DEVELOPMENT PROSPECTS AND MATHEMATICAL SOLUTION METHODS FOR INTEGRATING BEACON SYSTEMS INTO UAVS

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Abstract

The paper describes radio beacon systems and presents a mathematical solution for locating an unmanned aerial vehicle (UAV) equipped with a direction-finding device. This system provides continuous flight and allows you to determine the exact coordinates of targets regardless of satellite signals. It enables the successful execution of combat missions in adverse weather conditions and when using radio electronic warfare systems based on signals received from radio beacons. Thus, due to the recent development of unmanned aerial vehicles, many countries are improving their radio electronic warfare systems. Because in a real war, destroying cheap UAVs with expensive Air Defensive Systems missiles does not benefit any country financially. Radio electronic warfare systems are being developed rapidly because they are more effective in this respect. Taking this into account, it is possible to increase the resistance against radio electronic warfare systems by developing the issue of integration of the beacon systems into the UAV proposed in the article. Thus, by setting up beacon systems, it is possible to perform a UAV flight during radio electronic warfare application in any conditions.

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

I. Introduction

The analysis of the development directions of the forms and methods of modern military operations shows that unmanned aerial vehicles are now viewed as highly effective tools capable of solving a wide range of combat tasks. It is believed that in the near future, unmanned aerial vehicles 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 unmanned aerial vehicles [1,2]. Additionally, unmanned aerial vehicles 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 [3,4].

The article discusses the implementation of a stable navigation system in unmanned aerial vehicles, 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, unmanned aerial vehicles 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. Understanding how satellite navigation systems work

Currently, beacon systems integrated with UAVs change in a completely different form. They are mainly mounted on UAVs and are used for various purposes. The most common of them is the GPS beacon. They are a small device that initially determines its location based on the signals it receives from the GPS and transmits this information to a receiver [5]. They are mainly used to track the location of UAVs. They can usually be attached to UAVs, aircraft, other vehicles, and even people. They use signals from satellites to transmit location information in real time, allowing the movement of an object or person to be tracked. GPS beacons receive signals from satellites and use them to calculate their location. They transmit this information via radio signals to a radio receiver.

One possible solution to finding UAVs in an emergency could be the use of "emergency locator transmitters" used on manned aircraft. These transmitters operate at a frequency of 406 MHz to signal distress and communicate with the so-called Cospas-Sarsat System. This is an international satellite system for search and rescue operated by 43 countries and organizations. Its mission is to provide accurate, rapid, and reliable distress signals and location information for search and rescue operations to aircraft, ships, and other equipment in distress. Currently, more than 1.5 million Cospas-Sarsat emergency beacons are in operation. The price of 406 MHz radio beacons varies from $500 to $1,500, depending on their technical characteristics. Both the size and weight depend on the model of the radio beacon. However, in general, optimized hazardous situations for a manned aircraft, the transmitters are approximately 20 cm x 10 cm x 10 cm and weigh 1 kg [6]. The Cospas-Sarsat System can be used for important technological and life-saving tasks. It should not be made to unnecessary demands and its resources should not be wasted. When using a radio beacon, some characteristics of the UAV, such as weight, size and flight range, should be taken into account. In addition, the designed beacon should be as cheap as possible.

The most widely used field of lighthouses until modern times has been maritime. From ancient times to the present, they have been widely used for ship navigation and tracking systems to prevent collisions with coastal or other ships. They are designed to provide identification and position information to both ships and coastal stations. Currently, these systems are the most important means of navigational safety for every sailor after radar. This is a digital position information system operating in a very high frequency range and designed for the marine environment. Its purpose is to identify ships, assist in target tracking, search and rescue operations, simplify information exchange, and obtain real-time information about the current situation. This system was previously developed as a means for merchant ships to see each other more clearly in simple and complex conditions and to avoid collisions by providing detailed information about the environment to the sailor. Lighthouses can organize such safety rules by continuously transmitting the identification code, position, speed, and course of ships to other ships along with relevant information. The transmission range of beacon signals can vary from 20 nautical miles (37 km) to 350 nautical miles (648 km), depending on the power of the transmitting and receiving antenna, atmospheric conditions, and other conditions [7].

When installing radio beacons on the ground, the following requirements should be considered:

- Distance: The first consideration is how far the UAV can be from the beacon. If it is required to send a signal to the UAV over a longer distance, the power of the transmitter must be increased. In this case, the beacon system may be required to have a larger and higher transmission power.

- Environmental (meteorological) factors: If the beacon system will be used in extremely humid, cold or other harsh environments, it must be designed to withstand these conditions. This may require a more robust and weatherproof design.

