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Original Article

Risk-Oriented Geoportal Systems and the Internet of Things as a Tool for Managing Metageosystems

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Abstract - *The article describes the research in developing problem-oriented geoportal systems based on the concept of the Internet of Things and allowing them to solve the problems of managing metageosystems. The characteristic of the implementation process of SDI and geoportals for managing metageosystems based on the processes of identification, analysis and monitoring of risks is presented. It is shown that the risk management process can be integrated into the tasks of iterative design, development, implementation and use of SDI. The results of assessing the strength of risk events allow us to approach the solution of the problem of forming a set of controlled risks for the management of metageosystems and become the starting point in solving the problem of designing functional and qualitative requirements. The solution to the problem of effective iterative functional and qualitative enhancement of SDI is possible based on observing the SOLID principles, which determine the expediency of implementing the basic principles of object-oriented programming and design. The article proposes the architecture of a metageosystems management system based on the technology of the Internet of Things and geoportal systems, based on using the LoRaWAN long-range wireless communication standard. The basis of the Internet of Things network is represented by IoT devices consolidated around the head devices (gateways). It was developed based on a modular principle to achieve high rates of modifiability and extensibility. It is proved that in the case of using geoinformation web systems in conjunction with the Internet of Things technology, geoportals begin to play the role of dispatching centers along with their classic function of interactive visualization of spatial data.*

Keywords - *Geoportal, Internet of Things, Metageosystems, Natural-social-production systems, Spatial data infrastructure.*

1. Introduction

Currently, in solving the problem of managing Natural-Social-Production Systems (NSPS), a trend towards process automation has emerged [1]. Demanded nature is both a request to implement functions for remote monitoring of various processes and remote control [2]. Based on the definition of NSPS as a spatially distributed set of landscape, social and economic elements that function as a single whole due to the presence of relationships between them, it can be argued that geoinformation technologies play a leading role in the formation of tools for managing organizational systems distributed over a large area [3].

In this context, it is also relevant to use the term "metageosystems" as a combination of natural and man-made systems of various hierarchical levels interconnected with their spatial environment. In this context, it is important to note that in various countries of the world, the expediency of implementing measures aimed at solving the problems of limited use of modern geoinformation technologies, high-performance processing of spatial data, and artificial intelligence to increase the efficiency of digitalization of this area has been determined.

The solution to the problem of visualization and dissemination of spatial data about metageosystems can be achieved through the introduction and effective use of geoportal systems developed based on web technologies and providing access to the Spatial Data Infrastructure (SDI) of organizations and regions through interactive digital maps [4]. Within the framework of graphical geoportal interfaces, the tasks of layer-by-layer thematic visualization of heterogeneous (raster, vector, attributive) information and search and extraction of metadata are solved. Geoportals can be available both in the internal network of organizations and within the Internet, and access to distributed spatial information may require authorization and delegation of rights.

With the important role of accumulating spatially associated information about NSPS in multi-model SDI repositories, it is important to emphasize the special importance of data collected in real-time and are up-to-date. In this context, the concept of the Internet of Things (Internet of Things, IoT) is of interest, which involves the development of networks of connected physical devices that exchange data with each other and are capable of performing a set of targeted actions [5]. When solving the problem of managing the NSPS, the components of the Internet of Things can successfully solve both the tasks of collecting data from distributed sensors (on ambient temperature, soil moisture, illumination, and so on) and performing the functions of remote launch and activation of devices (including plant watering complexes, security and alarm systems). Thus, the concept of the Internet of Things strengthens the role of geoportal systems in solving the problem of managing NSPS, making them not only an access point to arrays of large spatial data but also a dispatching tool that allows the implementation of the function of centralized operational automated monitoring and control of NSPS.

The purpose of this article is to characterize the research results in developing risk-oriented geoportal systems based on the concept of the Internet of Things and allowing them to solve the problems of managing metageosystems.

2. Related Works, Materials and Methods

2.1. Risk-Oriented SDI and Geoportals as a Tool for Managing Metageosystems

SDI is a tool for managing data on natural-social-production systems. Improving the efficiency of the processes of design, development, implementation and use of SDI should be based on solving the problem of systematizing spatial data. The structure of studies of hierarchically organized natural-social-production systems (metageosystems) is based on the principles of (1) territoriality, consistency and environmental friendliness.

The problem of its theoretical and practical support should also be attributed to the category of key elements of the process of managing territorial systems. Management as a whole is supported by personnel, financial, material, scientific, methodological and legal support, relevant parts of the management process. The variety of enduring values of mankind can be reduced to three positions. Natural-social-production systems can be defined as systems for ensuring the population's security, stability and quality of life. On a global scale, states and unions of states become systems of this class as security systems organized for peoples' survival within certain geographical territories.

An important stage in the development of the SDI is the development of a set of measures to address priority regional environmental problems. Analysis and assessment of the development of geoecological situations is the basis for identifying regional priority problems of nature management and environmental protection. SDI should be focused on improving the efficiency of a set of measures aimed at eliminating problem situations characterized by dangerous and especially dangerous levels of pollutant concentrations and anthropogenic man-made loads on the natural environment; development of recommendations for achieving the normative level of environmental quality for a number of individual pollution factors; drawing up a work plan to prevent the negative dynamics of changes in the state of the environment and stabilize the current environmental situation.

As a basic information basis for developing a set of measures to address priority regional environmental problems, environmentally oriented planning tools are used, provided for by feasibility studies of enterprises, master plans for cities and regions, regional planning schemes and other available planning documents for the development of regions. The developed set of measures should be subdivided according to the sequence of their implementation, with the allocation of long-term, medium-term and short-term measures to solve the priority environmental problems of the region, indicating the mechanism for their implementation and financing.

