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Underwater Motion Characteristics Evaluation of a Bio-inspired Father-son Robot

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***Abstract* - Conventional underwater Sample Acquisition tasks are performed by underwater vehicles equipped with rigid multi-link arms. However, the motion of the conventional robotic arm interferes with the stability of the underwater vehicle when performing sampling tasks. In this paper, a fish-inspired small under robot is designed and developed as a son robot for sample acquisition, which is connected to the spherical underwater robot father robot by a tether. Firstly, we proposed the novel father-son robot system to realize the underwater sample acquisition task. And then, the motion control is proposed for the father-son robot system. The son robot actuated by one water-jet thruster can realize underwater basic motions. The hybrid thrusters as the thruster mechanism for the father robot. Also, the control circuit of the father-son robot system is designed. Finally, the hydrodynamic analysis and experiment results verify the validity and reliability of the father-son system.**

Index Terms - Father-son robot system, spherical underwater robot, hydrodynamic analysis.

I. INTRODUCTION

Multi-modal robot system has been extensively applied to underwater intervention missions, like underwater sample acquisition [1-3]. The father-son robot system is a form of multi-robot system, which can realize the functions of two kinds of robots. This extraordinary function is inspired by nature and can combine the advantages of different types of robots into one platform. It can realize effective movement in different underwater environments and convert between different environments underwater [4,5]. Therefore, the same robot can cover long distances and over obstacles, and effectively move in small underwater spaces. The combination of the advantages of the father-son robot system can adapt to the complex underwater environment and replace humans as much as possible.

The father-son robot system is a system in which a father machine with strong dynamic balance and large carrying capacity and a son machine with small disturbance and flexible movement are used as a system for the cooperative work of the father and son. Here, the father machine chooses to have no tether, and can work independently according to the pre-settings, without the need for human remote control of the autonomous water downloading tool. Instead of using a tether wrapped with copper wires and optical fibers to connect to the working mother ship, the operator can instantly transmit commands to the remotely operated submersible of the vehicle [6,7].

Usually the underwater manipulator, as the key equipment of the underwater vehicle, consists of an external mechanical arm, which is manually operated by humans and completes the planned tasks. Underwater robotic arms are usually very large and can realize the recovery of large objects. When performing underwater recovery tasks, the robotic arm is usually connected to the remotely operated underwater vehicle or the autonomous underwater vehicle. In this process, the underwater robotic arm will produce a reaction force on the underwater vehicle, which will have a certain impact on the stability of the underwater vehicle, resulting in the underwater vehicle deviated from the target point. It is necessary to use a compensation controller to stabilize the movement of the underwater vehicle, which increases the complexity of the overall control system. In order to overcome these problems, we propose a small robot as the father-son robot system of the hand manipulator, which can achieve underwater sample acquisition tasks. The father-son robot system includes a small bionic robot and a multiple degree of freedom autonomous underwater vehicle.

The Father-son Underwater Intervention Robotic System (FUIRS) that the amphibious underwater robot as the father robot and an ICPF actuators based micro-robot plays the role of the son robot was proposed in our group firstly [8]. In this system, it realized wireless communication between the father robot and the son robot. Also, the motion control of the son robot was realized. Amphibious underwater robot has developed into four generations. The amphibious underwater robot is inspired by the tortoise, which can realize the movement of the robot from land to underwater. The underwater robot has good performance in underwater and land movement. In our previous research, amphibious motion control has been realized [9-12], and communication between robots has been realized [13,14]. At same time, the function of the localization with the method of relative close-range [15] and the path tracking [16] also realized. In the subsequent research, we evaluated the performance of the amphibious robot [17-19]. There is also a spherical underwater robot in our group. The spherical underwater robot has good flexibility and good hydrodynamic performance. We have developed five generations of spherical underwater robots totally. SUR II has good motion performance. The robot is composed of two hemispheres. At the joint of the hemispheres, three vector water

