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MATHEMATICAL ASPECTS OF DETERMINING THE MOTION PARAMETERS OF A TARGET BY UAV

Abstract. Research relevance When performing reconnaissance missions, a UAV system primarily conducts surveillance of the target area, locates stationary or moving enemy targets, determines their coordinates or transmits their images directly to the command post. Directing artillery fire as well as guiding missiles or carrying out target designation (illumination of targets) for high-precision weapons, automatic determination of target coordinates and their prompt transmission to the appropriate ground stations is essential. This article provides a mathematical solution to the issue of determining the motion parameters of a target spotted during surveillance of an area by a reconnaissance drone (UAV). **The subject** of the study in the article is UAV-rocket-artillery systems. **The purpose** of the work is to develop a mathematical model for determining the parameters of the target's movement using a UAV. The following **tasks** are solved in the article: to develop target positioning diagram; to develop a mathematical model for determining the parameters of the target's movement. The methods used in the article are the methods of mathematical modelling. The following **results** were obtained: a target positioning scheme has been compiled to determine the coordinates and movement parameters; a mathematical dependence has been developed to determine the coordinates of a fixed target; a mathematical model has been developed to determine the parameters of the target's movement. **Conclusions:** by calculating the current coordinates of a moving target using the method proposed in this paper, it is possible to determine the coordinates of the target and parameters of the target's movement, including the direction of movement and the trajectory.

Keywords: reconnaissance drone (UAV); reconnaissance; target coordinates; heading angle; geographical coordinates; longitude; latitude; movement parameters.

Introduction

The experience of Karabakh and Russian-Ukrainian wars, as well as a number of local armed conflicts shows that, when it's impossible or not advisable to use manned aircraft (strong opposition of enemy air defence, use of chemical and bacteriological weapons in the area of operations, as well as in the need for long-term surveillance of an enemy, etc.) reconnaissance or armed unmanned aerial vehicle (UAV) systems are being used for various tasks [1, 2].

In the Second Karabakh War, the use of UAVs as a reconnaissance, battle, artillery and missile fire adjustment and as a means of direct attack caused significant changes in combat tactics and initiated a unique approach to the art of large-scale warfare. Thus, the combat tactics employed by the Azerbaijan Army using UAV differ significantly from those used in local armed conflicts. This difference was evident in the scale of the war, in the combat capabilities of an adversary, as well as in conduct of combat operations in mountainous and rough terrain. In mountainous terrain, with the sharply changing terrain profile, it becomes difficult to determine the enemy troops and equipment, and there is a lack of information about the enemy. This causes problems when planning combat operations, determining firing points, conducting reconnaissance and locating invisible enemy objects, and making last-minute decisions for commanders. In this regard, the widespread use of reconnaissance and attack UAVs of Azerbaijan Army in the Patriotic War was meant to solve the above problems.

In the Second Karabakh War, UAV systems were widely used for reconnaissance and strike missions, as well as for directing missile and artillery fire. Many high-precision rocket-artillery systems (RAS) in service in the Azerbaijan Army - SPIKE, URAGAN, POLONEZ, etc. have become more effective in interaction with UAV's.

So, the determination of location (coordinates) of invisible (unobservable and unknown by coordinates) enemy targets in mountainous and rugged terrain using UAVs and providing them to high-precision missile-artillery systems, as well as the determination and passing the information about the routes and speeds and engagement points of moving targets, decision making based on the assessment of damage and etc. once more proved the effectiveness of UAV-RAS interaction.

As mentioned above, the widespread use of UAVs has strongly influenced the warfare and combat tactics. Accordingly, these wars employ unconventional forms of warfare, employ weapons with high precision and targeting capabilities and give preference to information warfare, computer modelling, and new control and intelligence systems, as well as UAV reconnaissance systems. The widespread use of modem UAV systems, as well as weapons systems with artificial intelligence has significantly changed the way of combat operations, changed the technical specifications and effectiveness of advanced weapon systems and minimizes personnel losses.

