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CONCEPTUAL FOUNDATIONS OF THE SWARM EMPLOYMENT OF UNMANNED AERIAL VEHICLES AS INTELLIGENT MEANS OF ELECTRONIC WARFARE

The object of research is the process of functioning of a swarm of unmanned aerial vehicles (UAVs), equipped with artificial intelligence technologies, as intelligent means of electronic warfare (EW). The main attention is focused on their interaction and efficiency of functioning, their adaptive capabilities in a dynamically changing and complex electromagnetic environment.

One of the key problems is ensuring reliable, stable and flexible coordination of swarm actions in conditions of electromagnetic influence of enemy radioelectronic means (REM). Coordination of swarm actions and measures should include continuous monitoring of the spectrum, timely adaptation to enemy countermeasures.

To solve this problem, it is proposed to create an adaptive swarm architecture that implements the principles of decentralized control using machine learning algorithms, a multi-agent approach and software-configuration architecture of radio systems (SDR). The developed approach is based on the application of cognitive strategies for interaction between UAVs and the formation of a dynamic network structure that is self-repairing in the event of damage or interference.

The proposed conceptual approach allows for significantly increasing the effectiveness of influencing the enemy's REM environment through dynamic spatial-temporal distribution of interference, taking into account the tactical situation and spectral characteristics of threats.

It is envisaged to integrate strike and reconnaissance UAVs into a single swarm structure with autonomous coordination of actions, which expands the functionality of the swarm from the placement of multi-frequency interference to the detection, tracking and neutralization of critically important objects.

This approach provides a high level of autonomy, adaptability and survivability of unmanned platforms in difficult conditions of electronic warfare, and also creates the prerequisites for significantly increasing the effectiveness of combat operations in a modern high-tech environment by integrating reconnaissance and strike functions and EW means into a single information system.

Keywords: *swarm, obstacles, technologies, system, efficiency, integration, algorithm, methods, countermeasure, control.*

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1. Introduction

Modern military conflicts are characterized by the widespread use of unmanned aerial vehicles (UAVs) and electronic warfare (EW) [1, 2]. This provides a basis for the development of new approaches to ensuring advantages in the radio frequency spectrum. Traditional jamming methods often prove to be insufficiently effective due to the adaptability of enemy communication systems and electronic intelligence [3, 4]. At the same time, the use of swarm technologies in combination with artificial intelligence technology opens up new opportunities for increasing the EW effectiveness [5].

One of the key issues is ensuring reliable control of UAV swarm and dynamic coordination of their actions in conditions of active enemy countermeasures. The use of centralized control systems is limited due to the risks of their detection and destruction, and traditional coordination algorithms have low adaptability in a complex electronic environment [6]. This necessitates the development of new approaches and methods for decentralized control of swarms, which provide for an increase in their autonomy in performing missions.

Therefore, the relevance of the topic is due to the rapid development of unmanned technologies, as well as the growing requirements for means of electronic interference, the effectiveness of which depends on the ability to dynamically adjust the radiation parameters.

The proposed conceptual principles of an integrated UAV swarm allow significantly increasing the effectiveness of electronic interference on the enemy's radioelectronic means (hereinafter referred to as the REM), expanding the capabilities of UAVs in performing combat missions and ensuring their autonomy even in difficult electronic conditions.

The idea of using UAV swarms as EW means, combining the functions of radio monitoring, jammers, scouts and strike platforms, is not new and was proposed, for example, in [1, 2]. In particular, the literature [3] indicated the possibility of forming a moving antenna array by UAV swarm to solve the tasks of radio reconnaissance and directed generation of active jamming signals for radio communications, satellite navigation and radar.

In recent years, a significant number of publications have appeared that relate to both individual technical aspects of jamming and general issues of using UAVs as combat systems.

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Thus, in [5] approaches to strategic deployment and maintaining the reliability of UAV swarms in critical areas are considered. The main attention is paid to methods of organizing flight missions, adaptive control and ensuring resistance to external threats, in particular cyber-attacks and electronic interference.

In [6], the role of swarm technologies in modern military conflicts is analyzed, and key trends in their application are highlighted. The authors focus on the integration of artificial intelligence into the management of UAV swarms and consider the prospects for their use during combat operations.

Research on cooperative methods of combat operations using UAV swarms is presented in [7]. The article analyzes the algorithms for interaction between UAVs for effective suppression of threats in military operations. New approaches to UAV coordination based on machine learning are proposed.

Article [8] considers the tactics of deploying micro-UAV swarms to perform reconnaissance tasks. Autonomous route planning algorithms and the strategy for optimal distribution of UAVs in space to achieve maximum coverage of the surveillance zone are analyzed.

Research in [9] is aimed at studying cooperative reconnaissance technologies and combat use of UAV swarms. The use of artificial intelligence for autonomous detection and destruction of targets, as well as approaches to optimizing interaction between individual UAVs, are considered.

Article [10] analyzes the main challenges and prospects for the development of intelligent UAV swarms. The technical aspects of creating stable communication systems, autonomous decision-making and integrating artificial intelligence into swarm management are discussed in order to increase their effectiveness in the military and civilian spheres.

Research [11] is devoted to methods of countering enemy UAV swarms. The authors analyze modern algorithms for detecting and neutralizing enemy UAVs, consider the tactics of using electronic and kinetic countermeasures.

Article [12] considers the use of reinforced learning algorithms for coordinating UAV actions in large-scale military operations. The researchers propose a new approach to optimizing swarm movement and adapting its behavior to changes in the environment.

Work [13] is devoted to the analysis of algorithms for countering large UAV swarms. Methods of coordinating defense systems for neutralizing UAV groups based on adaptive frequency spectrum control and interference signal distribution are proposed.

The study [14] is devoted to the development of energy-efficient routes for UAVs in the EW field. Methods for optimizing UAV energy consumption using deep learning algorithms are proposed.

The article [15] proposes the concept of digital twins for monitoring and controlling UAV swarms. Algorithms for flight data analysis, failure prediction, and optimization of coordination between UAVs are considered.

