Research on Motion Control Method and Path Planning for Small Autonomous Underwater Vehicle

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Abstract. Marine resources are an important wealth for mankind. The development and application of underwater robots capable of efficiently performing various underwater tasks are of great importance for the exploration and utilization of resources. Motion control and path planning technologies are the core technologies that ensure the safe and stable operation of underwater robots in their working environment and have always been the focus of underwater robot research. This paper studies and classifies the motion control methods and path planning technologies of small Autonomous Underwater Vehicle. In terms of motion control, the content involves PID control, fuzzy control, and the sliding mode control. In terms of path planning, it analyzes the A* search algorithm, the artificial potential field method, and the ant colony algorithm, and elaborates on the characteristics of these commonly used technologies. It also compares and analyzes the advantages of the improved technologies. Based on the above investigation and research, it makes prospects for the motion control methods and path planning of small Autonomous Underwater Vehicle.

Keywords: AUV, Control Methed, Path Planning

1 Introduction

The ocean, encompassing 70% of the Earth's surface and rich in minerals, chemicals, and biological elements, serves as a crucial asset for human societies. In marine resource exploration, underwater robots, capable of executing diverse underwater functions, hold immeasurable significance. In terms of marine exploration, they can penetrate into extreme environments that are inaccessible to humans, such as the deep sea and extremely cold regions. They can contribute to scientific research and resource exploration. In industrial applications, underwater robots can be used for the maintenance of submarine oil and gas pipelines, underwater cable laying, etc., reducing the risks of human diving and improving efficiency. In environmental protection, they can monitor marine pollution and track ecological changes, providing data support for sustainable development. Moreover, underwater robot technology also promotes progress in fields such as artificial intelligence and materials science. They expand the boundaries of human activities, enhance the capacity for the utilization of marine

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resources, and play a crucial role in safety, scientific research, and environmental protection.

In the realm of marine engineering, these robots are commonly referred to as submersibles, differentiated by their control methods. These robots are categorized into Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), and Autonomous Remotely Vehicles (ARV) [1]. As per AUV industry norms, the primary size of these small underwater robots is under 2m [2], and this study focuses on small, autonomous underwater robots. Path planning technology and motion control technology are key technologies for underwater robots. In the intricate underwater environment, the motion control methods and path planning strategies of AUV ensure their safety and stability, preventing collisions. This allows the robots to move along the optimal path, ensuring operational accuracy and speed in reaching the target point. At present, in response to the adaptability requirements of underwater robots in various operational environments, researchers have proposed multiple path planning and motion control strategies. The motion control methods for underwater robots need to be selected based on task demands and environmental characteristics. Traditional methods such as PID have advantages in stability and real-time performance, while intelligent control methods such as neural networks and fuzzy control are more suitable for complex nonlinear scenarios. Path planning methods include path planning based on artificial potential field methods, which can effectively avoid obstacles and ensure the safe arrival of the robot at the target. However, its drawbacks in local minimum problems limit its application. In contrast, path planning methods based on graph search algorithms, such as A* algorithm, can find the shortest path in complex environments, but there may be bottlenecks in computational efficiency. This paper categorizes several commonly used underwater robot motion control strategies and path planning methods.

2 Existing Underwater Robot Control Methods

2.1 Integration of PID control with other control methods as a classical feedback control strategy

PID control can be used to stabilize the depth, heading, or position of an AUV, or to control the speed and direction of its propellers to perform the desired task, due to its simple structure, easy implementation, and lack of reliance on accurate mathematical models. The principle of PID control is depicted in Figure.1:

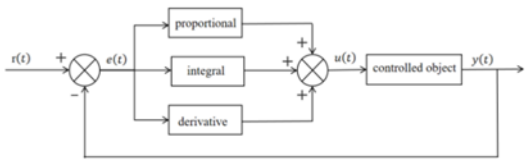

Fig. 1. PID schematic diagram

The regulatory formula for a PID controller can be expressed as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

K_p , K_i and K_d are the proportional, integral, and derivative coefficients, respectively, and $r(t)$, $e(t)$, $u(t)$, and $y(t)$ are the input value, the error value, the controller output value and the actual output value, respectively.

2.1.1 Fuzzy PID control.

Fuzzy control is to transform the experience summarized by human beings into control rules through fuzzy language and fuzzy conditional statements, and then realize it by computer to complete the control effect [3]. Fuzzy PID control merges elements of both PID and fuzzy control. Its structure is depicted in Figure.2.

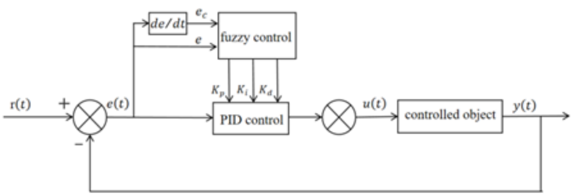

Fig. 2. Schematic diagram of fuzzy PID

Its input is e and e_c, namely deviation and deviation rate, and it uses fuzzy rules to adjust parameters K_p, K_i and K_d to correct the final output value.

