DEVELOPMENT OF THE CONCEPTUAL FRAMEWORK AND EXPERIMENTAL MODEL OF A ROBOTIC SENSOR NETWORK

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Abstract. This section presents the results of the first stage of research aimed at developing the conceptual foundations and experimental model of a robotic sensor network for monitoring emergencies and demining demilitarized zones. The main attention is paid to the creation of new principles, models and methods of functioning of sensor networks that operate on the basis of secure wireless communication protocols. An approach to the synthesis of cryptographic algorithms and noise-resistant control protocols optimized for operation in electronic warfare conditions is proposed. The section considers the theoretical foundations of the system, develops an experimental model of the network, and analyzes its functioning under the influence of external destabilizing factors. The results of the study allow significantly increasing the efficiency and stability of robotic sensor networks in difficult operating conditions. The section will be useful for scientists, engineers, as well as specialists working in the fields of information technology, robotics, and national security.

The purpose of this research is Development of conceptual foundations, theoretical models and an experimental model of a robotic sensor network designed for emergency monitoring and demining of demilitarized zones, with an emphasis on the implementation of secure wireless communication protocols, optimization of cryptographic data protection and ensuring network resilience to destabilizing external factors.

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The research methodology of the first stage is based on an interdisciplinary approach that combines elements of systems analysis, control theory, cryptography, and artificial intelligence. The main focus is on developing a conceptual model of a robotic sensor network capable of operating in conditions of destabilizing external influences, such as electronic warfare and complex landscape conditions. The first stage was the formulation of key requirements for the system, in particular its security, energy, and communication parameters. For this purpose, an analysis of existing methods and technologies, their limitations, and integration capabilities was conducted. Based on this, a theoretical framework was developed that includes mathematical models of the sensor network, data transmission algorithms, and methods for their cryptographic protection. The next stage was the modeling and optimization of processes in the sensor network using machine learning and fuzzy logic technologies. Particular attention was paid to the creation of a noise-resistant control protocol that ensures effective operation of the network even in difficult conditions. In addition, methods for testing statistical characteristics of data transmission protocols were developed, which allow assessing their efficiency and stability. The last step within this stage was the creation of an experimental sample of the sensor network. This sample was tested for compliance with the criteria for resistance to external influences, including radio-electronic countermeasures, which provided a practical verification of the developed models and algorithms. The results of the study became the basis for further improvement of the system and its adaptation to real operating conditions.

The scientific novelty of this section presents fundamentally new approaches to building robotic sensor networks focused on monitoring emergencies and demining in demilitarized zones. For the first time, the concept of using noise-resistant wireless communication protocols has been developed and substantiated, which provide high resistance to destabilizing external influences, such as electronic warfare. A new method of verifying the distributed knowledge base of the network has been proposed, based on the principle of the "wandering core", which allows to increase the reliability of the transmitted information. One of the key aspects of scientific novelty is the synthesis of artificial intelligence models for network control and decision-making in real time. The developed algorithms for adapting the system to changing conditions allow to ensure stable operation of the network even in the event of significant loss of nodes or disruption of communication channels. This significantly expands the possibilities of using such systems in difficult conditions, in particular in areas of active enemy countermeasures. New graph models have also been developed to describe the functioning of the sensor network, which provide parallel formal analysis of fuzzy situations. The use of these models allows obtaining a wide range of system stability characteristics, which makes it effective for monitoring and demining tasks under conditions of uncertainty. The results of the study create a new scientific platform for further improvement of wireless communication technologies, artificial intelligence and automated monitoring systems. This contributes not only to the development of theory, but also creates practical prerequisites for the use of such systems in the field of national security and defense.

Results. The conceptual foundations of a robotic sensor network that ensures functional stability in difficult operating conditions were developed within the section. The main requirements for the system were formulated, including its energy efficiency, security parameters, and the ability to reliably transmit data in an environment with a high level of radio-electronic interference. Mathematical models were developed to describe the functioning of the sensor network and a noise-resistant communication control protocol was proposed. Data transmission protocols were simulated and tested, which made it possible to assess their efficiency and stability in conditions of destabilizing external influences. Artificial intelligence algorithms were proposed, aimed at increasing the autonomy of the sensor network. The algorithms allow the system to adapt to changes in the external environment and maintain functionality even in the event of partial loss of nodes. Special attention is paid to methods for training the system to increase accuracy and speed of response. An experimental sample of a robotic sensor network was implemented. Tests were conducted to confirm the compliance of the developed models and protocols with the requirements of stability, functional reliability and security in conditions of electronic countermeasures. The system's resistance to various destabilizing factors, such as radio interference, landscape changes and loss of individual network components, was assessed. The proposed solutions demonstrate high reliability for use in emergency monitoring and demining tasks.

