo to infer emotional states such as joy or stress, adjusting its tone and phrasing to enhance perceived empathy, as seen when it softens delivery for a trembling voice. Supported by findings in Frontiers in Robotics and AI (2024), which link emotionally responsive interfaces to improved trust, EVI leverages emotional speech datasets akin to those in Scientific Data (2024), marking a shift toward emotionally intelligent AI.

However, integrating such innovations into broader intelligent systems remains a challenge, as real-time personalization across socio-cultural, professional, and psychological user profiles is still nascent. The OSTIS framework, with its semantic network approach, offers a solution by decoding vocal cues-pitch, rhythm, hesitations—beyond linguistic content to infer user traits and



Figure 1. Example of a personalized social robotics system for therapist-assisted interaction with children with autism [8]

adapt responses, such as adopting a formal tone for professionals or a calming cadence for stressed speakers [10], [11]. This capability is critical as anthropomorphic robots and virtual assistants increasingly dominate human-AI interaction, where voice often serves as the sole input. By formalizing vocal-emotional mappings in a scalable knowledge base, OSTIS can bridge the personalization gap, moving speech interfaces beyond functionality toward deeper, trait-sensitive communication that aligns with users' unique needs and expectations.

III. Problem of personality traits formalization and modeling

Personality traits are enduring patterns of thoughts, feelings, and behaviors that distinguish individuals from one another, shaping how they interact with the world. According to Matthews, Deary, and Whiteman [12], these traits are relatively stable over time and across situations, emerging from a complex interplay of genetic, environmental, and developmental factors. They provide a framework for understanding individual differences, influencing everything from social relationships to decision-making styles. In the context of intelligent systems, recognizing these traits via voice can enable more adaptive, user-centric interactions, making their formalization a critical step for advanced speech interfaces [13].

Various models have been proposed to categorize personality traits, including the Big Five, Myers-Briggs Type

Indicator (MBTI), HEXACO, Dark Triad, Eysenck's PEN model, and the 16 Personality Factors (16PF) [14]. Among these, the Big Five, HEXACO, Dark Triad, and 16PF stand out as the most scientifically verified, backed by extensive empirical research and widespread use in psychological studies. The Big Five, or Five-Factor Model (FFM), boasts over 10,000 citations in peer-reviewed literature (Costa & McCrae, 1992) [15], while HEXACO, an extension of the Big Five, gains traction for its inclusion of honesty-humility (Ashton & Lee, 2007) [16]. The Dark Triad-narcissism, Machiavellianism, and psychopathy-excels in clinical and forensic contexts with robust validation (Paulhus & Williams, 2002), and the 16PF, with decades of refinement, supports detailed profiling (Cattell, 1946). In contrast, MBTI and PEN, while popular, lack comparable empirical rigor, with fewer publications grounding their constructs in realworld data. The Big Five emerges as the most commonly used and cited system, owing to its simplicity, reliability, and cross-cultural applicability.

To evaluate the applicability of personality traits models for semantic analysis in voice user interfaces, a comparison of six prominent models is presented in Table I (where Emp. Val. – Empirical Usage, the degree to which the model is applied in professional settings for assessment, diagnosis, or therapy; Cross-Cult. – Cross-Culture, the degree to which the model's concepts and structure are consistent and applicable across different cultures). The data for this table was collected from semanticscholar.org by searching for the number of references to each model in scientific publications over the last five years in the fields of psychology and computer science. The models are assessed based on citation count, clinical usage, empirical validation, cross-cultural applicability, and simplicity, as these factors determine their suitability for intelligent systems requiring robust and adaptable frameworks.

The Big Five model stands out with over 10,000 citations [15], reflecting its widespread adoption and robust empirical support. Its simplicity and cross-cultural applicability make it ideal for general-purpose applications, including voice-based intelligent systems. HEX-ACO, while empirically strong, is less cited and primarily used in research due to its recent emergence [16]. The Dark Triad excels in clinical and forensic contexts [17], offering targeted insights into specific traits but lacking broad applicability. The 16PF provides detailed profiling for clinical diagnostics [18], though its complexity limits accessibility. MBTI and PEN models, despite popularity in non-clinical settings, suffer from weaker validation, reducing their reliability for advanced systems.

The Big Five model comprises five core scales, often described using the so-called OCEAN notation: Openness (creativity, curiosity, and preference for novelty), Conscientiousnes (self-discipline, organization, and dependability), Extraversion (sociability, talkativeness, and assertiveness), Agreeableness (compassion, cooperativeness, and trust) and Neuroticism (emotional instability, anxiety, and moodiness). Each of these scales represents a continuum of traits observable in behavior and, notably, vocal patterns [13]. These scales are:

- **Openness to Experience**: Reflects a person's imagination, creativity, and willingness to embrace new ideas or unconventional perspectives. High scorers are often curious and artistic, exhibiting varied pitch and expressive intonation in speech, while low scorers prefer routine and may speak in a more monotone, predictable manner.
- **Conscientiousness**: Measures organization, dependability, and goal-directed behavior. Individuals high in this trait are methodical and deliberate, often speaking with clear, steady pacing, whereas those low in conscientiousness may display erratic rhythms or frequent interruptions, signaling impulsivity.
- **Extraversion**: Captures sociability, assertiveness, and energy levels. Extroverts tend to speak loudly, quickly, and with animated prosody, reflecting their outgoing nature, while introverts use softer tones and slower tempos, indicating reserve or introspection.
- Agreeableness: Indicates compassion, cooperation, and likability. High agreeableness manifests in warm, gentle vocal tones and supportive phrasing, whereas low scorers may sound brusque or confrontational, with sharper intonation reflecting competitiveness or skepticism.
- **Neuroticism**: Assesses emotional instability, anxiety, and moodiness. Those high in neuroticism often exhibit tense, shaky voices or frequent hesitations under stress, while emotionally stable individuals maintain calm, even-toned speech even in challenging situations.



Figure 2. The Big Five personlity traits model [19]

Formalizing these scales within an ontology, such as the OSTIS framework, involves creating a structured knowledge base that maps acoustic features (e.g., pitch, tempo) to trait dimensions. However, real-world applications of models like the Big Five reveal limitations-scales often require clarification and expansion to capture a more comprehensive picture of personality traits, as their broad categories may oversimplify nuanced behaviors. Furthermore, intelligent systems benefit from combining different models (e.g., integrating HEXACO's honesty-humility with the Dark Triad's clinical insights) and flexibly adjusting to the specific needs of an application, such as mental health support versus professional training. OSTIS technology is essential here, offering a dynamic framework to refine and extend trait scales, merge diverse models, and adapt them contextually. By providing a machine-readable representation of personality, this semantic approach enables intelligent systems to systematically interpret vocal data, infer user traits, and tailor responses-e.g., slowing speech for a high-Neuroticism user to reduce anxiety. Ultimately, OSTIS enhances adaptability and empathy, laying the groundwork for next-generation speech interfaces that resonate with users' psychological profiles across varied use cases.

IV. Proposed approach

The formalization of the Big Five personality traits within the OSTIS framework offers a robust pathway to enhance speech interfaces by enabling semantic analysis of vocal characteristics. However, the challenge lies in bridging the gap between the raw physical parameters of a speech signal and high-level personality inferences. Low-level signal parameters are numerous and diverse,

Model	Citations	Clinical Usage	Emp. Val.	Cross-Cult.	Simplicity
Big Five (FFM)	> 10000	Moderate	Strong	High	High
HEXACO	~ 5000	Limited	Strong	Moderate	Moderate
Dark Triad	~ 3000	High	Strong	Moderate	Moderate
16PF	~ 2500	High	Strong	Moderate	Low
MBTI	~ 1500	Low	Weak	Low	High
PEN Model	~ 1000	Low	Moderate	Low	Moderate

Table I Comparison of Personality Traits Models

encompassing timbre descriptors like Fourier coefficients (FC), Linear Predictive Coding (LPC), cepstral coefficients (MFCC), harmonic representations, and filter bank outputs, as well as prosodic features such as fundamental frequency (F0), jitter, shimmer, syllabic/phrasal tempo, tempo deviation, and rhythm. These parameters can be measured across different psychoacoustic scales — logarithmic, Mel, Bark, etc. and ussualy supplemented by first- and second-order derivatives to capture dynamic changes. The resulting feature vector for a single analysis window often spans thousands of elements, creating high-dimensional data that is computationally intensive and not always optimal for personality trait recognition.

To address this, we develop a novel approach, initially proposed by Rudolf A. A., that compresses low-level signal features into a set of 14 high-level psychometric scales, designed to reflect human perception of a speaker's voice in intuitive and semantically meaningful categories. Using an acoustic-semantic analysis approach, proposed in [20], [21], and [22], and combining these with the semantic 14 psychometric scales, we derive a robust framework for voice quality assessment. This framework bridges the gap between objective acoustic measurements and subjective human judgments, enabling interpretable and perceptually relevant voice characterization. These scales are: Tempo, Tonality, Vibration, Voice Density, Structurality, Harmonicity, Atmosphere, Deafness/Voicefulness, Voice Volume, Voice Size, Nasalisation, Prosody, Musicality, Emotionality. Each scale is measured as a percentage ranging from 0 to 100, where these edge values represent the minimum and maximum possible expression of the given perceptual trait. Unlike raw signal parameters, these categories align with how listeners qualitatively perceive vocal traits e. g., a "dense" voice might suggest confidence, while high "emotionality" could indicate expressiveness. By reducing the dimensionality of the feature space, this approach enhances computational efficiency while preserving interpretability, making it suitable for real-time applications in intelligent systems.

These psychometric scales serve as an intermediate layer, linking physical signal parameters to the Big

Five personality traits (Openness, Conscientiousness, Extraversion, Agreeableness, Neuroticism) within an OS-TIS ontology. Using OSTIS's SC-code, we formalize relationships between low-level features, psychometric scales, and personality traits in a hierarchical semantic network. For instance, high tempo and emotionality might correlate with Extraversion, while stable tonality and structurality could indicate Conscientiousness. The ontology explicitly represents these mappings, allowing the system to reason about vocal cues and adapt responses dynamically. Below, we illustrate a simplified SC-code representation for the trait "Extraversion" and its associated vocal characteristics:

Extraversion

=

- := [Big Five personality trait]
- \in personality trait
- \Rightarrow description*:

[A trait characterized by sociability, assertiveness, and high energy, often reflected in animated and rapid speech patterns]

⇒ associated	psychometric	scales*:
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{● Tempo

- \Rightarrow description*:
 - [Rate of speech, measured as syllables per second, with higher values indicating faster delivery]
 - \Rightarrow correlation*:
 - [Positive correlation with Extraversion, as extroverts speak quickly]
- Emotionality
 - description*: [Degree of emotional expressiveness in voice, captured through pitch vari-
 - ation and intensity]
 - \Rightarrow correlation*:
 - [Positive correlation with Extraversion, reflecting animated prosody]
- Voice Volume
 - ⇒ description*: [Loudness of speech, measured in decibels]
 - \Rightarrow correlation*:
 - [Positive correlation with Extraversion, as extroverts tend to speak louder]

associated low-level parameters*:

}

{•

Fundamental Frequency (F0)

- \Rightarrow description*:
 - [Base pitch of voice, measured in

		Hertz]
	\Rightarrow	measurement scale*:
		[Mel scale]
	\Rightarrow	correlation*:
		[Higher variability in F0 linked to
		Emotionality]
•	Mel-F	<i>Trequency Cepstral Coefficients (MFCC)</i>
	\Rightarrow	description*:
		[Timbre descriptors capturing spectral
		envelope]
	⇒	correlation*:
	,	Dynamic MFCC patterns contribute
		to Voice Volume and Tempo]
•	Jitter	
	\Rightarrow	description*:

[Cycle-to-cycle variation in F0, measured as percentage]

correlation*: \rightarrow [Moderate jitter enhances perceived Emotionality]

} relation to personality inference*: \Rightarrow

vocal expression of Extraversion ł٠

- first domain*:
 - [Extraversion]
- second domain*: ⇒
 - {∙ Tempo
 - **Emotionality**
 - Voice Volume
 - Fundamental Frequency (F0)
 - Mel-Frequency Cepstral Coefficients (MFCC) Jitter

}

}

reasoning rule*: \Rightarrow [High values of Tempo, Emotionality, and Voice Volume, combined with variable F0 and dynamic MFCC, indicate a high likelihood of Extraversion]

This SC-code snippet formalizes "Extraversion" as a personality trait, linking it to three psychometric scales (Tempo, Emotionality, Voice Volume) and three lowlevel parameters (F0, MFCC, Jitter). Each scale and parameter is described with its measurement properties and correlations, while the "relation to personality inference" specifies a reasoning rule for trait detection. Similar formalizations are constructed for the other Big Five traits, mapping their respective psychometric scales-e.g., Structurality and Tonality for Conscientiousness, or Vibration and Nasalisation for Neuroticism-to relevant signal features.

The OSTIS framework's strength lies in its ability to manage this complexity. By organizing knowledge hierarchically, it integrates thousands of low-level parameters into a compact set of semantic categories, which are then probabilistically linked to personality traits. This reduces computational overhead, as the system processes fewer, more meaningful features. Moreover, OSTIS supports dynamic updates, allowing the ontology to refine correlations based on new data or incorporate additional models like HEXACO for enhanced precision. For intelligent systems, this enables real-time adaptation-e.g., softening tone for a high-Neuroticism speaker or accelerating dialogue for an extrovert-fostering empathetic, personalized interactions. Ultimately, the proposed approach leverages OSTIS to transform raw vocal data into a structured, interpretable representation of personality, paving the way for advanced speech interfaces that resonate with users' psychological profiles.

V. Conclusion

This study presents a transformative approach to enhancing voice user interfaces (VUIs) through the semantic analysis of vocal characteristics to infer speaker personality traits, leveraging the Open Semantic Technology for Intelligent Systems (OSTIS) framework. By formalizing the Big Five personality traits-Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism-within a structured ontology, the proposed method establishes a robust pipeline for decoding complex vocal cues and translating them into actionable insights about a speaker's psychological profile. The OSTIS framework plays a pivotal role by organizing thousands of low-level speech signal parameters, such as fundamental frequency (F0), Mel-Frequency Cepstral Coefficients (MFCC), jitter, and prosodic features like tempo and emotionality, into a compact set of 14 high-level psychometric scales. These scales, including Voice Density, Emotionality, and Tempo, serve as an interpretable intermediate layer, reducing computational complexity while preserving the semantic richness needed for real-time personalization in intelligent systems.

The significance of this approach lies in its ability to move VUIs beyond generic, transactional interactions toward empathetic, context-aware communication that resonates with users' individual needs. For instance, by detecting high Neuroticism through vocal markers like a shaky tone or frequent hesitations, the system can adopt a slower, calming speech pattern to reduce user anxiety. Similarly, identifying Extraversion via rapid tempo and loud volume enables the system to match the user's energy with animated, engaging responses.

The flexibility of the OSTIS framework ensures scalability and extensibility, allowing the integration of additional personality models, such as HEXACO's honestyhumility dimension or the Dark Triad's clinical insights, to refine trait detection. Its hierarchical knowledge representation supports continuous updates, enabling the system to incorporate new datasets or vocal-emotional correlations as they emerge, thus maintaining relevance in a rapidly evolving field. This adaptability is critical for applications ranging from virtual assistants and customer service bots to mental health support tools and educational platforms, where personalized interaction can significantly improve outcomes. For example, in therapeutic

settings, a VUI tailored to a user's emotional stability could guide conversations with greater sensitivity, while in professional training, it could adjust its tone to match the user's level of confidence or expertise.

Looking ahead, the proposed approach lays a foundation for next-generation speech interfaces that prioritize psychological nuance and cultural sensitivity. Future work could explore cross-linguistic vocal patterns to enhance global applicability, particularly for low-resource languages, or integrate multimodal cues, such as facial expressions or gestures, to complement vocal analysis. Additionally, addressing ethical considerations—such as ensuring user consent for personality inference and mitigating biases in trait detection—will be essential to maintain trust and fairness. By harnessing OSTIS's semantic capabilities, this research not only bridges the gap between raw speech data and high-level personality insights but also redefines human-machine interaction as a deeply personalized, empathetic experience.

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СЕМАНТИЧЕСКИЙ АНАЛИЗ ЛИЧНОСТНЫХ ЧЕРТ ДИКТОРА ДЛЯ ГОЛОСОВЫХ ИНТЕРФЕЙСОВ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ

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В статье представлен подход к повышению адаптивности и приданию свойств эмпатичного взаимодействия голосовым интерфейсам интеллектуальных систем за счёт семантического анализа личностных черт говорящего. Используя технологию OSTIS, предложено формализовать модель «Большой пятёрки» в семантической онтологии, связывающей акустические параметры речи с психометрическими шкалами и чертами личности. Это позволяет системам в реальном времени анализировать голосовые характеристики, такие как темп, эмоциональность и тональность, и адаптировать ответы под психологический профиль пользователя. Такой подход улучшает взаимодействие, делая его более персонализированным и эмоционально отзывчивым, что особенно важно для антропоморфных роботов и виртуальных ассистентов. Применение OSTIS обеспечивает гибкость и масштабируемость, создавая основу для нового поколения речевых интерфейсов, способных учитывать индивидуальные особенности пользователей.

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Features of the Assessment of Malicious Activity in Smart City Infrastructure Based on Information Granulation and Fuzzy Granular Calculations

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Abstract-The pervasive integration of digital infrastructures within urban environments, while increasing smart city operational efficiencies, has concomitantly engendered intricate security vulnerabilities. Conventional cybersecurity paradigms, predicated on deterministic models, frequently prove inadequate in addressing the dynamic and epistemically uncertain nature of cyber threats. This research introduces a novel methodological framework, leveraging ontology-driven information granulation and knowledge graph-enhanced fuzzy granular computations, to facilitate semantic assessment and mitigation of malicious activities. By transforming raw security telemetry into semantically enriched granules, contextual knowledge extraction is enabled, enhancing inferential efficacy. A case study, employing semantic intrusion detection systems (SIDS) within a simulated 'Smart City', elucidates the potential of the framework for proactive, knowledge-driven threat detection and semantic response strategies.

Keywords—Semantic Technologies, Smart City Infrastructures, Information Granulation, Fuzzy Granular Computations, Cybersecurity, Intrusion Detection Systems, Internet of Things (IoT) Security, Adaptive Machine Learning

I. Introduction

The inherent complexity of smart city environments, characterized by dynamic topologies and a multitude of interacting components, renders traditional cybersecurity paradigms increasingly inadequate. To address this exigency, emergent computational methodologies, particularly those leveraging semantic technologies, such as information granulation and fuzzy granular computations, have garnered scholarly attention. Information granulation, a construct originating from the seminal work of Zadeh (1965), entails the decomposition of raw, high-dimensional data into semantically enriched granules, facilitating knowledge extraction and representation. This approach aligns with human cognitive processes by prioritizing approximate reasoning and knowledge-based

inference over precise numerical representation, enhancing data interpretability and semantic interoperability. Recent investigations (e.g., Livi & Sadeghian, 2014) have demonstrated the efficacy of granular computing in managing ontological uncertainty and reducing computational complexity. Complementarily, fuzzy granular computations, when integrated with semantic reasoning, accommodate the inherent ambiguity and partial truths pervasive in real-world datasets. Unlike conventional crisp classifications, semantic fuzzy logic assigns degrees of membership to data elements within multiple granules, informed by domain ontologies, furnishing a nuanced framework for knowledge-driven uncertainty modeling. This is particularly significant within the domain of cybersecurity, where the delimitation between normative and anomalous behavior requires contextual semantic understanding. By using semantic inference systems and knowledge graphs, it becomes feasible to derive contextaware risk assessments that more accurately reflect the probabilistic nature of cyber threats. The synergistic integration of these semantic methodologies with machine learning (ML) techniques further augments the capacity of semantic intrusion detection systems (SIDS) to discern and respond to novel and sophisticated attack vectors. ML models, such as semantic neural networks, excel in the identification of intricate, knowledge-driven relationships within extensive datasets and have demonstrated considerable promise in enhancing the fidelity of threat detection. When amalgamated with semantically enriched information granulation and fuzzy granular computations, these models constitute a robust, adaptive framework that not only optimizes detection performance but also expedites real-time, knowledge-based decisionmaking.

This paper introduces an integrated semantic frame-

work that synergistically amalgamates these advanced computational techniques to address the cybersecurity challenges inherent in smart urban infrastructures. The subsequent sections provide a detailed exposition of the methodological components, encompassing semantic data acquisition, ontology-driven information granulation, knowledge graph-based fuzzy granular analysis, and semantic inference-based decision-making protocols, as well as a comprehensive case study illustrating the practical instantiation of the proposed approach. Through this research, we endeavor to contribute to the development of more resilient and adaptive semantic cybersecurity systems capable of mitigating the evolving threat landscape in smart urban environments

II. Background and Related Work

The rapid evolution of smart city infrastructures has precipitated a surge in the complexity of cybersecurity challenges. As urban environments integrate an evergrowing array of interconnected devices and systems, conventional security paradigms are increasingly inadequate for addressing the dynamic, heterogeneous, and semantically ambiguous nature of urban data. In this milieu, semantic technologies—when combined with advanced computational methodologies such as information granulation and fuzzy granular computations—offer a compelling framework for managing uncertainty and high dimensionality.

A. Information Granulation

Information granulation involves decomposing complex datasets into smaller, semantically coherent subunits known as granules. These granules encapsulate clusters of data points that share intrinsic attributes, thereby facilitating a reduction in computational complexity and enhancing interpretability. The theoretical foundation of this approach can be traced to Zadeh's seminal work on fuzzy sets (1965), which established a formal paradigm for representing imprecise information. This cognitive strategy, which mirrors the human tendency to process information in approximate, non-exact categories, has been pivotal in refining semantic data analysis. Recent empirical studies, including those by Livi and Sadeghian (2014), demonstrate that the application of granular computing principles can substantially improve the efficiency of data analysis in systems characterized by semantic ambiguity and uncertainty.

B. Fuzzy Granular Calculations

Building upon the principles of information granulation, fuzzy granular computations integrate fuzzy logic to more effectively manage imprecision within semantic granules. Unlike traditional crisp partitioning techniques, fuzzy granular methods allow data elements to exhibit varying degrees of membership across multiple granules. This approach enables the derivation of fuzzy measures that more accurately encapsulate underlying uncertainties. In this framework, each granule is delineated not by strict boundaries but through a membership function that quantifies the degree of affiliation of each data point. Such nuanced representations are crucial in decision support systems and pattern recognition tasks, where the inherent ambiguity of real-world data necessitates a flexible and semantically enriched computational model. In cybersecurity applications, for instance, the integration of fuzzy granular computations facilitates sophisticated reasoning over heterogeneous data sources, thereby enhancing the detection of complex, semantic cyber threats.

C. Applications in Smart City Infrastructures

Smart city environments generate vast and heterogeneous data streams from IoT devices, sensors, and control systems, posing unique analytical challenges. The integration of semantic technologies with information granulation and fuzzy granular computations creates a robust framework for synthesizing disparate datasets into actionable intelligence. By semantically enriching data granules and employing fuzzy logic to elucidate interrelationships, advanced security systems can more effectively identify anomalous patterns indicative of malicious activities. This methodological synergy is particularly valuable in scenarios where data uncertainty and the need for real-time decision-making converge, underpinning the development of adaptive, semantically aware cybersecurity infrastructures.

III. Methodology

This section articulates the proposed semantic methodology designed for the assessment and mitigation of malicious activity within smart city infrastructures, utilizing ontology-driven information granulation and knowledge fuzzy granular computations. The methodology comprises four integral phases: data collection, information granulation, fuzzy granular analysis, and semantic inference-based decision-making. Each phase is meticulously formulated to address the inherent complexities arising from the dynamic and heterogeneous semantic landscape of smart city environments.

A. Data Collection

The initial phase involves the systematic collection of security-related data from diverse sources within the smart city ecosystem. These sources encompass network traffic logs, sensor readings, device status reports, and user activity records. Given the vast and varied nature of this data, it is imperative to employ robust data aggregation mechanisms that ensure the integrity, accuracy, and timeliness of the collected information.

Table I provides an overview of the various sources from which data is aggregated in a smart city, highlighting the diversity and complexity of the data landscape.

 Table I

 Data Collection Sources in Smart City Infrastructure

Source	Data	Example	Description
	type	Devices	-
Network	Structured,	Routers,	Logs capturing
traffic	time-	gateways,	data packets
logs	series	switches	exchanged
			among IoT
			devices
Sensor	Numerical,	Temperature sen-	Real-time
readings	continu-	sors, air quality	measurement
	ous	monitors of environmen	
			and operational
			parameters
Device	Structured,	Smart meters,	Periodic reports
status	categor-	surveillance	on device health
reports	ical	cameras and performanc	
User	Structured,	Mobile	Records of
activity	textual	applications,	interactions
records		online portals	through smart
			applications

B. Information Granulation

This process is pivotal in reducing computational complexity and enhancing the interpretability of the data. The granulation process can be executed through various methodologies, including:

Clustering Algorithms: Techniques such as K-means, hierarchical clustering, or density-based clustering are employed to group data points exhibiting similar characteristics. These algorithms operate by minimizing intracluster variance while maximizing inter-cluster differences, thereby forming distinct granules that encapsulate specific patterns or behaviors within the data.

Discretization Methods: Continuous variables are transformed into discrete categories through methods like equal-width binning or entropy-based discretization. This transformation facilitates the handling of continuous data by converting it into categorical granules, which are more amenable to analysis within the granular computing framework.

Rough Set Theory: This approach deals with the vagueness and ambiguity inherent in data by approximating uncertain concepts through lower and upper approximations, effectively creating granules that represent the boundary regions of these concepts.

The selection of an appropriate granulation technique is contingent upon the specific characteristics of the dataset and the nature of the security threats under consideration. The primary objective is to construct granules that encapsulate meaningful patterns, thereby facilitating more efficient and insightful analysis.

Table II summarizes the various techniques used for information granulation, discussing their respective benefits and challenges of managing complex and uncertain data.

 Table II

 Data Collection Sources in Smart City Infrastructure

Technique	Advantages	Limitations	Description
Clustering	Simplifies	Sensitive to	Grouping
algorithms	high-	initialization	data into
	dimensional	and parameter	clusters
	data;	tuning	based on
	enhances		similarity
	pattern		metric (e.g.,
	recognition		K-means,
			hierarchical
			clustering)
Discretization	Reduces	May	Converting
methods	compu-	oversimplify	continuous
	tational	and lose subtle	variables
	complexity;	data variations	into discrete
	improves		categories
	inter-		(e.g., equal-
	pretability		width
			binning)
Rough set	Effective	Computationally	Approximating
theory	with	intensive; less	data with
	incomplete	intuitive	lower and
	data;		upper
	reduces		bounds
	uncertainty		to manage
	~		vagueness
Fuzzy gran-	Captures	Requires	Utilizing
ular method	uncertainty	careful design	fuzzy logic
	effectively;	of membership	to assign
	offers	functions	degrees of
	flexible clas-		membership
	sification		to date
			granules

C. Fuzzy Granular Analysis

Following the formation of information granules, the next phase involves the application of fuzzy granular analysis to assess the behavior of these granules under conditions of uncertainty. This analysis is conducted through the following steps:

Fuzzy Membership Function Design: For each granule, a membership function is defined to quantify the degree to which individual data points belong to the granule. These functions assign membership values ranging between 0 and 1, thereby accommodating the inherent fuzziness and partial truth present in real-world data.

Fuzzy Rule Base Construction: A comprehensive set of fuzzy rules is formulated to capture the relationships and interactions among different granules. These rules take the form of "IF-THEN" statements, where the antecedent specifies a condition based on the membership values of certain granules, and the consequent delineates the corresponding action or inference.

Fuzzy Inference Mechanism: Utilizing the constructed rule base, a fuzzy inference system is employed to evaluate the current state of the system. This mechanism integrates the membership values and applies the fuzzy rules to derive conclusions or predictions regarding potential security threats.

Defuzzification Process: The outcomes of the fuzzy

inference are typically in the form of fuzzy sets. To facilitate actionable decision-making, these fuzzy results are transformed into crisp values through defuzzification techniques, such as the centroid method or the maximum membership principle. This fuzzy granular analysis enables the system to effectively manage uncertainty and imprecision, thereby enhancing its capability to detect subtle and sophisticated malicious activities that may elude traditional binary classification approaches.

D. Semantic Inference-Based Decision-Making

The final component of the methodology encompasses the decision-making process, wherein the insights garnered from the fuzzy granular analysis are utilized to inform and execute appropriate security measures. This process involves:

Threat Level Assessment: The defuzzified outputs are interpreted to ascertain the severity and immediacy of identified threats. This assessment facilitates the prioritization of response actions based on the potential impact and urgency of the threats.

Response Strategy Formulation: Tailored response strategies are devised corresponding to the assessed threat levels. These strategies may encompass actions such as alert generation, automated system reconfigurations.

Iterative Semantic Feedback and Knowledge Refinement: To ensure adaptability and resilience, a feedback mechanism is established, where in the outcomes of implemented security measures are monitored and analyzed. This feedback enables the system to learn from past incidents, refine its fuzzy rule base, and adjust its granulation parameters, thereby perpetually enhancing its efficacy in threat detection and mitigation.

By integrating these components into a cohesive framework, the proposed methodology offers a robust and adaptive approach to cybersecurity within smart city infrastructures. It effectively addresses the challenges posed by data heterogeneity, volume, and uncertainty, thereby perpetually enhancing its efficacy in knowledgedriven threat detection and semantic mitigation.

IV. Intrusion Detection in Smart Cities

This study explores a machine learning-enhanced IDS framework underpinned by "semantic technologies", which enable contextualized threat analysis through ontological modeling and knowledge representation. Smart cities rely on IoT networks to optimize critical services—traffic control, energy distribution, and public safety—yet their interconnectivity exposes vulnerabilities to attacks like DoS, DDoS, Sybil, and DNS exploits. Conventional security mechanisms, constrained by static rule-based methodologies, struggle to interpret heterogeneous data streams or infer relationships between network entities. Semantic technologies address this gap by formalizing domain-specific taxonomies (e.g., device roles, attack patterns) and enabling reasoning over contextualized data. By enriching machine learning models with semantic metadata, IDS achieve enhanced interpretability and adaptive threat detection, aligning anomalous behaviors with predefined ontologies. This synergy ensures real-time, intelligence-driven mitigation of sophisticated cyber threats in IoT-dependent urban ecosystems.

A. Methodology

The IDS framework employed in this study integrates machine learning algorithms to enhance detection capabilities. The methodology encompasses the following stages: *Data Collection:* Network traffic data is gathered from various IoT devices within the smart city infrastructure. This dataset includes normal operational data and records of known attack patterns.

Feature Extraction: Relevant features are extracted from the collected data to serve as inputs for machine learning models. These features may include packet size, frequency, source and destination IP addresses, and protocol types.

Model Training: Machine learning classifiers, such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Deep Neural Networks (DNN), are trained using the extracted features to distinguish between normal and malicious traffic patterns. *Detection and Response:* The trained models are deployed within the IDS to monitor real-time network traffic. Upon detection of anomalies indicative of potential intrusions, predefined response mechanisms are activated to mitigate the identified threats.

Table III presents the comparative performance metrics of various machine learning classifiers used in the IDS, emphasizing the trade-offs between detection accuracy and computational resources.

B. Results and Discussion

The implementation of the machine learning-based semantic intrusion detection system (SIDS) demonstrated significant advances in discerning diverse cyber threats within the smart city IoT knowledge graph. In particular, the system achieved an elevated accuracy in identifying DoS / DoS attacks, with lower false positive rates compared to traditional signature-based SIDS. The adaptive capacity of semantic neural networks enabled the system to recognize novel, semantically contextualized attack patterns, thereby fortifying the overall semantic security posture of the smart city knowledge infrastructure. However, computational overhead and energy consumption challenges were observed, particularly in resourceconstrained semantic IoT endpoints.

The integration of ontology-driven information granulation, knowledge graph-enhanced fuzzy granular computations, and semantic machine learning within our

 Table III

 Data Collection Sources in Smart City Infrastructure

Classifier	Accuracy (%)	False pos- itive rate (%)	False neg- ative rate (%)	Computat- ional overhead	Notes
Artificial Neural Network (ANN)	97	2.5	2.0	Moderate	High adapt- ability; requires extensive training
Support Vector Machine (SVM)	94	3.5	3.0	High	Effective in high di- mensional feature spaces
Deep Neural Network (DNN)	98	2.0	1.5	High	Superior detection perfor- mance; resource- intensive
Random Forest	95	3.0	2.5	Low to moderate	Robust against overfitting; faster training times

SIDS framework provides a multi-faceted, knowledgecentric approach to addressing the inherent cybersecurity challenges of smart city infrastructures. Findings from our experimental evaluations and case study underscore several critical dimensions warranting in-depth semantic analysis.

The application of ontology-driven information granulation significantly attenuates the complexity of voluminous and semantically heterogeneous IoT data. By decomposing raw security telemetry into semantically coherent granules, aligned with domain ontologies, the framework not only reduces computational overhead but also enhances the semantic interpretability of underlying knowledge patterns. This aligns with theoretical insights from granular computing, which emphasize the cognitive advantage of processing knowledge in clustered semantic forms (Zadeh, 1965; Livi & Sadeghian, 2014). However, the efficacy of this approach is contingent upon the optimal instantiation of ontological granulation parameters.

The incorporation of knowledge graph-enhanced fuzzy granular computations has been instrumental in managing the pervasive epistemological uncertainty associated with cyber threat indicators within smart city knowledge domains. Semantic fuzzy logic enables the representation of security events as continuous membership functions, informed by knowledge graph relationships, thereby allowing the system to capture nuanced semantic anomalies overlooked by conventional binary models. This semantic fuzzy approach enhances the robustness of threat evaluation by providing graded, knowledge-driven risk assessments, facilitating nuanced semantic decision-making. However, the formulation of an effective, ontology-driven fuzzy rule base presents a significant challenge. The system's sensitivity to the selection of membership functions and rule thresholds necessitates iterative semantic calibration and expert ontological intervention.

Furthermore, the deployment of semantic neural networks has demonstrated considerable promise in classifying network behaviors with high semantic accuracy. The adaptive nature of these models allows the SIDS to learn complex, knowledge-driven patterns of both normative and malicious traffic, improving its ability to detect novel, semantically contextualized attack vectors. However, the integration of semantic machine learning introduces additional computational demands, particularly in resource-constrained semantic IoT environments. The observed trade-offs between detection performance and computational efficiency underscore the need for further ontological optimization, potentially through distributed knowledge processing or lightweight semantic model architectures.

In synthesizing these components, our framework represents a holistic, knowledge-driven departure from traditional signature-based SIDS. The synergistic application of ontology-driven granular computing, semantic fuzzy logic, and semantic machine learning enhances detection accuracy and provides a flexible, knowledge-adaptive platform. The continuous semantic feedback mechanism augments its ontological resilience, enabling real-time parameter tuning and knowledge graph refinement.

Despite these advancements, limitations warrant attention. The reliance on synthetic, semantically annotated datasets may limit external validity. Real-world deployments will encounter more heterogeneous, unpredictable, and knowledge-rich data streams, necessitating extensive field testing and iterative ontological refinement. Moreover, the balance between computational resource allocation and detection efficacy remains a critical constraint, particularly as smart city knowledge infrastructures scale.

This study elucidates the potential of integrating advanced semantic techniques to enhance cybersecurity in smart city knowledge domains. By addressing semantic heterogeneity, epistemological uncertainty, and computational constraints, our framework lays the groundwork for resilient and adaptive SIDS. A review of academic literature and case studies on advanced SIDS in smart cities underscored the importance of managing knowledge uncertainty and computational complexity through semantic granular and fuzzy methodologies (e.g., Livi & Sadeghian, 2014; Kozik et al., 2019). These insights informed the in-depth semantic discussion presented.

V. Conclusion

In summary, this study has significantly advanced the discourse on cybersecurity for smart city infrastructures by proposing an integrated framework that synergistically combines information granulation, fuzzy granular computations, and machine learning techniques within a semantic technologies context. The framework addresses the inherent challenges of dynamic, heterogeneous, and high-dimensional urban data by leveraging semantic enrichment to transform raw data into coherent, meaning-laden granules. This transformation not only reduces computational complexity but also enhances interpretability through semantic annotations and ontological mappings, thereby enabling more robust anomaly detection.

The accompanying tables encapsulate critical facets of the research: Table 1 delineates the diverse data sources essential for smart city security analytics; Table 2 provides a comparative evaluation of semantic-based information granulation techniques; and Table 3 offers insights into the performance of machine learning classifiers for intrusion detection within semantically enriched environments. Collectively, these empirical findings underpin the methodological framework and substantiate its efficacy.

Moreover, the incorporation of fuzzy granular computations has empowered the framework to manage uncertainty more effectively, offering a nuanced, graded assessment of cyber threats—a notable improvement over traditional binary classification approaches in complex IoT ecosystems. The integration of adaptive machine learning models, particularly artificial neural networks, has demonstrated considerable potential in capturing intricate patterns and novel attack vectors, thereby bolstering the overall accuracy and responsiveness of the intrusion detection system.

Despite these promising contributions, the study acknowledges several limitations. The reliance on synthetic datasets for initial training and evaluation may constrain the external validity of the findings, and the computational demands of the integrated approach pose challenges for deployment in resource-constrained IoT environments.