The author [16] considers the main directions of development of swarm technologies in the military sphere. Approaches to organizing UAV control, prospects for integrating artificial intelligence, and improving communication between UAVs are analyzed.

It should be noted that some researchers focus on issues of swarm coordination using decentralized algorithms and multi-agent technologies, while others emphasize the prospects of software-configurable radio system architecture [17, 18] as a basic component of an unmanned platform. At the same time, the topic of combining jamming with the use of strike UAVs and reconnaissance UAVs within a single network architecture has not yet been sufficiently studied, especially regarding the integration of artificial intelligence algorithms directly on board the aircraft. That is why there is a need for comprehensive research that combines the experience of previous work in the field of UAVs and distributed intelligent systems, but at the same time focuses on creating a multifunctional swarm capable of performing electronic suppression, collecting important data for planning combat operations and implementing strike tasks in the context of modern military conflicts.

Therefore, *the aim of research* is to substantiate the conceptual principles of building a swarm architecture of UAVs as intelligent means of electronic warfare, capable of autonomously forming spatio-temporal flickering jamming in a wide frequency range using artificial intelligence technologies.

The main emphasis is placed on the use of decentralized control algorithms, software-configuration architecture of radio systems, and artificial intelligence to ensure the autonomous functioning of the swarm in conditions of electronic countermeasures.

2. Materials and Methods

The object of research is the process of functioning of UAV swarm equipped with artificial intelligence technologies as intelligent EW means. This study is based on the analysis of modern methods of controlling UAV swarms and approaches to organizing EW. The following methods were used in the work:

– a systematic study of modern scientific research, regulatory documents and technical reports on swarm technologies, radio jamming and the use of artificial intelligence in autonomous systems was carried out;
– mathematical models of coordination of actions of UAV swarm were developed, which include the distribution of frequency ranges, algorithms for flickering the signal of radio jamming from UAVs and adaptive management of radiation resources;
– optimization and machine learning methods, in particular, reinforcement learning algorithms and cooperative multi-agent learning were used for swarm control, which allows to autonomously determine the optimal strategies for the location of UAVs, the choice of the frequency range and time intervals of transmitter operation.

In order to assess the effectiveness of the proposed algorithms, a series of computer simulations were conducted, including:

– analysis of the dynamics of radio interference propagation in a changing combat environment;
– detection and neutralization of enemy communication facilities;
– testing the effectiveness of decentralized swarm algorithms in difficult conditions.

The software-defined radio system architecture (SDR) was used to simulate the dynamic distribution of frequency resources, which allows adaptively changing the radiation parameters depending on the characteristics of enemy countermeasure systems.

The possibility of using blockchain technologies and distributed computing architectures to increase the system's stability in conditions of partial blocking of communication channels was analyzed.

Methods for optimizing the energy consumption of UAV swarm by predicting energy costs and controlling the rotation of UAVs in a combat group using energy management algorithms are considered.

The modeling was performed in the Python environment using the NumPy, Matplotlib, SciPy libraries and tools for numerical optimization. Calculations were performed using genetic algorithms and optimization methods, which allowed determining the optimal location of the UAV swarm to achieve the specified efficiencies.

Research methods. All results were obtained using an analytical model based on the system of equations (2)–(14). Optimization of the swarm location was performed using the methods of variational calculus and analytical gradient descent. For the multi-criteria weight function (9), the analytical hierarchical synthesis (AHP) approach with Saati normalization was applied. The sensitivity of the results to errors in the output parameters was assessed by differentiation of the basic equations and analysis of conditional derivatives.

Justification of the choice of methods. The analytical approach was chosen as one that allows for quick and informative tracking of the influence of individual parameters on the generalized indicators of the effectiveness of the swarm.

This ensured the accuracy of the obtained results and simplified the analysis of the variability of the parameters within the permissible tolerances.

Equations (2) to (7) form the energy and interference balance, (8) to (9) describe the combat effectiveness metric, and (10) to (14) set the resource and kinematic constraints within which the placement and operation mode of the swarm are optimized.

Assumptions and simplifications. An ideal intra-swarm communication channel (without interference between nodes), quasi-stationarity of targets during one tactical cycle, and a uniform distribution of enemy radio emitters were assumed.

The presence of nonlinear effects of amplifiers and intermediate phase noise were not taken into account and will be considered in further studies and publications.

Hardware and software. All calculations were performed in Python3.11 with the libraries NumPy1.26 (linear algebra), SciPy1.12 (optimization), SymPy1.13 (symbolic differentiation) and Matplotlib3.9. The calculation scripts were run on a regular Intel Core i7 12700F workstation, 32GB RAM; GPU was not used.

Summary. The study is entirely based on proven analytical formulas and numerical calculations in the Python environment.

Simulation and full-scale experiments are planned as the next stage of the study.

The following initial data were taken into account when performing the calculations:

Number of UAVs in each swarm:
- reconnaissance swarm: from 5 to 15 UAVs;
- jamming swarm: from 10 to 20 UAVs;
- strike swarm: from 5 to 10 UAVs.

Altitude and distance ranges:
- reconnaissance UAVs: altitude 500–1000 m, distance 2–5 km;
- jamming swarm: altitude 500–2000 m, distance 5–10 km;
- strike UAVs: altitude 300–2000 m, distance 6–10 km.

Algorithmic limitations:
- minimization of distances between UAVs to improve communication;
- use of stochastic methods for interference distribution;
- optimization of the location of strike UAVs to ensure the highest probability of hitting targets.

3. Results and Discussion

The proposed conceptual approach to using UAV swarm to create radio jamming involves the creation of several groups, each of which emits a signal in its own frequency range, ensuring a general overlap of the required spectrum. Each group operates on the principle of periodic switching on and off of emitters under the centralized control of the leading UAV in the group, due to which flickering of the interference is formed in space (Fig. 1).

This approach complicates the work of countermeasure systems that try to record and track radiation sources: if the interference stops at one frequency, a new one appears almost simultaneously at another, causing a dynamic change in signals in a wide frequency range.