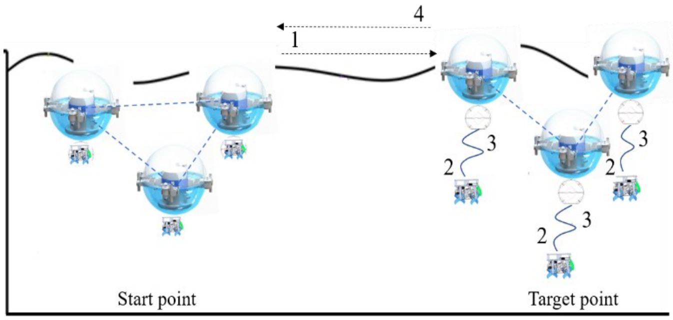


Fig. 1 Schematic of the father-son robot system.

jet thrusters are equipped, which are distributed in an equilateral triangle. SUR III realized underwater high-speed motion after SUR II [20-25]. Similarly, four vector water jet thrusters are equipped as propulsion systems at the junction of the two hemispheres [26,27]. In order to achieve the good motion performance and sampling ability of the parent subsystem, we redesigned the parent subsystem. This paper proposes a multi-robot parent system robot. This paper is organized as follows. Section II introduces the system overview of the father-son robots. Design and control mechanism of the father son robot system introduce in Section III. Simulation and underwater evaluation experiments of the father-son robots introduce in Section IV. Finally, Section V concludes this paper.

II. Father-Son Robot Configuration

A. *Inspiration for design of SUR V*

We propose a father-son robot system for the underwater sample acquisition, which used the microrobots as the acquisition tool, as shown in Fig. 2. The father underwater robot carries the son robot to the target point and then the recycling equipment is open. The son robot reaches the target underwater location. Photos is transmitted and a sample taken. After completing the collection task, the tether is coiled again and a recycling equipment is close. Finally, the father underwater robot back to the start point. And a spherical underwater father robot with two actuation modes, including the water-jet propulsion and the propeller propulsion, was developed in our previous research. The spherical underwater robot has the advantages of longer sailing ranges and fast deployment. And the symmetry of the spherical shape provides the superiority of flexibility. The spherical father underwater robot consists of two transparent hemispheroids, a recycling equipment with a motor which are fastened the bottom of the SUR for carrying the son robot. The spherical underwater father robot with a high speed can take the microrobots from the start point to the target points and return to the start point. It can keep itself to realize the microrobot precise manipulation underwater. The father-son robot system uses an Arduino MEGA 2560 main controller to control each servo motor and actuation module.

A spherical underwater father robot provides the power and commands to the son robot depends entirely on the tether. And the son robot relaying back data and live video to the father robot also used the tether. A design constraint for this system is its maximum depth, which has a direct impact on the required tether length. Furthermore, to minimize the impact of the tether

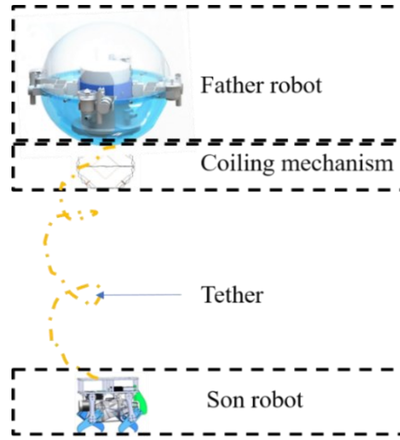


Fig. 2 Connection mechanism of the father-son robot system.

on the father robot, its stiffness needs to be reduced as much as the application permits and its buoyancy must be close to neutral. The end of the tether is connected with the main controller in the water proof boxes.

B. *Microrobots*

To operate the underwater sample acquisition of the object recovery, the microrobots should be capable of multi-functional performance, including horizontal actuation and buoyancy control, finding the target object and getting back to the recycling equipment of the father robot actively. In horizontal motion, the direction of motion of the underwater son robot is controlled by an external jet, and the position and angle difference of the jet is controlled by two steering gears to produce movement in different directions. The buoyancy movement is also realized by the steering gear controlling the direction of the jet. The vertical movement of the son robot is controlled by buoyancy adjustment. This strategy is inspired by fish, which usually control their depth in the water by changing the aeration or deflation of their bodies, thereby changing their buoyancy.

