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Design of a SMA-based Salps-inspired Underwater Microrobot for a Mother-son Robotic System

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***Abstract* – The traditional underwater robot has some limitations when conducting survey in underwater space. These limitations also reflect in some aspects, such as micro-structure, movement patterns, positional accuracy and endurance time. In order to overcome these shortages, a shape memory alloys (SMAs) actuator-based Salps-inspired son robot is designed and developed, which is connected with an amphibious spherical mother robot by wires. In this system, the mother robot could catch the son robot and supply energy and signal for the son robot through wires, and also ensure the retrieve of the microrobot. The Salps-like son robot was actuated by SMA wires and silica gel that could provides power of movement for the son robot in the way of time movement. The son robot could complete the basic movement; floating up and down, rotating and forward. And there is an independent battery in the son robot, which could make the microrobot move even get out of hand of the mother robot. The communication method used in this mother-son robot is point-to-point. Also, the power supply and the hardware of the mother-son robot were described in this paper. In order to do the experiments, the prototype of the son robot was developed. Then, we carried out the experiment to analyse the tail of the son robot. At last, to evaluate swimming ability, we conducted the forward and rotating movement experiments in a tank. The results shown that the maximum walking speed is 8.5mm/s and the maximum rotating speed is 11.3° /s.**

Index Terms - Mother-son Robot System; Underwater Robot; Microrobot; Shape Memory Alloy (SMA) Wire; Bionics

I. INTRODUCTION

In order to meet the growing demand for resources, ocean becomes a new avenue of exploration. As the vital equipment of underwater facility, underwater robots play an important role in this task, such as pipeline cleaning, data collection, inspection, construction and maintenance of underwater equipments [1]-[3]. There are some underwater robots that have been developed at home and abroad in recent years.

In 2013, the University of Denver built a small, compact, low-speed maneuvering underwater vehicles, which about 176-198 kg and has a hull length of 2.2m. It was driven by a linear actuator and uses different inflow and outflow nozzles to provide continuous propulsive force [4].

In 2014, the BioRobotics Institute of Italy developed a miniature underwater robot with docking system, which could provide energy sources and data exchange, promising approach to enable modularity and reconfigurability in underwater robotics [5]-[6].

Macro USA designed an amphibious called Stingray, in 2014, which served in Visit, Board, Search, and Seizure (VBSS) teams. It could cross flooded spaces and to allow inspection of flooded compartments [7]. In 2015, the University of Balearic Islands developed a micro-AUV that weighs only 3.5 kg and is equipped with an inertial unit, a pressure sensor and a camera, and it has three practical DOF, surge, heave and yaw [8]-[9].

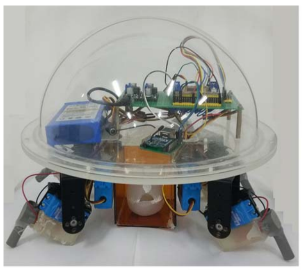
In 2016, University of Islamic Azad developed a Mini Unmanned Underwater Vehicle (MUUV) equipped with a new arrangement of water jet propulsion [10]. In these years, Kagawa University (Guo Lab) has done many works in the amphibious spherical robot. They developed a spherical robot, which driven by three vectored water-jet propellers [11]. Since then, they also proposed a novel underwater robot, employing a spherical hull and equipped with multiple vectored water-jet-based thrusters [12]-[13]. Spain has developed a Reconfigurable Autonomous Underwater Vehicle for Intervention which could manage to recover an object similar to an aircraft black box without the direction of any operator [14]-[15].

The development of the underwater robot also catches more attention at home. There are many institutions are exploring this field. University of Chinese Academy of Science had developed a jellyfish-inspired ropot , which could change its attitude through adjusting underwater robot's center of gravity position, and it possesses five DOF combining the propeller thrust. Its maximum cylinder diameter is 150mm, height is 300mm, weight about 3 kg [16].

