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SUBSTANTIATION OF REQUIREMENTS FOR THE STRUCTURAL AND ALGORITHMIC ORGANIZATION OF AN IOT MONITORING SYSTEM FOR SOIL AND CLIMATE PARAMETERS IN AGRICULTURAL CROP ENTERPRISES

Relevance. *As one of the key sectors of the global economy, agriculture plays a decisive role in shaping sustainable economic development and ensuring food security worldwide. Achieving satisfactory indicators of food security and the export potential of agricultural products is a domestic priority for economic recovery and sustainable development. Accordingly, the development and implementation of modern digital technologies in agriculture becomes a strategically important task. The utilization of cutting-edge technologies for the agricultural sector, coupled with the improvement of cultivation and processing methods for agricultural crops, is a key element in ensuring the resilience and efficiency of the industry.* ***The main aim*** *is to conduct a critical analysis of existing solutions in the field of information monitoring for agricultural purposes. This analysis will allow the development of an optimized structural and algorithmic organization for the computerized system. This system is designed to implement effective monitoring and decision support for managing agricultural processes.* ***The research object*** *is existing approaches and methods for organizing monitoring systems in the agricultural sector to collect, transmit, and process measurement data.* ***The research subject*** *is information and communication software and hardware solutions in the field of computerized monitoring for agricultural purposes.* ***Conclusions.*** *It has been substantiated that the development and implementation of conceptual software and hardware solutions in information technology for monitoring soil and climatic parameters when cultivating agricultural crops in open-field conditions are currently a relevant scientific and applied task. The set of requirements for the structural and algorithmic organization of the IoT technology for soil and climatic monitoring has been substantiated. An analysis and selection of technologies on which the investigated hardware and software solution will be based have been carried out. The overall and detailed structural and algorithmic organization of the investigated IoT system for agrotechnical monitoring has been developed, and priority directions for further research have been established.*

Key words: *Internet of Things, monitoring, architecture, wireless sensor network, agriculture.*

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ОБҐРУНТУВАННЯ ВИМОГ ДО СТРУКТУРНО-АЛГОРИТМІЧНОГО ЗАБЕЗПЕЧЕННЯ IOT СИСТЕМИ МОНІТОРИНГУ ҐРУНТОКЛІМАТИЧНИХ ПАРАМЕТРІВСІЛЬСЬКОГОСПОДАРСЬКИХ ПІДПРИЄМСТВ РОСЛИННИЦТВА

Актуальність. *Сільське господарство, як одна з ключових галузей світової економіки, має визначальне значення у формуванні сталого економічного розвитку та забезпеченні продовольчої безпеки у світі. Досягнення задовільних показників продовольчої безпеки та експортного потенціалу сільськогосподарської продукції є одним із вітчизняних пріоритетів економічного відновлення та сталого розвитку. Відповідно до цього розробка та впровадження сучасних цифрових технологій у сільське господарство стає стратегічно важливим завданням. Адже, використання новітніх технологій для цілей аграрної галузі, водночас з удосконаленням методів вирощування та обробки сільськогосподарських культур, є ключовим елементом забезпечення стійкості та ефективності галузі.* ***Метою роботи*** *є критичний аналіз існуючих рішень у сфері інформаційного моніторингу агротехнічного призначення, що дозволить розробити оптимізовану структурно-алгоритмічну організацію комп'ютеризованої системи, яка спрямована на реалізацію ефективного моніторингу та підтримки прийняття рішень щодо керування аграрними процесами.* ***Об'єктом дослідження*** *є існуючі підходи та методи організації систем моніторингу в агросекторі з метою збору, передачі та обробки вимірювальних даних.* ***Предметом дослідження*** *є інфокомунікаційні програмно-апаратні рішення в галузі комп'ютеризованого моніторингу сільськогосподарського призначення.* ***Висновки.*** *Доведено, що розробка і впровадження концептуальних програмно-апаратних рішень інформаційних технологій для моніторингу ґрунтокліматичних параметрів під час вирощування сільськогосподарських культур в умовах відкритого ґрунту є актуальною науково-прикладною задачею у теперішній час. Обґрунтовано сукупність вимог до структурно-алгоритмічної організації IoT технології ґрунтокліматичного моніторингу, здійснено аналіз і вибір технологій, на яких базуватиметься досліджуване апаратно-програмних рішення. Обґрунтовано загальну та деталізовану структурно-алгоритмічну організацію досліджуваної IoT системи агротехнічного моніторингу та встановлено пріоритетні напрямки подальших досліджень.*

Ключові слова: *IoT-технологія, моніторинг, архітектура, бездротова сенсорна мережа, сільське господарство.*

The relevance of the scientific and applied research task. As one of the key sectors of the global economy, agriculture plays a crucial role in shaping sustainable economic development and ensuring food security worldwide. The relevance of agriculture is directly linked to its impact on the social and economic aspects of society. Agricultural activities serve as the primary source of food production, a vital factor in providing the population with essential food products.