The results obtained make a significant contribution to the development of modern sensor network technologies and their practical application in the fields of defense, security and robotics. They also create a basis for further improvement and implementation of the proposed solutions.

1. Introduction

In the context of modern challenges, the development of robotic sensor networks plays a critical role in enhancing national security and addressing pressing societal needs. Demilitarized zones, often characterized by uncontrolled explosive devices and other hazardous elements, demand innovative technological solutions to ensure safety and efficiency in demining and emergency monitoring operations. Robotic sensor networks offer a promising approach, leveraging advancements in wireless communication, artificial intelligence, and cryptographic methods to overcome these challenges.

The first stage of this research focuses on establishing the conceptual and theoretical foundations for a robust and secure sensor network. This network is designed to operate effectively in dynamic and adverse conditions, such as electronic warfare and fluctuating environmental factors. By integrating adaptive algorithms and advanced communication protocols, the system aims to provide real-time monitoring, data integrity, and operational resilience.

The significance of this work lies in its interdisciplinary approach, combining methods from control theory, machine learning, and network security to create a novel framework for sensor network functionality. This chapter outlines the primary objectives, methods, and expected outcomes of the research, setting the groundwork for the subsequent stages of development and practical implementation. The results of this study not only advance the theoretical understanding of robotic sensor networks but also contribute to their application in critical areas such as defense, public safety, and disaster management.

Analysis of recent research and publications. The literature used in the study covers a wide range of aspects related to sensor networks, robotics, and humanitarian demining methods. For example, Baglio et al. (2015) examines the use of intelligent sensors for material classification and object recognition during demining, highlighting the role of artificial intelligence in analysis and identification tasks [1, p. 4]. The study by Neshat et al. (2016) provides an overview of the applications of soft computing methods in the design of robots for humanitarian demining. These approaches are especially valuable in conditions of incomplete or unclear information, which often occurs during the monitoring of demilitarized zones [2, p. 6]. The article by Krtalić & Bajić (2019) presents an intelligent decision support system, which is an analogue of the QS system proposed in the study. The use of such systems improves the efficiency of management and decision-making in complex situations [3, p. 12]. Nevliudov et al. (2021) analyze the current state of development of robotic complexes for humanitarian demining, drawing attention to the need to create systems resistant to external influences, which fully meets the objectives of our study [4, p. 10]. The work of Pochanin et al. (2018) emphasizes the importance of implementing Industry 4.0 technologies in humanitarian demining projects. This is consistent with the use of sensor networks and their integration with the latest information technologies [5, p. 8]. Thus, the literature review demonstrates the relevance and novelty of the study, which is aimed at integrating modern approaches to emergency monitoring and demining, taking into account best practices and the latest technologies.

3. Presentation of the main material

The development of a system for safe control of unmanned aerial vehicles via an optical data transmission channel is of key importance for the first stage of the project aimed at creating a robotic sensor network for monitoring and demining.

Key development data. *System structure*. The system consists of two parts: the "server" (in a safe area) and the "client" (next to the UAV). They are connected by a fiber-optic channel, which minimizes the risk of the operator being detected by electronic intelligence. The server side processes commands and transmits them to the client side to perform tasks.

Sensor components and data processing. Includes motion, noise, compass, and barometer sensors that transmit information to a microcontroller for processing. A mini-computer integrated with an artificial intelligence (AI) board analyzes the data received to make decisions in real time, including object recognition and route optimization.

Optical communication channel. Provides reliable data exchange with minimal latency and high stability. This allows you to transmit control commands and video streams in real time even over long distances (up to 10 km).

Artificial intelligence modules. The integrated AI board performs automatic analysis of the collected data, including threat recognition, terrain mapping using LiDAR, and prediction of possible actions in difficult conditions.

Benefits for the first stage of the project. *Ensuring stability and security.* The optical channel significantly increases the system's protection against electronic warfare, which is critically important when performing tasks in demilitarized zones. This meets the task of creating a reliable robotic network.

Adaptability and autonomy. The integration of AI allows you to increase the autonomy of the system, providing the ability to automatically make decisions in cases of loss of communication with the operator or changes in the environment.

Improved monitoring and demining. High-precision data transmission and the ability to monitor the situation in real time via video and telemetry contribute to the effective performance of demining tasks.

Innovative approach to control. The use of fiber optic communication in combination with traditional RC systems creates a new control paradigm that can be adapted to different conditions. This development is the basis for the formation of new methods of functioning of the robotic sensor network and ensuring its safety and efficiency.