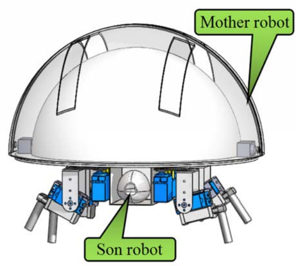
Harbin Engineering University developed a spherical underwater vehicle which has three DOF in water [17]. Beijing University of Posts and Telecommunication designed a new amphibious spherical robot [18], which was equipped with sensor devices and sent the real-time information back to the ground control system. The robot can roll on land or underwater freely and also can move in the water.

From the domestic and foreign research present situation, we can find that the research in the field of underwater robot has some limitations when conducting survey in underwater space, and the limitation also reflects in some aspects, such as micro-structure, movement patterns, location accuracy and endurance time. In this paper we develop a novel biomimetic underwater robot for a mother-son robot system, which is consisted of an amphibious spherical mother robot and a Salps-like son robot, as shown in Fig.1.

This paper is divided into five parts. Section II we introduce the design of the son robot, including the structure, the micro-actuators and the hardware. Then we describe the communication mode between the son robot and the mother robot, and also explain the swimming way of the son robot in Section III. In Section IV, some experiments about the tail and swimming ability of the son robot are carried out. Finally, we come to conclusions and bring forward future work in section V.



(a) Property design



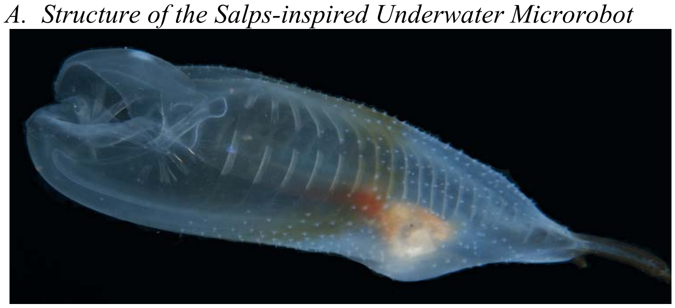
(b) Conceptual design

Fig.1 The property and the conceptual design of the Mother-son robot

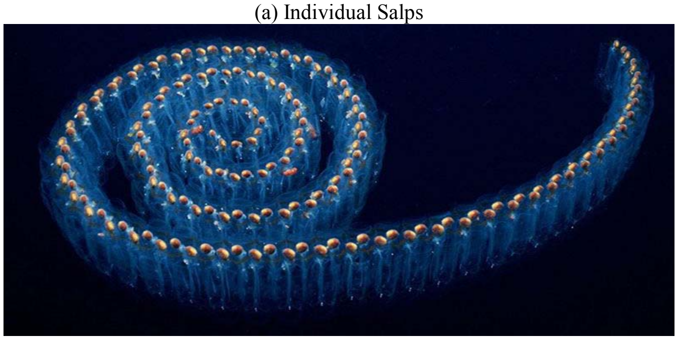
II. Design of the SMA-based Salps-inspired Underwater Microrobot

Bionic robots are good performance mechanical and electrical systems which imitate biological structures and motion characteristics of organisms according to the principles of bionics [19]. Design the robot according to the bionic could be use in the dangerous conditions to human beings, such as anti-terrorism, space exploration and rescue. It has great significance to the development of robots.

A. Structure of the Salps-inspired Underwater Microrobot



(a) Individual Salps



(b) A group of Salps

Fig.2 The Salps in different states

The Salps is a kind of small-scale sea-like colloidal chordate, as shown in Fig.2. They have a barrel body which surrounded by ring muscle belt, open at both ends. Their outer skin is thin and transparent that could protect them from natural damage of enemies. Their movement is jet-like which inhale water from the front and drain from behind.

