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Application of Unmanned Aerial Vehicles and Intelligent Systems in Forest Fire Monitoring and Management

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Keywords	Abstract
Forest fire localization Unmanned aerial vehicles (UAVs) Optimal operation planning Mathematical modeling Real-time monitoring	The article examines the possibilities of using unmanned aerial vehicles (UAVs) and modern digital technologies for monitoring and management of forest fires. The limitations of traditional methods for observation and prediction are analyzed, as they are characterized by low operational efficiency, high costs, and limited accuracy under dynamic conditions. An integrated approach is proposed, based on the use of UAVs, geographic information systems (GIS), and image processing methods, which enables real-time data collection and analysis. The structure of an information system for managing firefighting forces and resources is presented, including data acquisition, processing, and transmission from various sources, such as satellite systems and onboard UAV equipment. The study examines the mathematical modeling of forest fire dynamics using an agent-based approach, which allows simulation of both fire spread and suppression processes. The model is integrated with a geoinformation environment, ensuring higher accuracy and applicability in decision-making. The economic efficiency of the proposed solution is also considered, emphasizing the role of early detection and optimal resource allocation in reducing damage. The use of UAVs leads to a significant reduction in costs and an increase in the effectiveness of forest fire management. The integration of UAVs, neural networks, and intelligent systems creates new opportunities for sustainable environmental monitoring and effective management of natural disasters.
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1. INTRODUCTION

Forest fires represent one of the most serious natural disasters, having a significant impact on the ecological system, the economy, and public safety. In recent decades, their frequency and intensity have increased, leading to climate change and anthropogenic factors, which necessitate the development of new approaches for their early detection and effective management.

Traditional methods for monitoring and predicting forest fires are characterized by limited efficiency, especially when applied to large and hard-to-access areas. The use of unmanned aerial vehicles (UAVs) in combination with modern information and intelligent systems is emerging as a promising approach for improving the operational efficiency and accuracy of monitoring.

The present study aims to investigate the possibilities for the integrated use of UAVs, geographic information systems (GIS), and mathematical modeling methods in the monitoring and management of forest fires. The study examines the development of an information system for decision support, as well as to the evaluation of the effectiveness of the proposed solutions.

2. FOREST RESOURCE MANAGEMENT: FROM SATELLITE TO TREE

Forests are the lungs of the planet. They absorb carbon, produce oxygen, and provide habitat for more than 80% of terrestrial species. Their destruction continues at a catastrophic rate, with more than 10 million hectares of forest lost annually, according to UN data. Traditional monitoring through ground inspections is impractical due to the scale and inaccessibility of these territories. Satellite imagery, unmanned aerial vehicles (UAVs), and neural networks play a crucial role.

Models analyze high-resolution images by identifying changes in vegetation cover, canopy density, and leaf coloration. They can detect even minor signs of logging, such as cleared strips of forest, newly constructed roads, and traces of heavy machinery. Some systems are capable of distinguishing tree species—coniferous or deciduous—and assessing their condition based on leaf color. For example, yellowing leaves may indicate disease, water deficiency, or soil contamination. Neural networks can suggest appropriate measures such as irrigation, fertilization, or quarantine.

Such systems enable government agencies and private companies not only to detect violations but also to predict them. If, for example, an increase in new roads and intensified truck movement is observed in a given area over the past three months, the model may issue a warning: “Probability of illegal logging within the next 14 days – 78%”. This allows patrols to be deployed proactively rather than after the forest has already been destroyed.

Security policy is implemented through compliance with environmental assessment and protection standards, as well as participation in global and regional initiatives and environmental projects aimed at improving environmental quality and ensuring ecological security. The development of global aerospace engineering and digital technologies has enabled unmanned aerial vehicles (UAVs) to be applied in various fields of human activity. These include areas requiring high-quality spatial information from hard-to-reach territories within a short time frame. The use of UAVs for terrain imaging is considered one of the most significant directions in forestry activities (Manolis et al., 2019; Khafizov et al., 2011). This method of collecting geospatial data is characterized by high operational efficiency and is highly applicable under current conditions (Petrova & Marinov, 2019; Manolis et al., 2019). In the future, the primary users of UAV services will be activities requiring regular monitoring of linear and area-based objects (Khafizov et al., 2011).

