Research on Three Dimensional Global Path Planning of Unmanned Underwater Vehicle

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Abstract—The ant colony algorithm is used to solve the global path planning problem of unmanned underwater vehicle (UUV) in three-dimensional environment. On the basis of grid model environment, the traditional ant colony algorithm is optimized. In order to meet the needs of path planning, an improved algorithm is proposed to solve the problem of initial pheromone distribution. Simulation results show that the improved ant colony algorithm has the characteristics of fast convergence.

1. Introduction
With the development of artificial intelligence technology, the intelligence level of unmanned underwater vehicle (UUV) is developing continuously [1]. Global path planning in three-dimensional environment refers to finding an optimal path from the start point to the target point in the work space with obstacles according to certain rules [2]. The common optimal rules include the shortest path, the least time consuming and the least energy consuming. Global path planning results are directly related to the operability and security of UUV, so the research is of great significance.

Ant colony optimization (ACO) simulates the foraging behavior of ants in nature, and guides ants to find the optimal path through the change of pheromone. As a kind of intelligent heuristic search algorithm, ACO has strong characteristics of adaptability, robustness, distributed computing and self-organization [3]. ACO has great potential in the application of path planning. The result shows that the obstacle avoidance path planned by the improved ACO has a better follow-up effect and meets the requirements of vehicle lateral stability.

Document [4] established a two-dimensional environment model with obstacles by using MAKLINK graph theory. Document [5] aimed at the global path planning problem of robot in two-dimensional environment. The parameters of ant colony algorithm are changed. The influence of parameters on the optimal solution is analyzed. Document [6] proposed an improved parameter optimized ACO based on particle swarm optimization. The speed of the mobile robot move to reach the target points is improved.

In this paper, the grid method is used to model the three-dimensional marine environment. On the basis of traditional ACO, the search space, selection transfer probability, pheromone update and fitness value are designed. An improved algorithm of non-uniform distribution of initial pheromone is proposed.
and simulated by MATLAB. Compared with the simulation results, the improved algorithm has the ability to improve the convergence speed.

2. Model of three-dimensional environment

2.1. Environment Data Processing

Based on the environment data in the Document [7], the data is processed. In order to study, the height of the deepest point should be set as 0. The height of other points is referred to the deepest point. Samples were taken every 2 km along the longitude and latitude directions to form the environment matrix $H$ as follows.

$$
H = \begin{bmatrix}
2000 & 800 & 500 & 1000 & 900 & 700 & 1100 & 1000 & 1300 & 1200 & 1500 \\
200 & 600 & 600 & 1200 & 1500 & 600 & 600 & 600 & 600 & 600 & 1400 \\
700 & 500 & 600 & 500 & 300 & 600 & 600 & 600 & 600 & 600 & 1100 & 1500 \\
300 & 600 & 600 & 600 & 400 & 600 & 600 & 600 & 600 & 600 & 1400 \\
800 & 400 & 600 & 1700 & 900 & 1000 & 400 & 1700 & 1800 & 900 & 600 \\
500 & 700 & 800 & 1600 & 900 & 1600 & 2100 & 1700 & 900 & 1200 & 1100 \\
300 & 0 & 900 & 1500 & 1000 & 1400 & 1900 & 2100 & 1200 & 600 & 1800 \\
900 & 1100 & 1000 & 1700 & 1600 & 1200 & 1600 & 900 & 1600 & 1100 & 1300 \\
600 & 800 & 700 & 600 & 800 & 1600 & 900 & 1100 & 1000 & 600 & 900 \\
900 & 800 & 600 & 900 & 800 & 800 & 800 & 1100 & 600 & 1400 & 1300 \\
600 & 900 & 1100 & 800 & 800 & 600 & 900 & 1200 & 600 & 1100 & 600
\end{bmatrix}
$$

Through linear interpolation, the three-dimensional environment map is drawn as shown in Fig. 1.

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2.2. Grid-based Model of Environment

According to the characteristics of the existing three-dimensional environment, the grid method is used to model. As shown in Fig. 2, X axis is longitude direction, Y axis is latitude direction and Z axis is vertical sea level direction. $OC$, $OA$ and $OO'$ are the maximum length along X axis, Y axis and Z axis respectively. The three-dimensional cube $OABC$ is the planning space of the three-dimensional path planning.