According to the principle of the bionics, we developed a Salps-inspired microrobot, as shown in Fig.3. Its shell was designed by silica gel, which density is closest to water and almost transparent in the water that making the robot highly concealed. It was consisted by four parts; upper shell, lower shell, actuator and tail. Among them, the micro-actuator we designed was made by silica gel and SMA. The tail is connected to the body through a diamond-shaped distribution of four SMA wires. The dimensions of the microrobot were are determined to be 90 mm long, 50 mm width and 50 mm height.

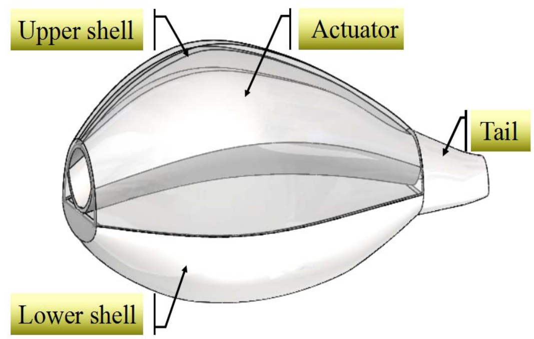


Fig.3 Conceptual structure of the Salps-like microrobot

B. The Designed Tail of the Microrobot

The tail of the son robot we designed was tapered and made by polyvinyl chloride (PCV). The tail and the body of son robot were connected by four basilar plates. This plate was designed by SMA wires, elastic body and skin. One side of the basilar plate was fixed on the body and another side was connects the tail. There are four plates and they are symmetrically distributed between the tail and the body. The diagrammatic sketch of the tail and the basilar plate were shown in Fig.4.

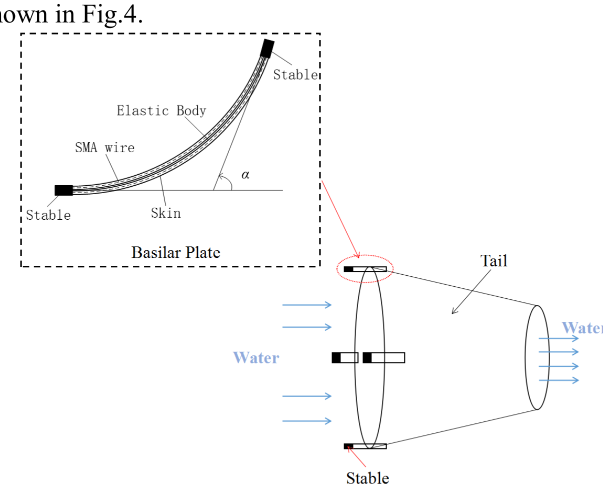


Fig.4 The diagrammatic sketch of the tail and the basilar plate

C. Actuator and Power Supply

The SMA is a kind of alloy which atomic arrangement regularly and the volume becomes less than 0.5% martensitic phase. This alloy in the external force will produce deformation, but when the external force removed, it will restore the original shape in a certain temperature conditions [20]. Compare to other functional materials, such as piezoelectric ceramics, IPMC and magnetostrictive material, etc. the SMA has advantages in high weight, strain, action silent, the closest to the biological muscle fibers, and easy to achieve miniaturization. It set the sensor and drive in the whole, it also has high commercialization rate.

The actuator was consisted by silica gel and four SMA wires. The working principle is shown in Fig.5. The diameter of the SMA wire is 0.3 mm. And the relationship between resistance and temperature was shown in Fig.6. In the Fig.6, M_f is 18.7° , M_s is 31.54° , A_s is 50.13° and A_f is 65.27° , and the T_1 is the hysteresis temperature of the SMA wire which affect the response speed of the actuator. In this paper, the underwater microrobot we designed was imitating the movement of the Salps, so squeeze four SMA wires in the silica gel sequentially that could work a jet-like movement.

