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Motion Stability Evaluation of the Improved Spherical Underwater Robot with Hybrid Propulsion Devices

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***Abstract* - To meet the challenges of different underwater environments, improve the operating efficiency of the underwater robots, this paper designed the spherical underwater robot with a hybrid propulsion devices (water-jet-device and propeller-device). The robot we designed has different motion modes such as propeller-drive, water-jet-drive, and hybrid drives. It can not only realize speed switching in complex environments, but also enhance motion stability and improve operation efficiency. Then, to analyze the motion characteristics of the SUR, this paper assembled the hybrid propulsion spherical underwater robot (HPSUR). Finally, this paper carried out the motion experiments in the pool, including forward-motion experiments and rotation-motion experiments. The motion experimental result showed that the improved hybrid propulsion devices we designed had better performance, improved the motion speed and work efficiency.**

Index Terms - Spherical underwater robot, Hybrid propulsion, motion mode.

I. INTRODUCTION

With the continuous development of control technology, communication technology and sensors, underwater robots have replaced humans in various unknown environment tasks, such as underwater rescue, ocean exploration, pipeline maintenance, etc [1]-[2].

At present, more and more institutions at home and abroad are conducting research on underwater propulsion devices. For example, *T G ao et al.* designed a propulsion device by imitating the fins of fish in 2019 [3]-[4]. *Gasparoto H et al.* designed a magnetic coupling propulsion device with features radially reconfigurable in 2017 [5]. *Kadiyam J et al.* proposed a hybrid propulsion device for underwater detection in 2019 [6]. *Kim H et al.* designed the D.BeeBot with a driving leg device that can move flexibly under water in 2017 [7]. In particular, the propeller is also a propulsion device often used by underwater robots. *Chen et al* designed a hybrid-driven underwater gliders in 2016 [8]. It has the advantages of strong flexibility and fast speed, but it is inconvenient to control in narrow area and is relatively noisy. In summary, most robots use a single driving device, which lacks adaptability and flexibility to unknown environments, such as a propeller device, a buoyancy drive device, or a water jet propulsion device, etc. When performing underwater missions, because the environment is unknown, the requirements for underwater driving devices are becoming higher and higher [9] - [10]. In order to meet the needs of underwater tasks and different application scenarios, it is necessary to develop underwater robots with multi-functional drive devices.

In our previous research, we designed a spherical underwater robot with water jet propulsion device [11] - [14]. The structure of the spherical underwater robot is symmetrical, and its propulsion device can ensure the slow-steady operation of the robot in narrow area [15] - [18]. In order to improve the work efficiency and flexibility of the spherical underwater robot in the unknown environment, it is necessary to design the spherical underwater robot with the advantages of low-high-speed motion. Therefore, in this paper, we designed the spherical underwater robot with hybrid propulsion devices. The robot can achieve slow-steady motion which is mainly used in narrow area to reduce noise and enhance concealment. It can also realize rapid-flexibility motion in spacious area which can improve the flexibility and work efficiency of the robot in unknown environment [19] - [21].

This paper is organized as follows: The Section II mainly introduces the structure of the novel spherical underwater robot with the hybrid propulsion devices. The main work of the Section III use ANSYS fluid analysis to calculate and analyze the overall mechanism and hybrid propulsion devices of the spherical underwater robot. The main work of the Section IV carries out corresponding underwater experiments for a variety of motion modes, and analyze the experimental results. Finally, Section V introduces conclusions and future work.

II. STRUCTURAL DESIGN OF THE SPHERICAL UNDERWATER ROBOT

A. The structure of the HPSUR

This paper designed a novel hybrid propulsion spherical underwater robot (HPSUR), as shown in Fig. 1. The robot

