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MODELS OF THE SYSTEM OF COLLECTIVE SELF-ORGANISATION OF UNMANNED AERIAL VEHICLES USING ARTIFICIAL INTELLIGENCE

Abstract. The article examines the current state and trends in the development of unmanned aerial vehicles (hereinafter - UAVs), methods and means of their control, self-organisation, flight routing, as well as the involvement of artificial intelligence technologies in the UAV teams system. The main trends in the use of UAVs in the defence sector are analysed. The key problems in this area are highlighted, as well as the shortcomings of existing methods and systems. The article analyses scientific works of domestic and foreign scholars, studies problematic issues and suggests ways of their solution. The introduction of artificial intelligence into the UAV control system has significant potential and makes the development of these technologies urgent. The development of UAV collective control systems, including those using artificial intelligence, allows for the effective use of technology in various fields, ensuring increased coordination, functionality and overall efficiency. At the same time, despite active research in this area, a number of problems related to the development of methods and algorithms for group work still remain unresolved. The issue of integrating information technologies created on their basis and the specifics of their implementation in collective intelligence systems in order to increase the efficiency of solving complex formalised tasks is not sufficiently studied. A method of self-organisation of the UAV team with decentralised control is proposed, in which a number of functions (route planning, distribution of roles, determination of optimal actions, obtaining and processing information) assigned to the onboard control system of the robotic air complex can be performed by each element of the UAV team system due to their self-organisation. The practicality of this method lies in the fact that the UAV's artificial intelligence will constantly self-learn and improve, and if necessary, can be reprogrammed to meet the required conditions of the task. As a consequence, the results and time required to complete missions will improve significantly, while the number of control operators will decrease. It solves a number of problems and shortcomings related to the organisation of the management system, route planning, distribution of roles, speed and completeness of receiving, processing and transmitting information, which in turn improves the security and performance of the system.

Keywords: agents, algorithms, artificial intelligence, aviation complex, division of roles, collective, coordination, control, information technology, multi-agent systems, routing, self-organisation, self-training, swarm, unmanned aerial vehicle.

Introduction

Relevance (Problem statement). Building models of the UAV collective self-organisation system is a very relevant topic in today's realities. In the context of the armed aggression of the Russian Federation, the need to develop and modernise UAVs, their control systems, improve tactical and technical characteristics, and introduce innovative technologies has intensified.

UAVs are used in all spheres of modern society, including agriculture, electricity, geodesy and cadastre, oil and gas mining, security, construction, forestry and road maintenance, as well as in law enforcement agencies, including the armed forces of states. This paper focuses on the implementation of the UAV collective self-organisation system in the security and defence system.

The relevance of the chosen research topic lies in the constant scientific and technological progress, the development of robotics and information technology (hereinafter - IT). Over the past few years, the technology of unmanned aerial vehicles has seen continuous technological development, from being used in the important defence sector to being used in all other areas. According to Globe Newswire, the global military drone market is projected to reach USD 23.78 billion by 2027 [1].

The introduction of artificial intelligence (AI) into the UAV control system has significant potential and makes the development of these technologies urgent. The use of AI in UAV systems allows for quick and adaptive decisions in changing circumstances. This is especially important for real-time tasks, such as threat detection or navigation in low visibility conditions. AI allows UAVs to efficiently and quickly process large amounts of data received from sensors and cameras. This improves the capabilities of reconnaissance, object detection and information analysis over large areas. In addition, the introduction of the method of collective use and control into the UAV control system allows UAVs to perform their tasks more efficiently by coordinating their actions together. In the military sphere, UAV collective control systems can serve to increase tactical flexibility and coordinate military operations. Ensuring synchronisation of actions, they can perform complex military tasks.

The development of UAV collective control systems, including the use of AI, allows for the efficient use of technology in various fields, ensuring increased coordination, functionality and overall efficiency.

