A Smart Actuator-based Underwater Microrobot with Two Motion Attitudes

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Abstract - Various microrobots were widely used in the fields of biomedical engineering and underwater operation during the last few years. By having a compact structure, low driving voltage and a simple control system, microrobots could complete a variety of underwater tasks, even in limited spaces. To realize the multifunctionality of the microrobot for adapting to complex underwater environments, we proposed a walking biomimetic microrobot with two kinds of motion attitudes, lying state and standing state. The microrobot used eleven ICPF (ionic conducting polymer film) actuators to move and two SMA (shape memory alloy) actuators to change motion attitude. In the lying state, the microrobot could implement stick insect-inspired walking/rotating motion, fish-like swimming motion, horizontal grasping motion, and floating motion. In the standing state, it could implement inchworm-inspired crawling motion along two directions and vertical grasping motion. Then we developed a prototype of multi-functional biomimetic microrobot and evaluated its walking, rotating and floating speeds experimentally. Experimental results indicated that the robot could obtain a maximal walking speed of 3.6mm/s, a maximal rotating speed of 9deg/s and a maximal floating speed of 7.14mm/s.

Index Terms – Underwater microrobot, Motion attitudes. ICPF actuator, Shape memory alloy actuator, Biomimetic locomotion.

I. INTRODUCTION

In the biomedical field and naval field, research of underwater biomimetic microrobots has been focused on applications, such as cleaning the micropipeline in a radiation environment, submarine sampling and data collecting and object recovery in limited and dangerous spaces, video mapping, scanning the blood vessel and so on [1] [2]. Robots in past research usually utilized screw propeller actuated by motor to be actuator, which holds the problems with the larger size and higher power consumptions. As the electromagnetic structure of traditional motor, shrinking the motor to a compact volume seems difficult to realize. Based on these problems, applications of the smart materials, including ionic conducting polymer film (ICPF), piezoelectric elements, pneumatic actuator, and shape memory alloy (SMA), become more and more in the field of microrobot [3] [4].

Many biomimetic microrobots actuated by smart actuators have been developed in recent years. However, developing a microrobot to implement compact structure, flexibility, and multi-functions at the same time still seems difficult by the reason of conflicts among these three properties.

ICPF actuators have been widely researched in the way of actuating microrobots, with the advantages of compact structure, soft characteristic, low-voltage driving, low noise driving, driving in water or wet environments, and having the similar density to the water. For its quick response property ICPF actuators are used as oscillating fins in swimming microrobots far and wide [5]-[12], and it is also used as legs in biped walking underwater microrobots [13] [14].

However, in the past researches, the fish-like robot could not ensure its position precision and its motion in limited spaces, and do some simple underwater tasks. So many researches chose to develop walking robots instead. But there were still certain aspects of the insufficiencies. One robot could only realize one function of underwater mission till now. Thus we should develop the robots to make up for the shortcoming of unrealized multifunctionality.

With the purpose of implementing more functions of microrobot, we proposed an insect-inspired microrobot with two motion attitudes in this paper. The microrobot used eleven ICPF actuators for locomotion and underwater mission, and used two SMA actuators for attitude change as well. The robot could change between two attitudes, lying state and standing state. Then we developed a prototype of the robot and conducted experiments to evaluate its performance.

This paper consists of the following five parts. In chapter II, we described the design of the robot and introduced the motion mechanisms of the robot in different motion attitudes respectively. Then chapter III showed experiments of smart actuators and the force analysis of attitude change of the robot. After that, a prototype was given in chapter IV and experiments were conducted. Finally, we drew the conclusions in chapter V.

II. DESIGN AND MOTION MECHANISMS OF THE MICROROBOT

A. Proposed Underwater Microrobot Structure

We proposed an insect-inspired underwater microrobot, which consists of a plastic body, eleven ICPF actuators, two SMA actuators, a tail fin and two plastic sheets, with the function of motion attitude change. With the SMA actuators fixed in the plastic sheets, the attitude of the microrobot can change between the lying state and the standing state, which are shown in Fig.1. The body of microrobot is 35mm long and 20mm wide, which is determined by the functions and balance of the total body. In order to implement more functions and insure that there is no mutual interference between each
actuator by considering its swing range, the size of the body is the minimum size we can set. In the lying state, the height of it is 3mm. And in the standing state, it is 21mm high. Eleven actuators are all 17mm long, 3mm wide and 0.2mm thick.

The microrobot uses eleven one-DOF actuators to realize walking, rotating, swimming and grasping motions. Fig.1 (a) shows the sequence for the eleven ICPF actuators. In the lying state, actuator I and J are called fingers for grasping object, and actuator B, C, F, G and actuator A, D, E, H are called supporters and drivers separately, used for locomotion of the robot. However, in the standing state, actuator B, C, F, G are called fingers, and actuator A, D, E, H are called drivers. And actuator K is called tail fin for swimming motion.

**B. Mechanism of the Walking/Rotating Motion**

In the lying state, the microrobot can implement stick insect-inspired walking/rotating motions by using supporters and drivers. The robot can finish one step cycle of moving forward/rotating motion through four steps, as shown in Fig.2 and Fig.3 respectively.

