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Research on Deep Bomb Delivery Strategy Based on Monte Carlo Simulation and Adaptive Optimization Algorithm

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Abstract. Aiming at the problem of insufficient precision of deep bomb delivery in traditional anti-submarine warfare, this paper proposes a novel algorithm combining Monte Carlo simulation and adaptive optimization [1]. The algorithm optimises the deep bomb delivery strategy by defining the probability distribution of the submarine position. Specifically, Monte Carlo simulation is used to generate samples of possible submarine positions, analyse the effect of the submarine's three-dimensional positional error underwater on the probability of hitting a single depth charge, and explore the role of the dual-fuse detonation mechanism [2]. On this basis, the submarine's orientation error in 3D space is further considered, and an optimisation model is used to determine the optimal fixed-depth fuse detonation depth to maximise the hit probability of a single deep bomb [3]. In addition, this paper extends to the case of multiple depth charges, and optimises the overall hit probability by designing the array of charges and plane spacing to ensure that at least one depth charge can hit the submarine [4]. The experimental results show that the algorithm significantly improves the hit probability of the deep bomb, effectively reduces the impact of positioning error on the combat effect and demonstrates its potential application in practical anti-submarine warfare.

Keywords: Monte Carlo; Optimization Models; normal distribution.

1. Introduction

Anti-submarine warfare is an important part of naval operations, and its success or failure directly affects the security of the sea area. The traditional deep bomb delivery method has a large positioning error in the face of complex sea area and submarine position uncertainty, resulting in a low hit rate. For this reason, this paper proposes a new algorithm combining Monte Carlo simulation and adaptive optimisation to improve the accuracy of deep bomb delivery. By modelling the probability distribution of the submarine position, we explore the application of random sampling and optimisation techniques in improving the hit probability. Meanwhile, the impact of the dual-fuse detonation mechanism is analysed and extended to the coordinated delivery strategy of multiple depth charges, aiming to provide more reliable technical support for anti-submarine warfare [5,6].

2. Probability of Hitting A Single Deep Bomb

In order to maximise the probability of hitting a depth charge, the precise delivery of a depth charge also takes into account the size of the submarine, the horizontal error, and the radius of the depth charge, and we can find the optimal solution through a mathematical expression.

Assuming that the horizontal coordinates (X, Y) of the submarine all obey a normal distribution $N(0, \sigma)$, and that the detonation depth $Z_{explode}$ is the key variable, the depth bomb explosion is divided into three cases:

Scenario 1: Trigger Fuse Detonation

At this point the depth charge falls within the plane of the submarine and the depth of detonation is below the upper surface of the submarine, the hit probability formula is:

$$P_{\text{hits1}} = P(X \in [-L/2, L/2], Y \in [-W/2, W/2]) \times P\left(Z \le D_{\text{top}}\right) \tag{1}$$

where the depth of the upper surface of the submarine is:

$$D_{\text{top}} = \text{depth} - \frac{H}{2} \tag{2}$$

Scenario 2: Fixed-depth fuse detonation (deep bomb on submarine protected from explosion but within kill range)

At this point the depth charge falls within the plane of the submarine and the depth of detonation is located above the upper surface of the submarine, but still within the killing range of the probability of hitting the formula is:

$$P_{\text{hits2}} = P(X \in [-L/2, L/2], Y \in [-W/2, W/2]) \times P\left(D_{\text{top}} < Z \le D_{\text{top}} + R\right) \tag{3}$$

Scenario 3: Fixed depth fuse detonation (depth charge falls outside the range of the submarine but within the kill radius).

At this point the depth charge falls outside the plane of the submarine and the depth of detonation is such that the submarine is within the kill radius:

$$P_{\text{hits 3}} = P(X \notin [-L/2, L/2] \cup Y \notin [-W/2, W/2]) \times P\left(Z \le D_{\text{top}} + R\right) \tag{4}$$

At this point we can derive the total hit probability as:

$$P_{\text{hits}} = P_{\text{hits 1}} + P_{\text{hits 2}} + P_{\text{hits 3}} \tag{5}$$

(X, Y) in the horizontal error obeys a normal distribution, i.e. the closer the drop point is to the centre of the submarine, the greater the hit probability of the depth bomb, so we have to adjust the fixed depth detonation depth $Z_{explode}$ according to the parameters of the submarine's upper surface and the kill radius, so that we can find the maximum hit probability.

