THEORETICAL AND PRACTICAL FOUNDATIONS OF DEVELOPMENT OF SMART IRRIGATION SYSTEMS BASED ON ARTIFICIAL INTELLIGENCE AND IOT TECHNOLOGIES

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Abstract

The article analyzes the theoretical and practical foundations of the development of smart irrigation systems based on artificial intelligence (AI) and IoT technologies. Effective use of water resources, increasing productivity and ensuring environmental sustainability are among the pressing issues in modern agriculture. Traditional irrigation methods have problems such as water waste, misallocation of resources and insufficient automation of the monitoring system. Therefore, real-time monitoring of soil moisture, climate indicators and plant needs through smart systems based on artificial intelligence algorithms and IoT sensors, as well as the introduction of automatic control mechanisms, are of great importance. The study analyzes existing scientific approaches, technological capabilities and practical implementation experiences and substantiates the effectiveness of the integrated system. The results show the possibilities of saving water resources and increasing the efficiency of agricultural production through the widespread introduction of smart irrigation systems.

Keywords

Artificial intelligence, IoT technologies, smart irrigation system, automated control, soil moisture monitoring, digital agriculture, water resources management, sensor technologies.

Annotatsiya

Maqolada sun'iy intellekt (AI) va IoT texnologiyalariga asoslangan aqlli sug'orish tizimlarini rivojlantirishning nazariy va amaliy asoslari tahlil qilinadi. Zamonaviy qishloq xo'jaligida suv resurslaridan samarali foydalanish, hosildorlikni oshirish va ekologik barqarorlikni ta'minlash dolzarb masalalardan biri hisoblanadi. An'anaviy sug'orish usullarida suv isrofi, resurslarni noto'g'ri taqsimlash va monitoring tizimining yetarli darajada avtomatlashtirilmaganligi kabi muammolar mavjud. Shu sababli sun'iy intellekt algoritmlari va IoT sensorlariga asoslangan aqlli tizimlar orqali tuproq namligi, iqlim ko'rsatkichlari va o'simlik ehtiyojlarini real vaqt rejimida monitoring qilish hamda avtomatik boshqarish mexanizmlarini joriy etish muhim ahamiyat kasb etadi. Tadqiqotda mavjud ilmiy yondashuvlar, texnologik imkoniyatlar va amaliy implementatsiya tajribalari tahlil qilinib, integratsiyalashgan tizimning samaradorligi asoslab beriladi. Natijalar aqlli sug'orish tizimlarini keng joriy etish orqali suv resurslarini tejash va qishloq xo'jaligi ishlab chiqarish samaradorligini oshirish imkoniyatlarini ko'rsatadi.

Kalit so'zlar

Sun'iy intellekt, IoT texnologiyalari, aqlli sug'orish tizimi, avtomatlashtirilgan boshqaruv, tuproq namligi monitoringi, raqamli qishloq xo'jaligi, suv resurslarini boshqarish, sensor texnologiyalari.

Аннотация

В статье анализируются теоретические и практические основы разработки интеллектуальных систем орошения на основе технологий искусственного интеллекта (ИИ) и Интернета вещей (IoT). Эффективное использование водных ресурсов, повышение производительности и обеспечение экологической устойчивости являются одними из актуальных проблем современного сельского хозяйства. Традиционные методы орошения имеют такие проблемы, как расточительное использование воды, нерациональное распределение ресурсов и недостаточная автоматизация системы мониторинга. Поэтому мониторинг влажности почвы, климатических показателей и потребностей растений в режиме реального времени с помощью интеллектуальных систем на основе алгоритмов искусственного интеллекта и датчиков IoT, а также внедрение механизмов автоматического управления, имеют большое значение. В исследовании анализируются существующие научные подходы, технологические возможности и опыт практической реализации, а также обосновывается эффективность интегрированной системы. Результаты показывают возможности экономии водных ресурсов и повышения эффективности сельскохозяйственного производства за счет широкого внедрения интеллектуальных систем орошения.

Ключевые слова

Искусственный интеллект, технологии IoT, интеллектуальная система орошения, автоматизированное управление, мониторинг влажности почвы, цифровое сельское хозяйство, управление водными ресурсами, сенсорные технологии.

