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Kinematic design as a means of specification of aircraft coordinates

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This study proposes a method for determining the spatial coordinates of a Shahed-type enemy UAV using 3D trilateration from three fixed ground observers with known locations. By measuring distances to the UAV at discrete time intervals, its flight trajectory is reconstructed. The analysis shows the UAV follows a uniform, curvilinear path with steady angular velocity and descending altitude, modeled through parametric equations. This allows accurate prediction of future positions and identification of an optimal interception point. The method ensures high spatial precision, supporting air defense operations even under conditions of signal loss or complex terrain. The results are particularly relevant for improving mobile detection and response systems in modern warfare contexts, such as in Ukraine.

Keywords: *Shahed UAV; 3D trilateration; trajectory prediction; interception modeling; uniform curvilinear motion; air defense; localization.*

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1. Introduction

The continuous use of reconnaissance and sabotage and strike drones by the enemy during military events on the territory of Ukraine causes significant damage not only to the military defenders of the state, but also to its civilians. The simultaneous launch of numerous groups of unmanned drones of the Shahed 131/136 type and similar modifications has been particularly harmful to the population. Their specificity lies in the fact that, in addition to numerous foreign supplies of these drones, Russia has also established their serial production at its own enterprises. Therefore, there is no doubt that the enemy will actively use them until the last moment of hostilities.

It would seem that small amounts of ammunition and the speed of spatial movement should not pose difficulties for the Armed Forces of Ukraine (AFU) in confronting Shahed 131/136. However, the enemy's preferred nighttime flight hours, low altitudes, and the resulting difficulty in detecting them over rough terrain means that these drones have to be eliminated at the final stage of their flight. In this case, the fragments of enemy drones shot down by small arms or short-range missiles falling on the buildings and streets of the attacked settlements cause not only significant material damage to the residents, but also pose a serious threat to their lives.

Therefore, it seems appropriate to improve the methods and ways of countering not only the Armed Forces of Ukraine, but also the forces of territorial defense groups of settlements to massive group attacks by unmanned aerial vehicles, including drones of the Shahed 131/136 model and their possible modifications such as the Geranium, etc.

2. Literature review

With a certain degree of plausibility, it can be argued that both in medicine, where the most important thing is to correctly diagnose a patient's illness, and in military affairs, the most important thing is to timely detect the enemy and choose an available means of destroying it. It was in this dual context that research in the field of countering enemy aircraft was perceived in the past:

- One part of the research focused on ensuring the maximum achievable accuracy of detecting and determining the coordinates of enemy aircraft [1–3];
- The other was aimed at improving methods and weapons to defeat and destroy these targets [4–6].

It should be noted that over the past two military years, both of these areas of countering enemy unmanned aerial vehicles have had quite tangible achievements [7, 8]. The once exotic, but now irreplaceable means of electronic warfare (EW) have been actively developed and are widely used, especially on the front lines and at the forefront of confrontations [9–11]. In fact, mobile mobile strongholds equipped with large-caliber small arms to defeat enemy aircraft have been formed around all more or less numerous settlements and significant objects of the military-industrial complex and urban infrastructure [3, 6], etc. Methods have been developed for refining the coordinates of enemy drones, which, through the use of mathematical tools and kinematic design methods, are able to determine the exact coordinates of enemy aircraft with an accuracy of $0.5 \div 1.0$ meters [4, 5].

However, the actual percentage of detected and destroyed enemy sabotage and strike drones still does not exceed 65% to 70% in real life [1, 6, 12]. That is, up to $30 - 35$ enemy drones out of a hundred aimed at civilian populated areas have a real chance of "falling on the heads" of civilians or damaging important infrastructure with their $40 - 45$ kilogram warheads.

And the main root cause of this is the inability of our existing weapons to hit enemy drones with a 100 percent guarantee. And given the low cost of Shahed drones for Russia, they will actively use them not only as a destructive weapon of destruction, but also as a weapon of psychological pressure on the population, as an effective weapon of hybrid warfare.

Therefore, research aimed at improving methods of countering enemy aircraft that can improve the accuracy of determining their time-varying coordinates remains relevant. As well as to improve existing means and equipment for detecting and defeating enemy aircraft and to search for new, more effective means of destroying enemy equipment and weapons.