In conclusion, by harnessing the capabilities of semantic technologies, the proposed framework represents a substantive step toward developing more resilient and adaptive cybersecurity solutions for smart cities. Future research should focus on refining granulation parameters, automating the fuzzy rule base, and further integrating semantic ontologies and knowledge graphs to accommodate emerging threats in evolving urban infrastructures. Such endeavors will be critical to ensuring the sustained security and operational integrity of smart city ecosystems in an increasingly interconnected digital landscape.

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ОСОБЕННОСТИ ОЦЕНКИ ВРЕДОНОСНОЙ АКТИВНОСТИ В ИНФРАСТРУКТУРЕ УМНОГО ГОРОДА НА ОСНОВЕ ГРАНУЛЯЦИИ ИНФОРМАЦИИ И НЕЧЕТКО-ГРАНУЛЯРНЫХ ВЫЧИСЛЕНИЙ

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Повсеместная интеграция цифровых инфраструктур в городскую среду, одновременно повышая эффективность работы умных городов, одновременно порождает сложные уязвимости в системе безопасности. Традиционные парадигмы кибербезопасности, основанные на детерминированных моделях, часто оказываются неадекватными при решении динамической и эпистемически неопределенной природы киберугроз. Это исследование представляет новую методологическую структуру, использующую грануляцию информации на основе онтологии и нечеткие гранулярные вычисления, улучшенные графом знаний, для облегчения семантической оценки и смягчения последствий вредоносных действий. Преобразуя необработанные телеметрические данные безопасности в семантически обогащенные гранулы, становится возможным извлечение контекстуальных знаний, что повышает эффективность выводов. Тематическое исследование, в котором используются семантические системы обнаружения вторжений (SIDS) в моделируемом «умном городе», раскрывает потенциал этой структуры для проактивного, основанного на знаниях обнаружения угроз и стратегий семантического реагирования.

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Asymmetric Semantic Search Using Multi-Dimensional Vector Text Data Representation

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Abstract—This paper aims to provide a comprehensive analysis of semantic search methodologies that leverage text embeddings and vector space models for semantics representation. Specifically, the objectives of this work are to: analyze the tasks and inherent problems associated with semantic search based on text embeddings and multidimensional vector text semantics representation; identify the specific challenges posed by asymmetric semantic search scenarios, where query and document characteristics differ significantly; analyze and generalize methodologies for creating effective vector space models capable of representing the semantic nuances of text data suitable for semantic search considering both computational cost and retrieval performance.

Keywords—semantic search, vector search, intelligent search, text embeddings, vector similarity

I. Introduction

In today's digital era we have seen an unprecedented expansion of the volume of information available online in open access and within organizational and enterprise knowledge bases. This exponential growth necessitates sophisticated search methodologies that go beyond of traditional keyword-based approaches, which often fail to recognize the underlying meaning and user intent. The development of semantic search has become essential in addressing this challenge, focusing on understanding the contextual meaning and intent behind a user's search query rather than relying solely on matching keywords. A cornerstone of modern semantic search is the utilization of sophisticated AI-based tools for natural language processing [1] and text embeddings, which are vector representations of natural language that encode its semantic information, and vector space models, which enable similarity-based retrieval by representing text data in a multi-dimensional space [2].

The growing amount of digital data demonstrates traditional search methods' inadequacy [3]. Users expect search engines to understand the meaning behind their queries, not just to find literal matches. Semantic search represents an evolution in information retrieval, striving to meet this expectation by employing techniques that capture the rich semantic content of language.

II. Background on semantic search

A. Definition and principles

Semantic search is a data searching technique that focuses on understanding the contextual meaning and intent behind a user's search query, rather than solely relying on the matching of keywords. [4] Unlike traditional lexical search, which operates on the principle of finding literal matches of the words in a query, semantic search analyzes the deeper meaning embedded within the query to deliver results that are more accurate and personalized to the user's intent. This approach seeks to improve search accuracy by comprehending the content of both the search query and the corpus being searched. Consequently, semantic search systems can effectively handle synonyms, abbreviations, and even misspellings, a capability often lacking or requiring extensive computation resources in keyword-based search engines that primarily find documents based on exact lexical matches [4].

Natural language processing (NLP) plays a crucial role in enabling semantic search by processing text or voice content to discern its underlying structure and sentiment, thereby facilitating a deeper understanding of the user's query. The fundamental advantage of semantic search is its capacity to interpret the meaning of language, thus overcoming the inherent limitations of simply matching keywords. While keyword-based search treats words as isolated entities, often missing the relationships between them and the broader context, semantic search, through the application of NLP, delves into the grammatical structure, identifies key entities, and aims to grasp the true intent behind the words used, ultimately leading to the retrieval of more relevant information [2].

B. Techniques underlying semantic search

A variety of sophisticated techniques underpin the functionality of semantic search systems, often working in conjunction to achieve a comprehensive understanding of both the user's query and the available data [3].

Knowledge graphs, for instance, are employed to model concepts and the relationships that exist between

them, significantly enhancing the accuracy and contextuality of search results. Semantic annotation and indexing techniques further contribute by linking textual content to specific concepts within these knowledge graphs. Semantic technologies, in a broader sense, are designed to interpret and make sense of large or complex datasets without relying on any predetermined knowledge about the data itself. These technologies encompass a range of methods, including NLP, data mining, classification techniques, and the semantic search technologies themselves. Query parsing is another important technique used in semantic search to identify the contextual meaning of a natural language query by discerning the essential words and filtering out those that are less significant for understanding the user's intent. Furthermore, a central approach in semantic search involves embedding both the queries and the documents within a high-dimensional vector space. By calculating the similarity between the vector representations of the query and the documents, the system can rank the results based on their semantic relatedness.

The effective integration of these diverse techniques allows semantic search to move beyond surface-level keyword matching and provide more meaningful and relevant search outcomes.

C. Importance and applications

Semantic search has become increasingly important in optimizing the accuracy of search results when navigating the vast expanse of the internet or exploring the internal knowledge repositories of organizations. Its core aim is to enable machines to understand the meaning of concepts and the intricate relationships between them, thereby facilitating a more intelligent and contextaware search experience. Semantic search has found widespread applications in various domains, including healthcare, where it can accelerate diagnosis and aid in drug discovery; e-commerce, where it powers personalized recommendations and enhances product search; education and research, by facilitating the discovery of relevant materials; and customer support, through AIdriven chatbots that can provide instant and accurate solutions to user queries [5]. The ability of semantic search to understand user intent and context makes it an indispensable tool in a multitude of applications where efficient and accurate information retrieval is paramount.

III. Text embeddings and vector space models for semantic representation

A. Concept of text embeddings

Text embeddings are fundamental to modern semantic search, serving as vector representations of natural language that effectively encode its semantic information [6]. These embeddings are widely utilized across various natural language processing tasks, including information retrieval, question answering systems, and the assessment of semantic textual similarity. The core idea behind employing text embeddings in semantic search is to map all entries within a given corpus, whether they are individual sentences, entire paragraphs, or complete documents, into a high-dimensional vector space. Subsequently, when a user submits a query, this query is also embedded into the same vector space. The semantic search process then involves identifying the embeddings from the corpus that are located closest to the query embedding within this space. This proximity is interpreted as a measure of semantic similarity.

These embeddings are designed to capture the meaning of words by considering the words that surround them in the text. Consequently, words that appear in similar contexts within a corpus are mapped to vectors that are positioned closely to each other in the embedding space. Text embeddings are typically dense vectors, meaning that most of the values within the vector are non-zero, and numerous algorithms have been developed to compute these representations effectively. This transformation from textual data into a numerical vector format is crucial as it allows computational models to process, compare, and ultimately understand the semantic relationships between different pieces of text.

B. Techniques for generating text embeddings

Various techniques have been developed to generate text embeddings, each with its own strengths and underlying principles.

1) Word2Vec: Word2Vec is a widely recognized machine learning technique in natural language processing used to obtain vector representations of individual words based on their surrounding contexts within a large text corpus. The algorithm operates through two primary architectural models: Continuous Bag of Words (CBOW) and Skip-gram. In the CBOW model, the objective is to predict a target word based on the context of the words that surround it within a specified window. Conversely, the Skip-gram model reverses this process, aiming to predict the surrounding context words given a particular target word [7].

A key capability of Word2Vec is its ability to capture semantic relationships between words. Through training on large datasets, words with similar meanings tend to be placed closely together in the resulting vector space. This means that the vector for "king" might be found to be closer to the vector for "queen" than to the vector for "airplane." Furthermore, Word2Vec is known for its efficiency and scalability, making it suitable for processing and learning from very large text corpora [8]. These word embeddings generated by Word2Vec have proven to be invaluable for a wide range of downstream NLP tasks, including but not limited to, text classification, sentiment analysis, and various information retrieval applications. 2) GloVe: GloVe, which stands for Global Vectors for Word Representation, is another prominent unsupervised learning algorithm used to obtain vector representations for words. Unlike Word2Vec, which primarily focuses on local word contexts, GloVe leverages the global word co-occurrence statistics across an entire text corpus. The algorithm functions by first constructing a comprehensive word-word co-occurrence matrix, which tallies how frequently words appear together within a defined context across the corpus. Following this, GloVe employs matrix factorization techniques, such as Singular Value Decomposition (SVD), to decompose this co-occurrence matrix and derive the word embeddings.

A significant advantage of GloVe is its effectiveness in capturing subtle semantic relationships between words, often outperforming other methods in tasks requiring a deeper understanding of these nuances. Additionally, GloVe is notable for its ability to combine both syntactic and semantic context in the generated embeddings. The training process for GloVe is also known for its efficiency, particularly in tasks such as word analogy solving, where it often demonstrates strong performance. By encoding global statistical information about the entire corpus, GloVe provides word embeddings that can be highly effective in various natural language processing applications, including semantic search, machine translation, and text classification.

3) BERT and Sentence-BERT: BERT (Bidirectional Encoder Representations from Transformers) represents a significant advancement in the field of natural language processing, particularly in its ability to capture intricate linguistic patterns and contextual nuances within text data. A key feature of BERT is its bidirectional training approach, which allows the model to consider the context of a word from both the left and the right sides within a sentence. This enables a deeper understanding of word meaning based on its surrounding words. Building upon the foundation of BERT, Sentence-BERT (SBERT) is a specialized modification of the original BERT model that is specifically designed to yield better computational performance and more efficient handling of sentence-level representations, making it highly suitable for semantic search tasks [9]. SBERT achieves this by incorporating siamese and triplet network architectures, which enable the model to generate semantically meaningful embeddings for entire sentences [6] [10]. This is crucial for semantic search, where the similarity between queries and documents often needs to be assessed at the sentence or paragraph level [11].

Both BERT and SBERT benefit from being pre-trained on vast amounts of text data, resulting in models that possess a strong understanding of language and can be further fine-tuned for specific tasks. The availability of these pre-trained models makes it easier to apply them to various applications, including semantic search, question answering, and text classification, often with impressive results. The contextual understanding provided by BERTbased models has significantly improved the accuracy and relevance of semantic search systems.

Beyond Word2Vec, GloVe, and SBERT, the field of text embeddings includes a variety of other techniques. FastText, developed by Facebook AI Research, extends Word2Vec by considering subword information, allowing it to generate better embeddings for rare and out-ofvocabulary words. Embeddings from Language Models generates word embeddings that are context-dependent, meaning the embedding for a word can change based on the surrounding words in a sentence, capturing more nuanced semantic information. Universal Sentence Encoder (USE), developed by Google, is designed to produce embeddings for entire sentences and short paragraphs, focusing on capturing the overall semantic meaning. Transformer-based models like RoBERTa and GPT have also been adapted to generate text embeddings, leveraging their deep contextual understanding of language. The continuous evolution of text embedding techniques reflects the ongoing efforts to improve the representation of semantic meaning in computational models.

Regardless the specific algorithm selected for embeddings initialization and tuning it is vital to select appropriate text corpus as it plays a crucial role in determining the quality and effectiveness of the generated text embeddings. Generally, models trained on larger and more diverse corpora tend to capture a broader range of semantic relationships, providing a more general understanding of language. However, for tasks requiring specialized knowledge, using domain-specific corpora can be highly beneficial. Training embeddings on legal texts, for example, will result in a better understanding of legal terminology and the nuances within the legal domain. Similarly, for medical applications, a corpus of medical literature will yield embeddings that better capture the specific vocabulary and relationships within the healthcare field. Numerous pre-trained embeddings are available, having been trained on various large-scale corpora such as Wikipedia, Google News, and Common Crawl, offering a convenient starting point for many applications. The selection of an appropriate training corpus should align with the specific requirements and domain of the intended application to ensure the generated embeddings effectively capture the relevant semantic information.

C. Constructing multi-dimensional vector space models

The process of building a multi-dimensional vector space model for semantic search involves creating a space where each text unit is represented as a vector in a high-dimensional space. The number of dimensions in this space is a crucial parameter, typically determined by the embedding model employed and the complexity of the semantic relationships it aims to capture. These dimensions correspond to latent semantic features that the model learns from the training data. The value within each dimension of a vector signifies the strength or relevance of that particular semantic feature to the specific text unit being represented.

The dimensionality of the vector space plays a significant role in the model's ability to discern semantic nuances. Higher dimensionality allows for a richer and more detailed representation of meaning, enabling the capture of subtle relationships between text units. However, this increased representational power comes at the cost of higher computational demands for both generating and searching through the embeddings, as well as increased storage requirements. To mitigate these challenges, dimensionality reduction techniques can be applied. These methods aim to reduce the number of dimensions while preserving the essential semantic information encoded in the embeddings.

The representation of different text units as vectors within a multi-dimensional space carries distinct implications for semantic search capabilities.

1) Word Embeddings: These embeddings operate at a fine-grained level, capturing the semantic meaning of individual words. While effective for understanding word-level semantics and relationships, word embeddings may not fully capture the meaning of words in varying contexts (polysemy) or the overarching meaning of sentences and larger text segments. Consequently, word embeddings are best suited for tasks where the individual meaning of words is vitally important, such as identifying synonyms or conducting word-level semantic analysis. They can also be aggregated using techniques like averaging to derive representations for sentences or documents, although this approach may lose some contextual information.

2) Sentence Embeddings: Designed to encode the semantic information of entire sentences, sentence embeddings take into account word order and the contextual relationships between words. This granularity makes them particularly advantageous for tasks such as question answering, paraphrase detection, and assessing semantic textual similarity, where understanding the complete meaning of a sentence is crucial.

3) Paragraph/Document Embeddings: These embeddings represent the semantic meaning of larger text segments, capturing topical information and the overall context of paragraphs or entire documents. While offering a broader contextual understanding, representing larger text units as single vectors can lead to a tradeoff, potentially losing some of the fine-grained semantic details present at the word or sentence level. Paragraph and document embeddings are particularly well-suited for applications such as document retrieval, topic modeling, and summarizing extensive bodies of text. The selection of the appropriate text unit for embedding is therefore contingent upon the specific requirements of the semantic search task. For instance, applications focused on retrieving answers to questions often benefit from sentence embeddings that can capture the meaning of both the query and potential answer sentences. Conversely, tasks involving the retrieval of entire documents based on a query might find paragraph or document embeddings more effective in capturing the overall semantic relevance.

There are also way to construct multi-dimensional vector space models (VSMs) without text embeddings, that employs traditional ideas such as document-term relation. They can be uses either as a replacement of VSMs bases on text embeddings, or in addition to them for specific tasks as semantic search result ranking or weighting. These models operating by representing thre relations between the documents and the terms. In this space, each unique term in the entire corpus of documents corresponds to a dimension. The process typically begins with the creation of a Document-Term Matrix (DTM) or a Term-Document Matrix (TDM). In a DTM, each row represents a document, and each column represents a term, with the value at the intersection indicating the frequency or weight of that term in that document. A TDM is simply the transpose of the DTM. To reflect the importance of different terms within the documents, a weighting scheme is often applied.

One of the most common weighting schemes is Term Frequency-Inverse Document Frequency (TF-IDF). A number of normalized or improved in other ways versions of TF-IDF exist such as Term Frequency-Category Ratio (TF-CR) or Okapi BM-25 (Best Matching) [8] [3]. TF-IDF assigns a higher weight to terms that appear frequently in a specific document but are rare across the entire corpus, thus highlighting their importance to that document's content. It is a statistical measure that reflects how important a word is to a document in a collection or corpus. t works by assigning a weight to each term in a document based on its frequency in that document and its inverse frequency across the entire corpus. The core idea is that terms appearing frequently in a specific document but rarely in the general corpus are likely to be more important to the content of that document.

$$\text{TF-IDF}(t, d, D) = \text{TF}(t, d) \times \text{IDF}(t, D)$$

TF measures the frequency of a term t within a document d. A common way to calculate TF is using:

$$\mathrm{TF}(t,d) = \frac{f_{t,d}}{\sum\limits_{t' \in d} f_{t',d}}$$

where $f_{t,d}$ is the raw count of the term t in the document d, and the denominator represents the total number of terms in the document d. This normalized frequency helps to account for variations in document length. It

is worth noting that other variations of TF exist, including the raw count itself, boolean frequencies (1 if the term occurs, 0 otherwise), and logarithmically scaled frequency. Fundamentally, TF aims to emphasize words that appear more often within a specific document.

IDF measures the importance of a term t across the entire collection of documents or corpus D. A common formula is:

$$IDF(t, D) = \log \frac{|D|}{|\{d \in D : t \in d\}|}$$

Here, |D| is the total number of documents in the corpus, and $|d \in D : t \in d|$ is the number of documents that contain the term t (also known as the document frequency). To prevent division by zero if a term does not appear in any document, a common modification adds 1 to the denominator as well as some implementations also use smoothing by adding 1 to both the numerator and the denominator or using variations with additional coefficients.

By multiplying TF and IDF, the resulting TF-IDF score reflects the importance of a term for a specific document within the context of the entire corpus. Terms that are frequent in a document but rare across the corpus will have high TF-IDF values, indicating their significance to that document.

Once the documents and queries are represented as vectors in this high-dimensional space, the relevance of a document to a query can be determined by comparing the angle between their respective vectors. A common metric used for this comparison is cosine similarity. Cosine similarity measures the cosine of the angle between two vectors, providing a value between -1 and 1, where a higher value indicates greater similarity. By ranking the documents based on their cosine similarity to the query vector, semantic search systems can retrieve the most relevant information [12]. The creation of these vector space models allows for a quantitative assessment of semantic similarity, enabling more effective information retrieval than traditional keyword-based methods.

IV. Analysis of semantic search tasks and problems

A. Tasks in semantic search

Semantic search encompasses a variety of tasks aimed at retrieving information based on meaning and context rather than just keywords. These tasks include finding documents that are semantically similar to a given query or document, answering questions by retrieving relevant passages from a text corpus, general information retrieval where the goal is to find documents relevant to a user's need, and paraphrase detection, which involves identifying if two pieces of text convey the same meaning despite using different words.

A crucial distinction within semantic search is between symmetric and asymmetric search. In symmetric semantic search, the query and the entries in the corpus being

searched are typically of similar length and content. An example of this would be searching for questions that are similar to a given question. In such cases, the relationship is often bidirectional, meaning if query A is similar to document B, then document B is likely to be considered similar to query A. Conversely, asymmetric semantic search usually involves a short query, such as a question or a few keywords, and the goal is to find a longer passage or document that answers the query or provides relevant information. In asymmetric search, the relationship is often unidirectional; while a document might answer a question, the question itself is not typically considered an answer to the document. Understanding this distinction is vital as different types of models and strategies are often required for optimal performance in symmetric versus asymmetric semantic search tasks.

B. Problems in semantic search

Despite the significant advancements in semantic search, several inherent problems and challenges persist. One major challenge is the complexity of natural language itself, with its context-dependent semantics and the phenomenon of polysemy, where a single word can have multiple meanings depending on the context. Accurately capturing these nuances and disambiguating word meanings remains a difficult task for computational models. Another significant issue is the handling of out-of-vocabulary (OOV) words, which are words that a model has not encountered during its training phase. When a model encounters an OOV word, it may not know how to interpret it or generate a meaningful embedding, potentially leading to inaccurate search results. The computational cost associated with generating and comparing high-dimensional embeddings, especially when dealing with large corpora, is also a considerable problem. Training and deploying complex models like BERT can require substantial computational resources and time. Furthermore, pre-trained embeddings can sometimes inherit biases present in the training data, which can inadvertently affect the fairness and accuracy of semantic search results.

Addressing these problems requires ongoing research and development in areas such as improving model architectures, devising more effective training methodologies, and developing robust techniques for handling linguistic ambiguity and unseen words.

C. Challenges of asymmetric semantic search

Asymmetric semantic search, where short queries are used to retrieve relevant information from longer documents, presents a unique set of challenges that are distinct from those encountered in symmetric search scenarios [5]. A core problem is the query-document length disparity. Standard text embedding techniques might be more naturally suited to embedding texts of similar lengths, and the embedding of a short query might not effectively

capture its relationship to a much longer document that contains the answer. For example, a short question might have a concise embedding, while the embedding of an entire document, even if it contains the answer, might be influenced by irrelevant information, making direct similarity comparison challenging. Another significant challenge arises from granularity differences between short queries and longer documents. A user's query is often focused on a very specific piece of information, whereas a document might cover a broader topic. The relevant information might be a small part of the document, and the embedding of the entire document might not adequately reflect the semantic connection to the query. Training models that can effectively bridge the semantic gap between queries and documents of such differing characteristics is also difficult. Models primarily trained on symmetric tasks, where inputs are of similar length and nature, may not perform optimally when applied to asymmetric search. Finally, determining appropriate similarity metrics and thresholds for comparing embeddings of varying lengths and information density poses a challenge. It is possible for irrelevant documents to receive relatively high similarity scores when compared to a short query, making it hard to establish a clear cutoff for relevance. Addressing these unique challenges is crucial for developing effective semantic search systems for asymmetric information retrieval tasks.

V. Creating vector space models for text data semantics

A. Selection of embedding techniques

For creating effective vector space models for asymmetric semantic search, the selection of appropriate embedding techniques is paramount. It is often beneficial to utilize pre-trained sentence embedding models that have been specifically trained for asymmetric search tasks, such as those trained on the MS MARCO dataset [5]. These models are designed to effectively handle the inherent differences in length and content between short queries and longer documents that contain the answers. Additionally, considering models that have undergone fine-tuning on task-specific data can lead to significant improvements in performance [13]. For instance, finetuning a Sentence-BERT model on design engineeringrelevant vocabulary resulted in enhanced retrieval accuracy [10].

The choice of the embedding model should also be guided by the specific requirements of the search task and the characteristics of the data being searched. For example, models that are tuned for cosine similarity might tend to favor the retrieval of shorter documents, while models tuned for dot-product might show a preference for longer documents. Cosine similarity is a widely used metric that quantifies the similarity between two non-zero vectors by calculating the cosine of the angle between them:

$$S_{cos}(\mathbf{A}, \mathbf{B}) = \cos(\theta) = \frac{\mathbf{A} \cdot \mathbf{B}}{\|\mathbf{A}\| \|\mathbf{B}\|}$$

In this formula, the numerator $\mathbf{A} \cdot \mathbf{B}$ represents the dot product of the two vectors which is the sum of the products of their corresponding components $\sum_{i=1}^{n} A_i B_i$. The denominator, $\|\mathbf{A}\| \|\mathbf{B}\|$ represents the magnitudes (or Euclidean norms $\|\mathbf{A}\| = \sqrt{\sum_{i=1}^{n} A_i^2}$, $\|\mathbf{B}\| = \sqrt{\sum_{i=1}^{n} B_i^2}$). Thus, the cosine similarity can be expressed as:

$$S_{cos}(\mathbf{A}, \mathbf{B}) = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i^2} \sqrt{\sum_{i=1}^{n} B_i^2}}$$

This measure essentially captures the directional relationship between vectors, irrespective of their magnitudes. The result of the cosine similarity S_{cos} calculation ranges from -1 to 1. A value of 1 indicates that the two vectors are perfectly aligned in the same direction, signifying the highest degree of similarity. A value of 0 implies that the vectors are orthogonal (at a 90-degree angle), indicating no directional similarity. Conversely, a value of -1 suggests that the vectors are pointing in exactly opposite directions, representing complete dissimilarity. Values between -1 and 1 reflect intermediate degrees of similarity based on the angle between the vectors.

As it was mentioned above, vector similarity can also be calculated as a result of the dot product of the corresponding vectors:

$$S_{dot} = \mathbf{A} \cdot \mathbf{B} = \sum_{i=1}^{n} A_i B_i$$

This can also be expressed in terms of the magnitudes of the vectors and the cosine of the angle between them:

$$S_{dot} = \mathbf{A} \cdot \mathbf{B} = \|\mathbf{A}\| \|\mathbf{B}\| \cos(\theta)$$

For vectors that are not normalized, the dot product's value is influenced by both the direction and the magnitude of the vectors. A larger positive dot product generally indicates higher similarity, suggesting that the vectors point in the same general direction and/or have larger magnitudes. Negative values of the dot product imply dissimilarity, as the vectors are oriented in opposite directions. A dot product of zero signifies that the vectors are orthogonal, indicating no similarity in their direction.

A critical relationship exists between the dot product and cosine similarity. When the vectors **A** and **B** are normalized to unit length (i.e., their magnitude is 1, so $\|\mathbf{A}\| = 1$ and $\|\mathbf{A}\| = 1$), the dot product simplifies to:

$$\mathbf{A} \cdot \mathbf{B} = \cos(\theta)$$

In this specific scenario, the dot product becomes equivalent to the cosine similarity, solely measuring the directional similarity between the normalized vectors. The choice of using the dot product directly as a similarity metric is often made in applications where the magnitude of the embeddings holds meaningful information.

Another approach to measure vector similarity is a Euclidean distance. It is a fundamental measure of the straight-line distance between two points (or vectors) in Euclidean space. For two n-dimensional vectors $\mathbf{A} = (A_1, A_2, \dots, A_3)$ and $\mathbf{B} = (B_1, B_2, \dots, B_3)$, the Euclidean distance $d(\mathbf{A}, \mathbf{B})$ will be represented as the square root of the sum of the squared differences between the corresponding components of the two vectors, essentially applying the Pythagorean theorem in n dimensions:

$$d(\mathbf{A}, \mathbf{B}) = \sqrt{\sum_{i=1}^{n} (A_i - B_i)^2}$$

Unlike cosine similarity and dot product (in its normalized form), Euclidean distance is a measure of dissimilarity. A smaller Euclidean distance between two vectors indicates that they are closer in the embedding space and thus more similar, while a larger distance suggests lower similarity. It is important to note that Euclidean distance is sensitive to the magnitude (scale) of the vectors. Vectors with larger component values will inherently have a greater Euclidean distance from other vectors, even if their directional relationship is similar to that of smaller vectors.

To utilize Euclidean distance as a similarity measure, it typically needs to be transformed. Common transformation methods include taking the inverse of the distance, often with an added constant to avoid division by zero:

$$S_{ecl} = \frac{1}{1 + d(\mathbf{A}, \mathbf{B})}$$

Another approach involves using a negative exponential function:

$$S_{ecl} = e^{-\alpha \cdot d(\mathbf{A}, \mathbf{B})}$$

where α is a scaling factor that controls the rate at which similarity decreases with distance. Additionally, if the maximum possible Euclidean distance d_{max} in the dataset is known, the distance can be scaled and inverted:

$$S_{ecl} = 1 - \frac{d(\mathbf{A}, \mathbf{B})}{d_{max}}$$

The suitability of Euclidean distance (or its transformed similarity score) often lies in applications where the magnitudes of the embeddings carry significant meaning, where absolute differences are important. Therefore, a careful consideration of the task at hand and the properties of different embedding models is essential to achieve optimal results in asymmetric semantic search.

B. Handling out-of-vocabulary words

Effective handling of out-of-vocabulary (OOV) words is a critical aspect of creating robust semantic search systems. One widely adopted strategy is to employ subword tokenization techniques. These methods break down words into smaller, more frequent units, such as prefixes, suffixes, or character n-grams, which can help in representing and understanding words that were not present in the model's training data. For example, Fast-Text is a word embedding model that utilizes character ngrams to infer embeddings for OOV words, allowing it to handle a much larger vocabulary and unseen words more effectively. Another approach involves exploring techniques based on morphological or semantic similarity to initialize embeddings for OOV words. This might involve finding a known word that is morphologically similar to the OOV word (e.g., using Levenshtein distance) and using its embedding, or by averaging the embeddings of words that frequently co-occur with the OOV word in the corpus. While a common practice is to represent all OOV words with a special <UNK> (unknown) token, which is then assigned a single embedding, this can lead to a loss of potentially valuable information. Therefore, techniques like subword tokenization and similarity-based initialization offer more nuanced ways to address the challenge of OOV words in semantic search.

C. Weighting schemes

In the context of creating vector space models for semantic search, the application of appropriate weighting schemes can significantly enhance the representation of document semantics. While traditionally used with bag-of-words models, techniques like TF-IDF can also be adapted for use with text embeddings [14]. TF-IDF aims to emphasize the importance of certain terms within a document relative to the entire corpus. This is achieved by increasing the weight of terms that appear frequently in a particular document but are infrequent in the broader collection of documents. When using text embeddings, weighting can be applied at the term level before aggregating these embeddings to form a document-level embedding. This allows for certain semantically important words to have a greater influence on the overall document representation. Additionally, more advanced weighting schemes have been proposed, such as the Term Frequency-Category Ratio (TF-CR). TF-CR is a weighting scheme designed to emphasize category-exclusive words that appear frequently within a specific category when computing word embeddings for text classification tasks [8]. While primarily developed for classification, the principles of TF-CR, which involve using class information to enhance the discriminativeness of words, could potentially be adapted for semantic search in corpora where documents are categorized or associated with specific topics. By carefully considering

and applying suitable weighting schemes, the resulting vector space model can better capture the semantic essence of the text data, leading to improved performance in semantic search tasks.

D. Dimensionality reduction

Dimensionality reduction techniques can play a valuable role in optimizing the efficiency of vector space models used for semantic search. These techniques aim to reduce the number of dimensions in the embedding vectors while retaining as much of the essential semantic information as possible. One common method is Principal Component Analysis (PCA), which identifies the principal components (directions of maximum variance) in the data and projects the high-dimensional embeddings onto a lower-dimensional subspace formed by these components. By reducing the dimensionality, PCA can potentially improve computational efficiency, decrease storage requirements, and sometimes even enhance the performance of downstream tasks by removing noise.

However, it is crucial to ensure that the reduction in dimensions does not lead to a significant loss of semantic information that is critical for the search task. Some advanced embedding models, such as Matryoshka Representation Learning (MRL), allows for effective dimensionality reduction by simply truncating the embedding vector to a shorter prefix, without a substantial degradation in quality [15]. This can be a very efficient way to reduce the size of the embeddings and the computational cost of similarity comparisons. When considering dimensionality reduction, it is important to be mindful of the trade-off between the representational complexity of the embeddings and their interpretability. While higherdimensional embeddings might capture more nuanced semantic relationships, they can be more computationally expensive to work with and harder to interpret. Therefore, the choice of dimensionality reduction technique and the final dimensionality should be carefully considered based on the specific requirements and constraints of the semantic search application.

This optimization approach can also be applied to the training process during the embedding space initialization as well as fine-tuning of large language models such as BERT (SBERT) and GPTs. Usage of pre-trained models often involves LLM fine-tuning and benefits in increasing relevance and enhanced feature extraction for the given context make this process inevitable part of initial set up of embedding space for further application for semantic search tasks. Known approaches in neural network model reduction has proven stated efficiency [16] and can be extended for natural language processing tasks.

VI. Estimation of efficiency of suggested solutions

A. Computational cost

Estimating the computational cost of the discussed approaches involves considering several factors, including the resources required for generating embeddings, building and maintaining the vector index, and the latency of query execution. Generating text embeddings, particularly using transformer-based models like BERT, can be computationally intensive, especially when dealing with long sequences of text. The computational cost scales with the size of the model, the length of the input text, and the number of documents in the corpus. For applications with limited computational resources, it might be beneficial to consider using smaller, more efficient models, such as the MiniLM variants, which are designed to offer a good balance between performance and computational efficiency. Building and maintaining the vector index also incurs a cost. While approximate nearest neighbor (ANN) indexing techniques, such as HNSW, FAISS, and Annoy, significantly reduce the search time for large datasets, they do introduce some computational overhead during the index construction phase [12]. The query latency, which is the time taken from when a user submits a query to when the relevant documents are retrieved, is another critical aspect of efficiency. For real-time applications, it is essential to aim for low query latency to ensure a responsive user experience. The choice of embedding model, indexing strategy, and the size of the corpus all impact the overall computational cost and query latency. Therefore, a careful trade-off needs to be made between the desired accuracy and performance of the semantic search system and the available computational resources.

B. Evaluation metrics

To comprehensively evaluate the efficiency and effectiveness of the represented approaches, it is crucial to employ appropriate evaluation metrics. Several metrics are commonly used in the context of semantic search:

- Precision, Recall, and F1-score: These metrics are fundamental for assessing the relevance of the retrieved documents. Precision measures the proportion of the retrieved documents that are actually relevant to the query. Recall measures the proportion of all relevant documents in the corpus that were successfully retrieved by the search system. The F1-score is the harmonic mean of precision and recall, providing a balanced measure of the system's accuracy [17].
- Mean Reciprocal Rank (MRR): MRR is a metric that evaluates the average rank of the first relevant item in the search results for a set of queries. It is particularly important in scenarios where finding the first relevant result quickly is crucial, such as

in question answering systems. A higher MRR indicates that, on average, the first relevant document appears higher in the ranking.

- Normalized Discounted Cumulative Gain (NDCG): NDCG is a more sophisticated metric that considers the relevance of each retrieved document as well as its position in the ranking. It assigns higher scores to relevant documents that appear earlier in the search results, reflecting the user preference for finding the most relevant information at the top of the list. NDCG is particularly useful when the relevance of documents can be graded on a scale.
- Novel methods for evaluating the performance of a content search systems constantly emerging and become focus pint of academia and professional community. Such approaches can be based on a nontrivial mathematical statistical models as well as be build on a top of Large Language Models [18] [19].

A holistic evaluation of a semantic search system should consider a combination of these metrics to assess both the relevance and the ranking quality of the search results.

VII. Conclusion

Semantic search and in particular its implementation based on a vector semantic text data representations has found widespread application across numerous domains, demonstrating its versatility and effectiveness in enhancing information retrieval. In internal knowledge management, semantic search can significantly improve the accessibility of company knowledge by understanding the informational needs of employees. This transforms disjointed corporate information into an intelligent knowledge base, boosting productivity through easier access to institutional knowledge. For research, particularly in legal and medical fields, semantic search assists professionals in navigating vast databases of case laws, statutes, medical literature, and patient data. By understanding the context of complex queries, semantic search filters out irrelevant information, enabling lawyers to find relevant case laws faster and doctors to quickly access the latest studies or treatment guidelines.

Mentioned applications usually employ most common and at the same time most troublesome type of semantic search – asymmetric search, when query-document obvious disparity in a data length and richness as well as context and specific vocabulary arises. This contradiction between query and target data tends to be more significant in case when domain-specific knowledge base become publicly available. For instance, user-oriented legal support system designed to provide relevant information and legal advice based on this data for query written by user who is not aware of specific legal terminology or even can have a number of misconceptions on legal vocabulary he is trying to use. Semantic search demonstrates distinct advantages over keyword-based search in handling specific types of tasks mentioned above. It is particularly well-suited for complex or ambiguous queries where understanding the user's intent is paramount.

This paper has provided a comprehensive analysis of semantic search based on text embeddings and multi-dimensional vector text semantics representation. It has examined the fundamental tasks within semantic search and highlighted the specific challenges associated with asymmetric search, particularly the query-document length disparity and differences in semantic granularity. Methodologies for creating effective vector space models have been suggested, including the selection of pretrained asymmetric embedding models, techniques for handling out-of-vocabulary words, the potential use of weighting schemes, and considerations for dimensionality reduction. A step-by-step approach for forming text embeddings and vector space models tailored for semantic search tasks has been developed, emphasizing the importance of careful model selection, thorough data preprocessing, the application of efficient indexing strategies, and the use of appropriate similarity metrics. The estimated efficiency of the suggested solutions reveals a trade-off between accuracy, computational cost, and query latency, underscoring the significance of employing metrics such as precision, recall, MRR, and NDCG for a comprehensive evaluation of system performance.

Future research could explore more advanced embedding techniques that are inherently better at handling long documents and the granularity mismatches prevalent in asymmetric search. Investigating adaptive similarity measures and thresholds that can dynamically adjust based on query and document characteristics could also lead to improved retrieval relevance. Additionally, further work is needed to optimize the computational efficiency of transformer-based models for semantic search applications, making them more accessible for resourceconstrained environments. The ongoing advancements in natural language processing and machine learning promise to continue enhancing the capabilities and practicality of semantic search technologies, paving the way for more intelligent and user-centric information retrieval systems.

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АСИММЕТРИЧНЫЙ СЕМАНТИЧЕСКИЙ ВЕКТОРНЫЙ ПОИСК С ИСПОЛЬЗОВАНИЕМ МНОГОМЕРНЫХ ВЕКТОРНЫХ ПРЕДСТАВЛЕНИЙ ТЕКСТОВЫХ ДАННЫХ Рябинкин Г. М.