Analysis of the latest research and publications

In their article "Organisation of the work of a group of unmanned aerial vehicles", Golembo V. A. and Melnikov R. G. considered the basic theories and algorithms that help to achieve joint coordinated actions of a group of objects, and proposed an algorithm for avoiding possible collisions between neighbouring UAVs by recalculating the flight path [2].

In their research article "Methods for solving tasks of planning agent behaviour in intelligent decision support systems", A. Berezhnyi, M. Soroka, and N. Salo determined that the tasks of planning agent behaviour in the environment of a decision-making/decision support system characterised by high dynamism require special

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flexibility of intelligent agent methods. In such systems, it is impossible or insufficient to find only a static plan, it is necessary to dynamically adapt some initial plan to a dynamic environment and, possibly, a dynamic goal directly upon receipt of new information, i.e., the development of the methods specified in this subsection lies in the plane of building methods of dynamic and adaptive planning [3].

In 2020, in his dissertation on "Methods and Information Technology for Automated Planning of UAV Flight Routes to Increase the Efficiency of Object Search", A. Berezhnyi solved the urgent scientific and technical task of developing methods and information technology for automated planning of UAV flight routes to increase the efficiency of object search [4].

In their monograph, Pogudina O. K., Krytskyi D. M., Bykov A. M., Plastun T. A., Pivovar M. V. on the topic "Methodology for the formation of the intellectual component of the agent system of a swarm of unmanned aerial vehicles", new scientific and practical justifications were formed, which together solve an important scientific task, which is to increase the efficiency of UAVs in performing various tasks by controlling swarm intelligence using the provisions of graph theory, multi-agent modelling and existing stereotypes of adaptive behaviour of swarm participants [5].

Demidov B. O., Borysenko M. V., Kucherenko Y. F., Zadorozhna A. Y. in their article "Perspective directions of development and application of artificial intelligence methods and technologies for the Armed Forces of Ukraine within the framework of implementation of modern innovations in the military sphere" consider priority directions and main tasks of development and application of artificial intelligence methods and technologies in the defence sector. The authors argue that in complex, poorly formalised or non-formalised management situations that cannot be interpreted within strict schemes, the use of AI becomes necessary to support the processes of effective management of activities in the defence sector, including the Armed Forces of Ukraine (hereinafter - the AFU). According to the concept of AI development, priority areas of activity are proposed for the foreseeable future, which are included in the strategic programme of measures in the field of development and implementation of AI technologies for use in the AFU [6].

Professor Nurul I. Sarkar in his paper "Artificial Intelligence-Based Autonomous UAV Networks" presented a comprehensive overview of autonomous UAV networks based on artificial intelligence. Conducted a thorough analysis of more than 100 articles on UAVs, including classification of autonomous functions, management and scheduling of network resources, multiple access and routing protocols, as well as power control and energy efficiency of UAV networks. A review and analysis of the literature on UAV networks has shown that AI-based UAVs are a technologically feasible and economically viable paradigm for the cost-effective design and deployment of such next-generation autonomous networks. This article identifies open research challenges in the emerging field of UAV networks [7].

Yograj Singh Mandloi & Yoshinobu Inada's research focuses on applying machine learning and neural networks to select actions and better understand the environment to control unmanned aerial vehicles, rather than using explicit models to achieve the same goal. Implementations of machine learning and deep learning algorithms, such as nonlinear regression, have been combined with neural networks to study the system dynamics of the drone to predict future states [8].

Shreyamsh Kamate and Nuri Yilmazer in their article obtained information using UAVs used to detect and track moving objects. The main goal of this research is to assist operators by implementing intelligent visual surveillance systems that help detect and track suspicious or unusual events in a video sequence [9].

Mustapha Bekhti, Marwen Abdennebi, Nadjib Achir, Khaled Boussetta in their article investigated the route planning of autonomous UAVs with tracking capabilities provided by ground-based wireless networks. They formalised this problem as a constrained shortest path problem, where the goal is to minimise the delay in reaching the destination while ensuring a certain delivery rate of UAV location messages [10].