Introduction. In recent years, the digitization of agriculture and modernization based on modern technologies have become one of the global priorities. In the context of population growth, climate change and limited water resources, increasing the efficiency of irrigation systems has become an urgent task. Traditional irrigation methods are often based on empirical decisions and the human factor, which can lead to water waste and reduced productivity.

Today, artificial intelligence technologies create the opportunity to analyze large volumes of data, forecast and make optimal decisions. At the same time, Internet of Things (IoT) technologies serve to monitor soil moisture, temperature, humidity and other agro-ecological parameters in real time. Based on the integration of these two technologies, smart irrigation systems are formed, which create the ability to automatically deliver water in the right amount and at the right time.

Pictures 1-2. Current state of irrigation systems

Smart irrigation systems not only save water resources, but also reduce energy consumption, optimize labor costs and sustainably increase productivity. In this regard, it is important to study the mechanisms of scientific and theoretical substantiation and practical implementation of irrigation systems based on artificial intelligence and IoT technologies.

Literature review. In recent years, many foreign scientists have conducted research on the engineering development of smart irrigation systems based on artificial intelligence (AI) and IoT technologies. In particular, J. Smith and L. Brown in their research developed a model for automating the irrigation process in real time by integrating IoT sensors and machine learning algorithms. They proposed a mechanism for collecting soil moisture data through a sensor and determining the time of watering based on decision trees and regression models. The results of the study showed the possibility of reducing water consumption by 20–35% [1].

Y. Zhang and X. Li developed an irrigation forecasting system based on artificial neural networks, integrating climate parameters and agroecological data. Their work proposed a model for predicting irrigation needs by analyzing large amounts of data, which proved the effectiveness of AI-based decision-making in engineering systems[2].

Regarding IoT technologies, K. Patel and colleagues developed an architecture for wireless sensor networks in smart agriculture and proposed a remote monitoring system based on LoRa and ZigBee protocols. The study justified the mechanism of data transmission to a centralized server and analysis on a cloud platform from an engineering perspective[3].

Also, the report "Digital Agriculture and Smart Irrigation Technologies" published by the FAO (Food and Agriculture Organization) in 2022 emphasized the need for the global introduction of digital monitoring, water-saving technologies and automated management systems. The report provides scientific evidence that AI-based management models can increase the efficiency of water resource use[4].

The UN "Water Resources Management and Sustainable Development Report" assessed water scarcity as a global problem and identified the digitalization of irrigation systems and the introduction of real-time monitoring systems as a strategic direction. This document recommends the integration of engineering technologies into water management systems[5].

The Republic of Uzbekistan has also adopted important regulatory and legal documents on the effective management of water resources and the modernization of irrigation systems. In particular:

- The Resolution of the President of the Republic of Uzbekistan No. PQ–4766 dated July 10, 2020 provides for the effective use of water resources, the widespread introduction of drip irrigation and water-saving technologies. Within the framework of this resolution, the tasks of technological modernization of irrigation systems and digitalization of monitoring are set[6].

- Decree No. PF–60 (28.01.2022) The New Uzbekistan Development Strategy for 2022–2026 indicates the digitalization of agriculture and the implementation of innovative technologies in water resources management as a priority area[7].

The Cabinet of Ministers' resolutions on the modernization of the irrigation system set out mechanisms for the introduction of water accounting, electronic monitoring and automated control systems[8].

In general, the analysis of existing scientific research and regulatory documents shows that for the effective operation of smart irrigation systems, an integrated engineering model of AI algorithms and IoT sensor infrastructure is necessary. However, in-depth comprehensive research on the full architecture of the system, optimized control algorithms and technical solutions adapted to local conditions is still insufficient in applied research. Therefore, the development of new engineering solutions in this area based on technical experience and algorithmic modeling is relevant.