3. Main results of the study

The objective of this study is to develop a methodology for determining the spatial trajectory of a hostile unmanned aerial vehicle (UAV) of the Shahed type, based on 3D trilateration and data extrapolation, in order to predict its future position and enable its effective destruction by air defense systems.

Key research tasks:

- Development of a geometric localization model for the UAV based on the coordinates of three fixed ground observers and their measured distances to the target.
- Construction of a mathematical framework to reconstruct the UAV trajectory in space using measured coordinates at selected time intervals.
- Extrapolation of the UAV trajectory beyond the observed interval, considering constant velocity and trajectory curvature.
- Determination of predicted UAV coordinates for planning the time and location of its interception by firepower systems.

Methodological Stages:

Stage 1. Detection of the UAV in the airspace by three spatially distributed ground observers capable of measuring the distance to the UAV in real time. At moments $t = 0, 10, 20, \ldots, 90$ seconds, the distances from each observer to the UAV are recorded.

Stage 2. Using the trilateration method, which calculates the intersection point of three spheres with radii equal to the measured distances, the UAV coordinates are computed for each of the specified time moments. This allows for constructing a discrete flight trajectory of the UAV.

Stage 3. Based on the computed points, the type of UAV motion is analyzed. In this case, the Shahed UAV is determined to be moving along a uniform curvilinear path at a constant speed (not exceeding 35 m/s) with a gradual decrease in altitude.

Stage 4. Trajectory extrapolation is performed using a parametric model of curvilinear motion. Calculations employ trigonometric functions along a circular arc, incorporating a progressive descent in flight altitude.

Stage 5. Based on the extrapolated trajectory segment, the predicted UAV coordinates are determined for the next 60 seconds. This enables the creation of a time-sensitive "interception window" for firepower assets such as short-range air defense systems or artillery.

Fig. 1. Shahed UAV tracking via ground observer trilateration system.

Figure 1 illustrates a spatial configuration for locating an unmanned aerial vehicle (UAV) of the Shahed type using three-dimensional trilateration. Three ground-based observation points, labeled Observer 1, Observer 2, and Observer 3, are equipped with rangefinders and positioned across moderately varied terrain. Each observer measures its distance to the UAV in flight, represented by red lines marked as distances 1, 2, and 3, respectively. The observers also form a triangle on the ground with known inter-observer distances a, b, and c. This geometric setup enables the use of trilateration methods to calculate the UAV's spatial coordinates based on six known distances. The system can be solved analytically or numerically, providing a robust basis for UAV localization in real-world surveillance scenarios.

In UAV localization tasks using three ground-based observers, it is practical to employ a local East–North–Up (ENU) coordinate system centered at a known reference point. This approach enables spatial calculations in meters, simplifies computation, and minimizes distortion arising from the Earth's curvature over small areas.

Conversion from geodetic coordinates (latitude, longitude, height) to Earth–Centered, Earth–Fixed (ECEF) coordinates is performed using the following formulas:

$$N(\phi) = \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}}, \tag{1}$$

$$X = (N(\phi) + h) \cos\phi \cos\lambda, \tag{2}$$

$$Y = (N(\phi) + h) \cos\phi \sin\lambda, \tag{3}$$

$$Z = \left[N(\phi)(1 - e^2) + h\right] \sin\phi, \tag{4}$$

where $a = 6378137$ m is the WGS-84 ellipsoid semi-major axis, $e^2 = 0.00669437999014$ is the square of the eccentricity, ϕ, λ are the latitude and longitude in radians, h is the elevation above mean sea level.

Transformation from ECEF to the local ENU coordinate system is calculated by:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{ENU}} = \begin{bmatrix} -\sin\lambda_0 & \cos\lambda_0 & 0 \\ -\sin\phi_0 \cos\lambda_0 & -\sin\phi_0 \sin\lambda_0 & \cos\phi_0 \\ \cos\phi_0 \cos\lambda_0 & \cos\phi_0 \sin\lambda_0 & \sin\phi_0 \end{bmatrix} \cdot \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix}, \tag{5}$$

where $(\varphi_0, \lambda_0, h_0)$ are the GPS coordinates of reference point A, (X_0, Y_0, Z_0) are its ECEF coordinates.

