Algorithm design and development for solving the target engagement problem on subsurface platforms

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ABSTRACT

Previous target engagement systems on subsurface platforms were electromechanical computers with highly complex mechanical structures, in which problems were idealized with predetermined parameters. With the current trend of digitalization, digital computers with high computational capabilities have replaced traditional electromechanical systems and are now installed and utilized on subsurface platforms. Based on theoretical studies of the AIUS (Automatic Information and Control System) on naval submarines, this paper presents research on the development of algorithms and software for target engagement using the established theoretical foundations. The proposed algorithm and software are then implemented and tested on a digital computer platform to evaluate their performance. The results demonstrate that the algorithm, when tested on a digital computer, achieves results comparable to those of electromechanical systems, with faster processing speed and the ability to adapt to continuous target movement.

Keywords: Firing algorithm; Fire control problem solving; Subsurface platforms; Autonomous weapons.

1. INTRODUCTION

The fire control problem is a complex and critical issue in the field of control and guidance for autonomous weapons. Determining the coordinates of the interception point between the weapon and the target - based on parameters such as velocity, trajectory, range, and bearing of the target [3] - is a key factor that directly affects the success of the interception process. In earlier systems, particularly electromechanical computers, solving this problem required precise input of target parameters from indication devices such as radar, navigation systems, and other observation instruments. However, in underwater operational environments, these observation systems become inoperable due to environmental constraints - for instance, radar waves cannot propagate through water. This poses significant challenges in determining the velocity and heading of underwater targets, especially when subsurface platforms are concealed beneath the ocean surface.

The development of algorithms and software for calculating and predicting target parameters in situations with limited information is of critical importance. For subsurface platforms, where observation systems are constrained and insufficient target data is available, developing interception solutions based on computational models and prediction techniques can significantly enhance operational effectiveness and combat capabilities. In recent years, the target interception problem has attracted considerable attention from researchers, with various studies aiming to address this challenge. Previous research has mainly focused on interception in surface or aerospace environments, where target parameters are fully provided by positioning and radar systems [5]. Other studies have concentrated on target detection and tracking, such as the improved YOLOv5 algorithm [7], DSW-YOLOv8n [8], and the LSTM - Kalman Filtering approach [9]. However, these works primarily optimize target recognition and do not tightly integrate with fire-control algorithms. Moreover, they have not been tested in environments where the target follows a nonlinear trajectory and is influenced by ocean currents or obstacles. Additionally, the processing speed of these approaches often does not meet real-time requirements. Very few studies have specifically addressed the interception problem in underwater environments, where observational data on targets is inherently limited.

In this paper, we propose a novel solution to address the target interception problem under conditions of incomplete target information. Rather than relying solely on fixed target parameters, the proposed approach focuses on developing an algorithm capable of continuously adapting to changes in the target's motion. This enables autonomous weapons to more accurately track and predict the interception point, even without support from observation systems such as radar. In addition to designing a new algorithm that automatically updates firing parameters and adapts to target variations under complex movement conditions, a dedicated software system is also developed to evaluate and verify the algorithm's performance. Experimental results demonstrate that the proposed software yields highly accurate outcomes, even in scenarios with limited information, and performs comparably to benchmark data. This confirms its effectiveness in solving the interception problem with high precision.

The remainder of this paper is organized as follows: Section 2 presents the formulation and solution of the target interception problem on subsurface platforms. Section 3 discusses the experimental results and software evaluation. Section 4 concludes the paper.

2. SOLVING THE TARGET INTERCEPTION PROBLEM ON SUBSURFACE PLATFORMS

2.1. The target engagement problem for autonomous weapons

Notation used in the target engagement problem:

- D : Range, measured in cables (1 calbe = 185.2 meters);
- H_{CM} : Course of the subsurface platform, in degree (ranging from 0° to 360°);
- G_M : Bearing angle of the subsurface platform, in degree (ranging from -180° to 180°);
- H_{CK} : Course of the target, in degree (ranging from 0° to 360°);
- P : Azimuth, in degree (ranging from 0° to 360°);
- V_M : Speed of subsurface platform, V_K : Speed of subsurface target, measured in knots.