We use the pressure sensor to obtain the current depth information to control the buoyancy, and finally reach the ideal depth. Once the underwater son robot receives the expected depth setting, it uses a pressure sensor to determine the current depth, and the difference between the current depth and the expected depth is sent to the control component, which determines the son robot to reach and maintain the target depth in required pressure difference. A Wi-Fi camera module is utilized on the son robot to realize the target object and to the communication protocol for catching the feedback signals.

III. Design and Control Mechanism of the Father Son Robot System

A. *Motion control*

The spherical underwater father robot has six degrees of freedom (DoF) and there are four degrees of freedom which they are surge, sway, undulation and yaw was applied as usual based on the relevant research proofs and the previous research experience of the laboratory. The spherical underwater father robot can achieve these four degrees of freedom in the previous research. Similarly, high-speed motion and low-speed motion can be quickly converted according to the task requirements. The propulsion system ensures the realization of four degrees of freedom of the robot, and further improves the thrust force of the robot and the stability of the robot movement. Due to the compact space and structure of the parent robot, in order to improve the control efficiency and motion performance of the robot, Figure 3 shows a new type of hybrid propulsion. The hybrid propeller consists of a set of propeller propellers and a set of water jet propellers. The propeller is connected with the servo motor through the bracket, so as to be fixed together. By controlling the angle of the servo motor, the movement angle of the hybrid propeller can be rotated from 0° to 360°. In order to realize the precise positioning of the robot, we use the water thruster with low-speed motion for short distance positioning. The propellers are used for long-distance movement to improve the working efficiency of the robot. Through the tether to connect the father-son robot, and has been verified in the underwater experiment, through the rope to connect the father robot, make the father robot get fast movement. When the father robot moves rapidly, the shape of the son robot will not be destroyed. The overall structure of the parent machine is compact and flexible.

The son robot is a miniature bionic underwater robot that can drill into coral cavities and rock gaps to solve the problem that people cannot enter the narrow space. In order to reduce the size of the son-robot as much as possible, the actuator of the son-robot only uses a water jet thruster. The multi-freedom movement of the son-robot is realized by connecting the multi-steering gear and the water-jet thruster. By adjusting the direction of the water jet thruster, the son-robot can move horizontally and buoyancy.

B. Control circuit

The control circuit of the father-son robot system is designed as shown in Fig. 3. By using the control system, it can realize the communication and electronics control for the father-son robot system. The father robot is based on an Arduino MEGA2560 and the son robot is based on a NANO 33 BLE SENCE micro-controller, which is suitable for the microrobot due to the compact structure. For the father robot, the SUR IV to switch the propulsion modes depending on the environment to realize the different movement. For horizontal movement, we use a set of symmetrical propulsion systems. The rapid motion of the robot can be achieved by using the propeller group, and for precise motion, we use the water-jet thruster to achieve. By switching between different propeller modes, accurate and fast horizontal movement of the robot is realized. We use a set of propellers to realize the underwater robot's movement in the heave motion. The diving and floating movement of the robot can be realized by switching the direction of the steering gear or the forward and reverse rotation of the propeller motor. Here, the steering gear is connected to the steering gear control board. The steering gear control board receives the PWM signal sent by the main control board, and different PWM signals can realize the speed adjustment and positive/negative rotation of the propeller. In the control system, we have added different sensors which have an inertial measurement unit (IMU), a

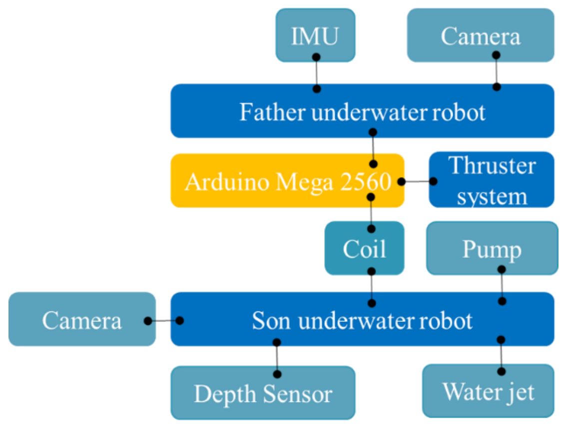


Fig. 3 Control circuit of the father-son robot system.