In contemporary times, as the world faces challenges such as global climate change and an increasing population, the significance of agriculture becomes even more pronounced. Achieving food security becomes a priority, and the integration of modern technologies into agriculture becomes a strategically important task. The use of cutting-edge technologies in agronomic practices, coupled with advancements in cultivation and processing methods of agricultural crops, is a key element in ensuring the resilience and efficiency of the industry.

The necessity to implement modern information and computer technologies in agriculture is also driven by the need to optimize production processes. Digitization and innovations contribute to increased productivity and quality of agricultural products, ensuring high competitiveness in both domestic and global markets.

The integration of modern technologies into agriculture is not only a national necessity but also a global trend that determines the effectiveness and competitiveness of Ukraine in the world market. It becomes a strategic direction of development, combining economic, technical, ecological, and social aspects.

The contemporary development of agriculture is accompanied by several important trends that define not only technological shifts but also strategic directions in the industry.

Firstly, the significant impact on agriculture is exerted by global digitization and the intellectualization of production processes. The use of modern information technologies, sensors, artificial intelligence systems, and big data allows the optimization of production processes, resource management, and the enhancement of farming efficiency.

The second important trend is sustainability and ecological resilience. Agriculture is becoming increasingly oriented towards environmental conservation. The use of environmentally friendly approaches to cultivation, the development of organic farming, and the implementation of resource-saving technologies become essential in meeting consumer demands and addressing global environmental challenges.

The third trend is the globalization of markets and increased competition. Agriculture is part of a global supply chain that requires a high level of competitiveness. Improving product quality, standardization, and the development of new markets are strategic objectives for the agricultural sector.

Additionally, a significant trend is the development and practical implementation of the conceptual principles of 'Agriculture 4.0'. The integration of the Internet of Things, robotics, as well as hardware and software solutions into the digitization of production processes, transforms agriculture, making it more efficient and high-tech.

Aim and objectives of the article. The main aim of the article is to analyse and synthesize approaches to the development of the structural and algorithmic organization of IoT technologies for implementing comprehensive digital monitoring of soil and climatic parameters of open-field crop farms. To achieve the set aim, the following objectives need to be met:

– critical analysis and logical generalization of existing approaches to the construction of information technologies and computerized systems for agrotechnical purposes;

– identification and study of the most effective architectural solutions in the construction of information technologies for agrotechnical monitoring;

– development of a structural diagram and algorithms for the functioning of the investigated IoT technology;

– substantiation of further directions for priority research in the declared subject area.

Critical analysis and logical generalization of recent research, publications, and scientific and technical developments. Based on the analysis of sources [1–3], the following aspects requiring development in the domestic and global agricultural sectors can be highlighted:

1. Strategies for agricultural digitization:

– investigation of specific strategies used in different countries for the development, improvement, and implementation of digital technologies in agriculture;

– overview of programs and initiatives aimed at supporting the digital transformation of the agricultural sector.

2. Regulations and standards:

– research the regulatory environment regulating the use of digital technologies in agriculture;

– review standards for data exchange between various agricultural systems.

3. Legislation:

– reviewing legislative initiatives aimed at supporting the integration of digital technologies into agriculture;

– studying legal aspects related to data use in agriculture and agrotechnologies;

– international research and collaboration;

– analysis of projects and research conducted internationally for the development of digital agriculture;

– considerations of opportunities for international cooperation in the digitization of the agricultural sector.

4. Innovations and start-ups:

– investigation of the role of innovations and start-ups in the implementation of digital technologies in agriculture;

– analysis of research works and innovative solutions being developed in this field.

5. Efficiency and challenges:

– study the results of implementing digital technologies in agriculture and their impact on productivity and the sustainability of agricultural production;

– analysis of challenges such as cybersecurity, data confidentiality, and technology accessibility for agricultural productions.

All these trends define a new dimension of agricultural development, requiring a combination of traditional methods with innovative technologies to ensure sustainable and efficient farming [1].

The main advantages of applying digital and information technologies include the following [2]:

– cost savings through efficient resource utilization;

– optimized crop monitoring and minimization of crop losses due to decrease of the destabilizing factors influence such as diseases or aggressive climatic conditions;

– predictive planning of agricultural activities.