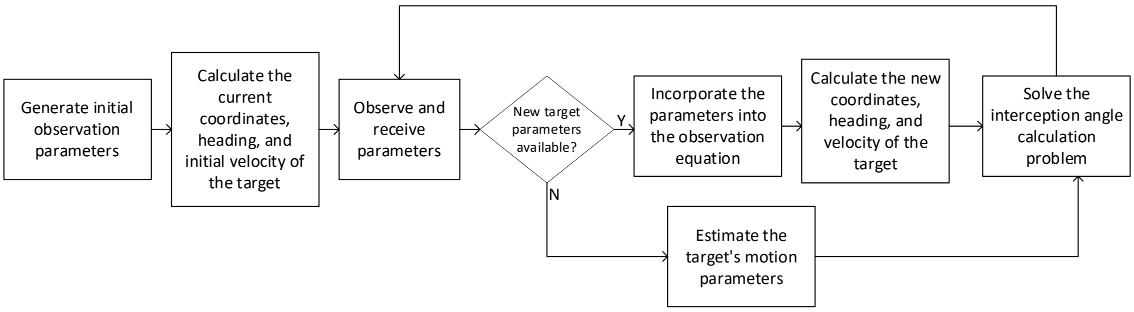

Figure 1. *Block diagram for solving the target engagement problem on subsurface platforms.*

To solve the target engagement problems using autonomous weapons in underwater environments, it is essential to describe the motion of the relevant objects: the subsurface platform, the target, and the autonomous weapon. This mathematical model will include the motion equations of the objects and the conditions for their interception at the engagement point. More specifically, it is necessary to accurately determine the position coordinates and the motion parameters of the target, such as bearing, range, course, and velocity. We consider the mutual motion of the target and the subsurface platform in the XOY coordinate system, where the origin represents the position of the subsurface platform at the time the problem is solved. The OX and OY axes are oriented towards true east and true north, respectively, and angles are measured in a clockwise direction from the OY axis.

Let the uninitialized three-component vector *Z*:

$$Z = \begin{bmatrix} D_0 & V_X & V_Y \end{bmatrix}^T \tag{1}$$

It includes the initial range D_0 and the projections of the target's velocity onto the coordinate axes, V_X and V_Y. Given these parameters and the initial azimuth P_0, the current coordinates, course, and velocity of the target can be calculated. The following formulas are used for the computations:

$$P = \tan^{-1}\frac{D_x}{D_y};\ K = \tan^{-1}\frac{V_x}{V_y};\ D = \sqrt{D_x^2 + D_y^2};\ V = \sqrt{V_x^2 + V_y^2}; \tag{2}$$

$$D_x = D_0\sin(P_0) + V_x\Delta T - \Delta X;\ D_y = D_0\cos(P_0) + V_y\Delta T - \Delta Y \tag{3}$$

Where: *K* - Target's course; *V* - Target's speed; D_x - Range to target onto X axis; *Dy* - Range to target onto Y axis.

These equations describe the system's variation over time Δt_i, based on the assumption of the target's uniform rectilinear motion, with projections onto the coordinate axes.

$$D_0\sin(P_0) + V_x\Delta t_i = \Delta X_i + D_{x_i};\ D_0\cos(P_0) + V_y\Delta t_i = \Delta Y_i + D_{y_i} \tag{4}$$

Where: ΔX_i, ΔY_i are projection of the movement in duration Δt_i.