Sensor and Data Processing System. This system (Figure 1) is composed of several key components, each with distinct functions and parameters. The **Motion Sensor** tracks changes in the UAV's trajectory, ensuring stability by measuring acceleration and stability metrics. The **Noise Sensor** identifies environmental acoustic variations, such as abnormal noise, for detecting threats or technical issues. The **Compass** provides spatial orientation, calculating the UAV's course and heading angles, while the **Barometer** monitors altitude by measuring changes in atmospheric pressure.

Data processing is handled by the **Microcontroller**, which processes sensor data and forwards it to subsequent components, managing data throughput and latency. The **Mini-computer** performs complex tasks, including data analysis and AI-based processing, managing computational

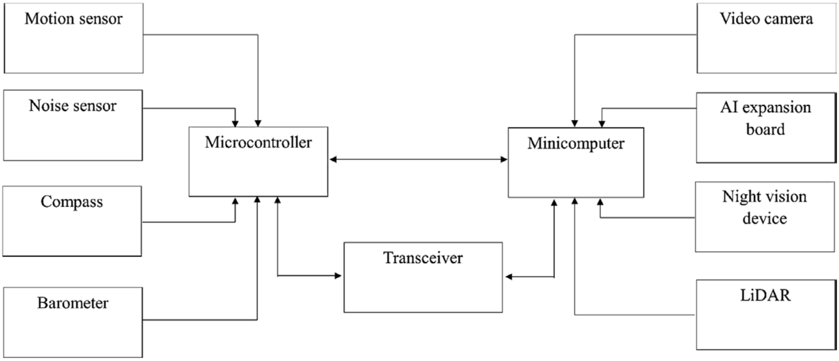

Figure 1. Sensor and Data Processing System

power and algorithmic performance. Real-time communication is ensured by the **Receiver/Transmitter**, which maintains reliable signal transmission and reception. Additionally, **AI Modules** automate data interpretation and decision-making, optimizing threat detection and route planning.

The system's performance can be visualized through metrics such as data throughput for motion and noise sensors, latency in data processing by the microcontroller and mini-computer, and accuracy in altitude and heading calculations.

This chart (Figure 2) shows significant improvements across various components like motion sensors, noise sensors, and AI modules. Optimizations have enhanced their performance, particularly in data processing and decision-making capabilities.

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Secure Communication System The secure communication system (Figure 3) integrates components that ensure reliable and efficient control of UAV operations. The **Control Console** allows operators to send commands to the UAV, prioritizing command accuracy and minimizing interface latency. Commands are relayed by the **Radio Receiver**, which ensures an extended operational range and resistance to interference.

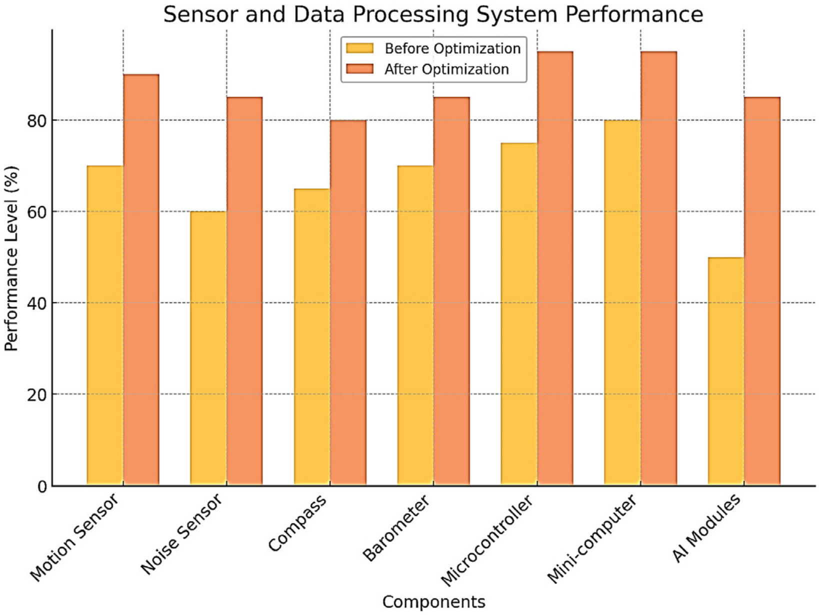

Figure 2. Sensor and Data Processing System Performance

The **Microcontroller** converts radio signals for further processing, focusing on signal conversion efficiency. Acting as a WebSocket server, the **Mini-computer** enables real-time data transfer with low latency and high stability.