The microrobot is controlled by the output voltage/current of power supply and the frequency of control signal. Assume that the tip displacement of an ICPF actuator is $d/2$, where $d$ is the distance that the robot advances, we can get the speed by (1), where $v$ is the average speed and $f$ stands for the frequency.

$$v = d \times f \quad (1)$$

The robot can rotate to an angle of $\theta$ in one step cycle, which is shown in Fig.4 (a). So it can be described by (2), where $L$ is the arc length which the moving side of the driver turns and $R$ is rotation radius with the centre of point O. Here we assume that $L$ is approximately equal to $d$, where $d$ is the motion length between initial position and final position of the moving side of the driver, that is the displacement of the driver. Through the calculation by (3), (4), (5) and (6), the rotation radius $R$ can be gotten. And equation (7) sets up a mathematical model, where $\omega$ and $f$ are the rotating speed and frequency respectively.

$$\theta = \frac{L}{R} \quad (2)$$

$$r \cos \alpha = r - \frac{d}{2} \quad (3)$$

$$l = \alpha \times r \quad (4)$$

$$\omega = \theta \times f \quad (7)$$

![Fig. 1 (a) Lying state of the proposed microrobot. (b) Standing state of the proposed microrobot.](image)

![Fig. 2 One step cycle of moving forward motion in the lying state (The marks ● indicate which actuator contacts the ground).](image)

![Fig. 3 One step cycle of rotating motion in the lying state (The marks ● indicate which actuator contacts the ground).](image)

![Fig. 4(a) The rotating angle in one step cycle. (b) The calculation of the value of $\theta$. (Only drivers are drawn).](image)

![Fig. 5 One step cycle of crawling motion in the standing state.](image)
In the standing state, the microrobot can implement inchworm-inspired crawling motion along two directions, longitudinal direction and transverse direction, by using the eight legs from A to H, as shown in Fig. 5. Leg A and E of the robot are used as leading legs and leg D and G are used as following legs, which realizes the walking motion along longitudinal direction. In this attitude, robot can implement more locomotion.

C. Mechanism of the Grasping Motion

The robot can grasp small objects with its finger I and J in the lying state. It can get to the desired place depending on the locomotion mechanism. Through the ICPF actuators bending inwards, objects can be caught hold of by the fingers. Then the robot brings the object to the designated place.

And the microrobot can catch objects in standing state too. It uses leg B, C, F and G to grasp the object and uses the other four legs to realize the locomotion. By way of the four legs in the middle bending inwards, it can hold the object then take it to the desired place.

D. Mechanism of the Floating Motion

By decreasing the frequency of driving voltage to 0.3 Hz, the water around the surface of the ICPF actuators can be electrolyzed. The buoyancy of the robot increases with the increasing volume displacement generated by the bubbles. In lying state, we use four drivers and four supporters to electrolyze water to realize the floating motion. And in the standing state, we electrolyze the leg A and E and following leg D and H to implement floating motion. Through the swing of the tail fin K, the swimming motion can be controlled.

E. Control System Mechanism

The control center of the microrobot is AVR atmegal16. The relays are used as both power amplifier and switch. One ICPF actuator is controlled by two relays, one of which is for controlling the control signals on and off, the other one of which is for controlling the bending direction.

III. EXPERIMENTS OF SMART ACTUATORS AND FORCE ANALYSIS OF THE ATTITUDE CHANGE

A. Performance Evaluation of ICPF Actuators

We did experiments on an ICPF actuator to evaluate its performance [15] [16] [17]. The displacement measuring system for ICPF actuators is shown in Fig. 6. This system has two main parts, including the section of control signal of ICPF actuators and the section of measuring displacement. Part one consists of function generator, DC power supply and electric relay. Part two contains an AD board and a laser sensor, which used as a proximity sensor, composed by an amplifier unit and a sensor head. Function generator is applied to control the frequency of the electric relay to make the DC power supply provide a rectangular wave signal for ICPF actuators. With the function of turning a distance signal into a voltage signal, laser sensor can measure the voltage of every moment. We use the AD board to record these voltage values. With the output characteristics of laser sensor, the output voltage of which is proportion to the distance, we can get the tip displacement of the ICPF actuator by calculating the distance difference.

Through changing the voltage and frequency, we can get the experimental results, as Fig. 7 shows, which indicate that the displacement is in inverse proportion to the frequency of input signal and in proportion to the input voltage in low frequency, but the variation of displacement is small when changing the voltage under a high frequency.

B. Performance Evaluation of SMA Actuators

We also did the SMA actuator experiments for evaluating its performance [18] [19] [20]. Fig. 8 shows the deformation measuring system for the SMA. We still used AD board and laser sensor to measure the stretched length of the SMA when changing the input voltage. Using the method of achieving the tip displacement before, we can get the tip displacement of the SMA as well.