In their 2021 research article, Zain Anwar Ali, Zhangang Han, and Rana Javed Masood proposed collective motion control and self-organisation of a swarm of 10 UAVs, which are divided into two clusters of five agents each. In this paper, we develop a 3D model of the entire environment using graph theory. To solve the above problems, this paper develops a hybrid metaheuristic algorithm by combining particle swarm optimisation (PSO) with a multi-agent system (MAS) [11].

In the research article "Nature-inspired self-organising collision avoidance for drone swarm based on reward-modulated spiking neural network", the authors build a model of obstacle avoidance for a swarm of drones based on the decentralised, self-organised method of swarm behaviour in nature. Each individual uses a spiking neural network with reward modulated bursts for autonomous learning and makes decisions based on local observations. The result is a swarm of drones with safe flight behaviour. This work demonstrates the biological plausibility of the mechanism of learning and cognitive behaviour, and provides a basis for the development of swarm intelligence [12].

The article aims to analyse existing methods of UAV self-organisation based on artificial intelligence and describe the communication of UAV team self-organisation for poorly formalised tasks (missions).

The solution

Methods for improving and implementing innovative technologies in UAVs' collective self-organisation systems have been studied by domestic and foreign scientists relatively recently [5,7,10,11]. Numerous scientific articles propose solutions to problematic issues in the field of AI application in UAV control systems, building a control system based on various systems and platforms, for example, using multi-agent systems. At the same time, there are still many gaps and shortcomings, methods to improve the already proposed research results.

One of the most pressing topics of current discussions and research is the improvement of the effectiveness of tasks, including combat ones, by robotic systems. During the armed aggression of the Russian Federation, special attention was focused on the use of UAV systems in combat, which was due to several significant reasons. Firstly, aerial reconnaissance and other units of the AFU demonstrated high combat results in performing tasks of varying complexity and nature. Secondly, we can see the high technical potential and relative safety of UAV operators during missions, as well as the economic feasibility of their use.

The military use of robotic systems has become an integral part of the armed forces of states in modern warfare strategies. UAVs are used to perform combat missions, such as distracting air defence systems, destroying military targets, equipment, enemy personnel, military infrastructure, as well as conducting aerial reconnaissance and monitoring of combat operations, coordinating and managing units, and delivering medicines and other important cargo. Unmanned aerial systems will continue to be used in various military operations due to their high effectiveness in performing combat missions, reducing losses, and because they can perform highly specialized and long-term missions. First of all, in order to understand the research problem, it is necessary to analyse and build a sequential series of UAV systems development (schematically shown in Fig. 1).

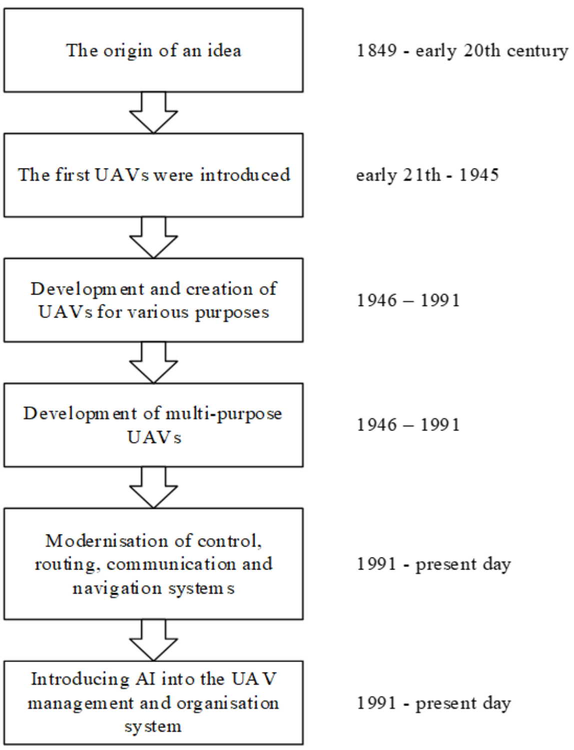

Fig. 1. Sequrnce of UAV development
(developed on the basis of research [14])