Upon applying the transformation equations (1)–(5), points B and C were successfully mapped to the local ENU frame centered at A, yielding the coordinates listed in Table 1.

Table 1. Coordinate transformation.

Observer	GPS Coordinates	ENU Coordinates (m)
A	49.8397°N, 24.0297°E, 296 m	(0;0;0)
B	49.8397°N, 24.0714°E, 296 m	(3000;0;0)
C	49.8667°N, 24.0506°E, 296 m	(1500;3000;0)
E	49.8846°N, 24.0297°E, 1498 m	(0;5000;1200)

The presented Figure 2 flowchart outlines the structured and sequential approach to intercepting and eliminating a hostile unmanned aerial vehicle (UAV), such as the Shahed, using a system based on spatial trilateration and predictive trajectory modeling. This scheme illustrates the operational logic from the moment of detecting the UAV to its physical neutralization. Each block in the diagram corresponds to a critical stage in real-time decision-making and engagement, which carries distinct practical implications for air defense operations.

The process begins with the input of measurement data from three spatially fixed observers, which enables accurate trilateration to determine the instantaneous 3D coordinates of the enemy UAV. This data-driven localization phase is essential for forming an initial spatial understanding of the threat.

Once the trajectory is reconstructed from multiple time-stamped positions, a prediction model is applied to extrapolate the UAV's future positions. This predictive capability allows command centers to calculate not only the UAV's future location but also the time at which it will reach certain critical zones, including infrastructure or populated areas.

With the prediction in hand, a command instruction is issued to fire units or automated systems to execute a targeted interception. The actual elimination process – represented in the flowchart as the destruction of the UAV – is then assessed: if the UAV is neutralized, the cycle ends successfully; if not, the system loops back to recalibrate predictions and issue new instructions in real time.

This logical cycle demonstrates a range of practical advantages essential for modern air defense operations. Its real-time adaptability enables dynamic recalculation and re-engagement whenever an interception attempt fails, maintaining continuous pressure on the target. The system's predictive engagement capability provides not only spatial tracking of UAVs like Shahed but also precise timing for effective neutralization. Through modular integration with automated command and control systems, this architecture enhances the responsiveness of short-range and mobile air defense units. Operational efficiency is achieved by focusing resources only on validated intercept opportunities, which reduces ammunition waste and operator fatigue. Ultimately, the system's value lies in its ability to transform raw sensor data into real-time, mathematically grounded decisions for UAV neutralization. The supporting flowchart emphasizes the deterministic, feedback-based structure of the process, where computational precision directly reinforces tactical success on the battlefield.

