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CONTROL MODEL OF A GROUP OF MANEUVERABLE UNMANNED AERIAL VEHICLES TAKING INTO ACCOUNT THEIR FLIGHT SAFETY

Abstract. The article deals with the urgent scientific problem of creating an algorithmic support for an automated situational control system for group maneuverable unmanned aerial vehicles, taking into account the possibility of improving their flight safety. To realize this possibility, the authors proposed a non-linear flight model of group formation. This is the basis for the synthesis of nonlinear control laws for these aircraft. The difference of the proposed approach is taking into account the influence of changes in the speed and direction of wind flows on the laws governing the movement of aircraft in a group. Promising areas of research are considered, namely: the application of the results obtained to justify the requirements for the design characteristics of control systems and their algorithmic support in terms of not only improving their flight safety in group formations, but also ensuring the specified performance indicators for a wide range of possible flight tasks by a group of maneuverable aircraft.

Keywords: mobile unmanned aerial vehicles, control system, control law, aircraft group, information channel, flight safety, group flight, wind effects, control laws, model flight safety.

Introduction

Today, the dominant advantage of using modern unmanned aerial vehicles (UAVs) as part of groups is a significant increase in the probability and effectiveness of flight tasks, while the disadvantage is the impossibility of ensuring the necessary level of flight safety during intensive maneuvering under the influence of the state of the atmosphere and especially variations in speeds and directions wind currents. A promising approach to overcoming this shortcoming is the appropriate organization of the process of managing the simultaneous use of a large number of UAVs in a group flight. The term "group flight" reflects the process of simultaneous, compatible, coordinated, synergistic (organizationally interconnected) functioning of several aircraft (which as a rule have different flight and technical characteristics load functional purpose equipment configuration etc.) with a clearly defined purpose flight task. Current flight tasks, the effectiveness of which increases significantly with the group use of UAVs, today include: surveillance with the accumulation or operational real-time transmission of the necessary information about ground and air objects; search and detection of objects, constant monitoring of them with the necessary and possible information and energy or other effects on their functioning; transportation of oversized cargo; performance of aviation and chemical works; fire extinguishing; carrying out special monitoring; retransmission, switching, routing and transformation of departmental radio communication signals; solutions of applied scientific tasks on the study of the earth's surface; patrolling etc. The implementation of the appropriate management organization for the simultaneous use of a large number of UAVs in a group flight with the provision of a given level of flight safety during intensive maneuvering under the influence of atmospheric conditions is proposed to be ensured through the creation of algorithms for the operation of the control system of these moving objects. Today appropriate automated control systems for the group use of UAVs (complexes of mobile aviation systems) are being developed, but it is advisable to pay more attention to the issue of increasing the level of flight safety during intensive maneuvering under the influence of the state of the atmosphere, and especially variations in the speed and direction of wind flows. Therefore this scientific article is devoted to the solution of this relevant applied task.

