MODEL OF MOTION ROUTE OF UNMANNED AERIAL VEHICLES OPERATIONS WITH OBSTACLES AVOIDANCE

Leonid Romaniuk [1], Ihor Chykhira[1], Halyna Tulaidan [2], Andriy Mykytyshyn[1]

[1]Ternopil Ivan Puluj National Technical University, 56 Ruska str., 46001, Ternopil, Ukraine; romanyuk@tntu.edu.ua
[2]1Ternopil Volodymyr Hnatiuk National Pedagogical University, 2 Maxyma Kryvonosa str., 46027, Ternopil, Ukraine; tulaidan@tnpu.edu.ua

Abstract: The aerodynamic model of the group of unmanned aerial vehicles in space with obstacles is investigated in this paper, the model development is based on the methods of Dubins trajectory formation and Pythagorean spatial theorem concerning hodograph. It is determined that one of the classic trajectories used for unmanned aerial vehicle maneuver from one height to another is the intersection of circular spiral projected onto the X-Y plane in the form of a circle. The problem of obstacle avoidance is determined and Dubins diagram for two unmanned aerial vehicles routes in the environment with obstacles is given. On the basis of the specified scheme the algorithm of re-laying the UAV route with curvature adjustment by means of intermediate point which is taken out on the second scheme is described. Analysis of the known solutions in the field of increasing the route stability control for unmanned aerial vehicles and electronic suppression demonstrate the importance of the problem of forming the flight routes of unmanned aerial vehicles by passing opposing enemy areas, taking into account the peculiarities of air defense and electronic warfare application. The functional scheme of UAV recognition mechanism in the conditions of radio attacks is developed and the mechanism of formation of UAV safe movement in the conditions of radio attacks based on three basic techniques is defined.

Keywords: *unmanned aerial vehicle, obstacles, space, aerodynamic model, air traffic control, security, flight.*

Introduction.

In the context of route planning for the group of unmanned aerial vehicles (UAVs) that connect selected points, the restrictions which should be taken into account are obligatory. The main limiting factor is the curvature or turning radius. This, together with the shortest route planning, require the development of approaches taking into account limitation in calculating the overall route and safe trajectory of the UAV group.

Often it is advantageous to have short routes in order to minimize flight time, as well as reduce fuel consumption and associated with it energy and power. Scheduling techniques can be extended for obtaining a shorter route from longer routes in order to bypass obstacles or to synchronize the UAV arrival time. The algorithms for designing the shortest routes are used in various scientific fields, such as computational geometry, operations research and logistics. One of the well-studied problems in computational geometry is the algorithm for finding the shortest route, discovered in 1987. The task of the salesman and the Chinese postman are widely investigated in the field of operations research, but they are built in the form of a graph and have no solutions.

At present, while planning the flight trajectory, three types of trajectories are important: Dubins - a route with arcs of constant curvature; clothoid - routes similar to Dubins ones, but with arcs of variable curvature; Pythagoras – route hodograph (PH). Each of them has a number of advantages and disadvantages, but in UAV route modeling, their application is necessary.

The main threats to unmanned aerial vehicles in modern conditions are the possibility of their destruction by air defense systems (air defense), as well as disruption of radio communication and control system between the control center and UAV by means of electronic suppression (RES). Analysis of technological solutions shows that in most UAV survivals under the conditions of air defense systems application and UAV stability under the RES influence is considered without taking into account the possibilities of UAVs spatial maneuvering to bypass the air defense and RES. Existing automated UAV control systems (ACS) do not take into account the possibility of timely formation of "unmanned" zones, where the probability of destruction by air defense systems is higher than the safe value, as well as automated formation of UAV flight routes providing the required stable control level UAVs, including the case under radio attacks influence.

Analysis of available investigations and publications. In the current decade, there has been a steady increase in the investigations and developments concerning aerodynamic modeling in the direction of unmanned aerial vehicles.

A number of authors R.O. Bieliakov, H.D. Radzivilov, O.D. Fesenko, V.V. Vasylchenko, O.H. Tsaturian, A.V. Shishatskii, V.P. Romanenko [1] developed the method of building the intelligent automatic control system for unmanned aerial vehicle in order to minimize the error of the platformless inertial navigation system due to neural network application.

