Method of AUV Heuristic Route Planning Based on Cost Estimation of Visibility

Jiaping Song[*], Xing Liu, Aigen Huang, Yibo Liu and Haiqin Wan
Systems Engineering Research Institute of CSSC, Beijing 100094, China
[*]Corresponding author

Abstract—**This paper provides a heuristic route planning method based on the cost estimation of visibility through which Autonomous Underwater Vehicle (AUV) can voyage safely and efficiently in complex Marine application environment. The optimized model of AUV is set up and deduced in this paper. Then the constraints and processing strategy of cost estimate is analyzed, and the planning method based on visibility the principle of cost estimate is discussed in detail. This paper verifies the feasibility and optimality of the heuristic route planning method based on the visibility cost estimation in performances of planning-time and distance through simulating comparing.**

Keywords—route planning; visibility; cost estimation; heuristic

I. INTRODUCTION

With the rapid development of marine application technology and requirement, Autonomous Underwater Vehicle (AUV) plays an important role in military and civilian application [1]. One of the core problems about AUV in the complex underwater environment when navigating is route searching and planning. How to obtain the optimal path quickly is the premise and guarantee for completing important task underwater successfully. The aim of route planning is to plan the optimal route for AUV to meet the constraints requirement considering AUV arrival time, distance, threat and specific voyage area, etc. based on the given planning task [2]. AUV route planning model needs to consider a lot of constraints to ensure voyage safety during route planning, including the AUV's own physical limits, the concealment of route, real-time demand and requirements of voyage tasks, etc. [3].

There are four types of Route planning methods which are frequently used: searching method based on geometric model, searching method based on virtual potential field and voyage function, searching method based on template matching, searching method based on intelligent [4]. Since these algorithms have their own advantages and disadvantages, and there is no a general method in practical application, the actual situation will be analyzed. In practical application the algorithm implementation of computer RAM storage and computing cost consumption are considered based on the expression of route planning space strategy and the assessment of constraints to obtain the optimal path in the shortest possible time. This paper adopts a heuristic route planning method based on the cost estimation of visibility to make strategy analysis and researching. Then the feasibility and optimality in performances of planning-time and distance by using the method based on the cost estimation of visibility is verified through simulating comparing with the planning of visibility analysis simply.

II. MATH MODELING

Since the problem of AUV voyage is complicated, the mathematical model of AUV needs to be simplified to facilitate its study according to the specific application problem. Planning the centroid trajectory is the main task of AUV for three-dimensional route planning. Therefore, the AUV movement can be regarded as a movement that can be controlled by the particle, without considering AUV rolling on voyage [5]. Based on this principle, it is assumed that AUV's rotation of the centroid on voyage is non-inertial. The control system works ideally without error or time delay, ignoring random disturbances such as ocean currents and waves. It is assumed that the speed of AUV is a constant given previously.

The discrete state space equation for simplified AUV three-dimensional route planning problems can be deduced and established based on the above assumptions.

Definitions of state variable and control variable

$$X_k = (x_k, y_k, z_k, \psi_k, \theta_k)^T \ and \ U_k = (\delta_{zk}, \delta_{yk}, dm_k)^T \tag{1}$$

Where x_k, y_k, z_k represent the barycentric coordinate of AUV, ψ_k and θ_k represent heading angle and trim angle.

Then the equation of state is derived as follow.

$$\begin{cases} (x_{k+1} - x_k) = v\cos\theta_k \cos\psi_{Sk} \Delta t_k \\ (y_{k+1} - y_k) = v\sin\theta_k \Delta t_k \\ (z_{k+1} - z_k) = -v\cos\theta_k \sin\psi_{Sk} \Delta t_k \end{cases} \tag{2}$$

The constraint conditions of Control variables U_k and state variables X_k is

$$U_k = \begin{cases} \delta_{zk} \in [\delta_{z\min}, \delta_{z\max}] \\ \delta_{yk} \in [\delta_{y\min}, \delta_{y\max}] \\ dm_k \in [dm_{\min}, dm_{\max}] \end{cases} \quad X_k = \begin{cases} y_k \geq h_{map} \\ \theta_k \in [\theta_{\min}, \theta_{\max}] \\ \psi_{Sk} \in [\psi_{S\min}, \psi_{S\max}] \end{cases}$$

(3)

In order to find out the route with minimum energy consumption and optimization time, function J is set.

$$J = \int S(x, \dot{x}) dt$$

(4)

Where $S(x, \dot{x})$ is safety estimation function, it can be a time constant or energy $\dot{m}$.

Since each discrete point of AUV in three-dimensional route between the starting point and target point meets the constraint conditions of state variables, so the control sequence along the route will be calculated to achieve voyage performance optimization.