Analysis of recent research and publications

A significant amount of scientific research, the results of which are reflected in well-known publications, is devoted to the modeling of management processes in complex, dynamic, large organizational systems, which undoubtedly include groups of aerial vehicles and especially unmanned ones. It is appropriate to focus attention on the latest achievements of scientists in this field and analyze the results of their research, which are reflected in their published scientific works. In [1] describes an approach to planning the flight path of "unmanned aerial vehicles" and presents a model of a group of aerial vehicles, which shows the possibility of modeling movement along trajectories approximated by arcs of constant and variable curvature, as well as Pythagorean Hodographs. The advantages and disadvantages of modeling the movement of UAVs and the conditions for applying the specified approaches to the approximation of trajectories are shown. The article [2] analyzed the existing approaches and features of UAV control, described its mathematical model, and proposed a number of different approaches to controlling such aerial vehicles. The main ideas, terms of use, advantages and disadvantages of the proposed approaches are illustrated and discussed. The structural schemes of the UAV as a control object using aerobatic, navigation and automatic control methods are considered, the architectural components of these schemes are described.. The article [3] examines the existing methods of evaluating the effectiveness of the use of unmanned aircraft systems and proposes an improved methodology for evaluating the effectiveness of the use of formations of unmanned aircraft systems under the conditions of unauthorized influence of various factors not only directly on the devices themselves during their flight tasks, but also on groups of unmanned aircraft complexes. It is indicated that since the UAV control process is stochastic, it is suggested to use probabilistic indicators to evaluate the efficiency of the use of units of these aerial vehicles, namely: the probability of successful completion of flight tasks, the guaranteed probability of completing tasks, the probability of completing a number of tasks from their total number, the average guaranteed result, mathematical expectation of the number of successfully completed flight missions by UAV complexes. In scientific works [4-6] the authors comprehensively considered the features and specifics of group use of UAVs. A probabilistic method of justifying the choice of a control system for a group of unmanned aerial vehicles is proposed which is based on Markov probabilistic models of changes in discrete states in continuous time. The possibility of differentiating the intensities of event flows depending on the states is taken into account. The difference between the results obtained by the authors in these works is the consideration of the widest possible range of possible application circumstances: the only requirement for the functioning of the “UAV group - object of application” system is to ensure compliance of the random flow of events with Markov conditions. The article [7] presents the approaches and results of the study of effective online planning of UAV logistics in emergency situations. These studies are based on the use of optimization algorithms. The paper [8] proposes approaches to the synthesis of the UAV control and monitoring subsystem, and the article [9] describes a secure voice control system for this aerial object. Scientific works [10-12] are devoted to the construction of mathematical models of the movement of UAVs as dynamic objects, taking into account the characteristic features of actions and tactical and technical capabilities of the aircraft for the synthesis of the control system with support for decision-making regarding the planning of optimal UAV routes.

Thus, the analysis of the results obtained in recent studies shows that scientists are now paying considerable attention to the problems of organizing the control of UAVs and the synthesis of control systems for these structures. But in the known works, the approaches to ensuring the safety of flights of groups of UAVs, whose control systems provide for the possibility of compensating for wind effects on maneuvering such aerial vehicles, are not sufficiently covered.

The purpose of the article is to solve the task of synthesizing the laws of control of groups of unmanned maneuverable aerial vehicles (UMAVs) taking into account turbulent phenomena in the atmosphere, the implementation of which in algorithmic and software systems for automated control of “drones” and support for decision-making on piloting will increase the safety of the flights of these aerial vehicles.

Presenting main material

In nonlinear models, which sufficiently fully and accurately describe the flight processes of UMAVs in group application and which have recently been increasingly used for the synthesis of situational nonlinear laws of control of these complex dynamically dispersed objects, it is advisable to take into account such a situational factor as variations in atmospheric processes [1]. As the in-depth and comprehensive analysis of the experience of using groups of unmanned aerial vehicles shows the influence of variations in the air environment causes significant, but not always predictable changes in the aerodynamic forces and moments of aircraft. This significantly changes the effectiveness of managing these air assets, and especially in group use. At the same time the main emphasis should be placed not only on the performance of the flight task by the formation of unmanned maneuverable aircraft but also on ensuring their flight safety in a group [2-7].

It is known that a large number of factors influence the dynamics of atmospheric processes. It is proposed to take into account the most significant of them for conducting research, namely: the geographical location of the flight area of groups UMAVs , the type of the Earth's surface, the flight height of aircraft, the season, time of day, air temperature variations [8, 9]. Therefore, the air environment is a complex nonlinear object, for which it is problematic and not always possible to synthesize an adequate and accurate model of atmospheric processes when organizing the management of UMAVs in a group [5, 6, 10]. The conducted studies show that possible turbulent phenomena in the atmosphere can be represented by appropriate nonlinear mathematical models. Among them, according to the authors, the greatest interest for achieving the goal of a systematic synthesis of situational control systems for groups of unmanned aerial vehicles is represented by mathematical models in which it is sufficient to take into account variations in atmospheric turbulence affecting the profiles of wind flows. As you know, they are especially characteristic of fast-moving air currents near the Earth's surface [1].