Deformation measuring system is built as Fig. 8 shown. DC power supply provides input signals to the SMA actuator. The payload weight is 53 grams and the testing time is 10 seconds. In these 10 seconds, we control the input signal on and off. Fig. 9 shows the relationship between input voltage signal and tip displacement of the SMA with this payload. Adjusting the voltage, we could realize that the power current is proportion to the power voltage. From Fig. 9 we could get the result that the higher the input voltage is, the bigger the deformation length of the SMA actuator is.
C. Force Analysis of the Attitude Change

SMA actuators were used for motion attitude change of microrobot. Before fixing the SMA actuator under the body of robot, we calculated the force of making the robot stand up. To transform horizontal forces to vertical direction, we used a spring dynamometer. As shown in Fig.10, we fixed a fishing line in points A, B, C and D. Then we connected the measuring terminal of the spring dynamometer to the lowest point (point O) of the line to measure the force in vertical. The force, changing the robot into the standing state, is described by (8), where \( F \) is equal to \( F_2 \) because of the characteristic of the force acting on a line. Using equations (9), (10), (11) and (12), we got the force \( F \) and then we got the force \( F_{\Sigma} \), which is 2.272 N.

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F_{\Sigma} = 2F_3 = 2F
\]  
\[
F = 2F_2 \cos \alpha
\]  
\[
F_2 = 2F_1 \cos \theta
\]  
\[
\cos \theta = \frac{O - O}{ED}
\]  
\[
\cos \alpha = \frac{E}{DO} = \sqrt{\frac{DO^2 - \left(\frac{AD}{2}\right)^2}{DO^2 - \left(\frac{AB}{2}\right)^2}}
\]

\[
DO = 62\text{mm}, \quad AD = 20\text{mm}, \quad AB = 23\text{mm}
\]

IV. PROTOTYPE MICROROBOT AND EXPERIMENTS

A prototype insect-inspired underwater microrobot with two motion attitudes was constructed, based on the design before, as shown in Fig.11. We chose a kind of enamel covered copper wires with a diameter of 0.03mm to receive control signals. The resistance of the wires could be ignored due to their high softness. The prototype control system consists of AVR atmega16 and twelve relays.

A. Walking/Rotating Experiments on the Underwater Flat

In the experiments, we changed the applied signals and calculated the walking/rotating speed of microrobot in each signal by recording the time required to advance a distance of 20mm and rotate an angle of 90° separately. All experiments were repeated 5 times in every set of control signal for achieving an average speed.

In a fixed current of 0.7A, we did two groups of walking experiments in different applied voltage, 4V and 6V, and three groups of walking experiments in different applied voltages, 3V, 5V and 8V, to get the speed in each frequency/current for performance evaluation, as shown in Fig.12 and Fig.13. From
the results, the walking motion has a high efficiency with a control frequency range from 2Hz to 5Hz and the walking speed is proportion to the input voltage and applied current respectively. And the robot keeps still with low current and low voltage. When increasing the control frequency to a larger value, the tip displacement of the ICPF actuator becomes smaller. So the displacement of the robot is small, with the reason of the slippery underwater flat as well.

B. Floating Experiments without Payloads

Because under a control frequency of 0.5Hz, ICPF actuators can electrolyze the water around their surfaces, so with the generating bubbles adsorbing to the body of the robot, the buoyancy of the microrobot increases, which causes the robot to float up in the water, as Fig.15 shows. And we can find the robot floats up steadily. In the floating experiments, we changed the control frequency, ranging from 0.05Hz to 0.5Hz, under a fixed voltage of 6V and a fixed current of 1A. Then we calculated the floating speed of the microrobot in each control frequency by recording the time required to float up to a height of 100mm, as shown in Fig.16. The experiment was also repeated 5 times in every set of control signal for achieving an average speed.

From the results, the average floating speed is in inverse proportion to the control frequency and the maximal speed of 7.14mm/s can be got under a frequency of 0.05Hz. We also can get the conclusion that the lower the control frequency is set, the faster the electrolytic rate can be.

C. Standing Experiments

In the standing experiments, we used two SMA actuators to make the microrobot stand up in the air and on the underwater flat respectively. Fig.17 shows the standing experiments on the underwater flat from the two perspectives of front and side. We did the experiments under a control voltage of 8V and a current of 1A. The SMA actuator has the property of shrinkage at high temperature. Therefore, we should better insulation especially in the water for the reason of fast heat dissipation. So we sealed the two SMA actuators with adhesive tape respectively to achieve a better effect on the standing motion.

V. CONCLUSIONS

To realize the purpose of multifunction of the microrobot aiming at adapting to the complex underwater environment, in
this paper, we proposed a walking biomimetic microrobot with two motion attitudes. It realized walking, rotating, floating motions and motion attitude change. From the results, the robot could get a maximal walking speed of 3.6mm/s under a control frequency of 2.5Hz and a fixed current of 0.7A, and a rotating speed of 9deg/s under a voltage of 6V and frequency of 3Hz. In addition, it could achieve a maximal floating speed of 7.14mm/s under a control frequency of 0.05Hz and a voltage of 6V. And with the SMA actuators, the robot could change its attitude on the underwater flat.

In the next step, we will do the experiments on walking, rotating and grasping motions to evaluate the performance of microrobot in the standing state. After that, we will equip some sensors on the robot to ensure its stability.

Fig. 17 Standing experiments on the underwater flat.

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REFERENCES


