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Energy Priority and Current Model Based AUV Cruise Path Planning Algorithm

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Abstract

In this paper, we study the influence of the current on the selection of the cruise path of AUV (Autonomous Underwater Vehicle). We extended the current model into 3D space. According to this extended current model, we analyze AUV's energy consumption under the affects of the water flow and compare it under different cruise paths. This study mainly focuses on the path optimization based on the current model and energy priority. To some extent, it provides a theoretical basis for the optimization of the AUV cruise path.

Keywords: *AUV, path planning, current model, energy optimization*

1. Introduction

AUV (Autonomous Underwater Vehicle) is a kind of underwater robot that controls and manages the tasks with their own autonomous control processing center. It is different from remote operated vehicle with wire. Path planning is an important link of the key technologies of mobile robot. According to some optimization criteria (*e.g.*, the shortest route, the shortest travel time and the minimum work load, *etc.*) the autonomous mobile robot can find an optimal path to avoid obstacles from the initial state to goal state in its movement space [1].

Global path planning for mobile robot mainly includes two parts: one is the environment modeling; the other is the valid path searching. Environment model is an abstract description of the robot's activity space. To build an environment model, commonly the first step is to abstract the environmental factors and then use these factors to describe the reality of the environment before the path planning algorithm execution. In other words, building an environment model is to use appropriate approaches to represent the impact factors of the environment. Common environment model include raster map, topology diagram, visual map and free space method, etc.

Path searching is to search out the feasible path from the established environment model [2, 3]. The common collision-free path search methods include Dijkstra, A *, heuristic search algorithm, genetic algorithm, neural network and other artificial intelligent algorithms. Finding out a feasible path from the entire collision-free path and making the path to be smooth and optimal based on the movement characteristics of mobile robot is the final goal of the path planning algorithm.

In this paper, we mainly study the energy consumption of the AUV affected by water flow in the process of tour with the modeling of current. Through the configured current

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model, randomly selecting three different travel paths to reach the same destination, comparing the energy decrease of three tour routes, and then to examine the flow's influence on the path of AUV cruises. With these influence, we would finally get the best path between the begin point and the destination. This article does not consider complex obstacle underwater environment, the purpose of this article is to provide theoretical basis for the research, which is using natural underwater conditions to improve the performance of the AUV, for route choice of more complex obstacle underwater is not the focus of this article.

2. State of Arts

In the past, AUV was mainly used in deep submergence assignments, such as submarine topography exploration, submarine cable accident repair, *etc.* In addition, due to its inherent ability to adjust its own position quickly and its good underwater maneuvering performance, AUV has been widely used in the underwater sensor network. AUV utilizes its maneuvering characteristics to avoid network deployment hole, or participates in the relay to enhance signal transmission and data collection. AUV can greatly improve the application ability of underwater sensor networks. According to different emphasis of path planning, the researchers have carried out related researches. Guldner J. *et al.*, [4] proposed a three-layer control structure is suitable for clutter environment robot path planning. In his research the first layer is the global path planning. The second layer is the local path planning of artificial potential field. And the last is the course Angle method. Dieguez A. R. [5] also presented a combination method of six levels, including global planning and local planning, sensor information fusion, path selection, intelligent supervision and navigation, this method can get a better path, and has the characteristic of real-time local planning. With the rapid development of science and technology, some intelligent techniques are applied to mobile robot path planning, such as neural network, genetic algorithm and fuzzy control [6], *etc.* Lee M. C. and Park M. G. [7] solved the problem of local minimum of artificial potential field with combined artificial potential field method and simulated annealing algorithm. Mbede J. B. [8] designed the fuzzy controller with combined fuzzy logic and artificial potential field function and this controller can solve the problem of real-time path planning with dynamic unknown obstacles. With their effort, the efficiency of path planning has significantly improved.

The current research of the AUV’s path planning is mainly focused on the real-time job environment. With this in mind, the most important factor in the AUV’s path planning is that AUV must finish its mission as soon as possible. Since the AUV is more and more valuable in the underwater sensor network applications, we gradually discovered that the cruising ability is another point. In the UWSN (Underwater Wireless Sensor Networks) application, the AUV should continuously cruise under the water to maintain the network topology. So in the study of the AUV’s path planning, the minimization of energy consumption is also very important. This paper just focuses on this issue and studies the current’s effect on AUV’s energy consumption.

3. Path Optimization Based on the Current Model

The AUV must have enough energy to improve its cruise ability. On one hand, we can study the efficient energy storage technology to extend the AUV’s cruise time. Some researchers presented the energy harvesting technology to harvest the environment energy for AUV’s cruise [9] which also improved the cruise time of the AUV. On the other hand, we can analyze the AUV’s cruise process to find out the optimal job scheme and reduce the energy consumption. The goal of this paper is to optimize the cruise project and reduce the energy consumption through the analysis of the AUV’s task processing during the AUV’s cruise course, and finally to improve the cruise ability.