When performing reconnaissance missions, a UAV system primarily conducts surveillance of the target area, locates stationary or moving enemy targets, determines their coordinates or transmits their images directly to the command post (Fig. 1). Directing artillery fire as well as guiding missiles or carrying out target designation (illumination of targets) for high-precision weapons, automatic determination of target coordinates [3] and their prompt transmission to the appropriate ground stations is essential.

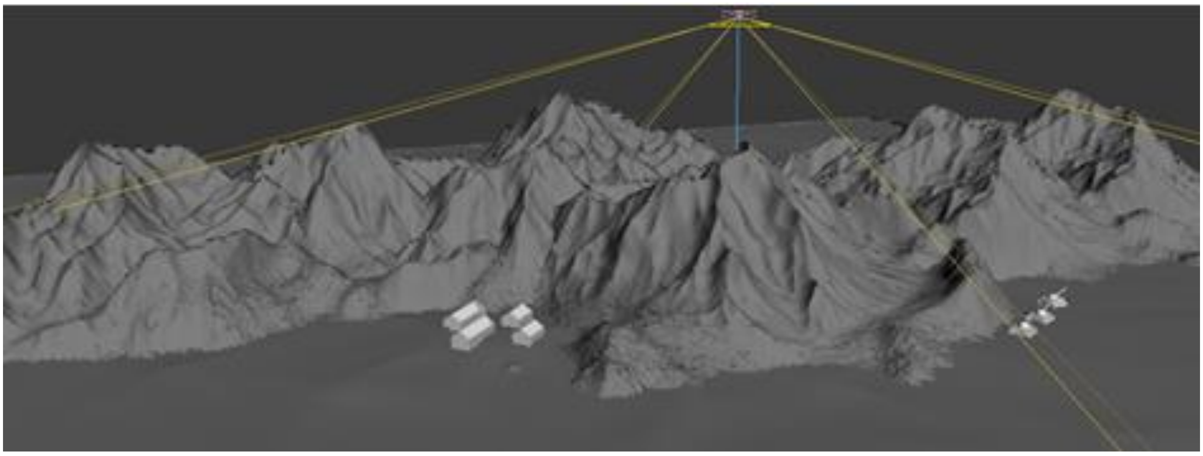

Fig. 1. UAV reconnaissance [3]

This problem was considered in [4]. The algorithms developed in this paper make it possible to carry out passive coordinate measurement of marine objects using a quadrocopter UAV.

To apply the developed algorithms in land conditions, it is necessary to correct the excess / underestimation of the target over the projection of the UAV on the terrain.

There are methods for radar detection and determination of target coordinates [5–7]. The main disadvantage of radar methods is the bulkiness of equipment and antennas that implement effective radiation patterns and information processing algorithms. Also, the disadvantages include the fact that radar methods are active and the carriers of these devices can be easily detected and destroyed.

In [8], an analysis of passive methods of measuring the range according to the data of the optoelectronic system of the UAV was carried out. The main disadvantage of passive radar methods is that they are not applicable to non-radiating objects, which in most cases are the targets in question (vehicles, armored vehicles, people, etc.).

In [9], a method was proposed for determining the spatial coordinates of terrain (object) points from the measured coordinates of their images in images obtained using an unmanned aerial vehicle. This result is achieved through the use of at least three ranging stations located at some distance from each other and from a remote object, within the line of sight of a remote object.

But this method is not suitable for the operational determination of the coordinates and parameters of the movement of objects of observation from the UAV.

Thus, the above works have shown that the problem of quickly determining the coordinates and motion parameters of objects of observation from UAVs has not yet been solved. Therefore, the task of mathematical solution of this problem and its further application in practice is relevant.

This article provides a mathematical solution to the problem of determining the movement parameters of a target detected by a reconnaissance drone during a reconnaissance mission.