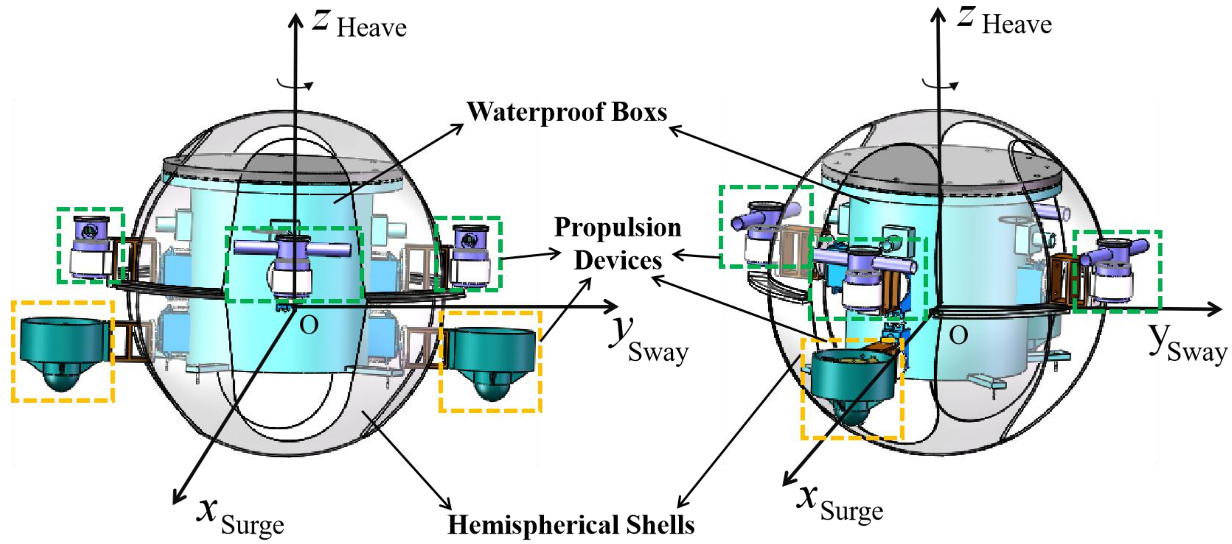
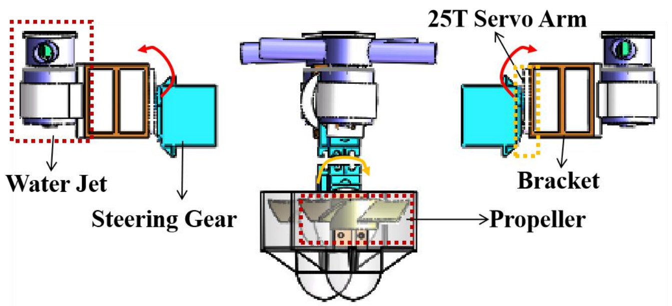
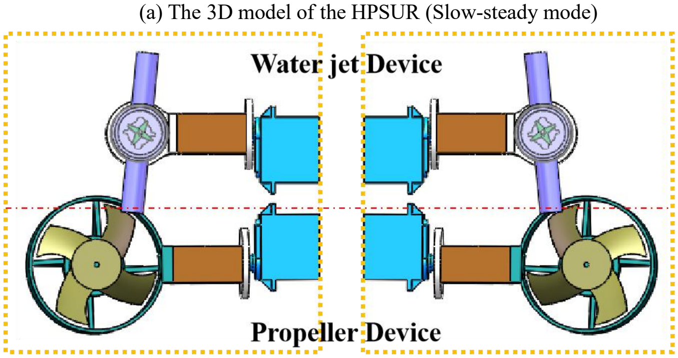


Fig. 1 The overall structure of the hybrid propulsion spherical underwater robot (HPSUR).

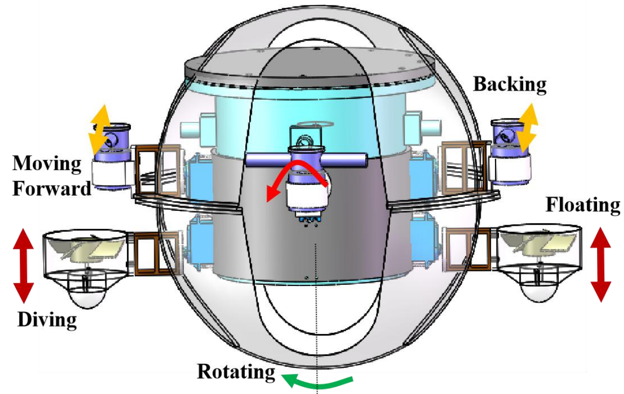


(a) The 3D model of the HPSUR (Slow-steady mode)

