Research on Penetration Path Planning Method on Near Sea Bottom Based on the Sonar Detection Blind Zone

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Abstract. To improve the survivability and penetration probability of unmanned undersea vehicle (UUV) on near sea bottom combat missions, the factors leading to sonar detection blind zone are analyzed, and the detection blind zone produced by underwater terrain obscuration is mainly studied. A detection range calculation method based on DEM and acoustic ray is proposed, and the simulation study of the near sea bottom penetration path planning is carried out by using terrain blind zone and invasive weed optimization algorithm. Simulation results show the effectiveness of the proposed algorithm. This method can be applied to path planning of the UUV on near sea bottom penetration, which helps to improve Combat effectiveness and Operational effectiveness of UUV.

1. Introduction

In recent years, with the pursuit of low casualties on the battlefield by various countries, Unmanned Undersea Vehicle (UUV) played more and more significant role in maritime warfare, and it can perform intelligence / surveillance / reconnaissance, anti-mine warfare, anti-submarine warfare, inspection and identification, marine survey, communication / navigation network nodes, load delivery, information warfare, time-sensitive strikes and other combat tasks. It is used as a “Power multiplier” has attracted more and more attention [1][2]. However, due to UUV, most aviation slow travel speed, poor maneuverability, weak self-protection ability, once discovered in the process, it is extremely easy to be hit by fire and lead to penetration failure. In order to improve the survivability of UUV and the probability of penetration success, the enemy sonar detection range and the firepower system, threats to UUV, should be fully considered during path planning, so it is necessary to make full use of sonar detection blind zone. Near seabed penetration path planning is key technology to ensure UUV underwater safe and concealed navigation and reliable and efficient completion of combat missions. At present, there are many documents studying the detection range of underwater sonar systems [3][4][5], and some scholars have also conducted certain research on the near seabed penetration path planning, and put forward some effective planning methods [7][8], but there are relatively few studies combining the actual underwater combat environment. For this reason, based on the analysis and study of the factors of the sonar system detection blind zone, a calculation method for the detection range of the sonar system is proposed, and then based on the sonar detection blind zone, the invasive weed optimization (IWO) algorithm is simple and easy to implement, and the global optimization capability is used. The characteristics of strong and fast convergence speed [9] plan a reasonable path for UUV penetration near the seabed, which helps to improve the combat effectiveness of UUV.
2. Factor analysis of sonar detection blind zone

When UUV is in use, the main threat is that the enemy detects, recognizes, locates, tracks and strikes it through the sonar system. The detection blind zone of the sonar system refers to the detection blind zone within the range of the sonar, due to the limitations of the sonar equipment performance, combat platform noise, reverberation, sound ray bending effect, and underwater terrain shielding. Reference to the low altitude of the drone Penetration [10]-[11], the unmanned submarine can use the enemy's sonar to detect blind spots to avoid detection during the near seabed penetration.

2.1. Blind zone of equipment performance limitation

The inclination angle of the transducer in the sonar system, the width of the pulse, and the propeller noise of the installation platform will all produce the sonar detection blind zone. For example, the limitation of the inclination angle of the transducer or the beam opening angle will cause the sonar system to detect the blind zone; because the ship's tail propeller noise is strong, the wake bubble is formed, forming a strong scattering zone in the ship's wake, which will also make the sonar difficult to receive the signal from this direction [12]; When the sonar system transmits a pulse signal, the receiver is often turned off due to the extremely strong signal, and for technical considerations, the off time is longer than the pulse duration. The target must be lost during this time.

2.2. Blind zones of marine environmental restrictions

Blind zones of marine environmental restrictions mainly include blind zones due to ocean reverberation and sound ray bending. Ocean reverberation mainly refers to volume reverberation, sea surface and submarine reverberation. When the active sonar system is working, volume reverberation, sea surface and seabed reverberation appear immediately after the pulse signal is transmitted, and the echo information appears at the input of the receiver after a delay. The reverberation is very strong at close range, and the receiver cannot receive it. Time gain or reverberation automatic gain control circuit is often used to normalize it, which at the same time suppresses the reception at close range, thus causing the detection blind zone of the sonar system [12]. In addition, since the sound velocity gradient will bend the sound ray in the vertical direction, some sound shadow zones will be generated, and detection blind zones will also be formed.