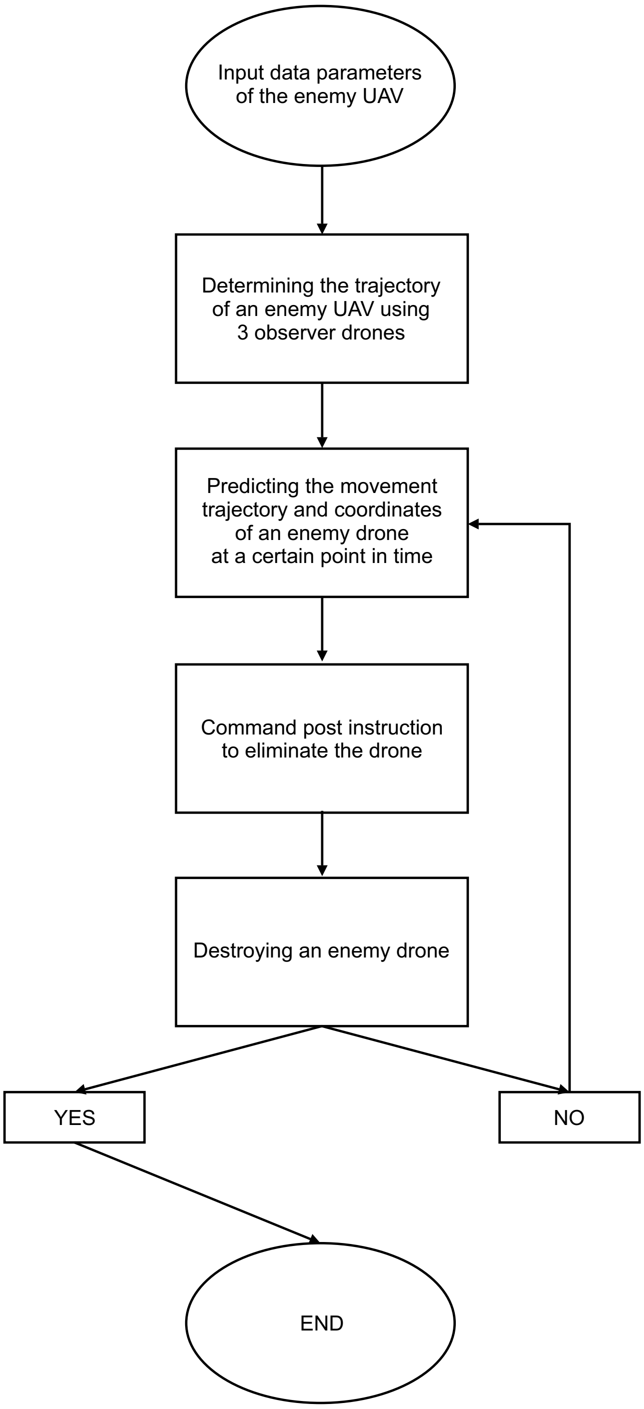

Fig. 2. Flowchart of actions and calculations when using kinematic design to destroy enemy aircraft.

4. Theoretical basis for extrapolation

Extrapolation is a classical analytical method used to predict the values of a function beyond the known range of data. In the context of motion modeling, extrapolation is based on the assumption that the trend or behavior of variables remains consistent in the immediate future. The core idea is to construct a function that approximates known data and extend it into a domain where new measurements have not yet been obtained.

Formally, if a function $f(t)$ is smooth on the interval $[a, b]$, and the values $f(t_1)$, $f(t_2)$, $\ldots$, $f(t_n)$, are known, extrapolation allows us to estimate $f(t^*)$, for $t^* > b$ assuming the structure of f, does not change significantly. In the case of UAV motion, the function $f(t)$, corresponds to the trajectory vector $\boldsymbol{r}(t)$ which consists of consistent components $x(t)$, $y(t)$, $z(t)$, derived from observations and kinematic equations.

Given the constant velocity and curvature of the UAV's trajectory, analytical extrapolation is the most suitable approach (in contrast to statistical or stochastic extrapolation), as the model is governed by physical laws rather than empirical data patterns. This makes the prediction stable, especially over short time intervals (up to 60 seconds), and ensures high accuracy even in the presence of partial data loss.

The extrapolation of the Shahed UAV trajectory is of critical importance under conditions of aerial threat and missile terrorism that Ukrainian cities and infrastructure are regularly subjected to. The ability to predict the target's future position with meter-level accuracy allows defense systems to:

— Identify the optimal time and location for drone interception;
— Avoid redundancy and overlap in response efforts by multiple air defense units;
— Reduce the workload for operators and control systems;
— Maximize kill probability while minimizing ammunition and time expenditures.

In situations where the UAV operates under radio silence or employs evasive routes, traditional tracking methods (radar, satellite navigation) may become ineffective. In contrast, extrapolation based on geometric modeling and thermal or acoustic observation enables continuous tracking, even under degraded sensing conditions.

This makes extrapolation a powerful tool in operational planning and rapid response, enhancing the effectiveness of Ukraine's multi-layered air defense systems.

5. Determining the coordinates of the enemy UAV

Assume three fixed observer stations are placed in the area: $A(0;0;0)$, $B(3000;0;0)$, $C(1500;3000;0)$. At each moment in time t, the distances from the UAV (Shahed) to each observer are known — obtained from sensors. The objective is to determine the 3D coordinates of the UAV at each time step: $t = 0, 10, 20, \ldots, 90$. Table 2 below presents a complete set of data for each 10-second time mark: including the measured distances from the UAV to observer stations A, B, and C, the computed coordinates (X, Y, Z) using trilateration, and the resulting UAV speed. Each row corresponds to one time step t. The first speed value is undefined as there is no prior point.