Целью данной работы является предоставление всестороннего анализа методологий семантического поиска, основанных на использовании векторного представления текстовых данных и моделей векторного пространства для представления семантической информации.

В частности, решены следующие задачи: проведен анализ актуальных проблем, связанных с семантическим поиском на основе многомерного векторного представления семантики текста; выявление конкретных проблем, возникающих в сценариях асимметричного семантического поиска, для случаев существенного различия характеристик запроса и искомого документа; анализ и обобщение методологий создания эффективных моделей векторного пространства, способных отражать семантические особенности текстовых данных для задача семантического поиска с учетом вычислительных затрат, так и результативности и производительности поиска.

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Constraint Satisfaction Method to Search Patterns in the Data Taking into Account the Hierarchy of Features

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Abstract-This article considers how the analysis of knowledge from subject domain ontology can help discover the most interesting and well-interpreted patterns in data. For this research area, the term "Pattern discovery guided by ontology" is used in the literature, and ontologies are considered as a means of semantic pruning of the search space. The analysis of ontologies in the pattern discovering can significantly reduce the enumeration of alternatives by pruning the search space, and also allows you to consider the elements of patterns at various levels of abstraction. The proposed approach to Data Mining is based on compact representation of the training sample using specialized matrix-like structures and the application of original inference procedures in these structures. Research lies at the intersection of such areas of artificial intelligence as data mining and semantic technologies for the representation and processing of information.

Keywords-frequent pattern discovery, data mining, ontology, machine learning, constraint satisfaction problem, semantic technology

I. Introduction

The presented research continues a series of works that deal with the application of the author's approach to solving Data Mining (DM) problems. Previously, the author's methods of clustering, closed pattern discovery, associative rule discovery were presented [1] as well as method that accelerates generating JSM-hypotheses in large databases [2]. The developed methods relate to methods of explainable Artificial Intelligent.

The article considers how the analysis of knowledge from subject domain ontology can help discover the most interesting and well-interpreted patterns in data by the end user. For this research area, the term "Pattern discovery guided by ontology" is used in the literature [3], and ontologies are considered as a means of semantic pruning of the search space. The analysis of ontologies in the pattern discovery can significantly reduce the enumeration of alternatives by pruning the search space, and also allows you to consider the elements of patterns at various levels of abstraction. Research lies at the intersection of such areas of artificial intelligence as DM and semantic technologies for the representation and processing of information.

In [2], a method was proposed for searching closed frequent patterns of the required type based on Constraint Programming Paradigm using the original representation of the training sample in the form of table constraints and the author's methods of constraint satisfaction. However, this method involves two stages in its implementation: 1) the stage of generating candidates for closed patterns and 2) the stage of verification of candidates and selection of those that satisfy the closeness property.

This publication presents research on the development of a method for closed frequent pattern discovery, taking into account hierarchy of features. The method is designed to quickly discover and enhance the interpretability of cause-and-effect relationships in multilevel descriptions of objects. Unlike the author's previous developments, the method avoids generating "redundant" nodes in search tree since it excludes the preliminary stage of generating candidates for the desired patterns.

II. Statement of the problem under discussion

We will provide information needed for further discussion [4]-[7].

As the initial information for the frequent pattern discovery problem is a *transactional database*, each row of which contains a transaction identifier, as well as a list of transaction elements. For example, analyzing purchases of goods in a store, the receipt number can be as a transaction identifier, and names of the purchased goods can act as elements. Also, the transactional database can be presented in the form of binary *object-feature table* where transactions are mapped to *objects*, and transaction elements are mapped to *features*. There is a "1" at the intersection of a row and a column in the table only if the object has this feature. A part of transactional database that is analyzed when pattern discovering we will refer to as a *training sample*.

A pattern A is any subset of features (elements). A *frequent pattern* is a set of features A that occurs at least in θ objects of the training sample. The θ is called a *frequency threshold*. The number of objects in which pattern A occurs is called an *absolute support* of pattern A and denoted *freq*(A).

It is usually necessary to find not all frequent patterns, but only those that have interesting features to the end user. Such patterns we will be refered to as *interesting*. Closed patterns are often considered as interesting because they can be used to express all other patterns. A closed set of features (pattern) is such that objects that have all these features at the same time do not have any other common features.

When generating interesting patterns, sometimes it is not enough to simply limit ourselves to searching for sets of features that meet the requirements for frequency and closeness, since there are too many such patterns and/or they are not well interpreted by the end user.

In this work, when discovering interesting patterns, an additional constraint is considered: features can be arranged in hierarchies. The inclusion of additional information about the grouping of elements in the form of hierarchies increases the interpretability of the DM results by the end user.

There are distinguishes of the representation of partonomies (based on relation "part–whole") and taxonomies (using relation "class–subclass") within the framework of the considered approach. They are explained below using the following example.

To illustrate the proposed method of pattern discovery taking into account hierarchy of features let's consider simplified example using the Figure 1. Let there be a set of hierarchically ordered features: the right tree corresponds to the taxonomy and the left one corresponds to the partonomy.

Now let's clarify which elements of hierarchies can be present in the records of the transactional database, that is, to form the initial description of transactions, and which can occur only in the generated patterns.

For a taxonomy, the transaction elements are leaf elements. In partonomy, each element can be included in the initial description of the transaction.

Table I shows an example of a fragment of a transaction database.

Table I Fragment of the transaction database

Transaction number	Elements
1	Cisterns, Oil Spill
2	Pipeline D, Pipe Break
3	Pipeline B, Pipe Break
4	Pipelines, Pipe Break
5	Cisterns, Pipelines, Pipe Break, Oil Spill
6	Pipeline D, Cisterns, Pipe Break, Oil Spill

The information contained in a transactional database and the knowledge contained in hierarchies of features can be combined and presented as an object-feature table (Table II).

Each row of the object-feature table corresponds to a transaction with the same number. The "1"s in the table mark the transaction elements themselves, as well as those elements that need to be included in the transaction description based on the analysis of hierarchies of feature.

If an element of a certain taxonomy occurs in a transaction, then in the corresponding row of the object-feature table, the "1"s also mark those elements that are higher in the hierarchy than the one under consideration. For example, since elements e ("Oil Spill") is included in transaction No1 it automatically includes element b ("Emergency") describing a superclass of the concept "Oil Spill".

If an element of a certain partonomy occurs in a transaction, then in the corresponding row of the object-feature table, the "1"s also mark those elements that are lower in the hierarchy than the one under consideration. For example, since element c ("Pipelines") is included in transaction Ne4 elements g ("Pipeline D") and h ("Pipeline B") which are parts of the element "Pipelines" should also be included in the transaction.

In this case, a pattern will be considered *acceptable* if any two elements of which are not connected by hierarchical relationships (either incomparable or belong to different hierarchies).

Let's set a value of minimal support $\theta=2$ (i. e. two transactions). It is necessary to find all closed frequent patterns taking into account the given relations of hierarchy of features and a fragment of the transactional database. The following sections considerates solving such problems within the framework of the author's approach.

III. The proposed approach to Data Mining

Recall that the Constraint Satisfaction Problem (CSP) is to find solutions for a network of constraint. The network of constraints is the following triple [8]–[10]: $\langle X, Dom, C \rangle$, where X is the set of variables, Dom are the domains of variables, Y are the constraints setting the permissible combinations of values of the variables. It is necessary to find such values of all variables that all constraints of network are satisfied.

The presented research uses the so-called table constraints. In addition to typical tables, *table constraints* include *compressed tables*, *smart tables*, etc. [11]. These types of constraints differ in what is meant by a tuple of relation. For further explanation, only compressed tables will be used. Tuples of compressed tables contain sets as components. Similar structures are described in [12] and are called *finite predicate matrices*.



Figure 1. The simplified example of the subject domain ontology

Table II Object-feature table

N⁰	а	b	С	d	e	f	g	h
	Fuel	Emer-	Pipe-	Cisterns	Oil	Pipe	Pipe-	Pipe-
	Storage	gency	lines		Spill	Break	line D	line B
1		1		1	1			
2		1				1	1	
3		1				1		1
4		1	1			1	1	1
5		1	1	1	1	1	1	1
6		1		1	1	1	1	

Within the framework of the approach developed in the work, DM problems are stated and solved as table constraint satisfaction problems. The approach relies on the representation of the training sample in the form of specialized table constraints that allow for compact expression of *n*-ary relations, as well as on the use of author's procedures for inference on these structures.

As in previous studies [2], [3], *compressed tables* of the D-type are used to model the training sample, which contain two attributes in their schema: attribute X, which corresponds to the objects of the training sample, and attribute Y, which describes the features of objects. So for the object-feature table under consideration (Table II) the corresponding compressed table of the D-type will be as follows:

$$\begin{array}{ccccc} X & Y \\ \{1,2,3,4,5,6\} & \{b,c,d,e,f,g,h\} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} \begin{vmatrix} 4,5,6 \\ \{1,5,6\} \\ \{2,3,4,5,6\} \\ \{2,4,5,6\} \\ \{2,4,5,6\} \\ \{b,c,d,e,f,h\} \\ \{3,4,5\} \\ \{b,c,d,e,f,g\} \end{vmatrix}$$
(1)

Here, the feature a is excluded from consideration in advance, since it does not occur in any transaction.

Each row of the compressed table can be interpreted as the following implication $(Y = m_k) \rightarrow (X \in O_k)$ (if feature m_k is under consideration, the set of objects that possess it is equal to O_k). For example, the following logical expression corresponds to the third row:

$$(X \in \{1, 5, 6\}) \lor (Y \in \{b, c, e, f, g, h\}) =$$

= $\overline{(Y \in \{b, c, e, f, g, h\})} \to (X \in \{1, 5, 6\}) =$
= $(Y \in \{d\}) \to (X \in \{1, 5, 6\}) =$
= $(Y = d) \to (X \in \{1, 5, 6\})$ (2)

This expression means the following: "The feature d is possessed by objects from the set $\{1, 5, 6\}$ ".

In order to search for closed frequent patterns within the framework of the proposed approach, the author's methods of inference on table constraints and methods of branching the search tree are used.

The author's methods of inference on tables of the *D*-type are implemented using rules 1-7:

Statement 1 (S1). If at least one row of a compressed table of the *D*-type is empty (contains all empty components) then the table is empty.

Statement 2 (S2). If all the components of an attribute are empty then this attribute can be deleted from the compressed table (all components of the corresponding columns are deleted).

Statement 3 (S3). If there is a row in the compressed table that contains single non-empty component then all values in domain that are not included in this component are deleted from the corresponding domain.

Statement 4 (S4). If a row of a compressed table of the D-type contains at least one full component, it is deleted.

Statement 5 (S5). If a component of a compressed table of the *D*-type contains a value that does not belong to the corresponding domain then this value is deleted from the component.

Statement 6 (S6). The components of a compressed table of the *D*-type corresponding to a variable X with cardinality below a certain threshold θ are replaced by empty components.

Statement 7 (S7). If a cardinality of the domain of a variable X is below defined threshold θ then a solution for the constraint satisfaction problem does not exist.

The statements 1-5 are used for closed pattern discovery. The last two statements are used for pruning infrequent patterns.

Taking into account the hierarchy relations on a set of features, in fact, requires the analysis of another additional type of constraints and, accordingly, the improvement of the mechanism of reasoning on constraints. The following section also discusses the specifics of the implementation of the search tree branching procedure for the case under consideration [2].

IV. The developed method and its illustration

The proposed method consists in the implementation of the following stages:

Stage 1. Representation of the training sample in the form of a special type of table constraints – compressed tables of the *D*-type, with the exception of those elements that have support below the specified one. Each row of the compressed table can be mapped to some feature m_k .

Stage 2. Formation of a binary tree based on a backtracking depth first search. The essence of this procedure is to select at each step of the search a certain feature m_k and form two subtrees: a) the left one, which serves to discover patterns containing this feature (an arc labeled m_k inputs to the left descendant node); b) the right one, to discover patterns that do not contain this feature the (arc with the label $\backslash m_k$ is aimed at the right descendant node). The feature m_k is selected among those features that have not yet participated in the selection and are included in the current domain of the variable Y. After selecting the descendant node, reduction procedures are used to discard obviously unpromising branches of the search tree, allowing to reduce a compressed table of the D-type characterizing the ancestor node to a table of a smaller dimension, excluding the "redundant" rows, columns, component values, attribute values from the domains of variables X and Y. The feature m_k is selected basing on the following heuristic: in the compressed table of the D-type obtained after applying the rules for reducing table constraints in the previous step, the row with the highest cardinality of the component Xis selected. In addition to the rules (S1-S7) discussed above, a specialized rule is applied – statement 8, which analyzes the hierarchy relations on features.

Statement 8 (S8). If it is assumed that some feature m_k must necessarily be included as an element in the desired pattern p, then all elements m_j that are above and below in hierarchy (taxonomy, partonomy) than

the one under consideration should be excluded from consideration (from the domain of attribute Y).

Stage 3. Listing patterns based on the analysis of the nodes of the search tree. To list patterns nodes are analyzed, the input arcs of which have a label that does not contain symbol "\". These nodes correspond to interesting patterns one by one. Listing patterns can be carried out during the construction of the search tree, rather than at the end of this procedure.

Unlike the methods "Apriori" and Eclat [4], [13], the proposed method implements a search tree traversal not in width, but in depth. The developed method uses a training sample representation similar to the TID representation in Eclat. As in the method "Close by one" [14], in the author's method, the main component is the logical inference procedure, which makes it possible to calculate its closure for a given set of features, but the proposed method reduces calculations by eliminating duplicate actions. Unlike the FP-Growth algorithm, the considered method makes it easy to integrate additional constraints on the required type of pattern and use them to reduce the search space. This makes it similar to various Apriori modifications.

Now let's return to our end-to-end example. The decision tree in this example built according to heuristic and constraint propagation rules considered above is shown below in Figure 2.

Let's demonstrate how pattern discovery is implemented taking as an example one of the branches of the search tree. So, initial table of the D-type is described by formula (1).

Let's first select feature b («Emergency») since it has maximum support. This means that component X of the first row is selected, but since this component matches the current domain there is no reducing the domain of X. According to **S8**, the features e («Oil Spill») and f(«Pipe Break») are excluded from consideration, since they are child nodes of the node b in the taxonomy. We have the following reminder of the initial compressed table of the D-type:

$$\begin{array}{c|cccc} X & Y \\ \{1, 2, 3, 4, 5, 6\} & \{\pmb{b}, c, d, g, h\} \\ 2 \\ 3 \\ 6 \\ 6 \\ 7 \end{array} \begin{vmatrix} 4, 5\} & \{b, d, g, h\} \\ \{1, 5, 6\} & \{b, c, g, h\} \\ \{2, 4, 5, 6\} & \{b, c, d, h\} \\ \{3, 4, 5\} & \{b, c, d, g\} \end{vmatrix}$$
(3)

Here and below, the features that form the desired patterns are highlighted in bold.

In the obtained compressed table of the *D*-type, the row 1 is eliminated based on statement **S4**, and a "tuning" to a new domain of the variable $Y: \{b, c, d, g, h\}$ is performed using **S5** and **S4**, and rows 4 and 5 are excluded from consideration. At this step, the pattern $[\{1, 2, 3, 4, 5, 6\}, \{b\}]$ is obtained.

Now the feature g is selected, and according to **S8** the feature c is excluded from consideration. The current domain of the variable Y becomes equal to the set $\{b, d, g, h\}$, and the domain of the variable X becomes equal to the set $\{2, 4, 5, 6\}$, i.e. to the component X of the sixth row. After "tuning" to new domains (statements **S5** and **S4**) we obtain the remainder:

$$\begin{array}{c|ccc} X & Y \\ \{2,4,5,6\} & \{\boldsymbol{b},d,\boldsymbol{g},h\} \\ 3 \\ 7 & \{5,6\} & \{b,g,h\} \\ \{4,5\} & \{b,d,g\} \end{array}$$
(4)

Here, row 6 is excluded due to reducing the domain of X, and row 2 is excluded due to narrowing the domain of Y. At this search step the pattern $[\{2, 4, 5, 6\}, \{b, g\}]$ has been discovered.

Next we select the feature d. This leads to narrowing the domain of the variable X to a set $\{5, 6\}$. As a result of "tuning" the compressed table to a new variable domain using statements **S5** and **S4**, row 3 is excluded from consideration, and in row 7 the component becomes equal to a single-element set, while the support threshold is two. After applying **S6** and **S3**, the domain of the variable Y is narrowed to a set $\{b, d, g\}$, and row 7 is eliminated according to **S4**.

At this step we obtain pattern $[\{5, 6\}, \{b, d, g\}]$. All rows of the compressed table have been deleted, which indicates that the study of the branch of the search tree has been completed. As a result of traversal of this branch of the search tree, three patterns were discovered.

Let's list all the closed frequent patterns discovered as a result of the application of the developed method:

$$\begin{split} [\{1,2,3,4,5,6\},\{b\}], [\{2,3,4,5,6\},\{f\}], \\ [\{2,4,5,6\},\{b,g\}], [\{3,4,5\},\{b,h\}], \\ [\{1,5,6\},\{b,d\}], [\{4,5\},\{b,c\}], \\ [\{2,4,5,6\},\{f,g\}], [\{3,4,5\},\{f,h\}], \\ [\{1,5,6\},\{d,e\}], [\{4,5\},\{c,f\}], \\ [\{5,6\},\{b,d,g\}], [\{4,5\},\{b,g,h\}], \\ [\{4,5\},\{f,g,h\}], [\{5,6\},\{d,e,f,g\}] \end{split} \tag{5}$$

Conclusion

The constraint programming paradigm is often used to solve complex combinatorial search problems, which include most DM problems. Within the framework of the proposed original approach, DM problems are proposed to be solved as table constraint satisfaction problems. To represent the training sample, it is proposed to use specialized table constraints – compressed tables of the D-type.

The proposed method of closed frequent pattern discovery taking into account subject domain ontology relies on the procedure of constructing a binary search tree, which provides interesting patterns without the preliminary stage of generating candidates for the desired patterns. Within the framework of the designed approach, it is quite easy to take into account additional requirements for type of discovered patterns. For each type of constraints on the type of pattern, appropriate rules of reduction of the search space are developed. In the presented study, an additional constraint is the requirement for a hierarchical ordering of features.

Constraints of hierarchy of feature are processed by specialized procedures for search space reduction. The application of the method makes it possible at each step of the search to reduce the existing problem to a problem of significantly smaller dimension, which eventually reduces the immediacy of the exponential catastrophe problem. In comparison with analogs using logical inference, the method allows to exclude repetitions of actions when calculating closures on sets of features.

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Figure 2. A decision tree based on the proposed method

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МЕТОД УДОВЛЕТВОРЕНИЯ ОГРАНИЧЕНИЙ ДЛЯ ВЫЯВЛЕНИЯ ПАТТЕРНОВ В ДАННЫХ С УЧЕТОМ ИЕРАРХИЙ ПРИЗНАКОВ Зуенко А. А., Зуенко О. Н.

В статье рассматривается, каким образом анализ онтологии предметной области способен помочь в выявлении интересных и хорошо интерпретируемых паттернов в данных. Для этой области исследований в литературе используется термин "Поиск паттернов, управляемый онтологиями", а онтологии рассматриваются в качестве средства семантической обрезки пространства поиска. Анализ онтологий при поиске паттернов позволяет существенно сократить перебор вариантов за счет редукции пространства поиска, а также рассматривать элементы паттернов на различных уровнях абстракции. Предложенный подход к интеллектуальному анализу данных основывается на компактном представлении обучающей выборки с помощью специализированных матрицеподобных структур и применении оригинальных процедур вывода на данных структурах. Исследования лежат на стыке таких направлений искусственного интеллекта как интеллектуальный анализ данных и семантические технологии представления и обработки информации.

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Automation of primary diagnostics of diseases of the human lumbar spine using intelligent analysis of CT images

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Abstract—This study aims to identify and detect vertebrae through CT image analysis, obtain the geometric dimensions of vertebrae, and assist in the diagnosis of degenerative spinal diseases in the human body. This study uses the YOLOv8-seg algorithm to segment vertebrae, extract geometric dimension parameters such as length and width of vertebrae, find the boundary lines between adjacent vertebrae, and calculate the corresponding angles. After verification, this study can provide strong support for clinical diagnosis in the early diagnosis of degenerative spinal diseases, help improve the diagnostic efficiency and accuracy of degenerative spinal diseases, and provide a scientific basis for early intervention and treatment of patients.

Keywords—detect vertebrae, image analysis, YOLO, degenerative spinal diseases, clinical diagnosis

I. Introduction

Lumbar degeneration is a physiological process that changes with age, manifested as low back pain, radiating pain in the lower limbs, numbness and inability to move, etc. It mainly includes diseases such as lumbar disc herniation, lumbar spinal stenosis, lumbar spondylolisthesis, degenerative lumbar scoliosis, etc. The proportion of adolescent patients is increasing, and adolescent patients are mostly related to unhealthy lifestyles (such as longterm sitting, lack of exercise), childbirth, trauma or genetics. Therefore, early detection and diagnosis can provide timely relief, delay lumbar degeneration, reduce obesity, and alleviate patients' pain [1] [2] [3] [4]. At present, the diagnosis of spinal degenerative diseases mainly relies on imaging examinations. There are many technical means of medical imaging, including X-ray imaging, computed tomography (CT), ultrasound imaging, and magnetic resonance imaging (MRI). CT images have the characteristics of high resolution and high contrast, and can clearly display the anatomical structure of the spine [5] [6] [7]. Yang Qiaohui et al. conducted a comparative study on the diagnostic accuracy of spinal fractures between X-ray and CT, and verified that CT is better than X-ray [8].CT images can clearly show the overall

picture and details of the fracture site, providing effective imaging data basis for clinical diagnosis and treatment.

With the application of artificial intelligence technology in the medical field, especially the advantages of deep learning in analyzing medical images, the diagnosis relies on the doctor's experience, is highly subjective, and has low efficiency, which effectively improves the diagnostic efficiency [9] [10].

Automatic diagnosis methods based on CT images have gradually become a research hotspot, such as vertebral segmentation, edge detection, and angle measurement.Kurochka et al. proposed a deep convolutional neural network as a classification method for an automatic detection model of vertebrae in X-ray images for osteoporosis diagnosis. In further research, an algorithm based on MaskR-CNN convolutional neural network was used to locate vertebrae on lumbar X-ray images and determine their geometric parameters to assist in the diagnosis of human spinal degenerative diseases [11] [12]. Hurtado-Aviles J et al. mathematically modeled the empirical data listed in the Raimondi table to use the Raimondi method in digital medical images more precisely and accurately, so as to use the axial vertebral rotation (AVR) parameters for the study of juvenile idiopathic scoliosis [13]. Based on the above research, this paper proposes a CT image analysis method based on the YOLO v8 model to determine the geometric dimensions and angles of the lumbar L1-L5 vertebrae, and then predict spinal degenerative diseases [14].

II. Materials and methods

The experimental environment is Windows 11 operating system, using Python 3.12 and PyTorch framework. The experimental tools include YOLOv8 model, OpenCV library, and the programming environment is PyCharm.



Figure 1. YOLOv8 network model structure diagram

A. Data collection and processing

- The experimental environment is Windows 11 operating system, using Python 3.12 and PyTorch framework. The experimental tools include YOLOv8 model, OpenCV library, and the programming environment is PyCharm.
- This dataset includes 99 lumbar CT images, each of which contains L1-L5 vertebrae. The data was annotated using the ImageMe tool, and the actual edge information of the vertebrae was annotated using the polygon tool.

B. Application of segmentation model

- YOLOv8 is a target detection model based on convolutional neural networks, which has the characteristics of fast detection speed and high accuracy. Compared with YOLOv5 and YOLOv7, YOLOv8 has significantly improved detection accuracy and speed. The backbone network (Backbone) of YOLOv8 usually adopts CSPDarknet, which reduces the amount of calculation and improves the feature extraction capability through cross-stage partial connections (CSP) [15]. "Fig. 1" is a diagram of the network model structure of YOLOv8.
- YOLOv8-Seg is an instance segmentation model based on YOLOv8, which increases the instance segmentation capability and can capture the detailed information of the target. It uses the target detection framework of YOLOv8 to detect the target in the image, and uses RoI (Region of Interest) alignment or RoI Pooling technology to extract the mask features of the target area from the feature map, which can

segment the target more accurately and realize target detection and pixel-level segmentation at the same time. It is particularly suitable for small targets and complex edge structures such as lumbar vertebrae [16]. YOLOv8-Seg can not only identify and locate the target, but also process multiple targets in the image at the same time and generate independent masks for each target. The segmentation branch can generate high-quality pixel-level masks, which is suitable for tasks that require fine segmentation (such as organ or lesion area segmentation in medical images) and facilitate the acquisition of the features of each mask.

Therefore, in order to accurately and efficiently obtain the features of the vertebrae, this paper adopts the instance segmentation algorithm model YOLOv8-Seg to detect the vertebrae of the lumbar spine and obtain the features of the vertebrae [17].

C. Model training

To ensure the prediction performance of the model, the optimized dataset needs to be classified. There are 99 image datasets in total, of which the training set, validation set, and test set are 70, 10, and 19 images respectively.

In order to facilitate the comparison of post-processing effects, this dataset did not undergo image preprocessing and was directly used as the original image input. The input image size of the YOLOv8 instance segmentation model is 1024 pixels x 1024 pixels; the epoch iteration of each training cycle is set to 200 times. Tables 1 and 2 show the detection data of the yolov8-seg model for

the lumbar vertebrae box and mask, with a recall rate of 88.5% and an accuracy rate of 89.8%. "Fig. 2" and "Fig. 3" show the parameter results of model training.

Table I Model training data display-box

Class	Instances	Р	R	mAP50
all	99	0.767	0.866	0.876
15	17	0.802	0.882	0.926
14	17	0.794	1	0.925
13	17	0.857	0.882	0.917
12	17	0.81	0.765	0.921
11	17	0.66	0.916	0.825

Table II Model training data display-mask

Class	Instances	Mask(P)	R	mAP50
all	99	0.767	0.866	0.876
15	17	0.802	0.882	0.926
14	17	0.794	1	0.925
13	17	0.857	0.882	0.917
12	17	0.81	0.765	0.921
11	17	0.66	0.916	0.825

Experiments have shown that the YOLOv8-seg model can accurately detect and segment lumbar vertebrae, and the recall rate (Recall) and average precision (mAP) have reached a high level, which is suitable for medical image analysis tasks.

D. Acquisition of vertebral geometric parameters

The YOLOv8-Seg model detects lumbar vertebrae based on the input image and generates a bounding box and pixel-level mask for each vertebra. The mask is a binary image, where the pixel value of the target area is 1 and the pixel value of the background area is 0. Through segmentation, we can accurately locate the shape and coordinate information of the target, thereby obtaining the geometric parameters of the vertebrae.Regarding the acquisition of geometric parameters, this paper achieves it by calculating the minimum enclosing rectangle of the contour [18].

The minimum bounding rectangle is a geometric concept that refers to the smallest rectangle that can completely enclose a two-dimensional figure (such as a polygon or a curve set). It is to find the minimum rectangle that encloses a point set. The characteristic of this rectangle is that its edge passes through certain points on the point set. The rectangle obtained in this way is the minimum bounding rectangle (MBR). The minimum adjacent rectangle can be used to obtain the bounding box of the figure, determine its center point, aspect ratio and rotation angle, and thus obtain a minimum rectangle that can cover the entire figure. The length and width of the rectangle can vary depending on the figure, but the purpose is to fit all the edges of the figure as closely as possible. The basic process of its implementation:

- Find a simple circumscribed rectangle of a twodimensional shape, whose sides are parallel to the x-axis and y-axis respectively.
- Algorithm for rotating any point on a plane around a fixed point to any angle.
- Rotate the original polygon. Calculate the simple circumscribed rectangle of the polygon after each rotation, save its area, vertex coordinates, and the rotation angle of the original polygon at this time.
- Calculate the simple circumscribed rectangle with the smallest area during the rotation process, and save the vertex coordinates and rotation angle of the smallest circumscribed rectangle.
- Rotate the simple circumscribed rectangle obtained in the previous step in the opposite direction by the same angle to obtain the minimum circumscribed rectangle.

The boundary of the minimum circumscribed rectangle is usually determined by the maximum horizontal coordinate, minimum horizontal coordinate, maximum vertical coordinate, and minimum vertical coordinate of each vertex of a given two-dimensional shape [19] [20]. It is often used in image processing, machine vision, target tracking, and other fields to determine the position and direction of the target object, which is the basis for target recognition and positioning. In the vertebra segmentation experiment, the minimum circumscribed rectangle of the segmented cone bone contour is calculated to obtain a rectangular contour with similar angles to the sides of the contour. Because the contour shape is mostly a quadrilateral, the calculated minimum circumscribed rectangle can restore the upper and lower boundary positions and inclination angles of the vertebra to a great extent, which plays an important role in the calculation of the size of each vertebra and the Cobb angle [21].

This article uses the OpenCV library function cv2.minAreaRect(points) to calculate the minimum enclosing rectangle. The parameter points of this function is the point set of the outline of the required minimum enclosing rectangle. The point set must be in the form of an array, for example, points=np.array([[x1,y1],[x2,y2],...,[xn,yn])). To do this, make sure that the contour information of the mask is converted into array form.The cv2.minAreaRect() function returns a Box2D structure, which includes three pieces of information: (center point coordinates, (width, height), and rotation angle).

• Get height and width:The second parameter returned by cv2.BoxPoints(points). For example: rect = cv2.minAreaRect(contour); w, h = rect[1]; At this time, the pixel value is obtained. If there is an actual size of the reference object, convert the pixel value to the actual size.The conversion rules are as follows:



Figure 2. Model training results(a)

Calculate the scale_factor:

scale_factor =
$$\frac{\text{real}_{\text{size}}}{\text{pixel}_{\text{size}}}$$

Calculate the actual vertebra size based on the scale_factor:

$$\begin{cases} actual_width = w \times scale_factor, \\ actual_height = h \times scale_factor, \end{cases}$$

Among them:

- real_size is the actual size of the reference object.
- pixel_size is the pixel size of the reference object in the image.
- w is the pixel width of the vertebra.
- h is the pixel height of the vertebra.
- Get the angle between vertebrae:After segmenting the vertebrae image, the coordinate information in the bounding box and mask contour image cannot directly calculate the angle (such as Cobb angle) of the segmentation result. Therefore, we must first perform contour recognition on the segmentation result to obtain the contour coordinate information of all vertebrae, and then calculate the coordinates of the upper and lower boundaries based on the vertebrae contours, and finally calculate the angle between the vertebrae.

In this experiment, we get the minimum circumscribed rectangle rect based on the vertebral contour, obtain the four vertices of the contour circumscribed rectangle through cv2.boxPoints(rect), determine the inclination direction of the cone bone according to the relationship between the width and height of the vertebra, and then determine the vertex position by sorting the four vertices.

"Fig. 4" shows the use of the minimum adjacent rectangle method to determine the upper and lower boundary vertices of the vertebrae and connect them with two line segments to calculate the angle between the vertebrae. The upper left corner shows the angle between 15-14.

It should be noted that when we draw the four sides of the adjacent rectangle, although we have obtained the four vertices of the adjacent rectangle, we cannot determine which vertex of the rectangle each of the four coordinate points corresponds to, so we still need to analyze according to the positions of the four coordinate points. The method used here is:

• Determine the arrangement structure of the vertebrae: Because the data set contains multiple different types of horizontal and vertical images, first determine whether the vertebrae are arranged horizontally or vertically. Different arrangements connect the vertices of the upper and lower boundary lines differently. Combine the position coordinates of 11 and 15, for example:

$$x_{abs} = |x_2 - x_1|$$
$$y_{abs} = |y_2 - y_1|$$



Figure 3. Model training results(b)



Figure 4. Geometric parameter display.

Among them:

- x_1 is the horizontal coordinate point of 11.
- x_2 is the horizontal coordinate point of 15.
- y_1 is the vertical coordinate point of 11.
- y_2 is the vertical coordinate point of 15.

Determine the size of x_{abs} and y_{abs} , determine the arrangement direction, and clarify the direction of the upper and lower boundary segments.

Determine the tilt angle and width and height char-

acteristics: Based on the comparison of the tilt angle and the width and height, sort the coordinates of the four vertices of the minimum adjacent rectangle according to the maximum horizontal coordinate, the minimum horizontal coordinate, the maximum vertical coordinate, and the minimum vertical coordinate.

- Determine the vertices of the upper and lower boundary segments: According to the sorting results of the previous step, the upper and lower boundary vertices of the corresponding rectangle of the vertebra are determined. In this experiment, the cv2.line() function is used to draw the line segments in combination with the boundary vertebrae. As can be seen from Figure 4, the upper and lower boundary vertex detection restores the upper and lower boundaries of the vertebrae well.
- Test the intervertebral angle: After the vertebral boundary segment is determined, the intervertebral angle can be calculated by finding the angle between the two line segments.

The above methods can be well verified for different lumbar CT image orientations, especially providing an important reference basis for the automated measurement of the lumbar Cobb angle, and playing a positive role in promoting the early diagnosis of lumbar degenerative diseases.

III. Summary

This study analyzed CT images and combined the YOLOv8-seg model to accurately detect and identify the lumbar vertebrae, and extracted the geometric parameters of the vertebrae based on the mask of the identified target, including the height and width of the vertebrae and the mask contour edge obtained by the minimum adjacency matrix, thereby obtaining the angle between the vertebrae. This provides a research idea for obtaining the Cobb angle and has important clinical application value in assisting the diagnosis of degenerative diseases of the lumbar spine.

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АВТОМАТИЗАЦИЯ ПЕРВИЧНОЙ ДИАГНОСТИКИ ЗАБОЛЕВАНИЙ ПОЯСНИЧНОГО ОТДЕЛА ПОЗВОНОЧНИКА ЧЕЛОВЕКА С ИСПОЛЬЗОВАНИЕМ ИНТЕЛЛЕКТУАЛЬНОГО АНАЛИЗА КТ-ИЗОБРАЖЕНИЙ

Курочка К.С., Ван Сюэмэй

Целью данного исследования является создание автоматизированной интеллектуальной системы для первичной диагностики заболеваний поясничного отдела позвоночника человека. Данная диагностика осуществляется посредством обнаружения и идентификации позвонков, а также получения геометрических размеров и взаимного их расположения относительно друг друга на цифровых КТ изображениях.

Ядром интеллектуальной системы является модель YOLOv8-seg, с помощью которой осуществляется локализация позвонков, после которой вычисляются углы между позвонками и осуществляется первичная диагностика. После валидации полученных результатов данное исследование может оказать хорошую поддержку медицинским сотрудникам при ранней диагностике дегенеративных заболеваний позвоночника, помочь повысить диагностическую эффективность и точность выявления дегенеративных заболеваний позвоночника и предоставить научную основу для раннего вмешательства и лечения пациентов.

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Intelligent System for Analyzing MRI Images to Find the Main Elements of the Human Spine

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Abstract—This study aims to build an intelligent system based on MRI image analysis to find the main elements of the human spine, such as vertebrae and intervertebral discs. The core of this intelligent system is to design a neural network model that can accurately identify and find vertebrae and intervertebral discs. Therefore, this paper proposes an improved YOLOv8-seg image segmentation model, which introduces two lightweight convolution modules, GhostConv and C3Ghost, to reduce the computational complexity and parameter complexity of the model while maintaining high performance; at the same time, the CBAM attention mechanism is introduced to focus on specific features to improve model performance. The results show that the intelligent system built based on the improved YOLOv8-seg image segmentation model can automatically find and segment the vertebrae and intervertebral disc areas in lumbar MRI images, with high accuracy and recall, significantly improving segmentation efficiency and reducing human errors. In the future, we will further optimize the model structure and increase the diversity and scale of the data set to further improve the performance and stability of the intelligent system.

Keywords—intelligent system, YOLOv8-seg, the human lumbar spine, MRI, CBAM

I. Introduction

With the rapid development of social economy, people's pace of life is accelerating, life pressure and work intensity are significantly improved, and the incidence rate of lumbar spine disease is also rising year by year, which seriously affects the quality of life of many people. Epidemiological studies around the world show that lumbar disc herniation and other lumbar diseases occur at all ages, but the middle-aged people between 40-60 years old are the most common, and the incidence rate of men in this age group is about twice that of women [1] [2].

The human lumbar spine is typically composed of 5 vertebrae, but due to developmental abnormalities or trauma, some individuals may have 4 or 6 vertebrae. The lumbar spine plays an extremely important role in the human body, with functions mainly including regulating lower limb movement, protecting abdominal organs, and transmitting systemic loads. In the past, imaging techniques such as ultrasound and computed Huanhai Ren

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tomography (CT) were widely used for the observation of lumbar spine diseases. However, these technologies have limitations in their ability to identify soft tissues, making it difficult to clearly display subtle lesions in structures such as intervertebral discs, ligaments, and nerve roots [3] [4]. In contrast, magnetic resonance imaging (MRI) technology stands out due to its significant advantages such as low radiation, high resolution, and multi planar imaging. MRI has extremely high resolution ability for soft tissue, which can clearly present details of lesions such as intervertebral disc herniation, nerve root compression, ligament damage, etc., providing important basis for medical personnel to accurately judge and evaluate the patient's condition [5]. Therefore, MRI imaging technology has become the preferred method for the examination of lumbar spine lesions, widely used in the evaluation and diagnosis of lumbar spine fractures, lumbar spondylolisthesis, lumbar disc herniation and other lesions. Medical personnel can obtain detailed soft tissue and lumbar spine bone structure images through MRI scans, accurately analyze the type, scope, and severity of lesions, and then develop personalized treatment plans. In addition, MRI can also be used to track treatment outcomes, monitor changes in the patient's condition, and provide comprehensive support for the patient's recovery.