The transition in the application of UAVs should be considered. The capabilities for real-time optical and radar observation can be redirected toward studying the geomorphological state of the planet, environmental pollution, early warning systems, and the occurrence and consequences of various natural disasters. An essential aspect of environmental security and sustainability is the prevention, management, and mitigation of industrial accidents involving harmful emissions, transboundary air and water pollution, coastal contamination, and potential threats related to the use of weapons of mass destruction. Synthetic aperture radar systems form the basis of interferometric SAR approaches for Earth observation, enabling the creation of three-dimensional maps of observed areas, as well as monitoring large-scale geological processes such as tectonic movements, volcanic and seismic structures, ice sheets, and icebergs (Carnec & Delacourt, 2000).

Water resource management is carried out through a unified information system based on interinstitutional mechanisms for planning, monitoring, and evaluation. Efforts are also directed

toward establishing an effective system for managing and mitigating the consequences of natural disasters with the active participation of citizens and their organizations.

Effective crisis response and the protection of citizens, their property, and critical infrastructure in the event of fires, disasters, accidents, and deliberate threats are achieved through a comprehensive approach to building an integrated, flexible, and sustainable national management system. UAVs have gained widespread popularity due to their ability to acquire various types of radio technical information from areas where it is difficult to deploy human operators.

The development of computing technology and digital signal processing has significantly improved the quality, speed, and volume of image processing, enabling its transmission over long distances. At the same time, digital technologies also have certain limitations that affect their effectiveness in observation systems. Various types of optical systems in UAVs are used for (Petrova & Marinov, 2019):

- surveying terrain and monitoring the situation;
- obtaining detailed images of specific areas and objects;
- detecting objects that are visually undetectable in the terrain.

Effective environmental monitoring and the detection of various objects on the Earth's surface or within its subsurface are important across a wide range of human activities and are often complicated by adverse factors such as increased radiation, the presence of hazardous substances, disasters, and accidents. This task is particularly important in combating poaching of valuable species, where UAVs prove especially effective.

In monitoring airspace, land, and water surfaces, depending on specific objectives, UAVs can be used for aerial imaging, hydrometeorological monitoring, atmospheric research, radiometric control of disaster zones, seismic monitoring, inspection of pipelines and power grids, geological observations, subsurface exploration, ice monitoring, and sea state analysis. Capacity is being developed for prevention, early warning, and crisis management based on information exchange and the use of space and other advanced technologies. For effective crisis management, integrated military and civilian capabilities are being developed at both national and European Union levels (Petrova & Marinov, 2019).

Climate change is no longer a future threat but a reality affecting all aspects of life, from agriculture to public security. Neural networks are becoming one of the key tools in addressing its consequences. Climate models consist of mathematical equations describing the interactions between the atmosphere, oceans, glaciers, and the biosphere. Traditional models require enormous computational resources and weeks of processing time. Neural networks significantly accelerate this process. They analyze data from thousands of satellites, meteorological stations, and ocean buoys—such as temperature, humidity, wind speed, sea level, and CO₂ concentration – and generate forecasts for decades ahead. These forecasts indicate how the climate will change, which regions may become unsuitable for agriculture, and where critical drought zones may emerge.

Such predictions assist governments in planning population relocation, restructuring infrastructure, and adopting sustainable agricultural practices. Neural networks can also operate at a local level. While global models may indicate that “by 2050 the average temperature in Europe will increase by 2.5°C”, a neural network can refine this prediction to “in village X, in July 2048, temperatures will exceed 35°C on 18 out of 30 days”. This level of accuracy enables local authorities to make targeted

decisions, such as creating shaded areas, installing cooling systems in public spaces, or adjusting school schedules.