The optimal optimisation objective is formulated as:

$$z_{\text{optimal}} = \text{argmax}_{z_{\text{cxplode}}} P_{\text{hits}}\left(z_{\text{explode}}\right) \tag{6}$$

Assuming that the submarine L = 100m, W = 20m, the drop point of the depth bomb if located in the submarine's planar projection range, for (X, Y) on the normal distribution mean 0, standard deviation of σ two-dimensional normal distribution. The density function of its joint probability is:

$$f_{X,Y}(x,y)=\frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \tag{7}$$

The probability of a hit within the plane is:

$$P(X\in[-L/2,L/2])=\Phi\left(\frac{L/2}{\sigma}\right)-\Phi\left(\frac{-L/2}{\sigma}\right) \tag{8}$$

$$P(Y\in[-W/2,W/2])=\Phi\left(\frac{W/2}{\sigma}\right)-\Phi\left(\frac{-W/2}{\sigma}\right) \tag{9}$$

The final total hit probability is:

$$P_{\text{hits}}=\left[\Phi\left(\frac{L/2}{\sigma}\right)-\Phi\left(\frac{-L/2}{\sigma}\right)\right]\times\left[\Phi\left(\frac{W/2}{\sigma}\right)-\Phi\left(\frac{-W/2}{\sigma}\right)\right]\times P(Z) \tag{10}$$

The hit distribution of the projectile drop for the same depth provision is shown in Fig. 1:

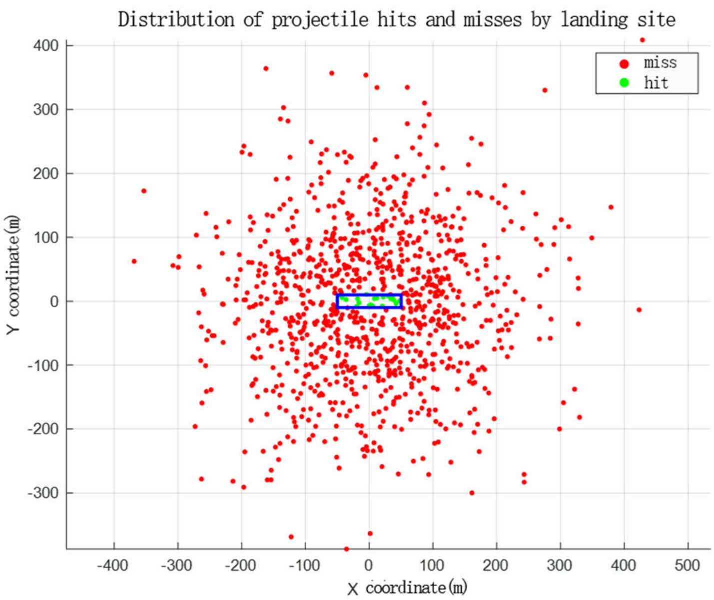

Figure 1. Distribution of hit projectile drop points

Probability of Hit with Detonation Depth Curve: shows the relationship between detonation depth and probability of hit, illustrating the trend of probability of hit with detonation depth and peaking at a certain depth, as shown in Fig. 2:

