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REVIEW PAPER

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DETERMINING THE COORDINATES OF UNMANNED AERIAL VEHICLES

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ABSTRACT

The purpose of the work was to develop a method for determining unmanned aerial vehicles' (UAVs) coordinates, trajectory and parameters of their spatial movements by means of kinematic projection. The paper analyses the use of technologies for determining coordinates and spatial movements of aircraft trajectories. The principle of the kinematic scheme of fixing moving objects by means of orthogonal and kinematic design has been developed. The principle scheme of determining UAV coordinates by kinematic projection was studied. The theoretical mathematical dependencies of the determination and calculations of the coordinates of spatial movements of unmanned aerial vehicles have been practically verified. The main object of research in this work was the theory of kinematic design as a means of graphically displaying the patterns of spatial movements of objects. The subject of the study was the specific features of searching and recording the trajectories of spatial movements of unmanned aerial vehicles in order to determine the coordinates of their instantaneous location in space. In the process of conducting theoretical and experimental research, methods and techniques of physical and mathematical modelling of fast-moving processes and mathematical statistics of analysis and classification of their results were used. The basis of the experimental study was the theory of mapping coordinates and trajectories of spatial movements of moving objects by means of graphic geometry when combining classical orthogonal design with dynamic features of kinematic design. For an objective assessment of the results of the theoretical and experimental study of the dynamics of objects moving in space, the classical theory of research planning with a mathematical apparatus for processing their results was used. Graphical models of UAV coordinate fixation were made with the use of computer technology and the AutoCAD graphic editor software.

Keywords: unmanned aerial vehicles, military sphere, kinematic scheme, electromagnetic radio waves

INTRODUCTION

In recent decades, unmanned aerial vehicles (UAVs) have been widely used in both the industrial and military sectors. Manoeuvrable, efficient in terms of energy consumption, relatively cheap in production and operating conditions, and easily remotely controlled by modern means of radar navigation, these flying machines are already widely used and have a very real prospect of even wider application.

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The range of fields of application of flying machines and the variety of their sizes and purposes are due, first of all, to the capabilities of radar digital communication, which ensures reliable control of the flights of these machines over considerable distances. The task of detecting the coordinates and trajectories of enemy reconnaissance or subversive unmanned aerial vehicles should be perceived as a separate and particularly important problem in military affairs.

Modern means of anti-aircraft defence are capable of neutralising any enemy aircraft that collects intelligence information both at low and high altitudes without any particular problems. However, for this, they need accurate (plus or minus a dozen metres) coordinates of the spatial location of the enemy flying object. However, it is extremely difficult to obtain such accurate information in the case of UAVs, including drones, using modern radar communication methods (Kutsenko, 2017; Chernyshev & Kutsenko, 2018).

That is why the task of creating a theory of kinematic mapping (Kalynovska, Hlohovskyy & Pulkevych, 1994; Pulkevych, 1994) arose before descriptive geometry as a science of geometric mapping of the interposition of space elements. “Kinematic projection” should be understood as a projection in which all its elements, namely the centre of projection, focal figures of projecting complexes and congruences, the object of projection (so-called proto-image) and the carrier of projections (so-called picture plane) can make mutually independent spatial movements in space and time.

The purpose of the research is to develop a method for determining UAVs’ coordinates, trajectory and parameters of their spatial movements by means of kinematic projection.

The main tasks of the study include:

- analysis of the technologies used for determining coordinates and trajectories of spatial movements of aircraft,
- development of a basic kinematic scheme for fixing moving objects by means of orthogonal and kinematic design,
- study of the principle scheme for determining UAV coordinates by kinematic projection,
- practical verification of the theoretical mathematical dependencies of the definition and calculations of coordinates of spatial movements of unmanned aerial vehicles.

MATERIAL AND METHODS

The main object of research in this work was the theory of kinematic design as a means of graphically displaying the patterns of spatial movements of objects.