Biodiversity is not merely a count of species, but a complex network of interdependencies, where the extinction of a single species can trigger a cascading collapse of the entire ecosystem. Neural networks help maintain this balance by automatically tracking populations of rare species, from the Amur tiger to specific butterfly species. Using cameras, UAVs, and acoustic trackers, these systems detect animal presence, behavior, and migration patterns. The collected data are used to generate “vulnerability maps” identifying areas where species are most at risk. Based on this information, priorities for conservation are established, including the designation of protected areas, restrictions on tourism, and allocation of funding.

In Africa, neural network-based systems assist in protecting elephants. Cameras positioned along reserve boundaries monitor the movements of animals and humans. If a group of armed individuals approaching a herd of elephants is detected, the system automatically alerts security and law enforcement. Similar systems are deployed in the Amazon region to monitor illegal logging and poaching activities.

The application of UAVs in forestry lacks a sufficiently developed theoretical framework that accounts for technical characteristics, flight optimization, and the required number of devices. This deficiency limits the practical capabilities and efficiency of the technology. UAVs should be considered as elements of a unified information system integrated with existing forestry management structures (Manolis et al., 2019). Several issues continue to hinder their practical use, including the absence of regulatory frameworks for airspace operation, lack of insurance mechanisms for third-party damages, insufficient ground control points, unsatisfactory image quality, complexity in organizing flight operations, and limited accuracy of onboard navigation systems (2; Manolis et al., 2019).

Forest fires pose a significant threat to national security, negatively impacting both the economy and the environment. Existing traditional models for predicting forest fires (wave-based, statistical, and simulation models) (Petrova & Marinov, 2019) exhibit several major limitations, including restricted functionality under non-stationary and uncertain conditions, low prediction accuracy, and high computational costs, making them less suitable for operational forecasting.

The introduction of new technologies for early detection of forest fires enables timely response, localization, and suppression, thereby minimizing losses. The problem of early fire detection and situational monitoring, as well as rapid response to illegal logging, can be effectively addressed through UAV-based forest monitoring.

UAVs vary in payload capacity, flight range, and onboard equipment. Advances in electronic engineering, precise satellite navigation systems, and component miniaturization have significantly expanded their capabilities. In practice, UAVs are autonomous robotic systems with various configurations, purposes, and cost levels. Equipped with photo, video, and thermal cameras, along with real-time automated data processing, they are widely used for monitoring forest conditions, detecting deforestation, fires, and floods. UAVs can also efficiently perform meteorological observations at different altitudes over large areas, monitor ice conditions and environmental status, and track wildlife populations.

In many regions, there is an urgent need for the delivery of chemical and technical resources for forest protection and fire suppression. This need often remains unfulfilled due to the lack of suitable year-round equipment. The use of UAVs for such purposes represents a realistic perspective in the

near future. A key role in the development of next-generation UAVs is played by flight control and navigation systems. These systems are based on onboard computers, advanced software, miniaturized components, and Global Navigation Satellite Systems (GNSS). They provide high positioning accuracy and reliability during automatic takeoff, flight, and landing operations, ensuring safety and ease of operation for various types of UAVs (Manolis et al., 2019; Carnec & Delacourt, 2000).

Neural networks rarely operate in isolation; their strength lies in integration.

Internet of Things (IoT). Thousands of sensors in forests, rivers, and oceans collect data in real time. Neural networks analyze these data and control systems by activating irrigation only when actual soil drought conditions are detected.

Blockchain. This technology ensures the authenticity of environmental data. If a sensor records deforestation, the entry in the blockchain network cannot be altered. This guarantees transparency and data integrity.