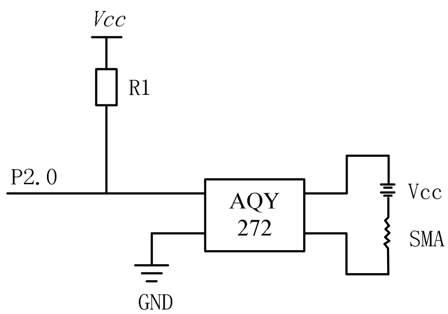


Fig.5 The working principle of the micro-actuator we designed

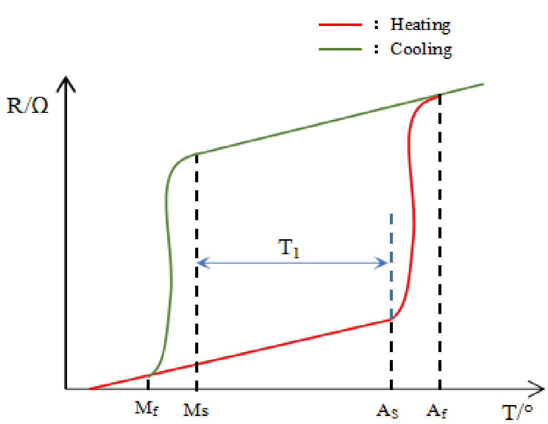


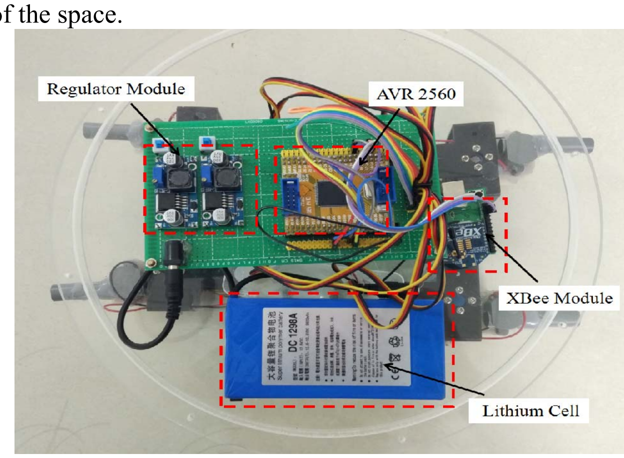
Fig.6 The relationship between temperature and resistance of the SMA wire

The AVR ATMEGA2560 was chosen as the micro-controller for the mother robot, and it also could control the son robot by the wire and supply power. The battery which the mother robot used, DC 1298A/12.6V, is lithium polymer battery. It provides 5V voltage to the micro-controller of the mother robot and the son robot. It also provides 7.4V voltage to eight servomotors and 3.3V to the XBee module. Four water-jet propellers and two direct-current dynamos also acquire power from this battery.

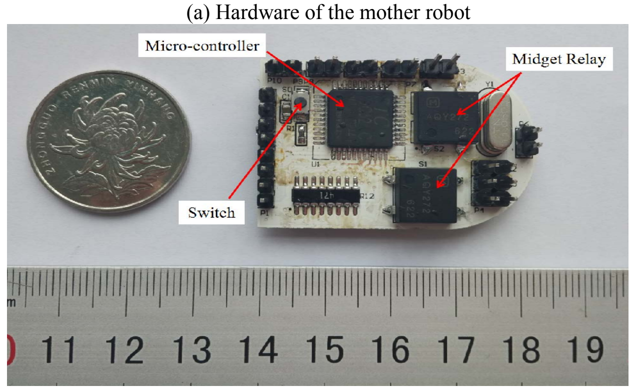
The son robot also has the independent power module. The button battery, LIR 2450/3.6V and LR44/1.55V, was used as the power supply when the son robot lost contact with the mother robot.

D. Hardware Circuitry of the Mother-son Robot

The hardware circuitry of the mother-son robot we designed was shown in Fig.7. In Fig.7 (a), it shows the basic control model of the mother robot, such as regulator module, AVR 2560 module, lithium cell, and XBee module which make mother robot receive the order by the upper monitor. In Fig.7 (b), it shows the content of the son robot, includes a micro-controller which is made as control centre and a midget relay, NAIS AQY272, as the switch. This smaller hardware circuity of the son robot we designed was satisfied the demand of the space.