The subject of the research was the specific features of searching for and recording the trajectories of spatial movements of unmanned aerial vehicles in order to determine the coordinates of their instantaneous location in space. In the process of conducting theoretical and experimental research, methods and techniques of physical and mathematical modelling of fast-moving processes and mathematical statistics of analysis and classification of their results were used. The basis of the experimental study was the theory of mapping coordinates and trajectories of spatial movements of moving objects by means of graphic geometry when combining classical orthogonal design with dynamic features of kinematic design. For an objective assessment of the results of the theoretical and experimental study of the dynamics of objects moving in space, the classical theory of research planning with a mathematical apparatus for processing their results was used. Graphical models of UAV coordinate fixation were made with the use of computing equipment and the AutoCAD graphic editor software.

REVIEW OF PRIMARY LITERARY SOURCES

The problem of finding and determining the coordinates of aircraft is quite actively dealt with by military specialists and scientists. Thus, a certain version of the solution to this problem is reflected in the work by Chernyshev and Kutsenko (2018). To improve the method of determining the coordinates of unmanned aerial vehicles in the area of anti-terrorist operation (ATO), the authors evaluated the accuracy of determining the coordinates of UAVs using the so-called difference-range method in a mobile passive radar system based on short-range anti-aircraft systems. The results of their research showed that the errors of the determined aircraft coordinates by this method are insignificant, and in some cases, the location of the UAV is generally commensurate with the size of the searched objects (Kalynovska, Hlohovskyy & Pulkevych, 1994; Pulkevych, 1994; Kutsenko, 2017; Chernyshev & Kutsenko, 2018). The mathematical dependencies obtained by the authors make it possible to choose the optimal ones from the point of view of ensuring minimal errors in the location of combat vehicles with passive direction finding equipment.

Certain disadvantages of this differential-range-measuring method are its unsuitability for UAVs flying along predetermined trajectories of movement without accompanying radio frequency control of their spatial movement. The absence of electromagnetic impulses to control the flight of such UAVs makes them “invisible” to direction finders and also makes it impossible to detect their coordinates.

An equally significant drawback of this method of determining UAV coordinates is the need for a significant amount of technical means for its implementation, in particular, four manoeuvrable radio direction finders and a command post located 500–3,000 m from each other. Between 10 and 15 people will be needed to service this equipment.

RESULTS AND DISCUSSION

The essence of the proposed method is illustrated in the figures. Figure 1 shows the layout of radar location stations (RLS) RLS N1 and RLS N2 on the Earth’s surface, which are distant from each other by a = 500–1,000 m. Here, the point $C \equiv CL$ shows the conditional location of the command post (CP), which is a certain distance from both radar location stations. Three points, A, B and C, define the basic reference plane, which is denoted by $\alpha(A, B, C)$.

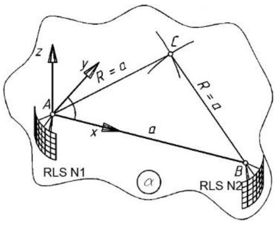

Fig. 1. Base plane α reference with the Cartesian coordinate system

Source: own work.

In one of the RLSs, for example, at point A, a Cartesian three-dimensional spatial coordinate system with mutually perpendicular axes X, Y and Z is introduced. The X axis of this coordinate system originates at point A and is directed at point B, which symbolises the location and coordinates of the second RLS device. The Z axis originates at point A, perpendicular to the X axis, and is directed upwards. The Y axis also begins at point A and is perpendicular to the X and Z axes. The X and Y axes, like two mutually perpendicular straight lines, form the so-called base plane α. It is in this base plane that the intermediate point C is located, equidistant at a distance a from both RLSs.

Having set the height H, which is 1.2–1.5 times greater than the approximate flight altitude of the UAV, points S, W and L are set on perpendiculars to the base plane at points A, B and C. As illustrated in Figure 2, These three points S, W and L are set in space picture plane $\beta(S, W, L)$, which is parallel to the base plane $\alpha(A, B, C)$ and removed from it at distance H, that is, $H = AS = CW = BL$; $\alpha(ABC)||\beta(SWL)$.

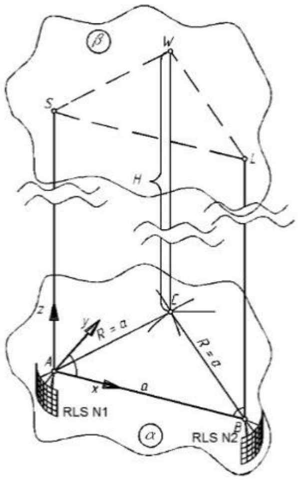

Fig. 2. Setting picture plane β of the calculation scheme

Source: own work.

