Motion Planning for Wave-Like-Actuated Manta-Inspired Amphibious Robots

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Abstract. Inspired by manta rays, an amphibious robot is designed by utilizing a wave-like mechanism for propulsion. In terms of robot design, the swimming characteristics of the manta ray are analyzed, and mechanical structures such as flexible biomimetic fins and wave-like propulsion mechanisms are designed, enabling the robot to move both in water and on land. Furthermore, the kinematic model of the wave-like-actuated manta-inspired amphibious robot is established. Then, a path planning method based on the improved Rapidly-exploring Random Tree (RRT) algorithm is proposed, and combined with S-curve acceleration and deceleration planning to achieve velocity planning for robots. Experiments are conducted to validate the robot's motion performance and the effectiveness of the motion planning algorithm.

Keywords: Wave-like propulsion · Amphibious robot · Improved RRT algorithm · S-curve acceleration and deceleration planning

1 Introduction

Amphibious robots capable of operating in both terrestrial and underwater environments are essential for various tasks, such as environmental monitoring, resource exploration, topographic mapping, pipeline and cable inspection, and more. However, these tasks often present significant challenges due to the unique characteristics of underwater environments, such as obstructed visibility, wave effects, and signal interference, which can impact the efficiency and accuracy of the robots.

To overcome these challenges, research on biomimetic amphibious robots has been conducted worldwide [1], demonstrating significant research and practical applications value [2]. Ma X et al. developed a multimodal amphibious robot with flipper paddles [3], designed as separate modules for water and land operations and ingeniously integrated together. ACM-R5 [4] employs deformable mechanisms and multi-joint mechanical design to achieve adaptability and flexibility in different environments.

Biomimetic robots, inspired by natural organisms, exhibit superior adaptability and flexibility. For example, biomimetic robots mimic the hexapod walking of insects [5], the

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flight of birds [6], and the swimming of fish [7]. In the realm of biomimetic oscillating fins, Katzschmann et al. developed a bio-inspired underwater soft robotic fish called SoFi [8], while Wang Y researched a flexible fin-propelled underwater robot [9].

Motivated by the above discussion, this paper aims to investigate the motion planning problem of wave-like-actuated manta-inspired amphibious robots, as depicted in Fig. 1. First, the swimming posture and movement patterns of manta rays are analyzed and studied, in order to cleverly apply them to the design of robots. Subsequently, by combining the physical model and kinematic equations of the robot, the kinematic model is established. Based on this, the motion planning algorithms for the robot in water and on land are deployed, including aspects such as path planning, velocity planning, etc., followed by the implementation and simulation verification of aforementioned algorithms. Finally, experiments are designed to validate the effectiveness and feasibility of the biomimetic manta ray amphibious robot's motion planning algorithms, providing new ideas and methods for research and applications in this field.

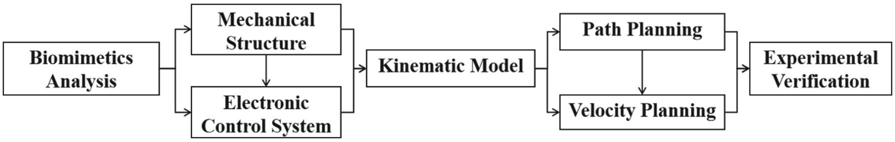

Fig. 1. Research content flowchart

2 Design of the Manta-Inspired Amphibious Robot

2.1 Analysis of Manta Ray Motion Mode

The manta ray is an underwater creature with a unique swimming style, as shown in Fig. 2. Its elongated undulating fins provide excellent maneuverability and high adaptability. It can cruise smoothly in calm waters, swim slowly in complex environments, make turns, and rapidly accelerate from a stationary position. Therefore, biomimetic studies of the manta ray's swimming style hold significant value for the robot design.

In the manta ray's locomotion, the main propulsive force is generated by its pectoral fins. The pectoral fins extend along a large portion of its body, gradually tapering towards the rear and displaying a substantial number of fin rays. Each fin-like ray oscillates around its equilibrium, and the phase difference between adjacent fin-like rays remains constant during swimming [10]. This continuous undulation represents the overall motion of the fins coordinated by the fish's nervous system. Unlike other fish species, the manta ray can smoothly transition from forward to backward swimming without turning its head, and vice versa. As a result, one of the unique features of the manta ray's pectoral fin undulation is its ability to provide bidirectional propulsion simultaneously [11].