(a) Hardware of the mother robot



(b) Hardware of the son robot

Fig.7 The hardware of the mother-son robot

III. THE CONTROL SYSTEM OF THE MICROROBOT

A. Communication between robots

The control system of the mother-son robot system is shown in Fig. 8. In this system, we used point-to-point to realize the communication between the mother robot and the son robot. The mother robot sends different characters which could receive from computer or itself, and then the son robot using the way of serial interrupt to receive control characters and carry out different swimming pattern; forward, float, dive, turns left and turn right. After the son robot complete the assignment this wire also convenient for the recovery of son robot.

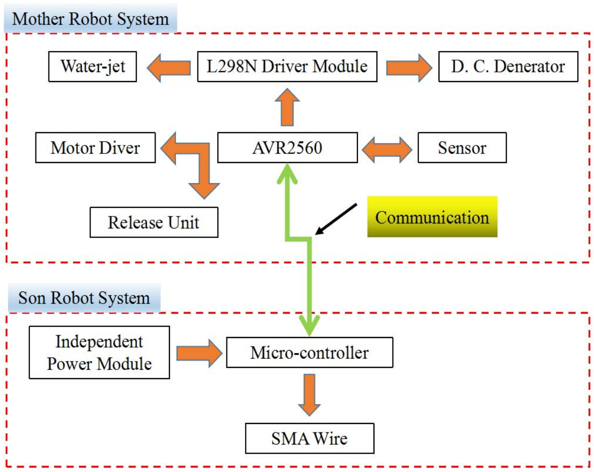


Fig.8 Control system of the Mother-son robot

B. Motion Control of the Microrobot

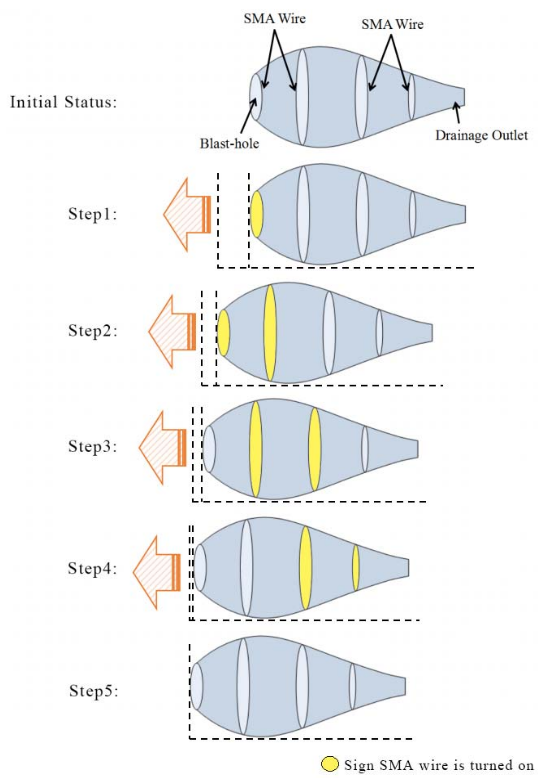


Fig.9 Schematic of the son robot movement pattern

Through makes the switching circuits sequential, the swimming of the son robot would be controlled. When the first SMA makes the blast-hole closed, quickly compress the second SMA wire. In this way, water in the actuator would be squeezed out. After the first SMA wire power interrupt, the second SMA wire still keep electrify, and then compress the third SMA wire. Then, we interrupt the second SMA wire, but keep the third SMA wire and then compress the last SMA wire. At last step, we interrupt all SMA wire for 300ms make the actuator to its initial status.

In this circle, as shown in Fig.9, we not only keep the water in the actuator squeezed quickly, but also let the water pour in actuator in the same time. That makes the robot movement speed is guaranteed. The son robot was move the biggest distance in step 2, because there is more space in the second SMA wire, it could collect more water to squeeze.