2.3. Blind zone of underwater terrain shelters

When the sound wave propagates in the water, it is blocked by the undulating terrain surface and obstacles, which will form a blind zone of underwater terrain shielding (as shown in Figure 1), causing the sonar system to be unable to detect the UUV navigating to its detection range. Under the undulating environment of troughs, islands and reefs in the ocean, there will inevitably be blind zones for underwater terrain shelter. The unmanned submarine path planning system can use this favorable condition to plan penetration path. The blind zone of underwater terrain shielding by sonar is mainly related to three factors: one is the operating distance and detection angle range of the sonar system; the second is the deployment position of the sonar system; the third is the terrain fluctuations within the sonar detection range. Since the detection distance of sonar is much shorter than that of radar, the influence of the curvature of the earth on the detection range of the sonar system is negligible.
3. Path planning method based on sonar detection blind zone

3.1. Calculation of sonar detection range under the cover of underwater terrain

Underwater Digital Elevation Model (DEM) is a discrete mathematical description of underwater topography. The DEM data of the actual underwater terrain can provide a reliable data basis for the calculation of the sonar detection range. Under the conditions of a given sonar deployment position, working distance, detected azimuth angle and height angle range, and underwater DEM data within the working distance, by judging the operability of sound wave propagation, the terrain shielding blind zone of the sonar system can be calculated, Complete the threat situation analysis of the path planning system. The method of combining underwater DEM and sonic rays is used to calculate the sonar detection blind zone. The steps can be summarized as follows: Figure 2 Schematic diagram of the sonar polar coordinate sector grid.

Step 1: Establish a polar coordinate fan grid with the sonar placement position O as the center. Figure 2 is a polar coordinate auxiliary network drawn by sonar in the horizontal plane detection azimuth range $\phi$. Firstly, take the sonar position O as the center, and draw an arc with the horizontal projection length OP of the sonar's maximum operating distance R, and then uniformly radiate out M acoustic rays, the angle between adjacent acoustic rays is $\Delta \phi = \phi / M$, and finally take the acoustic rays as the benchmark. Draw a vertical profile downward to obtain an elevation profile within the range of the detection height angle $\psi$, and subdivide the height angles according to a certain angle to obtain a series of acoustic rays, so that the direction of any acoustic ray can be determined by the current detection azimuth $\phi$ and height angle $\psi$. 

![Figure 1. Schematic diagram of sonar detection blind zone under undersea terrain](image1.png)

![Figure 2. Sonar polar coordinate fan mesh diagram](image2.png)
Step 2: Calculate the topographic shadowing point of each acoustic ray. Take the coordinates of point \(O(x_0, y_0, z_0)\) as the starting point for the search for the terrain sheltering point, and the end point of the acoustic ray as \((x_{\text{end}}, y_{\text{end}}, z_{\text{end}})\), which is specifically determined by the following formula:

\[
\begin{align*}
    x_{\text{end}} &= R \sin(\psi_0) \cos(\phi) + x_0 \\
    y_{\text{end}} &= R \sin(\psi_0) \sin(\phi) + y_0 \\
    z_{\text{end}} &= R \cos(\psi_0) + z_0 
\end{align*}
\]

The direction from the start point to the end point is used as the searched path direction, and the judgment search is sequentially performed according to a certain step length \(S\). The coordinates of the \(k\)-th search point on any acoustic ray can be expressed as:

\[
\begin{align*}
    x_k &= kS \sin(\psi_0) \cos(\phi) + x_0 \\
    y_k &= kS \sin(\psi_0) \sin(\phi) + y_0, \quad kS \leq R \\
    z_k &= kS \cos(\psi_0) + z_0 
\end{align*}
\]