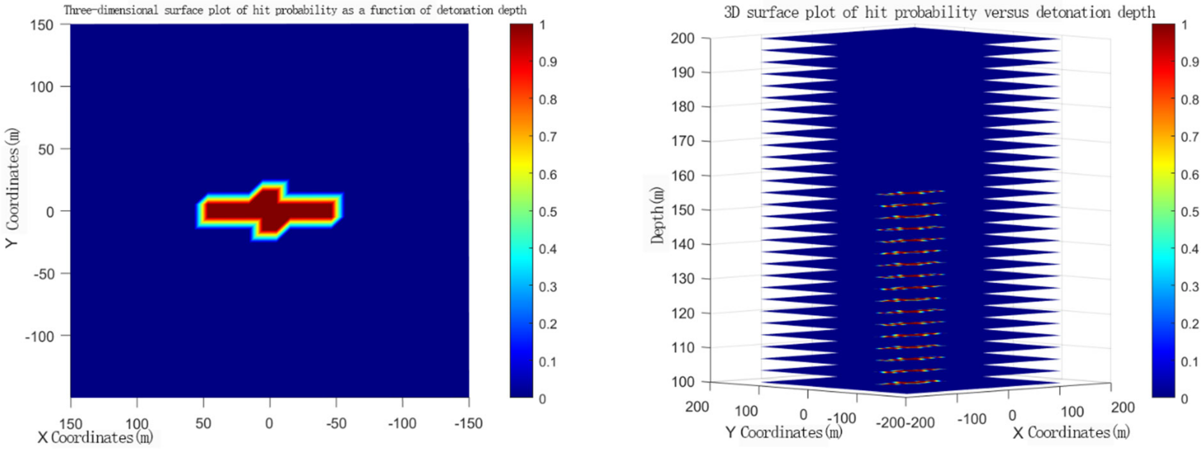

Figure 2. Three-dimensional plot of hit probability versus detonation depth (top top view, bottom front view)

Horizontal Hit Probability Contour Plot: Shows the contour plot of the hit probability on the horizontal plane at different coordinates, as shown in Fig. 3

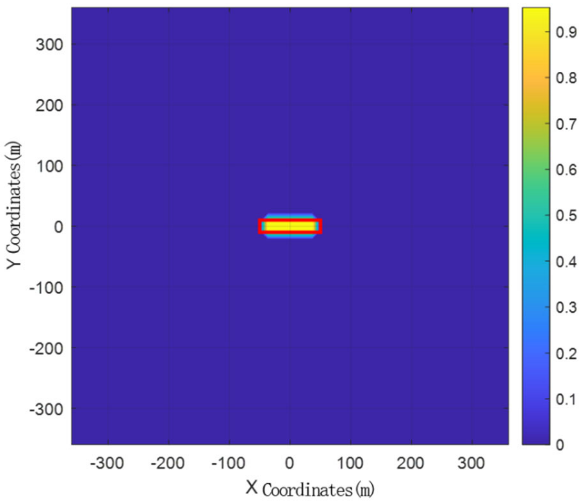

Figure 3. Horizontal hit probability contour plot

The three-dimensional view allows for a more intuitive demonstration of the combined effect of horizontal coordinates (X, Y) and z on the probability of hitting during the drop. The three-dimensional view shows how the probability of hit varies with depth and horizontal coordinates. The 3D image shows a complete probability distribution, highlighting the area where the maximum hit probability is located.

3. Optimal Fixed-depth Fuzing for Depth Coordinates to Trigger Depth

The submarine's position underwater is often uncertain, and this uncertainty is not only reflected in the horizontal coordinates, but may also include the depth direction. The introduction of depth error adds more uncertainties, such as the positioning error in horizontal position and the observation error in depth, so the joint density of horizontal and depth positions needs to be analysed in conjunction with the hit probability calculation. We need to find the optimal detonation depth $Z_{explode}$ in the

The detonation depth $Z_{explode}$ is needed to maximise the hit probability. The hit probability is the probability that a depth bomb will successfully kill a submarine at a certain detonation depth. Assuming that the error in the submarine depth Z_{sub} follows a normal distribution and is truncated at the minimum depth Z_{sub}, we need to calculate the probability of hit based on the drop point of the projectile and the detonation depth.

Setting submarine parameters: length L=100m, width W=20m, height H=25m

Error parameters: horizontal positioning error: standard deviation σ = 120m, submarine depth positioning error: standard deviation σ_z = 40m, expected value of submarine's centre depth μ_{depth} = 150m, actual minimum value of submarine's centre depth $z_{\min}$ = 120m, submarine's actual depth Z_{sub} obeys the truncated normal distribution:

$$z_{\text{sub}} \sim \text{TruncatedNormal}\left(\mu_{\text{depth}}, \sigma_z, z_{\min}\right) \tag{11}$$

where Z_{sub} as a random variable is in the range $[z_{\min}, \infty)$ and conforms to a normal distribution.

The horizontal drop point (x_{drop}, y_{drop}) of the projectile conforms to a normal distribution:

$$\left(x_{\text{drop}}, y_{\text{drop}}\right) \sim N\left(0, \sigma^2 \cdot I\right) \tag{12}$$

Considering the reasons for adding depth effects to the previous section in this section, there are three scenarios for determining whether a hit exists: (i.e., $|x_{drop}| \le L/2$ and $|y_{drop}| \le W/2$)

Scenario 1: The point of impact is within the horizontal range of the submarine and the depth of detonation is below the upper surface of the submarine.