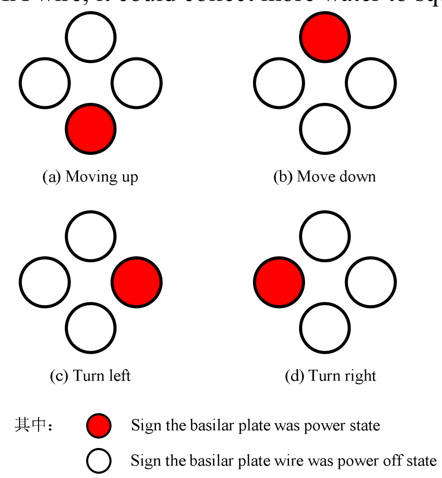


Fig.10 The tail control schematic of the son robot

The way control of the tail was shown in Fig.10, the red dot sign the basilar plate was electrified. When two symmetrical basilar plats are bending to one side and the tail while bending following. In this way, the direction of the son robot will be changed. So, we can make the principle of the direction changed; the bilateral plats could change the Left-to-right direction, the up and down plats could change the float or sink.

IV. PROTOTYPE OF THE MICROROBOT AND EXPERIMENTS

A. Prototype of the Microrobot

In order to overcome these shortages of the traditional robots, a SMA actuator-based Salps-inspired is designed and developed as a son robot for some small object, which is connected to an amphibious spherical mother robot by wires. The prototype of the son robot was shown in Fig.11. The silica gel was used to make the son robot shell. The tail of the son robot was made by PCV and was connected by four basilar plates. The dimension of the son robot is $90\times50\times50$ mm^3.

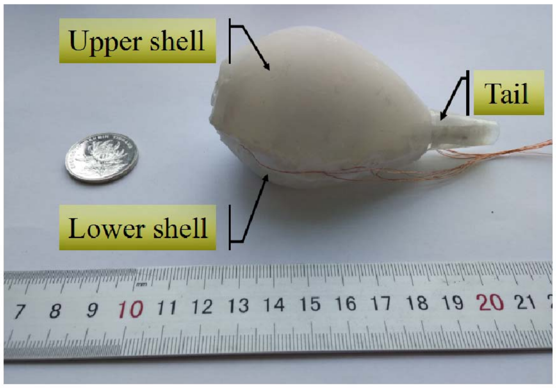
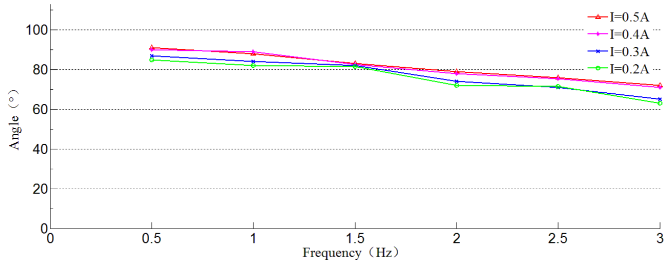


Fig.11 Prototype of the son robot

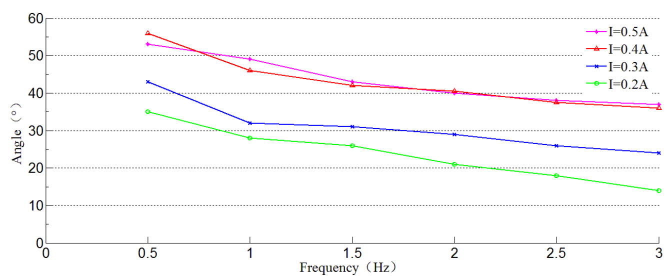
B. Analysis of the Tail for the Son Robot

In order to obtain the control of the tail, underwater experiments on the SMA based basilar plate is conducted. The angle α, as shown in Fig.4, is defined as the angle of the basilar plate. This angle is determined by the heating current is set as 0.5, 1, 1.5 and 2 Hz, respectively. Because the basilar plate is very short so the difference of the current has a great influence on the angle. There are different angle versus frequency of the basilar plate with different various diameters; 0.1 mm, 0.2mm and 0.3 mm.