D.I. Bondariev, D.P. Kucherov, T.F. Shmeliova [2], investigated the main aspects of optimization of the light unmanned aerial vehicle control system by frequency criterion, mathematically substantiating the direction choice and obstacles avoidance.

Regarding the modeling of UAVs kinematics and flight dynamics the works by Y.H. Danyk, I.I. Balytskii, [3] and I.S. Katerynchuk, Y.H. Danyk and I.I. Balytsii [4] are worth noticing. The authors describe in detail the possibility of using automatic control of the UAV navigation system in the conditions of obstacles and the mechanisms of flight trajectory formation.

The principles of formation of safe UAV movement in the conditions of radio attacks is considered by many national [5-7] and foreign scientists.

A.O. Popov, V.V. Tverdokhlib [8], formulated the main aspects of the general electronic warfare problem. The authors consider the general trends and directions of development of domestic and foreign electronic warfare means, which shoul be taken into account while constructing aerodynamic models.

The possibilities of UAV sounding in the tasks of monitoring terrorist threats are revealed in paper [9]. A number of authors, Orlov V.V., Lysyi M.I., Sivak V.A., Kuprienko D.A., Kulchytsii V.M., Dobrovolskii A.B. proposed the sonar system for detecting moving objects, which is constructed using the network of sensors located in space. The main difference from the existing sound-location systems is the determination of time delay not by mutual correlation function, but by mutual function of signal uncertainty between the sensors.

The works by C. Mu, D. Wang [10], Z. Lin, D. Ma, J. Meng, L. Chen, Y. Vovk [11, 12] should be noted among the foreign scientists works.

Statement of the problem. In this paper it is necessary to develop the aerodynamic model for a group of unmanned aerial vehicles in space under the radio attacks conditions.

Statement of the basic research material. The use of two-dimensional route planning is frequently found in the literature [4]. This is be due to the small number of investigations concerning the route planning for ground robots, however, while working with aircrafts, the motion plane should be added to the height in the calculations of maneuvers in space. From the point of view of trajectory planning, the beginning of route planning remains similar to the initial one, i.e. the parameters are the same at the starting and final points. In fact, there are three spatial coordinates (x, y, d), and three angular orientations (rolling, pitching, yawing).

The investigation is carried out on the basis of two methods:

I) Dubins trajectories;

II) Pythagorean spatial theorem with respect to the hodograph (hereinafter - PH).

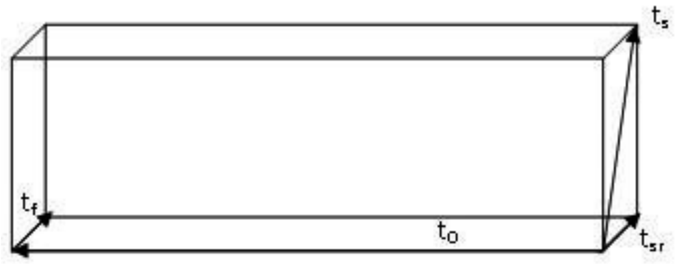

Figure 1 - Three-dimensional conditions of Dubins maneuver

One version of the "segment - arc" method is Dubins method. This smoothing method is to replace the adjacent to the polygonal line angle by the circle arc segments. It should be noted that, although the route according to Dubins method is smoothed, the curvature of this route is discontinuous, the gaps occur at the junction of segments and circles arcs.

Three-dimensional flight route $r(q)$ can be obtained by solving the following equation:

$$P_s(x_s, y_s, z_s, \theta_s, \psi_s) \xrightarrow{r(q)} P_f(x_f, y_f, z_f, \theta_f, \psi_f)$$
$$|k(t)| < k_{max}, |\tau(t)| < \tau_{max} \qquad (1)$$

where $\tau(t)$ is curvature;

$k(t)$ is trajectory rotattion;

$r(q)$ is flight route;

$x_s, y_s, z_s, x_f, y_f, z_f$ are coordinates of the route beginning and end, respectively;

$\theta_s, \psi_s, \theta_f, \psi_f$ are rotation angles of the route beginning and end, respectively;

.

