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INVESTIGATING THE INFLUENCE OF COMMUNICATION SYSTEMS ON THE PERFORMANCE OF UAV COMBAT MISSIONS

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Abstract—*This paper investigates the optimization of the communication system of unmanned aerial systems to improve the efficiency of combat operations. In particular, approaches to improving data transmission between unmanned aerial vehicles, manned aircraft and ground control points are analyzed, as well as routing algorithms to ensure control stability. The problem of countering electronic warfare and its impact on the effectiveness of unmanned aerial vehicles in combat conditions is considered separately. The article presents the results of evaluating the effectiveness of modern communication systems for unmanned aerial vehicles, develops mathematical models for calculating the cost and duration of a combat mission, and assesses the resistance of the communication system to electronic warfare. The results can be used to improve communication systems, increase the effectiveness of combat operations and develop a strategy for protection against electronic warfare.*

Keywords—Unmanned aerial systems; communication system; optimization; adaptive algorithms; electronic warfare; mathematical models; combat operations; autonomous systems; signal processing.

I. INTRODUCTION

The development of military technologies is leading to an increase in the use of unmanned aerial vehicles (UAVs) in combat operations. They provide reconnaissance, fire control, strikes against the enemy, and other tasks that significantly increase the effectiveness of the armed forces. One of the key factors in the successful use of UAVs is the effectiveness of the communication system between the vehicles, their interaction with manned aircraft and ground control points.

In addition to combat use, UAVs play an important role in providing communications, gathering intelligence, and coordinating the actions of military units. However, in today's environment, the use of unmanned aerial vehicles is complicated by enemy electronic warfare. This requires the development of new communication methods and algorithms that will ensure stable control and uninterrupted data exchange.

The peculiarity of using UAVs in combat conditions is the need to integrate their control systems with other elements of the combat infrastructure. Interaction between unmanned and manned aircraft, as well as with ground control systems, is an important aspect of increasing the effectiveness of military operations. This involves the creation of a unified information network capable of processing large amounts of data in real time.

In the context of this study, considerable attention is paid to the development of new technologies to improve the effectiveness of UAVs in combat. In particular, modern approaches to the integration of unmanned aerial systems into the overall command and control system of military operations, as well as methods of protecting their communication channels from interference are analyzed.

The article presents the results of an analysis of the effectiveness of modern communication systems for UAVs, and explores approaches to their optimization. The results presented here can be used to improve control algorithms for unmanned systems, develop strategies for interaction between manned and unmanned aircraft, and increase the overall effectiveness of combat operations.

II. ANALYSIS OF RESEARCH AND PUBLICATIONS

Research in the field of military use of UAVs occupies a significant place in the scientific literature, in particular in the context of their effectiveness, strategies for using and countering them. For example, [1] analyzes the strategy of defeating enemy UAVs and evaluates the effectiveness of anti-drone methods. Other studies, such as [2], examine the experience of joint use of manned and unmanned aircraft in the armed forces of different countries.

Study [3] proposes methods for autonomous UAV navigation in combat conditions using global positioning system signals and sensor monitoring. Similarly, paper [4] analyzes ways to improve the combat capabilities of military units through strike UAVs. Methods for assessing the effectiveness of UAV units are presented in [5], where the factors that affect their combat effectiveness are studied.

Papers [6], [7] consider the factors that affect the effectiveness of the joint use of manned and unmanned aircraft, as well as the benefits of using open-source autopilots. Study [8] analyzes the forms and methods of using UAVs in military operations, and [9] considers systems of protection against UAV strikes using neural network technologies.

Paper [10] analyzed the combat effectiveness of a UAV swarm using a system dynamic model. Similarly, study [11] examines the use of UCAVs (attack drones) in modern conflicts. Papers [12], [13] study the distribution of tasks for UAVs in order to increase their efficiency and select optimal designs for maritime operations.

In addition, study [14] examines the military application of UAV swarm technology, and [15] proposes strategies for combating drones and drone swarms in military conflicts.

