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Determining the location of the UAV equipped with a homing device based on radio beacons

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***Abstract*—The article describes radio beacon systems and presents a mathematical solution to determine the location of an unmanned aerial vehicle (UAV) equipped with a direction-finding device. This system ensures continuous flight and allows for determining the exact coordinates of targets, regardless of satellite signals. It facilitates the successful completion of combat missions in adverse weather conditions and when using radio electronic warfare (REW) systems based on signals received from radio beacons.**

Keywords—unmanned aerial vehicle (UAV), direction finder, beacon systems, radio beacons, navigation systems, air defense, radio electronic warfare (REW), GPS.

I. INTRODUCTION

The analysis of the development directions of the forms and methods of modern military operations shows that UAVs are now viewed as highly effective tools capable of solving a wide range of combat tasks. It is believed that in the near future, UAVs will play a significant role in determining the location of air defenses, silencing and destroying them, obtaining the exact coordinates of fortified enemy positions, as well as launching missiles and bombs at detected objects. Already, the course and outcome of military operations, the degree of army readiness for combat, and the ability to perform assigned tasks have begun to depend significantly on UAVs [1,2]. Additionally, UAVs have become a powerful factor for commanders when deciding on the initiation of combat operations. They are subject to constant development and improvement, necessitating a careful and detailed analysis of all aspects of their application [3].

The control, navigation, and flight route planning of UAVs are typically reliant on real-time signals received from GPS. UAVs follow a predetermined flight path and can track their position based on GPS signals along the way. However, there are situations when GPS signals may not be available, such as in enclosed areas, during the application REW systems, in forested areas, or when flying between high buildings in residential areas [4,5]. In these scenarios, significant obstacles hinder the flight of UAVs and their movement along the route, potentially leading to the loss of the UAVs or its control by the enemy.

The article discusses the implementation of a stable navigation system in UAVs, enabling them to successfully perform tasks in challenging weather conditions, closed spaces, and even during the application of radio-electronic combat systems. This advanced system allows uninterrupted flight and precise target coordinate determination, regardless of satellite signals. To achieve this, UAVs are equipped with a direction-finding device, which offers a mathematical solution to determine their location based on signals received from ground-based beacons.

II. IMPORTANCE OF APPLICATION OF BEACON SYSTEMS

Beacon systems are one of the widely used technologies in modern times. The main advantage of their use is to establish a stable and reliable data network. Beacons play a critical role in many industries, particularly in technological fields that rely on precision navigation or search and rescue operations. These devices provide valuable information for vehicle management and enable safe and efficient navigation, even in the most challenging environments [6].

The most prevalent types of beacons in modern times are radio beacons. Additionally, radio beacons can be installed at key points along coastlines or strategic elevations, enabling rescue teams to quickly locate lost vehicles. When a distress signal is received from an aircraft or ship, search and rescue teams can utilize the radio beacon's signal to locate it. There are several types of radio beacons, each with unique capabilities and applications [7-9].

III. WORKING PRINCIPLE OF SATELLITE NAVIGATION SYSTEMS

The main navigation system used in modern UAVs and airplanes is satellite navigation, which includes GPS, GLONASS, GALILEO, BeiDou, and others. UAVs use a satellite receiver to capture these signals, and the distance to the GPS satellites is calculated based on the time it takes for the signal to travel. To determine its position accurately in 3 dimensions (x, y, and z), the GPS receiver on the UAV must receive signals from at least 4 satellites.

Recently, the effectiveness of satellite navigation has been compromised due to the blocking of incoming signals caused by radio-electronic combat systems employed to thwart UAVs used for illicit purposes such as pillaging. When satellite signals are obstructed, determining the UAV's position becomes challenging.

To overcome this problem, a "beacon system" can be applied to UAVs, similar to the systems used for determining the correct position and direction of ships. In the absence of GPS signals, the UAV will automatically rely on signals from beacons to report its position and maintain navigation.