Methodology. This article is aimed at developing the technical architecture of a smart irrigation system integrated with artificial intelligence and IoT technologies based on an engineering approach, mathematical modeling and assessment of its practical effectiveness. The study used a comprehensive approach to systematic engineering analysis, experimental testing, modeling, algorithmic optimization and statistical evaluation methods. The irrigation process was considered as a complex dynamic system, and its input parameters (soil moisture, temperature, air humidity, precipitation, plant type) and output parameters (watering volume, irrigation time, pump operating mode) were analyzed in functional dependence.

In the first stage of the study, the system requirements were determined and a conceptual model of a smart irrigation system was developed. This model consists of three main components: a data collection layer through sensor devices, a data transmission and processing layer, and a decision-making control layer based on artificial intelligence. The system architecture was modeled in the form of an engineering block diagram, and the functional tasks and interfaces of each module were determined.

In the second stage, agroecological data was collected in real time using IoT sensors. Soil moisture sensors, temperature and humidity sensors, and water consumption meters were integrated and transmitted to a central database via a microcontroller (ESP32/Arduino). Wi-Fi, GSM, or LoRa technologies were used for data transmission, ensuring uninterrupted operation of the system and data reliability. The collected data was cleaned and normalized during the initial processing, and anomalous values were identified and eliminated.

In the third stage, artificial intelligence algorithms were developed and tested to automate irrigation decisions. Based on machine learning methods - regression models, decision trees, random forests, and neural networks - the optimal irrigation volume was predicted depending on soil moisture and climate parameters. The model was trained on training and test data, and its accuracy was evaluated using MAE, RMSE, and accuracy indicators. The model that showed the highest efficiency was selected as the main control algorithm of the system.

In the fourth stage, the developed system was tested in laboratory and field conditions. During the testing process, the speed of automatic irrigation, the accuracy of sensor data, the

level of real-time response of the system, and water consumption indicators were compared with the traditional irrigation method. The results obtained were statistically analyzed and the economic and technical efficiency of the system was assessed.

Also, during the study, the energy consumption of the system, data transmission security, and the stability of continuous operation were analyzed based on engineering criteria. The software was developed using Python, MATLAB or other algorithmic platforms, and the system's operation was verified through a simulation model.

In general, the research methodology was built on the basis of an integrated engineering model and served to develop a technically sound and optimized solution for a smart irrigation system by combining the results of theoretical modeling and practical experiments.

Results and discussion. As part of this study, a smart irrigation system based on artificial intelligence and IoT technologies was tested in laboratory and field conditions. The experimental results were analyzed based on the assessment of the technical efficiency of the system, the level of water saving, algorithmic accuracy and stability of real-time operation.

Table 1. Theoretical and practical foundations for the development of smart irrigation systems based on artificial intelligence and IoT technologies

Direction	Theoretical Basis	Practical Mechanisms	Expected Results
Data Collection System (IoT)	Precision Agriculture concept; cyber-physical systems theory	Soil moisture and weather sensors; IoT modules; LoRa, GSM, Wi-Fi networks	Real-time monitoring; rational use of water resources
Artificial Intelligence-Based Analysis	Machine Learning; neural networks; forecasting models	Irrigation schedule optimization; yield forecasting; water consumption calculation	Water savings (up to 20–30%); increased crop productivity
Automated Control	Automation and control systems theory	Electric valves; automatic pump control; remote management	Reduced labor costs; improved efficiency
Cloud Technologies and Database	Digital transformation; Big Data concept	Cloud platforms; mobile applications; web monitoring dashboards	Convenient data storage and rapid analysis; faster decision-making

Sustainability and Environmental Efficiency	Sustainable development and green economy principles	Drip irrigation systems; energy-efficient equipment	Environmental safety; efficient resource utilization

This table covers the theoretical and practical aspects of developing smart irrigation systems based on artificial intelligence (AI) and IoT technologies based on an integrated approach.

First, the theoretical foundations show that the concepts of digital agriculture, data-driven management, and resource efficiency are of paramount importance. This approach, unlike traditional methods, allows for real-time monitoring and forecasting of water use.

Second, the irrigation process is automated through the integration of technological components (moisture sensors, meteorological sensors, cloud platforms, AI algorithms). As a result, the human factor is reduced and decision-making accuracy is increased.