When multiplying the first equation by $\cos(P_i)$ and the second equation 2 by $\sin(P_i)$ and when computed from another equation, we obtain the following equation:

$$\begin{aligned} &D_0(\sin(P_0)\cos(P_i) - \cos(P_0)\sin(P_i)) + V_x\cos(P_i)\Delta t_i - V_y\sin(P_i)\Delta t_i \\ &= \Delta X_i\cos(P_i) - \Delta Y_i\sin(P_i) \end{aligned} \tag{5}$$

It can be rewritten to new form:

$$h_{i_1}D_0 + h_{i_2}V_x - h_{i_3}V_y = d_i \tag{6}$$

Where: $h_{i_1} = \sin(P_0)\cos(P_i) - \cos(P_0)\sin(P_i)$; $d_i = \Delta X_i\cos(P_i) - \Delta Y_i\sin(P_i)$; $h_{i_2} = \cos(P_i)\Delta t_i$; $h_{i_3} = \sin(P_i)\Delta t_i$. These are the relative equations of the variables D_0, V_X which are considered the i-th observation equation, with the parameters being the course and the target range at the i-th time step. It is a system of linear equations with three variables, at least three such equations are needed to determine them. This is achieved if and only if the positioning is accurate, and the bearing measurement values are free from random measurement errors. When additional observation equations are used (n > 3), an over-determined system of observations and solve for the three unknowns can be constructed. To solve this, the established mathematical method - the least squares method can be applied. In matrix form, the system of observation equations is written as follows:

$$HZ = D \tag{7}$$

Where, for the case of *n-th* observations, it can be seen:

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ \dots & \dots & \dots \\ h_{n1} & h_{n2} & h_{n3} \end{bmatrix}, D = \begin{bmatrix} d_1 \\ d_2 \\ \dots \\ d_n \end{bmatrix}$$

With each new measurement, a new row is added to the matrix H and the vector D. Suppose it has already obtained some vector Z. It is considered the quantity f_i, the quantity obtained when replacing the component of this vector in the i-th observation equation:

$$f_i = h_{11}D_0 + h_{12}V_x + h_{13}V_y \text{ - } d_i \quad (8)$$

f_i - The double error of the i-th observation equation. Next, the sum of the squared double errors of the observation equations is considered:

$$F = \sum f^2 \quad (9)$$

And the vector such that *F* is the minimum value.

In the case where the mobility of the subsurface platform is fixed in terms of velocity and heading, the projection of the subsurface platform's displacement over the time interval Δt_i can be calculated as follows:

$$\Delta x_i = V_{lx}\Delta t_i,\ \Delta y_i = V_{ly}\Delta t_i \quad (10)$$

In this case, the observation equation takes the form of:

$$D\cos(P_y - P_0) + (V_x - V_{ly})\cos P_i\Delta t_i - (V_y - V_{ly})\sin P_i\Delta t_i = 0 \quad (11)$$

New variables are introduced, which are the projections of the relative velocity vector onto the coordinate axes:

$$V_x^{"} = V_x;\ V_y^{"} = V_y - V_{ly} \quad (12)$$

For these variables, the observation equation takes the form of:

$$\mathrm{h_{i1}D_0 + h_{i2}V_x^{'} + H_{i3}V_y^{'} = 0} \quad (13)$$

It can be set an equation system from three above equations:

$$\begin{aligned} \mathrm{h_{i_{11}}D_0 + h_{i_{12}}V_x^{'} + H_{i_{13}}V_y^{'}} &= 0 \\ \mathrm{h_{i_{21}}D_0 + h_{i_{12}}V_x^{'} + H_{i_{23}}V_y^{'}} &= 0 \\ \mathrm{h_{i_{31}}D_0 + h_{i_{32}}V_x^{'} + H_{i_{33}}V_y^{'}} &= 0 \end{aligned} \quad (14)$$

Or, in matrix form:

$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} D_0 + \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} V_x^{'} + \begin{bmatrix} h_{13} \\ h_{23} \\ h_{33} \end{bmatrix} V_y^{'} = 0 \quad (15)$$

This system either has default solutions ($D_0 = 0;\ V_x^{'} = 0; V_y^{'} = 0$), or the vectors:

$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}, \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}, \begin{bmatrix} h_{13} \\ h_{23} \\ h_{33} \end{bmatrix} \quad (16)$$

These are linearly dependent vectors as they represent the linear constraint between the variables D_0, V_x, and V_y. Therefore, equation (14) is a linearly dependent system. However, from linear algebra, it is known that a matrix with linearly dependent columns has a determinant equal to zero, which means the system has an infinite number of solutions.