Directing artillery fire as well as guiding missiles or carrying out target designation (illumination of targets) for high-precision weapons, automatic determination of target coordinates and their prompt transmission to the appropriate ground stations is essential [3].

This article provides a mathematical solution to the problem of determining the movement parameters of a target detected by a reconnaissance drone during a reconnaissance mission.

Mathematical aspects of determining target coordinates

A military drone is an unmanned aerial vehicle is equipped with a video camera and a radio-rangefinder device. Considered that drone is equipped with device to determine the geographic coordinates and angle of the video camera and radio-rangefinder placed on board [3].

It is envisaged that the UAV will monitor (observe) terrain by hovering (without shifting) at a given altitude after detecting a target while performing a combat mission.

In this case, after identifying the detected target, the UAV determines the distance to the target by means of a radio-rangefinder. In the process of surveillance, the targeting angles of the video camera (radar) can be determined based on the data from the navigation devices on board the UAV.

The main objective of the study is to develop a model for determining the geographic coordinates of the target based on this information.

Mathematical formulation of the problem. Let us denote the geographic coordinates of the UAV as U_G, E_G, where U_G, $E_G$are longitude and latitude, respectively. Since the military UAV observation area is very limited, the observed part of the surface can be considered flat. This allows the use of a rectangular coordinate system to simplify the calculations. To formulize the problem, we introduce a rectangular coordinate system. $Oxyz$ located at the point $O(U_G, E_G)$ on the Earth's central surface as follows (Fig. 2).

Assume that the Ox axis is oriented parallel to the eastward direction, the Oy axis is oriented northward in the meridian direction, and the $Oxyz$ axis is perpendicular to the axis plane.

The camera direction to the target is determined by the following two angles:

φ - the angle between the projection of the camera gaze direction onto the $Oxyz$ plane and the Ox coordinate. This angle is considered positive when it is rotated clockwise and coincides with the axis;

ϑ - the angle formed by the viewing direction of the camera with the Oz axis. This angle is measured in all directions, starting from the positive direction of the Oz axis, and varies practically in the range $[\pi/2, \pi]$.

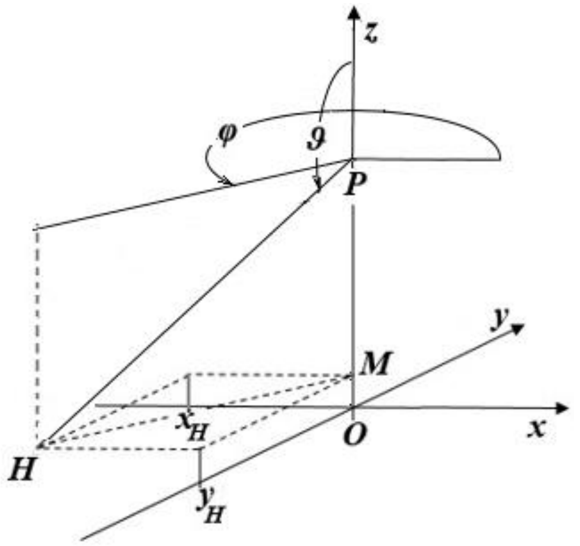

Fig. 2. Target positioning diagram

The point at which the UAV is in space relative to the $Oxyz$ coordinate system is P, the point at which the target is located is H, and the distance between them is $d = |PH|$. According to the exercise, the distance d is calculated with the help of a radio-rangefinder mounted on board the UAV, and therefore it is assumed to be known.

Based on the angles (φ, ϑ) representing the camera direction to the target, the position of the UAV and the target relative to the $Oxyz$ coordinate system can be schematically described as shown in (Figure 2). Thus, the solution to the problem in question is to find the geographic coordinates of point H by calculating the coordinates x_H, y_H with respect to the $Oxyz$ coordinate system.