After the security and defence forces started using single systems, the need to improve this area arose. In addition to upgrading the tactical and technical characteristics (TTC) of the UAVs, work was carried out to update the communication and routing control systems. More innovative technologies have been introduced following the emergence of scientific opinions on the collective use of UAV systems and the integration of AI into management and decision-making systems.

The chronological development of UAV systems was studied in the research paper by V. Ryazanov. The author notes that the history of UAV development can be divided into four main stages. Among the trends of modern development, he lists the expansion of UAV strike capabilities and the creation of a high-capacity strike UAV; creation of a rear support UAV; miniaturisation and "intellectualisation" of UAVs; increased survivability; and equipment unification. The main trend is the gradual transfer of manned aviation functions to unmanned aircraft [14].

Modern science has already developed a method of self-organisation of UAV teams by defining roles and selecting the necessary robotic "performers", each of which has its own characteristics and features, its own special role and tasks (schematically shown in Fig. 2, Tabl. 2). Assigning a specific element of the UAV team system to the role of leader or subordinate performer has advantages, but also a number of disadvantages.

In addition, the process and main features related to the formation of an "internal" information exchange environment within a self-organising UAV group have also been studied by domestic researchers [15].

At the same time, despite active research in this area, a number of problems related to the development of methods and algorithms for group work still remain unresolved. The issue of integrating information technologies created on their basis and the specifics of their implementation in collective intelligence systems in order to increase the efficiency of solving poorly formalised tasks is not sufficiently studied. There is a tendency to integrate global navigation systems with each other and other systems, which requires expanding the width of the frequency spectrum that should be subject to electronic interference, and, in order to protect against the effects of EW, it is proposed to use additional, developed independent navigation systems and methods [16].

A common disadvantage of collective intelligence systems that use actors is that actors are selected empirically, and after a complex task is solved by a team of actors, it is impossible to estimate the probability of correctness or error of its solution. This hinders the development of collaborative work methods that can effectively solve complex drone routing problems posed by practice and create appropriate tools. Thus, in order to improve the performance indicator when using collective UAV systems in solving a number of difficult-to-formalise tasks related to routing, it is possible to introduce a system for creating a UAV team, each element of which is similar to the other and can play both the role of a leader and a subordinate. Through optimisation and customisation, UAVs will be able to perform more complex tasks in less time. The essence of this method is to coordinate all actors in a system, the last link of which is the operator.

This method will be controlled by only one UAV, which in turn will analyse the information received from other agents of the system and use AI. After that, it will make a rational decision and transmit the necessary information and tasks to all other elements of the system.