One of the classical trajectories used to maneuver the unmanned aerial vehicle from one altitude to another is the intersection of the circular spiral, which is projected onto X-Y plane in the form of a circle. The trajectory can be represented as a winding on the vertical cylinder surface. An important property of this curve is that both the curvature and torsion of the steel, which together gives the cylinder radius and the spiral turn. Compared to PH, the length of the spiral trajectory is longer than any other and is more accurate in the trajectory shape.

The generalization of two methods is the theorem.

Theorem 1. If two tangent vectors t_s and t_f are linked by the vector line t_0, as shown in Fig. 1, then the maneuver can be performed provided that all vectors lie in the same plane.

Figure 1 shows that two tangent vectors are in different planes, and the beginning of the tangent vector t_s does not lie in the plane defined by two vectors $t_f$and t_0.

In order to obtain the flight route, it is necessary to determine the initial maneuver of the arc touching the tangent vector t_s in the plane to obtain t_{sr} . This will ensure that this vector lies in the same plane as t_f i t_0. Dubins trajectory can be calculated using the expanded vector t_{sr} as a new tangent start vector. The normal vector n_{sr} can be defined as the norm to the tangent vector, as well as lying in the plane defined byt_f and t_0. The vector binormal b_{sr} is the right triple.

The initial trajectory consists of combined trajectory curvature relatively to the vector binormal, followed by rolling to build normal and binormal vectors, to form the final Dubins trajectory. Therefore, Dubins trajectory consists of one plane of the trajectory circle with the definition of curvature k_s,with the normal start of the circle trajectory with the definition of curvature k_s and rectilinear trajectory, and finally the end of the circle trajectory with the definition of curvaturek_f.

The application of Dubins method lies in the fact that in differential-geometric concepts the method of Pythagoras RN spatial trajectory is obtained using the first order of Hermitian interpolation. The resulting trajectory is further tuned to increase the UAV flight route by increasing the tangent vectors length.

The beginning of the maneuver can be determined taking into account the centerline between two positions. From the point of view of each position, positive or negative rotation from the tangent vector to the central vector is determined by the curvature sign for each maneuver. At the beginning of the maneuver and at its end, the UAV rotates according to the tangent vector t_s. Hence:

$$[t_{ms}, n_{ms}, b_{ms}] = [t_s, n_s, b_s]R_s \qquad (2)$$
$$[t_{mf}, n_{mf}, b_{mf}] = [t_f, n_f, b_f]R_f$$

where

$$R_s = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(\phi_s) & -sin(\phi_s) \\ 0 & sin(\phi_s) & cos(\phi_s) \end{pmatrix}$$
$$R_f = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(\phi_f) & -sin(\phi_f) \\ 0 & sin(\phi_f) & cos(\phi_f) \end{pmatrix} \qquad (3)$$

ϕ_s and ϕ_f are the rotation angles for the initial and final aircraft maneuvers.

Radius vectors can be defined as

$$r_s = [t_{ms}, n_{ms}, b_{ms}] \begin{pmatrix} 0 \\ \pm {}^1/_{k_s} \\ 0 \end{pmatrix} \qquad (4)$$

and, similarly,

$$r_f = [t_{mf}, n_{mf}, b_{mf}] \begin{pmatrix} 0 \\ \pm {}^1/_{k_f} \\ 0 \end{pmatrix} \qquad (5)$$

The base vectors are related

$$[t_f, n_f, b_f] = [t_s, n_s, b_s]R \qquad (6)$$

where R is the rotation matrix which should replace the axis from the start to the end.