Technically, this is possible by combining small-sized broadband transmitters capable of providing the necessary signal power and a number of antenna systems that can be installed on UAVs in various configurations in addition to the existing on-board equipment [19].

An important component is programmable radio systems (SDR), which allow for rapid reconfiguration of frequency resources according to operational tasks (Fig. 2).

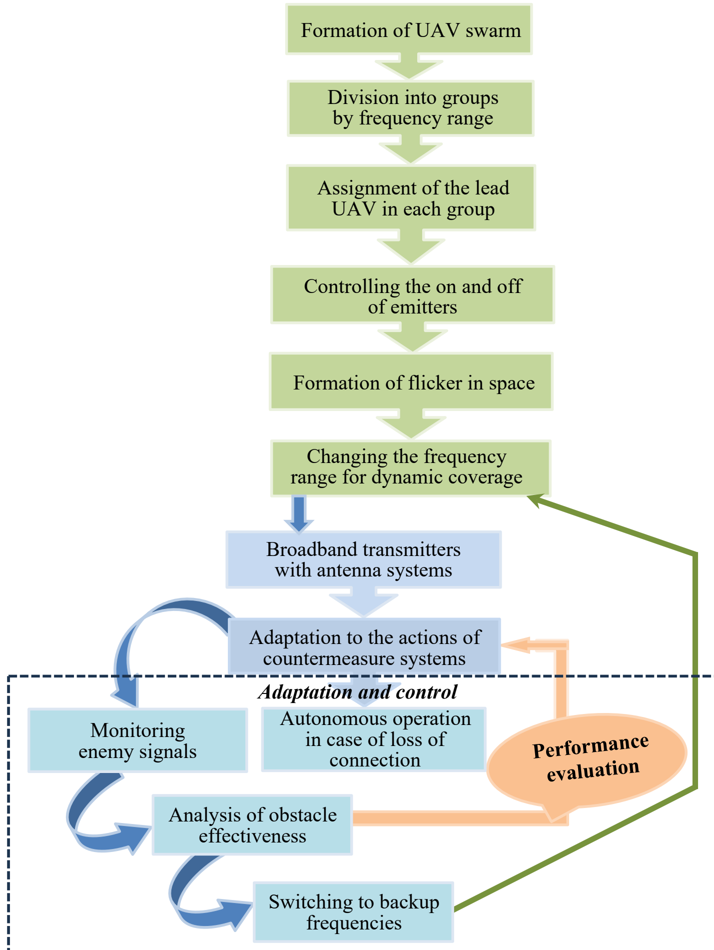

Fig. 1. Structure of UAV swarm for jamming

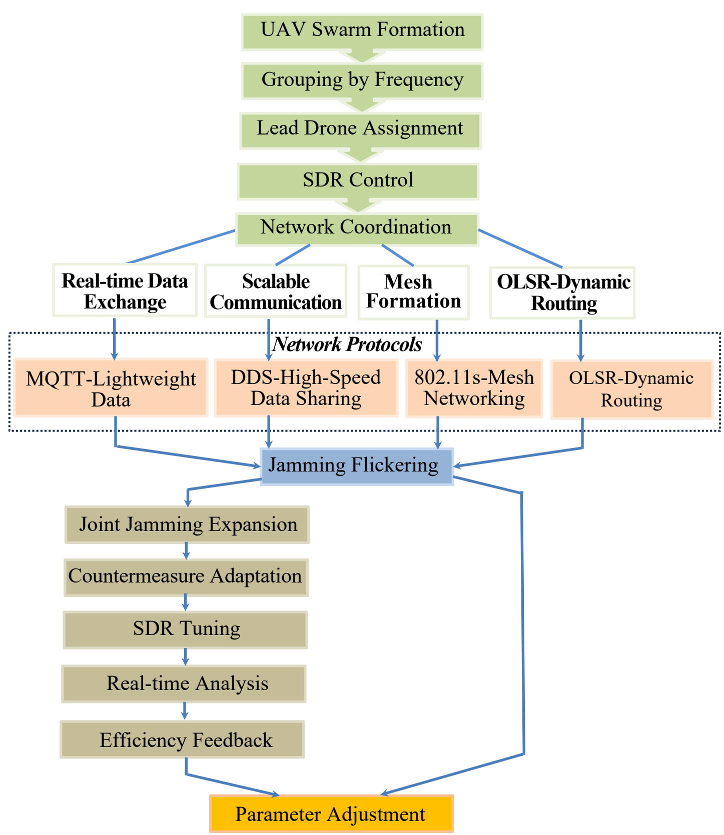

Fig. 2. Intelligent radio suppression system based on UAV swarm

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Swarm coordination is achieved using real-time network protocols that support a high level of decentralized interaction and ensure the adaptability of the swarm to changing combat conditions or environmental conditions [20]. The joint operation of many such groups within one swarm expands the total jamming band, making it difficult to overcome for enemy receivers and communication systems, even when using complex protection methods such as spectral division, frequency hopping spectrum spreading (FHSS), and spatial adaptation of antenna array patterns.

The use of flicker at each of the frequencies used allows to "layer" the interference in space and time, creating a continuous background of interference and complicating the tasks of electronic reconnaissance. In the described concept of a swarm of unmanned aerial vehicles, where each group of UAVs generates interference in a certain frequency range and flickers it in space, the use of artificial intelligence allows to significantly increase the efficiency and autonomy of such a system.

The use of machine learning methods, in particular reinforcement algorithms and collective intelligent strategies, allows the swarm to dynamically determine the optimal time windows for turning on and off the emitters for each group of UAVs. Instead of a rigid pre-set logic, the swarm is able to adapt to changing combat conditions or the electronic environment, analyzing input data from sensors, as well as predicting the reaction of enemy communication systems. Such a system provides for both centralized and distributed decision-making, which significantly increases the survivability of the swarm and resistance to the failure of individual UAVs.

Due to the high level of decentralization, due to intelligent algorithms, each group of UAVs independently selects signal parameters (frequency, power, waveform), and also plans spatial location in real time, coordinating actions with other groups. This makes it possible to create complex multi-frequency interference networks that can effectively counteract even technically advanced enemy communications and operate in conditions of intense electronic interference.