SDI as a risk management system: Digital infrastructures of spatial data is an effective tool for solving the problem of integrating, cataloging, distributing and visualizing geospatial information in order to support management decision-making in the field of optimizing the functioning of metageosystems in the direction of developing the digital economy. Based on the above definition of natural-social-production systems as systems for ensuring the safety, stability and quality of life of the population, it is possible to conclude that the task of management in organizational systems whose activities are built around the management of spatially distributed resources and objects through SDI should be based on solving the problem of planning, identification, analysis, monitoring and risk management [6].

Risk analysis methods in organizational and complex technical systems are defined by national and international standards. The key function of the standards is aimed at supporting activities to form and protect "organizational values through risk management, decision making, setting and achieving goals, and improving performance" [7].

The efficiency of managing organizational systems based on risk analysis can be improved through the following activities:

- Systemic identification of risks, including the formation of a register of risks, a qualitative and quantitative assessment of potential threats and opportunities;
- Determination of strategies in the field of risk management of various types based on the formation of a register of countermeasures that perform the function of

reducing the likelihood of risks and the degree of their impact, achieving preferable conditions for the functioning of organizational systems;

- Identification of cause-and-effect relationships in the processes of occurrence of risk events in order to enhance understanding of the purpose, structure, functional and qualitative features of management tools in organizational systems.

Information systems based on the use of spatial data are in demand in organizational systems whose activities are related to the use and management of spatially distributed resources in regional and municipal governments, emergency services, manufacturing enterprises and holdings, and logistics companies. For these organizations, the task of monitoring and managing risks has its own characteristics. The designed and implemented spatial data infrastructures should be information systems that are a tool for identifying, analyzing and monitoring risks that arise in organizational systems whose activities aim to manage natural-social-production systems (Figure 1).

Justification of the key processes of design, development, implementation and practical use of spatial data infrastructures should be based on solving the problem of identifying and analyzing risks arising from the use of geographically distributed natural-social-production systems. In this case, the technologies being introduced are able to show economic efficiency and become a tool to reduce the impact of negative natural, man-made and humanitarian processes.

Reducing the impact and minimizing the consequences of dangerous risks is possible when implementing both the process of monitoring the state of natural-social-production systems as a control object and the implementation of remote control functions, including those based on Internet of Things technologies.

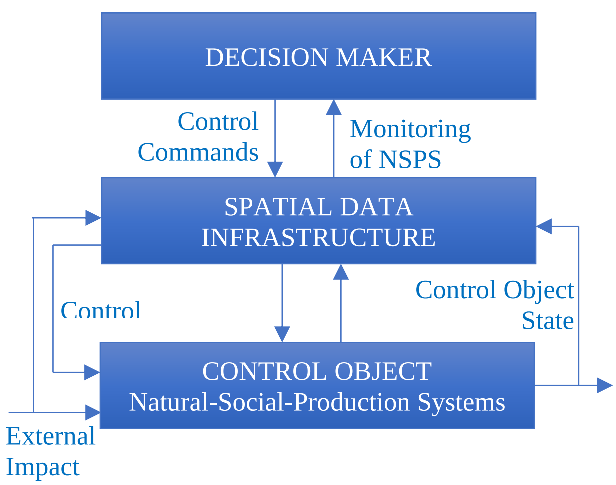

Fig. 1 Natural-social-production system as an object of control

The risk management process can be integrated into the process of iterative implementation and use of the SDI as an input step for the SDI requirements analysis stage. In turn, the developed or improved versions of the spatial data infrastructure become a tool for monitoring and managing risks in organizational systems whose activities are associated with the use of spatially distributed resources.

The risk management planning stage is a process based on solving the problems of preparing initial data for risk analysis and management, analyzing the structure and properties of the natural social production system as a management object.

In the course of risk assessment, they are identified (the stage, including the selection of the main threats that are important within the project, analysis of the cause-and-effect relationships of their occurrence, and classification), quantitative and qualitative analysis (the stage based on the assessment of the probability of occurrence of risks, the negative and positive impact of the consequences of risk events, the degree and direction of connectivity), hazard assessment and design of countermeasures (the stage, which involves ranking risks by importance, planning methods and resources for the implementation of countermeasures aimed at reducing dangerous and priority risks management of natural-social-production systems).

The final artefacts of the stage of assessing the risks of managing natural-social-production systems become the basis for planning the methodological and resource base for implementing countermeasures to minimize the consequences and reduce the likelihood of threats, increasing the positive effect and the frequency of positive opportunities that arise. The results of the stage also become the starting point for the distribution and fixation of the responsibility of specialists involved in the management of organizational activities in the field of operation of natural-social-production systems.

The solution to the problem of identification, analysis and monitoring of risks should be considered in the context of assessing the impact of negative and positive risk events on the effectiveness criteria of SDI in the field of managing natural-social-production systems, taking into account the presence of dependencies between the occurrence of risks. The degree of causal relationship between the occurrence of risk events can be defined as the Bayesian probability of the occurrence of one risk as a consequence of another at a certain stage in the functioning of natural social production systems.

The system of cause-and-effect relationships for the occurrence of risk events can be structured in the form of a tree (Figure 2). At the identification stage, risk events can be segmented into stages, which can either be tied to time or determined based on hierarchical models, from general to particular.