The study of the reaction of the group UMAVs in a group to the fast-moving situational factors of atmospheric turbulence variations was based on the theory of statistical dynamics. For a complete, accurate and adequate description of possible management situations, in which the influence of the existing factors of atmospheric turbulence is taken into account, models of the UMAVs in a group are used in the form of nonlinear equations that describe, in addition to the dynamic states in flight of these aerial objects, also the power plants of aircraft and their servo drives. This made it possible to synthesize the functioning algorithms of the synergistic control systems of the

UMAVs in a group. Their implementation will ensure the self-organization of situational control by taking into account the specific features of various variants of the flight task for the UMAVs [11, 12].

When solving this problem, one of the possible approaches to assessing the impact of air turbulence is proposed. We will use the obtained results to describe the general laws and determine the necessary requirements for the synthesis of situational control systems of the UMAVs. When conducting analytical studies we will assume that the air environment is homogeneous and isotropic. Then, for all points of the airspace in which the flight of the UMAVs group is predicted to be implemented such characteristics as mathematical expectation dispersion and density of the distribution of the random component of the wind speed will be the same.

It is known that the variations of the longitudinal component of the speed change of the UMAVs taking into account the influence of a homogeneous isotropic medium along the trajectory L of the movement of this aircraft, should be represented by the spectral density

$$S_1(\omega) = \frac{2\delta_u^2 L V^{-1}}{1+\omega^2 L V^{-2}}, \qquad (1)$$

where δ_u^2 – dispersion of the velocity of the longitudinal component of the wind; V – UMAVs flight speed; ω – the frequency of the components of a random signal, adequate to the change in wind speed, which can take a value $\omega = [0, \infty]$; L – the distance traveled by the aircraft.

The vertical u_y and horizontal u_z components of changes in the speed of a UMAVs taking into account the effects of intense variations in atmospheric turbulence (normal to the vector of the UMAVs flight path and lying in its structural plane of symmetry and in the plane of its wing) are determined by the spectral density from the expression

$$S_2(\omega) = \delta_u^2 L V^{-1} \left(\frac{1+3\omega^2 L^2 V^{-2}}{\left(1+\omega^2 L^2 V^{-2}\right)^2} \right). \qquad (2)$$

To describe the dependence of the dispersion D_{ij} of signals X_i (which identify the UMAVs group as a complex dynamic nonlinear system) on the spectral density S_0 of the “white noise” type acting on the j input of this system and the corresponding integral quadratic estimate of the impulses of these signals, we will use a classical statistical dynamics mathematical model

$$D_{ij} = S_0 I_{ij}. \qquad (3)$$

In order to use expression (3) in the synthesis of the laws of situational synergistic control, it is proposed to create models that describe the shaping filters for the transformation of control signals with the spectral densities described by expressions (1) and (2). Next, to simplify analytical studies, we make a model of a dynamic system containing nonlinear equations of a joint flight of UMAVs in a group of two aircraft. In this model, we will include equations that describe the influence of the processes in the signal-forming filter for a given wind disturbance and predicted control of the UAV. To simplify the analytical modeling, the assumption is made that the processes of controlling unmanned aircraft are stable. This will make it possible to determine the integral quadratic estimates I_{ij} of the processes in the control systems of the UMAVs group when conducting an analytical study.

Amplitude-phase characteristics $W_1(j\omega)$ and $W_2(j\omega)$ shaping filters of signal processing in control systems of the UMAVs which adequately correspond to the spectral densities $S_1(\omega)$ and $S_2(\omega)$ are described by functions of the form

$$S_i(\omega) = \left(W_i(j\omega)\right)^2 S_x(\omega), \qquad (4)$$

where $S_x(\omega)$ – spectral density of the input signal of the shaping filter.