The position (x, y, z) of the UAV is found by solving the following system of nonlinear equations:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i, \quad i = A, B, C. \tag{6}$$

We apply numerical minimization of the total squared error function:

$$E(x, y, z) = \sum_{i=A,B,C} (\|P - P_i\| - d_i)^2. \tag{7}$$

This computation is performed for each time t using the measured distances to the observers. Figure 3 presents a 3D side view of the Shahed trajectory from $t = 0$ to $t = 90$ seconds. The arc-shaped flight path is clearly visible from the side perspective ($elev = 20°$, $azim = 90°$). Blue points mark the UAV positions every 10 seconds, and dotted lines represent measurement beams from observer stations A, B, and C. The velocity in each interval $[t_i, t_{i+1}]$ is calculated as:

$$v_i = \frac{\|P_{i+1} - P_i\|}{t_{i+1} - t_i}. \tag{8}$$

For example, in the first interval $(0 - 10$ s):

$$v_0 = \frac{\|(344.8, 4959.8, 1193.5) - (0.3, 4999.9, 1200.3)\|}{10} \approx 34.83 \text{ m/s} \approx 125.4 \text{ km/h}.$$

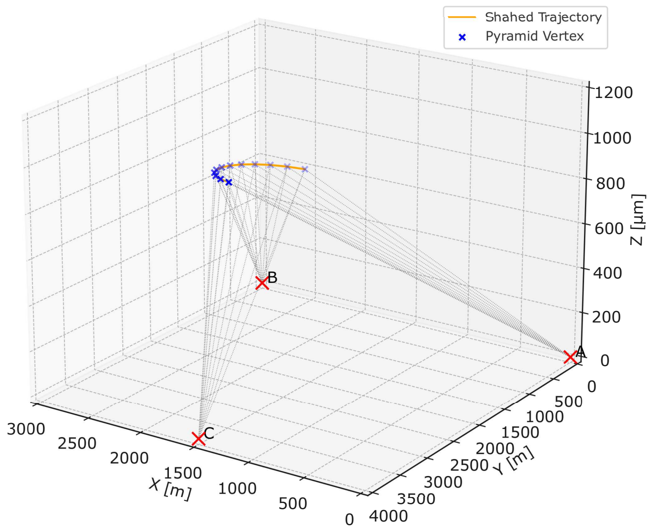

Fig. 3. 3D Trajectory of UAV and observer positions.

Analysis of velocities across all time intervals shows that the UAV's speed remains nearly constant with less than 0.2% variation. This indicates an absence of linear acceleration, implying uniform motion. Although the UAV follows a curved trajectory, the magnitude of velocity does not change, confirming uniform circular motion, where only the direction of the velocity vector changes.

3D trilateration based on distance measurements from three fixed observers provides an effective way to reconstruct the UAV trajectory and its dynamics with realistic accuracy. Computing position at each time step enables estimation of both movement and speed. The method proves efficient for air defense tracking scenarios and could be extended by incorporating Kalman filtering in future work to improve robustness under noisy measurements.

Table 2. Modeling and numerical example.

t (s)	d_A (m)	d_B (m)	d_C (m)	v_0 (m/s)	$x(t)$ (m)	$y(t)$ (m)	$z(t)$ (m)
0	5142	5953	2773		0.33	4999.94	1200.31
10	5113	5751	2569	34.83	344.79	4959.77	1193.55
20	5030	5501	2342	34.93	673.32	4841.0	1188.4
30	4894	5212	2101	34.87	964.38	4648.98	1186.67
40	4708	4893	1852	34.88	1203.97	4395.58	1180.95
50	4477	4558	1610	34.78	1378.03	4094.56	1174.38
60	4206	4222	1396	34.92	1477.53	3759.84	1170.88
70	3905	3907	1236	34.73	1497.4	3413.19	1164.89
80	3582	3635	1164	34.91	1436.25	3069.51	1160.17
90	3253	3434	1199	34.81	1298.28	2749.93	1155.15
Extrapolated UAV Coordinates							
t (s)	$x(t)$ (m)		$y(t)$ (m)			$z(t)$ (m)	
140	608.50		1152.19			1130.15	
150	470.54		832.64			1125.15	