Therefore, it is of great clinical significance to construct an intelligent system based on accurate identification and segmentation of the human lumbar vertebrae and intervertebral discs.In recent years, with the rapid development of artificial intelligence technology [6] [7], deep learning has been widely applied in computer vision fields such as image classification [8], image segmentation [9] [10], and object detection [11]. Deep learning methods, with their powerful feature extraction capabilities, are able to learn more complex and refined feature representations, demonstrating significant advantages in accuracy, robustness, and generality. This has led to its rapid rise in the field of medical image analysis and diagnosis, becoming the mainstream technology for current medical image segmentation and providing strong support for accurate diagnosis of lumbar

spine and intervertebral disc related lesions. In medical image analysis, deep learning algorithms can recognize complex patterns and subtle features that are difficult for the human eye to detect through large-scale data training. For example, models based on Convolutional Neural Networks (CNN) can efficiently segment medical images, accurately outline the contours of the lumbar spine and intervertebral discs, and provide clear anatomical information for clinical doctors. This high-precision image segmentation capability not only helps to detect lesions early, but also provides important basis for the development of personalized treatment plans.

This intelligent system is based on the PyTorch deep learning framework and uses an improved YOLOv8-seg lumbar image segmentation model. [12] [13]. It significantly improves the segmentation efficiency and accuracy by introducing two lightweight convolution modules, GhostConv and C3Ghost, as well as the CBAM attention module. These improved modules not only optimize the computational complexity of the model, but also enhance its ability to extract features of the lumbar spine and intervertebral discs, enabling it to quickly and accurately identify the contours of each segment of the lumbar spine and intervertebral disc. Through this efficient image segmentation technology, medical personnel can clearly understand the scope and degree of lesions, providing important imaging evidence for clinical diagnosis and treatment plan formulation.

II. Introduction to YOLOv8-seg

The YOLOv8-seg network architecture mainly consists of three core components: Backbone, Neck, and Head. The overall architecture is shown in Figure 6. Compared to YOLOv5, YOLOv8 introduces an innovative C2f module in the backbone network to replace the original C3 module. The C2f module significantly enhances the feature extraction capability by optimizing the gradient flow path, thereby improving the overall performance of the model.

In the neck network section, YOLOv8-seg adopts an advanced multi-scale feature fusion architecture combining FPN (Feature Pyramid Network) and PAN (Path Aggregation Network). This design effectively enhances the model's perception of target detail features and contextual information through multi-level feature aggregation and information transmission mechanisms, thereby improving the accuracy of object detection and instance segmentation.

The head network design embodies the architectural innovation of YOLOv8-seg, mainly including two key improvements: firstly, adopting a decoupled head structure to separate classification tasks from detection tasks. This design not only improves the professionalism of tasks, but also achieves a paradigm shift from anchor based to anchor free, significantly reducing the number of bounding box predictions and optimizing the computational efficiency of non maximum suppression (NMS); Secondly, in terms of loss function design, a task aligned allocator was introduced for positive sample allocation, and a distribution focal loss was adopted. These improvements effectively improved the training stability and detection accuracy of the model.

In terms of implementing instance segmentation functionality, YOLOv8-seg has added a segment segmentation branch in the head network, and its mask generation mechanism includes two key steps.

A. Prototype Mask Generation

Generate a fixed number of prototype masks (Prototype Masks) through the Protonet network in the P3 feature layer. These prototype masks are universal mask templates obtained through network learning, with global sharing characteristics, that is, all instance segmentation tasks are based on the same set of prototypes for mask reconstruction.

B. Mask coefficient generation

For each detected target instance, the model outputs a corresponding set of weight coefficients through the segment mask terminals of the P3, P4, and P5 feature layers. These coefficients determine the weighted combination of prototype masks, and ultimately generate the predicted masks (Masks) of the target instance through linear combination, as expressed mathematically in equation (1).

$$Masks = M_c P \tag{1}$$

In equation (1), P is the prototype mask with dimensions $B \times K \times H \times W$, and B is the batch size; K is the number of prototype masks generated, default is 32; $H \times W$ is the size of the prototype mask; M_c is the mask coefficient. By using mask prototypes and mask coefficient weighting, high-quality masks can be generated using simple linear calculations, which is more efficient than traditional two-stage instance segmentation methods and can achieve a better balance between speed and accuracy.

III. YOLOv8-seg Improvement

A. Lightweight Convolution Module

GhostConv and C3Ghost are two lightweight convolution modules introduced in YOLOv8, aimed at reducing the computational and parameter complexity of the model while maintaining high performance.

a) GhostConv: It is a lightweight convolution operation based on the Ghost Module concept. It reduces computational complexity by generating "phantom feature maps". The Ghost Module first uses a small number of convolution kernels to generate a portion of feature maps, and then performs simple linear transformations on these feature maps to generate more "phantom feature maps". Finally, concatenate the intrinsic feature map and the phantom feature map to obtain the final output.

b) C3Ghost: It is a lightweight module based on the GhostConv concept, which improves the efficiency of the model by reducing computation and parameter count while maintaining high performance.

B. CBAM attention mechanism

CBAM (Convolutional Block Attention Module) is an innovative attention mechanism designed specifically for convolutional neural networks, aimed at adaptively enhancing key information in feature maps. CBAM combines Channel Attention and Spatial Attention mechanisms to weight feature maps from both channel and spatial dimensions, significantly improving the model's representation ability. Its unique dual attention mechanism not only captures the dependencies between channels, but also recognizes the importance of spatial positions, making the model more robust in complex scenes. In addition, CBAM has extremely low computational overhead and hardly increases the number of parameters and computational complexity of the model, making it seamlessly integrated into existing CNN architectures and significantly improving model performance.

Through this dual attention mechanism, CBAM not only enhances the feature extraction capability of the model, but also achieves an excellent balance between computational efficiency and model performance, becoming an indispensable component in modern convolutional neural networks.

C. Improved YOLOv8-seg model

In the YOLOv8 seg model, GhostConv and C3Ghost lightweight modules are introduced to optimize the computational efficiency and parameter count of the model. Specific improvements include replacing most of the traditional Conv modules with GhostConv modules, and replacing the C2f module in the YOLOv8 seg model with the C3Ghost module. The GhostConv module reduces computational complexity by generating "phantom feature maps", while the C3Ghost module further reduces model complexity while maintaining feature expression ability. These improvements significantly enhance the inference speed of the model while maintaining high detection and segmentation accuracy. The improved YOLOv8seg model structure is shown in "Figure 1", which illustrates the overall architecture after module replacement.

In the YOLOv8 framework, targeted architecture optimization was performed on the yolov8-seg.yaml configuration file. Specifically, two important structural improvements were made to the backbone module: firstly, all standard convolutional layers (Conv) except for the initial layer (Layer 0) were replaced with lightweight Ghost Conv modules (GhostConv), which significantly reduced the computational complexity and number of parameters of the model while maintaining feature extraction capabilities; Secondly, the Convolutional Attention Mechanism module (CBAM) is integrated in level 10, which enhances the model's ability to extract key features through a dual mechanism of channel attention and spatial attention.

In the process of optimizing the model architecture, the configuration file of YOLOv8 (yolov8-seg.yaml) was adjusted. Specifically, the C2f structure in the original head module was replaced with a more efficient lightweight convolution module C3Ghost. This improvement aims to maintain the feature extraction capability while reducing the computational complexity of the model.

IV. Experiment and result analysis

A. Dataset preparation

The experimental dataset used in this study contains a variety of lumbar spine MRI images, covering different morphological features (such as disc herniation, spinal stenosis, etc.) and various sizes. All images are stored in JPG format. To verify the effectiveness of the model, we selected 512 representative sagittal MRI images of the lumbar spine from the public dataset. The dataset is divided into training set, test set and validation set in a ratio of 7:2:1. These sagittal images clearly show the anatomical structure of the lumbar spine, including key tissues such as vertebral bodies, and intervertebral discs, providing rich morphological information for model training. "Figure 2" shows samples of lumbar spine MRI images with typical pathological features in the dataset, which fully demonstrates the diversity and representativeness of the dataset.

In this study, the labeling of human lumbar sagittal MRI images was completed using the advanced labelme labeling tool to ensure the accuracy and consistency of the labeling. During the labeling process, we subdivided the lumbar structure into 10 categories, including 5 lumbar vertebral categories (L1, L2, L3, L4, L5) and 5 intervertebral disc categories (D1, D2, D3, D4, D5).

Since the number of original images is not too abundant, the original images are expanded by means of data augmentation. However, if the validation set is data augmented, the samples in the validation set will no longer represent the data distribution in the real scene, which may make the model too optimistic on the validation set and fail to accurately evaluate the generalization ability of the model. Therefore, in order to maintain the authenticity and representativeness of the validation set, data augmentation is only performed on the training set and the test set. Based on the Albumentations image enhancement library, the image is enhanced by vertical flipping, horizontal flipping, rotation, random scaling, random adjustment of image brightness and contrast, and addition of Gaussian noise to form an enhancement pipeline. Each enhancement operation has a certain probability of being applied, which ensures that the input image will be different each time training, enhancing



Figure 1. Improved YOLOv8-seg model.



Figure 2. The partial images in the dataset.

the robustness and generalization of the model while reducing overfitting.

B. Experimental environment

The experimental environment for segmenting MRI human lumbar vertebrae and intervertebral discs using the improved YOLOv8-seg segmentation model is shown in "Table I".

Table I Experimental environment

Software and hardware names	Specific parameters
CPU	Intel(R) Xeon(R) Gold 6226R
Memory	64GB
GPU	Quadro RTX 5000
Operating system	Window 10 Professional Edition
Software environment	Python3.12.7+torch2.6.0+cu118

C. Experimental process

In this experiment, the model training was performed for 200 rounds, and the batch size of each round of training was set to 16, with an initial learning rate of 0.01. The resolution of the input image was uniformly adjusted to 640×640 pixels to ensure that the model can fully capture the detailed features of the lumbar spine and intervertebral disc.

To comprehensively evaluate the segmentation perfor-

mance of the model, the mean average precision (mAP) was used as the core evaluation indicator, including mAP@0.5 and mAP@0.5:0.95. Among them, mAP@0.5 measures the segmentation accuracy of the model when the intersection over union (IoU) threshold is 0.5, while mAP@0.5:0.95 is the average value of multiple IoU thresholds (from 0.5 to 0.95, with a step size of 0.05), which comprehensively reflects the performance of the model under different accuracy requirements. The mAP indicator not only comprehensively considers the accuracy and recall of the model, but also can effectively evaluate the generalization ability and robustness of the model. Through the above multi-dimensional performance evaluation, the performance of the model in the lumbar spine and intervertebral disc segmentation tasks can be comprehensively measured.

For the model training data, the bounding box detection performance and mask segmentation performance are analyzed.

a) bounding box detection performance: The training data of bounding box detection performance is shown in "Table II". The accuracy of all categories is above 0.938, indicating that the model has high accuracy in detecting targets; the recall rate is above 0.965, indicating that the model can effectively detect most targets; the mAP50 value is above 0.983, indicating that the average accuracy of the model is very high when the IoU threshold is 0.5; the mAP50-95 value is between 0.684 and 0.847, indicating that the average accuracy of the model at different IoU thresholds has decreased.

Table II The bounding box detection performance

Class	Box(P)	Box(R)	Box(mAP50)	Box(mAP50-95)
a11	0.96	0.984	0.989	0.758
D1	0.938	0.985	0.986	0.697
D2	0.956	0.984	0.983	0.703
D3	0.975	0.985	0.992	0.694
D4	0.96	0.985	0.983	0.684
D5	0.962	0.985	0.994	0.768
L1	0.942	0.965	0.985	0.792
L2	0.944	0.985	0.994	0.78
L3	0.971	0.995	0.994	0.847
L4	0.974	0.985	0.994	0.823
L5	0.974	0.985	0.985	0.794

b) mask segmentation performance: The training data of mask segmentation performance are shown in "Table III". The accuracy of mask segmentation is above 0.938, indicating that the model also has high accuracy in the segmentation task; the recall rate is above 0.965, indicating that the model can effectively detect most targets in the segmentation task; the mAP50 value is above 0.983, indicating that the model has a high average precision in the segmentation task; the mAP50-95 value is between 0.663 and 0.839, indicating that the average precision

of the model in the segmentation task at different IoU thresholds has decreased.

Table III The training data of mask segmentation

Class	Mask(P)	Mask(R)	Mask(mAP50)	Mask(mAP50-95)
a11	0.96	0.984	0.989	0.752
D1	0.938	0.985	0.986	0.687
D2	0.956	0.984	0.983	0.692
D3	0.975	0.985	0.992	0.677
D4	0.96	0.985	0.983	0.663
D5	0.962	0.985	0.994	0.706
L1	0.942	0.965	0.985	0.806
L2	0.944	0.985	0.994	0.838
L3	0.971	0.995	0.994	0.839
L4	0.974	0.985	0.994	0.814
L5	0.974	0.985	0.985	0.802

D. Image prediction

Use a trained human lumbar vertebrae and intervertebral disc segmentation model to perform object detection and segmentation on multiple images, and output detection results, including category labels and accurate bounding boxes of human lumbar vertebrae and intervertebral discs.

The image prediction in this study selected two types of images for prediction. The first type is the test image in the public dataset, and the second type is the real unprocessed MRI human lumbar spine image collected from the hospital imaging center. Firstly, multiple test images in the public dataset were predicted, and the prediction results are shown in "Figure 3".



Figure 3. Public dataset image prediction.

Secondly, multiple real unprocessed MRI images of the human lumbar spine were predicted, and the prediction results are shown in "Figure 4".

V. Conclusion

In order to enable the intelligent system to more accurately and quickly find and segment the main elements of the human spine, such as the lumbar vertebrae and intervertebral discs, this paper proposes an improved instance segmentation model based on YOLOv8seg. By introducing the CBAM attention mechanism



Figure 4. Real unprocessed image Prediction.

and two lightweight convolution modules, GhostConv and C3Ghost, the segmentation accuracy and speed are improved. Experiments were conducted on the public human lumbar sagittal dataset. The overall accuracy, recall rate, and mAP50 of the model training were 0.96, 0.984, and 0.989, respectively. Good prediction results were obtained on a public human lumbar sagittal image dataset, proving the effectiveness and feasibility of the intelligent system.

Although the intelligent system based on this model performs well in the search and segmentation of the human lumbar spine and intervertebral disc, there are still some accuracy issues in the segmentation of the curved boundaries on both sides of the image. Therefore, in future research, it is possible to consider combining the deep learning model with the traditional edge extraction algorithm to further optimize the segmentation model and algorithm and enhance the practicality and accuracy of the intelligent system.

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ИНТЕЛЛЕКТУАЛЬНАЯ СИСТЕМА АНАЛИЗА МРТ ИЗОБРАЖЕНИЙ ДЛЯ ПОИСКА ОСНОВНЫХ ЭЛЕМЕНТОВ ПОЗВОНОЧНИКА ЧЕЛОВЕКА

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Целью данного исследования является создание интеллектуальной системы для анализа МРТ изображений с целью локализации и определения геометрических характеристик основных элементов позвоночника человека, таких как позвонки и межпозвоночные диски. Основой данной интеллектуальной системы является нейросетевая модель, которая может с достаточной для практического применения точностью идентифицировать и находить позвонки и межпозвоночные диски. В данной статье предлагается усовершенствованная модель сегментации изображений YOLOv8-seg, которая вводит два облегченных модуля свертки, GhostConv и C3Ghost, для снижения вычислительной сложности и уменьшения параметров модели при сохранении высокой производительности; в то же время вводится механизм внимания СВАМ для фокусировки на определенных функциях для повышения производительности модели. Результаты показывают, что интеллектуальная система, созданная на основе усовершенствованной модели сегментации изображений YOLOv8-seg, может автоматически находить и сегментировать области позвонков и межпозвоночных дисков на изображениях МРТ поясничного отдела позвоночника с высокой точностью и полнотой, что значительно повышает эффективность сегментации и снижает количество человеческих ошибок. В будущем мы продолжим оптимизировать структуру модели, а также увеличим разнообразие и масштаб набора данных для дальнейшего повышения производительности и стабильности интеллектуальной системы.

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Application of Semantic Technologies in a Model of Automatic Recognition and Analysis of Elements in Images of the Earth's Surface

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Abstract—This research investigates the impact of neural network model training parameters in the context of object classification within the framework of semantic technologies, specifically for the analysis of Earth's surface imagery.

It is shown how semantic technologies and their application to the task of classifying objects in earth surface images improve the ability of the model to process and classify objects.

A detailed analysis of the influence of key training parameters on the accuracy and stability of the model is carried out. These factors were assessed within the framework of the semantic technologies approach.

The findings highlight the effectiveness of the neural network model in semantic technology applications for Earth imagery analysis.

These results can be applied to improve the performance of neural network-based object classification systems within the domain of semantic technologies.

Keywords—semantic technologies, machine learning, neural networks, DARKNET, YOLOv3, geoinformation data processing

I. Introduction

Classification of objects in images of the Earth's surface is an important issue that finds wide application in various fields of science, technology and economics [1]. These images represent unique sources of information that allow to extract valuable data on the state of the environment [2].

Semantic technologies play a key role in interpreting Earth observation data, as they allow not only to identify objects, but also to extract their semantic characteristics, identify logical relationships, and analyze the context of the scene [3]. Unlike simple object recognition, which operates at the level of individual pixel areas, semantic analysis includes higher-level abstractions such as ontological modeling, logical-computational methods, and the extraction of hidden patterns.

One of the key issues of semantic technologies is the formation of knowledge based on multispectral and hyperspectral remote sensing data. This is achieved by integrating spectral, spatial, and textural features with semantic models, which allows distinguishing similar objects based on their physical and contextual characteristics [4]. For example, distinguishing natural and anthropogenic objects can be performed taking into account their shape, spatial distribution, and spectral response.

In addition, semantic technologies provide the ability to automatically perform logical inference based on rules and predicates. This is especially important in natural disaster monitoring, urban planning and agriculture, where not only detection of objects is required, but also analysis of their condition, dynamics of change and potential threats [5].

The aim of this research is to evaluate the impact of training parameters on the performance of a neural network model, using a semantic technology approach to classify objects in images of the Earth's surface.

II. Formalization of the system model

The issue of automatic recognition and analysis of elements in images of the earth's surface using the YOLOv3 neural network architecture implemented in the Darknet framework is in the context of semantic technologies, which are actively used to extract, classify and analyze objects in images. Semantic technologies are aimed at processing and understanding data in terms of their meaning, and not only based on structural features.

In this context, using YOLOv3 as a model for detecting objects in images helps to effectively perform the issue of recognizing various objects, such as buildings, roads, trees and other elements in images of the earth's surface. The YOLOv3 architecture uses convolutional neural networks (CNN) to solve the problem of classification and localization of objects in images in real time.

Semantic technologies are closely related to machine learning and artificial intelligence approaches. In the issue of image recognition, semantics is the ability of a neural network to understand objects and their contexts [6].

The YOLOv3 model also actively uses semantic approaches to improve prediction accuracy. The essence of the algorithm is that the network divides the image into a grid and for each cell determines bounding boxes with possible objects and their classes, predicting coordinates and probabilities. This makes it possible to quickly and accurately find and classify objects in the image.

One of the important aspects of using YOLOv3 is the ability to process images with different resolutions. The YOLOv3 architecture uses several levels of convolutional layers, which allows the model to effectively detect objects both at the global and local levels, maintaining rich semantic information about various objects.

Further the main aspects of semantic technologies implemented by the YOLOv3 neural network based on the DARKNET framework were presented.

To structure information, an ontological representation of knowledge is used, formalized in the form of triplets (O_i , R_{ij} , O_j), where O_i , O_j are objects detected by the neural network, and R_{ij} is the relation between objects, for example be near, cross, include. Formally, the semantic network is represented by a graph G =(V, E), where V is the set of detected objects, and E are the relations between them, determined using spatial proximity metrics, for example, the intersection coefficient:

$$IoU(A,B) = \frac{|A \cap B|}{|A \cup B|}.$$
 (1)

This approach allows for automatic analysis of spatial relationships between objects and the formation of meaningful conclusions about the structure of the scene.

Semantic interpretation of objects is performed using fuzzy logic and first-order predicates, which allows for formalization of relations between objects and logical inference based on rules. For example, if an object of the road class is adjacent to an unidentified object, the model can conclude that there is a high probability that this object is a car. This is formalized as a predicate:

$$(near(x, y) \land class(x) = road) \Rightarrow class(y) = car.$$
 (2)

This approach enhances the capabilities of traditional recognition by introducing elements of logical analysis.

For detailed analysis of spatial structures, segmentation using deep neural networks such as U-Net and DeepLabV3 is used. Unlike classical object detection, segmentation allows you to determine the exact boundaries of objects, not just bounding boxes. This is especially important when analyzing complex scenes, such as recognizing agricultural fields, water bodies, and urban structures.

Texture analysis plays an important role in semantic recognition. For example, the GLCM (Gray Level Cooccurrence Matrix) method allows you to describe the statistical properties of image texture structures. The main GLCM metrics include energy, which reflects the homogeneity of the texture, and entropy, which characterizes the degree of randomness of the pixel distribution.

Vegetation indices are used to analyze objects with characteristic spectral properties (vegetation, water bodies, snow cover). For example, NDVI (Normalized Difference Vegetation Index) is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED},\tag{3}$$

where

- NIR the value of the near infrared channel of the image,
- RED the value of the near red channel of the image.

Another important index, NDSI (Normalized Difference Snow Index), is used to detect snow cover and is calculated as:

$$NDSI = \frac{GREEN - SWIR}{GREEN + SWIR}.$$
 (4)

These characteristics are integrated into the semantic analysis process, allowing to increase the accuracy of detection and interpretation of objects.

The aim of the analysis of experimental data is to determine estimates of unknown parameters b in a certain given region of the factor space X. The statistical model of the system is presented in Fig. 1.



Figure 1. Statistical model of the system.

In real conditions, due to the presence of interference ϵ , instead of the true value of the output quantity η , it is necessary to measure the quantity Y. Therefore, based on the measurement results, it is impossible to obtain absolutely accurate values of b. Instead of the true parameters b, it is necessary to obtain estimates of the parameters β [8]. Then, the estimated equation for the model will have the form:

$$Y = Y(x,\beta),\tag{5}$$

where

- x factors (input measurements),
- β estimation of unknown parameters (coefficients),
- Y system response taking into account the interference ϵ (output value).

For the effective use of semantic technologies in the issues of analyzing images of the earth's surface, it is necessary to select the optimal parameters of the neural network model. Their correct configuration allows to improve the results of semantic analysis, providing more accurate recognition and interpretation of objects in images.

III. Experimental design

A. General structure of experimental design

The main steps of experimental design are: defining the aim of the experiment, selecting factors and levels of their variation, defining output variables (responses), defining the type of experiment, determining the training sample size, randomization, taking into account and monitoring external conditions, conducting a pilot (test) experiment, data processing.

B. Defining the aim of the experiment

The following hypothesis is proposed to be tested in this research: the combination of various factors, such as training sample size, number of batches, learning rate, and number of training epochs, significantly affects the accuracy, performance, and robustness of the model for automatic recognition and analysis of features in earth surface images. This hypothesis is hereinafter referred to as H_0 .

C. Selecting factors and levels of their variation

Each of the factors can significantly affect the results, and by changing their levels, it is possible to find the optimal settings for the issue at hand. Below, how each of these factors will change is presented.

Table I Factors and levels of their variation

Factor	Low level	High level
Training sample size	100	800
Number of epochs	50	300
Number of batches	8	16
Learning rate	0.001	0.01

Each of the proposed 4 factors will vary between 2 levels, which will give 16 possible combinations for experiments (2^4 =16). This will allow to explore how each factor affects the performance of the YOLOv3 model in recognizing objects in images of the earth's surface.

D. Defining output variables (responses)

The output variables (or responses) in this experiment are metrics that measure the performance of the YOLOv3 model in recognizing objects in images of the Earth's surface. These metrics reflect the accuracy of the model and its ability to correctly classify objects [9]. The geometric representation of the response surface is shown in Fig. 2.



Figure 2. Geometric representation of the reaction surface.

Average Precision (mAP) is the average Precision value at different confidence threshold levels for each class. For the issue of object recognition, where the model makes predictions on the location of objects and their classes, mAP takes into account both the classification accuracy and the correctness of localization [10].

Next, it is necessary to formalize the algorithm for calculating mAP.

Precision-Recall Curve is a curve that reflects how the accuracy changes depending on what confidence threshold is used to recognize the object.

Average Precision (AP) for a class is calculated as the integral of the Precision–Recall curve. In practice, it can be calculated as the area under this curve, or the average precision at different recall levels.

The equation for calculating AP for one class:

$$AP = \frac{1}{N} \sum_{i=1}^{N} Precision(i) * \Delta Recall(i), \quad (6)$$

where

- N number of points on the Precision–Recall curve,
- Precision(i) precision at the i-th point of the curve,
- Recall(i) difference in recall at the i-th point.

After each class has its Average Precision (AP), calculate mAP as the average of all APs for all classes. The equation for mAP:

$$mAP = \frac{1}{C} \sum_{i=1}^{C} AP_i, \tag{7}$$

where

- C number of classes in the issue (in the model under consideration 60),
- AP_i accuracy for the i-th class.

A high mAP value (e.g. close to 1) indicates that the model is effective at recognizing objects with high accuracy and minimal errors. A low mAP value (e.g. close to 0) indicates that the model is poor at recognizing objects, or the localization and classification error is too high.

E. Defining the type of experiment

The type of experiment that was chosen to achieve the stated aim in the issue of recognizing objects in images of the earth's surface is a full-factorial experiment.

A full-factorial experiment allows to explore all possible combinations of factors, which gives a complete picture of how each factor affects the result, and also allows to evaluate their interaction.

F. Determining the training sample size

The training sample size of an experiment is the number of observations or repetitions of the experiment that must be conducted for each combination of factors so that the results are statistically significant and provide an accurate estimate of the model's responses.

For each set of factors, several repetitions are planned (2-3 repetitions for each combination). This is necessary to account for random fluctuations associated with the initialization of the model weights and the random learning process.

G. Randomization

Randomization in an experiment is the process of randomly assigning different conditions and variants of an experiment to eliminate possible systematic errors and improve the reliability of the results.

For 16 factor combinations (a full-factorial experiment with 4 factors, each with 2 levels), the order of treatment of each combination in different rounds of the experiment will be randomly assigned. Thus, if 2 repetitions are planned for each combination, the order of execution of each of the 32 experiments will be randomly shuffled.

H. Taking into account and monitoring external conditions

The consideration and control of external conditions in the experiment are aimed at minimizing the influence of factors that are not part of the variables under research, but can have a significant impact on the results. In this case, this includes conditions that can affect the training and performance of the YOLOv3 model in recognizing objects in images of the earth's surface, such as hardware characteristics, execution environment, random fluctuations, and other unchangeable factors.

I. Conducting a pilot (test) experiment

A pilot experiment is a small preliminary experiment that is conducted before the main research to check the correctness of the selected factors, conditions, and equipment.

Table II Pilot Experiment Variant

Factor	Value 1	Value 2
Training sample size	100	100
Number of epochs	50	50
Number of batches	8	16
Learning rate	0.01	0.001

Table below summarizes the factors and their values that will be used for the pilot experiment.

After training the model with these factors combinations, it is necessary to calculate the average mAP values for each configuration and select the most appropriate factors for the main experiment.

J. Data processing

Since the experiment is full-factorial, each factor is coded using binary values (0 and 1) for ease of subsequent analysis. Low level is value 0, high level is value 1.

All collected data are entered into a table (the matrix of a full-factorial experiment), where each row corresponds to one combination of factors.

Analysis of Variance (ANOVA) is used to assess the significance of the influence of factors on the output variable - in this case, mAP.

For ANOVA, the ratio of intergroup and intragroup variances is calculated:

$$F = \frac{MS_{factor}}{MS_{error}},\tag{8}$$

where

- MS_{factor} = <sup>SS_{factor}/_{df_{factor}} average squared deviations of changes in factors,
 </sup>
- $MS_{error} = \frac{SS_{error}}{df_{error}}$ average squared deviations of random errors,
- SS_{factor} sum of squared deviations due to factor influence,
- df_{factor} sum of squared deviations due to factor influence,
- SS_{error} sum of squared deviations due to factor influence,
- df_{error} sum of squared deviations due to factor influence.

The total sum of squared deviations is the sum of squared deviations of all observations from the overall mean response value:

$$SS_{all} = \sum_{i=1}^{N} (Y_i - \overline{Y})^2, \qquad (9)$$

where

- Y_i response value (mAP) for the i-th combination of factors,
- \overline{Y} overall average mAP value across all experiments,

• N - total number of experiments.

Next, for each factor, its contribution to the variability of the response is calculated:

$$SS_{factor} = n \sum_{j=1}^{2} (\overline{Y}_{factor_j} - \overline{Y})^2, \qquad (10)$$

where

- \overline{Y}_{factor_j} average response value for the j-th level of the factor,
- n number of repetitions for each level.

Finally, the sum of the squares of the errors is calculated:

$$SS_{error} = SS_{all} - \sum SS_{factor}.$$
 (11)

Regression analysis is used to build a mathematical model that describes the dependence of the output variable (mAP) on the values of the factors. The aim is to determine which factors have a significant effect on the result and to obtain a regression equation that can be used to predict the mAP value for new combinations of factors. The least squares method is used to estimate the coefficients of the model.

Multiple linear regression assumes that the response (Y, in this case - mAP) is a linear function of the factors:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \epsilon, \quad (12)$$

where

- Y output variable (mAP),
- X_1, X_2, \dots, X_n factors,
- β_0 free term,
- $\beta_1, \beta_2, ..., \beta_n$ regression coefficients,
- ϵ random error.

The least squares method assumes that we minimize the sum of the squared deviations of the actual response values from those predicted by the model:

$$S = \sum_{i=1}^{N} (Y_i - \overline{Y}_i)^2 = \sum_{i=1}^{N} (Y_i - (\beta_0 + \sum_{j=1}^{n} \beta_j X_{ij}))^2.$$
(13)

To find the regression coefficients, it is necessary to solve the system of normal equations:

$$X^T X \beta = X^T Y, \tag{14}$$

where

- X matrix of factors,
- β vector of regression coefficients,
- Y vector of responses.

Based on the results of statistical and regression analysis, the values of the factors that provide the best response value (mAP) are selected. This allows to determine the optimal combination of parameters for training the YOLOv3 model.

IV. Conducting an experiment

Immediately after compiling the matrix of the fullfactorial experiment, randomization was performed, i.e. random distribution of the sequence of experiments. It was carried out by means of the Python programming language, namely using the random library to perform this issue.

To ensure stability and reproducibility of the results, the experiment was conducted on a single computing device, eliminating the influence of hardware differences on the rate and accuracy of model training. All versions of libraries and drivers were fixed to exclude incompatibilities and changes in calculation algorithms.

During the experiment, the mAP was recorded at each stage. All collected data are summarized in a table below, where each row corresponds to one combination of factors. The mAP values were calculated for two images whose terrains contain different classes of objects suitable for recognition.

Table III Extended Matrix of Full-factorial Experiment

Experiment number	Training sample size	Number of batches	Learning rate	Number of training epochs	mAP (1, 2)
1	0	0	0	0	0.124400, 0.107424
2	0	0	0	1	0.210523, 0.171322
3	0	0	1	0	0.135386, 0.125329
4	0	0	1	1	0.122273, 0.107425
5	0	1	0	0	0.211587, 0.174100
6	0	1	0	1	0.240295, 0.187991
7	0	1	1	0	0.217966, 0.191696
8	0	1	1	1	0.246674, 0.205587
9	1	0	0	0	0.198827, 0.177805
10	1	0	0	1	0.233914, 0.209292
11	1	0	1	0	0.205206, 0.195401
12	1	0	1	1	0.233914, 0.209292
13	1	1	0	0	0.286014, 0.244481
14	1	1	0	1	0.316848, 0.278746
15	1	1	1	0	0.287786, 0.261768
16	1	1	1	1	0.311532, 0.272263

A. Dispersion analysis

The F-criterion values obtained for each factor are summarized in table below. In this case, the tabular value of the F-criterion at a significance level of α =0.05 is 4.60. Based on this and the previously formulated hypothesis H₀, it was concluded that the influence of such factors as the size of the training sample and the number of epochs is significant, while the influence of the factors of the learning rate and the number of batches has a smaller effect, but it also cannot be excluded in further studies.

Table IV F-criterion Values for Each Factor

Factor	Value of the F-criterion
Training sample size (X_1)	10.48
Number of epochs (X ₂)	11.29
Learning rate (X ₃)	0.44
Number of batches (X_4)	0.83

B. Regression analysis

During this experiment, the following equation was obtained, describing the dependence of mAP on the model parameters:

$$Y = 0.07X_1 + 0.08X_2 + 0.01X_3 + 0.02X_4 + 0.12.$$
(15)

The t-statistic values obtained for each factor are summarized in table below. In this case, the tabular value of the t-statistic at a significance level of α =0.05 is 2.20. Based on this and the previously formulated hypothesis H₀, it was concluded that the influence of such factors as the volume of the training sample, the learning rate, the number of epochs and the number of batches is significant, while the influence of the learning speed factor has a smaller effect, but it also cannot be excluded in further research.

The analysis of the resulting equation also confirms the formulated hypothesis H_0 and indicates a significant influence of the factors put forward in the course of the research.

Table V T-statistic Values for Each Factor

Factor	Value of the t-statistic
Training sample size (X_1)	8.48
Number of epochs (X_2)	9.03
Learning rate (X ₃)	1.22
Number of batches (X ₄)	2.38

V. Conclusions

Based on the conducted experiment, it was concluded that the proposed hypothesis H_0 was confirmed through variance and regression analysis, validating the relationship between parameters and model performance.

In the context of semantic technologies, these improvements allowed the model to better interpret the meaning of objects within images. With a larger training sample, the model was able to capture a wider range of semantic features, improving its ability to detect and classify objects like roads, buildings, and vegetation. Fine-tuning the learning rate helped the model converge faster, leading to more accurate semantic segmentation and object detection.

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ПРИМЕНЕНИЕ СЕМАНТИЧЕСКИХ ТЕХНОЛОГИЙ В МОДЕЛИ АВТОМАТИЧЕСКОГО РАСПОЗНАВАНИЯ И АНАЛИЗА ЭЛЕМЕНТОВ НА СНИМКАХ ЗЕМНОЙ ПОВЕРХНОСТИ Катата Б. И. Манализа М. П.

Ковшер Е. И., Михальков М. Д.

Данное исследование направлено на оценку влияния параметров обучения нейронной сети в контексте классификации объектов на изображениях земной поверхности с использованием семантических технологий.

Показано, как семантические технологии и их применение в задаче классификации объектов на изображениях земной поверхности улучшить способность модели обрабатывать и классифицировать объекты.

Проведен подробный анализ влияния ключевых параметров обучения на точность и стабильность модели. Эти факторы были оценены в рамках подхода семантических технологий.

Полученные результаты подчеркивают эффективность предложенной модели нейронной сети в приложениях семантических технологий для анализа изображений земной поверхности.

Эти результаты могут быть использованы для повышения производительности систем классификации объектов на основе нейронных сетей в области семантических технологий.

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Identification and Classification of Train Timetable Deviations Using OSTIS Technology

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Abstract—A posteriori model of dispatcher train schedule correction is described, an integrated scheme of a hybrid operational problem solver is established, an algorithm for inducing a tree for classifying operational situations in TS is proposed, a method for identifying deviations in the train schedule using OSTIS technologies is described, the basic concepts of the subject area "Dispatching train schedule correction" are formulated and described

Keywords—Intelligent transportation process management system, train timetable, train schedule, transportation process, train, station, station interval, ontology, OSTIS technology

Introduction

Intelligent systems play a key role in the modern world, providing effective management of complex processes and tasks. In particular, in the field of railway logistics and transport, the development of innovative approaches to the management of the transportation process is becoming an increasingly urgent task. One of the important aspects here is the effective planning and adjustment of train schedules, which makes it possible to optimize the use of infrastructure and resources. Within the framework of this paper, a posteriori model of dispatching train schedule adjustments will be described, an integrated scheme of a hybrid operational problem solver is established, an algorithm for inducing a tree for classifying operational situations in TS is proposed, a method for identifying deviations in the train schedule using OSTIS technologies is described, and the basic concepts of the subject area "Dispatcher Train schedule adjustment" are formulated and described

I. Task definition

The train schedule (TS) is the basis for the organization of the transportation process on the railway. Its development and subsequent implementation make it possible to link the operation of railway stations, sections, operation of locomotives, etc. into a single technology. However, in an operational situation, a number of situations arise that do not allow the regulatory train schedule to be implemented: late departure of the train from the station due to the need to perform additional operations during maintenance of the trains, Ilya Erofeev Belarussian State University of Informatics and Radioelectronics Minsk, Belarus ilerofv@gmail.com

an increase in the parking time of the passenger train at an intermediate station to organize the boarding and disembarkation of a large number of passengers, etc. A dispatch control system is designed to respond to such situations on the railway.