In this case, when two of the three equations derived over a period of time are altered after changing the course and/or velocity of the subsurface platform, the relative velocity vector will no longer be constant. Therefore, the standard system of equations cannot be written in the form of (14), and the equations will no longer be linearly dependent, resulting in a unique solution – the values to be determined for D_0, V_x, and V_y. When the target parameters are not available in the next observation, the solution algorithm will provide the motion parameters based on the motion parameters of the subsurface platform and the previously calculated target parameters. If the target's course and velocity change, the observed parameters will be updated and incorporated into the observation equation, generating new motion parameters for the target, and the problem will be solved based on the updated motion parameters.

To solve the problem, an algorithm with a flowchart as shown in figure 1 is proposed. With the proposed algorithm, it is possible to program and develop software to run on a computer. In the case where the target and the subsurface platform are not in the same horizontal plane, and given the operational characteristics in a water environment, sound waves do not propagate directly along the vertical plane. Therefore, determining the depth using sonar at a long range will not be accurate. The method to solve the interception problem in the vertical plane is to use a formula to determine the assumed depth of the target. The autonomous weapon will set its trajectory at a depth equal to 0.5 times the depth of the ocean region where the subsurface platform is operating. Along with the target interception process, the subsurface platform will use a short-range sonar to detect the target along the vertical plane, thereby adjusting the depth to aim at the target.