camera, the acoustic communication module and the depth sensor. The feedbacks of the robot underwater by using the IMU, a camera and the depth sensor. The robot information feedback obtained by the sensor can adjust the robot's thruster device and the forward and reverse rotation of the motor to adjust the robot's posture in time. For the acoustic communication module, we use this module to realize the communication between the father robot and the base station. The base station can directly send instructions to the parent robot. Similarly, the parent robot can directly send the underwater detection results to the base station. The Micron data modem from Tritech was chosen for the acoustic communication module.

The Arduino Nano 33 BLE Sense module has some built-in sensors, such as accelerometer, gyroscope, magnetometer, pressure sensor, and proximity sensor. The module supplies power to 3.3V. It supports low-power operation, so it is very suitable for battery-powered designs. It uses the COM channels to connect with the father robot to receive the command from the father robot. The controller is equipped with a Nordic nRF52840 processor, which includes a powerful Cortex M4F and a NINA B306 module for BLE and Bluetooth 5.0 communication. This allows the controller to operate at very low power and use Bluetooth 5.0 for communication. Both wired and Bluetooth communication modes can be used. The sub-robot is also equipped with different sensors, including cameras and depth sensors, to obtain feedback of underwater information. The depth sensor can feed back the son robot underwater depth information in real time to realize the depth control of the son robot. The camera can realize underwater target recognition and perform underwater detection tasks.

IV. HYDRODYNAMIC ANALYSIS AND EXPERIMENTS

A. Hydrodynamic analysis results

In order to better verify the performance of the father robot, we first carried out the fluid simulation of the father robot to obtain the fluid dynamics characteristics of the father robot. We built a 3D model of SUR V in SolidWorks 2020. The key parameter for the efficiency and accuracy of the control system of a robot operating in an underwater environment is the hydrodynamic characteristics. We chose ANSYS-FLUENT to analyze the fluid dynamics characteristics. In order to better

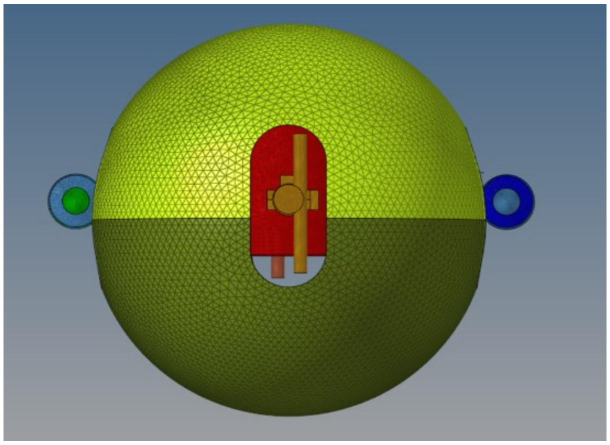


Fig. 4 Simulation model of the SUR in forward motion.

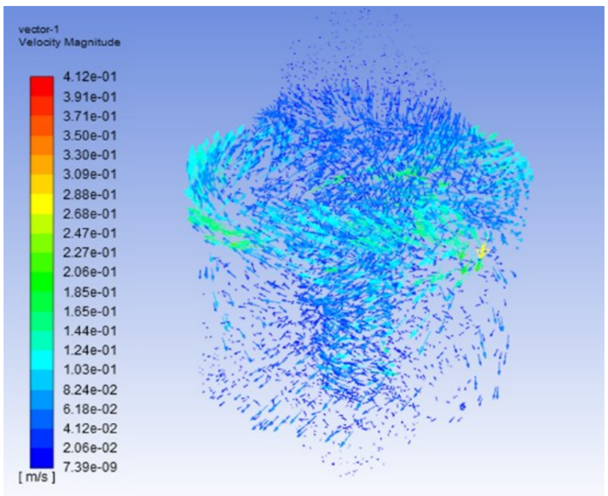


Fig. 5 The simulation result of the propeller velocity vector in forward motion.