A depth charge is considered to have hit the submarine if it falls within the horizontal projection of the submarine (i.e. $|x_{drop}| \le L/2$ and $|y_{drop}| \le W/2$) at a depth of detonation $Z_{explode}$ below the upper surface of the submarine ($z_{explode} \le z_{sub} - H/2$).

Scenario 2: The point of impact is within the horizontal range of the submarine and the depth of detonation is above the upper surface of the submarine but within the killing range.

A depth charge is considered to have hit a submarine if its point of impact is within the horizontal range of the submarine and the depth of detonation $Z_{explode}$ is higher than the submarine's upper surface plus the kill radius $z_{sub} + R$.

Scenario 3: Landing point outside the horizontal range of the submarine, but within the kill radius

A depth charge is a miss if it falls outside the horizontal projection of the submarine, but at a horizontal proximity to the submarine of less than R, and the depth of detonation, $Z_{explode}$, is within $z_{sub} + R$ of the top of the submarine.

We define the exponential function $I(x_{drop}, y_{drop}, z_{sub}, z_{explode})$, which indicates a hit when it returns 1, and 0 for a miss. The probability of a hit can be defined by the following equation:

$$P\left(z_{\text{explode}}\right) = \mathbb{E}\left[I\left(x_{\text{drop}}, y_{\text{drop}}, z_{\text{sub}}, z_{\text{explode}}\right)\right] \tag{13}$$

Expressed through the integral:

$$P\left(z_{\text{explode}}\right)=\int_x \int_y \int_{z_{\text{sin}}}^{\infty} I\left(x, y, z_{\text{sub}}, z_{\text{explode}}\right) p\left(x, y, z_{\text{sub}}\right) dz_{\text{sub}}\, dydx \tag{14}$$

Construct an expression for the maximised hit probability $P_{(z_{explode})}$ as:

$$\max_{z_{\text{explode}}} P\left(z_{\text{explode}}\right) \tag{15}$$

Characteristics of drop point distribution: Due to positioning errors, the drop points are distributed near the centre of the submarine. Drop points near the centre of the submarine are more likely to hit, while drop points far from the centre of the submarine have a lower probability of hitting, as shown in Fig. 4.

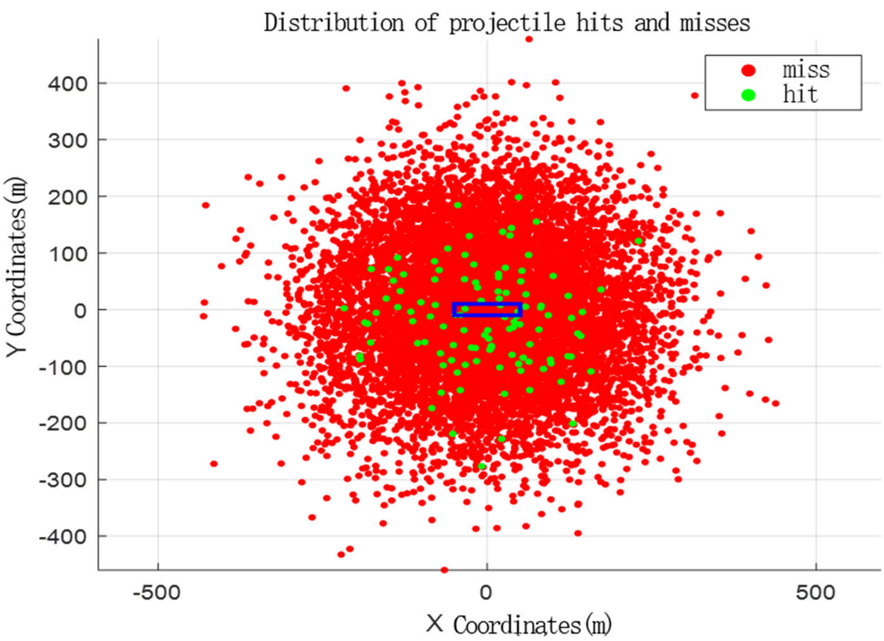

Figure 4. Distribution of hit projectile drop points

Through Monte Carlo simulation, the change curve of hit probability at different detonation depths was generated. The graphs clearly show that as the detonation depth changes, the hit probability first rises, reaches a peak and then falls.