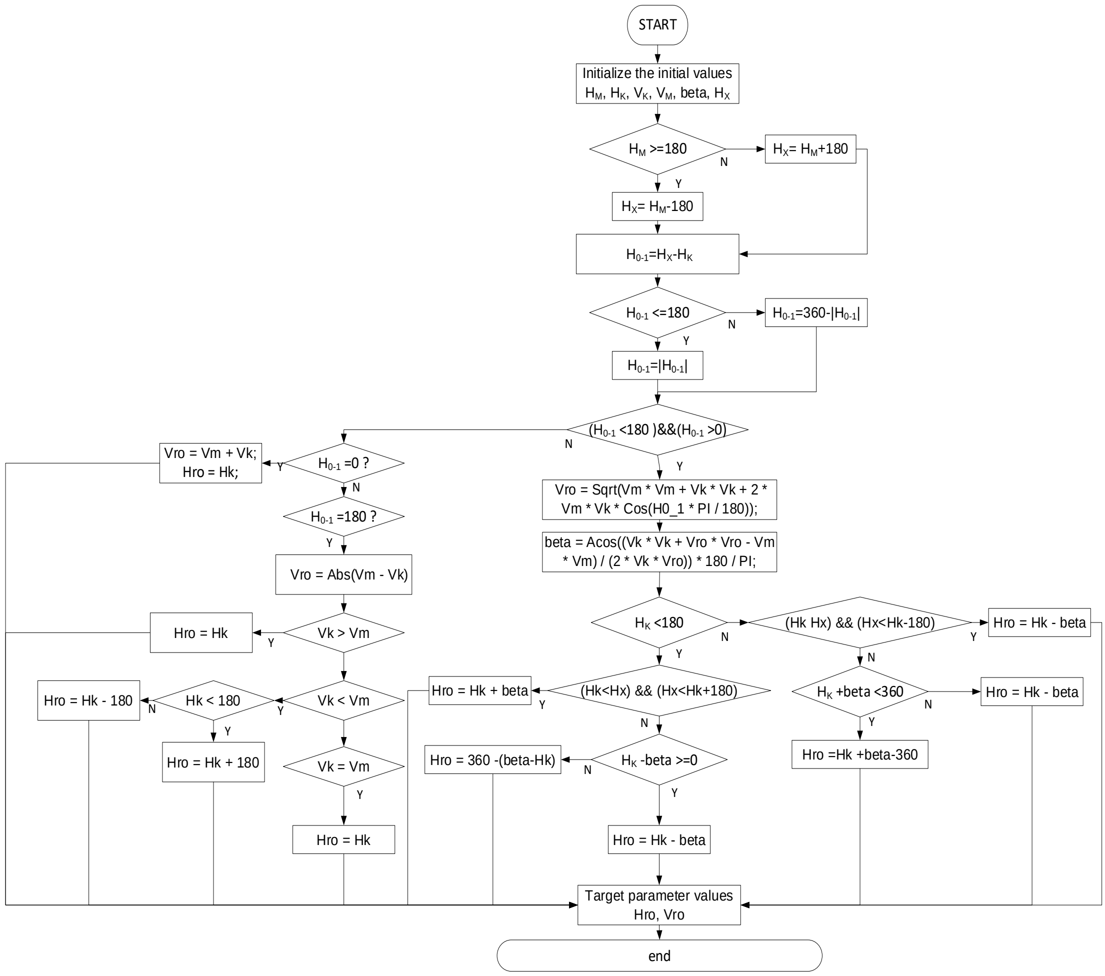

Figure 2. *Flowchart of the algorithm for calculating the target motion parameters.*

2.2. Algorithm for determining the parameters of the firing problem

Based on the target's course and velocity parameters calculated in section 2.1, the next step is to determine the parameters of the firing problem - that is, to determine the lead angle and the conditions required to hit the target. The target is considered as a point mass, located at the center of the target and referred to as the aiming point, denoted by point "K_p" (figure 2). It is assumed that at the moment of launching the autonomous weapon, the underwater vehicle is at point "M_p" and is moving along the course direction (launch direction of the autonomous weapon). After launch, the autonomous weapon travels at a velocity of V_{NL}.

Given the azimuth P_p and distance D_p, the position of the target (point "K_p") is determined. The target moves along the course H_{CK} with a velocity of V_K, and thus, after a time t, the autonomous weapon will intercept the target at point C. The problem requires determining the launch direction of the autonomous weapon and the position of point M_p relative to point K_p so that, after time t, both the autonomous weapon and the aiming point K_p arrive at point C - thereby ensuring the weapon hits the target. Where, φ is considered as the lead angle; G_K is the angle between the target's motion direction and the direction from the target to the underwater platform, while θ is the angle between the target's motion direction and the launch direction of the weapon, $H_{CĐ}$.

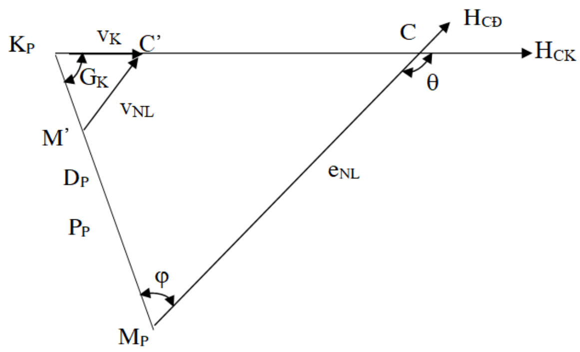

Figure 3. *Determining the launch direction of the autonomous weapon.*

From figure 2, the following conclusions can be drawn: for the autonomous weapon to travel in a straight line and intercept the aiming point, the following three conditions must be simultaneously satisfied:

- Condition 1: The launch direction of the autonomous weapon must intersect the target's direction of motion;

- Condition 2: The ratio between the distances traveled by the target and the autonomous weapon must be directly proportional to the ratio of their velocities, i.e. $\frac{S_K}{V_K} = \frac{e_{NL}}{V_{NL}}$;

- Condition 3: The actual distance traveled by the autonomous weapon from the launch moment (e_{NL}) to the point where it intersects the target's path must not exceed its maximum operational range (E_{NL}), that is: $e_{NL} \le E_{NL}$.