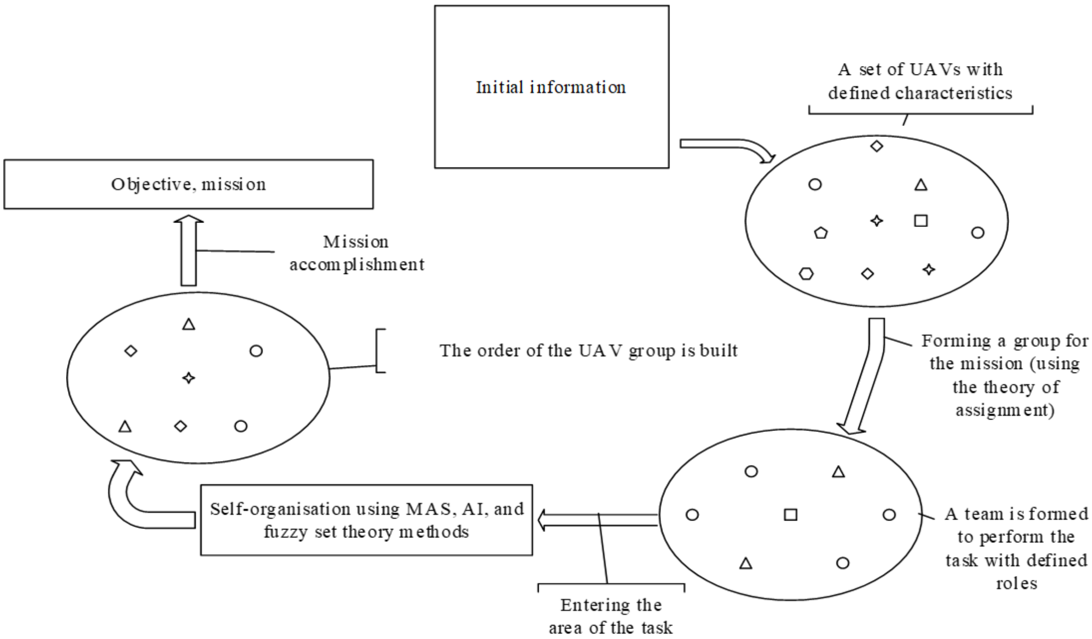

Fig. 2. Schematic representation of the existing UAV self-organisation method Source (developed by the authors)

Table 1 – **Main characteristics of existing methods of building a UAV team**

Features of the existing method of UAV self-organization:	**Theories and methods for construction are applied:**
1. Regarding control. With the advent of this method, the organisation of the UAV group management process has been simplified, and self-organisation has made it possible for one operator to manage a team of UAVs.	The theory of assignments; theory of fuzzy sets.
2. Efficiency. The effectiveness of this method lies in the proportional reduction in the time required to organise and manage the team, which in turn increased the performance indicator.	A method of building multi-agent systems; is a method of applying artificial intelligence.
Advantages	**Disadvantages**
Simplifying the management of the UAV team.	Vulnerability of the built team due to a single leader.
Reducing the number of operators and control points.	The inability to continue the task due to the destruction or loss of communication with the leader or operator (control point).
Reduce the time required to complete a task.	When building this team, it still takes too much time to select the elements of the UAV group.
Increase in the performance indicator.	The economic inexpediency of using this method, due to the possible loss of all UAVs after destruction or loss of communication with the leader.
Reduced cognitive load on the operator.	The difficulty of transporting the group to the area of operations.
Rational use of resources (through AI).	Vulnerability of the method due to the influence of enemy electronic warfare (hereinafter - EW).

The latter, in turn, firstly, have a clearly formalised task, and secondly, receive all the information accumulated and analysed by the leader. This, in turn, makes it possible for any agent to become the leader of the team in the event of the destruction or loss of communication with the agent who was in the role of leader at the time. An equally important fact is the bilateral nature of such information exchange, which is necessary to obtain the final situation not only for the operator but also for other members of the UAV team. Separately, it should be noted that all elements of the UAV team should not only self-organise into a system, but also have the ability to learn (the proposed method of organising the UAV team is shown in Fig. 3, Tabl. 2).

Thus, with each subsequent use of the team, each agent individually and the multi-agent system as a whole will have a certain knowledge base and algorithms for action when a certain task or difficult situation arises. When using the method of building a UAV team from identical elements, the problem that arises when the team leader is destroyed and the system is subsequently destroyed disappears.

Conclusions

Results of work. The author analyses the main trends in the use of UAVs in the defence sector at the moment. The article highlights the key problems in this area, as well as the shortcomings of existing methods and systems, and a number of unresolved issues related to the development of methods and algorithms for group work. The scientific articles of domestic and foreign scientists are analysed, problematic issues are studied and ways of their solution are proposed. A method of self-organisation of the UAV team with decentralised control is proposed, in which a number of functions (route planning, distribution of roles, determination of optimal actions, obtaining and processing information) assigned to the onboard control system of the robotic air complex can be performed by each element of the UAV team system due to their self-organisation and self-exchange.