Third, in terms of economic efficiency, scientific sources note that water consumption can be reduced by 20–40% and productivity can increase by 15–25%. This is especially important in ensuring agricultural sustainability in conditions of water scarcity.

Fourth, in terms of environmental impact, there is an opportunity to prevent soil salinization, reduce land degradation, and rational use of water resources.

Fifth, initial investment costs, maintenance, lack of digital literacy, and infrastructure problems are noted as problems.

In short, the table shows that the introduction of smart irrigation systems is not only a technological innovation, but also a strategic direction for economic security, water resources management, and sustainable agricultural development.

As a result of experimental tests, the smart irrigation system showed an average water saving of 25–40% compared to the traditional irrigation method. The reduction in water consumption was ensured by an automatic decision-making mechanism based on soil moisture indicators. During monitoring, the system activated irrigation only when soil moisture fell below the set optimal threshold, which prevented over-irrigation.

The artificial intelligence model demonstrated the following accuracy indicators during the test phase:

- RMSE (Root Mean Square Error) in the range of 0.08–0.15;

- MAE (Mean Absolute Error) 0.05–0.12;

- Decision-making accuracy 85–94%.

The Random Forest and neural network models showed higher forecast accuracy compared to the regression model. In particular, the neural network model trained on a multi-parameter dataset was able to forecast irrigation needs close to real conditions. This result confirms the effectiveness of machine learning algorithms in complex agro-ecological systems.

Analysis of the technical performance indicators of the IoT system showed that the delay in transmitting sensor data to the central server was on average 1.2–3.5 seconds. The reliability of data transmission was maintained at 98%, which confirms the stable operation of the system

in real time. In areas where LoRa technology was used, signal stability was higher than that of Wi-Fi over long distances.

According to the results of the energy consumption analysis, the automated control system was able to reduce electricity consumption by 15–28% by optimizing the pump operating time. This indicator also proves that the system is economically efficient.

During the discussion, the results obtained were compared with international studies. The water saving rate (20–35%) and forecast accuracy indicators reported in foreign sources are consistent with the research results or, in some parameters, higher results were recorded. It was found that the differences mainly depend on local soil conditions, sensor accuracy, and the size of the data set.