That is, solving the problem of the autonomous weapon traveling in a straight line to intercept the target's aiming point is equivalent to solving the problem that satisfies the above conditions.

To solve conditions 1 and 2, a graphical vector method is used. Take the target's velocity vector as the center (point C'), and draw a circle with a radius equal to the velocity of the autonomous weapon (V_{NL}). This circle intersects the azimuth line at M'. Thus, the launch direction of the autonomous weapon must be parallel to the line M'C'. To determine the launch direction of the autonomous weapon, finding the angle between M'C and M'KP is needed (the lead angle).

Application of the sine rule for M'K_pC' triangles:

$$\frac{V_K}{\sin\varphi} = \frac{V_{NL}}{\sin G_K} \tag{17}$$

Then:

$$\sin\varphi = \frac{V_K}{V_{NL}}\sin G_K \tag{18}$$

Assumed that $m = \frac{V_K}{V_{NL}}$, then:

$$\varphi = \arcsin(m.\sin G_K) \tag{19}$$

Next, calculate the azimuth of the target intercept point:

$$\theta = \varphi + P_p \quad (20)$$

To solve condition 3, use the actual distance calculation method and compare it with the maximum range based on the capabilities of the autonomous weapon. From figure 2, applying the sine rule to triangle M_pK_pC, it leads to:

$$\frac{D_p}{\sin(180^0 - \theta)} = \frac{e_{NL}}{\sin G_K} \quad (21)$$

Or:

$$e_{NL} = \frac{D_P \sin G_K}{\sin(180^0 - \theta)} = \frac{D_P \sin G_K}{\sin\theta} = \frac{D_P \sin G_K}{\sin(GK + \varphi)} = \frac{D_P \sin G_K}{\sin G_K \cos\varphi + \cos G_K \sin\varphi} \quad (22)$$

Thus, at each moment, the problem is solved by calculating e_{NL}, and then comparing it with E_{NL}. If $e_{NL} \le E_{NL}$, then the launch of the autonomous weapon is allowed. The flowchart for solving the lead firing problem is shown in figure 3.

3. SOFTWARE TESTING RESULTS AND DISCUSSION

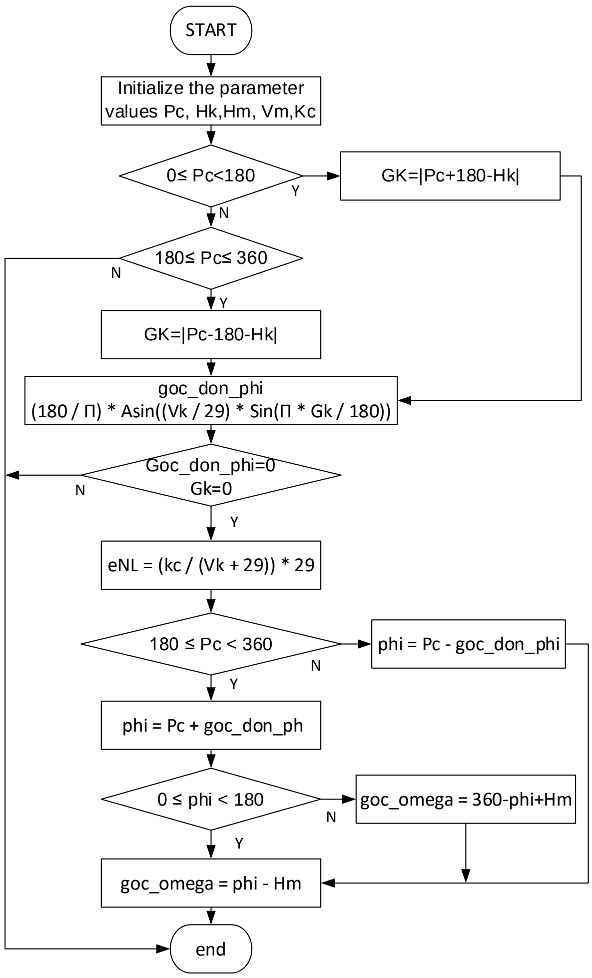

Figure 4. *Flowchart of the algorithm for solving the interception firing problem.*