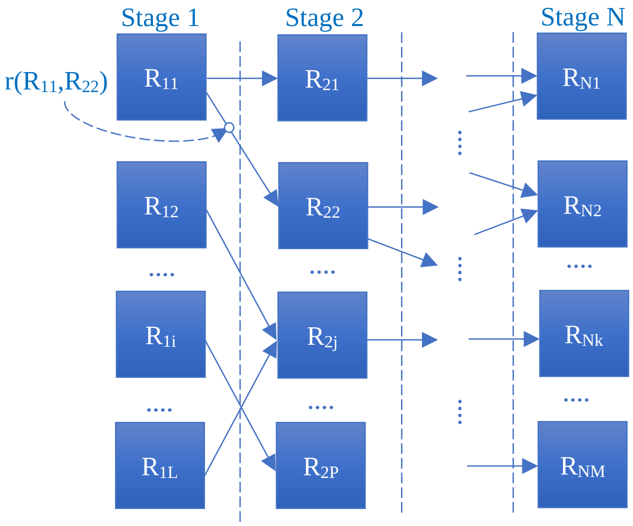

Fig. 2 Tree of cause-and-effect relationships between risks

The presented figure's objects with a dashed line indicate the terminal elements. These risk events directly affect the performance indicators of the management of natural-social-production systems. They are not the cause of significant risks at the next hierarchy level.

The solid line outlines the nodes of the tree of cause-and-effect relationships that have descendants and represent risk events that can both directly affect the performance criteria and cause new risks. Each tree edge connecting two vertices of the cause-and-effect tree is characterized by the weight $r(R_i, R_j)$, the probability of occurrence of one risk as a consequence of another.

By managing risk R_i, minimizing the negative consequences of its occurrence in natural-social-production systems, one can avoid or reduce the likelihood of risk R_j.

At the same time, an effective solution to the problem of root risk management minimizes the potential negative impact of all system risks. Let us define the strength P_{R_i} of the i-th risk in the form of a formula:

$$P_{R_i} = M_{R_i} + \sum_{j=1}^{n} r(R_i, R_j) \cdot P_{R_j}$$

Where M_{R_i} is a measure of the impact of the *i*-th risk on the criteria for the effectiveness of the management of natural-social-production systems,

$r(R_i, R_j)$ is the estimate of the probability of occurrence of the *j*-th risk as a consequence of the *i*-th risk,

P_{R_j} is the strength of the *j*-th risk, which is a consequence of the *i*-th risk.

Given the assessment of the strength of terminal risks that do not have descendants, the above formula will be reduced to the equality of the risk strength and the measure of its direct influence. The strength of risk events, displayed as root elements of the causal tree, can be calculated recursively, starting from the leaves.

The results of assessing the strength of risk events allow us to approach the solution to the problem of forming a quasi-optimal set of controlled risks in the management of natural-social-production systems. To solve this problem, the territorial systems management efficiency characteristics model can be represented as a tree, the root node of which determines a certain generalized efficiency criterion that determines the main goal of implementing SDI.

The second level of the hierarchy of control efficiency indicators determines the variant of the system grouping of parameters dictated by the characteristics of the problem being solved. As a basic approach, it is proposed to segment the indicators in the direction of the functioning of territorial security systems: protection from threats of humanitarian, natural (natural), and man-made nature. Elements of the third and subsequent levels define a structured system of indicators of the effectiveness of the management of natural-social-production systems.

It is advisable to start building a quasi-optimal set of controllable management risks by determining the degree of influence of child performance indicators on a generalized parent criterion, followed by ranking the elements and highlighting a significant set. The next step is forming a system of expert assessments of the degree and nature of the impact of the consequences of the occurrence of potential risks on the performance indicators of the management process of natural-social-production systems.

Finally, it is necessary to take into account the limitations: the resource intensity and complexity of the processes for designing, developing, implementing and supporting the SDI (or its new version) as a risk management tool (minimizing negative consequences and increasing the efficiency of using opportunities). If assessing potential costs for introducing new tools for managing spatial data and systems is less than the cost of managing risks without implementing a new solution, initiating a new stage in implementing geoinformation technologies becomes economically justified.

Another important feature of the approach to managing natural-social-production systems focused on risk analysis and monitoring is the need to focus on the flexible organization of the process of developing information systems (agile software development) [8], aimed at minimizing risks by reducing the chain of processes for designing, developing and implementing SDI to a series of short cycles (iterations), the artifact of each of which becomes, albeit limited in terms of functionality and quality, but nevertheless, a complete software and hardware solution focused on solving applied problems in the field of minimizing risks associated with the management of natural-social-production systems. With each new iteration, the possibility of developing the functional capabilities of SDI, strengthening its qualitative characteristics (reliability, fault tolerance, ergonomics), and, most importantly, more accurate and timely monitoring and control of natural-social-production systems is realized. Following the process of iterative, flexible development allows, in contrast to the application of the waterfall life cycle model, to reduce the risks of a sharp increase in the resource intensity of introducing new (including potentially unnecessary) technologies for managing natural-social-production systems.

An analysis of the experience of developing information systems proves the expediency of focusing on the principles of object-oriented analysis, design and programming [9] as a set of engineering approaches to the development of hardware and software systems formed on the basis of a system of interacting objects that encapsulate data and methods in themselves and interact based on interfaces.

The solution to the problem of effective iterative functional and qualitative enhancement of SDI is possible based on the observance of the SOLID principles [10], which determine the feasibility of implementing the 5 basic principles of object-oriented programming and design:

- Single responsibility principle, within the framework of which a single purpose should be defined for each system component of the SDI, and the resources necessary for its functioning should be subordinated only to this task;
- Openness/closeness (open-closed principle), under the condition of implementation of which the SDI becomes built in such a way that its key components become open for expansion, and at the same time, the need for serious modification of existing systems is minimized;
- Barbara Liskov substitution principle, which defines the SDI organization scheme, within which subsystems using certain basic modules should be able to derive components without significant and resource-intensive modifications;
- Separation of the interface (interface segregation principle), in which, in the event of a change in the interfaces of a component, subsystems that do not use this component should not change; 5) dependency inversion principle, the implementation of which implies such a construction of the SDI framework, within which the subsystems of the upper levels should not depend on the lower ones, while the interfaces should determine the linkage of the modules, and not by the specific implementation of the components.