Augmented Reality (AR). Environmental specialists use specialized devices that provide an additional information layer, such as: "A rare species X grows here. Recommendation: do not enter within a 10-meter radius".

Such systems are already being tested in national parks. They create a digital representation of nature – a digital twin of the ecosystem – that is continuously updated and allows simulation of the consequences of actions before their actual implementation.

Neural networks are powerful tools, but they do not replace science; rather, they complement it. Hybrid models combine physical laws (e.g., heat transfer equations) with machine learning data, resulting in more reliable predictions. For instance, while a traditional model may predict temperature increase based on the law of energy conservation, a neural network can add contextual analysis, such as: "Last year, with a temperature increase of 1.8°C, forest degradation began in region Y". Instead of a single value, a more comprehensive forecast is obtained. These models are less prone to errors and are more interpretable for researchers.

Climate processes are not confined to national borders. Forests in Brazil influence weather patterns in Siberia, and bird migration spans entire continents. Therefore, technological solutions must be shared globally. There is a need for international databases and open platforms where researchers from different countries can train models using shared datasets. Standardization of data formats is essential to ensure interoperability between systems developed in different regions. This requires political will, funding, and mutual trust. Successful examples already exist, such as global coral reef monitoring networks that integrate data from over 40 countries.

3. SYSTEM FOR MANAGING WILDFIRE SUPPRESSION USING UAVS THROUGH IMAGE GEOREFERENCING TO GEOGRAPHIC MAPS

Digital image processing and the analysis of the objects contained within them represent a fundamental problem. Its solution requires addressing a series of specific tasks and selecting an appropriate strategy for distinguishing objects from the background. Many tasks related to thematic image interpretation are reduced to the comparison of images obtained using sensors operating in different physical domains. A typical example is the development of remote sensing methods for monitoring natural resources and ecosystem dynamics, which involves comparing images of the same territory acquired at different times and/or using different sensors. Most commonly, optical,

radar, thermal, magnetic, and other types of data are used. The combined use of different physical sensing modalities requires preliminary image processing, for example, to transform images into a common spectral domain.

In practice, images of the same object or terrain area, obtained at different times or using different sensors, may differ significantly. This leads to several important challenges related to image registration, as well as precise geometric and radiometric correction for subsequent joint analysis. In all cases, it is necessary to establish correspondence between elements of the source images, which involves identifying so-called reference (control or tie) points. These points enable coordinate alignment of images along with simultaneous geometric corrections (points in two images are considered corresponding if they represent the same point in the observed scene (Petrova & Marinov, 2019)).

Aerospace computer-based monitoring assumes discrete observations over short time intervals. When a moving camera captures a bright image of an observed object (optical surface) as a sequence of frames, this image is deformed from frame to frame due to perspective distortions and changes in camera position. The geometry of these deformations is modeled using projective transformations, which form a broader class than classical Euclidean transformations (in projective geometry, lengths and angles are not preserved, and parallel lines do not remain parallel (Gonzalez & Woods, 2005)).

Reconstruction of terrain relief from stereo images leads to an identification problem, namely, determining precise point correspondences between elements of the stereo pair. The solution involves selecting pairs of reference fragments and estimating the disparity parameters of corresponding points, based on which the geometric transformation function can be reconstructed, and the three-dimensional surface (terrain) can be evaluated (Smolyakov & Fedorovich, 2006).

With the advancement of technology, it has become possible to capture images of the Earth's surface using UAVs. These systems are equipped with navigation units based on global satellite navigation systems and inertial sensors (Manolis et al., 2019). In order to use such navigation data for image georeferencing, a sufficiently high level of accuracy is required. Various algorithms are employed to reduce errors from inertial sensors and improve positioning accuracy (Manolis et al., 2019; Nicolae et al., 2019). The use of UAVs significantly reduces the cost of terrain imaging.