To verify the correctness of the proposed algorithm, calculating the firing parameters based on the derived algorithm was implemented. Subsequently, tests were conducted on various datasets to assess the applicability and reliability of the algorithms. To ensure that the obtained results are accurate and align with reality, comparing the experimental results with the reference results provided by the AIUS computer system onboard was carrying out. Through this comparison process, specific and important results were obtained, allowing for a comprehensive evaluation of the accuracy of the developed algorithms.

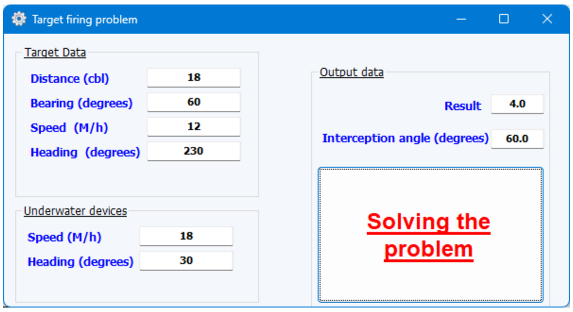

Figure 5. *Software interface of solving problem.*

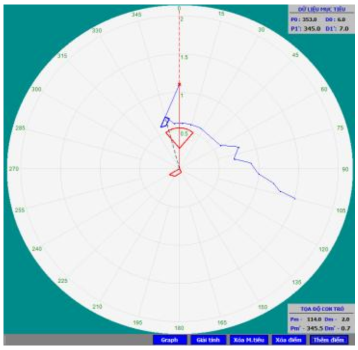

Figure 6. *Check the solution of the problem when the subsurface platform is in motion.*

Figures 4 and 5 illustrate the software interface for solving the firing problem, where users input parameters and compare the calculation results produced by the algorithm with the results table provided by the AIUS system [2]. The programming and display in the form of a moving grid for the submerged vehicle facilitate synchronized observation with other systems on the vehicle [1]. This allows for the automatic acquisition of additional target parameters and the automated processing of those parameters, accelerating the processing speed and enhancing the integration efficiency of the system. The results in table 1 show that the data generated by the software and the calibration table are equivalent. Tables 2 and 3 present the results obtained from the algorithm in the case of the submerged vehicle moving, as well as in the case of the submerged vehicle moving with varying velocity. In scenarios where the direction and target change, the software consistently generates firing parameters regardless of how the target changes, while also storing the trajectory to evaluate the target's movement, thus predicting the next point of aim.

Table 1. *Software's results and standard table.*

No.	Subsuface platform xxx		Target			Standard table			Note	Software's results
	Hm (degree)	Vm (knot)	T (s)	P (degree)	D (cable)	Hk (degree)	Vk (knot)	ω (cable)		ω (cable)
1	40.0	5.0	60	5.0	22.0	254.5	6.3	-51.1		-51.1
				1.0	21.0					
2	255.0	2.0	60	275.0	22.0	163.5	12.6	-9.5		-9.5
				270.0	21.0					

Thus, the proposed algorithm and the developed software have effectively solved the interception problem when compared to the standard method. In the test cases, the algorithm was able to compute the motion parameters of the target through values of range and azimuth. The target interception problem is executed as soon as the target's motion parameters are calculated. This is a key advantage of the proposed method compared to the old system, where the data had to be fully inputted before the interception problem could be executed. Comparison results with several existing algorithms, such as the extended Kalman filter (EKF)-based algorithm, Bayesian inference method, and nonlinear dynamics models, show that the proposed algorithm has comparable or even higher accuracy in most test scenarios. Specifically, in cases where the target moves nonlinearly and observation data is sparse, the proposed algorithm maintains an error margin below 5%, while other algorithms fluctuate between 7–15%.