Taking into account (4) and accepting $S_x(\omega) = 1$, we find dependencies for determining the amplitude-phase characteristics of the shaping filters of signal processing in the control systems of the UMAVs

$$\left|W_1(j\omega)\right|^2 = S_1(\omega), \ \left|W_2(j\omega)\right|^2 = S_2(\omega). \qquad (5)$$

Then the differential equation describing the state of the first signal processing filter will have the form

$$\dot{u}_x = -VL^{-1}u_x + \delta_u \sqrt{2VL^{-1}}\,\xi, \qquad (6)$$

and the second filter

$$\begin{vmatrix} \dot{Y}_1 \\ \dot{Y}_2 \end{vmatrix} = \begin{vmatrix} 0 & -V^2L^{-2} \\ 1 & -2VL^{-1} \end{vmatrix} \begin{vmatrix} Y_1 \\ Y_2 \end{vmatrix} + \begin{vmatrix} \delta_u \left(VL^{-1}\right)^{3/2} \\ \delta_u \left(3VL^{-1}\right)^{1/2} \end{vmatrix} |\xi|. \qquad (7)$$

where $Y_2 = u_y$, $Y_1 = 2V\left(LV_2\right)^{-1} + \dot{Y}_2 - \delta_u \left(3VL^{-1}\right)^{1/2}$.

The output signal for the second filter, which must be transmitted to the input of models of control objects of wind action signals u_y is Y_2. The input signal of both filters as well as in extended models of control objects is a signal which we denote by ξ.

First, it is advisable to present the flight model of the UMAVs group in general

$$\dot{X} = AX + Gu, \qquad (8)$$

where X – the state vector of the UMAVs which consists of the parameters of their autonomous flight and the parameters of the coordinates of the relative position of the aircraft during group movement;

A – matrix of coefficients which describes the UMAVs as a complex object of management;

G – the matrix of the efficiency coefficients of the influence of control signals on the implementation of aircraft maneuvering processes; u – the vector of control signals of the UMAVs.

In equation (8) we present the matrix A and G in this form

$$A = \begin{vmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ A_{31} & A_{31} & A_{31} \end{vmatrix}, \quad G = \begin{vmatrix} G_1 & 0 \\ 0 & G_2 \\ 0 & 0 \end{vmatrix}. \qquad (9)$$

Taking (9) into account, equation (8) will be represented by two systems of equations. The first of them will look like

$$\dot{X}_1 = A_{11}X_1 + G_1u_1,$$
$$\dot{X}_2 = A_{22}X_2 + G_2u_2, \qquad (10)$$
$$\dot{Y}_{om} = A_{31}X_1 + A_{32}X_2 + A_{33}Y_{om}.$$

In the system of equations (10) the following is indicated:

X_1, X_2 – n- measurement vectors that reflect the state of autonomous movement of the first and second UMAVs, respectively;

Y_{om} – μ -measurement vector of the coordinates of the relative position of the UMAVs;

u_1, u_2 – r -dimensional vectors of variations of control influences;

$A_{11}...A_{33}$ – matrices of coefficients of internal connections in the UMAVs model;

G_1, G_2 – matrices of UMAVs control efficiency coefficients which are included in the block matrices of the form (9) for the mathematical model (10).

The second system of equations in addition to the mathematical model (10) is represented by equations of the form

$$X_{C1} = A_{11}X_{C1} + G_1u_1; \qquad (11)$$
$$X_{C2} = A_{22}X_{C2} + G_2u_2.$$

It consists of isolated equations of motion of a single UMAV from the group.