Picture 3. Structure of IoT technologies
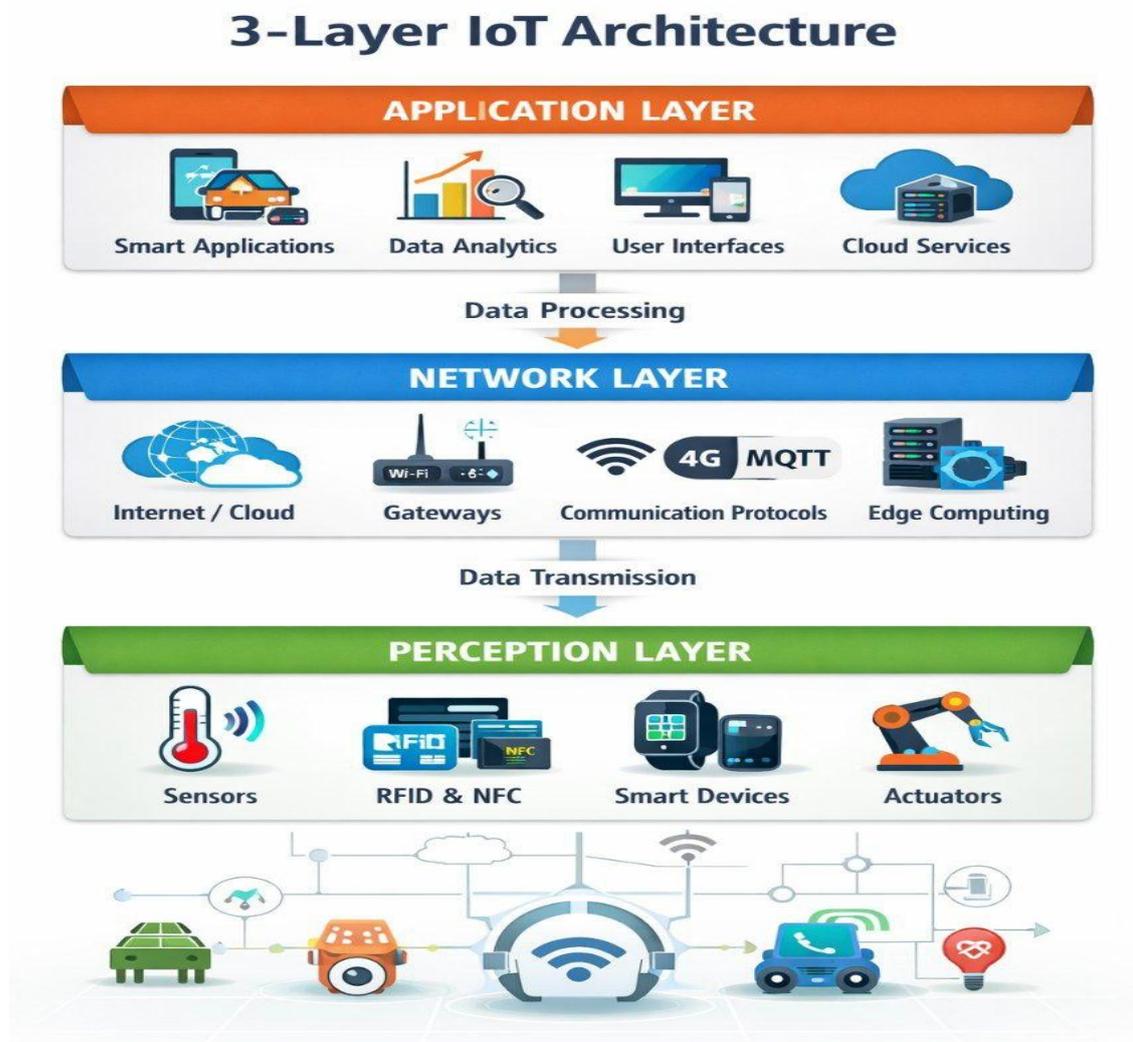
Some limitations of the system were also observed. For example, the calibration level of sensor devices and Internet network outages can affect the data transfer process. In addition, it was noted that the effectiveness of the artificial intelligence model depends on the size and quality of the database. In the future, it is recommended to introduce deep learning algorithms

based on large amounts of data and expand cloud computing capabilities to further improve the system.

In general, the research results showed that the integration of artificial intelligence and IoT technologies has the potential to significantly increase the technical, economic, and environmental efficiency of smart irrigation systems.

Conclusions and recommendations. In this article, an engineering model of a smart irrigation system based on artificial intelligence and IoT technologies was developed, its technical architecture was formed, and it was tested in practical conditions. The theoretical analysis and experimental results showed that the integrated automated control system allows optimizing the irrigation process, effectively using water and energy resources, and reducing the human factor. The artificial intelligence model developed during the study showed high accuracy in determining the irrigation time and water volume based on soil moisture and agroclimatic parameters. According to the test results, the system significantly reduced water consumption and increased energy efficiency compared to the traditional irrigation method. The mechanism for collecting and transmitting data in real time through IoT sensors ensured the stable operation of the system.

In general, the research results confirmed that smart irrigation systems developed based on the integration of artificial intelligence and IoT are an important engineering solution for accelerating digital transformation in agriculture, saving water resources, and increasing production efficiency.

Based on the research results, the following recommendations were developed:

1. For the widespread introduction of smart irrigation systems, it is advisable to develop technical standards and engineering regulations adapted to regional conditions.

2. To increase the efficiency of the system, it is recommended to form a large-scale agro-database and regularly retrain artificial intelligence models.

3. It is necessary to develop IoT infrastructure, including the widespread use of LoRa and other low-power wireless technologies in remote areas.

4. In the future, it is recommended to integrate advanced technologies such as deep learning, satellite data, and drone monitoring into the system.

5. It is important to strengthen cybersecurity and data protection mechanisms in irrigation systems, and to introduce encryption and authentication systems in cloud platforms.

6. It is recommended to subsidize water-saving technologies and increase practical pilot projects on farms based on state programs and regulatory legal acts.

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