IV. MATHEMATICAL FORMALIZATION AND SOLUTION OF THE PROBLEM

Taking into account that the area over which the UAV flies for the purpose of monitoring is quite limited, the curvature of the Earth's surface in the observed area can be ignored. Therefore, let's enter a rectangular positive Oxy coordinate system with respect to the Earth in order to locate the beacons and the UAV.

It is assumed that the UAV regularly carries out the bearing of its surroundings at a full angle, and at this time it can stably receive the signal of at least n≥3 radio-beacons. Let us denote the full bearing period by T. It is assumed that at a certain time t, the UAV was at the point A˜, whose coordinates relative to the Oxy system are known (x˜.y˜).

For simplicity, let's number the receiving stations as k=1,2,3,…,n clockwise according to the sequence of UAV coverage. It is considered that the coordinates of the k th beacon related to the Oxy system are known and are accordingly (xk. yk).

The angle between the direction beams of the UAV bearing towards the 1st, 2nd, 3rd, ..., nth station at the instant t+T is φ1,2, φ2,3, ..., φn-1,n.

Let us denote the coordinates of the UAV at the moment t+T related to the Oxy system as $(\tilde{x}^T.\tilde{y}^T)$. Then, the issue of determining the location of the UAV equipped with a direction finder device on the basis of radio beacons can be expressed as follows:

It is necessary to find the coordinates $(\tilde{x}^T.\tilde{y}^T)$ of the UAV corresponding to the moment of time t+T such that the remaining angle between the beams directed from that point to the k and (k+1)-th beacon is $\varphi_{k,k+1}$. The remaining angle between the beams directed towards the n th and 1st beacons be $\varphi_{n,1} = \left(2\pi - \sum_{k=1}^{n-2} \quad \varphi_{k,k+1}\right)$.

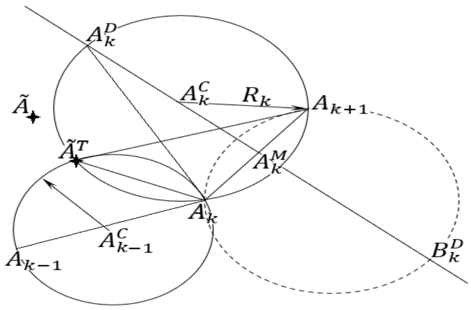

Figure 1. Determining the remaining angle between the beams.

To solve the problem, let's first determine the set of points that ensure that the angle $\varphi_{k,k+1}$ remains between the rays directed towards the k and (k+1)th beacon. Essentially, this set is a circle passing through the points $A_k(x_k, y_k)$, $A_{k+1}(x_{k+1}, y_{k+1})$ və $\tilde{A}^T(\tilde{x}^T.\tilde{y}^T)$ consists of (figure 1). To write the equation of that circle, find the coordinates of the point $A_k^D(x_k^D, y_k^D)$ located on it, so that it is on the perpendicular raised from the middle of the straight line segment connecting the points A_k, A_{k+1} and $A_kA_k^DA_{k+1}$. Let the angle $A_kA_k^DA_{k+1}$be equal to $\varphi_{k,k+1}$.

Let $A_k^M(x_k^M, y_k^M)$ be the middle point of the straight line segment connecting the points $A_k(x_k, y_k)$ və $A_{k+1}(x_{k+1}, y_{k+1})$. It is obvious that,

$$x_k^M = \frac{x_k + x_{k+1}}{2}, \qquad y_k^M = \frac{y_k + y_{k+1}}{2}. \qquad (1)$$

Let's write the equation of the straight line passing through the points $A_k^M(x_k^M, y_k^M)$ və $A_k^D(x_k^D, y_k^D)$ as follows:

$$(y_{k+1} - y_k)(y - y_k^M) + \\ +(x_{k+1} - x_k)(x - x_k^M) = 0. \qquad (2)$$

$A_kA_k^DA_{k+1}$ the condition that the angle is $\varphi_{k,k+1}$ can be written as follows:

$$\frac{\varphi_{k,k+1}}{2} = \sqrt{\frac{(x_k^M - x_k)^2 + (x_k^M - y_k)^2}{(x_k^M - x_k^D)^2 + (x_k^M - y_k^D)^2}},$$

or

$$\left(\left(x_k^M - x_k^D\right)^2 + \left(x_k^M - y_k^D\right)^2\right)\frac{\varphi_{k,k+1}}{2} = \\ = \left(x_k^M - x_k\right)^2 + \left(x_k^M - y_k\right)^2. \qquad (3)$$