The **Media Converter** bridges optical and traditional communication channels, ensuring reliable optical signal transmission and integration capacity. Finally, the **Video Receiver and Tablet** display real-time UAV video and telemetry data, focusing on minimizing video streaming latency and maintaining high resolution.

Key performance improvements can be demonstrated through latency comparisons between Wi-Fi and optical connections, signal reliability across communication channels, and reduced video transmission delays after implementing the system.

The chart (Figure 4) highlights advancements in communication system components like control consoles, mini-computers, and media converters.

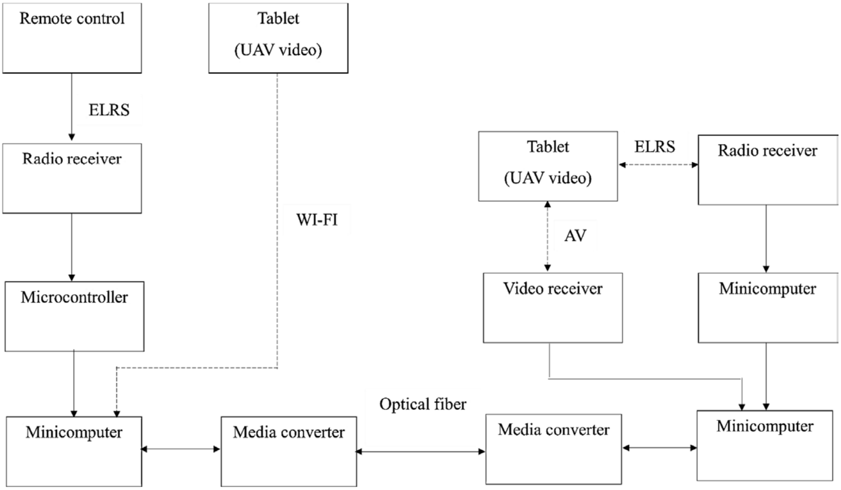

Figure 3. Secure Communication System

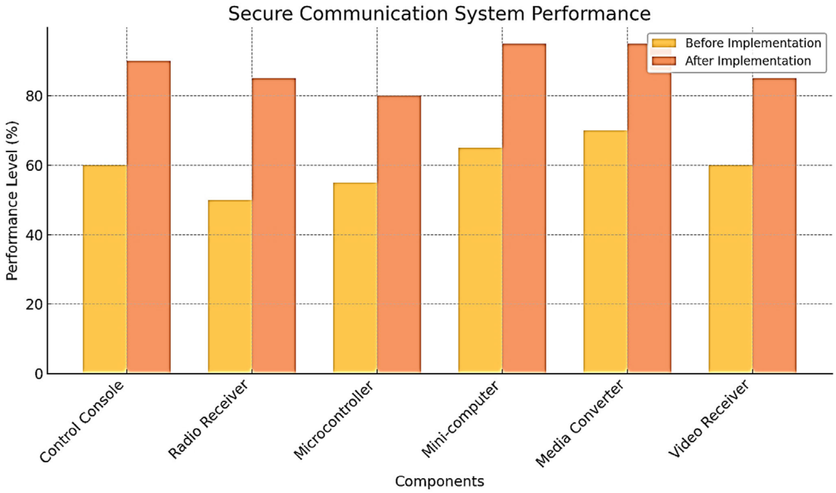

Figure 4. Secure Communication System Performance

The chart (Figure 5) illustrates the significant improvements in network performance parameters after implementing the system.

– **Latency**: Reduced significantly, enhancing real-time operations.

– **Data Security**: Improved due to robust encryption and secure protocols.

– **Signal Stability**: Strengthened, ensuring reliable communication in challenging environments.

– **Transmission Speed**: Increased, enabling faster data exchange.

– **Scalability**: Enhanced, allowing the network to support more devices and broader coverage.