Image acquisition from airborne platforms is inevitably associated with geometric distortions. These distortions are caused by several factors:

- camera perspective;
- motion of the aerial platform;
- spatial orientation of the platform;
- flight altitude and velocity;
- terrain relief;
- use of different sensors (infrared, video cameras, radar, etc.).

In order to compare and integrate images obtained from different sensors or at different times, it is necessary to perform geometric corrections. When aligning an image with a map, the image

coordinates must be transformed into the coordinate system of the map. Since many of these distortions are systematic, sufficiently accurate models can be developed to compensate for them to a large extent.

In order to compare and integrate images obtained from different sensors or from the same sensor at different points in time, it is necessary to first perform geometric corrections of the images. When aligning an image with a map, the image coordinates must be transformed into the coordinate system of the map. Since a large portion of these distortions is systematic, sufficiently accurate models can be developed, allowing them to be compensated to a significant extent.

Wildfires, including forest, steppe, peatland, and other types of natural fires, are hazardous and dynamic processes that cause significant damage to the environment and infrastructure and often result in human casualties, thereby posing a threat to national security. In many cases, firefighting requires the deployment of a large number of forces and resources, which leads to the need for their rational planning and management. A number of regulatory documents have been developed to address these challenges (Petrova & Marinov, 2019; Smolyakov & Fedorovich, 2006). Efforts have also been made to develop a theory for wildfire management (Manolis et al., 2019); however, in many cases, control is assumed to operate in an open-loop mode without consideration of the actual state of the system. Possible disturbances and incomplete information about the controlled object are also not taken into account.

In recent years, with the establishment of space-based forest fire monitoring systems and the rapid advancement of UAV technology, it has become possible to evaluate forest fire parameters in real-time. This paves the way for operational control systems with feedback loops (Nicolae et al., 2019). Given the impact of forest fires on national security, the primary parameters of a multifunctional information management system are examined. The block diagram of this system is shown in Figure 1, where $x(t)$ is the actual fire area, $u(t)$ is the control action, $y(t)$ is the estimated fire area, FRC is the fire risk class, $L(t)$ is the length of the burning edges, and W is the wind speed.

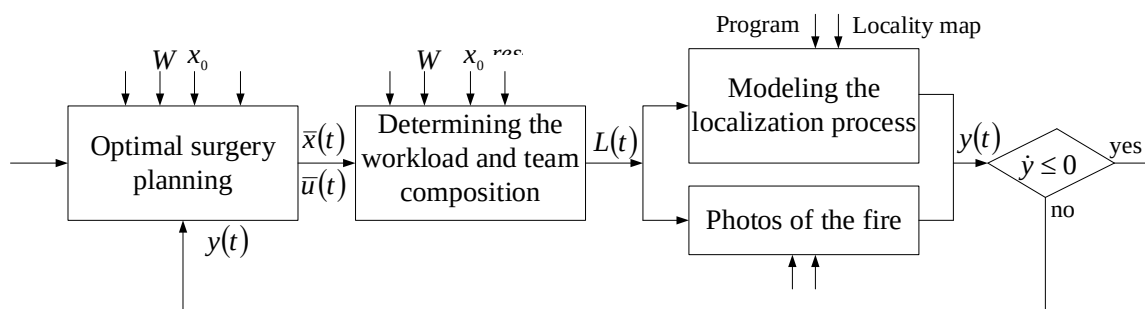


Fig. 1. Block diagram of the system for firefighting forces and resources

The system is designed for monitoring and operational management of wildfire suppression and is based on the use of satellite information and data obtained from UAVs. The system can also be used for training operational personnel in firefighting services. It is proposed that the task of managing firefighting forces and resources be divided into several levels (Nicolae et al., 2019).

At the first level, a model with a single state variable—the area affected by the fire - is considered. The dynamics of the fire zone are the most important indicator, as they determine both the extent of fire damage and the effectiveness of firefighting efforts. A dynamic equation is formulated for this variable, on the basis of which an optimal control algorithm can be derived using the theory of Analytical Construction of Optimal Regulators (ACOR) (Gonzalez & Woods, 2005). The obtained solution serves as a reference plan for implementation and adjustment at subsequent levels.