However, in practice, due to limited time and information resources, the dispatcher may not always be able to correctly develop an option for dispatching adjustments. In this regard, it is proposed to create a subsystem for intelligent dispatch control of the TS within the framework of the intelligent transportation process management system (ITPMS). [1]

The a posteriori model of intelligent dispatch correction of the TS assumes the solution of the problem **situational modeling** [2]:

- identification of deviations of the actual train line from the forecast one;
- classification;
- subsequent liquidation by one of the available methods.

It is assumed that at the stage of development of the regulatory TS preliminary optimization of the schedule was carried out and, taking it into account, control solutions have already been formed in the adjacent subsystems of the ITPMS. As a criterion of effectiveness in the a posteriori model, it is proposed to use the conditions of minimal changes in the TS relative to the normative one.

In this case, the hybrid solver of the operational task (HSOT) of the control correction of the TS will include procedures for identifying deviations, selecting a scenario for introduction the train into the TS and implementing the control correction in accordance with the selected action algorithm (Figure 1) [3].



Figure 1. Enlarged structure of the HSOT "Dispatch correction of the $\ensuremath{\mathsf{TS}}\xspace$ "

ITPMS should provide for the possibility of training, i. e. the formulation of new control management systems, new adjustment scenarios and algorithms for adjusting the TS depending on the initial scenarios.

In order to organize the set of possible options for dispatching adjustments and choosing a rational one, it is proposed to form a decision tree of the TS. A decision tree is a method of representing decision rules in a hierarchical structure consisting of two types of elements – nodes and leaves. The decision rules are located in the nodes and the examples are checked for compliance with this rule by some attribute of the training set [4].

In general, the *subject area* for solving the problem under consideration will include possible types of dispatcher adjustments, including [5]:

- changing the order of crossing trains;
- changing the train's receiving path due to the discrepancy between the length of the station tracks and the length of the train, if necessary, the train must stop at the station that it must pass without stopping according to the TS;
- selection of available tracks for receiving a train if it is necessary to stop at a station that, according to the TS, it must pass without stopping;
- organization of non-stop passage by train at the station where, according to the TS, the train has a stop;
- changing the arrival, departure, and passage times of passenger trains;
- canceling the TS route option;
- laying an additional thread in the TS;
- allocation of time in the TS for the production of works in the "window", etc.;
- change of the time for the provision of "windows", etc.

A lot of dispatcher adjustments to the TS can be reduced to five possible scenarios for the formation of MD:

- adjustment of the TS thread with subsequent TS changes;
- change of the train departure time from the station.
- linking the train to another nearby free route on the schedule;
- development of an additional route taking into account the preservation of the timetable of other trains;
- canceling the TS option.

During the operation of the ITPMS, other types of dispatching adjustments, scenarios for the formation of MD and methods of adjustments can be identified. That is, the system of dispatching adjustments should be developing and learning. For these purposes, it is proposed to use inductive rules, and the learning process itself will be the induction of trees. The TS decision tree is a model based on teacher-led learning, and target values should be set in the training set of dispatcher adjustments. At the same time, since the target variables are discrete and can be described by logical relationships (class labels), the model will be a classification tree [3].

The key feature of intelligent dispatch correction of the TS that, unlike classification models used in other subject areas, in which a value or function is considered as a leaf, it is proposed to consider the algorithm for performing actions for dispatching correction of the TS as a leaf of the tree.

Then HSOT will include the following operational tasks:

- definition of a set of class labels for each operational situation;
- selection using the classification tree of a rational algorithm for dispatching TS adjustment;
- implementation of the dispatcher adjustment algorithm for the current operational situation.
- II. Algorithm for the induction of a classification tree for operational situations in TS.

Let's set up a training set of operational situations S, (discrepancies between the planned and actual TSs), containing n options, for each of which a class label is set $C_i(i = 1...k)$, and m attributes $A_j(j = 1...m)$, which determine whether an object belongs to a particular class. At the same time, an automatic dispatch correction algorithm is installed for each C_i class.

The purpose of TS tree induction is to determine for any operational situation A_j class C_i (dispatcher adjustment algorithm).

There are three possible cases.

- 1) All examples of multiple operational situations S have the same class label C_i (i.e. all training examples belong to only one class). Obviously, learning in this case does not make sense, since all the examples presented to the model will be of the same class, which will "learn" to recognize the model. In this case, the decision tree itself will be a leaf associated with the class C_i . The practical use of such a tree is meaningless, since it will assign any new object only to this class.
- 2) The set S does not contain any examples at all, i.e. it is an empty set. In this case, a leaf will also be created for it (it makes no sense to apply the rule to create a node to an empty set), the class of which will be selected from another set (for example, the class that is most often found in the parent set).
- 3) Set *S* contains training examples of all classes C_k . In this case, you need to split the set *S* into subsets associated with classes. To do this, select one of the attributes A_j sets *S*, which contains two or more unique values $(a_1, a_2, ..., a_p)$, where *p* is

the number of unique attribute values. Then the set of *S* is divided into *p* subsets $(S_1, S_2, ..., S_p)$, each of which includes examples containing the corresponding the attribute value. Then the next attribute is selected and the partitioning is repeated. This procedure will be repeated recursively until all the examples in the resulting subsets are of the same class.

When using this technique, the decision tree will be built from top to bottom (from the root node to the leaves). Currently, a significant number of decision tree learning algorithms have been developed: ID3, CART, C4.5, C5.0, NewId, ITrule, CHAID, CN2, etc. [6]. In this paper, we do not evaluate the effectiveness of using one algorithm or another, but consider the specifics of setting the problem of induction of a decision tree for a dispatch control system.

A distinctive feature of TS from traditional classification objects is its continuous change over time. In this regard, it is proposed to consider a variety of parameters that characterize the TS threads as temporal data. Then the task of generalizing and classifying operational situations in the presence of temporal data is formulated as follows.

Let's assume that the graph of completed movement (GCM) is based on data on changes in the states of block sections q when trains pass through them. The states change at some discrete points in time: t = 0, 1, 2, 3, ... Then the train situation at the control range at some point in time i can be represented as a vector

$$S_i = \langle x_1(t=i), x_2(t=i), \dots, x_q(t=i), t=1 > 1.$$
 (1)

In order to trace the dynamics of the trains' progress along the section, their possible deviations from the planned lines of the TS, and the dynamics of changes in deviations (lagging or overtaking), it is necessary to consider an ordered set of such vectors obtained over a finite time interval t_i, t_{i+r-1} , r > 1.

Let q parameters be considered for the time interval om of length r. Let's present such data in the form of a matrix (Table I).

Each cell of the matrix represents the value of the location of the train q at the time i. Then each column of the matrix will describe a thread in the graph of the executed movement, and each row will represent the train position on the section at time points, respectively $i, i + 1, \ldots, i + r - 1$.

However, the operational situation on the stage is characterized not only by the relative location of trains on the section, but also by their compliance with the planned TS. In this regard, it is proposed to supplement the matrix with train values of the current TS (CTS).

Based on the data on the GCM and CTS trains, an estimated train situation is formed (the location of each

Table I Dynamic object of generalization of the graph of completed movement

	Train 1	Train 2	 Train g	Time t
(S_i)	$x_1(t=i)$	$x_2(t=i)$	$\begin{array}{c} x_g(t) = \\ i \end{array}$	i
(S_{i+1})	$\begin{array}{l}x_1(t \\ i+1)\end{array} =$	$\begin{array}{l} x_2(t) = \\ i+1) \end{array}$	$\begin{array}{l}x_g(t) = \\ i+1)\end{array}$	i + 1
(S_{i+2})	$\begin{array}{c} x_1(t) = \\ i+2) \end{array}$	$\begin{array}{rcl} x_2(t & = \\ i+2) \end{array}$	$\begin{array}{c} x_g(t) = \\ i+2) \end{array}$	i+2
(S_{i+r-1})	$\begin{array}{c} x_1(t) = \\ i+r-1) \end{array}$	$\begin{array}{rcl} x_2(t &= \\ i+r-1) \end{array}$	$\begin{array}{c} x_g(t) = \\ i+r-1) \end{array}$	i + 1

of the trains in motion at each moment of the planned period). The estimated value of the train location at the time t_{i+r+v} is defined as

$$x_v(t = i + v + r) = x_q(t = i + v) + \Delta x_{r-q}^{\text{прогноз}} (\Delta t = r - q). \quad (2)$$

Then the operational situation at the landfill will be characterized by a set of arrays of information about executed, planned and calculated train conditions (Table II).

 Table II

 Dynamic Operational Situation Generalization Object (CTS)

	Train 1	Train 1 (schedule)	Train 2	Train 2 (schedule)	 Train q	Train q (schedule)	Time (t)
S_l	GCM	Schedule					
S_{l+1}							
S_{l+2}							
S_{l+v}							
	Forecast						
Site							

Let's call the structure presented in Table II a dynamic object of generalization of the operational situation. Then the task is to assign the appropriate operational situation to a specific class, depending on the methods of dispatching adjustments being implemented.

The assignment of operational environments to the appropriate classes is performed using a decision tree.

Formally, a decision tree is a weighted directed graph T = (V, E). In the set of vertices V, select the vertex $v_0 \in V$ – the root of the tree. We will divide all the vertices into two classes:

- V_i ⊂ V the set of internal vertices (nodes) of the tree; V_i includes such vertices, of which arcs come out;
- V_l ⊂ V the set of external, final, tree vertices (leaves); V_l includes it includes vertices from which arcs do not exit; V_i and V_l form a partition of the set of vertices of the V decision T:

$$V_i \cap V_l = \emptyset; V_i \cup V_l = V.$$

The internal vertices of the V_i tree correspond to the attributes that are used in classifying the operational environment. The leaf vertices V_l correspond to the algorithms for dispatcher adjustment of TS.

Each arc of the *e* decision tree is weighted by the condition "attribute = attribute value" (for qualitative attribute values) or "attribute σ attribute value" (for quantitative attribute values, $\sigma \in \{\geq >=\}$).

III. The attribute selection rule for dividing a set of operational situations into subsets

The general rule for choosing an attribute for dividing a set of operational situations into subsets can be formulated as follows: the selected attribute should split the set of observations in the node so that the resulting subsets contain examples with the same class labels, or are as close to it as possible, i. e. the number of objects from other classes ("impurities") in each of these sets was as little as possible. To select attributes for dividing a set of operational environments into subsets, it is proposed to use an information-theoretical criterion based on the concept of information entropy.

$$H = -\sum_{i=1}^{n} \frac{N_i}{N} \log(\frac{N_i}{N}), \qquad (3)$$

where n is the number of classes in the original subset; N_i – the number of examples of the *i*th class; N – the total number of examples in the subset.

Entropy is considered as a measure of the heterogeneity of a subset according to the classes represented in it. When classes are presented in equal proportions and classification uncertainty is greatest, entropy is also maximal. If all the examples in the node belong to the same class, i. e. $N = N_i$, the logarithm of one turns the entropy to zero.

Thus, the best attribute of splitting A_j will be the one that ensures the maximum reduction in the entropy of the resulting subset relative to the parent. In practice, however, they do not talk about entropy, but about the inverse of it, which is called information. Then the best partitioning attribute will be the one that will maximize the information gain of the resulting node relative to the original one.:

$$Gain(A) = Info(S) - Info(S_A),$$
(4)

where Info(S) – information related to the subset of S before splitting; $Info(S_A)$ – information related to the subset obtained by splitting by attribute A.

As a result of the conducted research, it has been established that when classifying operational situations and selecting algorithms for dispatching adjustments to TS, it is advisable to use the following attributes A_i :

- for each of the trains, the estimated arrival time of the train at the station corresponds to the planned value;
- for each of the trains, the estimated departure time of the train from the station corresponds to the planned value;

- for each of the trains, the correspondence of the stage running times to the planned values;
- for each of the pairs of trains located next to each other in the TSTHE observance of station intervals;
- for each of the pairs of trains located next to each other in the TSTHE observance of inter-train intervals;
- availability of reserves in the driving times;
- availability of reserves in station and inter-train intervals;
- availability of reserves during train stops;
- availability of backup threads in TS;
- the category of the train that deviated from the planned TS (passenger, suburban, freight, long-range, heavy, etc.).

To implement the induction algorithm for the classification tree of operational situations in TS, the key task is the correct *identification of the current operational situation*. It is proposed to use OSTIS technologies for this purpose [7]–[10].

IV. The ontology of the TS domain.

The main objects of the TS subject area are stations and trains. Such concepts as stages, station tracks, schedules and intervals are also highlighted to describe them (Figure 2).



Figure 2. Objects of the TS subject area

In turn, trains have their own characteristics and are divided into freight and passenger trains. Passenger trains are generally divided into international, interregional (standart), regional, and urban trains. This classification is extensible. Freight or Catgo trains are divided into accelerated, through, district and collected, and may also have additional properties, such as container, heavy, long-composite, etc. An example of defining a train according to these classifications is *train_1* (Figure 3).

There are stages adjacent to the station. For each of the runs, the length, the value of station and inter-train



Figure 3. TS subject area section "Classification of trains"



Figure 6. Description of train length and station track length

intervals for all combinations of different categories of trains should be determined (Figure 4), as well as the travel time for different types of trains (Figure 5).

In addition, for each of the crossings, the parameters of the approaches to the station should be determined, including the slopes in the areas of approach to the station (Figure 6).

Depending on the magnitude of the slope on the approach to the station and the characteristics of the train, a decision is made on the possibility or impossibility of stopping the train in question at the station.

Each station includes in its structure specialized tracks designed for receiving and departing trains. The static characteristics of the tracks are their length (capacity in wagons), specialization, the possibility of receiving specialized trains, etc.) (Figure 7).

Each track can be free or occupied by a specific train at any given time.

In addition to the infrastructure and characteristics of the trains, it is necessary to describe the regulatory TS (Figure 8).

The regulatory TS defines for each train the arrival and departure times of trains at each station of the railway section, as well as the occupation of tracks by operations of passing, stopping and parking.

This ontology is the basis for the construction of the HSOT "Dispatching adjustment of TS". Of course, this ontology is not exhaustive and will be refined, modified and supplemented as it is used.



Figure 7. Description of the track



Figure 8. Description of the regulatory TS the station

V. Conclusion

In conclusion, it is worth noting that the development of intelligent transportation process management systems based on OSTIS technologies opens up new prospects for optimizing railway logistics and improving the efficiency of transport processes. The a posterior model of dispatching train timetable adjustments described in this paper represents an important step towards automation and intellectualization of railway transport management.

The use of classification tree induction algorithms to analyze and adjust operational situations in train schedules opens up new opportunities for rapid response to changing conditions and provides more flexible and efficient railway traffic management. The further development and application of such innovative approaches in the railway industry has the potential to change and improve transportation processes, providing a higher level of service and resource optimization.

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ИДЕНТИФИКАЦИЯ И КЛАССИФИКАЦИЯ ОТКЛОНЕНИЙ В ГРАФИКЕ ДВИЖЕНИЯ ПОЕЗДОВ С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИЙ OSTIS

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Дано описание апостериорной модели диспетчерской корректировки графика движения поездов, установлена укрупненная схема гибридного решателя эксплуатационных задач, предложен алгоритм индукции дерева классификации эксплуатационных ситуаций в ГДП, описан метод идентификации отклонений в графике движения поездов с использованием технологий OSTIS, сформулированы и описаны основные понятия предметной области «Диспетчерская корректировка графика движения поездов»

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Intelligent Systems in Assessing the Transport Potential of Railway Transport

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Abstract—The research demonstrates that intelligent systems can significantly enhance the assessment of the transport potential of railway infrastructure. These systems enable real-time data analysis, route optimization, and prediction of operational challenges. The Belarusian Railway has developed and implemented a series of information and management systems incorporating elements of artificial intelligence based on semantic knowledge bases, which have improved transport process management by increasing the accuracy and reliability of railway infrastructure capacity assessments.

Keywords—transport potential, railway transport, intelligent systems, artificial intelligence, machine learning, transport flow, throughput capacity, modeling

I. Introduction

Railway transport plays a pivotal role in ensuring the efficient and sustainable movement of goods and passengers. In this context, transport potential refers to the capacity of railway infrastructure to effectively handle transport flows, taking into account factors such as throughput, speed, reliability, safety, and environmental impact. Assessing this potential is crucial for operators and carriers to make informed decisions regarding infrastructure development, resource allocation, and operational management of transport flows. Traditional assessment methods, such as statistical analysis, have limitations, including the time-consuming nature of the process and the likelihood of human error. Intelligent systems based on artificial intelligence and machine learning offer a solution by enabling the processing of large volumes of data in real-time and providing accurate forecasts. This article explores the role of intelligent systems in assessing the transport potential of railway transport, analyzing their application across various operational aspects and presenting practical examples, including the forecasting of energy consumption for train traction using machine learning, modeling of transport flows, and calculation of the throughput capacity of railway infrastructure facilities using artificial neural networks.

II. Application of intelligent systems

The application of intelligent systems in railway transport management aims to assess and enhance transport potential through the modeling of transport flows, evaluation of infrastructure facilities' throughput capacity, and prediction of potential operational difficulties and shortages of shunting resources. A key component is the forecasting of energy consumption for train traction prior to departure, which helps reduce operational costs. To improve the accuracy and interoperability of data in these processes, semantic technologies are employed, ensuring structured information representation and integration from various sources.

A. Forecasting operational difficulties

The development of intelligent systems involves creating technical and technological solutions aimed at accelerating the movement of loaded and empty wagon flows, enhancing the efficiency of infrastructure and rolling stock utilization, reducing operational costs, and strengthening the competitiveness of railway transport. The research is based on a combination of methods, including a systemic approach to analyze the structure and interrelations of railway infrastructure, mathematical modeling using Petri nets to formalize the processes of organizing wagon flows and predicting operational challenges, graph theory for network representation and route modeling, as well as an algorithmic approach and software implementation in the form of the "Dynamic Wagon Flow Map" tool, integrated into the information system and tested at the Belarusian Railway [1], [4], [9], [18]. In addition to these methods, semantic approaches are applied, enabling the structuring of transport flow data in the form of ontologies, ensuring their semantic compatibility. This facilitates the unification of data from various sources, such as transportation planning and infrastructure monitoring systems, and the creation of a unified semantic space for analysis.

Using data from the cargo transportation plan and the table of route vectors for wagon flow correspondences across the railway network, the automated 'Dynamic Wagon Flow Map' system models the movement of transport flows and calculates transport flow parameters at railway network infrastructure facilities. The system generates tables with transport flow parameters categorized by the required classification criteria. Wagon flow correspondences are consolidated into arrays of combined and detailed wagon flow tables, organized by calculation polygons, movement directions (even and odd), wagon conditions, cargo types, rolling stock types, and other characteristics essential for differentiating the wagon flow. The semantic representation of data as an ontological model not only facilitates classification of these parameters but also uncovers hidden interrelationships, enhancing modeling and forecasting quality.

The automated "Dynamic Wagon Flow Map" system is an integral part of the information support complex for the transportation process at the Belarusian Railway, providing the wagon flow organization system with data on cargo and wagon flows enriched with a new set of attributes: route of movement, wagon condition, type of rolling stock, ownership, and more, enabling the resolution of transportation process organization tasks at a new level. The use of ontologies within the system ensures interoperability between different modules, allowing the integration of data from various sources and the formation of a unified semantic space for analysis. A variety of output forms with solutions from the "Dynamic Wagon Flow Map" system enable the calculation and assessment of transport load on infrastructure facilities, taking into account planned transportation volumes. Modeling the passage of transport flows can be conducted based on actual, shortest, and calculated routes, facilitating the evaluation of transport potential for individual railway stations or sections, as well as entire railway directions and the network as a whole, under different transport flow management scenarios. The semantic approach also allows for the consideration of contextual dependencies, such as the impact of weather conditions or infrastructure state, based on ontologically structured data.

To assess transport potential, a methodology has been developed for modeling station processes and forecasting potential operational difficulties, based on models of transport flow and railway station operations. Using the transport flow model within the railway network, the transport load on infrastructure facilities is simulated, enabling the forecasting of potential operational challenges at stations. This involves analyzing the properties of Petri nets corresponding to the structural-functional model of the railway station. A primary analysis method is the construction of a reachability tree a graph depicting all possible model states reachable from a given initial state. Each node in the graph represents a specific model state, while the edges indicate events triggering transitions between these states. Analysis of the reachability tree's properties allows for the identification of resource constraints and deadlock situations, which characterize station operations under conditions of shunting resource shortages and operational difficulties. The reachability tree also facilitates the identification of processes leading to operational challenges and the assessment of the station's throughput capacity utilization, thereby supporting the development of measures to enhance its operational efficiency. The model of the railway station yard is presented in Figure 1.



Figure 1: Model of the railway station yard for simulating train passage

Based on the presented Petri net (Figure 1), the modeling of transport flow passage through the railway station yard is conducted. For this purpose, a corresponding reachability tree (Figure 2) is constructed, describing the set of reachable states of the model.

The analysis of the reachability tree enables the determination of both the state and the sequence of transitions that must be executed to achieve the desired state. If the nodes of the tree lack outgoing arcs, the process in the analyzed model has halted, indicating potential operational difficulties in the passage of trains. In Figure 2, the states (nodes) S31 and S80 indicate that the process of modeling the railway station yard operation has stopped, while the analysis of transitions (arcs) reveals a series of events that led to these states.

The second proposed method for forecasting operational difficulties at the railway station is based on a matrix method for analyzing the properties of the Petri net. This approach allows for an analytical determination of the reachability of the investigated state without modeling all possible states of the model. The principle of this method involves solving a system of linear equations:

$$\mu' = \mu_0 + D \cdot x,\tag{1}$$

where μ_0 is the initial marking of the Petri net (system state); μ' is a potentially reachable marking of the Petri net; (x) is a non-negative integer vector; and (D) is the incidence matrix, which reflects the relationships between places and transitions.

То determine the possibility of the model (Figure 1) transitioning from the initial state $\mu_0 = \{0, 2, 0, 0, 1, 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1\}$ to the marking $\mu' = \{0, 0, 1, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0\},$ which corresponds to an operational difficulty in receiving (or passing) trains through the railway station yard, the system of equations (1) is formulated. If the solution yields integer roots, this serves as a necessary condition for the reachability of the given marking, thereby enabling the prediction of a potential undesirable operational situation at the railway station. Moreover, the roots of the equation represent the number of transition firings required to achieve this marking, i. e., the sequence of events that led to this state.



Figure 2: Reachability tree of the railway station yard operation model

The methodology for modeling and forecasting potential operational difficulties at railway stations, based on the application of Petri nets, serves as an effective tool for both operational management and station design. It enables the identification and prediction of potential operational challenges, facilitating improvements in operational technology and station topology, which contributes to enhancing its throughput capacity and operational efficiency.

It should be emphasized that the integration of data on transport flow parameters and railway station operational technology into the model is achieved through the semantic representation of information. The semantic approach ensures precise data structuring, interconnected representation, and enhanced analytical capabilities, allowing for the modeling of complex processes and the forecasting of operational scenarios with a high degree of reliability.

The application of this methodology during the design phase helps create more reliable and resilient railway systems, reducing the risks of future operational issues. The result of modeling station operations and analyzing the model is an assessment of the railway station's transport potential, which takes into account the structure of the transport flow and the parallelism of processes at the station. An example of the output form, including a diagram of the available throughput (processing) capacity of the Auls railway station, is presented in Figure 3. For a more detailed description of the operational performance of stations, taking into account the time standards for performing various technological operations, the category, and characteristics of the transport flow, it is necessary to utilize the capabilities of a timed colored Petri net. In such a net, transitions have associated time costs for execution, which makes the model closer to the behavior of a real system or process. Tokens can differ and have their own parameters,



(a) Legend:

VP Gorl.1 – switch throat of the Upper Yard from the Zhitoml side; VP – tracks of the Upper Yard; VP Gorl.2 – switch throat of the Upper Yard from the Grodno side; NP Gorl.1 – switch throat of the Lower Yard from the Zhitoml side; NP – tracks of the Lower Yard; NP Gorl.2 – switch throat of the Lower Yard from the Grodno side; Vytyazhka 1 – shunting track No. 21; Vytyazhka 2 – shunting track No. 22.

Figure 3: Diagram of the available throughput (processing) capacity of the auls railway station

which are considered during the activation and execution of transitions. At the same time, a colored Petri net can be transformed into a simple Petri net with a single type of token, allowing for network structure analysis based solely on its properties.

B. Forecasting energy consumption

The application of intelligent systems in railway transport encompasses a wide range of tasks: traffic analysis for schedule optimization, delay forecasting, and route improvement, as supported by research in the field of artificial intelligence in railway systems. Additionally, such systems are utilized for infrastructure management, including the assessment of station throughput capacity and the prediction of operational difficulties, as well as for enhancing energy efficiency through optimized energy consumption. In the domain of resource management, these systems demonstrate their effectiveness, as evidenced by the study on calculating fuel consumption norms for train traction, where regression analysis and neural networks achieved prediction accuracy with determination coefficients of 0.9131 and 0.8776, respectively.

To address the challenge of calculating fuel consumption rates for train traction, an approach based on analyzing and processing large volumes of data was employed. The data collected includes train movement parameters (operational factors) and fuel consumption records, which were thoroughly cleaned of outliers and anomalies. Statistical methods were applied to identify the most significant parameters influencing fuel consumption. Machine learning techniques, including regression analysis and gradient descent implemented via neural networks, were then utilized to develop predictive models for fuel consumption. Regression models help establish the relationship between movement parameters and fuel consumption, while neural networks enable the identification of complex nonlinear dependencies.

The calculation of fuel consumption norms for train traction using neural networks is based on a supervised machine learning methodology, which involves identifying an algorithm to transform input data (operational factors) into output data (fuel consumption). For this purpose, a fully connected neural network model is employed, integrated with a semantic knowledge base. The semantic knowledge base structures the input data, such as mileage, technical speed, and average axle load, into an ontological model, enabling unified interpretation and improving prediction accuracy [?]. The number of neurons is determined by the number of input operational factors used for training. The neural network consists of a single layer with five neurons, where the number of neurons corresponds to the number of operational factors (Figure 4).



Figure 4: Neural network for calculating fuel consumption norms for train traction

For training the model and subsequent comparative analysis of results, labeled source data previously used in constructing the regression model are employed. Within the framework of model development and training, the semantic approach facilitates the structuring and formalization of data, allowing the integration of various information sources into a unified model. During training, the semantic representation of data aids in interpreting input parameters by creating contextual relationships between operational factors. This enables the model to account for complex interdependencies among the data and enhance prediction accuracy. Semantic analysis also contributes to identifying patterns and hidden factors that influence the model's performance.

When constructing a multifactor model, attention should be paid to the mutual influence of the factors included. The presence of interrelated components in the model can lead to duplication of their impact on the response function, ultimately distorting the modeling results. To avoid this, it is necessary to identify factors with a high degree of mutual correlation and potentially exclude some of them. A correlation is considered high when characterized by a coefficient $r \ge 0.75$. To assess this, a matrix of pairwise correlation coefficients (correlation matrix) is constructed.

When developing a model for energy resource consumption per trip, it is also essential to define the durations of the forecasting and accumulation periods for the model. The accumulation period refers to the time frame from which the input data for training the model are sourced, while the forecasting period is the duration during which the developed model is used to predict energy resource consumption. After the forecasting period expires, the model is expected to undergo retraining, with the accumulation period shifted forward by the length of the forecasting period.

If the accumulation period is too short, the volume of data available for model construction may be insufficient. Conversely, if the accumulation period is excessively long, the model may become "inertial" and less responsive to changing conditions in train traction operations. Accordingly, the forecasting period must be determined in alignment with the accumulation period.

During training, an optimization function (mean squared error) is used to calculate adjustments to the values of internal variables (weights). The objective of this function is to determine the values of internal variables in the model that most accurately describe the correlational relationships between input data and the output. The learning rate coefficient (step size) for adjusting the internal variable values is set at 0.1. Throughout the training process, the model receives input values of operational factors, performs transformations using the internal variable values (weights), and produces output values intended to correspond to the fuel consumption in tons. The difference between the desired result and the actual output is calculated using a loss function, while the optimization function determines how the weights should be adjusted to minimize losses.

As a result of training the neural network, the appropriate weights for neuron connections were established. The neural network with these established weights can be formalized in the form of an equation.

$$B = 194,819 + 3,261L + 0,893A + 0,204v~7,873q$$
 (2)

Based on the obtained equation (2), calculations of fuel consumption values per trip were performed using the available labeled source data, and deviations of actual fuel consumption values from the norms calculated by the neural network were determined (Figure 5).



Figure 5: Histogram of relative deviations of calculated norms from actual fuel consumption per trip

The conducted experiments have demonstrated that the proposed approaches enable the development of models that provide sufficiently high accuracy in calculating and forecasting fuel consumption for train traction. However, these models have limited mechanisms for adapting to a wide range of parameters not considered in the analysis, such as the number of train stops, the driver's experience, the actual traction characteristics of a specific locomotive, and other factors. The achieved accuracy is largely due to multidimensional linear averaging of the input data within the scope of the conducted analysis and machine learning, which reduces their flexibility. This approach is effective for stationary conditions but does not allow the models to dynamically adapt to changing external factors or account for nonlinear relationships between parameters, potentially leading to a decrease in forecast accuracy under real operational conditions. In the second approach, based on neural networks, the semantic representation of data and ontological relationships between various input parameters, as well as the training process, become critically important; the latter can result in variations in weight values with each training run. To prevent overfitting and enhance model accuracy, it is essential to carefully select the training method. Overfitting can manifest as excessive tuning of the model to the training data, which diminishes its ability to generalize to new data, particularly under varying operational conditions.

To this end, it is proposed to use regression analysis to set the initial weight values of the neural network, followed by their adjustment using the gradient descent method. Future research prospects are related to improving the models, developing a semantic and ontological structure for representing various parameters, incorporating additional factors, and integrating the proposed solutions into practical railway transport management systems. A significant direction involves the implementation of deep learning methods to automatically identify hidden patterns in the data, as well as the development of semantically compatible platforms that ensure data unification and standardization to enhance interoperability between different intelligent systems.

III. Prospects for development

The integration of intelligent systems into railway transport marks a pivotal step toward enhancing its efficiency, safety, and competitiveness. The adoption of advanced technologies, including semantic approaches, is transforming traditional operational processes and management practices, unlocking new opportunities for the industry.

In the context of railway transport, digital transformation encompasses the use of technologies such as the Internet of Things (IoT) for real-time infrastructure monitoring, geographic information systems (GIS) for route optimization, artificial intelligence (AI) for process automation and predictive analytics, and semantic knowledge bases for data structuring and interpretation. Semantic technologies enable the creation of ontological models that unify data on operational factors, such as rolling stock condition, infrastructure status, and transport flows, thereby improving the accuracy of analysis and forecasting. These technologies fundamentally reshape workflows and necessitate new competencies among personnel.

A cornerstone technology is IoT, which facilitates continuous monitoring of rolling stock, infrastructure, and cargo. Sensors and smart devices installed on tracks and wagons collect data on vibrations, wear, and temperature. These data are integrated into a semantic knowledge base, which structures them into ontologies, establishing contextual relationships between parameters. This approach enables predictive analytics, uncovers hidden patterns, and prevents failures, minimizing downtime. Studies indicate that the combination of IoT and semantic analysis can reduce equipment failure rates by 20 to 30 percent, enhancing the operational reliability of railway infrastructure.

A critical component of intelligent system implementation is the development of a unified semantic knowledge base that consolidates data on operational processes, infrastructure, rolling stock condition, and maintenance activities. This base organizes information into an ontological model, ensuring consistent interpretation of data from diverse sources. When paired with AI, the semantic knowledge base enables the automation of operational management, forecasting of maintenance needs, optimization of train schedules, and enhancement of safety protocols. One of the most promising directions is the development of autonomous trains, which leverage semantic models for real-time data processing, minimizing human error, reducing accident risks, and improving schedule adherence, thereby enhancing both safety and efficiency.

To fully realize the potential of intelligent systems in assessing and enhancing the transport capacity of railway systems, a comprehensive approach is required. This includes the adoption of innovative technologies, such as semantic knowledge bases, infrastructure modernization, and continuous personnel training. These measures will not only optimize current operations but also prepare the industry for future challenges, ensuring more accurate assessment of transport potential and sustainable development of railway transport.

IV. Conclusion

The application of semantic technologies in the design of intelligent systems for railway transport management opens new opportunities for enhancing operational efficiency and reliability. The integration of diverse models for knowledge representation, data handling, and problem solving methods, as implemented in the system "Dynamic Wagon Flow Map," demonstrates the advantages of semantic compatibility and interoperability. However, the proposed approaches have limitations related to the need for ontology standardization, accounting for random factors (such as weather conditions), and ensuring system adaptability to new parameters through enhanced learning capabilities.

Future research could focus on developing ontological models for multimodal interfaces, which would improve interaction between various intelligent systems, as well as on creating hybrid problem solvers based on the semantic representation of knowledge bases. A key direction is the development of a comprehensive technology for designing next generation intelligent systems that supports all stages of their lifecycle, from design to operation, using semantically compatible platforms.

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ИНТЕЛЛЕКТУАЛЬНЫЕ СИСТЕМЫ В ОЦЕНКЕ ПЕРЕВОЗОЧНОГО ПОТЕНЦИАЛА ЖЕЛЕЗНОДОРОЖНОГО ТРАНСПОРТА Козлов В. Г.

Исследование показывает, что интеллектуальные системы могут значительно улучшить оценку перевозочного потенциала железнодорожного транспорта. Эти системы позволяют проводить анализ данных в реальном времени, оптимизацию маршрутов и прогнозирование эксплуатационных затруднений. Белорусская железная дорога разработала и внедрила ряд информационных и управленческих систем, включающих элементы искусственного интеллекта, основанные на семантических базах знаний, которые улучшили управление транспортным процессом за счет повышения точности и достоверности оценки пропускной способности железнодорожной инфраструктуры.

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The Development of Artificial Intelligence Technologies and Their Potential Applications in Supply Chain Management

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Abstract—The article under consideration here sets out to explore the practical applications of artificial intelligence technologies in the context of implementing digital ecosystems for the identification and traceability of goods within supply chains. The challenges associated with the modernisation of existing supply chain monitoring systems through the utilisation of AI technologies are emphasised. This text sets out the general requirements for a model of a digital ecosystem of supply chain support that uses the Internet of Things, a distributed registry (blockchain), artificial intelligence and other modern technologies. The issues of security and the need to prevent negative consequences of AI-based decisions by developing a model for assessing the risks of errors associated with the AI system as applied to the supply chain management process are highlighted.

Keywords-artificial intelligence, ecosystem

I. Introduction

Digitalisation, which has the potential to transform the modern rules of the market, is gradually transforming the competitive environment and society as a whole. At the same time, it necessitates a deep rethinking of established approaches to the creation of information and analytical systems, technologies and products.

These should be focused on the following:

- providing situational management and decisionmaking support in the republican bodies of state power and public administration;
- 2) managing the processes of planning, production and sales of products in industry;
- creating high-tech farms and processing enterprises that ensure the production of high-quality agricultural products, taking into account current market demands.
- the optimisation of commodity transport flows, risk reduction and stock reduction in trade, logistics and transport;
- 5) the introduction of new high-tech tools for training specialists in the education system;

6) the implementation of educational and entertainment events using modern technologies in the field of culture.

In order to facilitate the advancement of these aforementioned domains, there is an imperative for the proactive development of contemporary digital information technologies, including but not limited to artificial intelligence, the Internet of Things, blockchain, robotics, unmanned transport, aerospace technologies, augmented reality technologies, and other associated fields.

Among the technologies previously mentioned, one of the most debated at present is undoubtedly Artificial Intelligence (AI).

The evolution of AI is influenced by related technologies and processes of big data formation, without which AI training is not directly possible. In this section, there is an escalation of developments focused on the integration of AI with the Internet of Things technologies. Modern automated systems endowed with artificial intelligence capabilities are adept at interpreting and analysing data received from IoT objects (e. g. sensors and other data sources) in real time, thereby enabling businesses to respond and manage operations with greater efficiency and precision. [1], [2] The practical application of such integrated solutions has been identified in a number of areas of the economy, but primarily in trade, transport and logistics.

Experts estimate that companies that have implemented AI to optimise deliveries can reduce logistics costs by up to 20% [3]. The integration of AI within the domain of logistics has been demonstrated to facilitate warehouse operations. Robotic assistants have been shown to facilitate the expeditious and systematic organisation of tasks, including picking, packing, and delivery. The utilisation of AI-powered tracking sensors and video cameras has the potential to facilitate realtime management, thereby leading to substantial losses and cost reductions. The process of inventory control gives rise to a substantial amount of new data, which, when analysed, can assist in the creation of accurate forecasts for the organisation of stock in warehouses. The delivery process is accelerated, and customer and partner interactions are enhanced.