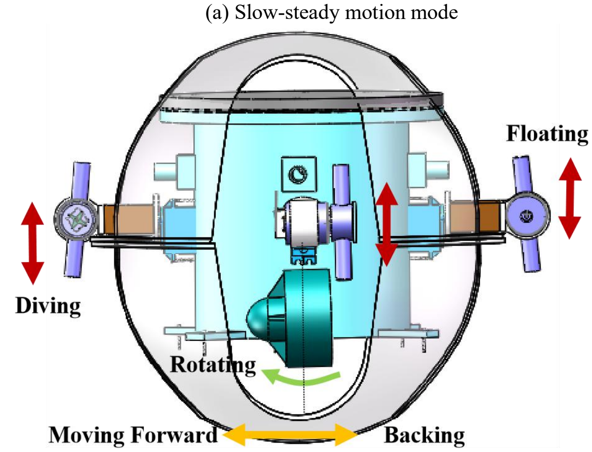


(b) Side view of the hybrid propulsion devices(Fast-flexible mode)

Fig. 2 The structure diagram of the hybrid devices.



(a) Slow-steady motion mode



(b) Fast-flexible motion mode

Fig. 3 Schematic diagram of the HPSUR motion in different modes.

consists of two hemispherical shells, the waterproof box and two sets of propulsion devices [22] - [25]. Its water-jet-propulsion device can achieve slow-steady movement by adjusting the direction of the four driving legs. The propeller-propulsion device is composed of two propellers which can realize fast-flexibility movement by changing its speed.

B. The hybrid propulsion device

Propeller device is widely used due to it's fast-speed and high flexibility. However, it is noisier than water jets. Therefore, we designed a hybrid propulsion device. Aim to improve the efficiency of the spherical underwater robot in performing tasks in unknown environments, and approach the target more quickly and effectively, also enhance flexibility and concealment.

The hybrid propulsion device is shown in Fig. 2. Each propulsion device includes two steering gears, a propeller, a water jet, a bracket and a servo arm. Both the water jet and the propeller are connected to the steering gear through the 25T servo arm and bracket, which can be controlled by the steering gear to complete underwater multi-degree-of-freedom motion and improve work efficiency. Fig. 2 (a) is a schematic diagram of the water jet dominating the forward motion, which can achieve slow-steady motion. Fig. 2(b) is a schematic diagram when the propeller is dominating the forward motion, which can realize fast-flexibility motion. Among them, both the propeller and the water jet can achieve a rotation of 0˚ to 180˚.

C. The motion mode of the HPSUR

After adopting the hybrid propulsion devices, the spherical underwater robot can still achieve water jet propulsion or propeller propulsion, and can also achieve hybrid propulsion. When performing tasks, different modes can be switched for different environments to improve work efficiency.

Fig. 3 is the motion mode of the spherical underwater robot when using hybrid propulsion, including rotating motion, forward-backward motion, floating-diving motion, etc. Each motion mode can be realized by different driving. When the water jet propulsion device is used to realize the forward movement, the propeller device can simultaneously control the robot's floating or diving, as shown in Fig. 3 (a). When the propeller is used to realize the forward movement, the robot also can simultaneously control the floating or diving by adjusting the positions of the four water jets, as shown in Fig. 3 (b). Rotation can be realized by adjusting the propeller device speed or water-jet-propulsion device thrust respectively. When the robot performs different tasks, the motion mode of the robot can be adjusted for different scenarios by changing the position of the driving device.

III. Control Method

The control diagram of the hybrid propulsion spherical underwater robot is shown in Fig. 4, which is mainly consisted of the controller unit, the driving unit, the data acquisition unit, and the power supply unit [22] - [25].

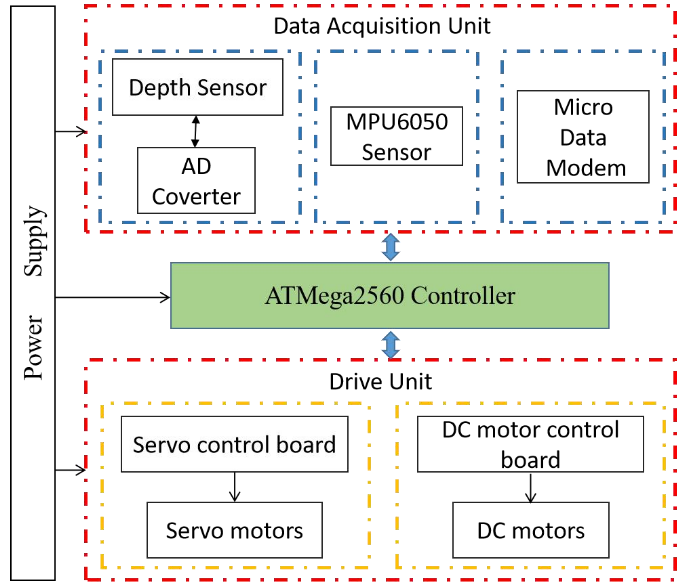


Fig. 4 Control diagram of the HPSUR.