These publications are devoted to various aspects of UAVs in the military sphere, including optimization of communication, control, and countering enemy systems. However, in order to assess the effectiveness of communication between UAVs, it is necessary to model data transmission parameters in various combat scenarios.

This paper uses the approaches proposed in [3], [10], [15] to analyze the efficiency of communication systems and develop recommendations for their optimization.

III. Task Statement

This study aims to develop mathematical models and methods for assessing the effectiveness of combat use of an UAV, as well as analyzing the impact of various factors, such as communication system, power consumption, and task efficiency, on the overall effectiveness of UAV operations.

IV. Presentation of the Main Material

A. Conceptual basis for the development of an unmanned aerial vehicle for special purposes

The development of a special-purpose unmanned aerial vehicle includes the definition of the main goals and objectives of such a vehicle, which will depend on its functional purpose. As part of this process, a detailed analysis of the needs and requirements for the functionality of the complex, including computing, navigation and communication systems, is carried out. In addition, the concept of hardware and software that will be used for effective control and navigation of unmanned vehicles is being developed. Special attention is paid to security issues, including data protection and privacy standards. An important component is the development of a communication system that ensures stable control over the complex, as well as testing and validation of the complex before its introduction into combat conditions.

B. Criteria for the effectiveness of combat use of unmanned aerial vehicles

The criteria for the effectiveness of a UAV's combat use are crucial in assessing its ability to perform its combat missions. The main criteria include a clear definition of operational goals and objectives, as well as the use of several parameters that are understandable to the personnel who control and manage the operation. Methods for calculating effectiveness in various combat scenarios are also important.

The main requirement for any combat operation is the need to solve the combat task at hand with minimal time and resources. In this regard, the first criterion for the effectiveness of the use of military UAVs will be as follows:

$$T = T(N) \to \min, \tag{1}$$

where T is the time for solving the assigned combat task, taking into account the time spent on preparation for the operation; N is the number of UAVs used in the operation. For some types of UAVs, such as repeater UAVs, UAVs-REBs, etc., the value T is a fixed deterministic or random value. In the course of any operation, including those involving UAVs, there are a significant number of random factors [39] that form the uncertainty of its final result. For military UAVs, such factors are the actions of enemy air defense systems, failures of UAV onboard systems, errors in UAV flight programs and in the actions of control operators, etc. To take into account the effects of random factors in the processes of UAV use, the type criterion is introduced:

$$P = P(N) \to \max, \tag{2}$$

where P is the probability of successful completion of a combat task assigned to a group of N UAVs.

The following criterion is proposed to be used as the third criterion of UAV efficiency:

$$N \to \min, \tag{3}$$

which describes such a natural requirement as solving a combat task with a minimum number of forces and means. If *n* types of UAVs are to be used in a planned operation, the criteria for the effectiveness of their use will be as follows:

$$P = \prod_{i=1}^{n} P(N_i) \to \max, \quad N = \sum_{i=1}^{n} N_i \to \min. \quad (4)$$

Here, N_i is the number of UAVs of the *i*-th type; $P(N_i)$ is the probability of a group of UAVs *of the ith* type successfully solving the problem, $i = \overline{(1, n)}$.

It should be noted that in solving certain problems of effective UAV use, auxiliary criteria for the optimality of the solutions formed, such as cost criteria, can be used.

One of the main criteria for assessing the feasibility of combat use of UAVs is the "effectiveness/cost" indicator, namely the cost of performing a combat mission $C_{cp.cm}$ [10]:

$$C_{cp.cm} = \frac{C_{cm}}{P_{c.cm}}, \quad (5)$$

where C_{cm} is the total cost of the combat mission; $P_{c.cm}$ is the probability of completing a combat mission based on statistical data.