At the second level, the model transitions to a new variable that defines the volume of work required to suppress the fire. This variable is the length of the fire front that must be extinguished. This parameter can be estimated either through the processing of real-time images of the fire or through the calculation and prediction of fire spread based on a geometric model (Manolis et al., 2019). At this stage, the problem of selecting the composition and required number of firefighting forces and resources is addressed.

The process of fire localization and suppression is simulated on a terrain map using a specialized GIS-oriented system, which predicts the fire configuration and determines the dynamics of its area, fire front length, and other parameters. All data can be obtained and updated through direct observation of the fire using UAVs. The estimated fire area serves as a feedback signal and is transmitted to the upper level of the system, where a Kalman filter is used to adjust the control input, and the entire control cycle is repeated.

The stopping criterion for the control process is the cessation of fire spread, i.e., when the time derivative of the fire area becomes zero. The quality of the control process is evaluated using a quadratic criterion, as adopted in ACOR theory.

System Structure. The system consists of the following components:

- a hardware and software complex, including UAVs, communication, and telecommunication systems;
- methods and algorithms for identifying parameters of wildfire models based on satellite forest monitoring and UAV data;
- mathematical models of wildfire dynamics and suppression processes, implemented as a software information system and oriented toward decision-making in forest protection and emergency situations;
- a computer simulation system for supporting operational decision-making and training personnel in wildfire response tactics (Carnec & Delacourt, 2000).

Functions of the Information System. The information system performs the following functions:

- data collection;
- data processing;
- transmission of information to end users.

During the data acquisition stage, the following sources are used:

Data on active fires and weather conditions were obtained from forest satellite monitoring information systems. These systems are used by organizations involved in wildfire suppression and provide up-to-date information, although typically with low spatial resolution.

Google Maps platform. The developed system uses this source to obtain terrain data, which are among the most accurate publicly available datasets and are accessible via a convenient API.

Data from onboard UAV equipment were collected directly from the fire location. These data have high spatial resolution and contain information about the fire, the forest environment, and

meteorological conditions. The data are transmitted to a server for storage and retransmission via a primary (GPRS) channel and a backup (radio) channel through a relay station. Data from different sources received by the server are analyzed and compared and, after initial processing, are stored in a database for further use.

The data can be accessed through various interfaces via a REST API and serve as a basis for rapid decision-making by firefighting specialists. They can also be utilized by third-party information systems.

During the data processing stage, the configuration and parameters of the detected fire are evaluated. Mathematical models are refined and adjusted based on newly acquired data, and the fire spread process is simulated using one or more algorithms. Operational forecasting of fire propagation is performed, along with an assessment of the required forces and resources for its suppression. The resulting data can also be used within the information system as a source for improvement, analysis, and statistical support in personnel training.

During the data dissemination stage, all information generated within the system is stored on a server and distributed to relevant users. A database server (MySQL) running on a GNU/Linux Debian operating system is used. Data exchange with UAVs is carried out via the HTTP protocol and REST API.

For data processing - due to its asynchronous nature, unpredictability of processing durations, and multiple processing stages - a multi-agent approach can be applied.

Type 1 agents receive raw UAV data and store it in the database.

Type 2 agents enrich these data using the Google Maps API with terrain characteristics in the vicinity of the fire.

Type 3 agents determine the coordinates of the fire front points based on sensor orientation and tilt angle, UAV geographic coordinates at the time of detection, terrain data, and UAV altitude above sea level.

Type 4 agents are responsible for exchanging processed data with other components of the developed hardware-software complex (HSC).