Since the active environment of the AUV is underwater, so the main resistance during the cruise is coming from the current. If we reduce the current resistance as much as we can, or even to make use of the water flow to drive the AUV, this would make great promotion to the AUV’s endurance ability.

3.1. Current Model

For the current model, there has been some valuable research in the early stage of the Physical Oceanography and the Pure Kinematics. In these studies, velocity field was used to describe the water flow. According to the scholar’s research, they found the oceans are a stratified rotating fluid, hence vertical movements are, almost everywhere, negligible with respect to the horizontal ones [10]. And the vertical movements of the float are usually limited to damped oscillations around the reference density surface triggered by internal waves [11]. With this study, Bower [12] used the current model to explain the properties of the observed paths of isopycnal floats released in the Gulf Stream. In paper [13] processed the key issues in the field of hydrology and water resources, the state-of-the art, the major progress and problems in studies and applications of distributed hydrological models.

This paper mainly studies the influence of the current on the selection of the AUV’s cruise path. Since the cruise path of the AUV is always in the three-dimensional space, we must build a current model in three-dimensional space to plan the AUV’s cruise path, and then we can get a real simulative environment. Up to now, the recent researches mainly analyze the current model in the two-dimensional space with plane analysis. To address this problem, we adopt the random offset vector to set the offset of the vertical direction based on the existing current model. With this offset vector we can simulate the current in the 3D space.

Figure 1 demonstrates a simulation water flow in the 3D space by the random offset vector and the stratified feature based on the existing current model. To study the energy consumption, we set three different paths for the AUV to reach the same destination. The point A is the current position of the AUV, and B is the destination. Among the three paths, the AB is the direct route. In the ACB route, AUV first go to C point and then goes to the destination B. In the ADB route, it first goes to D, and then goes to B point.

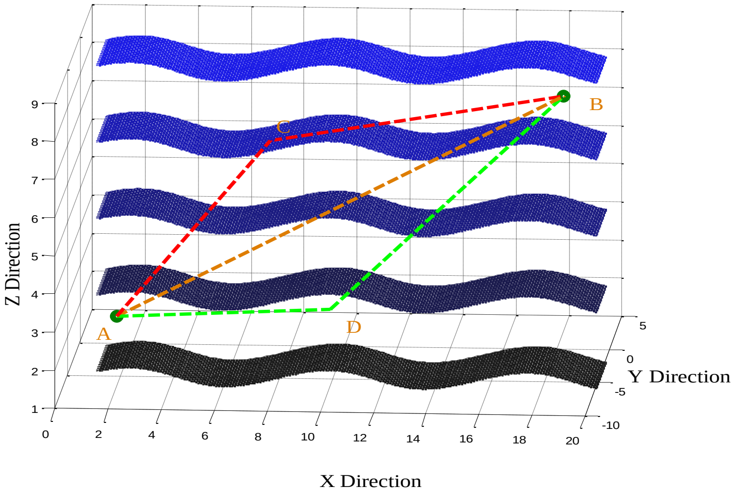

Figure 1. The current graded model and cruise path in 3D space

3.2. The Effect of the Current on Energy Consumption

The effect of the current is the most important factor to optimize the cruise path. When AUV is in the reverse flow, it must overcome the resistance of the current. Compared with the down-flow, it would consume more energy to go forward. So without considering the barrier and time priority, we should include the down-flow area in the path as much as possible, and use the current's flow to reduce the AUV's energy consumption, furthermore it can shorten the AUV's cruise time.

To make it clear, we suppose the AUV get the present current model and accurately get its logical position and the destination position. Once the cruise area model is established, the problem of the cruise path optimization would be converted to the problem of minimizing the angle between the tangent vector of the cruise path and the velocity field's tangent vector. When this angle is too large, then the water flow does negative work to AUV. At this stage the energy consumption is obvious. On the contrary, if this angle is small, water flow can do positive work. Water flow drives the AUV go ahead, so this can reduce the energy consumption. When AUV is in the ocean environment, it can even use the ocean current and vortex to cruise without power, which would effectively improve the AUV's cruise ability.