Compliance with the indicated principles when solving the problem of developing project-oriented SDI leads to the following effects: strengthening the connectivity of the system modules as a measure of their goal-setting for solving a single specific problem and weakening their mutual engagement and interdependence. SDI built on the basis of strongly coupled and, at the same time, weakly coupled components acquire the properties of modifiability, good maintainability, and fault tolerance.

The results of the risk assessment stage become the starting point in solving the problem of designing functional and qualitative requirements for spatial data infrastructure as a tool for managing natural-social-production systems. In the event that the ultimate goal of design work on the design, development, implementation and maintenance of SDI is to minimize threats and maximize positive risks (opportunities) associated with the management of geographically distributed resources, there is a reasonable opportunity to reduce the time, resource, technical and qualitative risks of the process of technical implementation of the spatial data management system.

The designed, developed and deployed SDI, in turn, becomes a tool for monitoring and managing the risks of organizational activities built around interaction with geographically distributed natural-social-production systems. The solution to the problem of optimizing the processes of consolidation and use of spatial data for the management of natural social production systems should be guided by the criteria: achieving the target effects of SDI, resource intensity and complexity (organizational, operational, algorithmic, competency-based, temporal) of support processes (construction, modification, practical use) in solving the problems of managing natural social production systems. From the point of view of the upper level of abstraction, SDI can be decomposed into analysis subsystems, spatial data storage centers and visualization components based on the use of geoportal systems.

The achievability of target effects (reducing the impact of negative risks and increasing the efficiency of using favorable opportunities), reducing the resource intensity and time complexity of modifying the SDI allows justifying the feasibility of introducing the SDI to solve the problems of managing natural-social-production systems. The key role in this context is played by the tasks of increasing the efficiency of monitoring the state of geographically distributed systems, strengthening the quality, accuracy and speed of the process of managing intermediary agents for interaction with remote objects and resources, and the speed of response to natural and natural-technogenic emergencies.

2.1. Internet of Things as a Technology for Increasing the Efficiency of SDI

The Internet of Things can be used in any sector of the national economy associated with managing space-distributed

NSPS and requiring automation: agriculture and forestry, industry, municipal government, and energy. The designated technology is one of the fastest-growing technologies in the world, forming the basis for close interaction between humans and technological devices [11, 12]. The Internet of Things forms ecosystems of various scales, ranging from human dwellings (smart homes) to smart cities and industries. It is important to remember that at the same time, the Internet of Things encounters problems of a different nature related to security, standardization, technical and legal aspects.

Standardization of the Internet of Things allows devices from different manufacturers to interact without compatibility problems and improves security and data protection. There are many communication standards for deploying Internet of Things networks that ensure compatibility and synchronization between devices: RFID, Bluetooth, LoRaWAN, ZigBee, Wi-Fi (IEEE 802.11), cellular networks of various generations (2G, 3G, LTE, 5G), etc.

It is important to understand that bandwidth and transmission distance are far from the only parameters that affect the choice of technology. Thus, cellular networks in areas with good coverage provide high data transmission capabilities depending on the mobile radio standard used and are, therefore, widely used. With the expansion of the network of devices, the cost of operating the IoT network can increase dramatically due to the need to pay for internet traffic or exchange SMS messages for each system agent.

In Figure 3, technologies are highlighted in red text, the implementation of which entails a significant increase in the cost of operation with an increase in the power of the Internet of Things network. Finally, it is important to remember that cellular communication is far from being available for the entire territory of the Earth.

The noted shortcomings of cellular networks can be solved by introducing other data transmission technologies. Thus, LoRaWAN is a long-range wireless communication standard used for data transmission over long distances in environmental monitoring systems and is used in various fields: urban planning, agriculture, industry, and logistics [13]. By means of the indicated technology, it becomes possible to reliably transmit telemetry data over a long distance while sacrificing transmission speed.

However, data from various sensors is often small, which makes it possible to neglect the significance of the disadvantage of low bandwidth. In addition, data transmitters based on LoRaWAN technology are characterized by high autonomy and low power consumption and have mechanisms for protecting transmitted information, further reducing the cost and risks of operating the Internet of Things. The described advantages determine the relevance of using LoRaWAN technology in building networks of the Internet of Things, which allow remote monitoring and control of metageosystems.