Noticing the wave-like characteristics of the elongated fin, it can be effectively parameterized using sinusoidal functions for enabling the design of a wave-like propulsion mechanism. Furthermore, by simply adjusting the parameters, it is easy to achieve bidirectional propulsion and freely switch between forward and backward movement, which

Fig. 2. The manta ray

has significant implications for designing autonomous underwater vehicles with higher maneuverability and stability.

2.2 Design of Mechanical Structure

In the control system architecture of the manta-inspired amphibious robot, the ESP32 acts as the robot's brain, facilitating communication with the upper computer, driving motors, and capturing motor speed data. The microcontroller receives wireless signals from the upper computer, transmitting speed signals to the drive module for motor rotation control through signal amplification. Encoders capture motor speed information, forming a closed-loop control system that precisely manages motor speed and direction. The motor which driven by the microcontroller rotates the helical rods, enabling wave-like propulsion and flexible biomimetic fin movements for linear advancement, deceleration, acceleration, and turning.

The mechanical structure of the wave-like-actuated manta-inspired amphibious robot, as depicted in Fig. 3, consists of multiple components. The entire robot comprises front and rear motor compartments, wave-like propulsion mechanisms, flexible biomimetic fins, a central electronic control compartment located above the middle section, and other fixed parts.

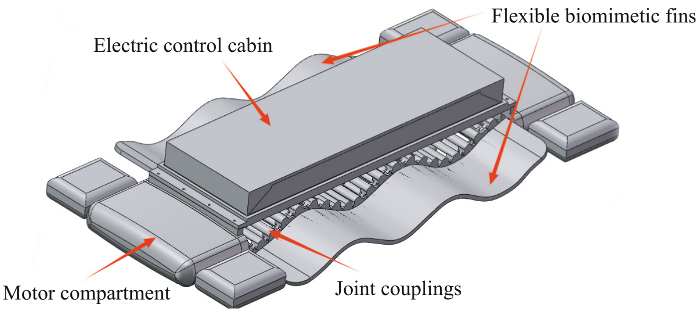

Fig. 3. Three-dimensional structure of the manta-inspired amphibious robot

Motor Compartment and Joint Couplings. The front and rear motor compartments have identical structures, each housing a brushless motor installed on the left and right sides. Each brushless motor's shaft is connected to a helical rod, where one end attached to the motor shaft serves as the active rod head, and the other end without a motor is connected to the passive rod head, forming a joint coupling. Each helical rod passes through n active linkages connected in series, creating articulated joint couplings that can swing up and down as the helical rods rotate. These joint couplings, as shown in the orange part in Fig. 4, are crucial components for actuating the robot motion.

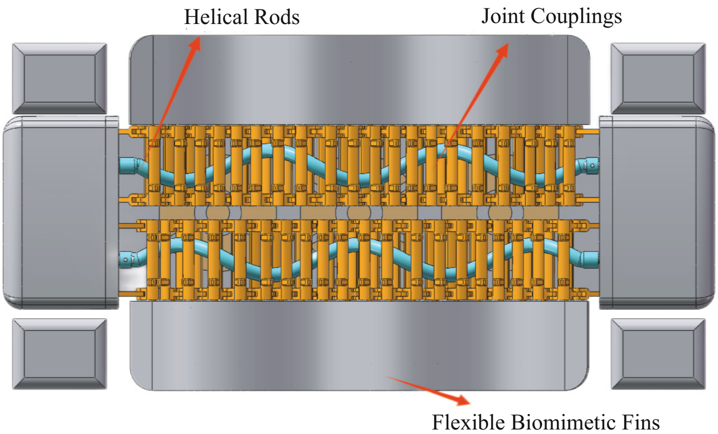

Fig. 4. Bottom view of the manta-inspired amphibious robot

Wave-Like Propulsion Mechanism. The middle wave-like propulsion mechanism [12] is also a vital component of the robot. It utilizes two parallel rows of helical rods to create a sinusoidal wave translation of the articulated joint couplings, as illustrated in Fig. 5. This sinusoidal wave enables the robot to move forward and backward on land.

The advantages of the wave-like propulsion mechanism include high efficiency, low energy consumption, as well as strong reliability. Compared with traditional wheeled or tracked robots, the manta-inspired amphibious robot exhibits more agile and flexible movement on land, which is beneficial for navigating through complex terrains. Furthermore, through the arrangement of parallel columns and differential drive, the wave-like propulsion mechanism can achieve turning the motion control, providing the robot with all-round mobility.