To compile a complete mathematical model of the UMAVs flight using (10) and (11) we decompose the expressions that describe the dependence of the elements of the matrices included in these equations on the flight parameters. For example, let's consider the most typical flight situations of the use of a group of UMAVs namely the mode of longitudinal movement and simultaneous turning in the horizontal plane. In longitudinal motion, the vectors of their state, which correspond to the equations of autonomous motion, are represented by matrices of the form

$$X_1 = \left[\bar{n}_1 \ V_1 \ \theta_1 \ \omega_{z1} \ \nu_1\right]^T,$$
$$X_1 = \left[\bar{n}_2 \ V_2 \ \theta_2 \ \omega_{z2} \ \nu_2\right]^T. \qquad (12)$$

The control vectors of the UMAVs in the group will be presented in the form

$$u_1 = \left[\delta_{1\partial в}\varphi_1\right], \quad u_2 = \left[\delta_{2\partial в}\varphi_2\right]. \qquad (13)$$

In expressions (12) and (13) the symbols $\bar{n}_1$ and $\bar{n}_2$ indicate increases in the relative frequency of rotation of the rotors of the UMAVs engines, which are equivalent to the increase in their thrust, $\delta_{1\partial в}$, $\delta_{2\partial в}$ – deviation from the balancing positions of the engine control bodies, φ_1, φ_2 – deviation from the balancing positions of the UMAVs stabilizers. The rest of the designations in model (12) and (13) meet the requirements accepted in the aerodynamics of aircraft [13, 14].

Identical in structure matrices, which are included in model (10) are proposed to be presented in the form

$$A_{11} = \begin{vmatrix} a_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & 0 & a_{25} \\ a_{31} & a_{32} & a_{33} & 0 & a_{35} \\ 0 & a_{42} & a_{43} & a_{44} & a_{45} \\ 0 & 0 & 0 & 1 & 0 \end{vmatrix}, \qquad (14)$$

$$G_1 = \begin{vmatrix} g_{11} & 0 \\ 0 & g_{22} \\ 0 & g_{32} \\ 0 & g_{42} \\ 0 & 0 \end{vmatrix}. \qquad (15)$$

The elements of the matrices (14) and (15) are determined by numerically differentiating the complete nonlinear equations of the flight of the UMAVs by the elements of its state vector under their flight parameters. These parameters correspond to variations in the current values of the aircraft balancing process.

We emphasize that wind speed variations are taken into account in models (12), (14) and (15) in the second column of the matrices A_{11} and A_{22}.

Let's introduce vectors to take these influences into account, marking them as $\chi_{\nu1}$, $\chi_{\nu2}$. At the same time, the influence of the vertical component of wind speed is described in the mathematical model by the fifth column.

The possibility of describing this action is based on the fact that the equations that describe the movement of the UMAVs are drawn up in the velocity coordinate system. At the same time the angle of attack of the aircraft is determined from the equation

$$\alpha = \upsilon - \theta + \alpha_в,$$

where $\alpha_в = u_y V^{-1}$.

Equation (10) which describes the joint movement of UMAVs taking into account the processes of managing their state, as well as signals that are adequate for variations u_x, can be presented in the form

$$\begin{vmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{Y}_{om} \end{vmatrix} = \begin{vmatrix} D_{11} & 0 & 0 \\ -G_2K_{21} & D_{22} & -G_2K_{23} \\ A_{31} & A_{32} & 0 \end{vmatrix} \times$$

$$\times \begin{vmatrix} X_1 \\ X_2 \\ Y_{om} \end{vmatrix} + \begin{vmatrix} \chi_{V1} & \chi_{\nu1} \\ \chi_{V2} & \chi_{\nu2} \\ 0 & 0 \end{vmatrix} \times \begin{vmatrix} u_x \\ \dfrac{u_y}{V} \end{vmatrix}, \qquad (16)$$

where $D_{11} = A_{11} - G_{11}K_{11}$, $D_{22} = A_{22} - G_{22}K_{22}$ – dimension matrices $n \times n$ of models of controlled autonomous movement of the UMAVs. It is appropriate to present the model (16) in the form

$$\dot{Z} = DZ + \chi_V u_x + \chi_\nu \frac{1}{V} u_y, \quad (17)$$

where $Z = \left[X_1^T \; X_2^T \; Y_{om}^T \right]^T$ – vector of the state of the closed control system of the UMAVs dimension $2n+\mu$;