It is important to note that, in general, supply chain business processes remain virtually unchanged (e. g. physical production of goods, transportation, etc.), however information about events related to these business processes and directly related to goods is subject to evolutionary changes. At present, GS1's approaches enable the execution of the conventional 5W model (i. e. what, who, why, when, where) [4] and the response to the query 'how' (in what state?) with respect to the designated object (i.e. goods, products). In recent years, the implementation of this approach has been constrained by technological limitations. However, contemporary digital technologies are now being incorporated into the process at an accelerated pace. GS1 standards facilitate the assurance of technological interaction between supply chain participants on a global scale, thereby enabling the creation of interoperable data exchange networks between digital objects. This is achieved by leveraging contemporary technologies, including the Internet of Things (IoT), distributed ledger (DLT), and artificial intelligence (AI), encompassing machine learning [5].

Concurrently, AI can be employed for more intricate tasks, such as supply chain network design, supplier selection, and demand planning. Consequently, such solutions have the potential to facilitate more efficient, sustainable, and environmentally sound supply chains. However, it should be noted that AI tools currently provide more of a predictive component to assist in decision making. That is to say, AI can take over some, but not all, tasks, as it does not involve autonomous decision making.

II. Goals, objectives and principles of creating

The primary objective of the development and subsequent operation of a digital traceability ecosystem based on AI technologies is to create a comprehensive system for supply chain participants, enabling the use of modern international standards and best practices aimed at ensuring the interoperability of digital platforms being developed and evolving, including cross-border ones, in the context of the ongoing digital transformation of the economy.

The utilisation of AI has the potential to facilitate the transformation of traceability technologies into a flexible, interconnected digital infrastructure, capable of supporting multiple virtual, non-linear supply chains. Consequently, virtual supply chains will supersede traditional fixed linear supply chains. Such approaches involve new options for information flows that enable faster order fulfilment, such as real-time order fulfilment, predicting potential risks and making decisions that minimise losses.

The process of transitioning towards a technologically mature digital supply chain can be conceptualised as a sequence of four distinct stages. The initial stage involves the establishment of data visibility within the supply chain. Subsequent stages entail the development of predictive analytics and a directive supply chain. Ultimately, the objective is to achieve a self-learning supply chain. As companies progress along the maturity curve, their reliance on manual management will be superseded by autonomous management, resulting in substantial efficiency gains and cost savings. There is now a strong focus on end-to-end supply chain visibility to help companies better manage constraints in the chain. At this stage of maturity, supply chain visibility is being established by various system integrators, including ERP systems. It is evident that businesses are able to obtain a comprehensive perspective on the movement of products through the supply chain by leveraging these types of solutions. The majority of contemporary enterprises are currently at the initial stage of digital supply chain maturity.

The subsequent stage of development (second) involves the development of predictive analytics. At this stage, predictive analytical algorithms based on big data, such as IoT sensor data, weather data, traffic levels on routes, restrictions and other related data, should be used to anticipate (predict) possible risks, respectively. This will enable the prediction of where problems may arise in the supply chain in the future. To illustrate this point, predictive analytics can be utilised to analyse data such as weather forecasts and port congestion, thereby enabling the assessment of the impact on in-transit shipping and the identification of potential delays in shipments.

The subsequent (third) stage of digital supply chain development should be a directive supply chain, powered by the application of machine learning technologies. At this stage, intelligent systems will be capable of predicting potential supply chain problems and suggesting an action plan to solve them. This technology has already been incorporated into the most advanced software solutions, in which directive analytics utilise historical data from planners. For instance, in the event of a shipment being predicted to arrive late, the software can provide a number of potential solutions, including the rescheduling of resources or the procurement of goods from an alternative supplier. The system will then recommend the most appropriate solution.

The final (fourth) stage of digital supply chain maturity should be a self-learning supply chain made possible by 'deep machine learning'. The capacity to deliver such software solutions will confer a substantial competitive advantage on both companies and software solution providers. At this stage of its development, AI is also being used for predictive analytics, taking into account an archive of data on similar deliveries under similar conditions. This helps to identify delivery problems (congestion, delays, damage, insurance, etc.) before they occur. Concurrently, AI technologies have the capacity to expeditiously and precisely analyse voluminous data in terms of demand and associated metrics. This can assist in the generation of forecasts for future sales. This approach serves to reduce the likelihood of stock formation and optimises the work of enterprises, taking into account the current and forecasted market situation for a particular period.

III. Problem Statement

The advent of contemporary digital technologies, underpinned by artificial intelligence (AI), has led to the facilitation of real-time monitoring of material flow traceability within supply chains. This development has been instrumental in the enhancement and progression of efficient logistics systems for cargo delivery, including in the context of international traffic. AI systems are capable of analysing vast quantities of data, including information on traffic situations, weather conditions, traffic congestion and delivery times. It is evident that, in consideration of the data presented, the utilisation of artificial intelligence results in the generation of optimal routes, thereby leading to a reduction in journey times, fuel consumption, and vehicle wear and tear. By leveraging data from sensors and connected devices to provide realtime insights into operations, companies can achieve cost reductions, address transport challenges and enhance productivity.

It is important to acknowledge that the implementation of AI technologies is concomitant with an elevated degree of risk. This thesis has been noted on multiple occasions in the reports of the participants of the 34th session of the Working Group on Standardisation, Policy and Regulatory Cooperation (WG.6) of the UN Economic Commission for Europe, which was held from 26-28 August 2024. [4]. In particular, the resolution of the meeting on the regulation of products and services with embedded AI or other digital technologies states the following: "When establishing objectives for AI regulation, it is imperative to recognise that the attainment of zero risk is an unattainable ideal.

In this regard, the United Nations Economic Commission for Europe (UNECE) has issued a recommendation for the conduct of risk assessments and the selection of appropriate conformity assessment methods. For instance, certain medical devices are equipped with sophisticated diagnostic systems that incorporate artificial intelligence. Despite the capacity of such medical devices to facilitate algorithmic decision-making processes, concerns regarding liability and the potential risks to patients have led to the recommendation that human involvement in the decision-making process should be incorporated wherever feasible. The necessity of mandatory human control and intervention for specific industrial equipment that incorporates human operators and programmable robots managed by AI systems should be contemplated. It is recommended that analogous approaches be formulated for other AI applications, including the automation of supply chain traceability processes [11].

It is important to acknowledge the complexity inherent in evaluating and identifying the algorithms embedded within these technologies. This is due to the fact that the methods and logics underpinning the outcomes are often not readily apparent. This element of uncertainty in technological systems is typically addressed through the implementation of a series of meticulously designed tests conducted under diverse conditions. However, it should be noted that these tests may not always prove adequate in identifying all the unknown characteristics of the system, thereby resulting in a residual risk. It is incumbent upon the regulators and distributors of such products to ensure that residual risks do not exceed an acceptable level of risk and to disclose them.

In circumstances where the potential for error associated with an AI system is deemed to be significant, it is imperative for humans to play a pivotal role in the decision-making process. It is imperative that AI systems do not possess the capability to override human control commands [3].

In view of the aforementioned points, the following tasks must be addressed:

- The establishment of requirements for automation objects, where the implementation of AI can yield substantial outcomes.
- The formalisation of the primary supply chain traceability processes, which can be enhanced through the integration of AI technologies.
- The development of a model for the digital ecosystem of supply chain support, utilising Internet of Things, distributed registry (blockchain), AI, and other contemporary technologies.
- The development of a model for the assessment of the risks of error associated with the AI system as applied to the supply chain management process is the primary objective of this study.
- The development and validation of a prototype of a digital ecosystem of supply chain support based on modern technologies is a secondary objective.

IV. Proposed approaches to the realisation of the digital ecosystem

Supply chains are complex systems, and the manner in which they are organised, transparent, flexible and scalable directly affects their success. Digitalisation is leading to the emergence of digital ecosystems for supply chain product identification and traceability, with the aim of ensuring integrity, transparency, monitoring, management and control for the entire product lifecycle. This includes the sourcing, manufacturing, warehousing, distribution and delivery of products to end consumers [3].

The digital ecosystem of supply chain identification and traceability involves the management of substantial volumes of both structured and unstructured data, the establishment of integration processes, and the coordination of logistics between supply chain actors across organisational boundaries. In addition, the design and implementation of modern integrated systems is necessary for the automatic, efficient, and secure processing of incoming orders for cargo delivery, thereby ensuring the availability of goods to intermediate and final consumers. On this basis, the formation of requirements for automation objects should be based on the analysis of a set of GS1 international standards, existing large-scale systems of goods traceability in supply chains, opportunities for their further modernisation and highlighting the main tasks where the use of modern technologies allows for significant effects to be obtained.

In terms of formalising the main processes of traceability and ensuring information interaction between the components of the digital ecosystem of traceability in supply chains, it is proposed to identify the following main architectural components, as presented in Figure [4].

The Digital Traceability Ecosystem is primarily supported by data from multiple transactional systems, including ERP, CRM, SRM and WMS [2], [12]. These systems facilitate the transfer of data on suppliers, customers, scheduled production resources, warehouse balances, and delivery schedules. Thereafter, the data is transferred through the corporate data bus to the messaging layer in accordance with the publish-subscribe model (pub/sub - publisher-subscriber – a messaging template in which messages are divided into classes and do not contain information about their subscribers (subscriber). Further templates can be used to build machine learning models in real time, for example, in order to categorise new products and upload information about them to a digital platform) [8], [10].

At the level of visualisation and decision-making, data are accessed by all stakeholders in the process, ensuring its efficiency and transparency. These stakeholders include suppliers, customers, and managers of production, warehouse, distribution of goods and/or services. It is at this level that operational, tactical and strategic management is performed, and that decision support is formed based on data analysis. These decisions may pertain to alterations in production schedules, optimisation of warehouse stock levels, the selection of suppliers and customers, and other related matters. It is imperative to acknowledge that all such decisions, made at this level, exert a direct influence on the order plans and records of customers and suppliers, consequently prompting alterations to the corresponding plans and records residing within the source systems.

In order to develop a model for assessing the risks of errors associated with the AI system, it is necessary to develop algorithms for monitoring decisions made using AI as applied to the supply chain management process. It is imperative that security policies are implemented with the primary objective of identifying and preventing potentially hazardous decisions that are made with the utilisation of AI, with a particular focus on its application in predictive analytics tasks. One possible variant of such a model could be the formation of 'AI decision sandboxes'. The purpose of the sandbox would be to allow the modelling of the consequences of proposed AI supply chain management actions before an agreed decision is made. At present, such decisions are insufficiently studied and require elaboration.

In order to develop and test a prototype of a digital ecosystem for supply chain support based on modern technologies, it is recommended that a set of existing systems for product monitoring and traceability be considered. The development of these systems should be ensured through re-engineering. The integration of novel technologies (e.g. the Internet of Things, distributed registry, AI) into existing systems should be economically viable and offer the potential for substantial impact.

A. Practical implementation

In the Republic of Belarus, components of Digital Ecosystems of traceability of individual groups of goods (products) that meet international and national standards [5], [6] exist and are developing at the level of business and at the level of the state.

These components include:

- Interdepartmental distributed information system 'Bank of electronic passports of goods' (http://epass.by/) [14]. A comprehensive information system that was developed to harmonize the existing procedures in trade, transport and logistics in Belarus with international rules and standards:
 - contains product descriptions in the format which complies with the international standards of eCommerce;
 - is a source of reliable product information provided by manufacturers and suppliers; creates conditions allowing to shorten the list of documents accompanying goods to points of sale;
 - facilitates the acceleration of commodity flows in supply chains and increases their transparency through the use of e-document management.

ePass application areas: trade, supply of raw materials and products, market analysis, logistics, control of distribution, quality and safety of goods.

The system includes the information resource (https: //epass.by) which contains descriptions of goods in a format that meets international standards. This allows participants of trade and transport operations to create and exchange electronic messages.



Figure 1. Basic model of interaction of architectural components of the digital ecosystem of traceability in supply chains

Product descriptions come from primary sources (manufacturers and importers). The descriptions are further transmitted to supply chain participants to be used in business process automation systems. This data capture algorithm makes it possible to:

- eliminate the expenses of multiple manual entry of product data into information systems;
- avoid errors and ensure uniformity of product data throughout the supply chain;
- automatically manage information about documents confirming quality and safety of goods and provide it to consumers.
- State information system of identification, registration, traceability of animals and products of animal origin (https://www.aits.by/) [15]. AITS is a system designated for state regulation and management in the field of identification, registration, traceability of farm animals (bovines, horses, pigs, goats, sheep) of all forms of ownership, livestock facilities, as well as identification and traceability of products of animal origin. A prerequisite for building safe and secure food supply chains is to adopt uniform national and international rules for identification, registration and traceability of farm animals and, basing on these rules, to develop technologies for traceability of products of animal origin.

AITS creates and keeps up-to-date databases and functional components for the identification and traceability of products of animal origin in supply chains, allowing to trace them from farm to fork and fork to farm in a "one step forward, one step back" manner.

AITS enables animal traceability in Belarus basing on national and international standards (GS1 global standards) for animal identification and registration.

The core of the AITS system uses modern international zootechnical and veterinary reference sources, global standards for identification, traceability and electronic data interchange, and has a flexible customization system. This allows it not only to be quickly tailored for the identification of different animal species, but also to take into account changes and differences in legislation, ensuring that the system can be quickly set up and implemented in other countries. This creates conditions for the development of effective traceability information technologies at the national, inter-agency and corporate level.

The aforementioned components of digital ecosystems of traceability of certain groups of goods (products) can be modernised through the implementation of contemporary technologies, including AI. In consideration of the significance of the implementation of these solutions for the nation's economic advancement, the re-engineering of these systems can be undertaken within the ambit of state-sponsored programmes, with the active participation of the most accomplished scientific and practical organisations within the country. In the domain of AI, it is imperative to consider priority markets and technologies in a holistic manner, with a view to identifying the most promising projects at the nexus of these areas.

The primary objective at present is to generate demand for the utilisation of AI technologies and to establish an environment conducive to the establishment of fundamentally novel technological enterprises based on novel combinations of AI technologies [3]. In order to address this challenge, it is imperative to establish a state programme on AI, within which a long-term strategy for the development of AI in Belarus can be articulated. This strategy should be focused on leveraging the existing backlog, while also fostering collaboration among scientific, design organisations and universities to create unified and promising solutions. The following links will facilitate the effective promotion of the nation's pressing sustainable development priorities and the introduction of solutions in new global markets for AI technologies and tools.

B. Conclusion

Supply chains are intricate systems, and the efficacy of their organisation, transparency, flexibility, and scalability directly impacts their development success. The application of AI technologies is leading to the emergence of digital ecosystems and their creation in the field of supply chains. The purpose of these ecosystems is to ensure integrity, transparency, monitoring, management and control for the entire product lifecycle. This includes the selection of suppliers, production, warehousing, distribution and delivery to the end consumer [7], [9].

The solution to the problem of modernising existing supply chain monitoring systems through the use of AI technologies provides an opportunity to obtain a significant effect through the implementation of predictive analytics approaches in the real sector of the economy. The execution of such a task can be achieved through the implementation of a digital ecosystem model for supply chain monitoring, which utilises the Internet of Things, distributed ledger technology (blockchain), artificial intelligence, and other contemporary technologies. The implementation of such an ecosystem should, in principle, provide opportunities to prevent negative consequences from AI-based decisions. One such opportunity would be the development of a model for assessing the risks of errors associated with the AI system as applied to the supply chain management process.

The utilisation of AI technologies is poised to further modernise a plethora of business processes, encompassing not only supply chains but also all phases of the product life cycle. Specifically, SCM based on artificial intelligence has the capacity to address the following tasks: modelling and simulation, optimisation, forecasting and risk analysis, decision support, inventory management, marketing and transportation.

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О РАЗВИТИИ ТЕХНОЛОГИЙ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА И ПЕРСПЕКТИВАХ ИХ ПРИМЕНЕНИЯ В УПРАВЛЕНИИ ЦЕПЯМИ ПОСТАВОК

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В статье рассмотрены вопросы практического применения технологий искусственного интеллекта для реализации цифровых экосистем идентификации и прослеживаемости товаров в цепях поставок. Освещены проблемы решения задач модернизации действующих систем мониторинга цепей поставок за счет применения технологий искусственного интеллекта. Описаны общие требования к модели цифровой экосистемы сопровождения цепи поставок с использованием технологий Интернета вещей, распределенного реестра (блокчейн), искусственного интеллекта и других современных технологий. Отмечены вопросы безопасности и необходимости предотвращения негативных последствий от решений, принимаемых на основе технологий искусственного интеллекта, за счет разработки модели оценки рисков ошибок, связанных с системой искусственного интеллекта применительно к процессу управления цепями поставок.

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Swarm Ant Colony Models to Control Flows in Intellectual Systems

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Abstract—It is considered the application of Swarm intelligence ant colony models to project complex intellectual systems. The boids behavior is to some extent similar to flows in energy supply (on transport) systems as subject field. There were proposed some improved ways to resolve dynamical tasks with indefiniteness with higher computational speed and better convergence of algorithms, that is confirmed by comparision of various schemes. Because of invariantness of the components and possibility to describe practically all of systems in flow model, it looks applicable in other spheres also. ACO algorithms can be used as a tool for high-level logical reasoning and optimization, regardless of the specific underlying hardware.

Keywords—ant colony algorithm, swarm intelligence, complex systems, energy supply on transport

I. Introduction

The ant colony algorithm (ACO), proposed by Italian scholar Marco Dorigo, aims to simulate the behavior of ants for-aging for food. In 1996, Dorigo et al. further elaborated the core idea of this algorithm. During ant foraging, they communicate by releasing pheromones, and paths with higher pheromone concentrations are easier to choose. When ants walk along a path without pheromones, they find new ones and leave pheromones on them. With the passage of time, the concentration of shorter path pheromones gradually increased, forming a positive feedback mechanism, and eventually enabling the ant colony to self-organize and to find the optimal path. This principle also provides a way to solve the shortest path problem. In general, ACO often relies on the mathematical modeling of problem domains in terms of path optimization and re-source scheduling, which is with the ontology design system development. In combination of consistent intellectual of deep learning and ant colony intelligence, the state transition rules of ACO can be modified to improve path planning representation.In the the compatibility and application of knowledge of swarm ant colony models to control flows in intellectual systems, the ACO embedded into algorithm can be the semantic knowledge base of intelligent computer systems to solve dynamic optimization problems.

II. Ant Colony Algorithm Model



Figure 1. The optimal path for solving TSP problem by ant colony

A. The Shortest Path

See Figure 1. Let point A be the colony, point E be the food source, and CF be an insurmountable obstacle between colony A and food source E. Ants can only travel to and from colony A and food source E through C or F, where the distances BF = DF = 2BC = 2CD. Let m ants arrive at E(A) from A(E) at a certain time. In the initial stage, since the initial pheromones of each path are evenly distributed (all 0), ants at points B and D will randomly select BC, CD, BF, FDand other paths with the same probability, and release pheromones on the passing path. Because the length of path BCD is half that of path BFD, the number of ants passing through route BCD is higher than that of route BFD in a unit time, and the pheromone concentration is relatively higher on the route. After a certain period, the pheromone concentration on path BCD will be twice that on path BFD, as shown in Figure 2-1(C). With the accumulation of pheromones, the ant will completely select the path BCD under this positive feedback mechanism, thus completing the search of the shortest path between ant A and food source E.

The above is the basic idea of ant colony algorithm. The idea of applying this idea to apply it to the actual optimization problem is as follows: Firstly, the actual problem to be optimized is abstracted as the ant foraging problem, and the foraging path of each ant is regarded as a feasible solution, and the whole solution space is formed by all the ant foraging paths. The shortest feeding path eventually found by the ant colony is the optimal solution to the problem. The whole feeding process of ant colony is the process of algorithm optimization.

B. The function of the shortest food source path

Ant colony algorithms can be abstracted as a method to find the shortest path of ants from the nest through each given food source and finally back to the nest. The specific modeling and implementation process is as follows: suppose there are n food sources, and the distance between food source i and food source j is d_{ij} (i, j = 1, 2, ..., n). The goal is to find the shortest route an ant can take from a food source to all food sources, ensuring each food source is visited only once.

The objective function of the shortest food source path can be formulated as:

$$\min(d_{\text{total}}) = \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij}.$$
 (1)

where d_{ij} represents the distance between food sources i and j. The algorithm iteratively optimizes this function using pheromone-based heuristic updates and probabilistic decision rules.

C. The provisions of the ant colony algorithm model

In order to facilitate the establishment of the ant colony algorithm model, the following provisions are usually made: (1) the ants start from a certain food source, and each food source can only arrive once. (2) The ants must leave a certain concentration of pheromone in their path; (3) The probability of ants choosing the next food source conforms to the state transition rule. According to the ant colony algorithm, the key steps of the algorithm are modeled, including pheromone initialization, state transition rule and pheromone update.

D. Pheromone initialization

At the initial stage, the pheromone concentration on each path is set to be equal, represented as a constant value. This is expressed as:

$$\tau_{ij}(0) = \mathbf{C}.\tag{2}$$

where $\tau_{ij}(0)$ denotes the initial pheromone level on the path between food sources *i* and *j*, and *C* is a predefined constant. This ensures that all paths start with the same pheromone concentration, allowing the ants to explore different routes without bias.

E. Tabu Table Mechanism in Ant Colony Optimization

In the ACO algorithm, the **tabu table** is a dynamic data structure used to store the nodes that an ant has already visited, ensuring that each one does not revisit previously traversed nodes (except for returning to the starting point) while constructing a solution. Each k ant maintains an independent tabu table, $tabu_k$, which initially contains only the starting node.

During the path construction process, whenever ant k selects the next target node j, this node is added to the

tabu table $tabu_k$ and removed from the candidate node set. This process continues until the ant has visited all nodes and formed a complete path. Once an iteration is completed, the ants update the pheromone levels based on the path length and pheromone update strategy, and the tabu table is reset to prepare for the next round of searching. The dynamic update mechanism of the tabu table not only effectively prevents local cycles but also enhances solution diversity during the cooperative search process of multiple ants, thereby improving the global search capability of the algorithm.

F. Tabu Table Update Process

The tabu table update process can be described as follows:

- 1) **Initialization**: Ant k starts at the initial node i_0 , and the tabu table is set as $tabu_k = \{i_0\}$.
- 2) State Transition: Based on the state transition probability $P_{ij}^k(t)$, the next unvisited node j is selected and added to the tabu table:

$$\mathsf{tabu}_k = \mathsf{tabu}_k \cup \{j\} \tag{3}$$

- 3) **Path Completion**: When all nodes have been visited, the tabu table contains the complete path information.
- 4) Tabu Table Reset: After the pheromone update based on the current path, the tabu table is cleared, and the ant selects a new starting node for the next iteration.

Tabu table is a path memory and restriction mechanism, by recording and limiting the path selection of ants, prevent the generation of repeated paths, avoid the dead cycle in the search process, enhance the local and global search, and guide the ants to develop in the direction of better solutions. This mechanism is one of the keys that ant colony algorithm can find the global optimal solution effectively when solving optimization problems

G. State transition rule

During the movement process, each ant k (k = 1, 2, ..., m) determines its transfer direction based on the pheromone concentration on each path. A tabu table, denoted as tabu_k, is maintained to record the food sources that ant k has visited. This tabu table is dynamically updated throughout the evolutionary process. Once a full cycle is completed, the path length is calculated, the tabu table is reset, and the ant reselects a starting point for a new cycle.

Throughout the search process, ants determine the state transition probability based on the pheromone concentration and heuristic information (known models from existed or newly prepared Data Knowledge Bases) associated with each path. In each iteration, under a given stopping condition, ant k independently selects the next unvisited food source based on the transition probability $P_{ij}^k(t)$, calculated using the following equation:

$$P_{ij}^k(t) = \frac{\tau_{ij}^{\alpha} \eta_{ij}^{\beta}}{\sum\limits_{s \in \text{allowed}_k} \tau_{is}^{\alpha} \eta_{is}^{\beta}}.$$
(4)

where:

- $P_{ij}^k(t)$ represents the probability that ant k moves from food source i to food source j at time t.
- allowed_k is the set of food sources that ant k is permitted to visit in the next step, defined as:

$$\operatorname{allowed}_k = C - \operatorname{tabu}_k \tag{5}$$

where C is the complete set of food sources.

- α is the pheromone influence factor, which controls the importance of pheromone concentration in path selection. A higher α value increases the likelihood of ants choosing paths previously traversed by other ants.
- β is the heuristic influence factor, which determines the importance of the heuristic function η_{ij} . A larger β value makes the state transition probability closer to a greedy strategy.
- η_{ij}(t) is a heuristic function that reflects the desirability of moving from food source i to food source j, expressed as:

$$\eta_{ij}(t) = \frac{1}{d_{ij}},\tag{6}$$

where d_{ij} represents the distance between two adjacent food sources. A smaller d_{ij} results in a larger $\eta_{ij}(t)$, thereby increasing $P_{ij}^k(t)$. This heuristic function encourages ants to prefer shorter paths during traversal.

A heuristic probability is a probability used to guide the ant to choose a path that combines pheromone concentration and heuristic information to determine the direction of the next move. In the ant colony algorithm, each ant needs to decide which node to go to next among several possible choices when building a solution, such as the path of the traveling salesman problem TSP. This decision is usually based on state(system staus) transition rules, in which heuristic probability plays an important role.

H. Pheromone update

When ants have traversed all food sources, they construct a complete and feasible solutions. However, excessive accumulation of pheromones may lead to an over-concentration, which can diminish the effectiveness of heuristic information and hinder solution diversity. To mitigate this issue, it is necessary to update the pheromone levels along the paths to prevent excessive influence. The pheromone update process follows the formula:

$$\tau_{ij}(t+n) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t),$$
 (7)

where the pheromone increment $\Delta \tau_{ij}(t)$ is given by:

$$\Delta \tau_{ij}(t) = \sum_{k=1}^{m} \Delta \tau_{ij}^{k}(t), \qquad (8)$$

In the above equations:

- $\Delta \tau_{ij}(t)$ represents the total pheromone increment on path (i, j) contributed by all ants during the current iteration.
- $\Delta \tau_{ij}^k(t)$ denotes the amount of pheromone deposited by ant k on path (i, j). The amount of pheromone left by an ant is inversely proportional to the total path length—i.e., shorter paths receive higher pheromone levels, whereas longer paths receive lower amounts.
- The term (1ρ) represents the pheromone evaporation coefficient, which prevents excessive pheromone accumulation and helps maintain exploration capabilities. Here, ρ is the pheromone evaporation rate, where $\rho \in (0, 1)$.

To prevent the algorithm from getting trapped in local optima, the pheromone concentration on the optimal path is not allowed to increase indefinitely. Instead, the evaporation mechanism ensures a balance between exploration and exploitation, improving the overall efficiency of the search process.

I. The solving process of ant colony algorithm

1) **Parameter Initialization:**

Set the initial time t = 0 and the number of cycles $N_c = 0$. Define the maximum number of cycles N_{cmax} . Deploy m ants at the starting element (food source) and initialize the pheromone level on each edge of the directed graph, representing the path between food source i and j, as $\tau_{ij}(0) = \text{const}$, where const is a constant. Set the initial pheromone increment $\Delta \tau_{ij}(0) = 0$.

2) Increment Cycle Count:

Increase the cycle count $N \leftarrow N + 1$ and set the initial index of the ant's tabu table as k = 1.

3) Ant Traversal Process:

Increase the ant index $k \leftarrow k + 1$. Each ant calculates the transfer probability using the state transition formula and selects the next food source j.

4) Tabu Table Update:

Update the tabu table after each movement, recording the newly visited food source.

- Traversal Condition Check: If there exist unvisited elements in C and k < m, return to step 3.
- 6) **Pheromone Update:** Update the pheromone levels on each path according to the pheromone update formula.

7) Termination Condition:

If the stopping condition is met, i.e., $N_c \ge N_{cmax}$,

terminate the process and output the result. Otherwise, reset the tabu table and return to step 2 for the next iteration.

III. Simulation Results

A. Case Description

A traveling businessman needs to visit 31 cities (capitals) in China. The goal is to find the shortest route that starts from a certain provincial capital, visits each of the 31 cities exactly once, and returns to the original starting city. This problem is a classic example of TSP as a NPhard problem in optimization. The 31 provincial capitals are represented by their coordinates, and the task is to compute the shortest path that satisfies given conditions. The coordinates of the 31 knowncapitals in China are as follows:

Table I Coordinates of 31 Provincial Capitals (in km)

City No.	X Coordinate (km)	Y Coordinate (km)
1	1304	2312
2	3639	1315
3	4177	2244
4	3712	1399
5	3488	1535
6	3326	1556
7	3238	1229
8	4196	1004
9	4312	790
10	4386	570
11	3007	1970
12	2562	1756
13	2788	1491
14	2381	1676
15	1332	695
16	3715	1678
17	3918	2179
18	4061	2370
19	3780	2212
20	3676	2578
21	4029	2838
22	4263	2931
23	3429	1908
24	3507	2367
25	3394	2643
26	3439	3201
27	2935	3240
28	3140	3550
29	2545	2357
30	2778	2826
31	2370	2975

B. Solution Process

The following table presents the parameter settings of the ant colony algorithm for solving the Traveling Salesman Problem (TSP):

C. Detailed Solution Steps

The detailed steps of solving the problem using the ant colony algorithm are as follows:

Table II Ant Colony Algorithm Parameter Settings for Solving the Traveling Salesman Problem (TSP)

Parameter	Value
Number of ants (m)	50
Information heuristic factor (α)	1
Expectation heuristic factor (β)	5
Pheromone evaporation rate (ρ)	0.1
Pheromone intensity (Q)	100
Maximum iterations (N_{cmax})	200

1) Initialization of Pheromones: Initially, m ants are randomly placed in n cities. Each ant maintains a tabu table, which records the cities it has already visited to prevent revisits, thereby improving search efficiency. The pheromone intensity on each edge is also initialized.

2) Path Construction: At time t, and k moves from city i to city j with the probability:

$$P^{k}(i,j) = \begin{cases} \frac{\tau_{ij}^{\alpha} \cdot \varphi_{ij}^{\beta}}{\sum\limits_{s \in J_{k}} \tau_{is}^{\alpha} \cdot \varphi_{is}^{\beta}}, & j \in J_{k}, \\ 0, & \text{otherwise.} \end{cases}$$
(9)

where $J_k = N - \text{tabu}_k$ represents the set of unvisited cities for ant k. The parameters α and β control the influence of pheromones and heuristic information (distance) on path selection. Here:

- τ_{ij} represents the pheromone intensity on edge (i, j).
- $\varphi(i, j)$ represents the heuristic desirability of moving from city *i* to city *j*, typically defined as $\frac{1}{d_{ij}}$.

Special cases:

- When $\alpha = 0$, the algorithm degenerates into a traditional greedy algorithm, where the closest city is always selected.
- When $\beta = 0$, the ants rely solely on pheromone concentration, which can lead to rapid convergence but may cause the algorithm to get trapped in suboptimal solutions.

Empirical studies suggest that setting $\alpha = 1 \sim 2$ and $\beta = 2 \sim 5$ yields better results.

3) Pheromone Update: After all ants have completed a valid path, the pheromone levels are updated according to:

$$\tau_{ij}(t+1) = (1-\rho) \cdot \tau_{ij}(t) + \sum_{k=1}^{m} \Delta \tau_{ij}^{k}(t,t+1).$$
 (10)

where

$$\Delta \tau_{ij}^k(t,t+1) = \frac{Q}{L_k}.$$
(11)

Here:

• ρ is the pheromone evaporation rate, typically set to 0.5. This prevents excessive accumulation of

pheromones and helps maintain exploration diversity.

- $\Delta \tau_{ij}^k$ represents the pheromone deposited by ant k on edge (i, j).
- Q is a constant controlling the pheromone amount, usually within the range [10, 10,000].
- L_k is the total length of the path traveled by the k-th ant.

4) Termination Condition: If the number of iterations reaches the predefined maximum, or if the algorithm stagnates (i. e., all found solutions are identical), the process terminates, and the best solution found so far is output. Otherwise, the tabu table is cleared, and the algorithm returns to step 2 for the next iteration.

D. Convergence Analysis and Optimal Solution

In the obtained results, the abscissa of the figure represents the city coordinates in the X-direction, while the ordinate represents the city coordinates in the Ydirection. For Figures 2-4, the abscissa represents the number of algorithm iterations, and the ordinate represents the shortest path length found at each iteration.

The solid curve in Figure 2-4 represents the **average distance convergence curve** obtained using the ant colony algorithm, whereas the dashed curve represents the **shortest distance convergence curve**. As shown in Figure 2-3, the **shortest path length** obtained by the ant colony algorithm for solving the TSP problem is 1.5602×10^4 km, which represents the **optimal solution**.

Additionally, from the convergence analysis, it can be observed that after approximately **90 iterations**, the **optimal solution convergence curve stabilizes**, indicating that the algorithm has successfully found the best solution within this range.

1) Optimal Path for Solving the TSP Problem Using the Ant Colony Algorithm: The optimal route determined by the algorithm demonstrates its capability in efficiently solving the TSP problem while maintaining solution accuracy.

2) Average Distance and Shortest Distance Convergence Analysis: The convergence trend of both the **average distance** and **shortest distance** further verifies the algorithm's performance. The gradual convergence of the curves indicates the algorithm's effectiveness in reaching an optimal solution.

IV. Discussion

Since the model components are not strictly related to the subject field ACO can be used as a reusable optimization com-ponent for different intelligent computer systems as a path search engine in traffic optimization, As a distributed inference mechanism in artificial intelligence decision-making systems it may be used for optimal flow scheduling in industrial pipeline transportation. This modular approach enables ACO to seamlessly integrate with other AI approaches (e. g., deep learning, reinforcement learning) to enable more complex intelligent system designs.Ant colony intelligence can be combined with knowledge graphs, semantic networks and other methods when solving path optimization and complex decision-making problems.This is in line with the goal of the conference, which is to make intelligent computer systems more adaptable and scalable by unifying logicsemantic descriptions.

A. Analysis of TSP Solved by Ant Colony Algorithm

In Figure 2, the x-axis represents city coordinates in the X direction, while the y-axis represents city coordinates in the Y direction. The optimal solution obtained by the ant colony algorithm for solving the TSP problem is a shortest distance of

$$1.5602 \times 10^4$$
 km.



Figure 2. The optimal path for solving the TSP problem by ant colony algorithm.

Figure 3 illustrates the convergence characteristics of the algorithm. The x-axis represents the number of iterations, and the y-axis represents the current shortest path length. The solid curve denotes the average distance convergence curve obtained by the ant colony algorithm, while the dashed curve represents the shortest distance convergence curve. As observed in Figure 3, the optimal solution stabilizes after approximately 90 iterations, indicating convergence.



Figure 3. Average distance and shortest distance convergence locus.

V. Conclusions

Swarm intelligence was developed to simulate the collective boids behavior in biological systems. Its algorithms, inspired by the self-organizing mechanisms of Nature, have demonstrated remarkable adaptability and robustness in optimization of complex intellectual investigation.

They have been already integrated into various disciplines, including physics, control systems, manufacturing, and service optimization, and can be applied in the energy supply on transport also.

In this work it was applied the Ant colony algorithm to solve the Traveling Salesman Problem as typical optimisation macro-task, reflecting client service and logistics behaviour also.

The results demonstrate that swarm intelligence and provided particularly ant colony optimization a powerful approach to combinatorial optimization problems solve by leveraging distributed decision-making and iterative learning.

Further development of swarm intelligence algorithms will focus on enhancing their convergence speed, adaptability, real-world applicability. Future research would include integrating with machine learning to improve accuracy and extend spheres of using. Additionally, realworld applications such as intelligent transportation systems, dynamic logistics planning, large-scale network optimization present promising opportunities for advancing the field. Furthemor, it may be even considered as the next step of intellectual system projection, meaning their strategical control, from analytical description, through statistic trends and set-theoretical paradigms, filling them by new causal relations as most important components of an investigation even at high speed computation.

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МОДЕЛИ МУРАВЬИНОЙ КОЛОНИИ РОЕВОГО ИНТЕЛЛЕКТА ДЛЯ УПРАВЛЕНИЯ ПОТОКАМИ В СЛОЖНЫХ СИСТЕМАХ

Хе Джи Пенг, А.А. Безродный

Рассматривается применение моделей муравьиной колонии роевого интеллекта для построения структур сложных интеллектульных систем как стратегического управления ими. В некотором смысле поведение муравьев аналогично потокам взаимодействия в сетях снабжения и системах обеспечения энергией на транспорте как рассматриваемой предметной области.

Предложены улучшенные способы решений динамических задач с неопределенностью. Путем сравнения различных оптимизационных алгоритмов подтверждается вычислительная эффективность и сходимость алгоритмов. В связи с инвариантностью применяемых компонент возможно распространение результатов и на иные предметные области.

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Geometric Interpretation of Semantic Relationships: Filtering and Signature Formation for Neural Network Interoperability

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Abstract—This paper proposes a method for filtering vector representations and forming universal signatures based on the geometric interpretation of semantic space as points on a hypersphere. The algorithm combines differential-geometric characteristics with statistical metrics to create a unified representation ensuring compatibility between various neural networks. The method reduces data dimensionality by selecting the most informative connections and forming compact signatures that are invariant to architectural features of models. Experiments confirm a reduction in computational complexity while simultaneously improving analysis quality. This approach potentially establishes a foundation for a universal knowledge exchange interface between heterogeneous neural network systems.

Keywords—Semantic technologies, geometric feature space, data signatures, neural networks, unified data representation, radius of curvature, angular deficit, filtering and interneural network exchange.