Solution of the problem. To calculate the coordinates of the rectangles x_H, y_H with respect to the $Oxyz$ coordinate system, the known values of the angles (φ, ϑ) can be applied as follows:

$$HM = d \cdot \sin\vartheta;$$
$$x_H = |HM| \cdot \cos\varphi = d \cdot \sin\vartheta \cdot \cos\varphi;$$
$$y_H = |HM| \cdot \cos\varphi = d \cdot \sin\vartheta \cdot \sin\varphi.$$

As can be seen from (Figure 1), the longitude circle of point $x_H, 0, 0$ coincides with the longitude circle of point H, and the latitude circle is equal to E_G. Therefore, the calculated formulas for the longitude circle of point $(x_H, 0, 0)$ are simplified. Similarly, we see that the latitude of point $(0, y_H, 0)$ coincides with the latitude of point H, and the longitude circle equals to U_G. Therefore, the formulas for calculating the latitude of point $(0, y_H, 0)$ are also simplified. To determine geographical coordinates of a point by calculated distances x_H and y_H one can apply, for example, Mercator projection formulas (6, p.44):

$$\begin{cases} X = R \cdot E, \\ Y = R \cdot \ln\left[\operatorname{tg}\left(\frac{\pi}{4} + \frac{U}{2}\right)\left(\frac{1 - \varepsilon \sin U}{1 - \varepsilon \sin U}\right)^{\varepsilon/2}\right], \\ \varepsilon = \sqrt{1 - r/R}. \end{cases} \quad (1)$$

where R and r are the equatorial and polar (polar) radius of the Earth, respectively; (E, U) and (X, Y) are the coordinates of the point in question in geographic and Mercator projection, respectively. Applying formula 1 of system (1), we can calculate the circumference of point H with respect to point O as follows:

$$E_H = E_G + x_H R. \quad (2)$$

Calculating the latitude of point H results in solving the following equation:

$$\operatorname{tg}\left(\frac{\pi}{4} + \frac{U_H}{2}\right)\left(\frac{1 - \varepsilon \sin U_H}{1 - \varepsilon \sin U_H}\right)^{\varepsilon/2} = \exp\left(\frac{y_H}{R}\right) \times$$
$$\times \operatorname{tg}\left(\frac{\pi}{4} + \frac{U_G}{2}\right)\left(\frac{1 - \varepsilon \sin U_G}{1 - \varepsilon \sin U_G}\right)^{\pi/2}. \quad (3)$$

Since equation (3) is non-linear with respect the unknown U_H, approximate calculation methods can be used to find its solution, e.g. the dichotomy method [10, p.39; 11, p.86].

Thus, formulas (1)- (3) can be applied to calculate the geographical (E_H, U_H) coordinates of the target based on UAV observation data.

Determination of target movement parameters using UAV

It is assumed that once a target has been spotted, the UAV can calculate the following parameters from on-board navigation and other tools as specific points in time $t_j, j = 1, 2, 3, \ldots$:

own geographical position U_{Gj} – the circle of geographical longitude;

E_{Gj} – the circle of geographic latitude;

z_{Pj} – the elevation relative to the level adopted as the calculation system;

the orientation angles of the video camera;

d_j – the distance to the target.

The camera direction angles refers to the following two angles (Fig. 2) [3]:

φ_j is the angle between the projection of the camera viewing direction on the Earth surface and the geographic meridian at the location of the UAV;

ϑ_j is the angle between the viewing direction of the camera and the perpendicular to the Earth's surface at the location of the UAV.

From this data, you can find the average speed of the target in each period $[t_j, t_{j+1}]$.

For this purpose, first calculate the position of the UAV in the Mercator projection [12, p.44], at each time point t_j, $j = 1, 2, 3, \ldots$, applying the transition formulas:

$$\begin{cases} X_j = R \cdot E_{Gj}, \\ Y_j = R \cdot \ln\left[\operatorname{tg}\left(\frac{\pi}{4} + \frac{U_{Gj}}{2}\right)\left(\frac{1 - \varepsilon \sin U_{Gj}}{1 + \varepsilon \sin U_{Gj}}\right)^{\varepsilon/2}\right], \\ \varepsilon = \sqrt{1 - r/R}. \end{cases} \quad (4)$$

where R is the equatorial radius of the Earth; r – the polar (pole) radius of the Earth.