When turned on, both RLSs direct electromagnetic radio waves in the expected direction of the location of the UAV (Fig. 3). On the RLS monitors, the direction of the projecting rays passing from each of the RLSs through the spatial location point of the UAV, and their angles of inclination to base plane α, i.e., $\gamma = p_1$^α and $\sigma = p_2$^α, are recorded. In addition, for a full-fledged coordinate binding of the projecting beams to the introduced coordinate system, for each of the projecting beams p_1 and p_2, the angle of its inclination to line a connecting both RLSs is also determined. That is, $\delta = p_1$^AB and $\phi = p_2$^AB (Fig. 3).

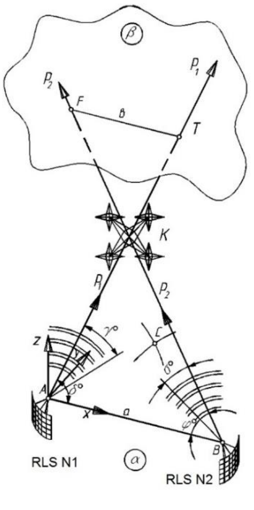

Fig. 3. Direction diagram of projecting beams p_1 and p_2

Source: own work.

According to the coordinates of the RLS location points and the angles of inclination γ, σ, δ and φ of the projecting beams to base plane α and line α connecting both RLSs, the computer of the command post displays both projecting beams p_1 and p_2.

The point of intersection of the projecting beam with the picture plane is sought either by analytical or graphical methods. In the analytical method of searching for the intersection point, the analytical equation of the projecting ray is specified as the equation of a straight line passing through a known point (A or B) with given coordinates at a known angle of inclination to base plane α, and the analytical equation of picture plane β passes through three points S, W and L with known coordinates. The point of intersection of the straight line with the plane in this case will be the desired point, the coordinates of which simultaneously satisfy both the equation of the straight line and the equation of the plane.

When applying the graphical method, the coordinates of the point of intersection of the projecting beam (p_1 or p_2) with picture plane n are searched for by the method of finding the point of intersection of the straight line with the plane.

Thus, in the introduced Cartesian coordinate system with the beginning of its axes at point A, which symbolises the location of one of the RLSs, it is possible to unambiguously indicate the location of the desired UAV. This can be done either by having significant calculations of the lengths of the segments $t_1 = AK$ and $t_2 = BK$ located on the projecting beams p_1 and p_2, and known from the RLS monitors of the angles of inclination to the base plane $\delta = \omega(p_1 \cap p_2)$^$\alpha(ABC)$ of the plane ω formed by the projecting beams. And also by the known angles of inclination δ and γ of the projecting beams p_1 and p_2 to the line connecting both RLSs.

Another possible option for determining the location of the UAV in the airspace is calculating its coordinates XK, UK and ZK using the proposed mathematical dependencies.

The instantaneous locations of the UAV, i.e. points with step-by-step calculated coordinates, displayed on the operator's screen in three dimensions, will display the spatial trajectory of the flying object's movement. And the recorded time intervals between the recording of the momentary locations of the UAV and the movements completed during these time intervals will provide information about the speed of movement of this object.

Consider an example of implementation of the proposed method. For simplicity, let the radar stations RLS N1 and RLS N2, as well as point C, be located at the same geographic height. Then, the base plane defined by these three points A, B and C will be an imaginary horizontal plane. Let the distance a between the radar stations be $a = |AB| = 500$ m, and the predicted flight height of the sought UAV is within 800–950 m.

Let us imagine projecting two projecting beams p_1 and p_2 onto the sought UAV, each of which starts at its point of installation of the radar station. That is, let RLS N1 ≡ $A_{\in p_1}$ and RLS N2 ≡ $B_{\in p_2}$.