The implementation of artificial intelligence technologies within the concept of creating UAV swarm with the function of creating radio jamming can be based on the use of an agent approach. The corresponding variant of the swarm can be organized by integrating reduced versions of large language models directly on each UAV. In this case, each UAV serves as a separate agent, capable of analyzing local and global data in real time and autonomously making decisions regarding its own flight path, turning on or off emitters, and optimal signal parameters (frequency, modulation, power). The basis of such autonomy is the mechanism of mixing several intelligent modules: a reduced language model allows processing complex information, and specialized action algorithms (RL agents [19, 20] or logical planners [21, 22]) control specific aspects of the UAV operation. Within the swarm, there is multilateral interaction between devices using direct UAV-UAV communication protocols, as well as through centralized servers at a certain level of the hierarchy, which allows increasing the overall coherence and flexibility of collective behavior. Due to the fact that the models have a reduced volume and are adapted to work on local computing resources, they can function without constant access to an external channel with high bandwidth, while maintaining the ability to self-learn if necessary. This gives the swarm an advantage in EW conditions, when traditional communication channels can be partially or completely suppressed.

Each UAV, guided by its own agent, can quickly adjust to alternative frequencies, change the strategy and structure of interference, and coordinate its actions with neighboring UAVs, choosing the optimal time intervals for the emitters.

That is, each UAV is an intelligent agent operating in an environment defined by the state space S, the action space A, the reward function $R(s, a)$ and the decision-making policy $\pi(a|s)$.

The state of the UAV at a certain time interval is determined by the following expressio

$$S_t=\left(x_t,\upsilon_t,\theta_t,P_t,f_t,m_t\right), \tag{1}$$

where x_t – the positioning vector in space; υ_t – the UAV speed; θ_t – the UAV spatial orientation; P_t – the radiation power; f_t – the signal frequency; m_t – the modulation type.

The space of UAV action is determined by the variable components, which can be described as follows [13]

$$A=\left\{a_1,a_2,a_3,a_4,a_5,\ldots,a_N\right\}, \tag{2}$$

where a_1 – the trajectory variable; a_2 – the interference frequency variable; a_3 – the power variable; a_4 – the coordination with other UAVs; a_5 – the selection of a new target.

The interaction between UAVs is expressed through a graph model, where the swarm is a directed graph $G=\left(V,E\right)$ in which the vertices V – denote UAVs, and the edges E – the communication channels between them.

Then the function that describes the correction of the UAV trajectory in the swarm is defined as follows [13]

$$x_i^{t+1}=x_i^t+\Delta x_i+\sum_{j\in N(i)}\omega_{ij}\left(x_j^t-x_i^t\right), \tag{3}$$

where Δx_i – the change in the UAV flight path due to local decision-making, and $\sum_{j\in N(i)}\omega_{ij}\left(x_j^t-x_i^t\right)$ – the influence of neighboring UAVs with weighting coefficients.

Each jamming UAV distributes the signal power in the frequency spectrum, which is determined by the equation [14]

$$P\left(f\right)=\sum_{i=1}^{N}P_i\delta\left(f-f_i\right), \tag{4}$$

where P_i – the signal power of the UAV i transmitter; $\delta\left(f-f_i\right)$ – the delta function that models the choice of a certain frequency f_i.

The temporal flicker of the interference emitted by the jamming UAV is determined by the following expression [11]

$$P_i\left(t\right)=P_{\max}\cdot\sigma\left(t\right), \tag{5}$$

where $\sigma\left(t\right)$ – the stochastic function that models the random change in the radiation parameters to complicate the enemy adaptive filtering.

Reconnaissance UAVs operate using the target capability assessment function [12]

$$Q\left(s,a\right)=\iota+\gamma\max_a Q\left(s,a\right), \tag{6}$$

where $Q\left(s,a\right)$ – the state value function; ι – the reward for detecting the target; γ – the discount factor.

The goal selection strategy is described by the following expression [10]

$$a^*=\arg\max_a Q\left(s,a\right), \tag{7}$$

where the action with the maximum expected result is chosen.

The optimal task distribution in the swarm is formalized as an optimization problem [12]

$$\min\sum_i c_iT_i, \tag{8}$$

where c_i – the cost of performing the task of UAV i; T_i – the execution time.

The described model allows to create a self-learning UAV swarm, in which language models simplify the analysis of situations, and RL agents or planners manage the optimal allocation of resources and UAV flight trajectories.

The definition of the objective function that optimizes the operation of the UAV swarm with the distribution of roles between reconnaissance and strike UAVs and jammers is formed on the basis of taking into account the maximization of the effectiveness of suppressing enemy radioelectronic means (hereinafter referred to as the REM), minimizing UAV losses in the swarm, maximizing the effectiveness of hitting enemy targets with reconnaissance and strike UAVs, as well as ensuring stable communication in the swarm and optimizing energy consumption.

Taking into account the above, the objective function can be represented as follows [12]

$$J = \max\left[\lambda_1 \sum_{i\in D_J} U_i^{EW} + \lambda_2 \sum_{i\in D_S} U_j^{Strike} - \lambda_3 \sum_{i\in D} C_i - \lambda_4 \sum_{i\in D} E_i\right], \qquad (9)$$

where D_j – the set of jamming UAVs; D_s – the set of attack UAVs; $D = D_J \cup D_S$ – the total set of UAVs; U_i^{EW} – the jamming efficiency of UAV i; U_j^{Strike} – the effectiveness of attack UAV j in hitting the target; C_i – the resource consumption of UAV i (fuel, ammunition, energy of radiated jamming); E_i – the electricity consumption of UAV i; λ_1, λ_2, λ_3, λ_4 – the weighting factors that determine the balance between tasks.

The swarm utility function is determined by three criteria, namely, estimates of the effectiveness of electronic suppression; target destruction; resource consumption.

The effectiveness of electronic suppression determines how successfully UAV swarm can weaken or completely block the enemy's REM capabilities by creating interference in a certain frequency range.