For the convenience of discussion, we make the following definitions:

$$f(x,y,t) = -\tanh\left[\frac{y - B(t)\sin(k(x-ct))}{\sqrt{1+k^2B^2(t)\cos^2(k(x-ct))}}\right] \tag{1}$$

$$dx = \frac{\partial f(x,y,t)}{\partial x} \qquad dy = \frac{\partial f(x,y,t)}{\partial y} \tag{2}$$

The $f(x,y,t)$ represents the observation spot's relative position in the plane with the time factor. In this function $B(t) = A + \varepsilon\cos(\omega t)$ modulates the width of the meanders. And the parameter k sets the number of meanders in the unit length; c is the phase speed with which they shift downstream; A determines the average meander width, ε is the amplitude of the modulation, and ω is its frequency. In this paper, we will use A = 1.2, c = 0.12, k = $2\pi/7.5$, ω = 0.4, ε = 0.3. To simplify the current model we set t = 0 and set the following offset to represent the current in the plane:

$$f_{yi} = f(x, y, 0)|_{y} + E - \alpha i \qquad (3)$$

The E is the maximum y position value of test area and α is the offset factor; i is the times of the offset. According to the expression (1), (2) and (3), we can get any point's derivative of the x-axis direction in the test area as follows:

$$F^{'} = -\frac{dx}{dy} \qquad (4)$$

The expression (4) also represents the current's instantaneous velocity direction. Next the pA represents the AUV's current position and pB is the destination. The vector $\overrightarrow{p}$ presents the AUV's instantaneous cruise direction. The $\vec{q}$ represents the current position's direction of water flow.

$$\overrightarrow{p} = pB - pA \qquad \vec{q} = (1, F^{'}) \qquad (5)$$

$$\gamma = < \overrightarrow{p}, \vec{q} > \qquad (6)$$

We can use γ to measure the current's effect to the AUV's cruise.

3.3. Get the Optimal path

Through the above discussion, it is clear that if the γ is bigger the resistance would be stronger. So to find out the optimal path, we should let the accumulated value of γ to be minimum. However, we've assumed that the AUV's move trend should be the destination's direction. To achieve the above discussions balance, we propose the following algorithm.

In this algorithm, we just focus on the current's resistance and energy efficiency. So we set aside the real-time, and we assume that during the selected path there will no barriers.

Algorithm 1

Variable descriptions: β is the angle of the next move direction vector and the current direction vector; e and g is the weighting factor; $0<e<1$, $0<g<1$;

```
if $\gamma == 0°$
    $\beta = 0°$ ;
endif
else
    if $\gamma > 0°$ and $\gamma < 90°$
        $\beta = e\gamma$ ;
    endif
    else
        $\beta = g\gamma$ ;
    endelse
endelse
```

According to the Algorithm 1, we can get the β value. And then we can get the AUV's next direction vector. Every several time intervals, we use this algorithm to correct the AUV's course.

3.4. Performance Analysis

As we discussed above, we adopt the MCM (Meandering Current Mobility) model [4] to study the effect of the current to AUV's cruise. Firstly we decompose the instantaneous velocity field to get the current direction vector, and then calculate the angle between the direction vector and the tangent vector of cruise path to measure the energy consumption. Finally we evaluate the pros and cons of different cruise paths by energy consumption. During the simulation, as the angle is the effect factor of the current cruise path, we can only consider the current's effect, which shows that the effect factor is proportional to energy consumption. The greater the angle, the stronger the resistance of the current and the more the energy consumption. In the 3D space underwater environment the vertical movements of the float are usually limited to damped oscillations around the reference density surface triggered by internal waves. So in our study, the paths in Figure 1 would be projected onto the horizontal plane. Figure 2 illustrated this condition. Figure 2 illustrates 5 paths, 3 Break Point Paths, one Down-flow Path and the Refulgence Path. When in the Break Point Path, the AUV goes to the destination following the straight line no matter in the down-flow or in the adverse current. The other two paths were the result of our algorithm respectively represents the down-flow path and the adverse current path. According to this figure, we can see that, in our selected path, the AUV would follow the current's flow trend to avoid the water flow's resistance.