The elevation value \(H_k\) of the current search point can be obtained by interpolation of known DEM data. In order to improve the efficiency of interpolation calculation, cubic spline interpolation calculation is selected. As shown in Figure 1, when the underwater terrain elevation value corresponding to the search point is greater than the \(z\) value of the sound wave ray search point, it can be judged that the sound wave propagation is blocked by the terrain shading, and the current point is the sound wave detection end point and recorded. Otherwise, continue to search and judge until the search point exceeds the maximum detection distance of the sonar system. When the terrain obscuration point cannot be found, the end point of the recording ray \((a_j, b_j, c_j)\) is the end point of sound wave detection, which can be expressed as:

\[
\begin{align*}
    \begin{cases}
        (a_j, b_j, c_j) &= (x_k, y_k, z_k), & kS \leq R \text{ and } H_k \geq z_k \\
        (x_{\text{end}}, y_{\text{end}}, z_{\text{end}}), & \text{else}
    \end{cases}
\end{align*}
\]

Step 3: Draw the sonar detection range under the cover of underwater terrain. Calculate the detection end point of each sonic ray according to step 2, and then increase the height angles and the azimuth in turn, and calculate the detection end points of all the sonic rays \((a_j, b_j, c_j)\) within the detection azimuth \(\phi\) and height angle \(\psi\) range. Finally, all the calculated sound wave detection endpoints are fitted to the space detection zone of the sonar system, and the detection range of the sonar system is obtained. The specific calculation process is shown in Figure 3.
3.2. Near-sea penetration path planning based on IWO algorithm

The definition of underwater path planning is: given the current position of the UUV and the marine environment information conditions, by optimizing an objective function related to the performance and obstacle avoidance of the underwater submarine, a path to the target position is calculated for the UUV [13]. When the IWO algorithm is used for the near seabed penetration mission of the UUV, the shortest path $Path^*$ is selected to guide the UUV from the starting point $p_{start}=\langle x_1, y_1, z_1 \rangle$, avoiding underwater terrain obstacles $O_{obstacle}$ and enemy weapon threats $R_{atk}$, and finally reaching the end $p_{terminal}=\langle x_n, y_n, z_n \rangle$ smoothly, which can be described as:

$$Path^* = \min \sum_{i=1}^{n} L(p_i, p_{start})$$

subject to $p_i = p_{start}, p_n = p_{terminal}$

$$\forall i \in [1, n], p_i \notin O_{obstacle}, p_i \notin R_{atk}$$

Where: $p_i=\langle x_i, y_i, z_i \rangle$ is the path node in $Path = \langle p_1, p_2, \ldots, p_n \rangle$.

In the path planning process, based on the acquisition of real seabed data, the Kriging smooth interpolation fitting method is used to construct the best three-dimensional navigation surface of UUV; then the method of B-spline curve [14] is used to describe the best three-dimensional navigation surface Projection of the planned path in the two-dimensional horizontal plane, which converts the problem of searching paths in three-dimensional space into the problem of finding $N$ finite control points in the horizontal plane. Finally, the shortest UUV navigation distance is used as the objective function, and the IWO algorithm is used in the horizontal plane. Find the optimal $N$ optimal control points within.

3.2.1. Constructing the best three-dimensional navigation surface.

Refer to the concept of minimum threat surface in the process of penetration [15], the minimum threat surface is equivalent to the best navigation surface for UUV near seabed penetration, then the three-dimensional best navigation surface can be expressed as:
\[ F(x,y) = f(x,y) + H_c \] (5)

In the formula: \( f(x,y) \) represents the three-dimensional surface fitted by the Kriging smooth interpolation algorithm using the known DEM data for penetration in the sea zone; \( H_c \) represents the best off-bottom height for UUV to avoid bottoming.

3.2.2. **Description of underwater path curve.** Given the start and end points, any curve on the best sailing surface can be regarded as a planned path. At the same time, the projection of each path in the horizontal plane is also a curve. As long as the path projection curve in the horizontal plane is found, the corresponding best path can be found on the best sailing surface. Therefore, the path projection in the horizontal plane can be defined by a B-spline curve, and the B-spline curve needs to have \( N \) control points, and each point can be represented by polar coordinates:

\[
\begin{align*}
X &= x_{start} + (i-1) \cos(\theta_i), i \in [2, N-1] \\
Y &= y_{start} + (i-1) \sin(\theta_i), i \in [2, N-1] \\
X &= x_{start}, X = x_{final} \\
Y &= y_{start}, Y = y_{final}
\end{align*}
\] (6)