This indicator also depends on the ratio of the enemy's useful signal power to the level of interference emitted by the jammers in the swarm. The more energetically the interference dominates the enemy signal, the more effectively the enemy's REM is disrupted, therefore [11]

$$U_i^{EW} = \int_{f_{\min}}^{f_{\max}} P_i(f) G_i(f)\, df, \qquad (10)$$

where P_i – the interference power at frequency f; G_i – the enemy signal suppression function at frequency f.

Target engagement efficiency determines how effectively strike UAVs can locate, attack, and destroy enemy targets on the battlefield. This indicator depends on many factors, including targeting accuracy, hit probability, priority of identified targets, and swarm UAV interaction [11]

$$U_j^{Strike} = \sum_{k\in T} \omega_k P_j^{hit}(k), \qquad (11)$$

where T – the set of all targets that can be attacked; ω_k – the weight (priority) of target k, indicating how important it is to destroy a specific target (for example, a command post may have a higher priority than conventional armored vehicles); P_j^{hit} – the probability of successful engagement of target k by reconnaissance and strike UAV j.

Expression (13) indicates that the effectiveness of the defeat depends not only on the technical characteristics of the UAV, but also on its strategy of actions, coordination with other UAVs and the current situation on the battlefield. A high level of autonomy and the use of artificial intelligence algorithms help the swarm to quickly identify priority targets and change tactics depending on the conditions.

Resource costs determine how much energy each UAV can use to generate obstacles, means of destruction and time during the performance of a combat mission [14]

$$C_i = \alpha P_i + \beta M_i + \gamma T_i, \qquad (12)$$

where P_i – the energy consumption for jamming (energy required for the operation of transmitters); M_i – the consumption of means of destruction (for a strike UAV); T_i – the duration of UAV operation in active mode (the longer it operates, the more resources it consumes, including fuel, battery charge, coolant of the cooling system, etc.); α, β, γ – the weighting factors that show the relative impact of each type of cost on the total UAV resource (for example, if the UAV consumes more energy than its means of destruction, then α will be higher than β.

Expression (12), which describes the cost of resources, indicates that the UAV must balance the duration of the mission, the level of energy use and means of destruction. This makes it possible to determine the optimal tactics of using the swarm and increase the overall efficiency of its work.

Optimization constraints are a set of rules or conditions that set limits for the parameters of the system. They ensure its effective and safe operation. In the context of UAV swarm, constraints are necessary for the rational use of resources, coordination of actions between UAVs and achieving specified goals at minimal costs.

Optimization constraints are defined as follows [14]

$$\sum_{i\in D_i} P_i(f) \le P_{\max}. \qquad (13)$$

Expression (13) means that the sum of the interference power emitted by all jammers in the swarm cannot exceed the maximum permissible power $P_{\max}$.

The limitations on the use of strike weapons by UAVs can be written as follows [14]

$$\sum_{j\in D_s} M_j(f) \le M_{\max}, \qquad (14)$$

i. e. the total number of weapons used by all strike UAVs should not exceed the maximum available reserve $M_{\max}$.

Thus, the target function allows UAVs to coordinate their actions, ensuring the maximum effect of jamming and strike operations with minimal expenditure of resources and energy.

Thus, within the framework of a single system, self-organizing processes appear that allow the swarm to adapt to the most complex application scenarios, increasing its resistance to dynamic and unpredictable radio-electronic interference from the enemy.

Within the framework of the complex use of UAVs, it is proposed to create an integrated swarm that combines as key components a group of jamming UAVs and strike UAVs with artificial intelligence on board. Due to the implementation of a swarm of jammers, a complex dynamic environment is formed in which enemy communication and guidance means lose their effectiveness due to multi-channel and temporal "flickering" of interference in a wide frequency range. At the same time, a swarm of strike UAVs operates in combat configuration, using artificial intelligence algorithms to detect [23], track and destroy priority targets, as well as to intercept enemy UAVs [24, 25], capable of breaking through radio interference. Such strike UAVs can contain on board a combination of a reduced language model for complex data processing and classical reinforcement or planning algorithms for rapid response to a threat. Thanks to this, they are able to autonomously analyze changing circumstances on the battlefield, instantly making decisions about the trajectory of rapprochement with the enemy or the search for new targets.

Both swarm segments share a common network infrastructure that provides a high degree of decentralized interaction, including the sharing of tactical information and guidance on priority jamming frequencies and strike points. In conditions of active electronic warfare, when communication channels may be partially blocked, the use of reliable direct UAV-UAV protocols, for example in the millimeter or terahertz wavebands based on spectrally efficient signals [26, 27], and adaptive self-configuration algorithms allows groups to reconfigure and remain functionally viable. Strike UAVs are able to quickly change their role:

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from hunting enemy UAVs to selectively engaging high-value targets, or, conversely, temporarily take over the functions of jammers if they lose contact or are damaged. Thanks to such deep integration, the swarm becomes a universal tool that not only suppresses enemy electronic means, but also provides active combat intervention, increasing the overall potential of unmanned systems on the battlefield.

In a more advanced version of the proposed integrated UAV system, in addition to the jamming swarm and the strike UAV swarm, a reconnaissance UAV swarm is added, specially designed to determine the radio frequency environment and search for potential targets. Such UAVs are equipped with a complex of analytical modules based on reduced versions of large language models and high-precision sensor systems, which allows them to intercept signals, analyze the frequency spectrum and assess the intensity and structure of the radiation of enemy communication or radar systems. Based on this data, the reconnaissance swarm forms operational recommendations for the jamming swarm, in particular regarding priority frequencies and time intervals when the effectiveness of the flickering of interference will be maximum.