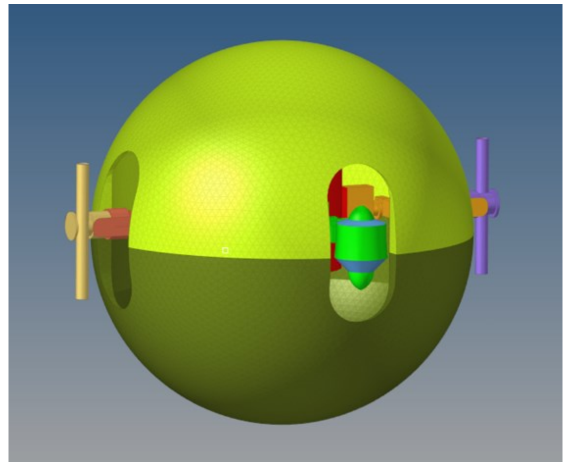


Fig. 6 Simulation model of the SUR in heaving motion.

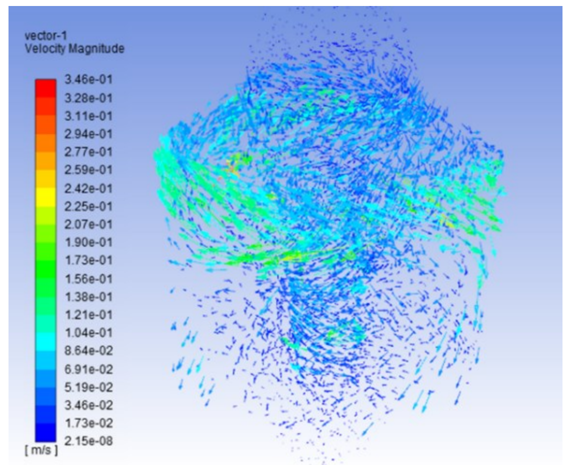


Fig. 7 The simulation result of the propeller velocity vector in heaving motion.

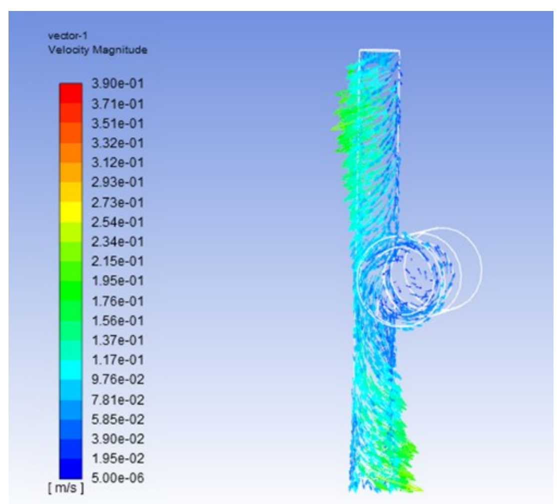


Fig. 8 The simulation result of the water-jet thruster velocity vector in rotation motion.

estimate the dynamics model parameters of the robot, we set the flow field environment as 20°C, and the flow field environment is free from external interference. It is necessary to pre-processor the 3D model of the SUR in hydrodynamic. Here, the pre-processor has many contents. To better display the 3D model of the robot that displays before the prototype, we described the 3D model in detail. However, overly detailed 3D models will increase the number of simulation calculations, and it is hard to obtain intuitive simulation results. Therefore, before performing hydrodynamic analysis, we should simplify the 3D model. The simplified parts are as follows:

(a) The parts on the SUR have been changed to a regular shape, such as a cylindrical shape;

(b) When the robot is equipped, a large number of screws and nuts need to be used, but these parts have little effect on the results of the simulation. Therefore, in this simulation, we have omitted the screws and nuts. And the simulation models are shown in Fig. 4 and Fig. 6.