III. ALGORITHM OF ROUTE PLANNING

A. Visibility Concept

Visibility analysis is a judgment of view connection between observation point and target point, namely a judgment of intersection between two points and various constraint areas of the Marine environment, which can be simplified to the collision detection process about line and polygon, circle, ellipse [6]. Constraints set C and two points P1, P2 are given in the vector space planning area.

For any constraint area $x(x \in C)$, if

$$\varphi(l_{P_1 P_2}, x) = 0, \quad y = \varphi(l, x)$$

(5)

Then the connection between P1 and P2 is visible, which $l_{P_1 P_2}$ represents line P1P2.

Where y is used to calculate whether intersecting between the line l and constraint areas x, the value of which can only be 0 or 1, if the value is 0, then means no intersection, otherwise means intersecting. That is, the condition for any two points P1 and P2 in planning space is

$$\forall x, x \in C, \varphi(l_{P_1 P_2}, x) = 0$$

(6)

B. Constraint Condition

The working environment of AUV is more complex, and various types of constraints need to be considered, including the Restricted Zone, the Current Zone, the Designated Zone, the Threat Zone, the Fetch Zone. The model, as well as the processing method is different according to constraint conditions.

Restricted Zone: If Restricted Zone between two points exists when visibility inspecting, the cost of AUV passing through this zone is infinity. So the route needs to reach the target point bypassing from the Restricted Zone. Since each part of the global shortest path must also be a local shortest path, the global shortest path can be constructed with the convex boundary and the common tangent.

Current Zone: The sea water flows steadily and regularly along a certain direction at a relatively steady speed in some areas of the ocean, which affects the heading and speed of AUV. The scope of a single discrete point in a Current Zone is:

$$S_{sea} = \begin{cases} P(x, y, z) \mid P(x, y, z) \in S, \\ (y \in [0, h] \cap [(x - x_0)^2 + (z - z_0)^2] \leq r^2) \end{cases}$$

(7)

Where S_{sea} is the scope of single discrete point in Current Zone; (x_0, o, y_0) is center coordinates of the base of cylinder; r and h is base radius and height of the cylinder respectively.

Since current velocity will affect the actual voyage speed when AUV passing through Current Zone, it is unreasonable to take the length measured directly as the cost of route, which should be the voyage time. As shown, the calculation formula of cost passing through Current Zone is:

$$f = (l_{SA} + l_{BT}) / v_u + l_{AB} / v$$

(8)

Where f represents the cost passing through Current Zone, l_{SA} and l_{BT} are the length of SA and BT respectively, l_{AB} represents the length of passing through Current Zone, v_u is the voyage speed out of Current Zone, v is the voyage speed within Current Zone.

Threat Zone: The enemy tends to deploy a large number of forces in a real battlefield environment, which poses a threat to

the voyage safety of AUV. Since the enemy generally uses sonar detection, an ellipsoid is used to represent the Threat Zone. AUV is destroyed in a certain probability when passing through Threat Zone.

$$S_{th} = \begin{cases} P(x,y,z) \mid P(x,y,z) \in S, \\ \left(y \in [0,h] \cap \left[(x-x_0)^2 / a^2 + (z-z_0)^2 / b^2 \right] \leq r^2 \right) \end{cases}$$

(9)

Where S_{th} is the action scope of Threat Zone; (x_0, o, y_0) is the center coordinate of the base of ellipsoid; a and b are the equatorial radius of ellipsoid (along the x and y axis); and c is the polar radius (along the z-axis).

The calculation formula of cost passing through Threat zone is:

$$f = \alpha * l / v_u$$

(10)

Where f represents the cost passing through Threat Zone; l is the length of passing; v_u is the voyage speed; α represents the threat coefficient of enemy. Threat Zone is divided into nine grades according to its threat levels. The threat coefficient varies alone with grades, the higher the grades, the greater the threat coefficient is.