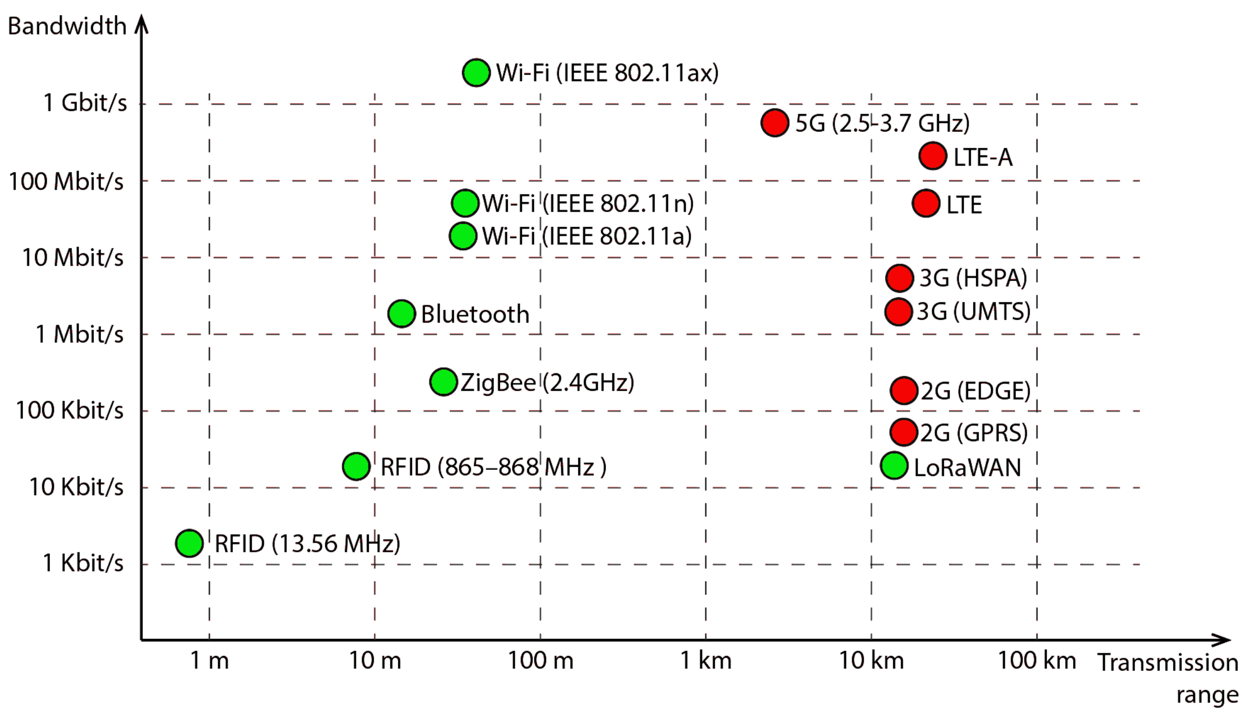

Fig. 3 Scatterplot characterizing the transmission rate and distance of various IoT network standards

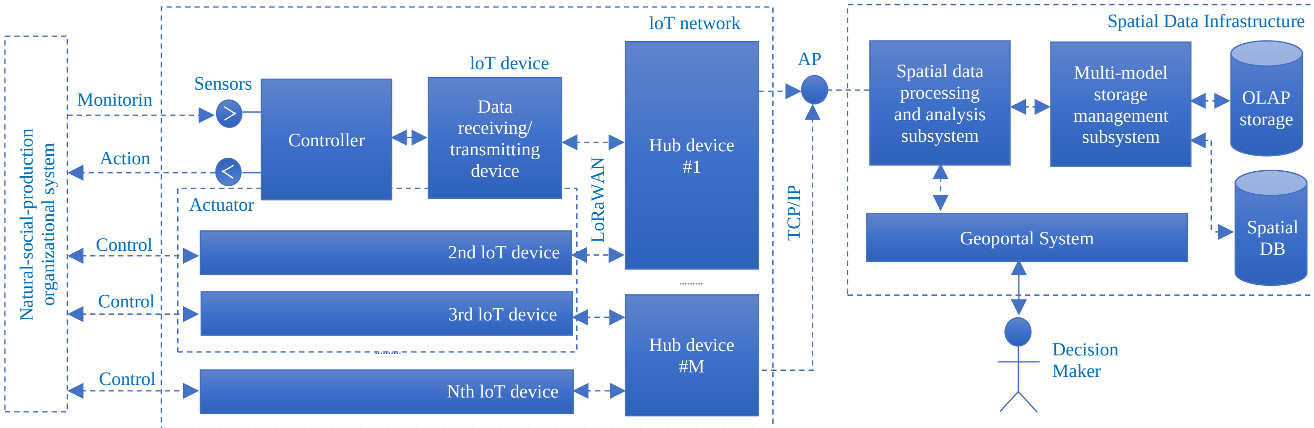

Fig. 4 Architecture of the natural-social-production control system based on the technology of the Internet of Things and geoportal systems

Now, it is possible to present the architecture of the NSPS control system, which can be built based on the Internet of Things technology using the energy-efficient LoRaWAN network (Figure 4).

The system's main goal is to provide a decision maker (DM) with a tool for monitoring and remote control of IoT agents operating within the territorial system as a control object. The basis of the IoT networks is represented by IoT LoRa devices consolidated around head devices (gateways or hubs). IoT devices must be initially formed based on a modular principle, which allows expansion and change of the device's functionality with minimal transformation of the existing organization.

The core of the IoT device is a controller that performs the function of collecting data from sensors of various types and sending control commands to actuators.

The task of the sensors is aimed at collecting up-to-date information about the properties of the components of geographically distributed systems (air temperature, illumination, soil moisture, geographic coordinates), and the actuators are aimed at performing a targeted action (automated irrigation, activation of an alarm signal, microclimate adjustment, and so on).

The high radius of stable data transmission based on LoRaWAN technology allows building a subsystem for managing the NSPS around the head units (gateways) at a distance of tens of kilometers around (the exact distribution potential depends on the characteristics of the territory, including the terrain and the presence of buildings).

The collection of telemetric indicators and the transfer of control commands within such a subsystem are carried out without the involvement of third-party communication providers, as happens in the case of using cellular communications.

This fact greatly reduces the cost of operating the NSPS control subsystem, bringing the cost of data exchange to the minimum possible value. At the same time, IoT LoRa devices are also characterized by high autonomy. Head units consolidate the information collected from IoT devices and take on the remote control role.

Due to the fact that the number of hubs is much less than the number of IoT devices located throughout the NSPS, data collection from them can be successfully and efficiently organized based on the TCP/IP network data transmission model, involving both cellular networks and wired communication channels. The host devices perform the function of linking the IoT network and the organization's Spatial Data Infrastructure (SDI) by sending data and receiving control messages through Application Programming Interfaces (APIs). As part of the SDI, telemetry consolidated with the IoT network is received by the data processing and analysis subsystem, reduced to the required standardized form, and sent to the multi-model storage management subsystem for recording in the database of interactive analytical processing (OLAP, online analytical processing) of data.

