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, pre-thermally 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 decision-making 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 multi-criteria 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 megΩ;
- "Norm 2" – 500 kΩ to 1 megΩ;
- "Norm 3" – 100 kΩ to 500 kΩ;
- "Norm 4" – 50 kΩ to 100 kΩ;
- "Norm 5" – 5 kΩ to 50 kΩ;
- "Wetting" – $<$ 5 kΩ.

Resistance of the signal conductor: "Open" – $>$ 200 Ωs [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.

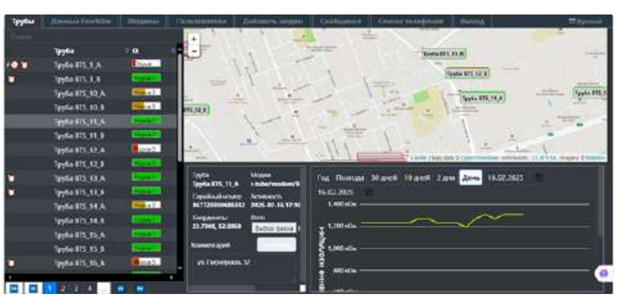

Figure 1. User interface

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 end-users, 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.

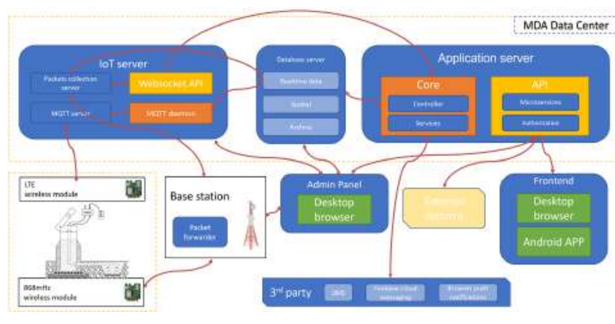

Figure 2. Architecture of the intelligent monitoring system

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

Коневцев Д. А.

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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