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Convert path planning for underwater vehicle based on sonar detection probability

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Convert path planning for underwater vehicle based on sonar detection probability

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Abstract. Underwater vehicle is essential for many tasks such as underwater exploration, equipment deployment and covert reconnaissance. Many underwater missions must be carried out with stealth to avoid being detected by enemy sonars, and safety and security are required in such high-risk situations. In this paper, a covert path planning algorithm for underwater vehicle is proposed based on the sonar detection probability analysis. First the sonar performance prediction model is constructed with sonar parameters, marine environment and underwater vehicle acoustic properties. Afterwards an improved ant colony algorithm is established by minimizing the cumulative detection probability. The evaluation indicate that the optimal covert path obtained for underwater vehicle is effective for reducing the cumulative detection probability.

1. Introduction

Underwater vehicles include manned underwater vehicles and unmanned underwater vehicles, which are competent for various underwater tasks such as spatial exploration, equipment deployment, communication relay and covert reconnaissance. In addition of avoiding underwater obstacles to ensure the safety of navigation, it is vital for the underwater vehicles to reduce the probability of being detected by enemy sonar to ensure the concealment of action.

Sonar is widely used in underwater surveillance and reconnaissance, which can detect, classify, locate and track underwater targets by using the propagation and reflection characteristics of sound waves in water. There are two types of sonar, active sonar and passive sonar. The active sonar works by transmitting particular sound pulse and measuring the time for the sound to be reflected, while the passive sonar doesn't send sound waves but just listens to the sound waves from engines of submarines or ships. Ocean is a complicated and changeable environment, which highly affected the performance of sonar system. The sound propagation in the ocean is determined by the spatial structure of the sound speed, which is dominated by the temperature and salinity. The sea surface and seabed also play an important role in the sound transmission process, leading to sound refraction, scattering, reflection, interference and attenuation.

In this paper, a method of convert path planning for underwater vehicle based on sonar detection probability is proposed. First the search area is set and rasterized into a volume grid. Then a sonar performance prediction model is built based on the marine environmental data, the sonar detection parameters and the acoustic properties of the underwater vehicle. Afterwards, the probability of underwater vehicle being detected by sonar at different locations on the lattice of the grid is calculated, which is then applied to improve the ant colony algorithm to implement the convert path planning for underwater vehicle. The evaluation shows that this method is capable of reducing the cumulative detection probability of the underwater vehicle during the navigation process.

2. Related Works

The existing hidden path planning methods for underwater vehicle are mainly divided into two categories, the specific analysis is as follows.

The first one is the most widely used method, which models the enemy sonar detection range as cylindrical, spherical or conical, then treats them in the same way as other environmental obstacles [1]. That is, this method tries to avoid these areas during path planning. It is easy to understand and simple to implement with high computational efficiency. The sonar detection access range is considered to be fixed in the environment modeling stage, and many universal path planning algorithms apply to this simplified analysis procedure. However, this method oversimplifies the problem and ignore the influence of the marine environment on the sonar detection performance. The detection probability inside or outside the modeled geometric shape is not consistent, and the applicability of this method is poor in practical situations.

The second one considers the influence of the marine environment on the sonar performance and constructs the sound field based on the marine environment data [2-4]. Afterwards, it uses the sound propagation model to calculate the sound propagation loss from the source to the sonar. The sound propagation loss information is used as the heuristic information of the path planning algorithm, and priority is given to the location with large sound propagation loss.

Compared with the first type of method, the second type of method introduces the sound field model to analyze the detection performance of the sonar, taking into account the influence of the marine environment. However, this kind of method is still not precise enough and the calculation process is overly simplified, which is only limited to the rough estimation of the sonar action distance. First, the sonar type and parameters are not considered, whereas different sonars have different characteristics under different working conditions. Second, the acoustic characteristics of the underwater vehicle are not considered, including the reflection characteristics and radiated noise intensity of the underwater vehicle relative to the sonar at different angles and distances. It is urgent to realize a safe and covert path planning method for underwater vehicles based on the sonar detection probability obtained by the detection performance model, taking into account the marine environment, sonar parameters and the acoustic characteristics of underwater vehicles.