4. MATHEMATICAL MODEL OF FIRE DYNAMICS AND THE SUPPRESSION PROCESS

In the field under consideration, a large number of mathematical models have been developed (Satyukov et al., 2012; Carnec & Delacourt, 2000), differing in the degree to which they account for the physicochemical processes of plant material combustion and their computational complexity. However, most of them do not simultaneously describe the processes of wildfire spread and its suppression. An agent-based modeling (ABM) approach is proposed in this dissertation. ABM is a novel approach to simulation modeling focused on complex dynamic systems by studying the behavior and interaction of autonomous and independent entities (agents) within a specific environment (Latypova & Popova, 2015).

For modeling forest fire situations, Geographic Information Systems (GIS) are of particular interest due to their ability to store and visualize spatial information. The combined use of ABM and GIS allows for the integration of the advantages of both fields, applying promising tools for modeling processes that occur in real landscapes. The idea of modeling wildfire perimeters using an agent-

based approach is not new (Petrova & Marinov, 2019; Khafizov et al., 2011). Such agent models have been created using specialized platforms for programmatic description of agent activities and environmental states, such as NetLogo, StarLogo, Repast Symphony, etc. While this approach simplifies the software implementation of the simulation model, it significantly complicates integration with GIS. In these works, a freely spreading fire is simulated without modeling firefighting forces and resources.

In the developed system, the model environment consists of a map section of actual terrain with an overlay describing fuel materials of plant origin (FMPO). This makes it possible to combine GIS data with the agent model. The model utilizes information regarding settlements, rivers, lakes, roads, valleys, forest plantations, etc. Positioning on the map is performed by defining spatial coordinates unique to each object. A thin-layer model is used as the combustion model (Petrova & Marinov, 2019; Gonzalez & Woods, 2005). In the thin-layer model, the forest cover is treated as a uniform layer on the Earth's surface with averaged FMPO characteristics. These characteristics are determined based on the pyrological description of the forest map sections. For each location on the map, the surface type is pre-determined, which identifies the presence and type of primary combustion carriers (PCC). Depending on the PCC type, the base fire spread rate V_{PCC} , m/min , and the layer ignition temperature Q , J/m^2 , are defined. The following parameters are adopted as key environmental indicators:

- Wind speed according to the nearest meteorological station V_w ;
- Wind direction vector W ;
- Fire danger class based on climatic conditions (FRC).

These parameters significantly influence the speed and direction of fire spread, as well as the intensity of combustion.

The model utilizes two types of agents. Type A agents are used to model forest fire behavior and together represent the fire contours on the map. The model allows for the simultaneous presence of several such contours, spreading independently in different parts of the map. The primary goal guiding Type A agents during execution is movement through environment modeling. The calculation of the spatial coordinates of the agents at each modeling stage is performed according to a pre-defined law. During execution, Type A agents can generate new agents or be removed under certain conditions. The calculation of new coordinates A_x , A_y at each simulation iteration is performed using an algorithm based on the moving grid method (Manolis et al., 2019).

Type B agents simulate the actions of firefighting forces and exert an influence on the first type of agents. During execution, Type B agents are guided by a single goal: to "extinguish" all burning points. To achieve this, a Type B agent moves through the environment to the nearest Type A agent A_i and affects its indicator, the combustion intensity I . As soon as this indicator reaches 0, the agent A_i changes its state to "not burning," and the Type B agent moves to the next agent $A_{R(i)}$.

The purpose of creating this computer simulation system is to improve the quality of training and retraining for specialists working in the field of forest fire protection. The goal of the computer simulation is to localize the fire by surrounding it with impassable boundaries to achieve minimum total damage, which consists of the costs of the forest damaged by the fire and the costs of localizing the fire. A set of forces and resources is available to the system operator, from which they can choose to localize the fire, but each involves specific costs.