I. Introduction

In modern neural networks, significant advances are observed in the fields of computer vision [1], natural language processing [2], and complex time series analysis [3]. Progress in these areas has substantially improved the quality of solutions for many practical artificial intelligence tasks. However, the fundamental problem of semantic compatibility and efficient knowledge exchange between heterogeneous architectures remains unresolved, creating a significant barrier to the further development of multimodal intelligent systems and collaborative artificial intelligence, where heterogeneous neural network models must function within a unified semantic space, ensuring coherent interaction.

The main difficulties in this field arise from the absence of mathematically sound and computationally efficient methods for optimal knowledge transfer between different neural network architectures. Currently existing methods of transfer learning [4] and knowledge distillation [5] require significant computational resources, structural compatibility of source models, and long training times, substantially limiting their practical applica-

tion in a number of important scenarios. Moreover, these approaches are often unable to preserve conceptual and semantic integrity of representations when working with complex structured data, which is critically important for modern artificial intelligence applications.

As Hinton et al. (2015) note, "knowledge distillation provides a mechanism for information transfer between models, however, it remains problematic when substantial architectural differences exist" [5]. This limitation becomes especially significant in the context of modern trends in deep neural network development, where there is considerable diversification of architectural solutions optimized for specific data types and tasks. Bronstein et al. (2017) emphasize that "non-Euclidean geometry provides an effective mathematical apparatus for processing complex-structured data" [7], which opens new perspectives for developing unified methods of knowledge representation in heterogeneous neural network systems.

This paper proposes an innovative method for forming unified signatures, based on the geometric interpretation of feature space as a multidimensional hypersphere. Such a geometric concept potentially allows overcoming limitations of existing approaches and likely can provide stable knowledge translation between different neural network architectures. The approach considered in this paper allows:

- reduce data dimensionality by selecting the most informative features;
- create compact signatures that can be used as normalized data representations;
- enable knowledge transfer between neural networks with different architectures.

The research objectives include attempting to develop a mathematically rigorous approach to feature selection, describing a possible algorithm for data signature formation, and verifying the method's effectiveness on synthetic data. Research object: methods for processing multidimensional data to create a unified representation.

Research subject: geometric approach to feature filtering and data signature formation to enable knowledge transfer between neural networks.

Research method: mathematical modeling and geometric analysis of the feature space, as well as experimental verification of the developed method on synthetic data.

The proposed approach aims to solve the problem of data unification for various neural network architectures, which will increase the efficiency of their joint use in multimodal systems.

II. Analysis of Existing Approaches to Organizing Interfaces for Inter-Neural Network Information

Exchange

A. Problem of Knowledge Transfer Between Neural Networks

Modern machine learning methods allow for effective training of neural networks on specialized tasks. However, when there is a need to transfer knowledge between neural networks, for example, between models with different architectures or tasks, significant obstacles arise. In particular, the lack of unified interfaces for representing data and knowledge complicates the implementation of collaborative learning or multimodal systems.

B. Main Approaches to Information Exchange Between Neural Networks

Transfer learning allows the use of a pre-trained model to accelerate the training of a new model on a similar task [4]. This is achieved by "transferring" weights or network layers to a new task. Examples include using pre-trained models such as ResNet [6] or BERT [2] for fine-tuning on specific tasks. Limitations:

- architectural similarity between models is required;
- it is impossible to use data with completely different structures;
- difficult to adapt to multimodal data (e.g., video, text, and numerical data).

Knowledge distillation allows transferring knowledge from a larger (teacher) model to a smaller (student) model, using the outputs of the teacher model as additional information when training the student model [5]. Limitations:

- dependence on the architectural features of the teacher model;
- complexity of training, especially in the case of significantly different architectures;
- high computational complexity for large models.

Training Multimodal Models Multimodal models, such as CLIP [8] or T5 [10], combine information from various sources (e. g., text and images) to solve tasks. These models are created using complex pretraining on enormous datasets. Limitations:

- enormous computational resources for training;
- lack of universality when adding new data types;
- inability to transfer knowledge between individual components of the model.

Geometric approaches Geometric methods, such as data representation on manifolds or in hyperbolic spaces [7], allow for considering complex dependencies between features. For example, graph neural networks (GNNs) use graph structures to transmit information. Limitations:

- high implementation complexity;
- limited applicability for tasks with time series or tabular data;
- necessity of prior knowledge of data structure.

Common Limitations of Existing Approaches

- architectural dependence: most methods require similar architectures for information transfer, making them unsuitable for heterogeneous systems;
- high computational complexity: methods such as knowledge distillation or transfer learning require significant resources for training;
- lack of normalized data representation: existing approaches do not offer a universal method for data representation suitable for transfer between neural networks;
- complexity of processing multimodal data: multimodal models are limited to predefined data types, making their extension difficult.

C. Potential Solution to Limitations Through the Proposed Method

Universality of data representation: potential data signatures can be compact, normalized vectors that can be transmitted to any neural network regardless of its architecture. This eliminates the dependency on architectural similarity.

Effective dimensionality reduction: using radii of curvature and angular deficits can allow selection of only the most important features, reducing data dimensionality and computational complexity.

Adaptability to data structure: the method can potentially automatically adapt to the data structure through analysis of the geometric properties of features. This allows for accounting for complex non-linear dependencies.

Noise resistance: noisy features can potentially be automatically excluded during filtering based on geometric criteria, increasing the quality of data representation. It should be noted that this research did not consider cases where noise contains useful information. This would require additional signature analysis prior to parameter filtering.

Multimodality: data signatures can potentially be formed for various data types (e. g., numerical, time series, images) and combined into a unified representation. Thus, spherical filtering and data signature formation can potentially provide a unified interface for knowledge transfer between neural networks, making it suitable for building collaborative and multimodal systems.

III. Mathematical Formalization of the Proposed Method

A. Mapping Characteristics into a Multi-level Hyperspherical Structure

The vector space of characteristics $X \in \mathbb{R}^{m \times n}$, where m represents the number of instances and n is the dimension of the characteristic vector, undergoes transformation to form a multilevel hyperspherical structure. Within the simplified model considered in this section, we focus on the basic mapping to a unit hypersphere S^{n-1} , which is accomplished through centering followed by normalization (1):

$$\tilde{x}_i = \frac{x_i - \mu}{|x_i - \mu|}, \quad \mu = \frac{1}{m} \sum_{i=1}^m x_i,$$
(1)

where μ denotes the centroid of the characteristic distribution.

The fundamental advantage of this approach lies in the ability to organize different contextual feature sets into separate unit spheres, which collectively form a multidimensional hyperspherical structure. This allows modeling complex semantic relationships, where features from different modalities or architectures can exist in their own spherical subspaces while maintaining consistency within the overall hyperspherical topology. Such an organization provides a natural mechanism for encapsulating context-dependent semantic spaces, simultaneously creating prerequisites for constructing a metaspace in which coherent interaction of heterogeneous neural network representations becomes possible.

In the simplified model described by Equation (1), we consider projection onto a unit hypersphere as a basic case that demonstrates the key properties of the proposed method; however, the complete concept envisions a more complex structure of nested and interconnected spherical spaces.

B. Correlation Matrix

To analyze the relationships between features, an adjusted correlation matrix C is calculated, representing the cosine similarity between normalized features (2):

$$C_{ij} = \frac{\langle \tilde{x}_i, \tilde{x}_j \rangle}{|\tilde{x}_i||\tilde{x}_j|}, \quad \forall i, j \in [1, n],$$
(2)

where $\langle \cdot, \cdot \rangle$ is the dot product. Cosine similarity allows to evaluate the degree of dependence between features, considering their direction in space. Values close to 1 indicate a strong correlation, while values close to 0 indicate independence.

It is important to note that in the context of normalized features on a hypersphere, cosine similarity has a natural geometric interpretation as a measure of the angle between vectors. Since all vectors \tilde{x}_i have unit length, the expression simplifies to the dot product of normalized vectors. For vectors located on the same hypersphere, this measure reflects their geodesic proximity and is more informative than traditional correlation measures in Euclidean space, especially when identifying non-linear dependencies in high-dimensional data.

The matrix C provides a complete topological map of relationships in the feature space, which is particularly important when integrating heterogeneous neural network architectures, where semantic consistency must be maintained not only at the level of individual characteristics but also at the level of their mutual relationships.

C. Radius of Curvature

The radius of curvature r_j determines the degree of independence of the feature j from other features (3):

$$r_j = 1 - \frac{1}{k} \sum_{i \in k \text{-neighbors}} |C_{ij}|, \tag{3}$$

where k is the number of closest neighbors, determined by the correlations $|C_{ij}|$. The larger the radius of curvature, the less dependent the feature is on others. This indicator is used to select features that contribute unique information to the model. Features with a low r_j can be considered redundant, as they have a strong correlation with other characteristics.

The concept of radius of curvature has a deep connection with the differential geometry of manifolds. In this context, it characterizes the local curvature of the information space around a specific feature. Mathematically, the value of r_j reflects the degree of "distinctiveness" of a feature in the overall data structure: high values correspond to features that form relatively isolated information clusters, while low values indicate features that are part of denser information structures.

The choice of parameter k in this context is critical and should be determined taking into account the dimensionality of the data and the expected degree of sparsity of the information space. Too small values of k can lead to noisy estimates of the radius of curvature, while too large values can level out local features of the data structure.

Applying the concept of radius of curvature allows effective solving the feature selection problem within the proposed hyperspherical representation, providing a balance between the informativeness of the model and its computational complexity. Furthermore, it creates a theoretical foundation for the subsequent development of mechanisms for combining heterogeneous neural network models through selective matching of their most informative components.

D. Angular Deficit

To evaluate the non-linearity of features, the angular deficit D_j is used, which is calculated as the deviation of the sum of angles from 2π (4):

$$D_j = 2\pi - \sum_{i=1}^k \arccos(C_{ij}), \tag{4}$$

where the angles $\arccos(C_{ij})$ are calculated for the nearest neighbors of feature *j*. The angular deficit allows for the identification of features with non-linear dependencies, since the sum of angles for linearly dependent features will be close to 2π .

The concept of angular deficit has roots in differential geometry, representing a measure of deviation of the local topology from Euclidean geometry. Positive values of D_j indicate positive curvature in the vicinity to the feature j, indicating non-linear relationships within the data structure.

The angular deficit and radius of curvature complement each other: while r_j characterizes the degree of independence of a feature, D_j evaluates the nature of this dependence. Two features may have similar r_j values but differ in D_j , indicating different types of relationships linear or non-linear.

For reliable estimation of the angular deficit, it is recommended to use a sufficiently large sample and perform data normalization. The combined use of metrics r_j and D_j enables multi-criteria feature selection, accounting for both informational uniqueness and ability to model nonlinear relationships, which is particularly valuable when integrating heterogeneous neural network architectures.

E. Feature Filtering

Feature selection is carried out the basis of the radius of curvature and angular deficit. Feature j is included in the final set if the following conditions are met:

- The radius of curvature r_j exceeds a specified threshold ϵ_r , indicating its independence.
- The angular deficit D_j has a significant positive value, indicating the feature's ability to capture nonlinear relationships in the data.

This approach allows reducing the dimensionality of the feature space while preserving the most important features that contribute unique information to the model, thus reducing data redundancy and improving model interpretability.

The feature filtering process represents a multi-criteria optimization problem, balancing feature independence and their ability to describe nonlinear relationships. High values of r_j (closer to 1) indicate that the feature j is weakly correlated with other features and carries unique information. For the angular deficit D_j , minimal values indicate linear dependencies, while higher positive values

correspond to nonlinear relationships. The selection of the optimal threshold ϵ_r depends on the specific domain and data characteristics, with adaptive thresholds sometimes preferable.

The methodology can be enhanced with a feature ranking procedure, where each feature is assigned a composite rating based on a weighted combination of r_j and D_j , allowing for more flexible control of the feature selection process.

F. Formation of Semantic Signature as a Unified Interface

For each time window X_t , a semantic signature is formed, representing a unified representation of aggregated characteristics of the selected features:

Signature
$$(X_t) = [\mu_1, \sigma_1, \text{kurt}_1, \text{skew}_1, \dots, \mu_p, \sigma_p, \text{kurt}_p, \text{skew}_p],$$
 (5)

where μ , σ , kurt, skew are the mean value, standard deviation, kurtosis, and skewness respectively, calculated for each selected feature.

The semantic signature serves as a unified interface enabling effective interaction between heterogeneous neural network architectures. This approach creates an intermediate abstraction layer allowing different types of neural networks to exchange information in a standardized format, functioning as a semantic data descriptor invariant to the internal architectural specifics of particular models.

The proposed interface addresses the problem of integrating heterogeneous neural components by forming a common semantic space for data interpretation. For example, a transformer-based model can utilize signatures from a convolutional neural network without transforming internal data representations. This is crucial in ensemble systems and multimodal architectures where subsystems specialize in different aspects of analysis.

From an ontological perspective, the semantic signature maps multidimensional feature space into a structured representation preserving key distributional characteristics of the original data. The semantic interoperability provided by this mechanism enables scalable hybrid architectures where different neural networks can be dynamically combined depending on the task context and input data characteristics.

IV. Experimental Results

To conduct experimental verification of the method, a synthetic dataset was used, containing 14 descriptive features of various types: independent basic features, linearly dependent derivatives, nonlinearly dependent derivatives, and stochastic noise components.

A. Description of the Experiment

Generation of Synthetic Data:

- 1500 samples were created using sinusoidal signals, noise, and nonlinear dependencies;
- the data includes independent features, derivative features, and noise components;
- the target variable (y) is constructed as a nonlinear combination of features with added random noise.

Feature Filtering:

- spherical filtering was performed using radii of curvature and angular deficits;
- 12 of the most informative features out of 14 were selected;
- filtering reduced the dimensionality of the space while preserving useful information.

Data Preparation:

- without using signatures: feature windows were used in their "raw" form;
- with signatures: statistical characteristics (mean, standard deviation, seasonality, and trend) were calculated for each time window.

Model Training and Evaluation:

- 6 models were used: MLP, Random Forest, Linear Regression, SVR, XGBoost, LightGBM, as well as the VotingRegressor ensemble;
- evaluation was conducted using cross-validation (TimeSeriesSplit, 5 folds);
- metric: MSE (Mean Squared Error).

Comparison of Results:

- MSE of models was compared when using "raw" data and data with signatures;
- For each model, it was determined whether the signature improved the forecasts.

Final Analysis:

- a table with results was constructed and conclusions were drawn about the impact of signatures on the performance of each model;
- it was noted that signatures are particularly useful for linear models and ensembles, but require refinement for nonlinear models.

B. Analysis of Results

Feature Selection Using Spherical Filtering:

- 12 features out of 14 were selected based on radii of curvature and angular deficits. The dimensionality of the space was reduced while preserving key information. This confirms the effectiveness of the selection method based on geometric characteristics of the feature space;
- The dimensionality of the hypersphere after feature selection: S^{13} , which corresponds to 14 features in the original space

Results Without Using Signatures:

- Linear Regression showed the worst MSE value (2409.5115), which is expected since it performs poorly with nonlinear relationships;
- SVR showed the best MSE value (12.0612), which is related to its ability to process nonlinear relationships;
- Ensemble methods (Random Forest, XGBoost, LightGBM, VotingRegressor) demonstrated MSE in the range of 15-79, which also shows their robustness.

Results Without Using Signatures:

- Significant improvement is observed for Linear Regression: MSE decreased from 2409.5115 to 117.0779 (95.1% reduction). This suggests that signatures help linear models better account for complex dependencies;
- Ensemble models (Random Forest, XGBoost, Light-GBM) also showed a decrease in MSE, confirming the value of signatures for models working with nonlinear data;
- For MLP and SVR, MSE increased, which may be related to signatures distorting the original data that these models could optimally process.

VotingRegressor: The average MSE of VotingRegressor with signatures improved: decreasing from 78.9186 to 20.9154. This indicates that combining multiple models benefits from using signatures.

Application of the developed filtering algorithm, based on evaluating the radii of curvature of spherical polygons and calculating angular deficits, made it possible to reduce the dimensionality of the feature space by 14.3%, reducing the number of features to 12.

When exceeding the critical volume of the feature set, which allows for generating new descriptors through algebraic or functional transformations of the basic subset, a significantly more pronounced dimensionality reduction is theoretically predicted. The prediction quality results are shown in Table I.

Table I Comparison of Mean Squared Error (MSE) for Various Models:

N⁰	Results			
	Model	Without signature	With signature	
1	MLP	14.5487	14.9106	
2	RF	15.8648	14.3694	
3	LR	2409.5115	117.0779	
4	SVR	12.0612	14.9699	
4	XGB	15.0982	13.7349	
4	LGBM	16.2109	13.8642	
4	Voting	78.9186	20.9154	

^aUsing synthetic data

The use of data signatures demonstrated a significant improvement in the quality of forecasts for most models, especially for Linear Regression (LR), where the reduction in Mean Squared Error (MSE) was 95%. This confirms the high efficiency of the method for models that are sensitive to input data quality and redundant features. However, for MLP (Multi-Layer Perceptron) and SVR (Support Vector Regression) models, the use of signatures led to a slight deterioration in forecast quality. Nevertheless, this deterioration is not significant and demonstrates that the method can be applicable to these models after additional refinement and optimization.

V. Conclusion

In this work, an innovative feature filtering method based on geometric formalization and data signature creation is presented. The method provides a unified information representation for compatibility between heterogeneous neural network architectures.

The proposed mathematical apparatus, utilizing geometric characteristics of the feature space (curvature radii, angular deficits), allows for efficient selection of the most significant descriptors. The formation of complex signatures achieves compression of semantic relationships while preserving contextual integrity.

Experimental verification confirmed the approach's effectiveness: on a heterogeneous dataset, a dimensionality reduction of 14.3% was achieved without loss of informativeness. The positive effect is particularly pronounced for linear models and ensemble algorithms (MSE reduction up to 95.1%).

Prospects for further research include adapting the method for nonlinear architectures (MLP, SVR) and expanding testing on complex multi-level data, approximating real-world semantic information processing tasks.

Method Advantages

- effective feature filtering based on geometric characteristics, providing a 14.3% dimensionality reduction without loss of informational significance;
- formation of informative signatures integrating statistical, frequency, and seasonal parameters, ensuring unified representation for various architectures;
- significant improvement in modeling quality for linear (95.1% MSE reduction) and ensemble methods;
- reduced computational complexity: decreasing the feature space dimensionality facilitates model training and reduces the risk of overfitting.

Method Limitations

- insufficient effectiveness for nonlinear architectures (MLP, SVR), requiring additional method adaptation;
- validation on synthetic data, necessitating verification on real-world multimodal datasets;
- sensitivity to filtering parameters, requiring careful tuning of geometric characteristics (curvature radii and angular deficits).

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ГЕОМЕТРИЧЕСКАЯ ИНТЕРПРЕТАЦИЯ СЕМАНТИЧЕСКИХ СВЯЗЕЙ: ФИЛЬТРАЦИЯ И ФОРМИРОВАНИЕ СИГНАТУР ДЛЯ ИНТЕРОПЕРАБЕЛЬНОСТИ НЕЙРОСЕТЕЙ

Евдокимов В. Г., Навроцкий А. А.

В данной статье рассматривается метод фильтрации векторных представлений и формирования универсальных сигнатур на основе геометрической интерпретации семантического пространства как точек на гиперсфере. Алгоритм объединяет дифференциальногеометрические характеристики со статистическими метриками для создания единого представления, обеспечивающего совместимость между различными нейронными сетями. Метод уменьшает размерность данных путем выбора наиболее информативных связей и формирования компактных сигнатур, инвариантных к архитектурным особенностям моделей. Эксперимент подтверждает снижение вычислительной сложности при одновременном улучшении качества анализа. Такой подход потенциально создает основу для универсального интерфейса обмена знаниями между гетерогенными нейронными сетевыми системами.

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Towards Semantic Representation of Dataspace Technology Platform Architecture

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Abstract—This paper explores the architectural principles and semantic aspects of building data space platforms with a focus on the MobiSpaces project centered on mobility and personal data protection. The paper describes the main technological components of the IDS RAM reference architecture, including data connectors, authentication, and certification services. Solutions for implementing an access security model, such as annotation of personally identifiable information and attribute-based access control (ABAC), are presented. Special attention is paid to state-of-the-art authentication techniques, including passwordless authentication using the FIDO2 standard and the use of electronic identity documents (eIDs), which contribute to achieving a high degree of trust and interoperability within data spaces. A key contribution of the research is the use of semantic technologies (in particular, the SCn/SCg OSTIS language) to describe architecture and access control, which increases the flexibility and context awareness of systems when exchanging data. The combined application of FIDO2 and ABAC is seen as a promising direction in the development of scalable and secure digital ecosystems.

Keywords—Data spaces, Data Space Protocol (DSP), semantic representation, technical components of the dataspace architecture, FIDO2 specification, eID card, FIDO-AC framework

I. Introduction

In an increasingly data-driven world, the ability to share information across organizational and sectoral boundaries is essential for innovation, efficiency, and social progress. However, traditional models of data sharing often compromise privacy, control, and interoperability. Data spaces have emerged as a novel approach to address these concerns by creating decentralized, interoperable environments for secure, and sovereign data exchange.

At their core, data spaces are ecosystems where multiple stakeholders -such as businesses, governments, and research institutions – can share data under commonly agreed upon rules and standards. Unlike centralized data platforms, data spaces emphasize data sovereignty, meaning that data owners retain full control over how their data aree accessed and used. This is achieved through mechanisms such as usage policies, access control, and trust frameworks, often supported by technologies such as decentralized identity management and secure data connectors.

One of the key drivers behind the development of data spaces is the growing recognition of data as a strategic asset. Data Spaces seek to empower sectors like healthcare, manufacturing, energy, and mobility by fostering cross-domain collaboration without sacrificing data governance.

Implementing data spaces, however, presents several challenges. Technical issues such as standardizing data models and ensuring interoperability between different IT systems must be addressed. Legal and ethical considerations, including compliance with data protection regulations like the General Data Protection Regulation (GDPR), are equally critical. Moreover, building trust among participants requires robust governance frameworks, clear contractual agreements, and transparent accountability mechanisms.

Despite these challenges, the potential benefits of data spaces are substantial. By enabling secure, scalable, and equitable data sharing, data spaces can drive innovation, reduce inefficiencies, and support the development of data-driven services and products. They also represent a step forward in achieving digital sovereignty, especially in contexts where data localization and regulatory compliance are paramount.

II. Semantic representation of concepts and components of data spaces

The SCn code (Semantic Code natural) and SCg code (Semantic Code graphical) of OSTIS technology [1] will be used to semantically represent dataspace concepts, standards, protocols and components. The materials published in [2] are used here.

Data Spaces

:= [An ecosystem of data models, datasets, ontologies, data exchange contracts and specialized management services provided by data centers, repositories, repositories, etc., and related soft competencies (governance, social interactions, business processes)]

- := [Federation of decentralized data ecosystems through the use of interoperable software components for data connectivity without the need for central governance]
- := [A large-scale heterogeneous collection of data distributed across multiple sources in multiple formats, with a mechanism for handling structured, semi-structured, and unstructured data]

Data Space Protocol (DSP)

:= [Designed for the seamless exchange of data by clearly defining procedures and rules for publishing, negotiating, and accessing data across multiple platforms and systems. DSP is not yet an ISO standard]

Technical components of the IDS RAM dataspace reference architecture

- := [IDS RAM defines the key components, their interactions, and the principles that govern the architecture of data spaces]
- ⇒ Partitioning the class of data space technical components by functional purpose*:
 - = {• data space connectors
 - ⊃ provides connectivity between data sources, manages data source metadata and data usage conditions, and sends or receives data based on its usage conditions
 - *authentication provider*
 - ⊃ is responsible for maintaining and validating the authentication of connectors (or more specifically, the participants themselves). The connector must be authenticated prior to performing any operations in the data space
 - Clearinghouse
 - → tracks all transactions; if the data is payable, the clearing center shares the information for settlement with the involved connectors.

- Partitioning *:
 - = {• *Certification Authority (CA Certification Authority*
 - → responsible for issuing and revoking credential certificates
 - Participant Information Service (ParIS – Participant Information Service)
 - ⊃ accepts, stores, and provides descriptions of connectors, so that other connectors can query and retrieve information about participant credentials
 - Dynamic Attribute Provisioning Service (DAPS)
 - ⊃ allows additional attributes (such as temporary changes in participant trust, information about known vulnerabilities or new versions of software components in use, and certificate revocation) to be added to the connector description and verified

The connectors are logically divided into two parts, shown in Figure 1: the control plane and the data plane. The control plane deals with data management (user identification, implementation of access and usage policies), routing and processing, while the data plane is responsible for data exchange.

}



Figure 1. Connector: Control Plane and Data Plane [?].

In the context of the MobiSpaces project itself, the principles of data processing have been formulated [3], [4]:

• The platform must process only the minimum amount of personal data necessary to fulfill the specified purposes.

Authentication provider

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- The platform must have a legal basis for processing personal data.
- The platform must include mechanisms to enable data subjects to exercise their rights.
- The platform must ensure the accuracy and relevance of the personal data processed.
- The platform should exclude indefinite storage of personal data.
- The Platform shall implement measures to protect the confidentiality, integrity and availability of personal data, as well as ensure secure data processing using appropriate technical and organizational measures.
- The Platform shall keep records of personal data processing operations in order to demonstrate responsibility for the processing of personal data.

Components of the Data Spaces data access security model developed in the MobiSpeces project [3], [4]:

- Security Risk Modeler (SRM): This tool identifies security threats and risks to the system at the design level, based on the risk assessment method outlined in ISO 27005.
- Personally Identifiable Information (PII) Annotator: This component identifies data as PII or non-PII, preventing the transfer of personal data outside the system.
- Compliance Auditing Engine (CAE Compliance Auditing Engine): This component is a distributed solution that processes the security pipeline in real time and includes monitoring agents.
- Protected Query Engine (PQE): This MobiSpaces component is implemented as a privacy-preserving algorithm that aims to protect data flows and provide query capabilities. It utilizes full homomorphic cryptography (FHE) for federated data sources.
- Attribute-Based Access Control (ABAC) mechanism: ABAC is a security model that uses attributes to grant access to MobiSpaces data and infrastructure. It can handle access control policy in a distributed and decentralized system.

III. Possible approaches to securing the use of data spaces

Data spaces consisting of multiple interacting information resources, software components and agents are characterized by high complexity in the context of user identity and privilege setting requirements. Organization of an effective and secure mechanism for authentication and authorization of users is a priority.

The authentication system should be compatible with various operating systems and platforms, as well as applications and devices. Such a system should be able to easily integrate with other systems without requiring significant changes to their structure and code. This can help reduce infrastructure and maintenance costs, since different authentication components do not need to be developed and maintained for each individual system. On the other hand, the ability to use a single authentication apparatus to access different systems can improve security because it can be designed to prevent different attacks.

The authentication system is an important element of the security system, but it works in conjunction with other components.

FIDO2 specifications. One of the trends in information security is the process of transition to passwordless authentication methods, in particular, more and more attention is paid to FIDO2 specifications [5]. Its application provides resistance to phishing, intermediary and replay attacks through the use of asymmetric cryptography and the generation of a cryptographically random buffer of bytes at each request.

The main components of the FIDO2 specification are the W3C WebAuthn web authentication standard and the Client-to-Authenticator Protocol (CTAP). Other key components of FIDO2:

- Platform Dependent Authenticator. This is a software module, implemented either as a standalone application or at the operating system level, used for authentication on a single device.
- Platform-independent authenticator. This is an external physical device, not tied to a specific platform (operating system), used for authentication on multiple devices. Platform-dependent and platformindependent authenticators act as a secure object integrated into or attached to the user's endpoint device (e. g., Windows Hello as a platform-dependent authenticator) (e. g., a USB hardware token as a platform-independent authenticator).
- Client. The client is played by the operating system and web browser. The client acts as the interface between the authenticator and the relying party.
- Relyiing party. Includes a web server and a FIDO server. The verifying party provides access to the protected resource, accepts requests from the Web server or application to enroll and authenticate users.

Semantic notation (using SCn and SCg languages of OSTIS technology) to the development of applications with passwordless authentication according to the FIDO2 specification is presented in [6]. One of the important processes in passwordless authentication is the user key registration process (see fig. 2).

Attribute-Based Access Control, ABAC. The increasing demand for the ABAC model is due to its advantages.

An important advantage is the absence of restrictions on the complexity of access rules. For example, when configuring access to some resource of the system, we can require from the user only his age or position, and also take into account a large set of rules, such as,



Figure 2. Key registration flow [6].

for example, department, specialization, project, level of experience or even citizenship. And for each resource the set of rules can be different. Support for dynamic attributes such as location or access time is provided.

The combined use of FIDO2 authentication and ABAC can significantly increase the level of flexibility and scalability of a security system. It is important to realize that these are two different processes, and the underlying FIDO2 specification (specifically WebAuthn) does not provide for such integration. Consequently, configuring ABAC and FIDO2 together may require additional effort and resources specific to each system or task.

The key issues here is which custom attribute medium to use. One proposal is to use the ABAC access model in conjunction with the OAuth 2.0 authorization protocol. This is a logical solution, but it does not provide a way to verify the user data provided by the service provider.

eID card. One option is the use of electronic identification documents (eID) storing the signature of the issuing party, the issuer.

The use of eID promotes interoperability on several levels: making it an effective and convenient means of confirming identity and sharing information in a digital environment.

One form of eID is a smart card with an embedded microchip. The chip contains an electronic means of biometric identification with personal data of the biometric document holder in accordance with the requirements of the International Civil Aviation Organization (ICAO) (fig. 3).

According to ICAO standards, to access the data presented on the electronic identifier the user needs to pass basic access control. For this purpose it is necessary to specify the number of the electronic document, expiration date, date of birth of the owner. After confirming the correctness of the data, the authorization system can receive user attributes. In order for the system to receive user attributes and perform all necessary checks, the application needs to be able to interact with the NFCchip and extract data from the electronic document. All modern smartphones are equipped with an NFC-reader.

Basic access control is designed to ensure that card data can only be accessed when the card is physically accessed. Passive authentication proves that the contents of the Document Security Object and LDS are genuine and have not been altered. Active authentication provides secure information exchange and one-way chip authentication.

The ID-card of the Republic of Belarus can be used as an electronic biometric document complying with the standards set by ICAO.

Joint use of FIDO2 authentication, attribute authorization and eID card. In [8], the FIDO-AC framework is proposed, which is an extension of the basic FIDO2 specification. The essence of the obtained solution is to create an additional party - a mediator (mediator), which is responsible for validation of user data obtained, for example, from an eID-document (fig. 4).

A component released by Rock Solid Knowledge (RSK) for the ASP.NET Core 8.0 platform may be chosen as the library that allows the web application under development to act as a relying party. The FIDO2 library developed by RSK allows the web application to act as a WebAuthn validator by providing an IFidoAuthentication service containing methods for generating requests to a client that interacts with the WebAuthn API [9].

A semantic representation of the joint use of FIDO2 authentication, attribute authorization and eID card is given in [10].



Figure 3. ICAO Logical Data Structure (LDS) [7].



Figure 4. Interaction of FIDO-AC framework components.

IV. Conclusion

The advancement of data spaces as a paradigm for decentralized, secure, and sovereign data sharing presents a transformative opportunity for how data is accessed, managed, and governed across sectors. This research has explored the architectural underpinnings, semantic representations, and technical challenges involved in developing such platforms, with particular attention to initiatives like the MobiSpaces project. The integration of interoperable components such as data connectors, identity providers, and compliance engines illustrates the modular and federated nature of data space infrastructures, enabling a flexible yet robust framework for data collaboration.

A key contribution of this work lies in emphasizing the role of semantic technologies in enhancing interoperability and context-aware access control. By leveraging semantic representations—alongside advanced authentication (e. g., FIDO2) and authorization (e. g., ABAC) mechanisms—data spaces can support nuanced, policydriven access to sensitive information while preserving privacy and user control. The combined use of electronic identification (eID) and secure cryptographic protocols further reinforces trust and transparency within these ecosystems.

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К СЕМАНТИЧЕСКОМУ ПРЕДСТАВЛЕНИЮ АРХИТЕКТУРЫ ТЕХНОЛОГИЧЕСКОЙ ПЛАТФОРМЫ DATASPACE

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В данном исследовании изучаются архитектурные основы, семантические представления и технические проблемы, связанные с разработкой технологической платформы dataspace, при этом особое внимание уделяется таким инициативам, как проект MobiSpaces. Интеграция таких совместимых компонентов, как соединители данных, провайдеры идентификации и механизмы обеспечения соответствия, иллюстрирует модульную и федеративную природу инфраструктур пространства данных, позволяя создать гибкую, но надежную основу для совместной работы с данными.

Ключевой вклад данной работы заключается в подчеркивании роли семантических технологий в повышении функциональной совместимости и управлении доступом с учетом контекста. Благодаря использованию семантических представлений, а также усовершенствованных механизмов аутентификации (например, FIDO2) и авторизации (например, ABAC) пространства данных могут поддерживать тонкий, определяемый политикой доступ к важной информации, сохраняя при этом конфиденциальность и контроль пользователей. Совместное использование электронной идентификации (eID) и безопасных криптографических протоколов еще больше укрепляет доверие и прозрачность в этих экосистемах.

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Application of Semantic Analysis and GMM Models for Anomaly Detection in Network Traffic

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Abstract—Network traffic contains numerous patterns, and deviations from these patterns can indicate cyberattacks or system failures. Traditional machine learning methods, such as the Gaussian Mixture Model (GMM), are effective in detecting anomalies, but do not provide meaningful interpretations of these anomalies. This paper presents an approach that integrates semantic analysis with GMM to improve anomaly detection accuracy and provide contextual insights into abnormal behavior in network traffic. Using cybersecurity ontologies and semantic reasoning, detected anomalies can be mapped to known cyber threats, improving the reliability of detection. The proposed method is evaluated using real-world network traffic logs, demonstrating its effectiveness in reducing false positives and enhancing interpretability.

Keywords—Anomaly detection, network traffic analysis, Gaussian mixture model (GMM), semantic analysis, machine learning, cybersecurity, intrusion detection systems (IDS), unsupervised learning.

I. Introduction

The rapid increase in cyberattacks poses a serious challenge to modern network security. Anomalous network traffic can indicate a variety of threats, including denial-of-service (DoS) attacks, unauthorized intrusions, and data exfiltration. Traditional methods for anomaly detection are based on statistical models and machine learning techniques, such as clustering and classification. Among these, the Gaussian Mixture Model (GMM) has proven to be effective in identifying outliers in network data. However, GMM has a significant drawback: it can identify anomalies but lacks interpretability, meaning that detected anomalies must be manually analyzed to determine their nature and relevance.

To address this limitation, semantic technologies can be leveraged. Semantic analysis provides a structured way to interpret and classify anomalies by linking them to ontologies, formal representations of knowledge that describe concepts, relationships, and rules. In the domain of cybersecurity, ontologies such as MITRE ATT&CK, STIX, and CybOX provide structured threat intelligence that can be used to categorize and explain network anomalies.

This paper proposes a hybrid approach that combines GMM-based anomaly detection with semantic reasoning, enabling automated classification and interpretation of detected anomalies. The primary contributions of this work are as follows.

1) Integration of semantic technologies and ontologies with machine learning for anomaly detection.

2) A methodology for mapping GMM-detected anomalies to known cyber threats using semantic reasoning.

3) An experimental evaluation that demonstrates the effectiveness of this approach in improving the precision and interpretability of network anomaly detection.

II. Related Work and Background

A. Gaussian Mixture Model (GMM) in Anomaly Detection

The Gaussian Mixture Model (GMM) is a probabilistic model that clusters data into multiple distributions, allowing for soft clustering – each data point can belong to multiple clusters with a certain probability. This makes GMM effective for detecting network anomalies because it can model complex traffic distributions and detect outliers in real-time.

B. Semantic Technologies and Ontologies in Cybersecurity

Cybersecurity Ontologies: Structured Knowledge of Threats

Ontologies provide structured knowledge bases that describe attack techniques, vulnerabilities, and network behaviors. Popular cybersecurity ontologies include:

- MITRE ATT&CK A global framework categorizing cyber threats based on real-world attack techniques.
- STIX (Structured Threat Information Expression) A language for sharing structured threat intelligence.

 CybOX (Cyber Observable Expression) – A format for describing network activities and anomalies.

How Semantic Analysis Improves Anomaly Detection

By combining GMM with semantic analysis, we can:

- Classify detected anomalies by mapping them to known cyber threats.
- Reduce false positives by filtering out normal variations.
- Describe the detected anomalies, making it easier for security analysts to respond.

Example: Suppose that GMM detects multiple failed login attempts followed by an unusual data transfer.

- Without semantic analysis: It is simply labeled as "anomalous".
- With semantic analysis: It is classified as a "Brute Force Attack" using the MITRE ATT&CK framework, triggering security recommendations.

Flowchart: Anomaly Detection with GMM and Semantic Technologies

The following diagram illustrates the step-by-step process of detecting anomalies using GMM combined with semantic technologies.



Figure 1. Detecting anomalies using GMM combined with semantic technologies.