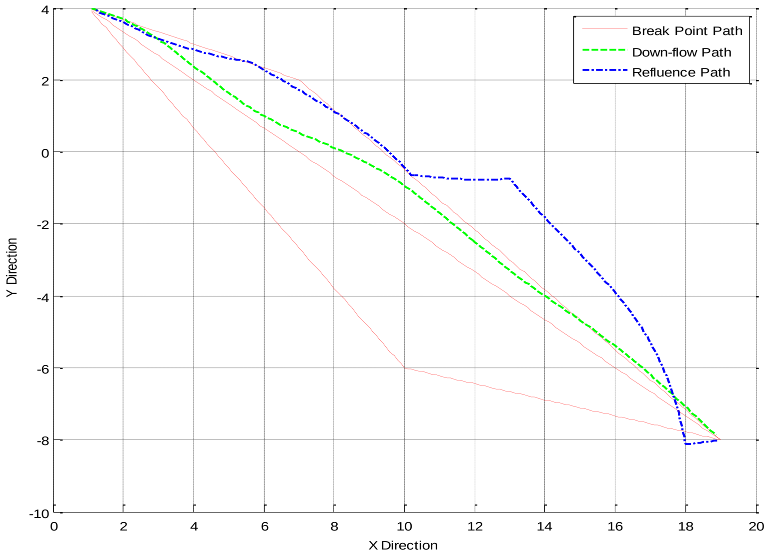

Figure 2. The projected paths

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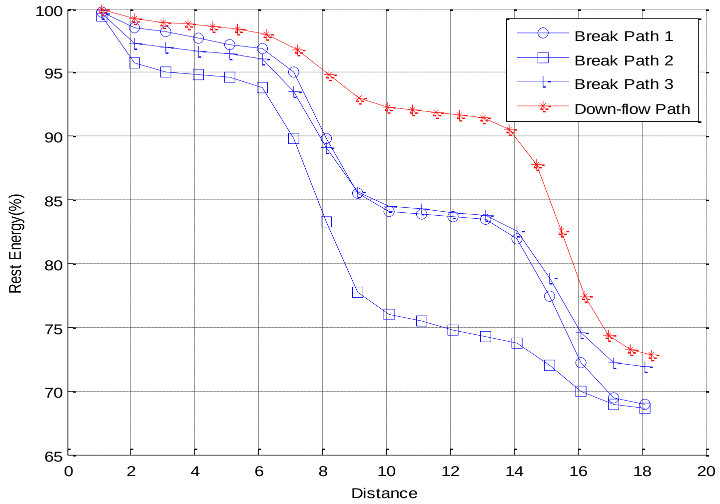

Figure 3. Energy consumption of different paths when in down-flow

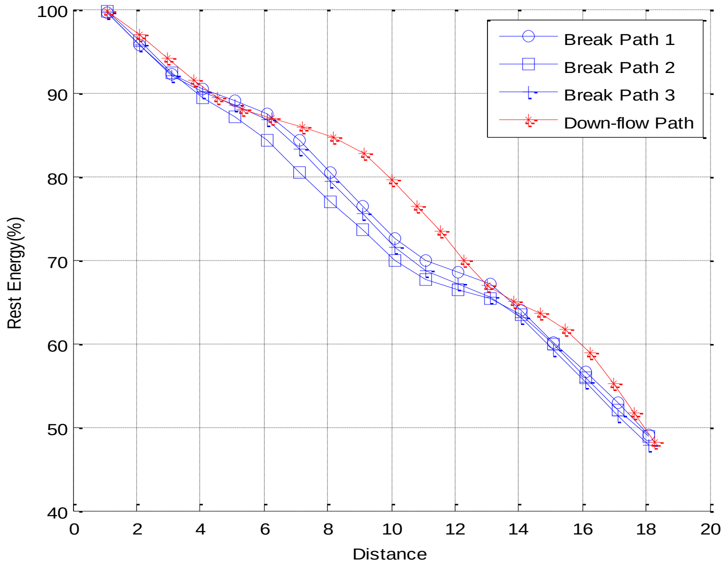

Figure 4. Energy consumption of different paths when in countercurrent

In our simulation experiment, we adjust the navigation direction according to the current position's water flow direction. So in our algorithm we firstly calculate the water flow direction vector. Then we can get the next step's direction. Figure 3 and Figure 4 illustrated the performance of our algorithm.

Figure 3 shows the different path's energy consumption when the AUV is in the down-flow. According to this figure, we can see that the path selected by our algorithm is always consuming less energy than other three Break Point Paths. During the whole route, the maximum distinction of the energy consumption is almost 8%, and at the end the Down-flow Path's rest energy is 2% larger than others.

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Figure 4 illustrats the AUV's energy consumption when it is in the countercurrent. From this figure, we can see that the red line which represents the selected path by our algorithm is above other lines. This means that even in the countercurrent our algorithm can also select the better path. But on the other hand, we can see that the superiority is not obvious. All of the five path's energy consumption trend is almost unanimously. That is because they are in the countercurrent and the resistance of the water flow covered the effect of the course adjustment.

The summarized experimental results tells us that we can adjust the AUV's course to comply with the water flow's trend to reduce the energy consumption. That is why our algorithm doesn't perform very well in the countercurrent environment. But in the down-flow it can get good results.

4. Conclusion

This paper investigated the different AUV cruise path's energy consumption under the current model. Our numerical and analytical results clearly show that it can reduce the energy consumption when we plan the AUV's cruise path. Our simulation results show that our algorithm is effective. The research of the effect to AUV is important. In the future we will continuously study the AUV's path planning based on the current model to improve the AUV's cruise ability and performance.

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