3. Method

In this paper, a method of convert path planning for underwater vehicle based on sonar detection probability is proposed, which starts from the working process and detection mechanism of sonar, and fully considers the main influencing factors in the underwater acoustic environment and target characteristics. First the search area is set and rasterized into a volume grid. Then a sonar performance prediction model is built based on the marine environmental data, the sonar detection parameters and the acoustic properties of the underwater vehicle. Afterwards, the probability of underwater vehicle being detected by sonar at different locations on the lattice of the grid is calculated, which is then applied to improve the ant colony algorithm to implement the convert path planning for underwater vehicle [5-8]. The calculation process is shown in Figure 1, including the following processing steps.

3.1. Establish boundaries

The positions of the field are represented by (x, y, z) triples, where x is longitude, y is latitude, and z is depth. The initial locations include the starting and target positions of the underwater vehicle, as well as the deployment positions of individual sonars. First we calculate the combination of the minimum value (x_{min}, y_{min}) and combination of the maximum value (x_{max}, y_{max}) of longitude and latitude, where x_{min} and x_{max} are the minimum and maximum longitudes of all units, and y_{min} and y_{max} are the minimum longitudes of all units.

Due to the reflection, scattering and refraction effects of sound, the boundaries of the computing field needs to be extended. First we set the area extension parameters, including the longitude direction extension parameter r_x and the latitude direction extension parameter r_y. For the vertical direction, since the underwater sound propagation is affected by the sea surface and the seabed, the corresponding depth range needs to be extended to [0, r_s], where r_s is the maximum sea depth in the area of the rectangle with diagonal point pairs (x_{min}-r_x, y_{min}-r_y) and (x_{max}+r_x, y_{max}+r_y). To sum up, the coordinates of the two diagonal vertices of the three-dimensional cube corresponding to the calculation area are determined as (x_{min}-r_x, y_{min}-r_y, 0) and (x_{max}+r_x, y_{max}+r_y, r_s), as shown in Figure 2.