The aforementioned features are part of the global trend in agricultural development. Similar stages correspond to the domestic strategy for the development of the agricultural sector. It is important to emphasize that the lack of uniform standards and precise solutions complicates the implementation of modern digitization strategies in agriculture. This problem hinders the integration of innovations and reduces their effectiveness, necessitating the search for scientifically grounded solutions. For the successful development of the agricultural sector and to ensure its sustainable functioning, active efforts are needed to create unified standards and develop precise strategies for implementing technological innovations, which will respond to modern challenges and contribute to the creation of a competitive and sustainable domestic agricultural sector [3].

In terms of the possible architecture of IoT systems, various approaches to monitoring crops using innovative Internet of Things (IoT) technologies can be implemented for the optimization of agriculture. Through the use of high-precision sensors, data collection, and analysis, comprehensive monitoring of plant growth can be realized, supporting decision-making regarding the rational use of resources and the control of soil quality and fertilizer levels. The diversity of approaches lies in the use of various types of sensors, graphical images obtained from drones or satellites, and automated data collection systems that are integrated to create comprehensive solutions aimed at optimizing processes in agriculture [2].

The Internet of Things (IoT) is based on a hierarchical architecture that includes multiple levels for effective data management and processing. A typical IoT architecture includes the following levels, as shown in Figure 1 [2].

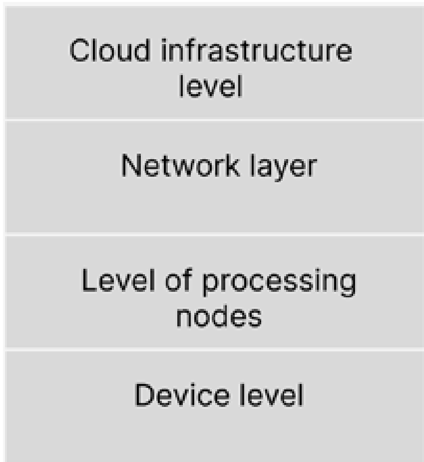

Fig. 1. Generalized Architecture of IoT Systems for Agrotechnical Purposes

The main advantages of the implementation of software and hardware solutions of IoT in agriculture are described in Table 1. The results of the comparison, which are given in Table 1, are the result of a logical generalization at the qualitative level of current global developments and used technologies for agrotechnical purposes [4].

Based on the conducted analysis, it can be concluded that ground monitoring, using wireless sensor networks, proves to be the most reasonable approach for optimizing processes in crop farming through the implementation of the conceptual IoT principles based on hierarchical structural and functional organization (see Fig. 1).

This method not only ensures high measurement accuracy but also allows obtaining real-time information about the condition of plants, soil, and other aspects of agriculture. This approach also considers the advantages of designing computerized systems, taking into account their mobil-

Table 1

The results of comparing IoT monitoring technologies

Parameter	Computerized Systems	IoT technologies
Support for collective farming	Almost absent	High level of support
Logistic and quality tracing of food production	Average level	High level
Direct interaction with consumers	N/A	Available
Harvest monitoring	Available	Available
Automated systems	Available	Available

Table 2

The results of the comparison of agrotechnical monitoring technologies

Parameter	Classical Computerized	Satellite	Ground Stationery	Ground Wireless
Coverage	Low	High	High	High
Integration	Low	High	Medium	High
Ease of Use	Medium	High	High	High
Mobility	Low	High	High	High
Resource Conservation	Medium	Medium	Medium	Medium
Energy Efficiency	Low	Medium	Medium	Medium
Maintenance Complexity	Medium	High	Medium	Low
Economic Efficiency	Low	Low	Medium	High

ity, scalability, and benefits for small and medium-sized businesses in the digital agriculture sector by realizing the following trends: precision, responsiveness, mobility, scalability, and investment attractiveness for small and medium-sized enterprises.

Therefore, this approach enables the creation of flexible, mobile, and scalable solutions that meet current conditions for projects in the field of digital agriculture, especially for small and medium-sized enterprises [4].

The next step in the research is to carry out a comparative analysis of four types of

agrotechnical monitoring systems: classical computerized, satellite-based, ground-based stationary, and ground-based wireless. During the comparative analysis, the following criteria were taken into account: accuracy of data collection, reliability of data transmission, coverage area, implementation and operating costs, the ability to simultaneously detect various physical and chemical parameters (humidity, temperature, chemical composition of the soil, etc.), energy consumption, protection against external influences, system response time, weather resistance, scalability, and ease of integration with other technological systems [5]. The qualitative results of the comparative analysis are presented in Table 2.