The thrust of the robotic thrusters is set to 400 RPM and 4,200 RPM respectively. The number of surface grids of the robot model is 213498. The basic size of the grid is 2mm, and the maximum size is 10mm. The grid type is triangle. The number of the volume mesh is 981888, the mass of the mesh is 0.83, and the mesh type is tetrahedron. The flow field is the turbulence handled by the $k-\varepsilon$ model.

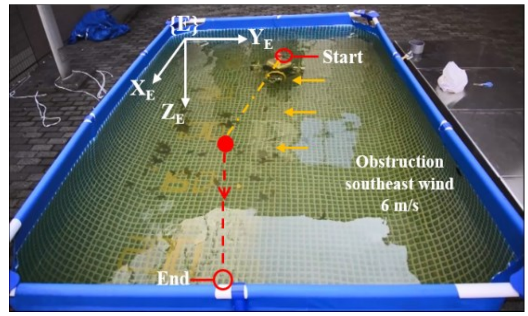
After solver execution, some results can be extracted from the post-processor of ANSYS CFX. The results of the vector in the forward motion, the heaving motion and the rotation motion are shown in Fig. 5, Fig. 7 and Fig. 8. In this part, we mainly carried out the fluid dynamics analysis of the father-son robot system. Here, we mainly analysed the velocity vector of the three basic motion states of the father robot. Since this part mainly analyses the dynamic state of the father robot, we assume that there is no interference in the flow field. From the vector simulation results, we can see that the driving device of the robot is stable. In the ANSYS FLUENT software, after iteration 500 steps, the drag coefficients for forward motion, heaving motion and rotation motion were $C_d = 0.494$ approximately. In previous research, we obtained the theoretical value of spherical robot are $C_d = 0.394$. Due to the max error of the simulation result and the theoretical value was 2% approximately, the hydrodynamic analysis results were acceptable. Based on these results, we provide a basis for our subsequent optimization of the control circuit of the father-son robot system. In the subsequent research, we will focus on improving the control accuracy and stability of the system.

B. Underwater experiments and results

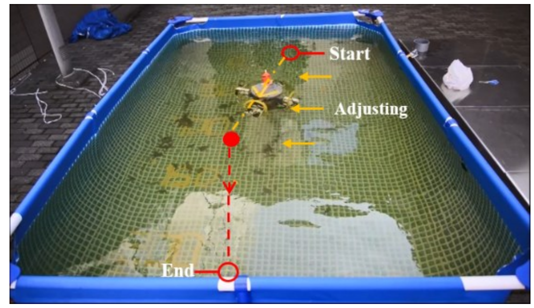
In order to further verify the accuracy and carrying capacity of the father robot's motion, so as to realize that the father robot can carry the son robot to the destination and realize the detection of the son robot in a small space, we conducted the experiment in this chapter. The underwater experiments were completed in a swimming pool with the 3.0 m × 2.0 m × 0.6 m (the length × the width × the depth). The experiment carried out a high-speed forward movement in a surge.

In order to verify the robot's anti-interference and forward motion capabilities, we conducted a high-speed forward motion experiment at first. In high-speed forward motion, the father robot uses a set of propellers. The total movement time of the high-speed forward experiment is 18s, and the total movement distance is 3m. The circle logos is the start point of the SUR IV was shown in Fig. 9. During the movement of the underwater robot, the wind will affect the stable movement of the robot [28]. The father-son robot system starts from the starting point, until 12s, the robot system has been resisting the interference of the wind on the robot. The father-son robot system adjusts its posture in 12s-18s, and the experiment moves forward in a straight line. From the experimental results, we can see that the father robot can resist wind interference. Also, it verifies the performance of the father-son robot system forward motion by these experiments.