- Power source: The power source for the beacon system will affect its size and design. If the system is battery-powered, the size of the battery must be considered when designing the system. There are many different types of batteries, each with their own characteristics and advantages. The most common types of batteries for beacon systems are alkaline, lithium-ion and lithium polymer. Of these, alkaline batteries are widespread and relatively inexpensive, but their lifespan is shorter than other types of batteries. Lithium-ion and lithium polymer batteries have a longer lifespan and are often used in high-performance devices, but they can be more expensive. If the battery is rechargeable, the design of the beacon system should also include a charging system. If the battery cannot be recharged, the system should be designed to allow for easy battery replacement. In general, the design of a battery-powered beacon system should depend on the size, capacity, power consumption, and whether the battery is rechargeable or replaceable. Careful consideration of these factors will help ensure that the beacon system provides reliable performance and meets the needs of the intended application.

- Type of UAV: The size of the UAV into which the beacon system is integrated should not affect the size of the beacon system. The UAV can be small or large. The most important consideration here is that the UAV must be equipped with a receiver capable of receiving the signal sent by the beacon. The receiver must be integrated into the UAV's on-board computer system, which can then use the information received from the beacon system to perform navigation, tracking, or other tasks. These beacon systems can be activated for any type of UAV if their transmission and reception systems are properly coded in advance.

The development of beacon systems and their integration into UAVs can be applied for the following purposes:

1. Increasing navigation capabilities in the operational area. If REW is applied in the operational area, pre-installed beacons will send their location to the UAV through stronger radio signals or laser signals, helping it to accurately calculate its coordinates and apply correct navigation. There were many such problems during the Second Karabakh War. Also, during the Russian-Ukrainian war, the REW systems used by Ukraine caused Iranian UAVs to go to the wrong coordinates and miss the target, and the antiaircraft systems could easily detect and destroy them.

2. Safe takeoff and landing in the runway when REW is applied. Since the takeoff and landing of large UAVs are directly related to GPS, major problems arise when REW is applied in the runway. The reason for this is that the INS, which is considered the second type of navigation in this type of UAVs, takes its origin from GPS. If GPS is obstructed, this means that it will not be able to take its origin. For this reason, the system does not allow takeoff. If it takes off, the risk of the UAV crashing is very high because it does not have a correct starting point and is close to the ground. If the operator waits for the GPS signal to arrive, the takeoff will be delayed for hours, which will also delay the operation. On the other hand, if the GPS is not correct during landing, the UAV will not be able to determine its location and the risk of leaving the runway and crashing is very high. To prevent these problems, if we place a beacon in an area close to the runway, the UAV will determine its exact location based on the signals from the beacon in the event of a GPS obstruction. In this way, we will have prevented the accident situation [8].

The main navigation system used in modern UAVs and airplanes is satellite navigation, which includes GPS, GLONASS, GALILEO, BeiDou, and others. Satellites are positioned approximately 20,000 km above the Earth's surface and continuously transmit their location and real-time data to ground receivers. 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.

During the landing, if the GPS is not correct, the UAV cannot determine its location, and the risk of an accident after leaving the runway is greatly increased. To avoid these problems, if we place a beacon in an area close to the runway, the UAV will determine its exact location based on the signals from the beacon during GPS interference. Thus, we will have prevented the accident situation [9].

According to Fig. 1, GPS signals are intercepted by radio-electronic warfare means. Since GPS signals are in a single frequency range, it is possible to easily block those frequencies [10]. But we can control the frequencies of the beacon signals as we want, within the secret range.

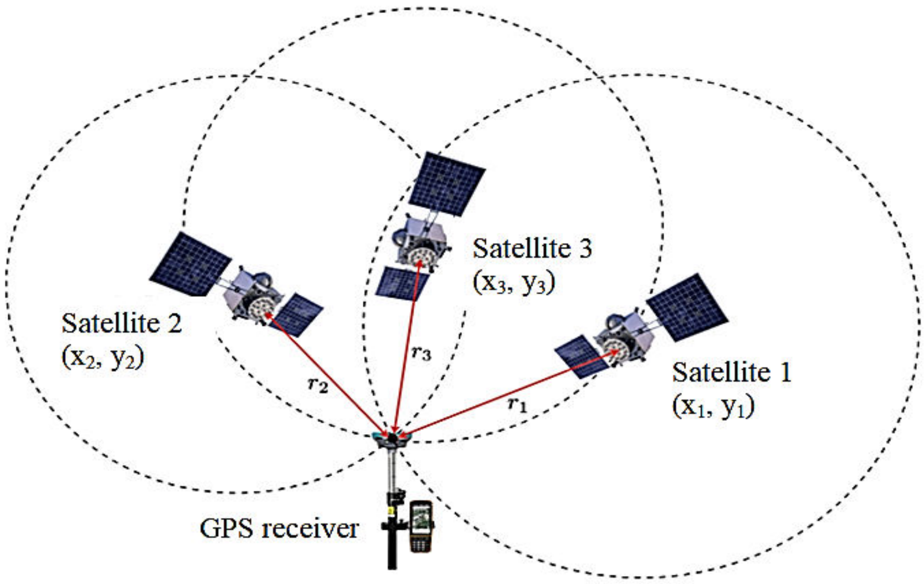

Figure 1: *GPS principle of operation*

Proper installation of beacon systems will significantly increase the stability and effectiveness of UAVs during radio-electronic warfare deployment. For this, a highly accurate and stable technology using different algorithms should be developed. Environmental factors, topography, and other geological factors should be taken into account when installing beacons in the area.

