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, neuro-symbolic 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.

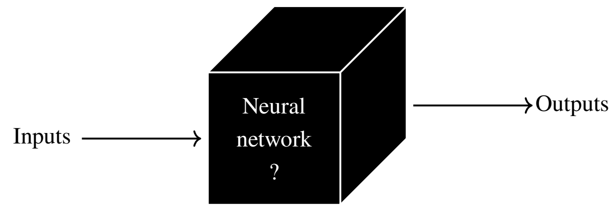

Figure 1. Neural Network as a Black Box

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

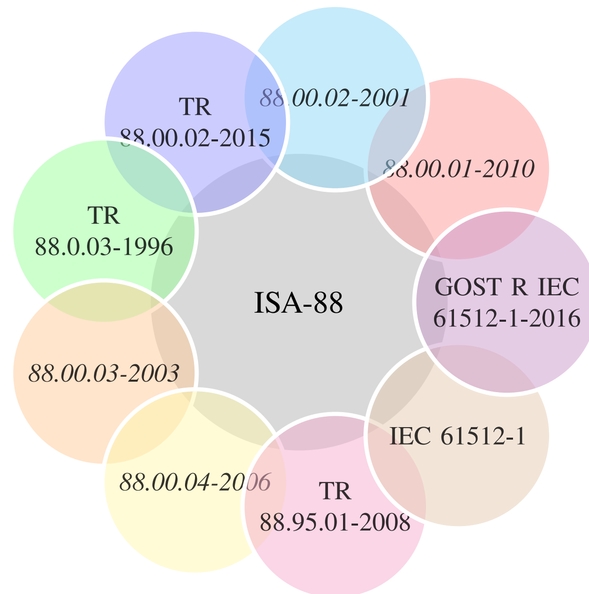

Figure 2. ISA-88 parts

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

Figure 3. ISA-95 parts

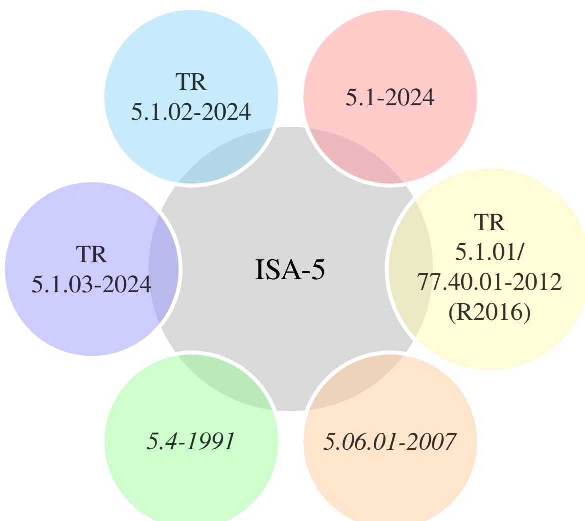

Figure 4. ISA-5 parts

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).

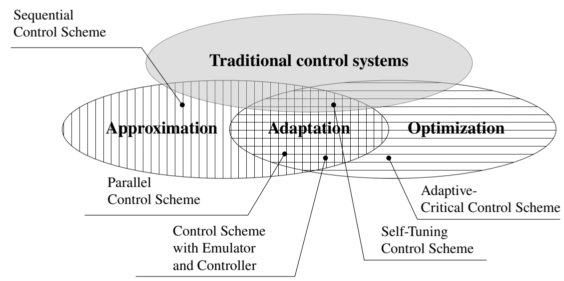

Figure 5. Classification of Neural Network Methods for Solving Control Problems

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.

$$\begin{aligned} u_k &= u_{k-1} + \Delta u_k, \\ \Delta u_k &= q_0 e_k + q_1 e_{k-1} + q_2 e_{k-2}, \\ q_0 &= \mathbf{K}\left(1 + \frac{T_D}{T_0}\right), \\ q_1 &= -\mathbf{K}\left(1 + 2\frac{T_D}{T_0} - \frac{T_0}{T_I}\right), \\ q_2 &= \mathbf{K}\frac{T_D}{T_0}. \end{aligned} \tag{1}$$