Where: \( L_s \) represents the projection distance of the starting point and the end point in the horizontal plane; \( X \) and \( Y \) represents the horizontal and vertical coordinates of the i-th control point respectively; \( \theta \) represents the angle between the line from the control point to the start point and the line from the start point to the end point in the water surface, \( \theta \in [0, 2\pi) \). In this way, by searching for \( N-2 \) values \( \theta \), \( \theta \in [0, 2\pi) \), \( N \) path control points can all be obtained, and finally a series of path navigation point sequences \( Path = \{p_1', \cdots, p_l', \cdots, p_{N'} \} \) are obtained by uniformly dividing the B-spline curve.

3.2.3. **Optimal path planning based on IWO algorithm.** In the IWO algorithm, each weed is a solution to the problem. In the near seabed penetration path planning based on the IWO algorithm, the information \( a_i = (\theta_1, \theta_2, \cdots, \theta_n) \) carried by a weed can be calculated through the B-spline curve equalization and curved surface projection to obtain the penetration path node \( Path = \{p_1, p_2, \cdots, p_n \} \). The current fitness of the weed can be expressed as:

\[
Fit(i) = \sum_{i=1}^{n} k_i L_i(p_i, p_{i+1})
\] (7)

Where \( L_i(p_i, p_{i+1}) \) represents the distance from node to in the current path; represents the distance coefficient between nodes \( p_i \) to \( p_{i+1} \). The value \( k_i \) of can be expressed as:

\[
k_i = \begin{cases} 
10000, & \text{if } p_{i+1} \text{ is within the enemy threat range} \\
1, & \text{else}
\end{cases}
\] (8)

Through the reproduction of weeds in the population, spatial diffusion and competitive elimination, iteratively search for seeds with better adaptability, and finally search for the optimal solution to the problem.

4. **Simulation results and analysis**

The simulation software platform is Matlab R2016a. The real sea zone of E116.8°~E117.8°, N18.6°~N19.6° is selected as the mission planning zone. In order to facilitate calculation, the Mercator projection is selected for the sea zone map, and the plane rectangular coordinate transformation is performed with (E116.8°, N18.6°) as the coordinate origin. Assume that the UUV performing a certain combat mission arrives at the end \( p_{final} = [8000, 8000, -3600] \) of the mission from the starting point \( p_{start} = [1000, 3000, -3700] \), and the enemy deploys an upward-detecting reconnaissance sonar system (azimuth angle \( \phi = (0-360°) \), height angle \( \psi = (0°-90°) \)) at \([5500, 5500, -3700]\), with a range of \( R = 3000 \text{m} \). In
order to ensure the concealment of UUV navigation, the shortest total length of the planned path is used as the objective function, and the IWO algorithm is used to plan the near seabed penetration path for UUV. Set the parameters of the IWO algorithm as shown in Table 1, and the simulation results are shown in Figure 4 and Figure 5.

Table 1. IWO algorithm parameter settings

| Variable symbol | Variable meaning            | Value   |
|-----------------|-----------------------------|---------|
| $P_{\text{initial}}$ | Initial population          | 15      |
| $P_{\text{max}}$  | Maximum number of population| 25      |
| $\text{iter}_{\text{max}}$ | The maximum number of iterations | 500 |
| Dim             | Problem dimension           | 10      |
| $S_{\text{max}}$  | Maximum number of seeds     | 5       |
| $S_{\text{min}}$  | Minimum number of seeds     | 2       |
| $n$             | Nonlinear index             | 3       |
| $SD_{\text{initial}}$ | Initial value of standard deviation | 3 |
| $SD_{\text{final}}$ | The final value of the standard deviation | 1.00E-03 |
| X               | Initial search space        | (0, 0.5$\pi$) |

![Stereoscopic view of the penetration path planning results](image1)

![Top view of the penetration path planning results](image2)

Figure 4. Calculation process of sonar detection range under undersea terrain

Adaptive value curve of planned path From the simulation results, the detection range of the sonar system can be calculated by the method based on DEM and sonic rays. From Figure 4(a), it can be seen that due to the occlusion of the underwater terrain, the propagation of the sonic rays is blocked, thereby forming Sonar detection blind zone; from the simulation results of Fig. 4(b) and Fig. 5,
Figure 5. Adaptive value curve of planned path

The near seabed penetration path planning method based on the IWO algorithm can successfully plan a reasonable penetration path for UUV, and the algorithm has better Convergence. Without considering the terrain shadowing blind zone, the total length of the planned optimal path is 10,870.7m. When the terrain shadowing blind zone is fully utilized, the total length of the planning optimal path is 8,869.5m, which can save 18.4% of the range, so UUV can make full use of the sonar detection blind zone performs penetration path planning, so as to reach the combat zone safely and quickly to complete the combat mission.