Table I Comparison of technologies for anomaly detection

Technology	Purpose	Advantages	Limitations
GMM	Detects	Flexible clus-	No inter-
	network	tering, handles	pretability,
	anomalies.	complex data.	high false
			positives.
MITRE	Classifies cy-	Knowledge	Needs
ATT&CK	ber threats.	base of real-	integration
		world attack	with detection
		methods.	systems.
STIX	Standardized	Improves	Doesn't detect
	cyber threat	collaboration	attacks on its
	information	across	own.
	sharing.	organizations.	
CybOX	Describes	Helps analyze	Requires
	network events	network	integration
	and attack	traffic.	with other
	indicators.		tools.

By integrating GMM and semantic technologies, we create a smart, context-sensitive anomaly detection system that not only finds network anomalies but explains and classifies them for an effective cybersecurity response.

III. Proposed Methodology: Integrating GMM with Semantic Analysis

A. Overview of the Hybrid Approach

The core of our approach lies in the use of the Gaussian Mixture Model (GMM). Mathematically, the GMM is represented as a weighted sum of multiple Gaussian distributions:

The proposed system combines Gaussian Mixture Models (GMM) for anomaly detection with semantic reasoning to interpret and classify these anomalies. The hybrid approach leverages the strengths of both techniques to create a robust and scalable solution to detect and understand cybersecurity threats in network traffic. The system consists of three main components:

1) Anomaly detection using GMM: GMM is applied to network traffic data to identify clusters of normal and abnormal behaviors. This probabilistic model helps identify deviations from expected network patterns by grouping data points into distinct groups. Each group represents a specific pattern of behavior, and anomalies are detected when traffic deviates significantly from the norm.

2) Semantic Interpretation of Anomalies: The raw output from GMM, which identifies anomalies in network traffic, is mapped to a more meaningful context using cybersecurity ontologies. Ontologies provide structured frameworks that categorize different types of cybersecurity threats and network behaviors. This allows the system to interpret what each anomaly represents in terms of known attack types.

3) Threat Classification and Explanation: After identifying and interpreting the anomalies, the system proceeds to categorize them into specific types of cybersecurity threats (such as DDoS, phishing, or brute-force attacks). In addition, the system automatically generates textual explanations, helping security analysts understand the nature of the threat, its potential impact, and recommended countermeasures.

Together, these components enable the system to not only detect anomalies, but also contextualize and classify them, providing deeper insights into network security.

B. Ontology-Based Threat Mapping

Once GMM detects an anomaly, the next step is to determine the nature of the anomaly. This is done using an ontology-based reasoning system, which integrates the anomaly detection results with a comprehensive cybersecurity knowledge base. The reasoning system classifies the anomaly and provides an explanation leveraging the following two key components.

1. Semantic Knowledge Base: The knowledge base consists of a comprehensive set of cybersecurity-related

rules, patterns, and attack signatures. These patterns include both high-level attack types (such as DDoS, malware propagation, and brute-force attacks) and low-level network behaviors (such as packet frequency, failed login attempts, and unusual traffic patterns). The knowledge base is structured to accommodate a wide variety of network security events, providing context and detailed relationships between different types of anomaly and attack categories.

For example, the knowledge base might include the following.

- Behavioral patterns: Normal and abnormal behavior associated with different network protocols (e.g. HTTP, FTP, DNS) and network devices (e.g. routers, switches).
- Attack signatures: Known attack patterns such as port scanning, SQL injection, or Distributed Denial of Service (DDoS).
- Contextual rules: Rules that define the relationship between different network events, such as multiple failed login attempts leading to a brute-force attack or a sudden spike in traffic indicating a potential DDoS attack.

The knowledge base is regularly updated to include the latest attack techniques and evolving network traffic patterns, ensuring the reasoning system remains effective over time.

2. Reasoning Engine: The reasoning engine is responsible for inferring the most likely type of attack based on the data provided by the GMM and the knowledge stored in the semantic knowledge base. The engine applies semantic reasoning techniques to map the anomalies detected by GMM to specific attack types. The reasoning process follows a rule-based inference mechanism, which can be implemented using logical rules or machine learning models.

The engine operates by processing the output from GMM, which includes a set of anomaly scores or data points. Then these are compared against the patterns and relationships in the knowledge base. The system uses inference rules (e.g., if X and Y occur simultaneously, the event is classified as Z) to determine the most likely attack type. The reasoning engine can also handle complex scenarios, in which multiple anomalies must be considered together to accurately classify an attack type.

For example, if the system detects an anomaly involving unusually high packet frequency along with a high number of failed authentication attempts, the reasoning engine might infer that this is a brute-force attack. Maps these two factors (high packet frequency and authentication failures) to predefined rules in the knowledge base that describe brute-force attacks.

C. Benefits of the Hybrid Approach

By combining GMM and semantic reasoning, the proposed system offers several key advantages over traditional methods. 1) Scalability: GMM is highly scalable and can handle large volumes of network traffic data, making it suitable for real-time network monitoring.

2) Accurate Threat Classification: The integration of semantic reasoning ensures that detected anomalies are accurately classified into meaningful cybersecurity threat categories. This reduces false positives and improves the reliability of the system.

3) Explainability: The system generates automated explanations of detected threats, providing security analysts with clear and actionable insights into the nature of the attack, its potential impact, and appropriate countermeasures.

4) Adaptability: The system's knowledge base can be updated with new attacks and patterns, which allows it to remain relevant in the face of evolving cyber threats.

IV. Experimental Evaluation

In this section, we evaluate the effectiveness of the proposed methodology by conducting experiments using real-world network datasets. The evaluation focuses on evaluating the performance of the anomaly detection system, its ability to classify network traffic anomalies, and its overall accuracy in identifying various types of cyber threats.

A. Dataset and Preprocessing

The proposed method is evaluated using two widely recognized datasets commonly used in network intrusion detection research. These data sets provide diverse and comprehensive examples of both traditional and modern attack scenarios, ensuring that the proposed system is tested under varied conditions.

- KDD Cup 1999: This data set is one of the most well known in the field of intrusion detection and contains network traffic data captured from a simulated military network. It includes both normal traffic and multiple types of attacks, such as DoS (Denial of Service), U2R (User to Root), R2L (Remote to Local), and probing attacks. The data set is used to assess the ability of the system to detect different types of attacks and to assess its general performance in intrusion detection.
- CICIDS2017: This data set contains modern attack scenarios, including advanced threats such as botnets, DoS attacks, and malware activities. It offers more realistic network traffic compared to KDD Cup 1999, including a mix of benign and malicious traffic from both known and unknown attack patterns. The CICIDS2017 data set is designed to test the system's adaptability to more contemporary attack vectors.

Data Preprocessing: The raw data from these datasets are preprocessed to extract key features that are relevant for the detection and classification of anomalies. The preprocessing steps include the following.

• Packet Sizes and Intervals: The size of each packet and the time intervals between packets are important features in detecting anomalies. For example, in a DDoS attack, there might be a sudden surge in packet sizes or a high frequency of packet transmissions in a short period.

- Source and Destination IP Addresses: The source and destination IP addresses help to identify the origin and target of the network traffic. Suspicious behavior, such as traffic from a single IP address targeting multiple destinations, may indicate a botnet or other malicious activity.
- Protocol Types and Connection Attempts: The types of protocols (e.g., HTTP, FTP, ICMP) and the number of connection attempts are key indicators of malicious activity. Abnormal patterns, such as multiple failed connection attempts using a particular protocol, may point to a bruteforce attack or scanning attempts.

By extracting these features, the data become suitable for analysis by the GMM-based anomaly detection system, enabling the identification of deviations from normal behavior in the network traffic.

B. Performance Metrics

The effectiveness of the proposed anomaly detection method is evaluated using several standard performance metrics, which provide insight into the system's ability to detect anomalies and classify threats accurately. These metrics include:

1) Accuracy: Accuracy is one of the most straightforward metrics used to evaluate the overall performance of the detection system. It is calculated as the ratio of correctly identified anomalies (both true positives and true negatives) to the total number of instances. High accuracy indicates that the system is good at distinguishing between normal and anomalous traffic.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$
(1)

where:

- TP: True Positives (correctly identified anomalies)
- TN: True Negatives (correctly identified normal traffic)
- FP: False Positives (normal traffic incorrectly identified as anomalous)
- FN: False Negatives (anomalous traffic missed by the system)

2) Precision: Precision measures the accuracy of positive predictions made by the system. In the context of anomaly detection, precision represents the proportion of correctly detected anomalies out of all instances that were classified as anomalous by the system. A high precision value indicates that the system produces few false positives.

$$Precision = \frac{TP}{TP + FP}$$
(2)

Precision is particularly important in situations where false positives are costly, such as in a security system where falsely flagging normal traffic as anomalous may disrupt business operations or waste resources. *3) Recall:* Recall (also known as Sensitivity or True Positive Rate) measures the ability of the system to detect all actual anomalies. It is the proportion of true anomalies that were correctly identified by the system. A high recall value indicates that the system is good at identifying most of the malicious activity present in the network.

$$Recall = \frac{TP}{TP + FN} \tag{3}$$

4) False Positive Rate (FPR): The False Positive Rate measures the proportion of normal traffic that is incorrectly classified as anomalous. It is calculated as the number of false positives divided by the total number of actual normal instances. A low FPR is crucial for ensuring that the system does not generate too many false alarms, which can lead to alert fatigue among security analysts.

$$FPR = \frac{FP}{FP + TN} \tag{4}$$

A high FPR can reduce the effectiveness of the system, as analysts may ignore or overlook legitimate alerts if too many false positives are raised.

5) F1 score: The F1 score is the harmonic mean of precision and recall. It provides a balanced measure of the system's performance when both false positives and false negatives are important to consider. The F1 score is particularly useful when there is an imbalance between the number of normal and anomalous traffic instances.

$$F1 = 2 \times \left(\frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}\right)$$
(5)

Using these metrics, we can comprehensively evaluate the performance of the proposed anomaly detection system, ensuring that it strikes an optimal balance between identifying threats and minimizing false alarms. Furthermore, performance can be compared between different datasets and compared against existing anomaly detection methods to demonstrate the advantages of the proposed approach.

C. Results and Analysis

The experimental evaluation reveals several key insights into the performance of the proposed hybrid system, which combines Gaussian mixture models (GMM) with semantic analysis for network anomaly detection and threat classification. The results were analyzed in comparison to using GMM alone, as well as against existing baseline methods.

1) Performance of GMM Alone: When applied independently, GMM achieves high anomaly detection rates, demonstrating its effectiveness in detecting deviations from normal network behavior. The model is able to identify various outliers in traffic data and can effectively group normal and anomalous behavior into separate groups. However, while GMM excels at detecting anomalies, it suffers from a high false positive rate (FPR). This means that benign traffic, which exhibits slight deviations due to network variability, is often misclassified as anomalous. As a result, security analysts may be overwhelmed by a large number of false alarms, making it difficult to prioritize real threats.

Despite this drawback, the strength of GMM lies in its unsupervised nature, which allows it to work with diverse and large datasets without requiring labeled training data. This makes it particularly useful in real-world scenarios where labeled data may be scarce or hard to obtain.

2) Improvement with Semantic Analysis: When combined with semantic analysis and the use of a cybersecurity ontology, the system shows a substantial improvement in both the accuracy and reliability of anomaly detection:

- Improved Classification Accuracy: Using the semantic analysis component, the system can map detected anomalies to known cyber threat categories, such as DDoS, brute-force attacks, and malware. This contextualization improves the system's ability to classify anomalies accurately. For example, a high number of failed login attempts combined with abnormal packet patterns can now be confidently classified as a brute-force attack based on the reasoning engine's inference from the ontology. This mapping process significantly improves the overall classification accuracy, as the system now classifies detected anomalies with a clear understanding of their underlying cybersecurity implications.
- Reduced False Positives: One of the primary advantages of integrating semantic reasoning is the reduction in false positives. The semantic engine helps filter out benign anomalies that may have been incorrectly flagged by GMM. For instance, certain traffic spikes or slight variations in packet sizes that are normal in specific network contexts can be recognized as nonthreatening based on the semantic rules in the ontology. This selective filtering minimizes the risk that benign traffic is misclassified as an attack, allowing security teams to focus on genuine threats. Consequently, the false positive rate (FPR) is significantly reduced, leading to a more efficient and manageable workflow for cybersecurity professionals.
- Automated Threat Explanations: Another key benefit of integrating semantic analysis is the automatic generation of threat explanations. When an anomaly is detected and classified, the system provides detailed information on the nature of the detected threat. These explanations include the type of attack, the key features or behaviors that led to the classification, and potential mitigation strategies. For example, in the case of a DDoS attack, the explanation might describe the abnormal traffic patterns observed, such as the volume of incoming requests and the specific targets affected. This transparency helps cybersecurity analysts make more informed decisions, reducing the time required to understand the nature of the attack and respond effectively.

3) Comparative Performance: To further validate the effectiveness of the proposed hybrid approach, a comparative analysis was performed against other existing methods in the field of anomaly detection.

- Accuracy: The hybrid system showed a significant improvement in accuracy over GMM alone, demonstrating a better balance between true positive detections and minimizing false positives. When tested on both the KDD Cup 1999 and CICIDS2017 datasets, the hybrid system outperformed traditional methods, particularly in detecting complex attack patterns that GMM alone struggled to identify.
- Precision and Recall: Precision and recall were also improved in the hybrid model. The integration of semantic reasoning allowed the system to be more selective in flagging anomalies, leading to higher precision in attack classification. At the same time, the system recall rate remained high, ensuring that most attacks were still detected. This balance is critical in ensuring that the system does not sacrifice the detection rate for fewer false alarms, a common issue in many anomaly detection systems.
- False Positive Rate (FPR): As mentioned, the false positive rate saw a significant decrease when semantic analysis was applied. This is crucial for operational efficiency, as high FPR can lead to alert fatigue, where security teams become desensitized to the large number of false alarms. By reducing FPR, the system ensures that security personnel can focus their efforts on investigating real threats.

4) *Performance of GMM Alone:* The results of the experimental evaluation suggest that the proposed hybrid approach offers a highly practical solution for real-time network traffic monitoring and cyber threat detection.

- Enhanced Threat Detection: By combining the statistical clustering of GMM with the semantic understanding provided by the ontology, the system can detect and classify a wide range of cyber threats more accurately and reliably than GMM alone.
- Operational Efficiency: The reduction in false positives and the ability to provide automated and understandable explanations of detected threats help improve the overall operational efficiency of cybersecurity teams. Analysts can make quicker decisions, reduce response times, and allocate resources more effectively to mitigate real threats.
- Adaptability: The system's reliance on an evolving semantic knowledge base means that it can be continuously updated with new attack patterns and emerging threats, making it adaptable to the changing landscape of cyber attacks.

5) *Future Work:* Although the current results are promising, further improvements can be made to increase the robustness and efficiency of the system.

- Expansion of the Knowledge Base: The knowledge base can be expanded to include additional attack patterns, protocols, and more fine-grained network behaviors. This would improve the system's ability to detect new and evolving threats.
- Real-Time Deployment: Future work will focus on optimizing the system for real-time deployment in live networks, ensuring that it can scale to handle large volumes of traffic without compromising detection performance.
- Integration with Other Security Tools: The system could also be integrated with other security solutions, such as firewalls and intrusion prevention systems (IPS), to provide a more comprehensive security infrastructure.

D. System Diagram

A high-level overview of the proposed hybrid system architecture can be visualized in the form of a system diagram. This diagram will help illustrate the components involved in the anomaly detection pipeline, showing how the Gaussian Mixture Model (GMM) interacts with the semantic analysis component to improve detection accuracy and reduce false positives.

The system consists of the following key components:

1) Data Collection: Raw network traffic data data collected and preprocessed. This data includes packet sizes, IP addresses, protocol types, and connection attempts.

2) Anomaly Detection (GMM): The Gaussian Mixture Model (GMM) is used to model network traffic and identify potential anomalies based on statistical deviations.

3) Semantic Analysis: Once anomalies are detected, the system uses an ontology-based semantic reasoning engine to interpret and classify the anomalies. This engine links the detected anomalies to known cybersecurity threats.

4) Threat Classification: The system classifies the anomalies into specific cyber threats such as DoS, DDoS, brute-force attacks, and more.

5) Explanations and Decision Support: The system generates automated explanations for detected threats, providing security analysts with context and reasoning behind each classification.



Figure 2. System diagram which shows the flow of data from one component to another.

E. Explanation of the System Diagram

- Data Collection: This block represents the initial step where raw network traffic is gathered and preprocessed. Preprocessing includes feature extraction such as packet sizes, IP addresses, protocols, and connection attempts. The preprocessed data are then passed to the next stage for anomaly detection.
- Anomaly Detection (GMM): GMM models normal traffic behavior and flags deviations as anomalies. These are passed to semantic analysis.
- Semantic analysis: Using a cybersecurity ontology, the system interprets anomalies by matching them to known attack patterns (e.g., DoS, brute force, botnets).
- Threat Classification: The mapped anomalies are categorized (DDoS, malware, etc.) to assess the type and potential impact.

• Explanations and Decision Support: The system generates human-readable explanations to help analysts understand and respond to threats effectively.

V. Conclusion

This paper presents a novel hybrid approach for network anomaly detection and threat classification that combines Gaussian Mixture Model (GMM)-based anomaly detection with semantic reasoning. The integration of these two techniques significantly improves the effectiveness of cybersecurity analysis by addressing some of the key limitations of traditional machine learning approaches.

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ПРИМЕНЕНИЕ СЕМАНТИЧЕСКОГО АНАЛИЗА И МОДЕЛЕЙ GMM ДЛЯ ОБНАРУЖЕНИЯ АНОМАЛИЙ В СЕТЕВОМ ТРАФИКЕ

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Сетевой трафик содержит многочисленные шаблоны, и отклонения от этих шаблонов могут указывать на кибератаки или сбои системы. Традиционные методы машинного обучения, такие как модель гауссовской смеси (GMM), эффективны для обнаружения аномалий, но не дают содержательной интерпретации этих аномалий. В этой статье представлен подход, который объединяет семантический анализ с GMM для повышения точности обнаружения аномалий и предоставления контекстуальных сведений об аномальном поведении в сетевом трафике. Используя онтологии кибербезопасности и семантическое обоснование, обнаруженные аномалии можно сопоставить с известными киберугрозами, что повышает надежность обнаружения. Предлагаемый метод оценивается с использованием журналов реального сетевого трафика. демонстрируя его эффективность в снижении ложных срабатываний и улучшении интерпретируемости.

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Introducing the STEM Approach to Teaching Mathematics with AI: Practical Application and Effectiveness

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Abstract—STEM education integrates science, technology, engineering, and mathematics into a unified learning model that emphasizes real-world applications, critical thinking, and problem solving. The rise of artificial intelligence (AI) introduces new possibilities for enhancing STEM-based mathematics education by enabling personalized learning, automating assessments, providing intelligent tutoring, and incorporating semantic technologies. This paper presents a novel AI-driven adaptive learning model that customizes STEM-based mathematics instruction based on individual student progress. The proposed model combines deep learning, reinforcement learning, and semantic technologies to dynamically adjust content difficulty, optimize instructional strategies, and provide interpretable realtime feedback. Experimental results from an AI-enhanced mathematics course demonstrate significant improvements in student engagement, problem solving efficiency, and semantic alignment of content.

Keywords—STEM education, mathematics education, artificial intelligence (AI) in education, semantic technologies, personalized learning, AI-enhanced learning, adaptive learning systems, intelligent tutoring systems, mathematical concept mastery, interactive learning systems, ontologies, semantic feedback, educational ontologies

I. Introduction

STEM education aims to equip students with essential analytical and technological skills by integrating multiple disciplines. Mathematics plays a fundamental role in STEM, yet traditional teaching methods often fail to engage students effectively or adapt to diverse learning needs. Incorporation of artificial intelligence (AI) in education has shown promise in automating instruction, improving engagement, and improving the learning experience. In addition, the integration of semantic technologies, such as ontologies, knowledge graphs, and semantic annotation, offers new opportunities to improve AI-based mathematics education by enabling more interpretable and personalized learning pathways. However, current AI applications remain limited in their ability to dynamically adapt to student learning patterns.

This paper proposes a new AI-based adaptive learning framework for teaching mathematics in a STEM environment. By integrating deep learning, reinforcement learning techniques, and semantic modeling, our approach personalizes instructional content in real time, optimizes difficulty levels, and provides automated, semantically informed feedback to improve learning outcomes.

II. The STEM Approach to Mathematics Education

STEM education integrates science, technology, engineering, and mathematics to develop critical thinking, problem solving, and analytical skills. Mathematics serves as the foundation for STEM disciplines, enabling students to model real-world phenomena, design engineering solutions, and analyze scientific data. However, traditional approaches to STEM-based mathematics education often struggle to accommodate diverse student learning needs.

A. Traditional STEM-Based Mathematics Instruction

STEM education incorporates various pedagogical strategies to enhance mathematical learning:

- 1) Project-Based Learning (PBL):
 - Encourages students to apply mathematical principles to engineering design, physics experiments, and computational simulations.
 - Develops problem solving skills by integrating real-world applications (e. g., designing a bridge using geometry or modeling planetary motion with calculus).
- 2) Inquiry-Based Learning:
 - Promote exploratory thinking, where students investigate mathematical concepts through self-guided inquiry.
 - Enhances conceptual understanding by focusing on the why and how behind mathematical formulas rather than rote memorization.
- 3) Simulation and Modeling:
 - Uses computational tools, visualization software, and mathematical models to explore complex concepts.
 - Example: Differential equations in physics are solved numerically using Python-based simulation tools such as Matplotlib, SymPy, or SciPy.

Despite these advantages, traditional STEM mathematics instruction has limitations:

- Lack of Personalization: One-size-fits-all instruction fails to adapt to the individual learning pace of students.
- Limited Engagement: Static textbooks and repetitive exercises may distract students.
- Assessment Challenges: Teachers struggle to provide instant feedback and adaptation in real time to students' strengths and weaknesses.

B. AI as a Solution to STEM Mathematics Challenges

AI introduces intelligent and adaptive learning systems that dynamically respond to student needs:

- Personalized learning pathways: AI-driven platforms analyze student performance and adjust instruction accordingly.
- Automated Feedback and Assessment: AI-powered tutors provide instant solution tips and corrections.
- Interactive and gamified learning: AI enhances engagement through adaptive challenges, interactive simulations, and real-time assessments.

III. AI in STEM Mathematics Education: A Novel Adaptive Learning Model

A. Limitations of Existing AI-Based Approaches

Current AI applications in mathematics education primarily include the following:

- AI-powered tutoring systems (e. g., MATHia, Socratic).
- Automated problem-solving platforms (e. g., Wolfram Alpha, Photomath).
- Gamified learning tools (e. g., Prodigy Math Game, DragonBox).

Although these systems improve accessibility and engagement, they lack real-time adaptability and predictive learning mechanisms. Existing AI tools often provide static recommendations, failing to fully adapt instruction based on individual learning behaviors over time.

B. Proposed AI-Driven Adaptive Learning Framework

To address these limitations, we introduce an adaptive AI learning model that continuously optimizes mathematics instruction through a combination of:

- Deep Learning-Based Student Profiling Neural networks analyze historical student performance data to predict learning trajectories.
- Reinforcement Learning-Based Content Adaptation – AI dynamically adjusts the difficulty of the problem and the instructional strategies based on the feedback of the students.
- Real-Time AI-Powered Feedback System An intelligent agent evaluates student responses and provides step-by-step guidance tailored to individual learning patterns.
- Semantic Modeling of Content The system uses ontologies to define the hierarchies and dependencies of concepts, enabling better content alignment and more precise adaptation.

C. Algorithm Design and Implementation

To develop an AI-driven adaptive learning system for STEM-based mathematics education, we employ a Deep Reinforcement Learning (DRL) approach. This system continuously learns from student interactions and dynamically adjusts the content to optimize learning outcomes. The algorithm consists of four core components:

Step 1: Observing Student Interactions

The AI agent collects real-time data on student interactions, including:

- **Response time** for solving mathematical problems.
- Accuracy of answers at different difficulty levels.
- Number of hints requested before reaching a solution.
- **Patterns in errors**, such as common misconceptions in algebra or calculus.

Mathematical Representation:

Let S_t represent the student's current knowledge state at time t. The system records an interaction tuple:

$$(S_t, A_t, R_t, S_{t+1}) \tag{1}$$

where:

• S_t = Student's current skill level.

- A_t = Student's action (e.g. solving a problem, requesting hints).
- R_t = Reward (e.g., correct solution = +1, incorrect = -1).
- S_{t+1} = Updated knowledge state after learning.

Step 2: Predicting Student Understanding Levels

A deep neural network (DNN) analyzes historical data to estimate the probability that a student has mastered a concept. The network takes input features such as:

- Number of correctly solved problems on a given topic.
- Time spent solving problems.
- Student engagement metrics.

The result is a confidence score P(c), representing the probability that the student has mastered the concept c:

$$P(c) = \sigma(WX + b) \tag{2}$$

where:

- X = Feature vector (student performance data).
- *W*, *b* = Trainable parameters.
- σ = Activation function (softmax for multiclass mastery prediction).

If P(c) falls below a predefined threshold θ , the system assigns additional practice problems on that topic.

Step 3: Dynamic Difficulty Adjustment through Reinforcement Learning

Using Reinforcement Learning (RL), the system dynamically adjusts the difficulty of the problem. The AI agent selects a difficulty level D_t for the next problem using a Q-learning approach, where:

$$Q(S_t, D_t) = Q(S_t, D_t) + \alpha \left[R_t + \gamma \max_D Q(S_{t+1}, D) - Q(S_t, D_t) \right]$$
(3)

where:

- $Q(S_t, D_t)$ = Expected reward for assigning difficulty D_t at state S_t .
- α = Learning rate (controls how fast the system adapts).
- γ = Activation function (softmax for multiclass mastery prediction).
- $\max Q(S_t, D_t) =$ Maximum expected reward for future difficulty levels.

Difficulty Selection Strategy (ϵ -Greedy Exploration)

- With probability *ε*, the AI explores new difficulty levels (random selection).
- With probability $1-\epsilon$, the AI exploits past knowledge (chooses the difficulty level with the highest value Q).
- The AI adapts in real time, progressively fine-tuning the difficulty of the problem for each student.

Step 4: Providing real-time tips and explanations

The AI generates personalized hints and explanations based on the knowledge gaps detected.

- If a student requests a hint, the AI analyzes where errors occur and provides step-by-step guidance.
- If a student makes repeated errors, the system switches to an alternative explanation (e. g., using visualizations or interactive simulations).

Hint Generation via natural language processing (NLP) Hint generation

A Transformer-based AI model (e. g., GPT or BERT) generates dynamic hints based on student errors.

Example:

- Student mistake: Misapplying the quadratic formula.
- AI-generated hint: "Recall that the quadratic formula applies to equations of the form $ax^2 + bx + c = 0$. Check your coefficients!"

The AI model continuously learns from past student interactions, refining hints for maximum effectiveness.

The system iterates through these four steps, continuously learning and improving.

- Short-term adaptation: Adjusting difficulty and hints in real-time.
- Long-term optimization: The AI updates its deep learning models using new student data.

IV. Experimental Evaluation

A. Study Design

To assess the impact of our AI-driven adaptive learning framework in STEM mathematics education, we conducted a controlled experiment in a university-level mathematics course.

1. Participants and Grouping

The study involved 120 undergraduate students enrolled in a first-year calculus course. Participants were randomly assigned to two groups:

a) Experimental Group (AI-Enhanced Learning, 60 students):

- We used our AI-powered adaptive learning system, which dynamically adjusted content based on individual learning progress.
- Received real-time AI-generated hints and feedback during problem solving.
- Participated in interactive AI-driven assessments that modified difficulty levels based on student performance.

b) Control Group (Traditional STEM-Based Learning, 60 students):

- Followed standard classroom instruction with digital resources (e.g. PowerPoint, online exercises, and simulation software).
- Received fixed problem sets and manual teacher feedback without AI-based adaptation.
- No real-time difficulty adjustment or personalized instruction.

2. Learning Modules and Duration

The experiment was carried out over a 12-week academic semester, covering key mathematical concepts relevant to STEM disciplines.

- Weeks 1-4: Functions, Limits, and Differentiation.
- Weeks 5-8: Integration Techniques and Applications.
- Weeks 9-12: Differential Equations and Mathematical Modeling.

Each group attended four 90-minute sessions per week and both groups received identical sets of problems, exams, and project-based assessments.

3. Evaluation metrics

To measure the effectiveness of our AI-driven framework, we analyzed the following performance indicators: c) Problem-Solving Accuracy (%):: Measured students' ability to solve mathematical problems correctly.

d) Conceptual Understanding (Score 0-100):: Assessed through conceptual quizzes and explanatory questions.

e) Time Efficiency (Minutes per Problem):: Recorded the average time taken per problem-solving task.

f) Student Engagement (Survey-Based, 1-5 Scale):: Evaluated based on student responses regarding motivation and ease of learning.

g) Retention Rate (% Improvement in Post-Test vs Pre-Test Scores):: Measured knowledge retention using pre-tests (before AI implementation) and post-tests (after 12 weeks).

B. Results and Analysis

Results and Analysis

To evaluate the effectiveness of AI-enhanced STEM mathematics education, we analyzed three key performance metrics.

- Efficacy in problem solving (%): Percentage of correctly solved problems.
- Time to Master a Concept (minutes): Average time required to solve problems related to a specific mathematical concept.
- Engagement Metrics: Time spent on learning activities and frequency of AI interactions.

Metric	Control Group	AI- Enhanced Group	Impro- vement
Problem Solving Accuracy	72%	89%	+17%
Time to Master a Concept	35 minutes	21 minutes	-40%
Engagement (Time on Platform)	50 min/day	78 min/day	+56%

Table I

The results indicate that:

- 1) AI-Enhanced learning improved problem solving accuracy by 17%, demonstrating a better conceptual understanding.
- Learning efficiency increased significantly, with students requiring 40% less time to grasp mathematical concepts.
- Higher levels of engagement were observed, as AIdriven interactivity led to 56% more time spent on learning activities.

The AI-enhanced group achieved higher accuracy, required less time to master concepts, and demonstrated significantly higher engagement compared to the control group.



Figure 1. Simulation will simulate the impact of AI-enhanced teaching on student performance.



Figure 2. Simulation will simulate the impact of AI-enhanced teaching on student performance.

C. Semantic Technologies in AI-Enhanced

STEM Mathematics To enhance personalization and explainability in AI-driven adaptive learning, we propose the integration of semantic technologies into our system. These include ontologies, knowledge graphs, and semantic annotation mechanisms that enable machines to reason about structured educational content.

Educational Ontologies



Figure 3. Simulation will simulate the impact of AI-enhanced teaching on student performance.

We use domain-specific ontologies to model mathematical concepts, learning objectives, and their interdependencies. These ontologies define semantic relationships such as is-a, part of, requires, and analogous to facilitating structured reasoning. For example, the system can identify that mastering "quadratic equations" requires prior knowledge of "factoring polynomials". These relationships are encoded using OWL and stored in a semantic triple store.

Knowledge Graphs for Learner Profiling

The learner knowledge states are represented using knowledge graphs, where the nodes denote concepts, and the edges encode mastery relationships. This semantic layer enables more accurate content recommendation, explanation of adaptive logic, and identification of learning gaps.

Semantic Feedback Generation via NLP

The AI system uses semantic parsing to interpret student input and generate feedback. For example, if a student writes an incorrect expression, the system parses it and matches it to known misconceptions defined in a structured semantic database.

Semantic Interoperability

Using semantic metadata (e.g. Learning Object Metadata – LOM), educational resources are tagged to support discoverability, alignment with curriculum standards, and reuse across platforms.

V. Discussion

The study confirms that AI-driven adaptive systems significantly improve STEM mathematics education. Students using AI tools showed improved accuracy, faster learning, and greater engagement, highlighting the potential of AI as a powerful educational asset.

Key Advantages of AI in STEM Mathematics Education

Our findings highlight several benefits of AI-driven learning systems:

- **Personalized Learning Paths** AI adjusts difficulty and feedback in real time, tailoring the learning experience to the needs of each student and improving comprehension and retention.
- Efficient Knowledge Acquisition Adaptive strategies speed up concept mastery and focus attention on weaker areas through targeted support.
- Higher Student Engagement Interactive tasks and gamified elements motivate learners. Students using AI tools spent 56% more time actively participating.
- Semantic Explainability Ontologies and knowledge graphs clarify AI recommendations, making learning paths and feedback more transparent and easier to interpret for both students and teachers.

Challenges and Limitations

Despite its advantages, integrating AI into STEM education presents several challenges:

- High Computational Demands Running advanced AI platforms requires powerful hardware and infrastructure, posing challenges for institutions with limited resources.
- **Teacher Training Needs** Educators must learn to interpret AI outputs and integrate them into teaching. Lack of training may slow adoption.
- **Bias in AI Models** If not carefully developed, AI systems may reflect dataset biases, risking unequal learning experiences and assessment outcomes.

Although AI has a strong potential to improve STEM mathematics instruction, success depends on overcoming challenges in infrastructure, training, and fairness challenges to ensure inclusive and scalable implementation.

A. Future Directions

To address these challenges, future research should focus on:

Developing Efficient AI Models

- Exploring lightweight AI architectures that require less computational power while maintaining high adaptability.
- Using edge computing to reduce the dependency on cloud-based AI models.

Improving AI Transparency

- Enhance explainability in AI-driven feedback to ensure that teachers and students understand how recommendations are made.
- Incorporating human oversight mechanisms to prevent biased learning paths.

Integrating AI with Hybrid Learning Models

- Combining AI-driven adaptive learning with teacher-led instruction to maximize educational effectiveness.
- Implement AI-based tutoring assistants that support, rather than replace, educators.

Although AI-based adaptive learning presents substantial advantages for STEM mathematics education, it is essential to address computational constraints, teacher readiness, and fairness in AI models. Future advancements should focus on efficient, transparent, and accessible AI solutions to ensure widespread adoption and equitable learning opportunities.

VI. Conclusion and Future Work

This study presented an AI-driven adaptive learning model aimed at improving mathematics instruction within STEM education. The experimental results revealed strong improvements in key areas: students using the AI-enhanced system demonstrated 17% higher problem solving accuracy, learned concepts 40% faster, and engaged 56% more actively in learning tasks. These results underscore the transformative potential of AI in reshaping the way mathematics is taught and learned. The core advantage of the proposed model lies in its ability to personalize learning. By analyzing student progress in real time, the system adjusted content difficulty, provided targeted feedback, and supported individualized learning trajectories. This adaptive approach improved concept retention and fosterred a deeper understanding of mathematical principles.

Furthermore, the integration of semantic technologies, such as ontologies and knowledge graphs, strengthened the transparency of AI decision making. Rather than providing opaque recommendations, the system made its instructional logic clear to both learners and educators. This interpretability increased trust and supported more effective pedagogical decisions based on data.

Looking ahead, this research opens new avenues for development. Future work should explore deeper personalization, incorporating not only student performance, but also factors such as motivation, cognitive styles, and prior knowledge. Emerging technologies such as augmented reality (AR) could further enrich AI learning environments by enabling interactive 3D representations of complex mathematical concepts and real-world simulations.

A key priority for ongoing research is the semantic expansion of educational ontologies. Creating standardized, domain-specific knowledge structures will improve content alignment, foster interoperability among platforms, and support intelligent guidance in diverse learning contexts.

Ensuring equitable access to AI-enhanced education is also essential. Scalable and resource-efficient systems should be designed to operate in low-bandwidth environments and be accessible in underfunded educational settings. This will help bridge digital divides and provide all students with equal learning opportunities. Importantly, AI should be seen as a complement – not a replacement – for teachers. Educators play an irreplaceable role in fostering critical thinking, encouraging inquiry, and offering social-emotional support. AI can assist by providing real-time data insights, automating routine feedback, and allowing more focused and informed instruction.

In conclusion, this study demonstrates that AI has the capacity to revolutionize mathematics education in STEM by delivering personalized, interactive, and datainformed learning experiences. Through thoughtful design and inclusive implementation, AI can help close achievement gaps, enhance student engagement, and support more effective learner-centered education models.

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ВНЕДРЕНИЕ STEM-ПОДХОДА В ОБУЧЕНИЕ МАТЕМАТИКЕ С ИСПОЛЬЗОВАНИЕМ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА: ПРАКТИЧЕСКОЕ ПРИМЕНЕНИЕ И ЭФФЕКТИВНОСТЬ

Ораздурдыева Г. О., Оразова О. Г., Бекиева М. Б., Яздурдыева М. А., Ягмырова М. М.

STEM-образование интегрирует науку, технологии, инженерное дело и математику в единую модель обучения, ориентированную на применение знаний в реальных ситуациях, развитие критического мышления и навыков решения проблем. Появление искусственного интеллекта (ИИ) открывает новые возможности для повышения эффективности STEM-обучения математике за счёт персонализированного подхода, автоматизированной оценки знаний, интеллектуального наставничества и использования семантических технологий. В данной работе представлен инновационный адаптивный обучающий ИИ-модуль, настраивающий математическое обучение в рамках STEM в зависимости от индивидуального прогресса учащихся. Предложенная модель объединяет глубокое обучение, обучение с подкреплением и семантические технологии для динамической настройки уровня сложности контента, оптимизации стратегий преподавания и предоставления интерпретируемой обратной связи в режиме реального времени. Экспериментальные результаты, полученные в рамках курса математики с применением ИИ, демонстрируют значительное повышение вовлечённости студентов, эффективности решения задач и семантической согласованности учебного контента.

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