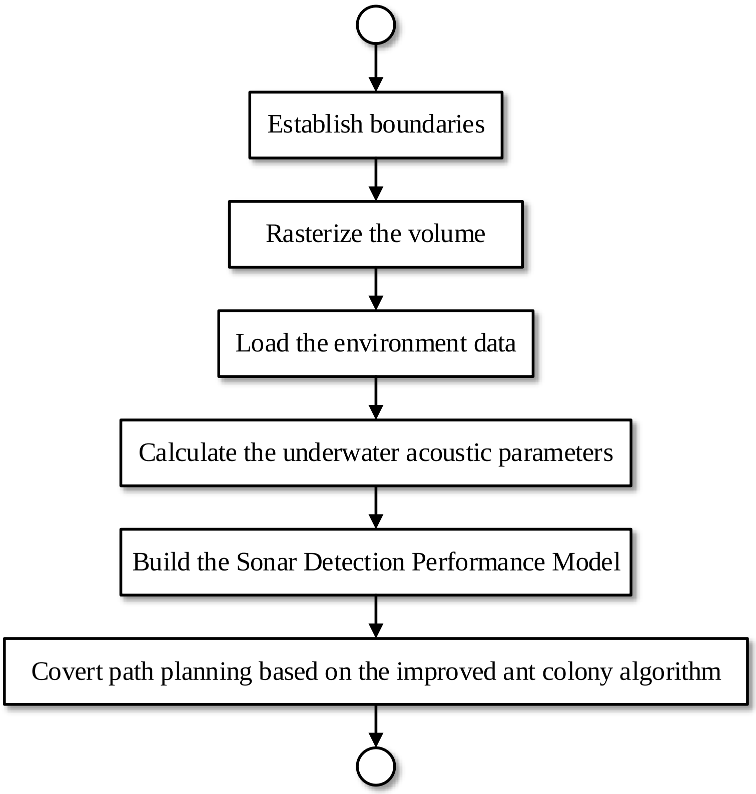

Figure 1. The convert path planning process for underwater vehicle

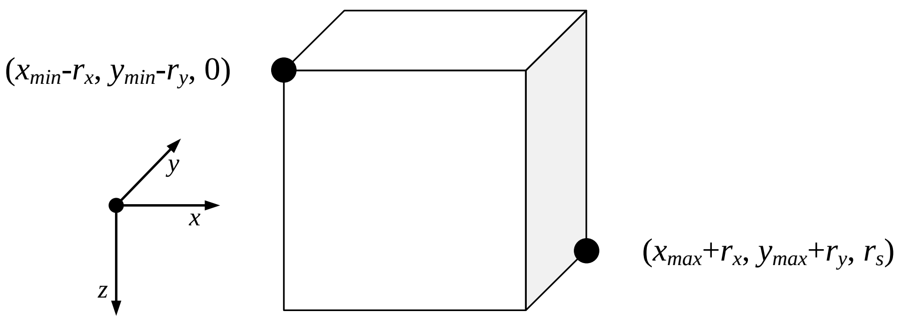

Figure 2. The coordinates of the two diagonal vertices of the three-dimensional cube.

3.2. *Rasterize the volume*

The rasterization parameters of the calculation area include the grid granularity s_x in the longitude direction, s_y in the latitude direction, and s_z in the depth direction. According to the above parameters, the volume of the calculation area is rasterized, in which the longitude direction is evenly divided into $\lceil(x_{max}-x_{min}+2r_x)/s_x\rceil$ segments, the latitude direction is evenly divided into $\lceil(y_{max}-y_{min}+2r_y)/s_y\rceil$ segments, the depth direction is evenly divided into $\lceil r_z/s_z\rceil$ segments.

3.3. Load the environment data

The marine environment data in the geographic range of the calculation area is loaded, including temperature, salinity, surface wind, ocean depth and seafloor sediment. Among them, the temperature and salinity are three-dimensional data, which is mapped to each three-dimensional grid point of rasterized mesh by means of interpolation. The sea surface wind, sea depth and seabed sediment are two-dimensional data, which is mapped to each two-dimensional grid point of the surface of the rasterized mesh by means of interpolation.

3.4. Calculate the underwater acoustic parameters

Using the underwater acoustic empirical formula, the acoustic velocity of each mesh grid point is calculated based on the temperature, salinity and depth. The acoustic velocity formula uses:

$$c = 1449.2 + \Delta c_T + \Delta c_{TS} + \Delta c_z \quad (1)$$

$$\Delta c_T = 4.6T - 0.55T^2 + 0.00029T^3 \quad (2)$$

$$\Delta c_{TS} = (1.34 - 0.01T)(S - 35) \quad (3)$$

$$\Delta c_z = 0.016z \quad (4)$$

T is the temperature value in degrees Celsius, S is the salinity value in thousandths, and z is the depth value in meters. In addition, according to the sea depth and the type of seabed sediment, the average value of the acoustic parameters of the seabed sedimentary layer is calculated.

3.5. Build the Sonar Detection Performance Model

Calculate the signal margin. The sonar detection performance is closely related to the signal margin. The larger the signal margin, the greater the sonar detection probability. There are two types of sonar, the active sonar and the passive sonar, which have different working principles and need to use different equations to calculate the signal margin.

1) Active sonar performance prediction.

In the case of noise as the dominant background disturbance, use the equation:

$$SE = SL - 2TL + TS - NL + DI - DT \quad (5)$$

where SE is the signal margin, SL is the active sound source level, TL is the propagation loss, TS is the target reflection intensity, NL is the marine environment noise level, DI is the receiving directivity index, and DT is the detection threshold.

In the case of reverberation as the dominant background distraction, use the equation:

$$SE = SL - 2TL + TS - RL - DT \quad (6)$$

where SE is the signal margin, SL is the active sound source level, TL is the propagation loss, TS is the target reflection intensity, RL is the marine environment reverberation level, and DT is the detection threshold.

The active sound source level SL, detection threshold DT and receiving directivity index DI are determined by the working mode of the active sonar. When the azimuth relative to the sonar is determined, the target reflection intensity TS of the underwater vehicle is also determined. To simplify the processing, it is categorized into three types: the front target reflection intensity TS_{front}, the side target reflection intensity TS_{side} and the rear target reflection intensity TS_{rear}.