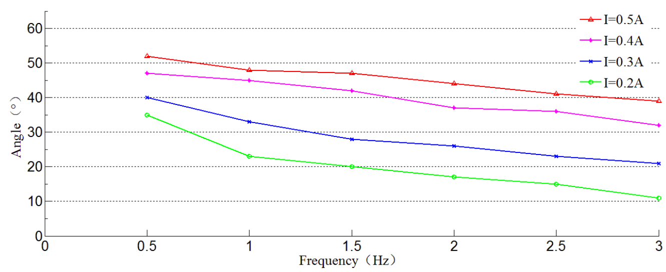
The experimental results are shown in Fig.12. It can be concluded from this result that when the diameter is 0.1 mm, as shown in Fig.12 (a), the bending angle α was too large, that would make the microrobot imbalance. When the diameter is 0.2 mm, as shown in Fig.11 (b), the bending angle α was not in the range we need. From Fig.11 (c) we can see that when the diameter is 0.3 and the current is 0.4A the bending angle of the basilar plate would turn between 50 and 30. In this rang of angle, the microrobot could turn around stably.



(a) d=0.1mm



(b) d=0.2mm



(c) d=0.3mm

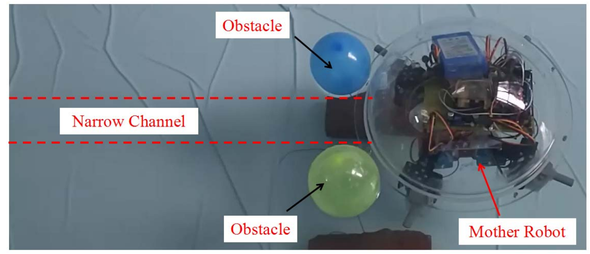
Fig.12 Angle of the basilar plate with different diameters

C. *Forward and Rotating movement Experiments*

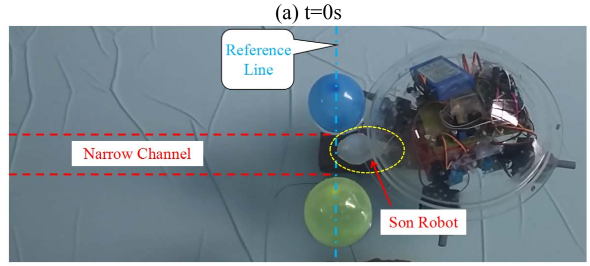
Forward and rotating movement experiments were carried out in a water tank to evaluate the performance of the basic of the son robot. The process of forward movement was shown in Fig.13 and rotating movement as shown in Fig.14. In experiments, the power of the movement was supplied by the mother robot. We released the son robot in the narrow channel we built and measured the speed of forward movement. And then, we measured the speed of rotating.

Fig.15 shows the relationship between the forward speed and time of the son robot, we achieved a maximum forward speed of 8.7mm/s. Because of hysteresis of the SMA wire and restoring force of the actuator would be reduced during the forward program. The forward speed of the son robot was slightly slow down and then flattens after about 19s.

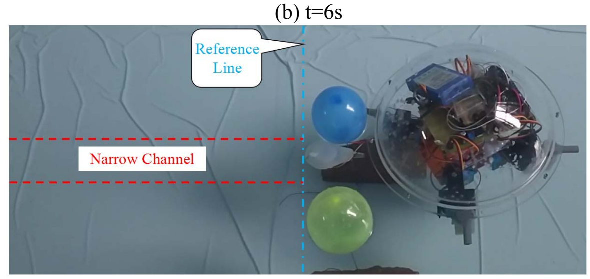
The experimental result of the rotating movement was shown in Fig.16. The maximum rotating speed we achieved is 0.23 rad/s.