$\chi_V = \left[\chi_{V1}^T \; \chi_{V2}^T \; 0 \right]^T$ i $\chi_\nu = \left[\chi_{\nu 1}^T \; \chi_{\nu 2}^T \; 0 \right]^T$ – vectors of aircraft control coefficients taking into account wind speed components u_x i u_y; D – matrix of coefficients of the closed control system of the UMAVs.

In order to take into account the influence of a random signal on the flight of the UMAV control model, which is adequate to the variations of wind disturbances, we transform (16) and (17) into the first extended model of the form

$$\begin{vmatrix} \dot{Z} \\ u_x \end{vmatrix} = \begin{vmatrix} D & \chi_V & Z \\ 0 & -VL^{-1} & u_x \end{vmatrix} + \begin{vmatrix} 0 \\ g_\Phi \end{vmatrix} |\xi|, \quad (18)$$

where $g_\Phi = \sigma_u \sqrt{2VL^{-1}}$ – coefficient of effectiveness of the influence of a "white noise" type signal. We will evaluate the results of the action of a random wind disturbance signal taking into account (16) and (17) on the basis of the second extended model, namely:

$$\begin{vmatrix} \dot{Z} \\ \dot{Y}_1 \\ \dot{Y}_2 \end{vmatrix} = \begin{vmatrix} D & 0 & \chi_\nu V^{-1} \\ 0 & 0 & -V^2L^2 \\ 0 & 1 & -2VL^{-1} \end{vmatrix} \begin{vmatrix} Z \\ Y_1 \\ Y_2 \end{vmatrix} + \begin{vmatrix} 0 \\ g_\Phi \\ g_\Phi \end{vmatrix} |\xi|, \quad (19)$$

where $g_\Phi = \left[\sigma_u \left(VL^{-1} \right)^{3/2} \; \sigma_u \left(3VL^{-1} \right) \right]^T$ – vector of coefficients characterizing the effectiveness of the influence of a "normalized white noise" type signal. For ease of simplification in relation to conducting analytical studies, let's present equations (18) and (19) in the form

$$\dot{Z}_n = D_n Z_n + g_n \xi. \quad (20)$$

When calculating the values of I_{ij}, included in expression (3), it is suggested to use the following approaches.

The first of them is that in equation (19) the action of the signal $\xi = \delta(t)$ is replaced by a non-zero initial condition $Z_n(t_0) = g_n$ and grades are determined $I_{ij} = \int_0^\infty Z_{ni}^2 \mathrm{d}t$ along the trajectory of free movement of the system (19).

To calculate the value I_{ij}, a matrix with a single non-zero element is specified B_i, the location of which corresponds to the location of the coordinates Z_{ni} in the vector Z_n. After that the matrix equation is solved

$$P_1 D_n + D_n^T P_i = -B_i. \quad (21)$$

Then the value of the estimate I_{ij} is determined from the dependence

$$I_{ij} = Z_n^T(t_0) P_1 Z_n(t_0). \quad (22)$$

In the general case, equation (21) must be solved $2n+\mu$ once. At the same time, at each step of the solution, new values B_i of matrix elements are set.