For the three-dimensional mesh grid space, the SE from the central grid to the adjacent 26 grids needs to be calculated separately, as shown in Figure 3. The signal margin on the path from the grid numbered i to the adjacent grid numbered j is SE_{ij}.

2) Passive sonar performance prediction.

Use the equation:

$$SE = SL - TL - NL + DI - DT \quad (7)$$

Where SE is the signal margin, SL is the target sound source level, NL is the marine environmental noise level, TL is the propagation loss, DI is the receiving directivity index, and DT is the detection threshold.

The detection threshold *DT* and receiving directivity index *DI* are determined by the working mode of the passive sonar. When the azimuth relative to the sonar is determined, the target acoustic source level *SL* of the underwater vehicle is also determined. To simplify the processing, it is categorized into three types: the front target acoustic source level SL_{front}, the side target acoustic source level SL_{side} and the rear target acoustic source level SL_{rear}.

For the three-dimensional mesh grid space, the *SE* from the central grid to the adjacent 26 grids needs to be calculated separately, as shown in Figure 3. The signal margin on the path from the grid numbered *i* to the adjacent grid numbered *j* is SE_{ij}.

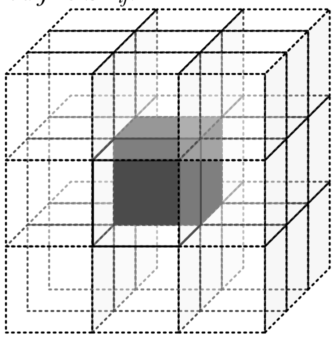

Figure 3. The adjacent 26 grids needs to be calculated for the three-dimensional mesh.

Calculate the instantaneous detection probability. For each grid point of the three-dimensional mesh of the calculation area, the instantaneous detection probability of sonar is calculated respectively on the basis of the signal margin *SE* corresponding to each sonar. Let the number of sonars be *n* (numbered 1, 2, ..., *n*), and for sonar *k*, let the signal margin of the grid point *i* in the calculation area pointing to the grid point *j* be $SE_{ij}(k)$, then the calculation formula of the instantaneous detection probability $DP_{ij}(k)$ is:

$$DP_{ij}(k) = \int_{-\infty}^{\frac{SE_{ij}(k)}{\sigma SE_{ij}(k)}} \frac{e^{-\frac{x^2}{2}}dx}{\sqrt{2\pi}} \tag{8}$$

Further calculation is made to obtain the comprehensive instantaneous detection probability DP_{ij} considering all sonar detection probabilities. The calculation formula is:

$$DP_{ij} = 1 - \prod_{k=1}^{n}(1 - DP_{ij}(k)) \tag{9}$$

3.6. Covert path planning based on the improved ant colony algorithm

The ant colony algorithm uses the same three-dimension mesh of the calculated areas. First it is necessary to construct the seabed terrain based on the depth data, and set the obstacles as the forbidden area, and the underwater vehicle needs to implement avoidance during the traveling process to ensure the safety of navigation. Besides it is necessary to design a path planning strategy based on the sonar detection probability to reduce the cumulative detection probability of the planned path, so as to ensure the concealment of the underwater vehicle during the traveling process.

The initialization parameters of the ant colony algorithm include the starting position (starting point) and target position (ending point) of the underwater vehicle, the three-dimensional matrix *DP* of the comprehensive instantaneous detection probability, the number of ants in each iteration *M*, the maximum number of iterations *N*, and the information heuristic factor *α*, the expected heuristic factor *β*, the total amount of pheromone *Q*, the pheromone volatility coefficient *ρ*, the detection probability weight coefficient *ω*, the initial pheromone c_s, and the initial pheromone decreasing coefficient *e*. The improved ant colony algorithm includes the following steps.