Algorithm for operation of **neuro-PID adjuster** [18]:

$$\begin{aligned} y_j &= F(\sum_i \omega_{ij} y_i - T_j), \\ \gamma_j &= y_j - t_j, \\ \gamma_i &= \sum_i \gamma_i F'(S_i)\omega_{ji}, \\ \omega_{ij}(t+1) &= \omega_{ij}(t) - \alpha\gamma_j F'(S_j) y_i, \\ T_j(t+1) &= T_j(t) + \alpha\gamma_j F'(S_j), \\ E &= \frac{1}{2}\sum_{k=1}^{L}\sum_j ({y_j}^k - {t_j}^k)^2. \end{aligned} \tag{2}$$

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 — $E_{n-p}, ...E_{n-2}, E_{n-1}, E_n$, 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:

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http://industry.ostis.net?sys_id=unit
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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 high-level 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

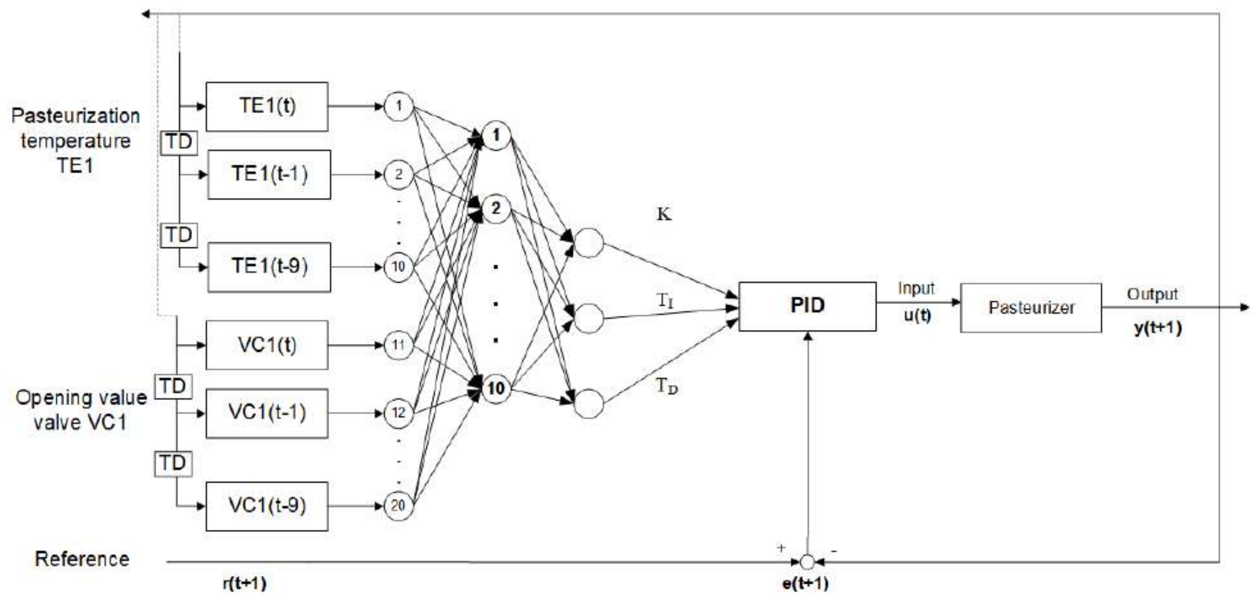

Figure 6. The developed Neuro-PID controller (TD means delay operator)

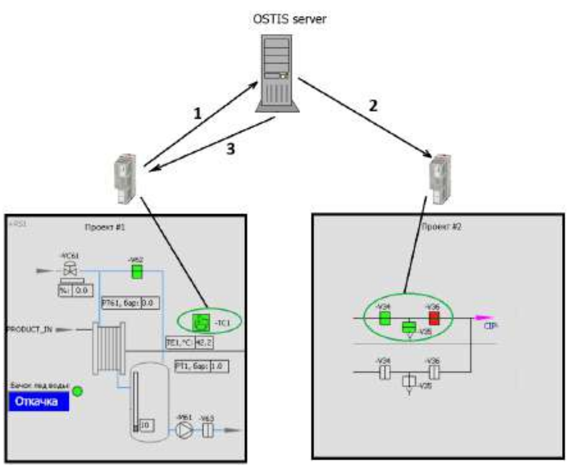

Figure 7. OSTIS in control systems

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

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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