Miao used the Simulink simulation model to test the performance of the classical PID and fuzzy PID in heading and depth control of the AUV. The data shows that the influence of the fuzzy PID controller on control applied to direction and depth control has smaller overshoot, adjustment time, and steady-state error than that of the classical PID controller [4].

2.1.2 Cascade PID Control.

Cascade PID control generally consists of multiple PID controllers connected in series with the controlled objects. The output value of one regulator serves as the setpoint for another. In the application of underwater robots, it is commonly used to control the pitch angle by constructing two closed-loop circuits to control both the angle and angular velocity. In the research by Wang et al. tested that the cascade PID controller demonstrated higher control accuracy in controlling the pitch angle of underwater robots compared to the classical PID controller, but the control was not completely stable [5].

2.2 Sliding Mode Control and Its Improved Control Methods

Sliding mode control is an efficient nonlinear control strategy with strong robustness and has been applied in the field of AUV. A sliding mode control system needs to meet three conditions:
(1) Reaching condition: The system can reach and enter the switching surface from any position within a finite time.
(2) Existence condition: There exists a sliding mode region on the switching surface.
(3) Stability condition: The system's motion on the sliding mode region is asymptotically stable and has good dynamic performance.

Creating a sliding mode controller for subaquatic robots primarily involves a two-step process: Choosing a suitable sliding surface and formulating a control law, which allows the system to near the sliding surface within an effective time. Sliding mode control also needs to minimize the negative effects caused by chattering.

Li tested three control methods in his self-designed underwater robot motion control simulation experiment using Matlab, namely classical PID control, fuzzy PID control, and sliding mode control. Experimental data show that in the simulation of surface swimming motion, the stabilization time of sliding mode controller is shorter than that of classical PID controller and fuzzy PID control, and there is no obvious overshoot [6]; in the simulation of turning motion, compared to the two PID controllers, the sliding mode controller excels in stabilizing time and reducing overshoot.

Guo improved the conventional sliding mode controller in his research. He proposed to use an RBF network to approximate the model change and a saturation function instead of a sign function to reduce system chattering. Findings from the simulations indicate the efficacy of this technique in diminishing chattering. [7].

2.3 Other Control Methods and Summary

There are numerous motion control methods for underwater robots. This paper elaborates only on several common methods, such as neural network control and expert control. The integration of multiple control methods has become a current development trend in the motion control of underwater robots, especially when combined with PID control. For instance, Mohammad Hedayati Khodayari et al. designed an adaptive fuzzy PID controller for the dual-channel tracking control of the heading and depth of underwater robots, achieving good robustness, dynamic performance, and stability [8].

3 Current Path Planning Strategies for Underwater Robots

Path planning ensures the safety of underwater robots and helps them find the shortest and most optimal path. Currently, there are numerous path planning methods applied to AUV,which can be broadly categorized into three distinct groups: geometric model-based search methods, virtual potential field-based search methods, and artificial intelligence-based search methods [9]. This article will elaborate on several commonly used methods within the three categories.

3.1 A* Search Algorithm and Its Improved Methods

In the path planning of underwater robots, geometric model search methods require the construction of an underwater environment model first. Modeling methods include the visibility graph method, the grid method, and others. Then, the best path is searched for according to the search algorithm. Currently, the A* search algorithm is a relatively common search algorithm. The A* search algorithm merges the benefits of both the Dijkstra and BFS algorithms into a heuristic approach, allowing it to quickly search for optimal path nodes to form a path.

The expression for the evaluation function f(n) of the A* algorithm is:

$$f(n) = g(n) + h(n) \qquad (2)$$

Among them, the actual path distance $g(n)$ is from the starting point to node n, and the estimated path distance $h(n)$ is from node n to the target node, which represents the heuristic function; $f(n)$is the estimated distance from the starting point through the current node n to the target point. The methods for calculating distances $g(n)$ and $h(n)$encompass measurements such as Euclidean distance and Manhattan distance, etc.

The benefits of the A* algorithm include its minimal computational demand and superior efficiency when applied to search for the best path in underwater robots. However, it also has some shortcomings, such as the generation of redundant points and turning points, resulting in a less smooth path.

Wang and colleagues initially enhanced the precise computation technique for the assessment function in the conventional A* algorithm, reducing the computational load and enhancing the algorithm's efficiency in searching. Then, they changed the weight ratio in the evaluation function to minimize the number of turning points and superfluous points in the created path. They also improved the path generation strategy of the traditional A* algorithm, making the generated path smoother [10]. Gao et al. applied the improved A* algorithm to the path planning of underwater robots. According to the simulation data, the A* algorithm with the improved evaluation function has a faster planning speed than the traditional A* algorithm, significantly reducing planning time, removing redundant turning points, improving path smoothness, and better meeting actual needs [11].

3.2 Artificial Potential Field Method and Its Improved Approaches

Khatib and colleagues introduced the concept of the artificial potential field method. The idea is to artificially build a virtual potential field. When an underwater robot is placed in this field, areas it is not expected to enter or dangerous areas are defined as repulsive poles, while areas it is expected to enter or the target position is defined as attractive poles. The underwater robot moves in the potential field under the combined force of repulsive forces from the repulsive poles and attractive forces from the attractive poles, heading towards the target direction. The principle is illustrated in Figure.3.