5. Conclusion
The factors that cause the sonar detection blind zone are analyzed, and the impact of underwater terrain masking on the detection range of the sonar system is carried out in-depth research. A calculation method for the terrain masking blind zone of the sonar system is proposed. Finally, the detection blind zone of the sonar system is used. The IWO algorithm is used to plan the near seabed penetration path for UUV. The simulation results show that the underwater vehicle can safely sail near the seabed to avoid terrain threats and enemy sonar detection threats, and navigate towards the target point, and finally obtain a safe and effective navigation path.

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References
[1] UNITED STATES NAVY. The navy unmanned undersea vehicle master plan[R]. U.S.: Department of the Navy, 2004.
[2] PAN G, SONG B W, HUANG Q G, et al. Development and Key Techniques of Unmanned Undersea Systems [J]. Journal of Unmanned Undersea Systems, 2017,25(1) : 44-51.
[3] YANG L, CHEN L, HEINZELMAN, WENDI B. Analysis of detectable region for the bistatic sonar in reverberation background [J]. Journal of Harbin Engineering University, 2006,27(4): 597-602.
[4] GUO L, LIU T, ZOU J, et al. Research on performance analysis and optimization methods of bistatic collaborative detection [C]. Proceedings of the Thirteenth ACM International Conference on Underwater Networks & Systems, 2018:45.
[5] TAO C F, XU Y C, ZHOU X H, et al. The impacts of complex terrain to the side scan sonar detection: The example of the submarine pipeline inspection [J]. Periodical of Ocean University of China, 2019, 49 (5):071-077.
[6] HE X Z, XU F. Characteristics of dynamic positioning noises interference to panoramic scanning sonar [J]. Journal of Harbin Engineering University, 2017, 37(7):1031-1034,1064.
[7] YAN Z P, DENG C, ZHAO Y F, et al. Path planning method for UUV near sea bottom [J]. Journal of Harbin Engineering University, 2014, 35(3): 307-312.
[8] HAO Y L, ZHANG J J. AUV path planning in 3D seabed environment using genetic algorithm [J]. Engineering Science, 2003, 5(11): 56-60.
[9] MEHBRBIAN A R, LUACAS C, A novel numerical optimization algorithm inspired from weed colonization [J]. International Journal of Systems Science, 2006, 1(4): 355-366.
[10] ROBERGE V, TARBOUCHI M, LABONTE G. Comparison of parallel genetic algorithm and particle swarm optimization for real-time UAV path planning [J]. IEEE Transactions on Industrial Informatics, 2013, 9(1): 132-141
[11] GUO J, LEI X Y. Three-dimensional Route Planning Considering Threat Blind Zone [C]. Proceedings of 2016 IEEE Chinese Guidance, Navigation and Control Conference, Nanjing, China, 2016:1774-1779.
[12] TIAN T, LIU G Z, SUN D J. Sonar technology [M]. 2nd ed. Harbin: Press of Harbin Engineering University, 2010.
[13] KUWATA Y, SCHOUWENAARS T, RICHARDS A et al. Robust constrained receding horizon control for trajectory planning [C]. AIAA Guidance, Navigation, and Control Conference and Exhibit, 2005:6079.
[14] CONNORS J, ELKAIM G. Analysis of a spline based, obstacle avoiding path planning algorithm [C]. 65th Vehicular Technology Conference, Dublin, Ireland, IEEE, 2007: 2565-2569.
[15] CAUGHEY T K. Random excitation of a system with bilinear hysteresis [J]. ASME Journal of Applied Mechanics, 1960, 12: 649-652.