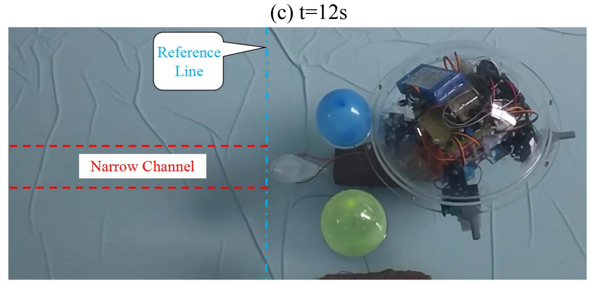
(a) t=0s



(b) t=6s



(c) t=12s



(d) t=18s

Fig.13 The forward movement of the son robot

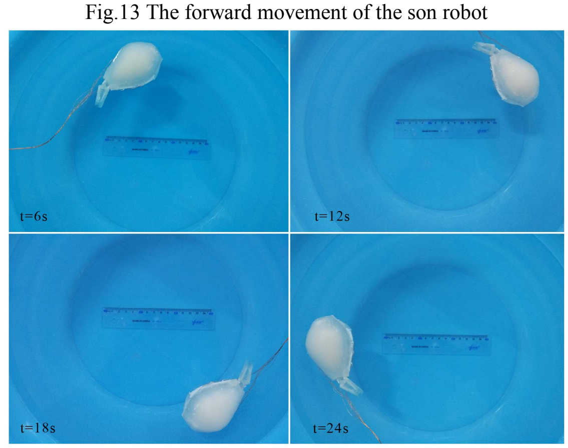


Fig.14 The rotating movement of the son robot

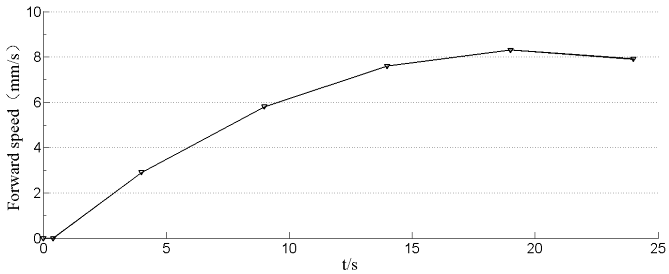


Fig.15 Experimental result of the forward movement

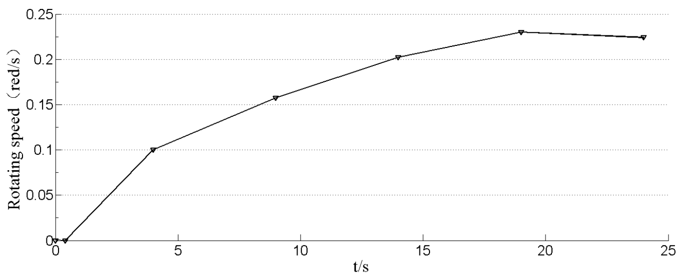


Fig.16 Experimental result of the rotating movement

V CONCLUSIONS

In this paper, we proposed a Salps-inspired son robot for the mother-son robot system. The son robot was actuated by SMA actuator, which could perform floating up and down, rotating and forward motion in the water. At first, we designed the hardware circuitry of the mother-son robot. Then we illustrated the power apply of the mother-son robot and the way of communication between the son robot and the mother robot. We described the son robot movement pattern when it is forward and rotating.

The tail of the son robot was analysed to obtain the control of the tail. We also carried out the underwater experiments to evaluate the performance of forward and rotating and to describe the performance of the basic motions of the robot. The results shown that the maximum forward speed is 8.5mm/s and the maximum rotating speed is 11.3 ° /s.

In the future work, the son robot could through reduce the hysteresis quality of the actuator to improve the swimming speed.

ACKNOWLEDGMENTS

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