6. Extrapolation of Shahed UAV trajectory based on spatial trilateration

After determining the coordinates of the hostile Shahed UAV using three stationary observers placed at known locations and analyzing its motion over a 90-second flight interval, the task of predicting the UAV's future trajectory arises. Based on the calculated positions and the constancy of the UAV's velocity, trajectory extrapolation makes it possible not only to forecast the UAV's future spatial position but also to ensure timely response by air defense systems.

It was found that within the examined time interval, the UAV's motion is uniform – its velocity does not change significantly (deviation does not exceed 0.2%), and the trajectory forms a smooth arc. This indicates that the magnitude of the velocity remains constant, with only the direction of the velocity vector changing. Such motion is characterized as uniform curvilinear motion, which is mathematically described by angular velocity ω and a radius of curvature RRR, all situated within a defined plane in three-dimensional space.

To describe this type of motion, we employed a parametric model of the UAV's trajectory as a function of time, incorporating both horizontal movement along a circular arc and vertical descent. The general formula for the UAV's position in space is given by:

$$\boldsymbol{r}(t) = \boldsymbol{r}_0 + R \cdot [\cos(\omega t) \cdot \hat{e}_1 + \sin(\omega t) \cdot \hat{e}_2] + z(t) \cdot \hat{k}. \tag{9}$$

In this expression $\boldsymbol{r}_0$ is the center of the curvature arc, R is the radius, $\omega = \frac{v}{R}$ is the angular velocity, $\hat{e}_1$ and $\hat{e}_2$ are mutually orthogonal unit vectors in the trajectory plane, $z(t) = z_0 - a_z \cdot t$ describes the descent in altitude over time, where $a_z \approx 0.5$ m/s.

Based on the computed trajectory data, the following parameters were determined: the average velocity of the UAV is approximately $v = 34.87$ m/s, and the radius of curvature is about $R = 1500$ m. Thus, the angular velocity is calculated $\omega = 0.0232$ rad/s. During each 10-second segment, the Shahed UAV traverses a circular arc of approximately $13 - 14^\circ$ (0.232 radians). The altitude decreases at a rate of roughly 5 meters every 10 seconds, consistent with the gradual gliding descent characteristic of many Shahed-type drone models.

Accordingly, extrapolating the UAV's trajectory for the interval $t \in [100; 150]$ seconds involves computing its future coordinates by extending the arc and applying a consistent vertical descent. This model preserves the smooth curvature of the flight path without abrupt changes in direction, which aligns with the behavior of cruise-type UAVs equipped with inertial autopilot systems.

Figure 4 presents a three-dimensional schematic for determining the spatial position of a hostile Shahed UAV using three ground-based observers, designated as points A, B, and C. These observers record the distances to the target at specific time intervals using rangefinders. To enhance clarity, not only are the discrete positions shown, but also a smooth arc-like line interpolates these points to illustrate the overall trajectory shape. According to the data analysis, the UAV moved with a constant speed and no acceleration, following a smooth curved path.

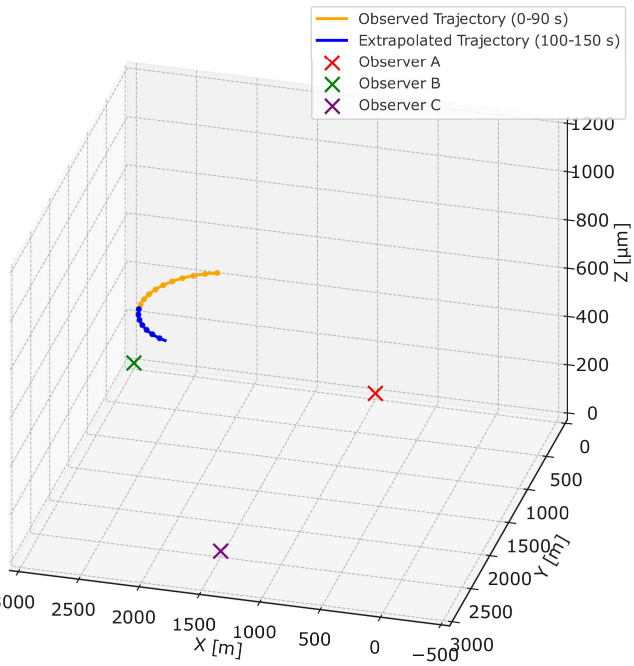

Fig. 4. Extrapolation of UAV trajectory.