Strike UAVs, in turn, with the support of reconnaissance UAVs, receive information about the location of enemy equipment or control points, as well as about UAVs that can potentially break through obstacles. Such coordinated interaction between the three swarms is ensured not only by specialized communication protocols, but also by distributed computing architectures [28], which allow each device to receive critical information in real time and dynamically change its behavior. For example, if the reconnaissance swarm detects a jamming-resistant enemy system that can bypass current jamming schemes, data on the new signal characteristics instantly enters the jamming swarm, which adjusts the frequencies of the jamming signals to intercept this particular threat. At the same time, strike UAVs receive updated target designations in order to either neutralize the signal source physically or destroy functionally important objects associated with it. Such a comprehensive approach makes it possible to more effectively defeat enemy air defense and electronic warfare systems, as reconnaissance, jamming, and target destruction now occur in a coordinated manner, creating an extremely complex environment for the enemy, in which every move by the enemy is instantly recorded and neutralized by the high level of autonomy of the swarms.

The tactics of using a combination of swarms involves multi-level construction and their separation in space and time in order to simultaneously form both an interference barrier and strike enemy targets, as well as collect detailed data on the radio frequency situation. A reconnaissance swarm to detect the positions of UAV operators and network units or enemy strongpoints is usually located at a distance of about 2–5 km from the front edge, moving at low and medium altitudes (from 500 to 1000 meters). Each such swarm can have from 5 to 15 UAVs, which are kept at a distance of 500–1500 m from each other, forming a network configuration for uninterrupted exchange of data on the frequency spectrum and the location of enemy forces. To determine the location of radio emission sources, a circular trajectory with a radius of 600–900 m or a straight flight along the contact line can be used, similar to what was done in the Russian Orlan-10 UAV of the Leer complex [29, 30]. The information collected by this reconnaissance swarm is promptly transmitted by a swarm of jammers, which often operates at the same distances or deeper behind enemy lines (usually in a strip 5–10 km from the front edge) and covers a wide range of altitudes – from 500 to 2000 meters. The number of UAVs in such a swarm can vary from 10 to 20, but in practice it is advisable to divide the swarm into groups of 4–6 devices for the installation of frequency-separated flickering jammers. Between groups of UAVs operating at different frequencies, a distance of 500–1500 m is maintained. The interval between the UAVs in the group is 500–1000 m or more, depending on the distance to the enemy's electronic means to be suppressed. In this case, the calculation of the distances between the UAVs is carried out taking into account the angle of divergence at the point of reception of interference signals. This angle must be at least 5 degrees so that in the case of using digital antenna arrays by the electronic means, this angular distance does not allow different UAVs to be perceived as one source in space.

A strike swarm, which is used to destroy important targets and intercept enemy UAVs, can usually be deployed in an intermediate or more remote sector depending on the terrain and the specific tactical situation, operating in an echelon from 300 to 2000 meters in height. Such a swarm involves 5–10 UAVs equipped with weapons and artificial intelligence systems for autonomous tracking and attacking targets, as well as for coordination with obstacle setters and a reconnaissance group. The strike group of anti-aircraft UAV interceptors, which covers important objects in its depth to intercept enemy UAVs, focuses on distances of up to 1–3 km from the cover objects. This will ensure its safety from small arms fire and its own anti-aircraft weapons. Of course, the indicated numerical indicators are purely indicative and can be specified and adapted to specific tactical realities.

Equipped with artificial intelligence algorithms, a strike swarm can be divided into two echelons to simultaneously perform tasks deep inside enemy territory and intercept enemy UAVs that have broken through to attack our facilities. The first echelon, as a rule, goes a greater distance from the front line, focusing on destroying high-value targets in the enemy's tactical or operational depth [31, 32]. These can be communication nodes, control points, long-range radars, air defense systems, and ammunition depots. Artificial intelligence algorithms on board the UAV help determine the optimal routes for bypassing enemy air defense zones, adjust flight trajectories taking into account changes in the radar environment, and select the most vulnerable points for strikes. The second echelon remains at a safer distance from the front line or closer to our key infrastructure and acts as a barrier against enemy UAVs that can break through the "screen" of obstacles created by swarms of jammers. The second echelon's interceptor UAVs, equipped with detection sensors and systems for rapid rapprochement with the enemy, track any threats approaching our positions and carry out interceptions. At the same time, the second echelon can receive tactical information from a network of ground-based radars, reconnaissance UAVs and swarms of jammers, which record the characteristics of enemy signals and help determine the likely trajectories of enemy UAVs. If, thanks to electronic warfare systems, most enemy UAVs are knocked off course or deprived of their control channel, the remnants that are still able to continue flying are under the influence of the strike echelon, which closes the last line of defense. This combination of deep strikes and close-in interception allows for effective defense of one's own facilities while successfully engaging critical targets behind enemy lines. All three types of swarms are interconnected by decentralized network protocols, which allows for rapid information exchange even with partially blocked channels. They can be reorganized as needed: the reconnaissance swarm moves closer, changing its route depending on the activity of enemy radar systems, the jamming swarm responds to changes in the frequency spectrum and focuses on the most dangerous threats, while the strike swarm acts on priority targets confirmed by intelligence data or intercepts enemy UAVs that have managed to break through obstacles. The described three-level structure can operate as a separate tactical element within a battalion or even a brigade, depending on the scale of the operation. In the case of battalion-level deployment, swarms can support a direct offensive or defense at a depth of up to 10 km from the front line, while the brigade level provides for wider deployment and integration with other branches of the military, which allows for multifaceted support of combat operations and creates the effect of a comprehensive electronic and strike presence on the battlefield.