The values of the radii R and r can be taken, for example, in accordance with [13, p.53], R≈6378.245 [km] and r≈6356.863 [km].

Denote by X_{Hj}, Y_{Hj}, Z_{Hj}j the coordinates of the target at time t_j. On the questions of determining the target coordinates, it is possible to determine the elevation according to the calculation system and coordinates in the Mercator projection of the target in accordance with the given location of the UAV $(U_{Gj};\ E_{Gj};\ Z_{Gj})$ at each time of t_j, $j = 1, 2, 3, \ldots$ [12]. Namely, at each moment of time t_j from Fig. 2, we sequentially determine the elements HM, PM, OX_H, OY_H. Let's denote the coordinates of point H as X_{Hj}, Y_{Hj}, Z_{Hj}. Since, $HP = d_j$, we get

$$HM = HP \cdot \sin\vartheta_j = d_j \cdot \sin\vartheta_j,$$

$$PM = HP \cdot \cos\vartheta_j = d_j \cdot \cos\vartheta_j,$$

$$OX_H = HM \cdot \cos\varphi_j = d_j \cdot \sin\vartheta_j \cdot \cos\varphi_j,$$

$$OY_H = HM \cdot \sin\varphi_j = d_j \cdot \sin\vartheta_j \cdot \sin\varphi_j,$$

Therefore, the following representations are obtained for the target coordinates:

$$\begin{cases} X_{Hj} = X_j + d_j \cdot \sin\vartheta_j \cdot \cos\varphi_j\,, \\ Y_{Hj} = Y_j + d_j \cdot \sin\vartheta_j \cdot \sin\varphi_j\,, \\ Z_{Hj} = Z_j + d_j \cdot \cos\vartheta_j\,. \end{cases} \qquad (5)$$

At these scales the ground surface can be assumed a flat with sufficient accuracy. Hence, applying formulas (4) and (5), the average velocity $\boldsymbol{V}_{Hj} \equiv (V_{HXj};\ V_{HYj};\ V_{HZj})$ of the target at the time interval $[t_j, t_{j+1}]$ can be calculated using the following formula:

$$\begin{cases} V_{HXj} = \dfrac{X_{Hj+1} - X_{Hj}}{t_{j+1} - t_j}; \\ V_{HYj} = \dfrac{Y_{Hj+1} - Y_{Hj}}{t_{j+1} - t_j}; \\ V_{HZj} = \dfrac{Z_{Hj+1} - Z_{Hj}}{t_{j+1} - t_j}. \end{cases} \qquad (6)$$

Obviously, the speed of the target will not be constant due to the terrain and due to uneven terrain. Assuming that the interval $\Delta t_j \equiv t_{j+1} - t_j$ between measurements t_j, $j = 1, 2, 3, \ldots$ is small enough, the absolute value of the target velocity in the time interval $[t_j, t_{j+1}]$ can be calculated as following:

$$|\boldsymbol{V}_{Hj}| \equiv \sqrt{V_{HXj}^2 + V_{HYj}^2 + V_{HZj}^2} =$$

$$= \sqrt{\left(\frac{X_{Hj+1} - X_{Hj}}{t_{j+1} - t_j}\right)^2 + \left(\frac{Y_{Hj+1} - Y_{Hj}}{t_{j+1} - t_j}\right)^2 + \left(\frac{Z_{Hj+1} - Z_{Hj}}{t_{j+1} - t_j}\right)^2} =$$

$$= \frac{1}{\Delta t_j}\sqrt{\left(\frac{X_{Hj+1} - X_{Hj}}{t_{j+1} - t_j}\right)^2 + \left(\frac{Y_{Hj+1} - Y_{Hj}}{t_{j+1} - t_j}\right)^2 + \left(\frac{Z_{Hj+1} - Z_{Hj}}{t_{j+1} - t_j}\right)^2},$$

i.e.