Thus we have

$$R = (t_f, n_f, b_f) \cdot (t_s, n_s, b_s) \qquad (7)$$

Hence

$$R = \begin{pmatrix} t_f \cdot t_s & t_f \cdot n_s & t_f \cdot b_s \\ n_f \cdot t_s & n_f \cdot n_s & n_f \cdot b_s \\ b_f \cdot t_s & b_f \cdot n_s & b_f \cdot b_s \end{pmatrix} \qquad (8)$$

Connecting vectors form orthogonal set of vectors. Each vector lies in the corresponding plane of maneuver, which do not coincide. The internal connecting vector is common for both UAV maneuvers. Thus, you can write it in the following form:

$$a_s = a[t_{ms} \quad n_{ms} \quad b_{ms}]\alpha_s$$
$$a_f = a[t_{mf} \quad n_{mf} \quad b_{mf}]\alpha_f \qquad (9)$$

from

$$\alpha_s = \begin{pmatrix} \alpha_{ts} \\ \alpha_{ns} \\ \alpha_{bs} \end{pmatrix} \text{та } \alpha_f = \begin{pmatrix} \alpha_{tf} \\ \alpha_{nf} \\ \alpha_{bf} \end{pmatrix} \qquad (10)$$

Frenet frame for two planes of maneuver is related to

$$[t_f \quad n_f \quad b_f] = [t_s \quad n_s \quad b_s]R,$$
$$[t_{mf} \quad n_{mf} \quad b_{mf}] = [t_f \quad n_f \quad b_f]R_f,$$
$$[t_{ms} \quad n_{ms} \quad b_{ms}] = [t_s \quad n_s \quad b_s]R_s. \qquad (11)$$

By

$$[t_{ms} \quad n_{ms} \quad b_{ms}]R'_s = [t_s \quad n_s \quad b_s],$$
$$[t_{mf} \quad n_{mf} \quad b_{mf}]R'_f = [t_f \quad n_f \quad b_f] = [t_s \quad n_s \quad b_s]R = [t_{ms} \quad n_{ms} \quad b_{ms}]R'_s R \qquad (12)$$

and

$$[t_{mf} \quad n_{mf} \quad b_{mf}]=[t_{ms} \quad n_{ms} \quad b_{ms}]R'_s R R_f \qquad (13)$$

This means that

$$\alpha_s = R'_s R R_f \alpha_f$$
$$\alpha_f = R'_f R R_s \alpha_s \qquad (14)$$

The radius vectors R_s and R_f can also be described in the axes of the maneuver beginning, as

$$r_s = [t_{ms}, n_{ms}, b_{ms}]\begin{pmatrix} 0 \\ \pm {}^1/_{k_s} \\ 0 \end{pmatrix}$$
$$r_f = [t_{ms}, n_{ms}, b_{ms}]R'_s R R_f \begin{pmatrix} 0 \\ \pm {}^1/_{k_f} \\ 0 \end{pmatrix} \qquad (15)$$

Vectors can also be defined in the axes of the maneuver beginning , in the form

$$\alpha_s = {}^{\pm 1}/_{k_s}\,[t_{ms}, n_{ms}, b_{ms}]\beta_s,$$
$$\alpha_f = {}^{\pm 1}/_{k_f}\,[t_{mf}, n_{mf}, b_{mf}]\beta_f,$$
$$\alpha = {}^{\pm 1}/_{k_f}\,[t_{ms}, n_{ms}, b_{ms}]R'_s R R_f \beta_s \qquad (16)$$

The length of Dubins route is the sum of lengths of these segments which is given as

$$h_{\text{Dubins route length}} = h_i + h_s + \alpha_t + h_f = {}^{\alpha_i}/_{k_s} + {}^{\alpha_s}/_{k_s} + \alpha\, {}^{\alpha_f}\big/_{k_f} \qquad (17)$$

where h is the route length;
s, t and f are the initial route arc, the total route length, the final route arc;
i is the arc segment;
α is the arc angle;
k is rotation.
The PH route provides the curve displacement in closed polynomials form.