Let us take different values of the angles of inclination of the projecting rays to the line a connecting the radar stations. That is, let $\delta = |p_1\text{^}AB| = 70°$ and $\phi = |p_2\text{^}AB| = 80°$. Let us set the distance of the sought UAV from the radar stations through the angle of inclination v formed by the projecting rays p_1 and p_2 to the base plane $\omega(p_1 \cap p_2)$, $\alpha(A, B, C)$, i.e., $v = \omega\text{^}\alpha$. Let $v = 60°$. In the example we considered, angle $\delta = 70°$, $\varphi = 80°$ and $v = 60°$ are set, and in real situations, the numerical values of these angles will be set and fixed on the monitors of radar stations according to the directions of the vectors of the radio waves generated by them, which will pass through the wanted UAV. That is, relatively speaking, in this case, it does not matter whether the wanted UAV is distant from the radar, for example, by 1 km, 1.5 km or 2 km. Instead, it is important that the projecting beam clearly indicates the direction of the locations of this UAV, and the available technical means fix the above-mentioned angles of its inclination to the AB line and the base plane α.

Let us set a picture plane located in the air space at a height of, for example, $H_1 = 1{,}000$ m, $H_2 = 1{,}250$ m, $H_3 = 1{,}500$ m.

The task is to calculate the coordinates of the wanted UAV in the three-dimensional Cartesian coordinate system arranged at the initial point A = RLS N1.

The calculated mathematical dependencies, initial data and calculation results are given in Table 1. The final results of the calculations are the coordinates of the wanted UAV displayed in the table. Thus, for the first option considered, with a conditionally specified angle $v = 60°$ of the inclination of the plane

$\omega(p_1 \cap p_2)$ formed by the projecting rays p_1 and p_2 to the base plane $\alpha(\Delta ABC)$, the calculated coordinates of the location of the UAV were $K(X_K; Y_K; Z_K) = K(337; 463; 802)$ m. That is, its flight height is $Z_K = 802$ m, and it is $t_1 = 985$ m distant from the first radar station RLS N1 and $t_2 = 940$ m from RLS N2.

In the second variant, when changing the angle to $v = 70°$, coordinate $X_K = 337$ m remained unchanged, coordinate $Y_K = 317$ m, and the flight height (Z coordinate) increased to 870 m. A similar pattern is observed when the angle v is further increased to 800 – coordinate X_K is unchanged, coordinate $Y_K = 162$ m decreases, and the flight height, displayed by coordinate $Z_K = 912$ m, increases. This shows that the obtained mathematical dependencies respond sensitively to changes in initial conditions and are amenable to logical interpretation.

Table 1. Calculated dependencies for determining UAV coordinates

Calculation parameters		Dependencies of parameter calculation	Value of the parameters at angle $v°$ of the inclination of the plane of projecting ray $\omega(p_1 \cap p_2)$ to base plane $\alpha(\Delta ABC)$		
Parameter name mathematical	Marking				
Tilt angles					
– planes of projecting rays to the base plane	v	$v° = \omega(p_1 \cap p_2)$^$\alpha(\Delta ABC)$	60°	70°	80°
– of the first projecting beam p_1 to the line between the radars	$\delta°$	$\delta° = p_1$^a	70°	70°	70°
– of the second projecting beam p_2 to the line between the radars	$\varphi°$	$\phi° = p_2$^a	80°	80°	80°
– angle between two projecting rays	$\gamma°$	$\gamma° = p_1$^α	30°	30°	30°
– distance between radar N1 and radar N2	a	set	500 m	500 m	500 m
Distance to the picture plane	H	set	1,000 m	1,250 m	1,500 m
Distance between the basic α and picture plane β along plane $\omega(p_1 \cap p_2)$ of the projecting rays	L	$L = \frac{H}{\sin v_0}$	1,155 m	1,330 m	1,523 m
Distance from the UAV to line a between radar N1 and radar N2	h	$h = L\left(1 - \frac{b}{a+b}\right)$	926 m	926 m	926 m
Distance from the UAV to radar N1	t_1	$t_1 = h_1\sqrt{1 + (\mathrm{ctg}\,\delta)^2}$	985	985	985
Distance from the UAV to radar N2	t_2	$t_2 = h_1\sqrt{1 + (\mathrm{ctg}\,\phi)^2}$	940	940	940
Distance between the projections of projecting rays on picture plane β	b	$b = \frac{L \cdot \sin\gamma}{\sin\delta \cdot \sin\phi} - a$	124 m	218 m	322 m
UAV coordinates					
X	X_K	$X_K = t_1 \cdot \cos\delta$	337	337	337
Y	Y_K	$Y_K = h_1 \cdot \cos v$	463	317	162
Z	Z_K	$Z_K = h_1 \cdot \sin v$	802	870	912

Since the mathematical dependencies, as follows from the examples given, are quite simple and are derived from stereometry and analytical geometry, the calculation programs created for the calculations will not be complicated. However, they must be compatible with the radar software.