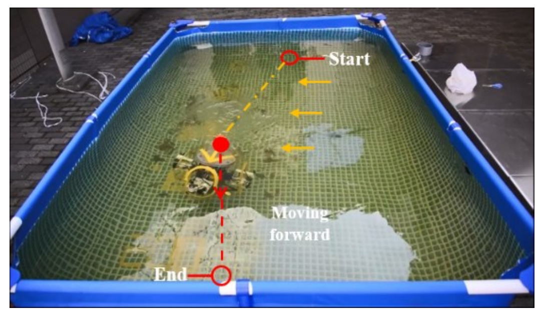
Rotation motion in place is one of the main advantages of the spherical underwater robot. At the same time, in the father-son robot system, the father robot needs to release the son robot at the target point. In order to realize the characteristic that the father robot rotates and releases the son robot after reaching the target point, we conducted an experiment in which the father robot rotates and stops holding. Due to the water-jet thruster has the good in-situ control performance, it can better to carry out the precise position control. In order to obtain the accurate angle rotation, we mainly use the water-jet thruster in the father robot to move in the rotation movement as shown in Fig.10. From the experimental results, we can see that the father robot can reach the position of 90 degrees within 2s and remain stationary.



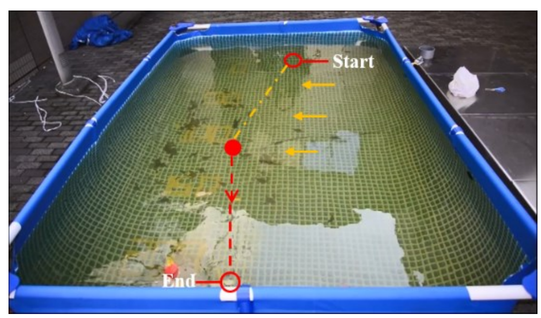
(a) at 0s



(b) at 6s



(c) at 12s

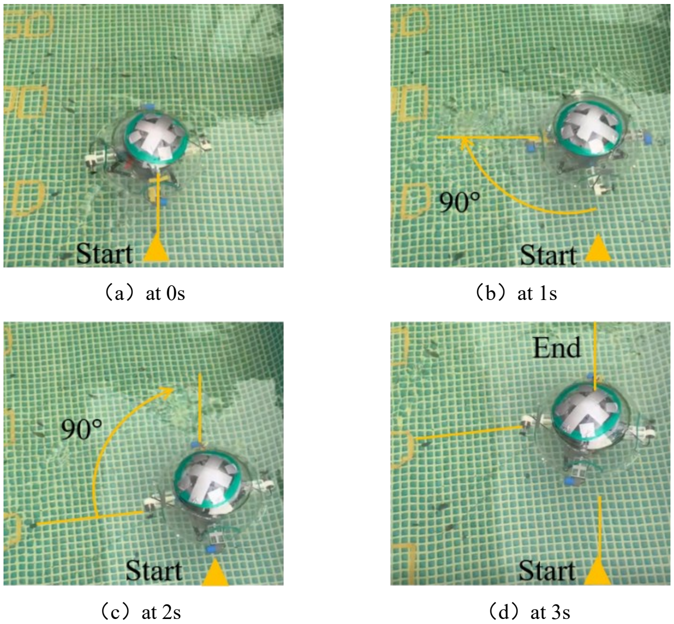


(d) at 18s

Fig. 9 Video snapshots of the forward motion.

V. CONCLUSION

This paper presented a father-son robot system to realize the sample acquisition task. First of all, the novel mechanism of fish-inspired small under robot is designed and developed as a son robot in the father-son robot system. And then, the motion control and the control circuit are designed for the father-son robot system. The son robot contains a thruster, which realizes the basic movement of the robot through the thruster direction



(a) at 0s (b) at 1s (c) at 2s (d) at 3s

Fig. 10 Video snapshots of the rotation motion.

regulator. The father robot is composed of two sets of hybrid thrusters, which can realize six-degree-of-freedom motion control. The hybrid thrusters can realize switching motion mode fast. Finally, the hydrodynamic analysis and experiment are conducted. The hydrodynamic analysis of SUR by using ANSYS FLUENT. The simulation results show that the robot can move stability in forwarding motion and heaving motion and provide validity and reliability for subsequent tasks realized. At the same time, the experiments of the forward motion and the rotation motion were conducted. The experimental results showed the father robot of father-son system can realize the stable forward motion and rotation motion.

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