Equation (18) is polynomial designed to interpolate free vectors at the boundary. Free vectors have positions (x, y, z) and direction (θ, ψ) in space. The interpolation curve of such two vectors is called Hermit interpolation. The resulting curve will have tangent continuity, but not heredity of curvature. For UAV applications, it is important that the continuity of curvature is proportional to the lateral acceleration of the UAV. Thus, it is necessary to have controlled curvature at the boundaries of the interpolation curves, as well as to limit the maximum curvature.

$$Q(q) = \sum_{i=0}^{2} Q_i \binom{2}{i} q^i (1-q)^{2-i}, \qquad q \in [0,1] \qquad (18)$$

This will ensure smooth UAV route. Now, PH curve is represented in the fifth order of the polynomial form as

$$r(q) = \sum_{k=0}^{5} b_k \binom{5}{k} q^k (1-q)^{5-k}, \qquad q \in [0,1] \qquad (19)$$

where $b_k = (x_k, y_k, z_k)$ are control points, the vertices of which are determined by Bezier polygon control of with $k = 0, \dots, 5$.

The initial and final configurations are $p_s\ (x_s, y_s, z_s, \theta_s, \psi_s)$ and $p_f\ (x_f, y_f, z_f, \theta_f, \psi_f)$, respectively. Four control points of Bézier polygons are calculated by first-order Hermitian interpolation in the following way:

$$b_0 = (x_s, y_s, z_s),$$
$$b_5 = (x_f, y_f, z_f),$$
$$d_0 = m_0[cos(\theta_s)cos(\psi_s), cos(\theta_s)sin(\psi_s), sin(\theta_s)],$$
$$d_5 = m_5[cos(\theta_f)cos(\psi_f), cos(\theta_f)sin(\psi_f), sin(\theta_f)],$$
$$b_1 = b_0 + {}^1/_5\, d_0,$$
$$b_4 = b_5 + {}^1/_5\, d_5, \qquad (20)$$

Spherical coordinates are used for orientation. Constants m_0 i m_5 play an important role in compiling the interpolation curve.

The problem of bypassing obstacles is closely related to route planning, because the obstacles presence usually results in routes re-planning. Route planning with obstacles bypassing in 3D is more complicated, because in such planning there are infinite number of directions for maneuvers for both UAVs and obstacles.

In order to maneuver in the environment full of obstacles, the UAV should be able to calculate the trajectories that will float around these obstacles and should be able to reach the final point. Therefore, there is requirement to calculate Dubins composite trajectories that include evasion maneuvers. In case of single obstacle crossing rectilinear segment of the standard Dubins trajectory, two trajectory avoidance options should be calculated for each obstacle. The standard Dubins trajectory consists of five segments, with initial, intermediate and final arc maneuvers, along with two straight segments. In the initial and final arc, the maneuvers are modified in such a way that the segments are tangent to the obstacle circle.

If the UAV detects an obstacle by means of a sensor located on board, the airplane should re-plan the route either by changing the curvature between two points of the case or re-plan the route using the intermediate point. Obstacles are tested to determine if the radius of the obstacle crosses the trajectory or UAV "safety" . If the obstacle radius does not cross the UAV trajectory, then re-planning is not required. This can be done either by increasing the trajectory curvature, or by creating the intermediate point and simulating a new route which includes new track point.

Assuming that $O_{obstacle}$ is an obstacle in the UAV safety radius O_{safety}, the condition for collision avoiding is

$$O_{obstacle} \cap O_{safety} = \emptyset \qquad (21)$$

The scheme for the environment full of obstacles is shown in fig. 2.

Obstacles are modeled in the form of polygons, the areas and coordinates of which are known. Route planning of a group of unmanned aerial vehicles can be written in the following form:

$$P_{s,i,j-1}\left(x_{s,i,j-1}, y_{s,i,j-1}, \theta_{s,i,j-1}\right) \xrightarrow{r_{i,j-1(q)}} P_{f,i,j}\left(x_{f,i,j}, y_{f,i,j}, \theta_{f,i,j}\right) \qquad (22)$$

$$i = 1, \dots, n_{UAV}, \quad j = 2, \dots, n_p, \; |k_i(q)| < k_{max}, \; \coprod_{safety}, \coprod_{length}, \qquad (23)$$