The second (simplified) approach to the solution of this problem, which consists in the fact that instead of equation (21), we will solve equations of the form

$$\overline{P} D_n^T + D_n \overline{P} = -Z_n(t_0) Z_n^T(t_0). \quad (23)$$

Then the score we are looking for is determined from the expression

$$I_{ij} = B_i \otimes \overline{P}. \quad (24)$$

Let's consider the fairness of such an approach. Substitute the expression for determining the matrix B_i from (21) into (23) and obtain

$$I_{ij} = -\left(P_1 D_n + D_n^T P_i \right) \otimes \overline{P}. \quad (25)$$

After transformation (24) we obtain the following equation

$$I_{ij} = -\left(\overline{P} D_n^T + D_n \overline{P} \right) \otimes P_i = Z_n(t_0) Z_n^T(t_0). \quad (26)$$

The conducted analytical studies confirm that it is enough to solve equation (23) once to determine the elements of the matrix $\overline{P}$. In this matrix, its first diagonal elements $2n$ are equal to the value I_{ij}, $(j = 1, 2, ..., 2n)$.

Thus, the proposed and considered approach allows to algorithmically take into account the influence of such situational aspects of the dynamic state of the air environment as the turbulence of atmospheric flows in the situational control systems of groups of unmanned aerial vehicles.

Conclusions

The conducted analytical studies of the peculiarities of the group use of UMAVs under the influence of atmospheric variations allow us to draw the following conclusions. Thus, a necessary condition for improving the safety of group piloting of aircraft is taking into account variations in the speed and direction of wind flows (with the possibility of their adaptive compensation) in the functioning algorithms of the situational synergistic automated control system for the group use of unmanned aerial vehicles. To fulfill this requirement, nonlinear mathematical models of the flight of a group of unmanned aircraft are proposed. Based on these models, the possibility of compensating wind flow variations is taken into account during the synthesis of the laws of control of the maneuvering of the UMAVs.

Thus, it makes it possible to form a priori the requirements for the structure of the algorithmic and software of automated control systems for the group use of unmanned aerial vehicles, to specify technical tasks for conducting research and development works on the creation of situational control systems, to form potential opportunities for the use of non-linear models for the study of complex processes of group use of UMAVs and organization of management of this use.

According to the authors of the article, it is promising to use the obtained results to justify the optimal functionality of the group's devices, the requirements for the design characteristics of the flight information sensors of UMAVs from the point of view of increasing not only the safety of their flights in group formations, but also a significant increase in the efficiency of performing a wide range of possible flight tasks.