Designated Zone: A dynamic heuristic route planning method is used to guide AUV passing through the Designated Zone. There are three Designated Zones in Figure I, each of which has a guided point C1~C3. The guided point C1 is taken as interim target in initial phase of route planning. Then the sub-nodes are extended from the starting point. The cost of each sub-node is calculated. The optimal node is selected as the route node forward to interim target point C1. The interim target point will be change to C2 to continue guiding route forward when the node of route access to the Designated Zone of C1. Based on this strategy, the target point will be reached in an optimal route by passing the guided point C1~C3 (See Figure II).
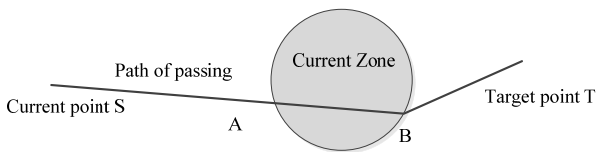

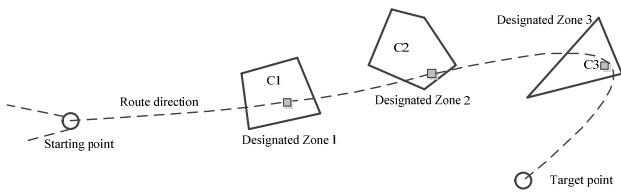FIGURE I. OPERATION METHOD OF PASSING THROUGH CURRENT ZONE

FIGURE II. ROUTE PLANNING WITH GUIDANCE POINTS

C. Cost Estimation Method

1) Cost estimation function

The rationality of cost estimation function directly influences the planning speed and the optimal result of heuristic cost method. Therefore, the physical and environmental constraints of AUV should be analyzed comprehensively when selecting the cost estimation function, which will reflect the various constraint conditions.

Relative to other fixed types of route planning method, the biggest characteristic of traditional heuristic method is joining the heuristic information through the cost calculation function:

$$f(n) = g(n) + h(n)$$

(11)

Where $f(n)$ represents the cost calculation function; $g(n)$ represents the actual cost from starting point to current node n; $h(n)$ represents the estimates cost from current node n to target point.

The heuristic route planning method with dynamic guidance can switch the guiding point with the searching deeply in real time when planning. The cost estimation function of heuristic route planning is as follow.

$$f(n) = g(n) + h_i(n) + \Delta H_i$$

(12)

Compared with the cost estimation function of traditional heuristic route planning, the heuristic route planning method with dynamic guidance has changed the cost calculation function from $h(n)$ to $h_i(n) + \Delta H_i$. Where $h_i(n)$ is the estimates cost from current point to interim target point C_i, which is calculated and changed in the extension of nodes; ΔH_i represents the estimates cost from current estimates target point C_i to actual target point. Since the value of ΔH_i is only related to the guidance point, its value can be calculated in advance when setting guide points, which is conducive to obtain the optimal path quickly.

2) Cost calculation strategy

Judge whether the environmental constraint zone exists between current point and target point is the main strategy of calculating the heuristic cost on visibility. If not, the estimates cost from current point and target point can be calculated directly, otherwise, the planning task should be decomposed into multiple tasks to calculate the heuristic cost separately.

Figure III shows the calculation strategy of heuristic cost method. Firstly, judge whether the path from extension point S to target point T exists Restricted Zone. SMT is the shortest tangent path passing Restricted Zone A. The cost from point S to T can be decomposed into subtasks 1 which calculating the cost from point S to point M and subtasks 2 which calculating the cost from point M to point T. Secondly, judge whether the Restricted Zone exists in the path of subtasks 1 and subtasks 2. The Restricted Zone B exists in the path of subtasks 1, so the subtasks 1 can be decomposed into subtasks 3 which calculating the cost from point S to point N and subtasks 4 which calculating the cost from point N to point M. There is no Restricted Zone or other types of constraint zone in subtasks 3 and subtasks 4, the cost of which can be calculated directly. The next step is to judge whether there are other types of constraint zones. There is no Restricted Zone but Current Zone D in subtasks 2. MKT is the path passing Current Zone D, which have intersection K and J. So the subtasks 2 can be decomposed into subtasks 5 which calculating the cost from point M to intersection K and subtasks 6 which calculating the cost from intersection J to point T. Since there are no Restricted Zone and other types of constraint zones in subtasks 5 and subtasks 6, the cost of which can be calculated directly. The cost from point S to T can be acquired by calculating the sum of subtasks 3, 4, 5 and 6 (See Figure IV).
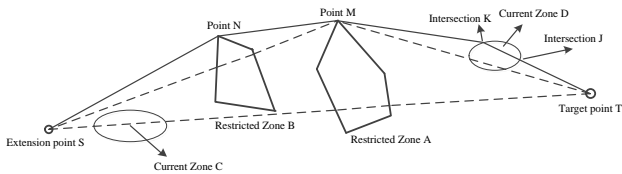