n_{UAV} is the number of unmanned aerial vehicles,

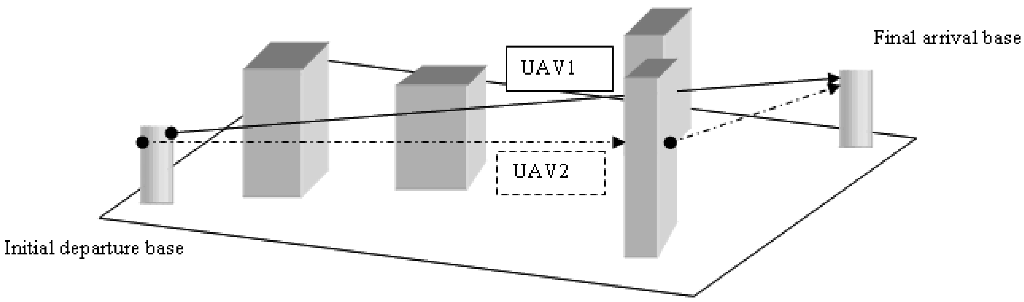

Figure 2 - Dubins routes for two unmanned aerial vehicles in the environment with obstacles.

In order to implement the algorithm, we take two UAVs. Both UAVs are homogeneous in their physical capabilities, and therefore they both move with the same speed and have curvature limitations.

The trajectories of two unmanned aerial vehicles in the environment with obstacles is shown in Fig. 2. The flight route of the second unmanned aerial vehicle UAV2 intersects the obstacle and the flight route of the first unmanned aerial vehicle UAV1. The curvature of Dubins route arc is varied to avoid the threat radius. The new safe route after increasing the curvature of UAV2 trajectory, to solve the same problem using the intermediate point is presented in Fig. 3.

Once the intersection obstacle is detected, the intermediate points are generated.

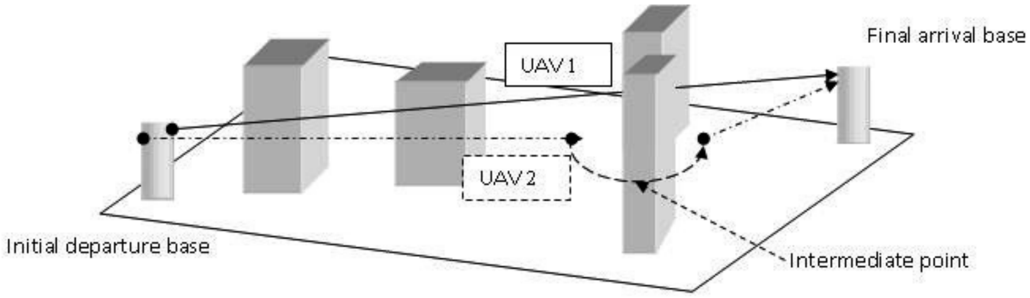

Figure 3 – Re-planning of UAV2 route with curvature adjustment using the intermediate point

The route intersection is determined interactively for the clothoids of arc segments, and the intersections of lines from ellipses can be detected using simple geometry.

The intermediate route is made for each intersection within the obstacle radius zone. After that, the routes are re-planed in order to pass through new UAV route modeling points.

The mechanism of UAV safe movement formation in the conditions of radio attacks is based on three basic techniques:

1) the method of clustering UAV flight zones according to the degree of control stability;

2) the method of UAV flight routes formation, taking into account the location of air defense and electronic warfare means;

3) methods for assessing the stability of providing information about the UAV route in terms of using air defense and REW means.

The technique of clustering flight zones for unmanned aerial vehicles according to the degree of control stability should automatically allow to form "non-flying" zones based on geotopological models of UAV flight zones and known location of air defense systems, in which drones and control zones can be damaged due to REP.

Elements of the novelty of this methodology, which distinguishes it from the results of the work known in the field of UAV flight route formation [9] and the work known in the field of cluster formation, are the consideration of two types of destabilizing effects as obstacles to UAV flight - air defense systems and electronic warfare effects as integral metrics of graph nodes of geotopological models of flight zones. At the same time, it is proposed to use the Lance-Williams mathematical hierarchical clustering algorithm and test the connectivity of the route network, using the strong connection method in order to create unmanned areas where UAVs can be damaged and areas with impaired control due to REP on UAVs from UAV graphic areas.