The total cost of a combat mission is defined as:

$$C_{cm} = N_l C_{1\text{UAV}} + C_{1h} T_n \left(N_{\text{UAV}} - N_l \right) + C_{ca} + C_{en}, \quad (6)$$

where N_{UAV} is the number of UAVs in the outfit performing the combat mission; N_l is the number of lost UAVs; $C_{1\text{UAV}}$ is the cost of one UAV; C_{1h} is the cost of one hour of UAV flight; T_n is the duration of the UAV's flight during a combat mission; C_{ca} is the cost of ammunition spent during a combat mission; C_{en} is the cost of ensuring the fulfillment of a combat mission.

The total cost of the UAV $C_{1\text{UAV}}$ is divided into:

- *Body and aerodynamic elements* – material and production costs.
- *Power plant* – engine, batteries, power supply system.
- *Navigation and control system* – sensors, computing modules, autopilot.
- *Communication system* – data transmission modules, antennas, electronic warfare (EW) protection equipment.
- *Weapons or payloads* – sensors, cameras, ammunition.

The cost of the communication system consists of:

- Ground equipment (base stations, repeaters, control servers).
- UAV on-board equipment (radio modules, antennas, EW protection).
- Software (communication algorithms, encryption and interference adaptation tools).

Operating costs (energy consumption, maintenance, modernization).

C. Mathematical models for estimating the cost and duration of a UAV combat mission

Mathematical models for calculating the cost and duration of a UAV flight:

1) The cost of one hour of UAV flight:

$$C_{hour} = \left(\frac{C_{total}}{T_{life}} \right) + C_{fuel} + C_{maintenance},$$

where C_{total} is the total cost of UAV production (dollars, UAH); T_{life} is the total resource of the UAV (flight hours); C_{fuel} is the cost of fuel or energy per hour; $C_{maintenance}$ is the cost of maintenance per hour.

2) UAV flight duration during a combat mission:

$$T_{flight} = \frac{E_{\max}}{P_{avg}},$$

where $E_{\max}$ is the maximum capacity of the fuel tank or battery (*J*, *W–h*); P_{avg} is the average power consumption per hour of flight (*W*, l/h).

If we take into account the dependence on the weight of the ammunition:

$$T_{flight} = \frac{E_{max}}{\left(P_{base} + k \cdot M_{payload} \right)},$$

where P_{base} is the power consumption without load; *k* is the coefficient of influence of the additional mass; $M_{payload}$ is the weight of ammunition and additional load.

3) The cost of ammunition consumed in the performance of a combat mission:

$$C_{ammo} = N_{ammo} \cdot C_{unit},$$

where N_{ammo} is the number of ammunition used; C_{unit} is the cost of one ammunition.

4) The cost of providing support for the combat mission

$$C_{mission} = C_{flight} + C_{ammo} + C_{support},$$

where $C_{flight} = C_{hour} \cdot T_{flight}$ is the flight cost; C_{ammo} is the cost of ammunition; $C_{support}$ is the cost of support (operators, communications, ground infrastructure.

The probability of performing a combat mission by a squad of similar UAVs is determined by the probability that at least one UAV will complete the combat mission:

$$P_{c.cm} = 1 - \left(1 - P_{c.cm1}\right)^{N_{uav}}. \quad (7)$$

Formula (8) expresses the probability of a single UAV performing a combat mission, which is a convolution of the private probabilities of this UAV performing individual stages of a combat mission [11]:

$$P_{c.cm1} = P_{td} P_{po} P_{st} P_{it}, \quad (8)$$

where P_{td} is the probability of a UAV's timely departure, which characterizes the efficiency of the ground control system and technical means of engineering, aviation and airfield support; P_{po} is the probability of overcoming the UAV air defense and electronic warfare zone, characterizes the maneuverability of the UAV, the efficiency of flight route selection, the resistance of the UAV and its onboard equipment to the effects of air defense and electronic warfare; P_{st} is the probability of successful targeting, which characterizes the efficiency of the UAV's onboard equipment, targeting and navigation system, and ground control system; P_{it} is the probability of successful impact on the target: for reconnaissance UAVs – successful disclosure of the target's intelligence parameters, for strike UAVs – successful defeat.

The probabilities in the last expression are conditional, and each subsequent probability takes on its own specific value, provided that the probabilities of the previous stages are already equal to one.