Optimal Detonation Depth: The hit probability reaches a maximum value near a certain depth, indicating that this is the optimal detonation depth. The curve shows that the depth of detonation is very important to the probability of hit, and finding the optimal depth of detonation can significantly increase the probability of hit, as shown in Fig. 5:

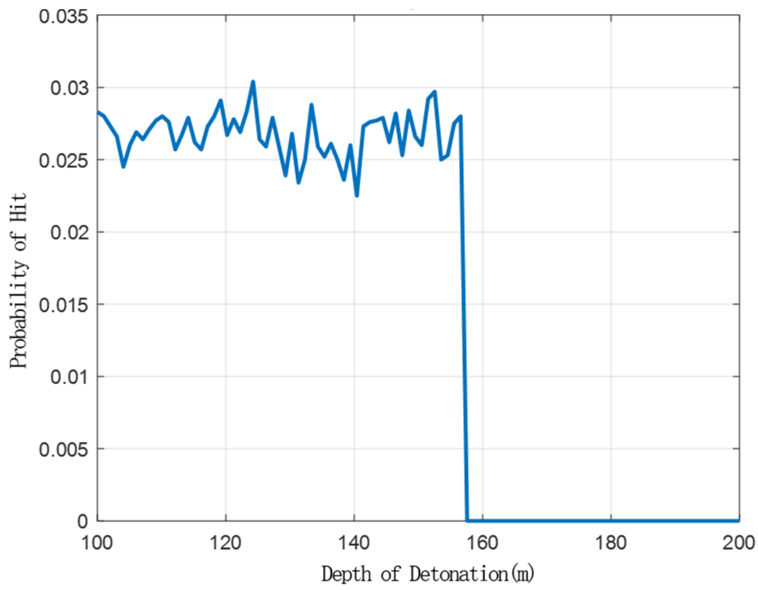

Figure 5. Variation curve of hit probability with detonation depth

Optimal fixed-depth detonation depth: Through simulation and calculation, the optimal fixed-depth detonation depth $Z_{explode}$ is about 150 metres.

4. Monte Carlo Model-based Simulation of Multiple Deep Bomb Drops

Using the Monte Carlo simulation method to address the hit probability of multiple depth charges, the objective is to calculate the probability of at least one depth charge hitting the target. Each depth charge has its unique hit probability. During the launch, it is necessary to consider both depth and horizontal errors, which means the probability of hitting the submarine depends on factors such as the launch point and submarine position. We define three conditions for a hit and denote $P_{hit}(x_{drop}, y_{drop}, z_{explode})$ as the probability of a depth charge hitting the submarine given a specific launch point and detonation depth. Its expression can be defined using a piecewise function as follows:

$$P_{\text{hit}}\left(x_{\text{drop}}, y_{\text{drop}}, z_{\text{explode}}\right)=\begin{cases}1, & \text{If case 1 or case 2 is satisfied} \\ 1, & \text{If case 3 is met} \\ 0, & \text{Otherwise}\end{cases} \tag{16}$$

The probability that at least one of the nine depth charges dropped will hit the submarine can be calculated by the complementary set method, i.e., the probability that all the depth charges will miss is:

$$P_{\text{all miss}}=\prod_{i=1}^{9}\left(1-P_{\text{hit}}^{(i)}\right) \tag{17}$$

Therefore, the probability that at least one hits the submarine is:

$$P_{\text{at least one hit}}=1-P_{\text{all miss}}=1-\prod_{i=1}^{9}\left(1-P_{\text{hit}}^{(i)}\right) \tag{18}$$

The curve of hit probability versus detonation depth is shown in Fig. 6:

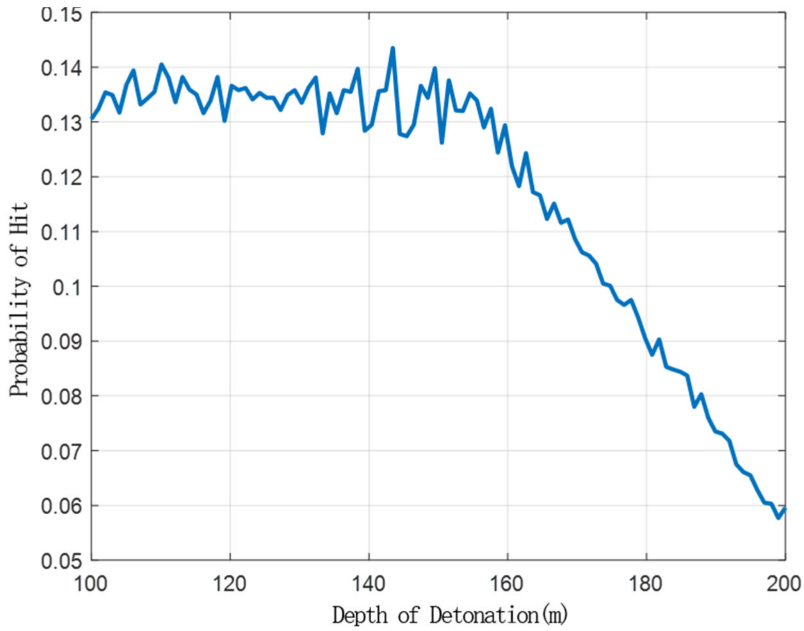

Figure 6. Variation curve of hit probability with detonation depth

As shown in Fig. 7 the curve shows the change of hit probability under different detonation depth. Through simulation analysis, with the increasing detonation depth, the hit probability shows a trend of increasing and then decreasing. The figure shows that the hit probability reaches the maximum value near the optimal detonation depth, which indicates that the optimization of the detonation depth is crucial for improving the hit rate.

Horizontal coordinates (X,Y): represent the error of the drop point. Since the depth charge array is dropped in the horizontal plane, the coordinates in the X and Y directions represent the horizontal offset from the center of the submarine for different drop points, respectively.

Vertical axis: indicates the probability of hit. The vertical axis shows the probability of hit for different drop positions and detonation depths.

In this 3-D plot, we can see that:

(1) The hit probability is highest near the center of the submarine (i.e., the area with smaller horizontal error).

(2) The hit probability decreases as the drop position is shifted. When the horizontal error is large, the hit probability decreases significantly when the drop position is far away from the submarine.

(3) Changes in the depth of detonation also affect the hit probability. The optimal detonation depth can maximize the hit probability at the drop point. As shown in Fig.7:

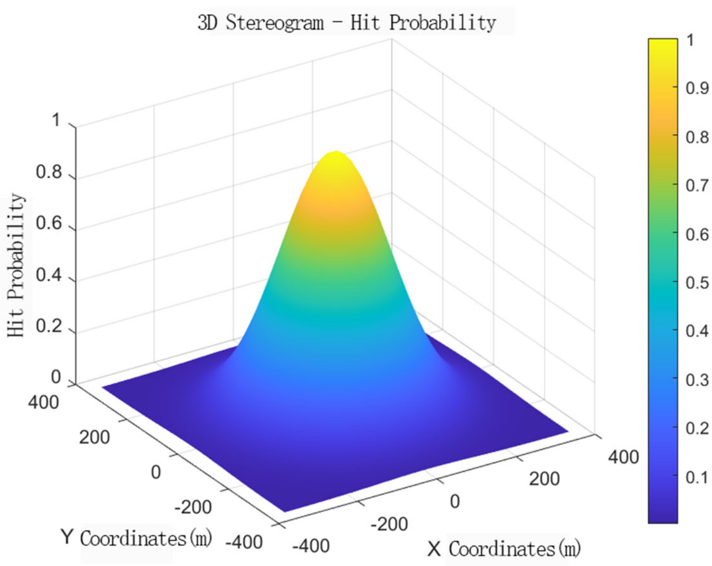

Figure 7. Three-dimensional hit probability distribution

5. Summary

The novel algorithm combining Monte Carlo simulation and adaptive optimization proposed in this paper significantly improves the hit probability of deep bombs in anti-submarine warfare. By modeling the probability distribution of the submarine's position, as well as optimizing the detonation depth and throwing strategy, the experimental results show that the method effectively reduces the impact of the positioning error on the combat effect. In addition, the comprehensive consideration of the dual-fuse detonation mechanism further enhances the practicality of the algorithm. Future research can further explore the adaptability and application potential of the algorithm under different sea conditions to provide a more solid theoretical foundation and practical support for enhancing the overall effectiveness of anti-submarine warfare.

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