It should be noted that when using UAVs in swarms, energy management plays an important role, ensuring continuous operation of the swarm for a long time. In particular, timely recharging of batteries is required for 24-hour task performance, as well as optimization of energy consumption during flight. In practice, this requires cyclical updating of the swarm composition: when the charge level of individual UAVs approaches a critically low level, they return to the base point (or nearby mobile charging stations, which can be used as ground or surface unmanned platforms), where batteries are quickly recharged or replaced. At the same time, a new group of UAVs with identical functions and a full energy reserve immediately takes their place. Such rotation allows for continuous maintenance of the defined combat capabilities of the swarm, without stopping the processes of creating obstacles or inflicting fire damage even for a short period of time. Additionally, energy management tasks may include trajectory analysis and load distribution on UAV engines and electronics in such a way as to reduce energy consumption during periods of passive waiting. If there are many UAVs in a swarm, artificial intelligence algorithms can coordinate the sequential connection of various system nodes to minimize consumption at a time when they are not performing direct tactical actions. Optimization of weight characteristics is also important: modern developments suggest using light but capacious batteries, as well as developing schemes for quick attachment and replacement of power cells, which allows saving time on maintenance and extending the overall period of continuous operation of the swarm. It is essential that to ensure continuous operation of the swarm during long missions, two related tasks must be solved: flying UAVs in the swarm to the maximum range and ensuring the maximum flight time of each UAV in the swarm. This is solved by using both more advanced power sources and monitoring and forecasting the operational state of the existing battery fleet. This is especially true for Class I UAVs, whose electric power plant is the main one [33]. The use of new types of batteries, such as lithium-sulfur, metal-air and some others, with higher energy density and lower specific gravity, will potentially allow increasing the maximum flight time [34, 35]. The use of hydrogen fuel cell technologies [36, 37] is also promising to increase the flight duration of UAVs by 2–3 times compared to existing types of batteries. However, these technologies currently have certain limitations, especially for use in swarms with a large number of UAVs, as they require a network of hydrogen refueling stations/hydrogen cylinder replacement points, specific equipment with increased safety requirements [36]. A possible solution is to use fuel "processors" to generate hydrogen from diesel or JP-8 jet fuel [38]. However, this reduces the "energy density" of the UAV power source and increases the burden on the logistical component of flight mission support. Hydrogen technologies are advisable to use in heavier UAVs with a limited number of units in a swarm to perform specific tasks.

Considering the above, it is relevant to use artificial intelligence technologies for planning the energy component of flight missions of UAV swarms, pre-flight monitoring of UAV power sources, detection of hidden signs of failures and selection of batteries for a specific task with the required predicted technical resource and the number of available operating cycles [38]. To achieve this goal, intensive research is being conducted in the field of artificial neural networks of various architectures, suitable for data analysis in the form of time series [39]. The introduction of pre-trained neural networks in the form of modules into UAV control systems, logistics systems and situational awareness systems using the network-centric principle will contribute to successful preparation for flight missions and missions in general. At the stage of implementing combat missions by swarms of unmanned aerial vehicles, energy management can be significantly improved through the use of artificial intelligence technologies based on large language models or action agents that allow making optimal decisions in real time. In particular, systems based on machine learning and reinforcement learning (RL) algorithms [40] can predict the current level of remaining energy for each UAV, taking into account individual flight parameters, existing weather conditions and the current mode of operation (interference, strike, reconnaissance). Based on these predictions, artificial intelligence determines the most favorable moment for returning individual devices to the base for recharging or quick battery replacement. At the same time, other UAVs with a full energy reserve are connected to perform the same mission, maintaining a single functionality within the swarm. This approach allows to maximize the balance of energy consumption and reduce downtime, as well as increase the survivability of the entire system. In addition, artificial intelligence can dynamically plan flight routes, optimize the altitude, speed and spatial location of UAVs to minimize energy consumption when moving between combat areas. In case of changes in the operational situation (for example, the emergence of a new threat or obstacle), the algorithms rebuild the swarm, redistributing the UAVs in such a way as to most effectively combine tactical tasks and the process of maintaining batteries in working condition. Ultimately, continuous monitoring of the charge level of each device and analysis of its current state in real time allow to prevent emergency situations and continue the swarm's round-the-clock operation without loss of combat effectiveness.

In the process of replacing one segment with a swarm, another critical task is to ensure safe mutual flight of UAVs without collisions. This requires the use of special algorithms for collective route planning that use artificial intelligence technologies and multi-agent methods for coordinating flight trajectories. Each UAV receives data from neighboring devices about their spatial location, speed and predicted trajectory, and then adjusts its own route taking into account the tasks it performs. The already mentioned decentralized data transfer protocols between UAVs provide real-time information exchange, allowing to maintain a sufficient distance between each UAV and avoid potential intersection points. For additional safety, control programs can dynamically allocate different altitude levels when one swarm flies through another, and introduce mechanisms for priority right of way. This is especially important when part of the swarm with a critically low battery level returns to the service point, while newly arrived UAVs with a full energy reserve take their position in the combat configuration. Such a planning system allows the swarm to operate in difficult aerodynamic and electronic environments, minimizing the risk of collisions even with a large number of aircraft simultaneously performing different missions.

According to the results of modeling the optimized location of the UAV swarm, the target values of the effectiveness of reconnaissance, electronic suppression and strike swarm were achieved. Based on the obtained numerical indicators, the average distance between reconnaissance UAVs is 95.30 m, which ensures sufficient coverage of the observation area and uninterrupted data exchange between UAVs (Fig. 3).

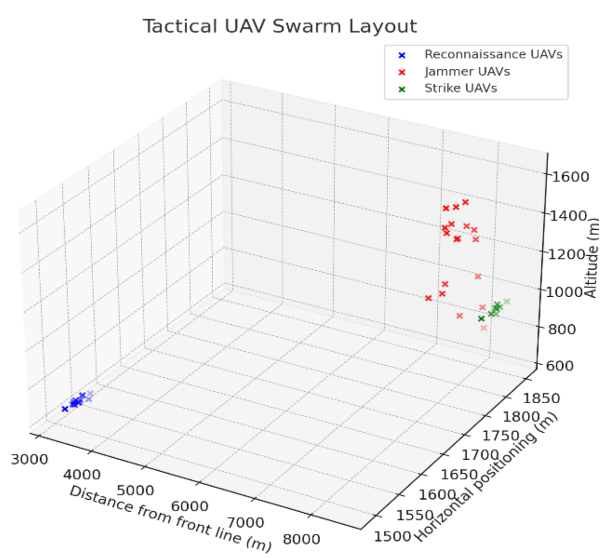

Fig. 3. Modeling the optimal location of UAV swarm

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The standard deviation of the distance between them is 4.25 m, which indicates a relatively uniform distribution of the devices in space. The calculated reconnaissance efficiency reached 0.90, which meets the specified criteria and indicates the high quality of information collection regarding the location of enemy positions and analysis of the spectral characteristics of signals.