The method of forming UAV flight routes, taking into account the location of air defense and electronic warfare means, should automatically provide the formation of a series of UAV flight routes, ranked according to the degree of control stability, based on geotopological model of UAV flight zone and known unmanned areas where the UAV will be damaged, taking into account the potential loss of control in case of impact with UAV switchgear. At the same time, air defense zones should be completely excluded from consideration when forming UAV routes by cutting the scheme of geotopological model of the flight zone. REP zones are used to create routes [7]. However, it is necessary to choose the UAV flight route, where the total value of the suppression probability of the switchgear is minimal. This route corresponds to the trajectory with maximum stability control for unmanned aerial vehicles.

Conclusions. The method of construction the aerodynamic model of a group of unmanned aerial vehicles in space with obstacles is revealed in this paper. This model is an improved method of constructing the UAV flight route in the conditions of interference. The described aerodynamic model can be used as a stable model of the UAV group in the conditions of flight trajectory formation under the influence of radio attacks. The development of the mechanism of UAV safe movement formation in the conditions of radio attacks based on the methods for the increase of stability of providing information about the unmanned aircraft route the in the conditions of REP and air defense systems application is proposed. The improvement of the stability of providing information about the route will be achieved by grouping the unmanned aerial vehicles flight zones in the areas of air defense and electronic warfare influence, followed by the exclusion of air defense zones.

The algorithm for construction the aerodynamic model of a group of unmanned aerial vehicles in space with obstacles is resistant to external and internal influences.

References:

1. Belyakov, R.O., Radzivilov, G.D., Fesenko, O.D. (2019). Romanenko Methods of building an intelligent system for automatic control of unmanned aerial vehicles. *Radio electronics, informatics, management*, *1*, 218-229.
2. Bondarev, D.I., Kucherov, D.P., Shmelyova, T.F. (2015). Models of group flights of unmanned aerial vehicles using graph theory. *Science and Technology of the Air Force of the Armed Forces of Ukraine*, *3*(20), 68–75.
3. Danyk, Y.G., Balytsky, I.I. (2018). Methods for determining the safety of unmanned aerial vehicles. *Science-intensive technologies 4*(40), 526–534.
4. Danyk, Y.G., Katerynchuk, I.S., Balytsky, I.I. (2017). Methods of ensuring the safety of UAVs when performing special tasks in difficult conditions. *Modern information technologies in the field of security and defense*, *3*(30), 80–89.
5. Romaniuk, L., Chykhira, I. (2020). Aerodynamic model of a group of unmanned aerial vehicles in space with obstacles. *Computer-integrated technologies: education, science, production*, 38, 59-66.
6. Romaniuk, L., Chykhira, I. (2020). Automated air traffic control system for unmanned aerial vehicles. *Scientific notes of Tavriya National University named after V.I. Vernadsky. Series: Technical Sciences*, *31*(70), 131-135.
7. Romaniuk, L., Chykhira, I. (2020). The mechanism of formation of safe movement of UAVs in terms of radio attacks. *Municipal utilities. Series: Technical sciences and architecture*, *4*(157), 178-183.
8. Popov, A.A., Tverdokhlibov, V.V. (2014). General trends in the development of electronic warfare. *Military-Technical Policy*, *4*, 4-11.
9. Orlov, V.V., Lysyi, M.I., Sivak, V.A. (2019).*Visnyk NTUU KPI. Seriia Radiotekhnika Radioaparatobuduvannia*, *79*, 24-32.
10. Mu, C., Wang, D. (2017). Neural-network-based adaptive guaranteed cost control of nonlinear dynamic systems with matched uncertainties. *Neurocomputing*, *245*, 46–54.
11. Lin, Z., Ma, D., Meng, J., Chen L. (2018). Relative ordering learning in spiking neural network for pattern recognition. *Neurocomputing*, *275*, 94–106.
12. Vovk, Y. (2016). Resource-efficient intelligent transportation systems as a basis for sustainable development. Overview of initiatives and strategies. *Journal of Sustainable Development of Transport and Logistics*, *1*(1), 6-10.