Table 2. *Input/output data for solving in case of unmovement subsurface platform.*

Input	H_k	283.4	267.3	294.9	277	254.3	274.9
	Vk	17.1	29	15.9	22	24.3	19.3
Output	ω	30.3	12.7	12.7	-5.5	-9.2	-22.3
	e_{NL}	2.8	2.4	2.3	2.1	1.8	1.7
Input	H_k	265.0	273.5	292.9	220.1	288.0	217.6
	V_k	19.9	11.7	13.5	19.2	19.2	15.1
Output	ω	-35.2	-23.8	-30.8	-49.4	x	-33.0
	e_{NL}	1.6	1.6	1.7	1.5	x	1.6

Table 3. *Input/output data for solving in case of movement subsurface platform.*

Input	H_k	1.5	26.5	26.5	26.5	26.5	300
	Vk	12.3	14.3	13	14.3	14.3	13.6
Output	ω	18.5	11	6.9	6.9	6.9	22.1
	e_{NL}	1.3	1.2	1	1.2	1	1
Input	H_k	300	18.7	18.7	18.7	352.4	352.4
	V_k	13.6	16.3	16.3	16.3	9.9	9.9
Output	ω	9.4	-5.9	-10.1	-10.1	-0.9	-10.4
	e_{NL}	0.9	0.9	0.9	0.7	0.7	0.8

4. CONCLUSIONS

The paper studied the theory, developed an algorithm, and created software for solving the target interception problem on subsurface platform. The results serve as the basis for building a software system that can compute at higher speeds and with greater visual clarity. Compared to solving the problem using electromechanical computers previously, there are differences such as: no need to manufacture complex gear systems, cam shafts, and oscillators; the software is easy to modify to suit specific usage conditions; it has the capability to store data and display results visually; and it offers higher upgrade potential. The results of solving the problem have been tested and yielded results that are equivalent to those of the AIUS system's computer. Future research could focus on developing algorithms that account for the effects of nonlinear disturbances when processing targets in motion with constraints on the final impact angle, and mitigating the undesirable deviation caused by nonlinear disturbances affecting the target [4].

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TÓM TẮT

Xây dựng và phát triển thuật toán cho bài toán bắn mục tiêu trên thiết bị ngầm

Các hệ thống bắn mục tiêu trên phương tiện ngầm trước đây là các hệ máy tính điện cơ có kết cấu cơ khí vô cùng phức tạp, các bài toán được lý tưởng hóa với các thông số được thiết lập trước. Hiện nay, với xu hướng số hóa, các loại máy tính số với khả năng xử lý tính toán cao đã thay thế các máy tính điện cơ trước đây và đã được lắp đặt, sử dụng trên các phương tiện ngầm. Trên cơ sở nghiên cứu lý thuyết từ hệ thống thông tin - điều khiển tự động hóa AIUS trên tàu của lực lượng Hải quân, bài báo sẽ trình bày nghiên cứu về xây dựng thuật toán và phát triển phần mềm bắn mục tiêu trên cơ sở lý thuyết đã có. Sau đó, tiến hành cài đặt và thử nghiệm trên máy tính số để kiểm tra. Kết quả nghiên cứu cho thấy thuật toán thử nghiệm trên máy tính số có kết quả tương đương máy tính điện cơ, tốc độ xử lý nhanh và đáp ứng được các thay đổi liên tục của mục tiêu.

Từ khoá: Thuật toán bắn; Giải bài toán bắn; Phương tiện ngầm; Vũ khí tự hành.