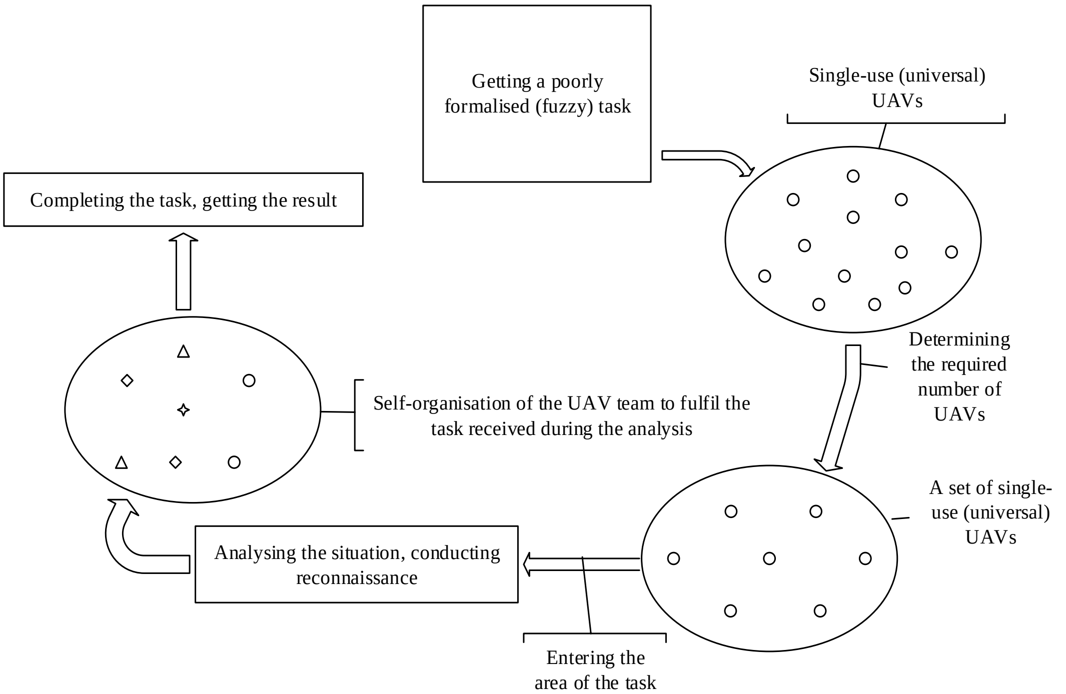

Fig. 3. Proposed model for building a UAV team Source (developed by the authors)

Table 2 – **Main characteristics of the proposed method of building a UAV team**

Features of the existing method of UAV self-organization:	**Theories and methods for construction are applied:**
1. Regarding the selection of team members. As each UAV is an identical element of the system, the time required to prepare and transport the group is reduced significantly.	Theory of fuzzy sets
2. Regarding control. The development of this method will further simplify the organisation of the UAV group management process, due to their self-organisation and the ability to change their assigned roles, the operator performs an additional, supervisory function.	A method of building multi-agent systems; method of applying artificial intelligence; optimisation methods.
3. Efficiency. The effectiveness of this method lies in the reduction of the time required to organise and manage the team, the unification and identity of the system elements, and, in addition, the team is more protected from complete destruction, which in turn will increase the performance indicator.	
Advantages	**Disadvantages**
Simplifying the management of the UAV team.	Vulnerability of the method due to the impact of enemy EW.
Reducing the number of operators and control points.	The complexity of creating and building algorithms for the interaction of system elements.
Reduce the time required to complete a task.	
Relative simplicity of transporting the team to the area of the task	
The security of the built team, due to the identity of its elements.	
The ability to continue the task after the leader or operator (control point) has been destroyed or lost.	
It doesn't take much time to build a team.	
Simplification of the UAV production process due to their identity.	
Increase in performance indicators, etc.	