Comparing the aforementioned agrotechnical monitoring technologies, it can be concluded that ground-based wireless monitoring is the most optimal in terms of utilization based on integral characteristics. Specifically, such systems offer high accuracy, mobility, a scalable coverage area, the ability to detect multiple parameters simultaneously, resistance to weather conditions, low energy consumption, and attractive investment in implementation and ongoing maintenance.

It is also worth noting that the ground-based wireless sensor networks demonstrate high efficiency in tracking environmental parameters and respond to changes in real-time, making them an effective tool for resource management to enhance crop yields. Such an approach can also be a beneficial investment solution, ensuring optimal resource utilization and improved productivity in agriculture [6].

Research results. Based on the results of the analysis of monitoring technologies, a generalized structural diagram of the soil and climatic parameters monitoring system during the cultivation of agricultural crops has been developed. The proposed structural diagram is based on the technology of wireless sensor networks, as shown in Figure 2.

Infrastructure for information processing is a server environment designed for receiving, processing, and storing data, providing access to information for users with different rights, as well as updating network nodes and sensors as needed.

Sensors are end devices of the technology that, during interaction with the surrounding environment, transmit data to the network and exchange service information with network nodes.

Further specification of requirements for the investigated IoT technology necessitates the

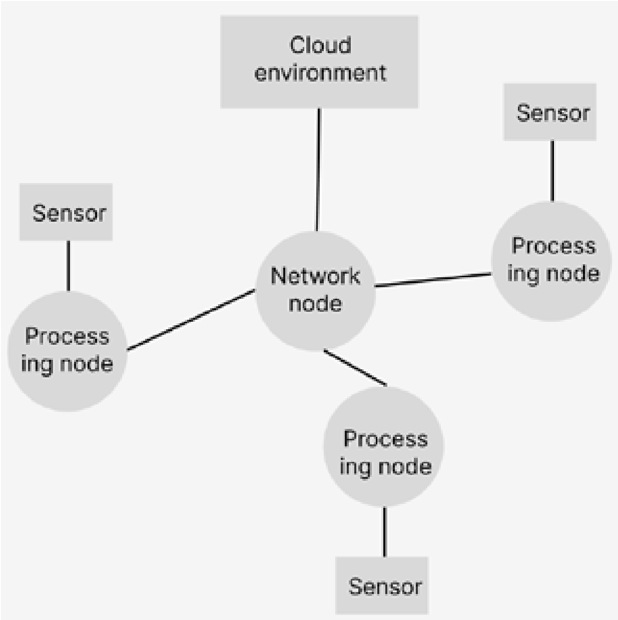

Fig. 2. Generalized structural diagram of the infocommunication network for wireless monitoring of soil and climatic parameters

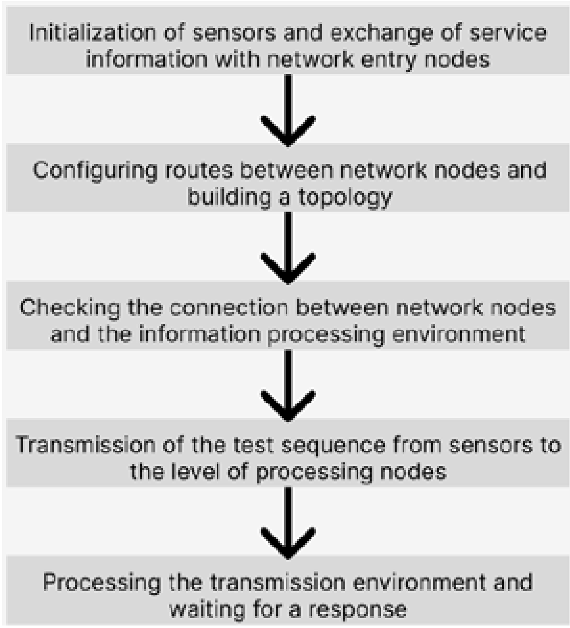

Fig. 3. Algorithm for the initial setup of the investigated IoT technology

establishment of a standard for further research and system development. To achieve this, two main types of interaction algorithms are proposed [7]:

1. Establishing interaction (processing and transmission) of data between all levels of the architecture.
2. Configuring the algorithm of actions in case of emergencies.

The initial setup algorithm is triggered in the event of the first installation of the technology or its complete reboot. In such a case, the sequence of actions after the connection and activation of all system components is shown in Figure 3.