Among them, ATMega2560 controller communicates with the servo control board to realize the switching of different modes; the ATMega2560 controller communicates with the DC control board to adjust the speed of the robot by PWM method, The communication way of the ATMega2560 controller and the micro data modem is RS232. The data acquisition unit is used for the collection of underwater movement information, and also to form the closed-loop control which can enhance the stability of underwater movement. The ATMega2560 controller communicates with the MPU6050 sensor through the analog port to collect data.

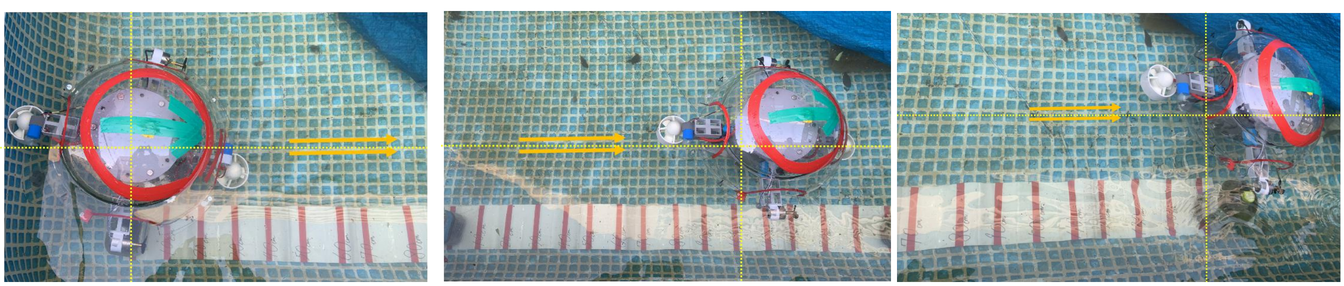

(a) t = 0s (b) t = 3s (c) t = 6s

Fig. 5 The forward-motion progress of the hybrid propulsion spherical underwater robot (HPSUR).