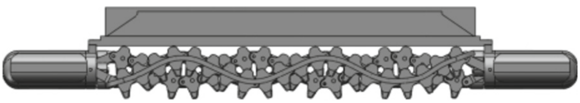

Fig. 5. Side view of the manta-inspired amphibious robot

Flexible Biomimetic Fins. The design of the flexible biomimetic fins involves simulating and optimizing the fins found in biology, resulting in efficient fins capable of propelling the robot efficiently underwater. The use of silicone rubber covering not only protects the supporting bones but also enhances the flexibility and durability of the fins, allowing the robot to move more flexibly and smoothly in water. Besides providing excellent stability and maneuverability, the biomimetic fins achieve efficient propulsion with lower energy consumption, while reducing noise and hydrodynamic resistance in water.

3 Establishment of the Manta-Inspired Amphibious Robot's System Model

The helical rod of the manta-inspired amphibious robot can be represented as a helix with the following expression [12]:

$$\begin{aligned} x &= Db, \\ y &= A\sin(2\pi b), \\ z &= A\cos(2\pi b), \end{aligned} \tag{1}$$

where D is the length of the helix pitch, A is the radius of the helix, and b is the independent parameter.

The two parallel rows of the wave-like propulsion mechanism convert the helix motion into the sinusoidal wave translation of the articulated joint couplings. The two-dimensional projection of the helix on the X-Z plane ($y = 0$) produces a sinusoidal function curve, as shown in Fig. 6.

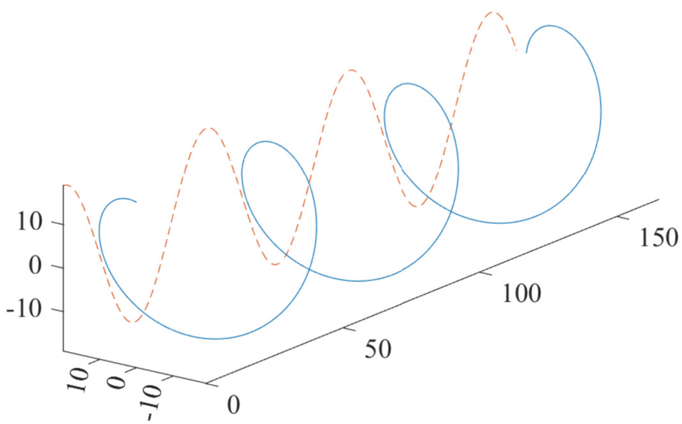

Fig. 6. Representation of the helical rod and wave-like propulsion

The two-dimensional projection expression is

$$\begin{aligned} x &= Db, \\ z &= A\cos(2\pi b) = A\cos\left(\frac{2\pi x}{D}\right). \end{aligned} \tag{2}$$

Based on the structural design of the manta-inspired amphibious robot, the relationship for wave speed and frequency, and the relationship between the rotation radius and rotation angle, can be derived as $\boldsymbol{q} = [\,x\ y\ \alpha\,]^{\mathrm{T}}$:

$$\dot{\boldsymbol{q}} = \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{D\cos\alpha}{120} & \frac{D\cos\alpha}{120} \\ \frac{D\sin\alpha}{120} & \frac{D\sin\alpha}{120} \\ \frac{D}{120l} & -\frac{D}{120l} \end{bmatrix} \begin{bmatrix} n_L \\ n_R \end{bmatrix} \tag{3}$$

where n_L and n_R are the respective speeds of the left and right motors, respectively, α represents the pose angle of the robot, and l represents the vertical distance of the robot's center of mass to the line of wave mechanism velocities on the left and right sides.

To describe the robot's motion patterns more clearly, we set the positive direction of the *x-axis* as the forward direction of the robot. The motor shaft of the front-end motor rotates clockwise, and the connected helical shaft points to the positive direction of the *x-axis*, giving the robot a tendency to move towards the positive *x-axis*. Conversely, the motor shaft of the rear-end motor rotates counterclockwise, and the connected helical shaft also points to the positive direction of the *x-axis*, similarly giving the robot a tendency to move towards the positive *x-axis*. When both motors have the same speed, the robot will move in a straight line along the *x-axis*. However, when the speed of the front-end motor is greater than that of the rear-end motor, the robot will tend to turn towards the negative *y-axis*. Conversely, when the speed of the rear-end motor is greater than that of the front-end motor, the robot will tend to turn towards positive *y-axis*. The greater the speed difference between the two motors, the more pronounced the turning tendency of the robot will be.