Figure 1 Linear interpolation result

Figure 2 Three-dimensional environment space
Steps of environment model based on grid method are as follows [8]:

**Step1**: Along the direction of X axis, the maximum length is divided into \(N\) equal parts. \(N + 1\) planes \(\Pi_i, (i = 0,1,2,\ldots,N)\) are obtained;

**Step2**: Along the direction of Y axis, the maximum length is divided into \(M\) equal parts. Along the direction of Z axis, the maximum length is divided into \(L\) equal parts. Each plane is divided into \(M \times L\) grids. Fig. 3 shows the grid division of the plane \(\Pi_i\).

![Grid division diagram](image)

So far, the three-dimensional cube \(OABC'\) is divided into \(N \times M \times L\) cubes. Any point has two coordinate representation methods: the sequence coordinate and the position coordinate. The sequence coordinate \(P_1=(i,j,k)\) \((i=0,1,\ldots,N; j=0,1,\ldots,M; k=0,1,\ldots,L)\), represents the partition number relative to point \(O\). The position coordinate \(P_2=(x_i,y_j,z_k)\) represents the offset distance from the latitude, longitude, and depth of point \(O\).

3. **Design of ACO**

3.1. **Search Space Design**

Based on the grid environment established above, the path is searched according to the hierarchical search method. Set the main search direction of UUV is the X axis direction. The plane where the start point is located is the initial plane, and the plane where the target point is located is the end plane.

According to the order of the plane, path planning is to find the best path point from the next plane. If each node is searched, the space complexity of algorithm will increase. Considering the maneuverability of UUV, the maximum transverse distance \(y_{\text{max}}\) and the maximum longitudinal distance \(h_{\text{max}}\) are designed. The sketch map of search space is shown in Fig. 4. Only grid nodes in corresponding search box should be considered during path search. The search space will be greatly simplified. The search efficiency will be improved at the same time.

![Sketch map of search space](image)
3.2. Heuristic Value Design
The convergence, stability and optimization of ACO largely depend on the setting of heuristic value. The principle of global path planning in this paper is the shortest path. Combined with the difference between three-dimensional path planning and two-dimensional path planning, the heuristic value from the node in plane t to the node in plane t + 1 named $Q_{t,t+1}$, is set as follows:

$$Q_{t,t+1} = \frac{w_1}{D_{t,t+1}} \cdot \frac{w_2}{D_{t,t+1,T}} \cdot S_{t+1}$$  \hspace{1cm} (1)

Where:
1. $D_{t,t+1}$ is the distance between node t and t+1, which can be calculated by:
   $$D_{t,t+1} = \sqrt{(i_t - i_{t+1})^2 + (j_t - j_{t+1})^2 + (k_t - k_{t+1})^2}$$  \hspace{1cm} (2)
2. $D_{t,t+1,T}$ is the distance between node t and initial node T, which can be calculated by:
   $$D_{t,t+1,T} = \sqrt{(i_T - i_{t+1})^2 + (j_T - j_{t+1})^2 + (k_T - k_{t+1})^2}$$  \hspace{1cm} (3)
3. $S_{t+1}$ is the ratio of feasible node number $N_{t+1}$ to total node number $N$ in plane t+1, which can be calculated by:
   $$S_{t+1} = \frac{N_{t+1}}{N}$$  \hspace{1cm} (4)
4. $w_1$, $w_2$ and $w_3$ are weight parameters. According to the actual problem, the appropriate values are selected.

3.3. Selection Transfer Probability Design
Ants select the next node according to the size of the selection transition probability. The selection transfer probability is closely related to the pheromone and heuristic value of the node. Roulette method is used in node selected. Nodes with higher probability can be selected with higher possibility. The equation of probability from the node in plane t to the node in plane t + 1 is:

$$P_{t,t+1} = \begin{cases} \left(\frac{Q_{t,t+1}}{\sum Q_{t,t+1}}\right)^\beta, & \text{node } \in \text{allowed} \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (5)

Where, $\tau_{t+1}$ is the pheromone value on the nodes in plane t+1. $Q_{t,t+1}$ is the heuristic value from the node in plane t to the node in plane t +1. $\alpha$ is the pheromone importance factor, and $\beta$ is the importance factor of heuristic function.