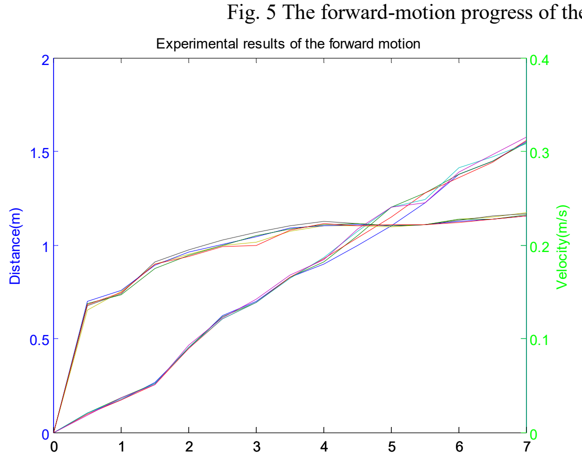


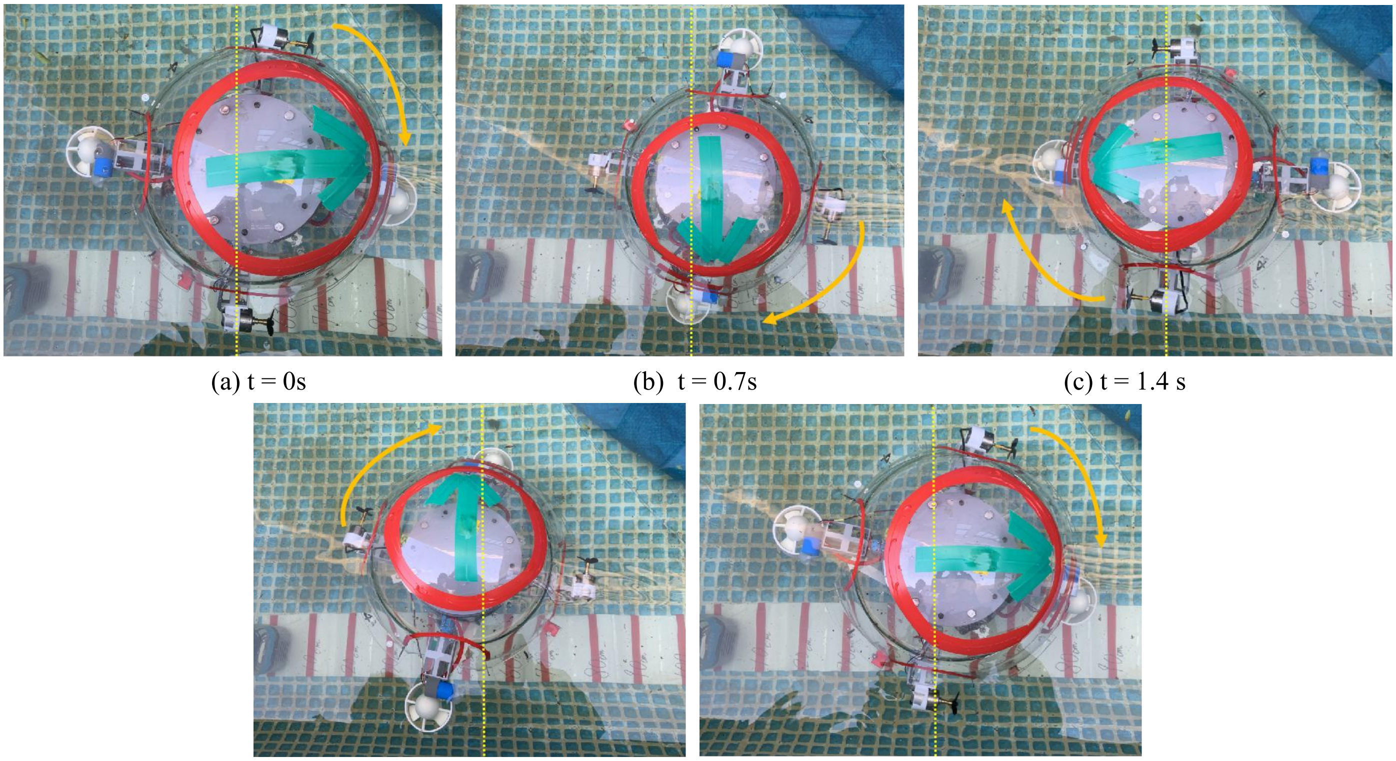
Fig. 6 The forward-motion experiment results of the HPSUR.

The depth sensor is used for the depth collection of the spherical underwater robot, and the maximum depth is 7m. In order to ensure the stability of the spherical underwater robot movement, the robot adopt the modular and symmetry design, which provides convenience for the robot's maintenance and protection.

This paper, then, assembles the prototype of the hybrid propulsion spherical underwater robot with a diameter of 44cm, and the height of 52 cm.

IV. Motion Experiments Analysis of the Hybrid Propulsion Spherical Underwater Robot

In order to verify the stability of the designed robot, this



(a) t = 0s (b) t = 0.7s (c) t = 1.4 s

(d) t = 2.1s (e) t = 2.8s

Fig. 7 The rotation-motion progress of the hybrid propulsion spherical underwater robot (HPSUR).

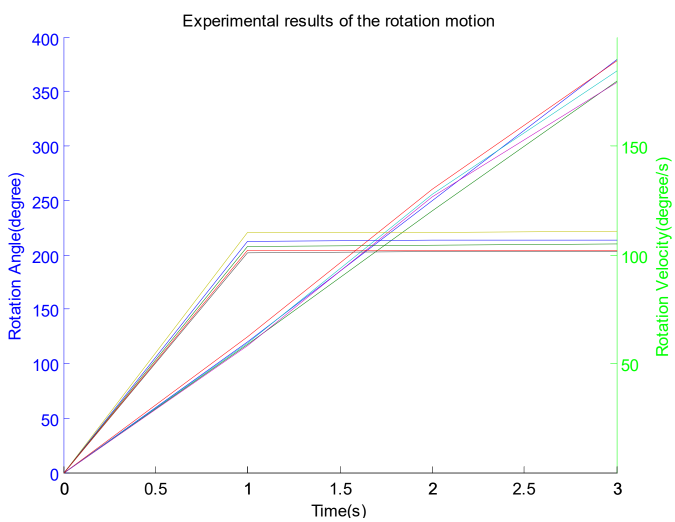


Fig. 8 The rotation-motion experiment results of the HPSUR.