Initialization of Pheromone Matrix. In order to reduce the blindness of the initial search of the basic ant colony algorithm and improve the convergence speed, an initial pheromone matrix is established based on the sonar detection probability and path cost. Each grid needs to be saved to the pheromone concentration of 26 adjacent grids, corresponding to 26 different path options. The prime concentration is denoted as $\tau_{ij}(1)$. The initial pheromone is unevenly distributed, and the concentration of the pheromone on the line connecting the starting point to the end point is strengthened and decreased outward, and is corrected by the sonar detection probability. The details of the construction method of the initial pheromone are as follows:

S1: For all non-obstruction grid points in the three-dimensional mesh of the calculation area, the initial pheromone concentration on the path to the adjacent 26 grids is set to 0.

S2: For all non-obstruction grid points located on the straight line connecting the starting position and the target position of the underwater vehicle, they are enqueued onto Q_u in turn, and the pheromone concentration on all paths to adjacent grids are assigned as c_s.

S3: The first grid point in the queue Q_u is dequeued, and the pheromone concentration c_t of its path to the adjacent grid is recorded. All the grid points directly adjacent to it are checked, and those non-obstacle points with zero pheromones concentration are enqueued onto Q_u, as well as assign the pheromone concentration on all paths to the adjacent grid as $e*c_t$, where $0<e<1$.

S4: If the queue Q_u is not empty, go to step S3; if the queue Q_u is empty, go to step S5.

S5: For all non-obstacle grid points of the three-dimensional mesh of the calculation area, the pheromone concentration on the path is corrected using the comprehensive instantaneous detection probability of the grid position to all paths of the adjacent grid, that is, for the direction from grid point i to grid point j, $\tau'_{ij}(1) = \tau_{ij}(1) * (1 - DP_{ij})$, where DP_{ij} is the comprehensive instantaneous detection probability of the same grid point.

Ant Algorithm Implementation. The iteration counter n is initialized to 1. All the ants are placed on the grid point where the underwater vehicle starts, and for the ants numbered k (k = 1, 2, ..., M), perform the following calculation steps independently and in parallel.

T1: The probability of the ant selecting the next candidate grid is calculated according to the following formula:

$$P_{ij}^{k}(n) = \begin{cases} \frac{[\tau_{ij}(n)]^{\alpha}[\eta_{ij}(n)]^{\beta}}{\sum_{s\in A_i^k}[\tau_{is}(n)]^{\alpha}[\eta_{is}(n)]^{\beta}}, & j \in A_i^k \\ 0, & j \notin A_i^k \end{cases} \tag{10}$$

where $\tau_{ij}(n)$ is the pheromone concentration on the path from grid point i to grid point j in the n-th iteration. A_i^k represents the set of all adjacent feasible grid points of ant k of the grid point i, which includes all the non-obstacle grids directly adjacent to grid i that are not part of the current iteration path record. $\eta_{ij}(n)$ is the heuristic information on the path from grid point i to grid point j in the n-th iteration, and the calculation formula is:

$$\eta_{ij}(n) = \frac{1-DP_{ij}}{d_j(n)} \tag{11}$$

where DP_{ij} is the comprehensive instantaneous detection probability of the path from the grid point i to the grid point j. $d_j(n)$ is the expected distance from grid point j to the target position of the underwater vehicle in the n-th iteration, and $d_j(1)$ is initialized as the straight-line distance from grid point j to the target position of the underwater vehicle.

T2: Based on the probability of the ants selecting the next candidate grid point, the roulette algorithm is used to determine the target grid point for the ants to move. This grid point is then added to the ant's path record $R^k(n)$, and the path length traversed by the ants and the cumulative detection probability of the path are updated. The calculation formula of the cumulative detection probability for the path of the k-th ant is:

$$CDP^k(n) = 1 - \prod_{<i,j>\in R^k(n)}(1 - DP_{ij}) \tag{12}$$

If the ant reaches the target grid point or has no way to go, the current iteration of the ant ends, and proceeds to step T3; otherwise, proceeds to step T1.