4 Motion Planning Algorithms, Simulations and Experiments

Motion planning is an important research direction in the field of robotics, with the aim of designing algorithms to enable robots to perform specific tasks in complex environments. Over the past few decades, various motion planning algorithms have been proposed [13]. For the motion planning of the bionic aquatic-terrestrial amphibious robot inspired by the manta ray, it is possible to explore a novel motion planning algorithm to enhance the robot's motion control capability and accuracy for better task completion. Additionally, this research can offer new ideas and innovative points for the development of motion planning in the field of robotics.

4.1 Path Planning

Principles of Path Planning Algorithm. The Rapidly-exploring Random Tree (RRT) algorithm [14] is a single-robot path planning algorithm based on a tree-like structure. The basic idea of the RRT algorithm is to randomly sample points in the configuration space and gradually connect these sampled points together through a certain expansion strategy, forming a tree-like structure. Figure 7 illustrates the node expansion process of the Rapidly-exploring Random Tree.

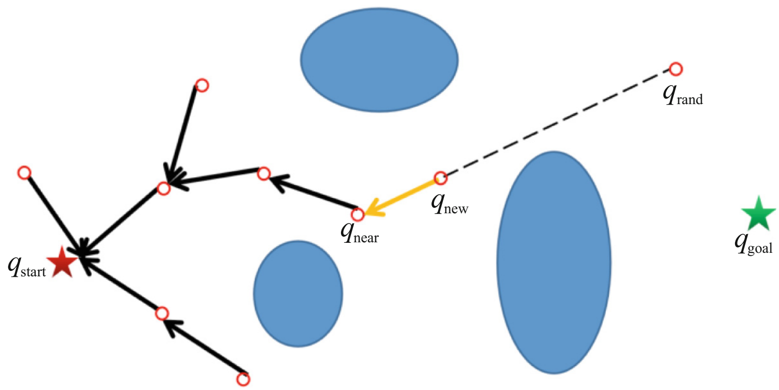

Fig. 7. Illustration of node expansion process in Rapidly-exploring Random Tree

The RRT algorithm is well-suited for solving path planning problems in high-dimensional and continuous spaces, and it can perform online path planning during runtime. Nevertheless, it may produce relatively longer paths and cannot guarantee to find the optimal solution. Therefore, in this paper, the RRT algorithm is optimized based on specific conditions.

Specific Steps for Implementing Improved RRT Algorithm. The improvement of the RRT path planning algorithm focuses on the termination condition and path optimization.

First, the process is initialized by setting the step size and maximum number of iterations, selecting the start and target points, and constructing them in the form of a tree. Random sampling is then performed, introducing a method of random direction. When selecting a parent node, the closest point to the sampled point is chosen as the parent node, avoiding the need for nearest neighbor search during parent node selection, thus saving computational time. Moreover, this method increases the coverage of the search space, enhancing the success rate of path planning. During path planning, collision detection is conducted when extending towards the sampled point. If there is no collision in this distance, and the distance between the new point and all existing points is greater than a certain threshold, the new point is added to the RRT tree.

To expedite the search process and conserve resources, two main improvements are made to the basic RRT. Firstly, after each iteration of generating a new point, it checks whether a direct connection can be made between this new point and the target point. If a direct connection is feasible, the algorithm connects this point directly to the target point, resulting in the target path. After reaching the maximum number of iterations, if no solution path is found, the path planning is considered a failure.

Secondly, considering that the manta-inspired amphibious robot may need to repeatedly go back and forth between the target point and the start point, this paper optimizes the already explored path to obtain a smoother trajectory. The approach is as follows:

1. Start from the initial node as the first node and traverse the entire path step by step.
2. Connect the starting node and the node being traversed (ending node).
   a. If there is no collision between the starting node and the ending node, directly connect them to eliminate intermediate redundant nodes.
   b. If a collision occurs, determine the previously traversed start and end nodes (line segment) as part of the new path and update the starting node to be the previous ending node from the previous iteration.
3. Repeat the above iteration until the entire path is traversed.