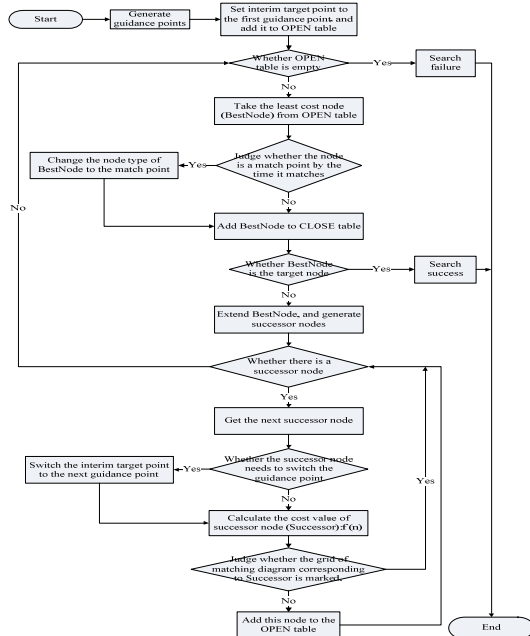FIGURE III. COST CALCULATION STRATEGY WITH DIFFERENT TYPES OF ENVIRONMENTAL CONSTRAINTS

FIGURE IV. FLOW DIAGRAM OF AUV HEURISTIC ROUTE PLANNING METHOD BASED ON COST ESTIMATION OF VISIBILITY

IV. SIMULATION VERIFICATION

A vector electronic map of approximately 1793×2167 km2 rectangular geographical area will be used in this experiment. The maximum step of AUV extension is 4 km, the minimum step is 2.5 km, and the cruising speed is 5 knots. The environmental constraint areas considered include Designated Zone, Current Zone, Threat zone and Restricted Zone. Two experiments in route planning of simple marine environment and under complex marine environment respectively will be executed in this paper, the result of which based on the method of planning of visibility analysis and based on the cost estimation through visibility of heuristic route planning method will be compared and analyzed.

In experiment 1, AUV needs to pass through Fetch Zone and Threat zone. Figure V(a) is the result using method based on planning of visibility analysis. The planning time of this method is 0.012 seconds and length of route is 391.510km. Figure V(b) is the result using method based on the cost estimation through visibility of heuristic route planning, which takes the time of 0.1 seconds and length of route is 382.720km.
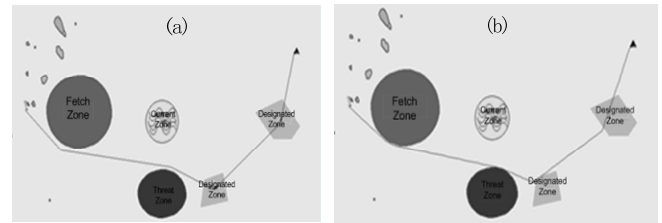

FIGURE V. ROUTE PLANNING RESULT OF EXPERIMENT 1

In experiment 2, the marine environment is much complex. Figure VI(a) is the result using method based on planning of visibility analysis, the planning time of this method is 0.37 seconds and length of route is 278.238 km. Figure VI(b) is the result using method based on the cost estimation through visibility of heuristic route planning, which takes the time of 6.31 seconds and length of route is 270.513km.
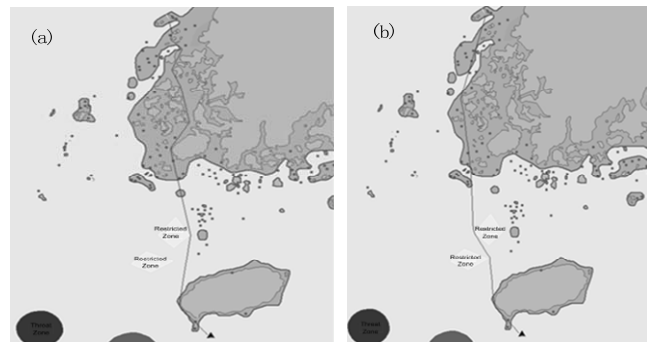

FIGURE VI. ROUTE PLANNING RESULT OF EXPERIMENT 2

It can be seen from the simulation comparison that by using the planning method based on visibility analysis and based on the cost estimation through visibility of heuristic all can plan the satisfactory route. Obviously the planning time of former takes smaller, planning speed is much quickly, but the route planned of latter will be much better.

V. CONCLUSION

This paper adopts a heuristic route planning method for AUV based on the cost estimation of visibility to make strategy analysis and researching. Through simulation comparison, the planning speed of route planning method based on the visibility analysis is much quickly, but the optimality of route is less, which is suitable for the conditions of higher requirements on speed but not too high requirements for route optimality. And the planning speed of heuristic route planning method based on the cost estimation of visibility is slower relatively, but the optimality of route is superior to the former, which is suitable for the condition of high requirements for route optimality. Therefore, the feasibility and optimality in performances of planning-time and distance by using the method based on the cost estimation of visibility is verified through simulating comparing with the planning of visibility analysis simply.

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