CONCLUSIONS

1. The types of RLS search for moving objects that were created at the time were determined to be insufficiently effective for determining the coordinates, velocities and trajectories of the spatial movement of unmanned aerial vehicles flying mainly at high altitudes. The main reason for this layering on the return signal reflected from the sought moving object is other extraneous signals reflected from the Earth's terrain, tall trees, hills, buildings, etc.
2. The method of determining the position of the UAV in the airspace by means of kinematic design, which is based on the calculation of the distance of the aircraft from the RLS stations in the Cartesian coordinate system, is not sensitive to extraneous false signals reflected from the Earth's terrain. Due to this, it is more accurate compared to the difference-ranging method and other methods of RLS search for aircraft.
3. In addition to determining the coordinates, velocities and trajectories of UAV spatial movements, the kinematic design method is suitable for determining the location of moving objects on land and water surfaces, as well as in water depths. This gives it prospects for wide application in both military and civilian fields. In particular, in construction and aerial surveying, during automated processing of forest lands and land plots, and when searching for schools of fish in deep waters.

Authors' contributions

Conceptualisation: I.A., I.S.; methodology: I.S., D.B.; validation: I.A., O.S.; formal analysis: I.S., O.S.; investigation: Y.R., D.B.; resources: Y.R., I.K.; data curation: I.A.; writing – original draft preparation: Y.R., V.R.; writing – review and editing: I.S., V.R.; supervision: O.S., I.K.; project administration: O.S., V.R., I.K.

All authors have read and agreed to the published version of the manuscript.

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WYZNACZANIE WSPÓŁRZĘDNYCH BEZZAŁOGOWYCH STATKÓW POWIETRZNYCH

STRESZCZENIE

Celem pracy było opracowanie metody wyznaczania współrzędnych, trajektorii i parametrów ruchu przestrzennego bezzałogowych statków powietrznych (BSP) za pomocą projekcji kinematycznej. W artykule dokonano analizy zastosowania technologii wyznaczania współrzędnych i trajektorii ruchów przestrzennych BSP. Opracowano zasadę kinematycznego schematu mocowania poruszających się obiektów za pomocą konstrukcji ortogonalnej i kinematycznej. Badano podstawowy schemat wyznaczania współrzędnych BSP metodą rzutu kinematycznego. Teoretyczne zależności matematyczne wyznaczania i obliczania współrzędnych ruchów przestrzennych BSP zostały zweryfikowane w praktyce. Głównym przedmiotem badań w tej pracy była teoria projektowania kinematycznego jako środka graficznego przedstawiania wzorców przestrzennych ruchów obiektów. Przedmiotem badań była specyfika wyszukiwania i rejestracji trajektorii ruchów przestrzennych BSP w celu wyznaczenia współrzędnych ich chwilowego położenia w przestrzeni. W procesie prowadzenia badań teoretycznych i eksperymentalnych wykorzystano metody oraz techniki modelowania fizycznego i matematycznego procesów szybko przebiegających oraz statystykę matematyczną analizy, a także klasyfikacji ich wyników. Podstawą badań eksperymentalnych była teoria odwzorowywania współrzędnych i trajektorii ruchów przestrzennych poruszających się obiektów za pomocą geometrii graficznej przy połączeniu klasycznego projektowania ortogonalnego z dynamicznymi cechami projektowania kinematycznego. Do obiektywnej oceny wyników teoretycznych i eksperymentalnych badań dynamiki obiektów poruszających się w przestrzeni wykorzystano klasyczną teorię planowania badań z matematycznym aparatem do przetwarzania ich wyników. Graficzne modele fiksacji współrzędnych BSP wykonano przy wykorzystaniu technologii komputerowej oraz oprogramowania edytora graficznego AutoCAD.

Słowa kluczowe: bezzałogowe statki powietrzne, sfera wojskowa, schemat kinematyczny, elektromagnetyczne fale radiowe