T3: After all the ants complete the current iteration, the paths taken by the ants that finally reach the target point are sorted. The calculation formula for the path evaluation of the k-th ant in the n-th iteration is:

$$V^k(n) = L^k(n) * (CDP^k(n))^{\omega} \quad (13)$$

where $L^k(n)$ is the path length of the k-th ant in the n-th iteration. $CDP^k(n)$ is the cumulative detection probability of the path of the k-th ant in the n-th iteration, and ω is the detection probability weight coefficient. The smaller $V^k(n)$ is, the better the path is. The optimal path obtained in this iteration is compared with the optimal path obtained in the previous iterations, and the current global optimal path is updated.

T4: The pheromone and expected distance on the path is updated. For the pheromone on the path from grid point i to grid point j, the update formula is:

$$\tau_{ij}(n+1) = \rho * \tau_{ij}(n) + \Delta\tau_{ij} \quad (14)$$

where $\Delta\tau_{ij} = \sum_{s=1}^{m} \Delta\tau_{ij}^{s}$, which indicates that m ants have successfully reached the end point in this round of iteration. ρ is the pheromone volatility coefficient, and s is the sequence number of the ants sorted according to the path. $\Delta\tau_{ij}^{s}$ is the pheromone increment when the rank s-th ant passes through grid point i and reaches grid point j, which is calculated as:

$$\Delta\tau_{ij}^{s} = (m - s + 1) * \frac{Q}{L^k(n)} \quad (15)$$

where Q is the total amount of pheromone, and $L^k(n)$ is the path length of the k-th ant in this iteration. If the ant does not go through the path from grid point i to grid point j, $\Delta\tau_{ij}^{s}$ is 0.

For the expected distance $d_i(n)$ from grid point i to the end point, the update method is as follows. If $d_i(n)$ has not changed since initialization, it is directly set to the minimum value of the path length from grid point i to the end point on the paths traversed by all ants. Otherwise $d_i(n)$ is compared with $d_i^t(n)$, which is the minimum path length from grid point i to the end point traversed by all ants passing through grid point i in this iteration. If $d_i^t(n)$ is less than $d_i(n)$, update $d_i(n)$ to $d_i^t(n)$.

T5: If the number of iterations is less than the maximum iterations number N, the iteration counter n is updated to n+1 and continue to T1; otherwise, the algorithm ends and the currently obtained global optimal path is saved.

4. Evaluation

Assuming the initial position coordinates of the underwater vehicle are (117°E, 13°N, -4000m), and the target position coordinates are (118°E, 14°N, -3500m). The No. 1 sonar is an active sonar, and the position coordinates are (117.6°E, 13.2°N, -2500m). The No. 2 sonar is a passive sonar, and the position coordinates are (117.8°E, 13.5°N, -2500m). According to the above positions, the minimum value combination (117°E, 13°N) and the maximum value combination (118°E, 14°N) of longitude and latitude are calculated. The extension parameter r_x in the longitude direction is set to 0.1°, and the extension parameter r_y in the latitude direction is set to 0.1°. The maximum depth within the square range is 4500 meters, therefore the coordinates of the two diagonal vertices of the three-dimensional cube corresponding to the calculation area are (117°E, 13°N, 0) and (118°E, 14°N, -4500m).

The grid granularity s_x in the longitude direction is set to 0.01°, the grid granularity s_y in the latitude direction is set to 0.01°, and the grid granularity s_z in the depth direction is set to 50 meters. According to the above parameters, the calculation area is rasterized, and the longitude direction is evenly divided into ⌈(118-117+2*0.1)/0.01⌉=120 segments, the latitude direction is evenly divided into ⌈(14-13+2*0.1) /0.01⌉=120 segments, and the depth direction is evenly divided into ⌈4500/50⌉=90 segments.

For the active sonar (No. 1 sonar), the active sound source level *SL* is set to 240dB, the propagation loss *TL* is calculated using the ray model, the marine environment reverberation level *RL* is set by the empirical formula. The detection threshold *DT* is set to 10dB. For the target reflection intensity *TS*, according to the different angles of the underwater vehicle relative to the sonar, the front target reflection intensity TS_{front} is set to 30dB, the side target reflection intensity TS_{side} is set to 200dB, and the rear target reflection intensity TS_{rear} is set to 30dB.