$$|\boldsymbol{V}_{Hj}| = \frac{1}{\Delta t_j} \times$$

$$\times \sqrt{\left(X_{Hj+1} - X_{Hj}\right)^2 + \left(Y_{Hj+1} - Y_{Hj}\right)^2 + \left(Z_{Hj+1} - Z_{Hj}\right)^2} \qquad (7)$$

In the particular case where the roughness of the working area is negligible, formula (7) is simplified as follows:

$$|\boldsymbol{V}_{Hj}| = \frac{1}{\Delta t_j} \times$$

$$\times \sqrt{\left(X_{Hj+1} - X_{Hj}\right)^2 + \left(Y_{Hj+1} - Y_{Hj}\right)^2}. \qquad (8)$$

Aspects (opportunities) of practical application. The mathematical model for calculating coordinates does not impose additional conditions and restrictions related to the geography of the operation zone or the frequency of the operating range of the radio equipment used. Therefore, if the problem of detecting floating objects is being solved, the proposed approach can also be applied in marine reconnaissance to determine the coordinates of floating targets.

The discussion of the results. It should also be noted that the proposed approach is based on the use of information from the onboard navigation system of the UAV and on measuring the distance to the detected target. Comparing it with widely used radar systems, as well as with other methods for determining the coordinates of objects from UAVs, we can draw the following conclusions:

– this method does not require the installation of additional equipment and antennas on board the quadrocopter that implement radiation patterns;

– the mathematical apparatus is simple and easily implemented by the onboard UAV processor with limited resources.

Conclusions

Automatically determination of the target coordinates and parameters of moving objects when correcting artillery fire, as well as guiding missile or precise weapons, and prompt transmission of the gained information to the appropriate ground stations is essential. When using a UAV, the velocity of a moving target at a certain time interval can be calculated using the formulas (7) to (8), formulas (1)- (3) can be applied to calculate the geographical (E_H, U_H) coordinates of the target based on UAV observation data. By calculating the current coordinates, one can determine the target motion parameters, including the direction of motion and trajectory.

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Математичні аспекти визначення параметрів руху цілі БПЛА

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Анотація. Актуальність дослідження. При виконанні розвідувальних завдань система БПЛА в першу чергу веде спостереження за районом мети, визначає місцезнаходження нерухомих цілей супротивника, що рухаються, визначає їх координати або передає їх зображення безпосередньо на командний пункт. При наведенні артилерійського вогню, а також наведенні ракет або здійсненні цілевказівки (підсвічування цілей) для високоточної зброї істотне значення має автоматичне визначення координат цілей та їхня оперативна передача на відповідні наземні станції. У цій статті наведено математичне вирішення питання визначення параметрів руху мети, виявленої під час спостереження за місцевістю розвідувальним безпілотником (БПЛА). Предметом дослідження у статті є БПЛА-ракетно-артилерійські комплекси. Мета роботи полягає у розробці математичної моделі визначення параметрів руху мети за допомогою БПЛА. У статті вирішуються такі завдання: - розробити схему позиціонування мети; розробити математичну модель визначення параметрів руху цілей. У статті використано методи математичного моделювання. Отримано такі результати: складено схему позиціонування мети для визначення координат і параметрів руху; розроблено математичну залежність для визначення координат нерухомої мети; розроблено математичну модель для визначення параметрів руху мети. Висновки: обчислюючи поточні координати мети, що рухається за допомогою методу, запропонованого в даній роботі, можна оперативно визначити координати мети і параметри руху мети, в тому числі напрям руху і траєкторію.

Ключові слова: безпілотник-розвідник (БПЛА); розвідка; координати цілі; курсовий кут; географічні координати; довгота; широта; параметри руху.