The role of the access point to the actual spatial data of the SDI is implemented by geoportal systems (geoportals) [14]. This class of information systems is implemented using web technologies that make it possible to use a software product within an enterprise's local network and via the internet.

The central functional component of the geoportal is an interactive digital map that allows you to visualize a dynamically adjustable set of different thematic layers of spatial data [15]. It should also be noted that within the framework of one SDI, several isolated geoportals can be deployed at once, differing in functional and qualitative characteristics and allowing solving of different tasks in the field of NSPS management.

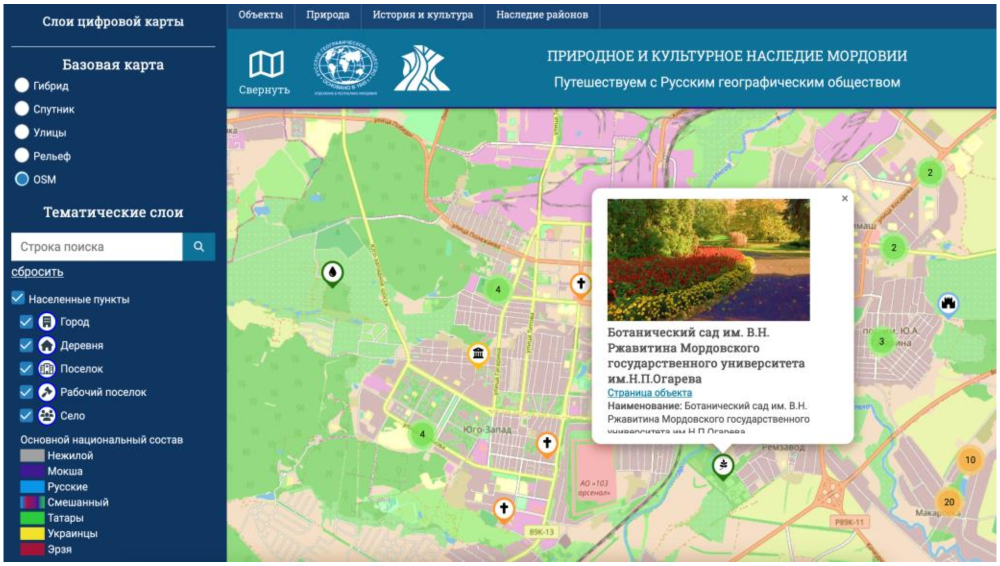

Fig. 5 Geoportal system "Natural and Cultural Heritage of Mordovia"

To solve the problem of building geoportal systems, the team of authors developed a software framework based on the use of open-source software without the involvement of ready-made geoinformation systems for managing geospatial content. The framework was first tested when creating the geoportal "Natural and cultural heritage of the Republic of Mordovia" (Fig. 5).

Geoportal provides access to an interactive digital map of the region containing objects of natural, historical and cultural heritage, including the following thematic layers: specially protected natural areas, rivers, archaeological sites, characteristics of settlements, religious sites, museums, ethno-cultural centers and tourist routes.

Although the geoportal framework formed the basis for forming a digital map of natural, historical and cultural heritage, it can be successfully applied to solve the problem of monitoring Internet of Things objects due to the modular and expandable organization of software components. Problem-oriented geoportal systems are used in various sectors of the national economy, solving the problems of managing negative and positive risks.

3. Research Results

To test the technology of the Internet of Things in solving the problem of managing the NSPS, a system prototype was implemented based on the LoRaWAN network construction technology, including the following system components.

- Head units (hubs) are designed based on the ESP8266 microcontroller based on the NodeMCU board, which has a built-in ability to use wireless Wi-Fi networks. A power supply or a computer can power the device. The master device can interrogate the slave devices, collecting information from the sensors and sending a control command to them to activate the automated watering function. The collected telemetry is sent to the SDI APIs and written to the OLAP data warehouse. The designed hub can be located at any point that has a stable connection to the internet (or the internal network of the organization). Data exchange with the SDI is organized based on the MQTT (message queuing telemetry transport) network protocol, which is focused on messaging based on the "publisher-subscriber" principle.
- Slave IoT devices are based on the Arduino Nano board, to which sensors are connected: resistive sensors for temperature (B3950) and humidity (FC-28), soil, air temperature and humidity (DHT22), carbon dioxide (MQ135). To implement the function of automated watering, a water gear pump based on a motor (RS-360SH) is integrated into the prototype of the device. The IoT device is designed with modularity and extensibility in mind, which allows it to be used with a different set of sensors (sensors) and actuators.
- To ensure communication between the slave and the master, a LoRa transceiver (LLCC68) is integrated into each of them, operating at frequencies of 868 and 915 MHz 915 MHz, and allowing to achieve of a stable communication range of 10 kilometers in line-of-sight conditions.

The software for the operation of the SDI is implemented based on open-source software. The software framework is built based on the MVC architectural pattern using the Python language and the Django framework with the GeoDjango extension, which allows the implementation geospatial web infrastructures based on spatial data of various types. The architecture of the SDI components involves the decomposition of subsystems into components for managing the operation logic (controllers), data models and graphical interfaces.

From the point of view of the upper level of organization of the SDI architecture, subsystems are distinguished: management and analysis, storage and visualization of spatial data. Geoportal systems represent the last block of programs.

It is important to note that the organizational SDI subsystems are implemented based on a microservice approach, which involves the formation of such a system architecture in which its modules are isolated components (services) that are loosely linked to each other and perform their own and only their specific task. Under the conditions of this approach, the system acquires an important property of modifiability: the introduction of new components does not require a radical reworking of an already existing, implemented and functioning solution. So, for example, the need to implement a flood area forecasting module during the spring flood should not lead to a change in the system's existing functionality.