In terms of electronic suppression, the total radiation power of the jammers was 17.97 conventional units, which allows for effective suppression of the enemy's REM. The average radiation power per jammer is estimated at 1.00 conventional units, which is optimal for a uniform distribution of interference in a wide frequency range. The calculated efficiency of electronic suppression was 0.60, which provides a significant reduction in the enemy's signal-to-noise ratio, making stable communication and data transmission impossible.

Regarding the strike swarm, it should be noted that the average distance between the strike UAVs was 110.25 m, which should be considered optimal for coordinating the attack and avoiding mutual influence on combat maneuvers. The average target destruction efficiency was estimated at 0.75 conventional units, which indicates high accuracy in detecting and destroying priority enemy objects. The overall effectiveness of the strike swarm is calculated at 0.80, which meets the specified requirements and allows for effective performance of tasks to eliminate enemy UAVs and important objects in the depth of the enemy's defense (Fig. 4).

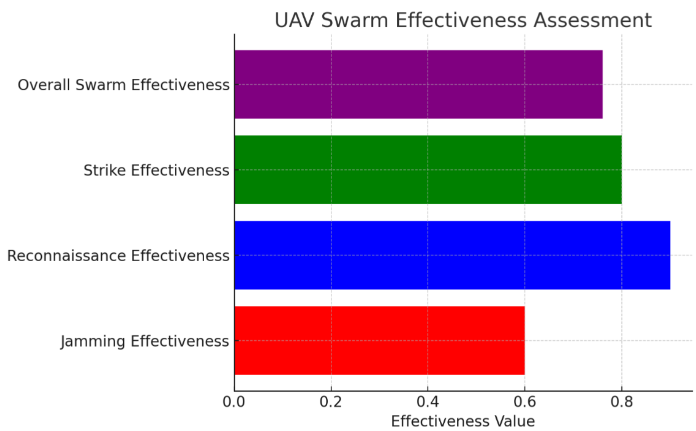

Fig. 4. Effectiveness evaluation of the UAV swarm

The comprehensive effectiveness evaluation of the entire UAV swarm, including reconnaissance, electronic suppression and strike functions, was 0.76. This confirms the optimal combination of the tactical location of the UAVs and their functional capabilities.

Thus, the obtained modeling results indicate the effectiveness of the proposed UAV swarm configuration for performing tasks in difficult combat conditions, providing simultaneous reconnaissance coverage, neutralization of enemy communications and effective destruction of key targets.

The classic concept of reconnaissance and strike systems of the 1970s was based on a centralized control hierarchy: reconnaissance aircraft transmitted the collected information to command posts, after which high-precision weapons were remotely guided from the centres.

The disadvantages of this approach were the low noise immunity of the control and data transmission channels, as well as the complete absence of decentralized system control.

The proposed conceptual framework is based on a decentralized UAV swarm, which is divided into groups, namely: reconnaissance UAVs, jamming UAVs and, as an additional option, strike UAVs, which perform the functions of reconnaissance, jamming and air strikes (under operator control), respectively.

The key feature of the swarm is the built-in artificial intelligence. Reconnaissance UAVs and jamming UAVs independently analyze the electromagnetic environment in real time, identify the types of enemy electronic equipment, dynamically optimize the parameters of the jamming and adjust their own trajectories and the trajectory of the entire swarm, eliminating dependence on a single control center. Jamming UAVs provide electronic protection and high survivability of the swarm in conditions of intense electronic warfare.

The practical significance of the results obtained is that the proposed conceptual principles of a multifunctional UAV swarm provide an effective combination of electronic warfare, reconnaissance and strike capabilities, which allows to increase the effectiveness of combat operations. The proposed approach helps to improve the resistance of unmanned systems to electronic interference, allows to ensure adaptability and autonomy in difficult combat conditions, and also contributes to the improvement of methods of suppressing enemy electronic means and destroying critically important targets.

The limitations of research are that the proposed model of a UAV swarm requires significant computing resources to implement artificial intelligence and machine learning algorithms, which may limit its practical application to certain frameworks of real combat operations. In addition, the effectiveness of the concept depends on the quality of network interaction between UAVs, which in conditions of electronic suppression can create certain challenges. It is also necessary to take into account the energy limitations of unmanned platforms, which requires further improvement of power systems and optimization of energy consumption.

Prospects for further research include the development of decentralized control technologies for UAV swarms, the improvement of algorithms for coordinating actions in a changing electromagnetic environment, and the integration of new types of sensors and navigation systems to increase the effectiveness of the combat use of unmanned aerial vehicles. Further research of the capabilities of artificial intelligence in the processes of self-learning and adaptation of the swarm to dynamic conditions in the environment during combat operations will allow improving the autonomy and survivability of such systems. Another important direction is the development of new types of power supply to increase the duration of the swarm's operation in autonomous mode.

4. Conclusions

As a research result, a holistic concept of a multifunctional UAV swarm was formed, capable of providing multispectral jamming, collecting intelligence data on the radio frequency environment and conducting strike actions. The proposed approach is based on the use of artificial intelligence and agent technologies, which makes it possible to increase the autonomy of UAVs and dynamically change the tactics of their use depending on the current combat situation. The use of flickering emitters in different frequency bands and decentralized communication protocols make it difficult for the enemy to suppress or bypass electronic warfare systems. Coordination of three key elements – swarms of jammers, strike UAVs and the reconnaissance segment – makes it possible to create a powerful integrated mechanism capable not only of blocking or distorting the operation of enemy communication and guidance systems, but also of purposefully destroying critical enemy targets. This significantly increases the maneuverability and resilience of combat units, as UAVs can quickly rebuild and continue to perform the task even in the event of failure of individual elements of the swarm. Also, the proposed conceptual framework creates a basis for further research on the use of adaptive artificial neural networks, machine learning systems and high-performance computing on each UAV, which potentially opens up new opportunities for increasing the effectiveness and scalability of swarms in modern conflicts.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial technologies intelligence when creating the presented work.

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