Currently, almost all types of UAVs use GPS navigation. However, beacon systems can be used in non-GPS areas during radio-electronic warfare application.

In the scientific literature, it is impossible to find information about radio beacons specially designed for UAVs.

In order to implement this system, a considerable number of fixed beacons need to be strategically placed across the operational area or at various strategic locations throughout the country. These beacons will be spaced approximately 20-30 km apart and will continuously emit circular signals on pre-coded frequencies. Similar to GPS, these signals will contain precise coordinates of the beacon and the time of transmission.

The UAV's receiver, installed on board, will be capable of determining its exact coordinates, altitude, and speed by receiving signals from at least four beacons. To ensure comprehensive coverage, it is recommended that radio beacons be positioned in proximity to the operational area in such a way that each point in the area can receive signals from at least three radio beacons via the UAV's bearing.

Once the necessary information is obtained, the UAV will be able to effortlessly and accurately follow the operator's commands for navigation. Furthermore, all the collected data will be transmitted to the Ground Control Station (GCS) through a dedicated communication channel (datalink).

III. 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 $n \geq 3$ 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 $\tilde{A}$, whose coordinates relative to the Oxy system are known $(\tilde{x}, \tilde{y})$.

For simplicity, let's number the receiving stations as $k = 1, 2, 3, \dots, n$ 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 (x_k, y_k).

The angle between the direction beams of the UAV bearing towards the 1st, 2nd, 3rd, ..., n-th station at the instant $t + T$ is $\varphi_{1,2}, \varphi_{2,3}, \dots, \varphi_{n*1,n}$.

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 $\varphi_{n,1} = \left(2\pi - \sum_{k=1}^{n-2} \varphi_{k,k+1}\right)$.

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 (Fig. 2). 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 $A_k A_k^D A_{k+1}$. Let the angle $A_k A_k^D A_{k+1}$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,

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

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:

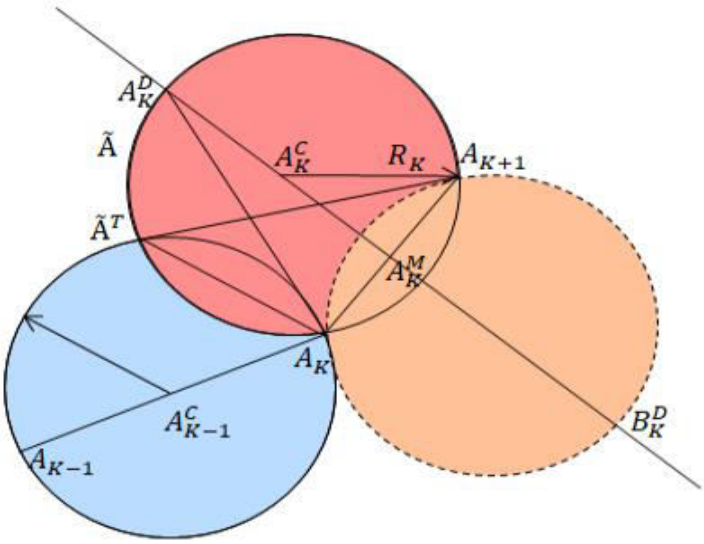

Figure 2: *Determining the remaining angle between the beams*

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

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

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

or

$$((x_k^M - x_k^D)^2 + (x_k^M - y_k^D)^2)\,\mathrm{tg}^2\frac{\varphi_{k,k+1}}{2} = (x_k^M - x_k)^2 + (x_k^M - y_k)^2 \tag{3}$$

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 Fig. 2. 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,

$$(x_k^D, y_k^D) = \arg\min\{|A_k^D - \tilde{A}|, |B_k^D - \tilde{A}|\} \tag{4}$$

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 $A_k^D A_k^C$:

$$(x_k^C - x_k^D)^2 + (y_k^C - y_k^D)^2 = (x_k^C - x_k)^2 + (y_k^C - y_k)^2$$

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

$$\begin{cases} (x_{k+1} - x_k)x_k^C + (y_{k+1} - y_k)y_k^C = (x_{k+1} - x_k)x_k^M + (y_{k+1} - y_k)y_k^M \\ 2(x_k^D - x_k)x_k^C + 2(y_k^D - y_k)y_k^C = (x_k^D)^2 + (y_k^D)^2 - x_k^2 - y_k^2 \end{cases} \tag{5}$$

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}:

$$(x - x_k^C)^2 + (y - y_k^C)^2 = R_k^2 \tag{6}$$

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:

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

(7) Numerical methods can be applied to find the minimum of the functional [5].

IV. Conclusion

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 radioelectron warfare application. Currently, new research is being conducted to detect, identify and neutralize UAVs, anti-GPS signal jamming systems are being developed, and their false spatial deviation is being applied. Considering these methods, 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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