Ultimately, this results in an optimized path consisting of a few line segments. The visualization of path planning is shown in Fig. 8 (where the start and target points are located at [0, 0] and [10] respectively, the green line represents the path obtained from the Rapidly-exploring Random Tree search, the red line represents the optimized path, and the black squares represent the obstacles).

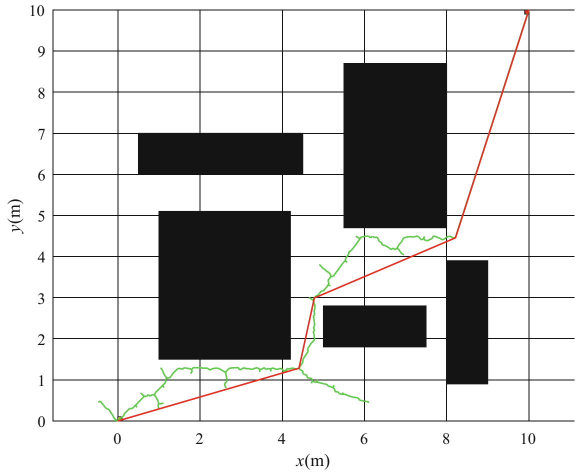

Fig. 8. Simulation results of path planning

It can be observed that the original RRT algorithm takes a longer and more winding path, with frequent changes in the robot's direction, leading to the energy loss. The improved RRT, on the other hand, simplifies the path into a straight line, shortening the distance and allowing the robot to achieve higher speeds on the straight segments, further reducing the overall travel time.

4.2 Velocity Planning

To address the drawbacks of the trapezoidal acceleration/deceleration planning method, the S-curve acceleration/deceleration planning method is chosen. The S-curve acceleration/deceleration planning method is an advanced motion control technique aimed at achieving smoother and more precise motion control by controlling the changes in acceleration and deceleration, resulting in an S-shaped trajectory during the acceleration, constant velocity, and deceleration phases. The advantages of the S-curve acceleration/deceleration planning method are as follows:

1. Smooth motion: The S-curve acceleration/deceleration planning method ensures smooth velocity changes during the acceleration, constant velocity, and deceleration phases, reducing motion impacts and vibrations, thereby achieving smoother motion.
2. High motion efficiency: Compared to the trapezoidal acceleration/deceleration planning method, the S-curve acceleration/deceleration planning method allows for faster velocity changes, leading to shorter motion duration and improved motion efficiency.
3. High control precision: The S-curve acceleration/deceleration planning method enables precise control of velocity and displacement changes, resulting in higher motion control accuracy.

In general, the S-curve acceleration/deceleration planning method offers higher motion control precision and efficiency compared to the trapezoidal acceleration/deceleration planning method. However, it requires more advanced algorithms and equipment support, and also places higher demands on the mechanical structure. Fortunately, the mechanical structure and controller of the manta-inspired amphibious robot can meet these requirements effectively. Therefore, the S-curve acceleration/deceleration planning method, which provides better results, is chosen for implementation.

According to the method described in reference [15], the displacement profile as a function of time is given by:

$$S(t) = \begin{cases} J\tau_1^3/6 & 0 \le t < t_1 \\ S_1 + v_1\tau_2 + JT_1\tau_2^2/2 & t_1 \le t < t_2 \\ S_2 + v_2\tau_3 + JT_1\tau_3^2/2 - J\tau_3^3/6 & t_2 \le t < t_3 \\ S_3 + v_3\tau_4 & t_3 \le t < t_4 \\ S_4 + v_4\tau_5 - J\tau_5^3/6 & t_4 \le t < t_5 \\ S_5 + v_5\tau_6 - JT_1\tau_6^2/2 & t_5 \le t < t_6 \\ S_6 + v_6\tau_7 - JT_1\tau_7^2/2 + J\tau_7^3/6 & t_6 \le t < t_7 \end{cases} \tag{4}$$

After conducting the simulation, the curves for acceleration, velocity, and displacement are obtained, as shown in Fig. 9.