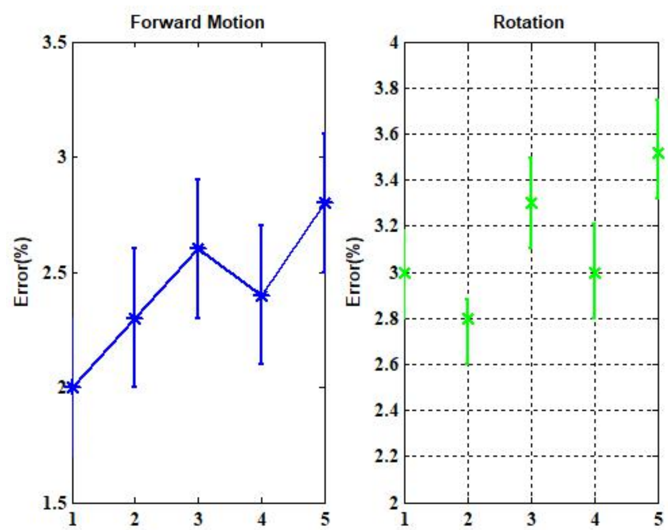


Fig. 9 The rotation-motion experiment results of the HPSUR.

paper conducted some experiments in the pool, including the forward motion experiments and the rotation experiments. The underwater experiments is carried out in a pool with the length of 5 m, the width of 2.5 m, and the depth of 1 m.

In the forward motion experiments, in order to effectively verify the effectiveness of the hybrid propulsion device, this paper mainly conducted the hybrid propulsion motion experiments, as shown in Fig. 5. The distance of the start point and end point is set to 1.5 m, and a total of 5 experiments are carried out. The experimental results as shown in Fig. 6, we can see that the time for the robot to reach the target position is 65s. After adopting the hybrid propulsion, its speed is about 0.24 m/s, which increase about 0.06 m/s than water jet propulsion. And the robot can achieve higher speed and its movement is more flexible. Due to the rated voltage of water jet motor is 8 v, so we adopt the same voltage to conduct this experiments.

Then, we conducted the rotation experiments for five times. The starting and ending positions were the same each time. The rotation process is shown in Fig. 7. The experimental results are shown in Fig. 8. The experimental results show that it takes about 2.8 s to rotate once time (360˚), which is about 0.3 s shorter than the previous time, which further proves the rationality and effectiveness of the designed robot.

After performing out the forward and rotation motion experiments, we further carried out the error analysis of the true and expected value to verify whether it meets the needs of underwater engineering tasks, as shown in Fig. 9. The experimental errors of forward and rotational motion is calculated, respectively. In forward motion, we performed five experiments, and the average error of the robot's motion trajectory was measured, less than 2.5%. Then, the average error of the robot's rotation motion trajectory is also measured, about 3%. It is worth noting that the error of the rotation motion due to inertia will be larger than the expected error. But it also meets engineering needs, which further verifies the rationality and effectiveness of the proposed hybrid-device structure.

V. CONCLUSIONS

In order to improve the work efficiency and its adaptability to the unknown environment of the spherical underwater robot, this paper designed a spherical underwater robot with a hybrid propulsion device. The robot had a variety of motion modes, which could achieve fast-flexible and slow-steady motion, ensuring that the spherical underwater robot could perform tasks more stably. Then, this paper built an spherical underwater robot prototype and completed the underwater motion experiments, including the forward motion experiments, the rotation experiments, and the diving-floating experiments. The experimental results showed that the underwater robot with hybrid propulsion device had better performance and optimal time. The experimental error of the forward and rotation motion is calculated, respectively. The average error of the forward motion is less than 2.5%, and the average error of the rotation motion is about 3%, which further verified the rationality and effectiveness of the designed mechanism. In the future, we will design a stable controller and conduct experiments in the lake to further verify the performance of the designed prototype.

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