Equations (2)-(3) are a system of algebraic equations of the second form with respect to the unknowns x_k^D, y_k^D, and it is clear that it has 2 solutions. Those solutions will correspond to the coordinates of points A_k^D və B_k^D, as shown in figure 1. According to the essence of the problem, the closest to the point $\tilde{A}(\tilde{x}.\tilde{y})$ should be chosen from the points A_k^D və B_k^D, in other words,

$$\left(x_k^D, y_k^D\right) = arg\ arg \left\{\left|A_k^D - \tilde{A}\right|, \left|B_k^D - \tilde{A}\right|\right\}. \qquad (4)$$

Suppose that the center of the circle passing through the points A_k, A_{k+1} və $\tilde{A}$ is located at the point $A_k^C(x_k^C, y_k^C)$. The coordinates of this point must satisfy the equation (2) and also satisfy the following equation, which expresses the equality of the radii $A_k A_k^C$ və $A_k^D A_k^C$:

$$\left(x_k^C - x_k^D\right)^2 + \left(y_k^C - y_k^D\right)^2 = \\ = \left(x_k^C - x_k\right)^2 + \left(y_k^C - y_k\right)^2.$$

Thus, the calculation of coordinates x_k^C, y_k^C leads to the solution of the following system of linear algebraic equations:

$$\{(x_{k+1} - x_k)x_k^C + (y_{k+1} - y_k)y_k^C = (x_{k+1} - x_k)x_k^M + (y_{k+1} - y_k)y_k^M, 2(x_k^D - x_k)x_k^C + 2(y_k^D - y_k)y_k^C = (x_k^D)^2 + (y_k^D)^2 - x_k^2 - y_k^2. \quad (5)$$

Using the solution of system (5), we can write the equation of the circle with its center at the point A_k^C and passing through the points A_k, A_{k+1}:

$$\left(x - x_k^C\right)^2 + \left(y - y_k^C\right)^2 = R_k^2, \quad (6)$$

here $R_k = \sqrt{(x_k - x_k^C)^2 + (y_k - y_k^C)^2}$ - is the radius of the circle.

It is clear that the coordinates of the UAV corresponding to the moment T+t must satisfy equations (6) with a certain accuracy for each k. This means that the new coordinates of the UAV can be calculated as $(\tilde{x}^T . \tilde{y}^T)$ giving a minimum to the following functional:

$$J(\tilde{x}^T . \tilde{y}^T) = \sum_{k=1,2,\dots,n} \left\{\left(\tilde{x}^T - x_k^C\right)^2 + \left(\tilde{y}^T - y_k^C\right)^2 - R^2\right\}^2. \quad (7)$$

Numerical methods can be applied to find the minimum of the functional [10].

ACKNOWLEDGMENT

In order for UAVs to successfully perform their combat tasks in all operational conditions, it is possible to create stable navigation systems that ensure its uninterrupted flight and determine the exact coordinates of targets, regardless of satellite signals, in closed space and during REW. It is necessary to create new stable navigation systems for UAVs to successfully perform reconnaissance tasks without satellite signals. The biggest research effort against UAVs is to disable them by affecting their navigation systems and thereby preventing their deployment. The development of radio-beacon systems and their integration into UAVs will greatly expand navigation capabilities.

Thus, a mathematical solution to the issue of determining the position of UAVs provided with a direction finder device using the equations shown in expressions (6) - (7) is provided. Using these equations, it is possible to use radio beacons as an additional navigation tool in an environment where there is no GPS.

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