The implementation of the proposed method is possible if the AFU have universal, multi-purpose UAVs in service, the communication system of which is based on the proposed method. The following methods are missing to build the proposed system: 1) self-organisation of a team of homogeneous UAVs in solving poorly formalised tasks; 2) model of rules for collective intelligence of unmanned aerial vehicles when working as part of a group; 3) A method of self-organisation of unmanned aerial vehicles team for monitoring ground objects; 4) a method for coordinating decisions when monitoring ground objects by a team of unmanned aerial vehicles; 5) a method for routing flights of a team of unmanned aerial vehicles when monitoring ground objects. The practicality of this method lies in the fact that the UAV's artificial intelligence will constantly self-learn and improve, and if necessary, can be reprogrammed to meet the required conditions of the task. As a result, the results and time required to complete missions will improve significantly, while the number of control operators will decrease. It solves a number of problems and shortcomings related to the organisation of the management system, route planning, distribution of roles, speed and completeness of receiving, processing and transmitting information, which in turn improves the security and performance of the system.

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Моделі системи колективної самоорганізації безпілотних літальних апаратів з використанням штучного інтелекту

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Анотація. У статті розглядається сучасний стан та тенденції розвитку безпілотних літальних апаратів (далі – БпЛА), методів та засобів управління ними, самоорганізації, маршрутизації польотів, а також залучення до системи колективу БпЛА технологій штучного інтелекту. Проаналізовано основні тенденції застосування БпЛА в оборонній сфері. Виділені ключові проблеми в даній області, а також недоліки вже існуючих методів та систем. Проведено аналіз наукових праць вітчизняних та закордонних науковців, вивчено проблемні питання та запропоновані шляхи їх вирішення. Впровадження в систему управління БпЛА штучного інтелекту має значимий потенціал і обумовлює актуальність розвитку цих технологій. Розвиток систем колективного управління БпЛА, у тому числі із використанням штучного інтелекту, дозволяє ефективно використовувати технології в різних областях, забезпечуючи підвищену координацію, функціональність та загальну ефективність. Разом з тим, незважаючи на активні дослідження в цій галузі, все ще залишаються не повністю вирішеними ряд проблем, пов'язаних із розробкою методів та алгоритмів групової роботи. Недостатньо опрацьовано питання інтеграції створених на їх основі інформаційних технологій та особливості їх реалізації в системах колективного інтелекту з метою підвищення ефективності вирішення складно формалізованих завдань. Запропоновано метод самоорганізації колективу БпЛА з децентралізованим управлінням, при якому ряд функцій (планування маршруту, розподіл ролей, визначення оптимальних дій, отримання та обробка інформації), покладених на бортову систему управління, роботизованого повітряного комплексу, можуть вирішуватися кожним елементом системи колективу БпЛА за рахунок їх самоорганізації. Практичність застосування зазначеного методу полягає у тому, що штучний інтелект БпЛА буде постійно самонавчатися й удосконалюватися, а при необхідності можна перепрограмувати під потрібні умови поставленого завдання. Таким чином, результати та час, необхідний на виконання місій покращиться у рази, а кількість операторів управління навпаки зменшиться. Вирішується ряд проблем та недоліків, пов'язаних з організацією системи управління, планування маршруту, розподіл ролей, швидкості та повноти отримання, обробки та передачі інформації, що в свою чергу покращує захист та продуктивність системи.

Ключові слова: авіаційний комплекс, агенти, алгоритми, безпілотний літальний апарат, інформаційні технології, колектив, координація, маршрутизація, мультиагенті системи, рій, розподіл ролей, самонавчання, самоорганізація, управління, штучний інтелект.