5. ECONOMIC EFFICIENCY OF USING UNMANNED AERIAL VEHICLES IN FOREST FIRE MONITORING AND MANAGEMENT

The economic efficiency of implementing modern technological solutions in the field of forest fire monitoring and management is a key factor in assessing their applicability and sustainability. Under conditions of limited resources and an increasing frequency of natural disasters, the selection of appropriate monitoring and response tools must be justified not only in terms of technical capabilities but also through an analysis of costs and expected benefits.

Traditional methods for monitoring forest areas include ground patrols, observation towers, and manned aviation. These approaches are characterized by high labor intensity, high operational costs, and limited effectiveness in covering large and hard-to-access regions. An additional drawback is the delay in fire detection, which often leads to uncontrolled fire spread and significantly increased damage to forest resources, infrastructure, and the economy as a whole.

The introduction of unmanned aerial vehicles (UAVs) creates conditions for substantial improvement in the economic performance of monitoring systems. UAVs enable rapid and flexible deployment, repeated use, and data acquisition with high spatial and temporal resolution. The operational costs of UAVs are significantly lower compared to manned aircraft, while also eliminating risks to human life in hazardous environments. This results in a reduction of both direct costs and potential losses associated with accidents and incidents.

A significant contribution to improving economic efficiency is achieved through the integration of UAVs with geographic information systems (GIS) and data processing algorithms, including neural networks. Real-time data analysis enables early detection of fire outbreaks, accurate identification of their parameters, and prediction of their development. This allows for timely and efficient allocation of firefighting forces and resources, avoiding both shortages and excessive concentration of resources in specific areas.

The ability to minimize damage through early intervention is of particular importance. Reducing response time leads to a decrease in the affected area, which directly impacts the value of destroyed forest resources, restoration costs, and environmental consequences. Investments in UAV-based systems can be considered a preventive measure with long-term economic benefits.

For quantitative assessment of economic efficiency, various indicators can be used, such as:

- monitoring cost per unit area;
- fire detection time;
- reduction in the affected area;
- ratio between invested resources and prevented losses;
- efficiency of utilization of firefighting resources.

An additional advantage of these systems is their applicability in training and personnel preparation through simulation models. This reduces the costs of real-world exercises while improving the qualification of specialists without requiring significant resource allocation.

The implementation of UAVs and intelligent fire management systems contributes to the sustainable management of natural resources and to the reduction of economic losses caused by natural disasters. Despite the need for initial investments in equipment and software development, the achieved benefits justify these costs and make such systems economically viable solutions.

6. CONCLUSION

Neural networks are not a magic solution. They cannot solve environmental problems on their own, but they are becoming a powerful tool that enables humanity to better understand nature, respond more rapidly, and manage resources more effectively. Their application is transforming ecology from a science based on assumptions and sporadic observations into one characterized by high accuracy and predictability. They allow us to perceive what is invisible to the human eye - changes at the cellular level of a leaf, the sound of an insect, or subtle variations in ocean temperature. Ecology becomes not only a scientific discipline but also an efficient one.

The power of these technologies requires responsibility. Without ethics, they may become instruments of control. Without fairness, they may deepen inequality. Without international cooperation, less developed regions may remain unprotected. The future of ecology lies not in replacing humans with machines, but in their synergy. Researchers, engineers, local communities, and policymakers must work together to ensure that technologies serve nature rather than the opposite. Every kilometer of forest is preserved through algorithms, every species saved through detection, every drop of clean water protected through sensors - these are not merely data points, but elements of our planet's future. Technology alone will not save nature, but it provides us with the opportunity to understand ongoing processes and make informed decisions. This opportunity may be the most valuable resource we have.

The advantages of the proposed system include multifunctionality - combining fire detection, identification, and operational selection of alternative firefighting strategies - as well as autonomy, which is particularly important for operations in remote areas. Another positive feature is the capability for personnel training in a simulation environment.

AUTHOR CONTRIBUTIONS

All authors (V.T., T.P., M.G.) contributed equally to all stages of the research, including conceptualization, methodology, software, analysis, and writing of the manuscript.

All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper. This research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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