3.4. Pheromone Updating Design
ACO includes local pheromone updating and global pheromone updating. The purpose of local pheromone updating is to reduce the pheromone value of the ant passed nodes and increase the probability of being selected for the failed nodes. After ants complete a path planning, global pheromone updates is carried out. The pheromone value of the best path is increased, and the probability of being selected is improved at the same time. Both local updating and global updating ensure the successful searching ability of ant colony algorithm.

The equation of local pheromone updating is as follows.

$$\tau_i = (1 - \gamma) \tau_i$$  \hspace{1cm} (6)

Where, $\tau_i$ is the pheromone value of nodes in plane t, $\gamma$ is the attenuation coefficient of local pheromone.

The equation of global pheromone updating is as follow.
\[ \tau_i = (1 - \rho) \tau_i + \rho \Delta \tau_i \]  
\[ \Delta \tau_i = \frac{K}{\min(\text{Distance}(m))} \]

(7)

(8)

Where, Distance(m) is the path length of ant m, \( \rho \) is the updating coefficient of global pheromone and \( K \) is a constant coefficient.

3.5. Fitness Value Design

After each iteration, the path planning results are evaluated according to the fitness value. In this paper, the length of current path is closely related to fitness value. In the process of navigation, UUV navigates along the seabed to improve its safety and concealment. Therefore, it is necessary to introduce the height information about the planning path nodes into the fitness value to ensure the feasibility of the planning path. The equation of fitness value is as follow.

\[ f = \text{Distance(path)} + \sum_{i=1}^{N} H_i \]

(9)

Where, Distance(path) is total length, \( \sum_{i=1}^{N} H_i \) is the cumulative height of nodes along the path.

4. Improved ant colony algorithm and steps of path planning

4.1. Improved Ant Colony Algorithm

Due to the incomplete environment search, in the initial stage of ACO, the positive feedback effect of pheromone is not good. Convergence of the early stage of search is low, which greatly reduce the search efficiency of the algorithm. Therefore, the initial pheromone should be improved according to the relative position of the start point and the target point.

In this paper, the initial pheromone is set to 1. And then, set initial pheromone along the line between the start point and the target point to 10. The region located in the vicinity of the line can be searched at higher possibility. The distribution of initial pheromone can improve the convergence speed of ACO and reduce path planning time.

4.2. Steps of Path Planning

According to the design of ACO, the application of improved ant colony algorithm in three-dimensional path planning is realized. The flow chart of improved ant colony algorithm is shown in Fig. 5.
The specific operation steps are as follows:

**Step 1**: The three-dimensional environment is model with the use of grid method. The starting point and target point are determined. According to the relative position of the start point and the target point, the initial pheromone value is distributed;

**Step 2**: Selecting parameters in ant colony algorithm, including: ants’ number $m$, maximum iteration number $\text{iteration\_num}$, maximum transverse distance $y_{\text{max}}$, maximum longitudinal distance $h_{\text{max}}$, the attenuation coefficient of local pheromone $\gamma$, the updating coefficient of global pheromone $\rho$, constant coefficient $K$ and so on. Ant colony is initialized.

**Step 3**: According to the equation (6), the node is selected and the path search is completed.

**Step 4**: According to equations (7) to (10), the fitness value is calculated and the pheromone is updated.

**Step 5**: Judge whether the number of iterations exceeds the upper limit. If it reaches, the next step will be executed. Otherwise, the path search will be repeated.

**Step 6**: The simulation results such as optimal path information and fitness change information are saved.

**Step 7**: Results output and visualization. The algorithm comes to end.

5. Simulation results and analysis

5.1. Simulation Parameter Setting
The position coordinate of start point is set as (1,10,800). The corresponding sequence coordinate is (1,10,4). The position coordinate of target point is set as (21,9,1000). The corresponding sequence coordinate is (21,9,5).