Also, taking into account the modern regulations in the field of open-field crop production regarding the soil and climate parameters influencing the efficiency of growing agricultural crops [8], as well as taking into account the technical and functional characteristics of wireless information and communication technologies, the detailed structural diagram of the IoT technology of agrotechnical monitoring has been substantiated, as shown in Figure 4 [9].

In the specified diagram (see Fig. 4), information processing occurs at the processing nodes (ZigBee) to perform preliminary analysis of the information and unload the network at the next level of data collection. Subsequently, the data passes to processing centres, which are optimally located in cloud infrastructure in terms of providing a high level of support and servicing dedicated resources of the processing system [8, 10–12].

Therefore, based on the conducted research, it has been established that the indicated structural and algorithmic organization of the IoT technology for monitoring soil and climatic parameters during the cultivation of crops correlates with general conceptual trends in the field of information technology in terms of precision, speed, scalability, adaptability, and the complexity of aggregating and transforming measurement data.

Priority directions for further research. Based on the analysis and formulation of key requirements, the next steps involve addressing three crucial tasks:

1. Development and modelling of a network capable of qualitatively and reliably performing the functions of collecting and processing measurement information regarding a set of soil and climatic parameters at multiple hierarchical levels of the system.
2. Development of an infocommunication standard that unifies the general concept of the architecture and demonstrates the functioning aspects of monitoring systems at all stages of system operation.
3. Experimental testing of the system and verification of algorithms under emergency conditions of system operation.

Conclusions. It has been proven that the development and implementation of conceptual hardware and software solutions of information technologies for monitoring soil and climatic parameters during the cultivation of crops in open-field conditions is a relevant scientific and applied

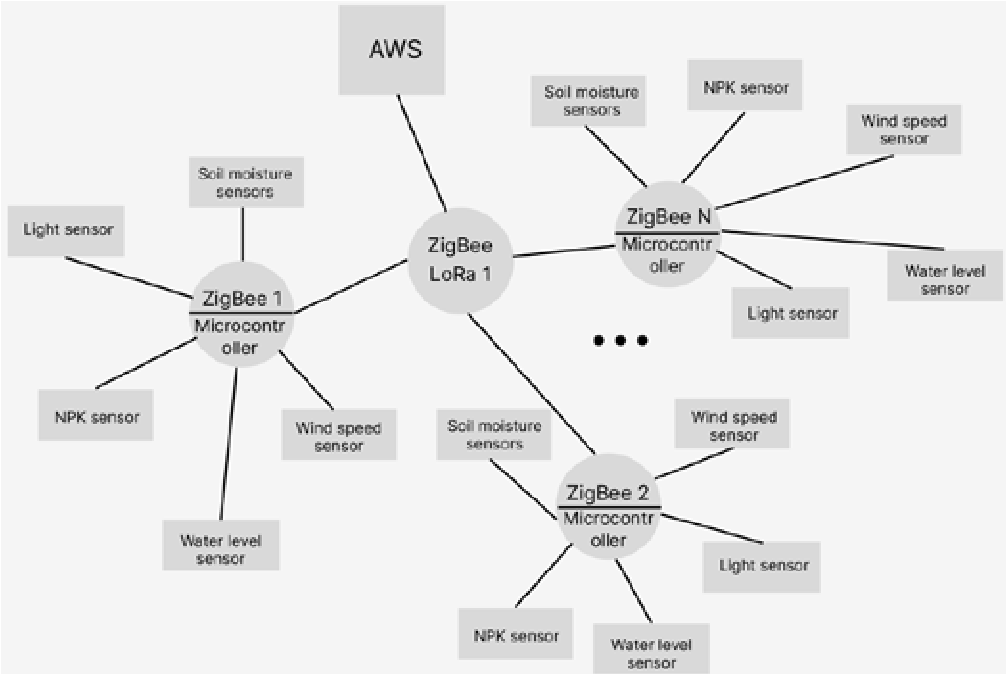

Fig. 4. Detailed structural diagram of the infocommunication network for wireless monitoring of soil and climate parameters

task at present. A set of requirements for the structural and algorithmic organization of the IoT soil and climatic monitoring technology has been substantiated, as well as an analysis and selection of technologies on which the investigated hardware and software solutions will be based have been carried out. The general and detailed structural and algorithmic organization of the investigated IoT agricultural monitoring system has been substantiated. As a result of this scientific work, basic principles, and directions for the development of IoT technologies for effective monitoring of soil and climatic conditions on open-field crop farms have been identified.

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