This characteristic enabled the application of trajectory extrapolation to forecast the UAV's future position over the next 60 seconds. Such an approach is especially important under wartime conditions – particularly in the context of Russian aggression against Ukraine, where Shahed drones are widely used as loitering munitions targeting civilian and critical infrastructure. Extrapolation allows air defense units to predict the future position of the threat in advance, which is especially useful when direct visual observation is hindered by weather or terrain.

A key advantage of this method lies in its high spatial accuracy and computational efficiency. Unlike approaches that require advanced machine vision or radar tracking, trilateration is grounded in basic geometric principles and can be implemented on systems with limited computing capabilities. This makes it well-suited for integration into mobile threat detection platforms.

Thus, the presented graphical model illustrates the fundamental principles of spatial trilateration and its role in constructing extrapolated trajectory models for hostile UAVs. In turn, this forms the basis for rapid response decision-making in the context of modern hybrid warfare.

7. Conclusions

1. The results of this study confirm the feasibility of using spatial trilateration and trajectory extrapolation methods to determine and predict the movement of hostile unmanned aerial vehicles (UAVs) such as the Shahed-131/136. The proposed model provides a foundation for the potential integration of interception systems, particularly kamikaze drones, which have already demonstrated effectiveness against ground targets but are currently being considered as a promising tool for engaging aerial threats.
2. The high accuracy in determining both the time interval of a warhead explosion and the spatial coordinates of its detonation necessitates more accurate methods than radio-electronic methods for determining and predicting the motion parameters and coordinates of objects moving in space. Such methods, which, based on accurate measurements of the parameters and coordinates of moving objects in the past, could predict with high accuracy these indicators in the near future. In this case, we are talking about predicting, on the basis of preliminary data, the future coordinates of an enemy aircraft at the point of its destruction and the exact time of its arrival there to the hundredth of a second.
3. Of the possible theoretical methods for calculating the parameters of bodies moving in airspace, one of the most suitable for predicting future coordinates and motion parameters is the methodology and accompanying mathematical apparatus of the so-called "kinematic design". This method of kinematic projection makes it possible to determine with high accuracy the coordinates of solids moving in space while all projection objects, i.e. observers, projection objects, picture plane and projecting rays, move independently in this space. It is kinematic projection that is the basis of the method of eliminating enemy unmanned aerial vehicles studied in this paper.

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Кінематичне проєктування як засіб визначення координат безпілотного літального апарата

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У цьому дослідженні запропоновано метод визначення просторових координат ворожого БпЛА типу "Shahed" за допомогою тривимірної трилатерації від трьох стаціонарних наземних спостерігачів із відомими координатами. Вимірюючи відстані до БпЛА через дискретні інтервали часу, відтворюється його траєкторія польоту. Аналіз показує, що БпЛА рухається рівномірно-криволінійною траєкторією зі сталою кутовою швидкістю та зниженням висоти, що моделюється за допомогою параметричних рівнянь. Це дає змогу точно прогнозувати майбутні положення та визначати оптимальну точку перехоплення. Запропонований метод забезпечує високу просторову точність і може ефективно застосовуватися в операціях протиповітряної оборони навіть за умов втрати сигналу або складного рельєфу місцевості. Отримані результати мають особливу актуальність для вдосконалення мобільних систем виявлення та реагування в умовах сучасних воєнних дій, зокрема в Україні.

Ключові слова: *БпЛА "Shahed"; 3D трилатерація; прогнозування траєкторії; моделювання перехоплення; рівномірний криволінійний рух; протиповітряна оборона; локалізація.*