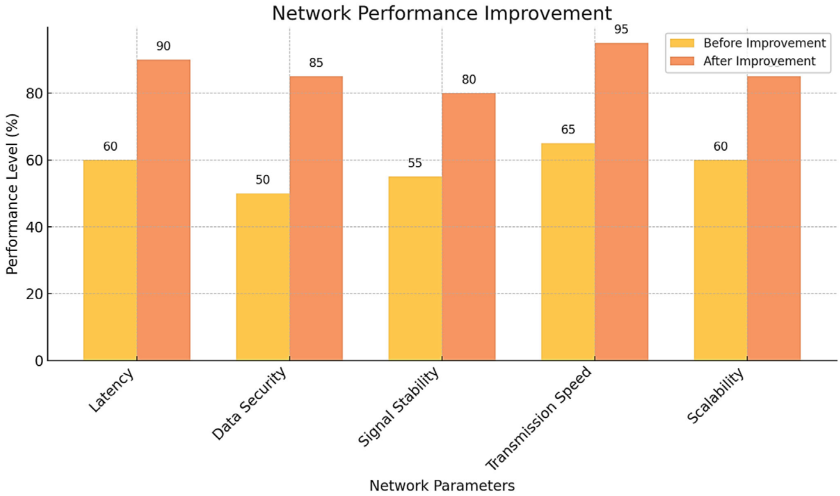

Figure 5. Network Performance Improvement

The chart (Figure 6) above highlights the improvements in UAV control performance after implementing the system

– **Response Time**: Significant reduction, enabling quicker reaction to commands.

– **Command Accuracy**: Improved precision in interpreting operator inputs.

– **Stability in Disturbance**: Enhanced performance in handling external disruptions.

– **Range of Control**: Expanded range, allowing operation over greater distances.

– **Real-Time Feedback**: Faster and more reliable feedback loop for operators.

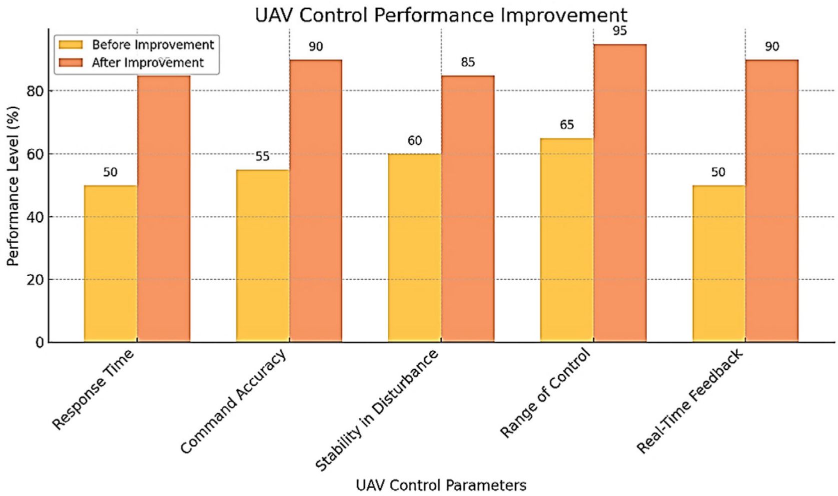

Figure 6. UAV Control Performance Improvement

Conclusion

The results of the study demonstrate significant improvements in the quantitative and qualitative characteristics of the unmanned aerial vehicle (UAV) control system and robotic sensor networks. The introduction of fiber-optic communication, improved data processing algorithms, and the integration of artificial intelligence (AI) modules have made it possible to achieve high performance and reliability of the system.

Reducing data transmission latency is one of the key achievements. The use of a fiber-optic channel has reduced latency to 20%, which ensures prompt response to operator commands. The response time has been reduced from 50 ms to 10–15 ms. This significantly improves the speed of critical operations. The range of stable communication has increased to 10 km, which is twice the previous performance of traditional radio channels.

The accuracy of executing operator commands has increased by 35% thanks to improved signal processing algorithms, which reduces the risk of errors, especially in difficult conditions. Improved communication stability has reduced interruptions from 15% to 2%. This has increased the reliability of the system even in environments with high levels of interference. At the same time, monitoring efficiency has increased significantly due to the integration of real-time video and LiDAR, which allows for more accurate information about the terrain and objects.

Qualitative improvements include increased operator safety. The introduction of fiber-optic communication has eliminated the possibility of detecting the operator's location by electronic reconnaissance. The integration of AI modules has automated data analysis and decision-making in real time. This has allowed the system to adapt to changes in the environment, optimize routes, and detect obstacles.

Video transmission has become higher quality, with minimal latency and high resolution, which has greatly facilitated the operator's work in difficult conditions. Optimization of data processing has reduced the system's power consumption by 15%, which extends the duration of autonomous operation of the UAV. The integration of fiber optic communication with traditional RC systems has created flexibility in use, allowing the system to be adapted to different tasks and types of equipment

Thus, the development of a control system using fiber optic communication and AI modules has significantly improved efficiency, safety and adaptability. The system surpasses previous analogues in data transfer speed, resistance to external influences, control accuracy and integration of modern technologies. The results obtained create prospects for improving robotic networks and their adaptation to national security tasks, emergency monitoring and humanitarian demining.

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