The SDI spatial data storage operates based on the PostgreSQL relational database management system with an open PostGIS extension that allows you to flexibly and efficiently manipulate various spatial data types. The Citus extension was used to transform PostgreSQL storage into a distributed database to achieve high performance when working with IoT components, including by forming columnar storages that allow accumulating and efficiently processing consolidated telemetry data.

Information collected from IoT devices is visualized as part of a digital map of the geoportal system: components are displayed with spatial reference, and for each of them, meta-information can be asynchronously loaded, including information collected from sensors. Within the framework of user interfaces, the task of sending a control signal can also be solved (using the example of launching an automated irrigation function). Graphical geoportal interfaces are implemented in accordance with the HTML5 standard, and styling is done using CSS cascading style sheets. To implement the qualitative requirement of adaptability of user interfaces to screens of various types and sizes (smartphones, tablets, desktops), media constructions were used. Dynamic interaction of interfaces with the user is implemented using the JavaScript language and the technology of asynchronous AJAX requests.

The use of geographic information web systems in conjunction with the deployment of the Internet of Things adds to geoportals the capabilities of a dispatching tool along with the classic function of interactive visualization of spatial data. The use of geoportal systems at the same time allows the decision maker to monitor the state of organizational natural-social-production systems in real-time, based on the possibility of a comprehensive analysis of data of various thematic directions, visualized by means of a dynamic digital map. To solve the problem of manipulating arrays of SDI spatial data within the framework of the data management and analysis system, an interactive administration function has been implemented that allows you to add new spatial objects and edit the meta-data of existing ones.

The geoportal "Natural and cultural heritage of the Republic of Mordovia", shown in Figure 5, is an example of an information system implemented using a design paradigm based on risk management processes. The solution to the problems of heritage conservation provides for both the direct protection and restoration of natural, historical and cultural monuments, as well as their systematic study, rational use, and popularization of knowledge in society, including among young people. The project aims to solve the problem of using the image potential of the natural and cultural heritage of the region as a system of positive risks (opportunities). Digital mapping, system analysis and dissemination of knowledge about the key components of the natural and historical heritage of the Republic of Mordovia in the cultural landscape provide an opportunity for the development of the tourism industry, which can become one of the drivers of socio-economic development of Russian regions.

The effectiveness of the development of the tourism industry is largely based on the realization of the need for multi-level geographic information about the territory, containing knowledge about the properties of objects of interest and presented in the form of a system of interactive digital maps. The functioning of the geoportal "Natural and cultural heritage of the Republic of Mordovia" is based on a relational data warehouse that systematizes spatial data on spatial objects of the following thematic categories:

- "Rivers": the hydrological characteristics of more than 170 rivers of the region are given;
- "Specially Protected Natural Territories" (PAs): a systematic description of the National Park, State Nature Reserve, botanical, geological, hydrological, dendrological, zoological, complex monuments of nature (more than 90 objects);
- "Archaeological objects" of the region with a description of the age and cultural aspects: settlements, ground burials, mounds, locations, settlements, parking lots, and fortifications (690 objects);
- "Settlements", including information on toponymy, the time of occurrence or first mention, the predominant nationality, and the features of the development of cities, villages, towns and villages (more than 1200 objects);
- "Religious objects": characteristics of temples of various denominations, including cathedrals and mosques (more than 550 objects);
- "Objects of culture": ethno-cultural centers, museums, venues for holidays and festivals, memorial monuments associated with the life of remarkable people (more than 80 objects).

Also, the digital map of the geoportal provides information on tourist river routes that reveal the tourism potential of the region in order to solve the problem of managing positive risks. In general, within the framework of the digital map "Natural and cultural heritage of the Republic of Mordovia. Traveling with the Russian Geographical Society" (the geoportal is available at: https://map.rgo.life/) provides information on more than 2,800 objects of natural, historical and cultural heritage. The geoportal is aimed at facilitating the management of the processes of tourist and recreational development of the region, based on the use of thematic spatial data on regional metageosystems.Within the framework of the project, the ultimate goal of the work on the development of the portal was the need to maximize the effect of using positive risks (opportunities) associated with the management of natural, historical and cultural heritage systems. The achievement of this result becomes possible through the effective dissemination of complex (landscape, historical, cultural, sociological, economic, environmental) information about the region through the created geoportal, which solves the formulated problem by contributing to the achievement of the following target effects: 1) organizing information support for the process of conducting investment campaigns to raise funds for the conservation of heritage sites; 2) informing about the processes of development of tourism infrastructure; 3) drawing attention to the problems of preserving and developing folk traditions and crafts; 4) implementation of a set of measures to improve the image of natural and historical heritage elements.

To test the performance of the geoportal system under high load conditions, one hundred virtual machines were deployed that implement the ability to simulate user actions based on technology for automating web browser actions. The frequency of simultaneous requests from the web interfaces of the digital map during testing reached 89 requests per second (Figure 6). The server response time was analyzed, followed by object rendering on a digital map. In total, as part of a separate experiment, 8 thousand requests were made to the geoportal system, emulating the actions of real users. The experiment showed the stability of the geoportal system to the presence of a significant number of simultaneous requests: the response time increased from 190 to 225 milliseconds, which is a good indicator for web applications, including from Google's point of view. Additionally, it should be noted that during high-load testing, no server failures were noted due to the inability to process requests.

To confirm the stability and relevance of the experimental data, a series of 100 experiments were carried out, followed by a calculation of the mathematical expectation and standard deviation of the page response time values under high load conditions. The mathematical expectation based on the results of a series of experiments took the value of 210, while a low value of the standard deviation was achieved. This fact confirms the stability of the geoportal system to high loads under the conditions of a series of experiments.