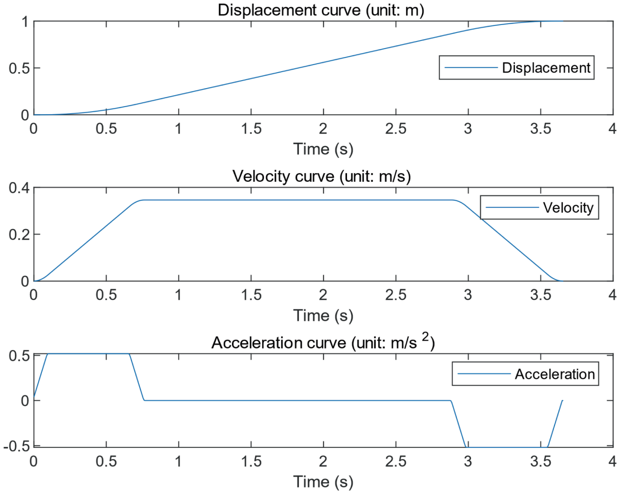

Fig. 9. Simulation results of velocity planning

4.3 Experiments

The experimental prototype is depicted in Fig. 10, and the preliminary experimental results of path planning are shown in Fig. 11.

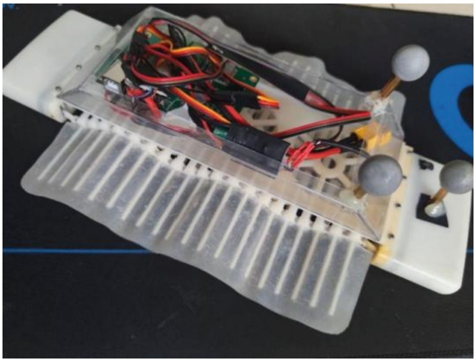

Fig. 10. The experimental prototype

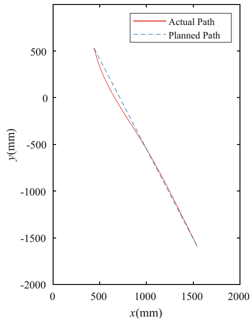

Fig. 11. Preliminary experimental results of path planning

As seen in the actual path compared to the planned path, the deviation is minimal. This confirms the reasonable design of the robot's mechanical structure and the effectiveness of the electronic control system, indicating stable motion performance. Furthermore, it demonstrates that the robot can follow the planned trajectory to a satisfactory extent, achieving the preliminary application of path planning and laying a solid foundation for the future application of more advanced algorithms.

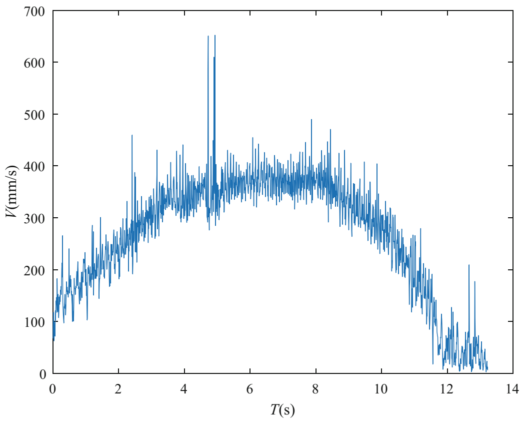

Fig. 12. Preliminary experimental results of velocity planning

The preliminary experimental results of velocity planning, shown in Fig. 12, demonstrate that the robot can successfully start and stop with smooth acceleration and deceleration. However, during startup, the robot did not fully track the expected S-curve for acceleration due to the maximum static friction being greater than sliding friction. This analysis suggests that improvements can be made in the control algorithm to optimize velocity planning.

In this section, through the conducted experiments, the motion performance of the designed bionic amphibious robot and the effectiveness of the motion planning algorithm are verified. In the initial validation experiments without velocity planning, an unexpected situation occurred due to poor motor gear engagement, highlighting the importance of velocity planning. The experimental results show that the designed robot can achieve motion and exhibits good stability and accuracy. The motion planning algorithm enables path and velocity planning, resulting in smoother and more natural robot motion.

5 Conclusion

In this paper, a bionic amphibious robot inspired by the manta ray is designed. Overall, the structural design of this manta-inspired amphibious robot is utilized by the principles of wave propulsion and biomimetic fins to achieve amphibious motion. By designing and constructing the robot's mechanical and circuit structures, successful emulation of the manta ray's swimming motion is achieved. The model is established, and an improved RRT algorithm is used for path planning. A S-curve acceleration and deceleration planning method is adopted for the speed control, enabling precise robot control. Finally, the experimental results demonstrate that the amphibious biomimetic robot designed in this paper exhibits relatively good motion smoothness and control stability.

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