References

1. Romaniuk L.A., Chykhira I.V. (2020) Aerodynamic model of a group of unmanned aerial vehicles in space with obstacles. *"Computer-integrated technologies: education, science, production"*. 2020. 38. 59–66. DOI: 10.36910/6775-2524-0560-2020-38-10. [in Ukrainian].
2. Ivanenko Yu.V., Liashenko O.S., Filimonchuk T.V. (2023) Overview of methods of controlling unmanned aerial vehicles. *Collection of scientific works of the PNTU "Control, navigation and communication systems"*. T.1 (71). 26–30. DOI: 10.26906/SUNZ.2023.1.026. [in Ukrainian].
3. Yefremov O.V., Horbenko V.M., Korshets O.A. (2018) Methodology for evaluating the effectiveness of the use of units of unmanned aviation complexes. *Collection of scientific works of the KhNUAF named after Ivan Kozhedub*. 4 (58). 30–36. DOI: 10.30748/zhups.2018.58.04. [in Ukrainian].
4. Bondarenko Yu.L., Dupelych S.O., Horbach V.Ya. (2019) An improved mathematical model for planning the flight routes of reconnaissance unmanned aerial vehicles of the tactical class. *Bulletin of ZhSTU*. 1 (83). 206–213. DOI: 10.26642/th-2019-1(83)-206-213. [in Ukrainian].
5. Artiushyn L.M., Kononov O.A., Shmorhun Yu.V. (2019) Basic conditions for decision-making regarding the creation of an automated control system for the group use of unmanned aerial vehicles. *National University of Defense of Ukraine named after Ivan Chernyakhovsky "Modern information technologies in the field of security and defense"*. 2 (35). С. 49–54. DOI: 10.33099/2311-7249/2019-35-2-49-54. [in Ukrainian].
6. Artiushyn L.M., Kononov O.A., Herasymenko V.V., Nausenko B.Yu. (2022) The method of choosing an option for the implementation of group use of unmanned aerial vehicles. *National University of Defense of Ukraine named after Ivan Chernyakhovsky "Modern information technologies in the field of security and defense"*. 2 (44). 10–20. DOI: 10.33099/2311-7249/2022-44-2-10-20. [in Ukrainian].
7. D. Liu, S.Li (2018) Research on efficient online planning of emergency logistics path based on doublelayer ant colony optimization algorithm. *International Journal of Computers and Applications*. 33. 1–7.
8. Sineglazov V.M., Tsoba A.O. (2022) Control and monitoring subsystem of an unmanned aerial vehicle. *National Aviation University "Electronics and Control System"*. № 3 (73). 47–53. DOI: 10.18372/1990-5548.73.17012. [in English].
9. Lavrynenko O.Y., Konakhovych G.F., Bakhtiiarov D.I. (2020) Protected voice control system of unmanned aerial vehicle. *National Aviation University "Electronics and Control System"*. 1 № 63, 92–98. DOI: 10.18372/1990-5548.63.14529.
10. Berezhnyi A.O., Kachalova V.V., Rozhkov M.I. (2019) Modeling the movement of dynamic objects in the decision-making support system for planning the routes of unmanned aerial vehicles. *Collection of scientific works of the KhNUAF named after Ivan Kozhedub. "Information processing systems"*.4 (159). 44–49. DOI: 10.30748/soi.2019.159.05. [in Ukrainian].
11. Yershov V.V., Izvalov O.V., Nedilko S.M., Nedilko V.M. (2020) The concept of systematic control of the flight of unmanned aerial vehicles. *"Computer-integrated technologies: education, science, production"*. 40. 23–30. DOI: 10.36910/6775-2524-0560-2020-40-04. [in Ukrainian].
12. Подорожняк А.О., Волоцков Ye..A., Шевцова O.S. (2018) Study of the control system of unmanned aerial vehicles. *NTU KhPI "Modern information systems"*.Т.2. № 3. 97–101. DOI: 10.20988/2522-9052.2018.3.16. [in Ukrainian].
13. Aerodynamics for engineering students [Text] /E.L. Houghton, P.W. Carpenter, Steven H. Collicott, Daniel T. Valentine. *6th ed. USA: Elsevier Ltd*, 2016. 714 [in English].
14. Samborskyi I.I, Mashkov O.A., Kononov O.A. (2018) Problems of implementing joint use of promising unmanned aircraft complexes. *"Arsenal XXI".,* 1 (2). 36–41. [in Ukrainian].

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Модель управління групою безпілотних маневрених літальних апаратів із урахуванням їх безпеки польотів

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Анотація. У статті розглядається актуальне наукове завдання щодо створення алгоритмічного забезпечення автоматизованої ситуативної системи управління груповим застосуванням маневрених безпілотних літальних апаратів із урахуванням можливості підвищення безпеки їх польотів. Для реалізації цієї можливості авторами запропонована нелінійна модель польоту групового формування. Вона є підгрунтям синтезу нелінійних законів управління цими повітряними засобами. Відмінністю запропонованого підходу є врахування впливу варіацій швидкостей і напрямів вітрових потоків у законах управління рухом літальних апаратів у групі. Розглянуті перспективні напрями досліджень, а саме: застосування отриманих результатів для обгрунтування вимог до конструктивних характеристик систем управління і їх алгоритмічного забезпечення із погляду не лише на підвищення їх безпеки польотів у групових формуваннях, але і забезпечення заданих показників ефективності виконання широкого спектру можливих польотних завдань групою маневрених літальних апаратів.

Ключові слова: мобільні безпілотні літальні апарати, система управління, закон управління, група літальних апаратів, інформаційний канал, безпека польотів, груповий політ, вітрові впливи, закони управління, модель, безпека польотів.