It should be noted that within the geoportal system, technology has been implemented for asynchronously loading data on the geometry of significant area objects within the current screen boundaries. This allows you to maintain system performance even when it is necessary to load data on objects of complex geometry due to the gradual loading of visible and fairly large polygons and lines.

4. Conclusion

Based on the research presented in the article, the following conclusions can be drawn.

- In the management of NSPS, a trend towards process automation has emerged, including implementing functions for remote monitoring of operational processes and remote control. The main purpose of the implemented automated information systems is to provide a decision maker (DM) with a tool for monitoring and remote control of Internet of Things agents operating within the territorial system as a control object.
- The solution to the problem of visualization and dissemination of spatial data on regional metageosystems can be achieved by introducing and effectively using geoportal systems developed based on web technologies and providing access to the spatial data infrastructure of organizations and regions through interactive digital maps. In the field of management of metageosystems, geoportals begin to play the role of dispatching centers along with their classic function of interactive visualization of spatial data.

Fig. 6 High-load testing of a geoportal system

- The central functional component of the geoportal is an interactive digital map that allows you to visualize a dynamically adjusted set of different thematic layers of spatial data. Within the framework of one SDI, several isolated geoportals can be deployed at once, differing in functional and qualitative characteristics and allowing solving of various problems in the field of metageosystems management.
- Internet of Things technologies, which involve deploying networks of connected physical devices that exchange data with each other and are capable of performing a set of targeted actions, play an important role in consolidating relevant spatially associated information about metageosystems. The Internet of Things, together with the introduction of geoportal technologies, finds application in all sectors of the national economy and involves the formation of ecosystems of various sizes.
- The article proposes the architecture of the NSPS control system based on the technology of the Internet of Things and geoportal systems, based on the use of the LoRaWAN long-range wireless communication standard to achieve the possibility of sustainable resource-efficient transmission of telemetry data over a considerable distance. The basis of the Internet of Things network is represented by IoT devices consolidated around the head devices (gateways). It was developed based on a modular principle to achieve high rates of modifiability and extensibility.
- The collection of telemetric indicators and the forwarding of control commands within the LoRaWAN network are carried out without the involvement of third-party communication providers, which greatly reduces the cost of operating the NSPS control subsystem, bringing the cost of data exchange to the lowest possible value. Head devices perform the function of connecting the IoT network and the organization's SDI by exchanging messages through APIs. The data processing and analysis subsystem receives telemetry consolidated from the IoT network, is reduced to the required standardized form, and is sent to the multi-model storage management subsystem for recording in OLAP storage.
- The article gives a description of a geoportal framework that allows solving the problem of rapid deployment of a problem-oriented decision support tool for managing geographically distributed organizational systems through monitoring objects of the Internet of Things and remote control of them. The software solution is built based on the MVC architectural pattern using the Python language, and the spatial data warehouse operates based on the PostgreSQL relational database management system with PostGIS and Citus extensions. Information collected from IoT devices is visualized as part of an adaptive digital map of a geoportal system with spatial reference. It is supplemented by the ability to send a remote control signal. Dynamic interaction of interfaces with the user is implemented using the JavaScript language and the technology of asynchronous AJAX requests.
- Hierarchically ordered natural-social-production systems (metageosystems) can be defined as systems for ensuring the population's security, stability and quality of life, realizing the function of protection against threats of a humanitarian, natural (natural) and technogenic nature. Based on this provision, it can be argued that the task of management in spatially distributed systems should be based on solving the problem of planning, identification, analysis, monitoring and risk management. Thus, the designed and implemented spatial data infrastructures should be information systems that are a tool for identifying, analyzing and monitoring risks that arise in organizational systems.
- The risk management process can be integrated into the iterative implementation and use of the SDI as an input to the SDI requirements analysis stage. In turn, developed or enhanced versions of the spatial data infrastructure become a tool for monitoring and managing risks in organizational systems whose activities are associated with the use of spatially distributed resources. The tasks of identifying, analyzing and monitoring risks should be considered in terms of assessing the impact of negative and positive risk events on the criteria for the effectiveness of SDI in the field of managing metageosystems, taking into account the presence of dependencies between the occurrence of risks. The results of assessing the strength of risk events allow us to approach the solution of the problem of forming a set of controlled risks in the management of natural-social-production systems and become the starting point in solving the problem of designing functional and qualitative requirements for the infrastructure of spatial data as a tool for managing metageosystems.
- Optimization of the processes of consolidation and use of spatial data in the management of natural-social-production systems should be guided by the criteria of attainability of the target effects of SDI, resource intensity and complexity of the processes of supporting the implemented information systems. The achievability of target effects (reducing the impact of risks), reducing the resource intensity and time complexity of modifying the SDI allows for justifying the feasibility of introducing the SDI to solve the problems of managing natural-social-production systems. An important feature of the approach to the management of natural-social-production systems, focused on the analysis and monitoring of risks, is the need to focus on the flexible organization of the process of developing geographic information systems. The solution to the problem of effective iterative functional and qualitative development of SDI is possible based on compliance with the principles of SOLID.
- The article presents the results of the design and development of geoportal systems as tools for managing spatially distributed resources and objects designed to

solve the problems of managing positive and negative risks. The geoportal system for visualizing the flooded area allows visualizing the potential flooding area on a digital map under the condition of varying degrees of water level rise. The geoportal "Natural and Cultural Heritage of the Republic of Mordovia" is aimed at solving the problem of using the image potential of the natural and cultural heritage of the region as a system of positive risks (opportunities) within the digital interactive map of the system, information is provided on more than 2,800 objects of natural, historical and cultural heritage. The geoportal is aimed at facilitating the management of the processes of tourist and recreational development of the region, based on the use of thematic spatial data on regional metageosystems.

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