According to the experience, the experimental parameters are setting as follows:

| Parameter name                        | Symbol | Number |
|---------------------------------------|--------|--------|
| Equal fractions along the X axis      | $N$    | 21     |
| Equal fractions along the Y axis      | $M$    | 21     |
| Equal fractions along the Z axis      | $L$    | 10     |
| Maximum transverse distance           | $y_{\text{max}}/\text{km}$ | 2      |
| Maximum longitudinal distance         | $h_{\text{max}}/\text{km}$ | 0.4    |
| Weight parameter                      | $w_1$  | 50     |
| Weight parameter                      | $w_2$  | 50     |
| Weight parameter                      | $w_3$  | 1      |
| Pheromone importance factor           | $\alpha$ | 0.9   |
| Heuristic function importance factor  | $\beta$ | 6.8    |
| Attenuation coefficient of local pheromone | $\gamma$ | 0.5  |
| Updating coefficient of global pheromone | $\rho$ | 0.2    |
| Constant coefficient                  | $K$    | 100    |
| Iteration number                      | $\text{iteration\_num}$ | 400    |
| Ants’ number                          | $m$    | 10     |

5.2. Simulation Result
According to the parameter settings in Table 1, comparative simulation experiments are carried out to verify the correctness of the algorithm. The simulation results are shown in the figures below.
Total path length of the algorithm without initial pheromone optimized is 28.4659 km. Total path length of the algorithm with initial pheromone optimized is 28.8413 km. The data of the optimal fitness value, the minimum number of iteration and simulation time consumption are recorded in Table 2.

| Algorithm     | The optimal fitness value | Best iteration number | Time consumption |
|---------------|---------------------------|-----------------------|------------------|
| Before optimized | 106.6695                 | 255                   | 2.6988           |
| After optimized  | 105.1655                 | 193                   | 2.5428           |
Due to the randomness of ACO, it is not enough to rely on a single simulation data to illustrate the effectiveness of the algorithm. Therefore, 20 times simulation experiments are carried out for the two cases, and the average value of the above three indexes are obtained. The relevant simulation data are recorded in Table 3.

| Algorithm          | The optimal fitness value | Best iteration number | Time consumption |
|--------------------|----------------------------|-----------------------|------------------|
| Before optimized   | 106.27790                  | 262.2000              | 2.0093           |
| After optimized    | 106.75600                  | 232.4500              | 1.9543           |

5.3. Simulation Result

It can be seen from Fig. 6 and 7 that both the original and optimized algorithm can realize the three-dimensional path planning. In the two cases, the path found is basically the same, and the path length is also basically the same.

From Fig. 8, the fitness value of the optimization algorithm converges quickly. When the iteration number is 193, the optimal fitness value is found.

Compared with simulation data shown in Table 2 and 3, the minimum number of iteration is optimized. The average value was optimized nearly 30 times. The effectiveness of the optimized algorithm is verification.

6. Conclusions

The traditional ACO is designed and the initial pheromone is optimized, based on grid-based Environment. Simulations were carried out. The simulation results show that the optimization algorithm is effective for improving the convergence speed.

References

[1] Robert D Holzer."Unmanned Maritime Systems: An Update on Core Technologies." Sea Technology 60.11(2019).
[2] Chang Hui Song."Global Path Planning Method for USV System Based on Improved Ant Colony Algorithm." Applied Mechanics and Materials 3252.(2014).
[3] Sabrine Chaouch, et al."Colour recipe prediction using ant colony algorithm: principle of resolution and analysis of performances." Coloration Technology 135.5(2019).
[4] ZHAO Youqun, YAN Xi, GE Zhaohao, LI Haiqing."Vehicle Obstacle Avoidance Path Planning Based on Improved Ant Colony Algorithm." Journal of Chongqing University of Technology(Natural Science) 34.1-10(2020).
[5] Shi Enxiu, Chen Minmin, Li Jun Huang Yumei."Research on Method of Global Path-planning for Mobile Robot Based on Ant-colony Algorithm."Transactions of the Chinese Society for Agricultural Machinery 45.53-57(2014).
[6] Du Yuhong, Zhang Yan, Zhao Huanfeng."Research on robot path planning based on parameters optimized ant colony optimization."Modern Manufacturing Engineering 09.7-14(2020).
[7] LIU Li-qiang, YU Fei, DAI Yun-tao."Path Planning of Underwater Vehicle in 3D Space Based on Ant Colony Algorithm."Journal of System Simulation 14.3712-3716(2008).
[8] Ali Hub, et al."Path Planning of Mobile Robot With Improved Ant Colony Algorithm and MDP to Produce Smooth Trajectory in Grid-Based Environment." Frontiers in neurorobotics 14.(2020).