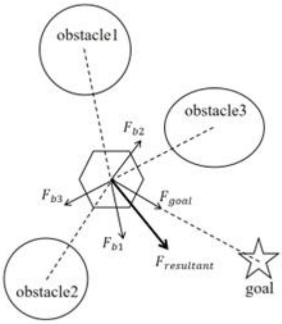

Fig. 3. Schematic diagram of the artificial potential field method.

The magnitudes of the thrust and gravitational force of underwater robots are related to the potential field function. Different potential field functions lead to different effects on path planning. However, the traditional artificial potential field method has two problems in practical application: the problem of unreachable targets and local minimum points. Zhan proposed solutions in his research. He re-constructed the thrust potential field function and proposed the "outer tangent circle of equipotential lines" escape method. The simulation tests confirmed that the improved artificial potential field method is more suitable for actual working environments [12].

3.3 Ant Colony Algorithm and Its Improved Methods

Italian academics M. Dotigo and colleagues introduced the ant colony algorithm. This refers to a population-based heuristic random search algorithm, influenced by ants' natural path-finding patterns [13]. Because ants leave pheromones when they search for paths, if a path leaves more pheromones, the likelihood of subsequent ants passing through this path is higher. Through this positive feedback mechanism, the optimal path is eventually found. The transition probability determines the selection of the next node by ants, and the likelihood of transition correlates with the concentration of pheromones along the route to the node. The likelihood of transition is denoted as:

$$P_k(i,j) = \begin{cases} \frac{\tau_{ij}^{\alpha}(t)\,\eta_{ij}^{\beta}(t)}{\sum \tau^{\alpha} \eta^{\beta}} & ,j \in J_k(i) \\ 0\,, otherwise \end{cases} \quad (3)$$

Among them, α and β respectively represent the pheromone heuristic factor and the expected heuristic factor. $J_k(i)$ indicates the node that ant k can choose next,$\tau_{ij}^{\alpha}(t)$represents the pheromone concentration on the L(i, j) path, and $\eta_{ij}^{\beta}(t)$ is usually the inverse measure of the distance separating two nodes. After all ants have traversed once, the way of pheromone update on each path is expressed as:

$$\tau_{ij}(t+n) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij} \quad (4)$$

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta^k \tau_{ij} \quad (5)$$

$$\Delta\tau_{ij}^{k} = \begin{cases} \frac{Q}{L^*} \\ 0 \end{cases} \quad (6)$$

Among them, ρ denotes the volatility coefficient of pheromone, τ_{ij} is the increment of pheromone concentration on the path (i,j) of this cycle, $\Delta^k\tau_{ij}$ represents the quantity of pheromone emitted by the kth ant during this cycle, Q represents the cumulative pheromone build-up along the path of the kth ant, while L* denotes the current shortest path's length.

When the traditional ant colony algorithm is applied to practical application of underwater robot path planning, Issues like sluggish rate of convergence, tendency to fall into local optimal situations, large cumulative turning angles, and susceptibility to collisions with obstacles occur. Qian et al. proposed methods such as improving the initial pheromone and pheromone update methods of the ant colony algorithm, fusing it with the genetic algorithm, and adopting smoothing mechanisms for optimization processing. Through simulations, it was proved that the enhanced ant colony algorithm holds substantial benefits compared to the conventional ant colony algorithm in the realm of AUV path planning, exhibiting commendable overall efficacy [14].

3.4 Other Path Planning Methods and Summary

Based on the current application results, methods such as the A* search algorithm, artificial potential field method, ant colony algorithm, and their improved versions have the advantage of being easy to operate in practice and yielding good path-planning results. However, many excellent path planning algorithms are still under development. Currently, research focuses not only on improving commonly used algorithms but also on integrating artificial intelligence algorithms with path planning. For example, path planning methods based on machine learning, which plan the movement paths of underwater robots through learning and training, can be used without relying on built environment models and can plan paths in real-time.

4 Conclusion

There are numerous studies on the motion control methods and path planning of AUV. This paper classifies them, analyzes, and elaborates on the characteristics of common methods. In terms of motion control methods, this paper covers improved control methods which integrate PID control alongside various other control techniques, as well as sliding mode control and its improved versions. It is believed that the integration of multiple control methods has become the current development trend in AUV motion control.

In terms of path planning, this paper discusses three types of path planning strategies: geometric models, virtual potential fields, and artificial intelligence. It reviews methods like the A* search algorithm, the artificial potential field method, and the ant colony algorithm, as well as their improved versions. It is believed that future path planning strategies should not only focus on improving classic methods but also pay attention to their integration with artificial intelligence and machine learning. Unlike land environments, underwater environments are complex and changeable. As the tasks that AUV need to complete become increasingly complex, the demand for accuracy and efficiency will continue to grow. During this research process, simulation results made up the majority. In the future, more methods will be put into practical use.

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