The analysis of impressions for $C_{cp.cm}$ shows that current trends in the use of UAVs are reducing their weight and size parameters, reducing the cost of construction and increasing maneuverability $\left(C_{1\text{UAV}} \downarrow, C_{1h} \downarrow, C_{ca} \downarrow, C_{en} \downarrow P_{po} \uparrow\right)$, combining them into groups $\left(N_{\text{UAV}} \uparrow\right)$, which proves that even with an increase in the number of lost UAVs $\left(N_l \uparrow\right)$, they perform their combat mission at about the same level:

$$\left(P_{c.cm} \approx \text{const},\ C_{cp.cm} \approx \text{const}\right).$$

V. Evaluation of the Effectiveness of the Communication System for UAVs

A. Taking into account the efficiency of the communication system

To assess the impact of the communication system on the effectiveness of the UAV's combat mission, it is proposed to add the following parameters:

1) Continuous communication probability (CCP) is an indicator of the stability of the communication channel and its level of noise immunity.

2) Data transmission delay time (DTT) is critical for real-time control.

3) Resistance to electronic warfare (EW) – the impact of enemy EW means and adaptation of the communication system to such conditions.

4) Channel bandwidth is necessary for high-quality video and telemetry transmission.

5) Communication autonomy – the ability of the UAV to continue the mission in case of loss of the control channel.

B. Formalizing the impact of the communication system

The overall probability of completing a combat mission, taking into account communications:

$$P_c = P_{td} \cdot P_{po} \cdot P_{st} \cdot P_{it},$$

Calculation of efficiency losses in case of communication disruption:

$$C_{cm} = \left(C_{\text{UAV}} + C_h \cdot T_n + C_{ca}\right) \cdot f\left(P_{it}\right),$$

where is the coefficient of losses due to unstable communication, is the cost of the communication system.

VI. Conclusions

The study found that optimization of the communication system of UAVs is an important factor in increasing the effectiveness of combat operations. The use of adaptive routing algorithms and ensuring stable data transmission through reliable communication channels can significantly improve the quality of control and monitoring of UAVs in difficult combat conditions. In addition, the impact of EW by the enemy is one of the main factors that reduces the effectiveness of UAVs.

Therefore, the development of methods to counteract electronic warfare is a critical task to ensure the stable operation of unmanned systems.

It was also found that taking into account the characteristics of the communication system, such as the probability of continuous communication, data transmission delay, and EW resistance, allows for a more accurate assessment of the effectiveness of the combat mission. The developed mathematical models for calculating the cost and duration of a UAV flight provide more detailed resource planning and optimization of mission costs.

The results of the study can be used to improve the technical means and tactics of combat use of UAVs, as well as to develop recommendations for improving communication systems in the face of modern threats.

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В. М. Єгунько, С. С. Чумаченко. Дослідження впливу комунікаційних систем на ефективність виконання бойових завдань безпілотних літальних апаратів

Роботу присвячено дослідженню оптимізації системи зв'язку безпілотних авіаційних комплексів з метою підвищення ефективності виконання бойових завдань. Представлено концептуальні підходи до інтеграції системи зв'язку безпілотних літальних апаратів з іншими елементами бойової інфраструктури, а також методи покращення стабільності передачі даних у складних бойових умовах. Окрему увагу приділено аналізу впливу радіоелектронної боротьби на ефективність роботи безпілотних літальних апаратів, а також розробці адаптивних алгоритмів маршрутизації для забезпечення безперебійної роботи системи зв'язку. Запропоновано математичні моделі для оцінки вартості та тривалості виконання бойових завдань, а також оцінки стійкості системи зв'язку до зовнішніх загроз. Результати дослідження можуть бути використані для вдосконалення технічних засобів управління та підвищення ефективності бойових операцій за допомогою безпілотних літальних апаратів.

Ключові слова: безпілотні авіаційні системи; комунікаційна система; оптимізація; адаптивні алгоритми; електронна боротьба; математичні моделі; бойові операції; автономні системи; обробка сигналів.

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