For passive sonar (Sonar No. 2), the environmental noise level *NL* is obtained from the Wenz curve. The propagation loss *TL* is calculated using the ray model. The receiving directivity index *DI* is set to 15dB, and the detection threshold *DT* is set to 10dB. For the target sound source level *SL*, according to the different angles of the underwater vehicle relative to the sonar, the front target sound source level SL_{front} is set to 95dB, the side target sound source level SL_{side} is set to 95dB, and the rear target sound source level SL_{rear} is set to 100dB.

For the ant colony algorithm, the number of ants M in each iteration is set to 50, and the maximum number N of iterations is set to 2000. The information heuristic factor α is 1, the expected heuristic factor β is 5, the total pheromone Q is 10, the pheromone volatility coefficient ρ is 0.9, the detection probability weight coefficient ω is 1.2, and the initial pheromone c_s is 0.2, and the initial pheromone decreasing coefficient e is 0.8.

The convert path for the underwater vehicle in the simulated environment is shown in Figure 4. The initial position of the underwater vehicle is represented by a pentagram, and target position is represented by a triangle. The No. 1 sonar is represented by a black point and the No. 2 sonar is represented by a gray point. The evaluation shows that this method is capable of reducing the cumulative detection probability of the underwater vehicle during the navigation process. Compared with classical ant colony algorithm, our method reduces the cumulative detection probability by 31.6%.

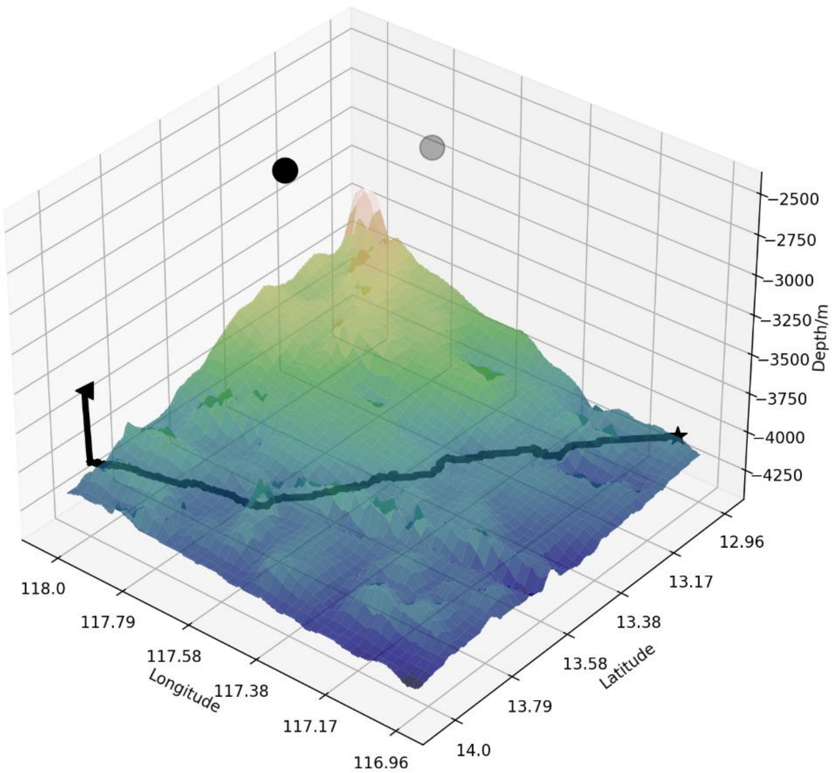

Figure 4. The convert path for the underwater vehicle in the simulated environment

5. Conclusion

In this paper, a method of convert path planning for underwater vehicle based on sonar detection probability is proposed. First the search area is set and rasterized into a volume grid. Then a sonar performance prediction model is built based on the marine environmental data, the sonar detection parameters and the acoustic properties of the underwater vehicle. Afterwards, the probability of underwater vehicle being detected by sonar at different locations on the lattice of the grid is calculated, which is then applied to improve the ant colony algorithm to implement the convert path planning for underwater vehicle. The evaluation shows that this method is capable of reducing the cumulative detection probability of the underwater vehicle during the navigation process.

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