The development of a hybrid underwater micro biped robot

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S. Guo[1], Y. Okuda[1], W. Zhang[1], X. Ye[2] and K. Asaka[3]

[1] *Faculty of Engineering, Kagawa University, Hayashi-cho 2217-20, Takamatsu 761-0396, Japan*
[2] *Automation College, Harbin Engineering University, 145 Nantong Street, Nangang District, Harbin, China*
[3] *Kansai Research Institute, AIST, 1-8-31 Midorigaoka, Ikeda, Osaka 563-8577, Japan*

Abstract: There has been a great demand, in the medical field and in industrial applications, for a novel micro biped robot with multiple degrees of freedom that can swim smoothly in water or in aqueous medium. The fish-like micro-robot studied is a type of miniature device that is installed with sensing and actuating elements. This article describes the new structure and motion mechanism of a hybrid type of underwater micro-robot using an ion-conducting polymer film (ICPF) actuator, and discusses the swimming and floating characteristics of the micro-robot in water, measured by changing the voltage frequency and the amplitude of the input voltage. Results indicate that the swimming speed of the proposed underwater micro-robot can be controlled by changing the frequency of the input voltage, and the direction (upward or downward) can be manipulated by changing the frequency of the electric current applied and the amplitude of the voltage.

Key words: micro-robot, micro biped robot, micro-actuator, propulsion, ICPF actuator, propulsion, optimization.

INTRODUCTION

Intracavity intervention is expected to become increasingly popular in the medical practice, both for diagnosis and for surgery. Recently, many micro-robots have been developed for various purposes owing to the advances of the precise process technology, and further progress in this field is expected. There has been a great demand, in the medical field and in industrial applications, for a new type of fish-like micro-robot that can swim smoothly in water or in aqueous medium (Dario 1988; Special session on Biorobotics 1990; Maddock 1994). The fish-like micro-robot is a type of miniature device that is installed with sensing and actuating elements and can swim smoothly in water or in aqueous medium, which can be used for in-pipe inspection and micro-surgery of blood vessel.

Recently, several types of fish-like micro-robots using shape memory alloy, giant magnetostrictive alloy, piezoelectric and polymer actuators have been reported (Fukuda *et al.* 1991, 1994, 1995; Oguro *et al.* 1993; Mojarrad and Shahinpoor 1997; Guo *et al.* 1998, 2005; Osada 1992). However there are some problems, such as compact structure, low response, leaking electric current, safety in water, and so on. We aim to develop a type of fish-like micro-robot that can swim smoothly in water or in aqueous medium. It has the characteristics of flexibility, is driven by a low voltage, and shows good response and safety in the body. Biomimetic fish-like propulsion using an ion-conducting polymer film (ICPF) actuator as a propulsion tail fin for an underwater micro-robot swimming structure in water or aqueous medium is developed. The ICPF actuator is made from a film of perfluorosulfonic acid polymer (Nafion 117, DuPont) chemically plated on both sides with platinum. In many aspects, the ICPF actuator is superior to the usual polymer gel actuators; it has fast response, can be driven by low voltage (about 1.5 V) in wet conditions without electrolysis, and is safe in the body and so on (Tadokoro *et al.* 1998, 2000). The use of ICPF actuators now make it possible to replicate the undulating motion of marine animals in a more direct way (Guo *et al.* 2003, 2004, 2005c; Wang *et al.* 2006; Zhang *et al.* 2005a, 2005b, 2006). This article describes the structure and the mechanism of motion of a novel underwater micro-robot having an ICPF actuator, and discusses the swimming ability of the micro-robot in water. The characteristics of the underwater micro-robot are measured by changing the frequency (from 0.1 to 5 Hz) and amplitude (from 0.5 to 10 V) of the input voltage. Results indicate that the swimming speed and the buoyancy

Corresponding Author:
Shuxiang Guo
Faculty of Engineering
Kagawa University, Hayashi-cho 2217-20
Takamatsu 761-0396, Japan
Tel: +81-87-864-2333; Fax: +81-87-864-2369
Email: guo@eng.kagawa-u.ac.jp

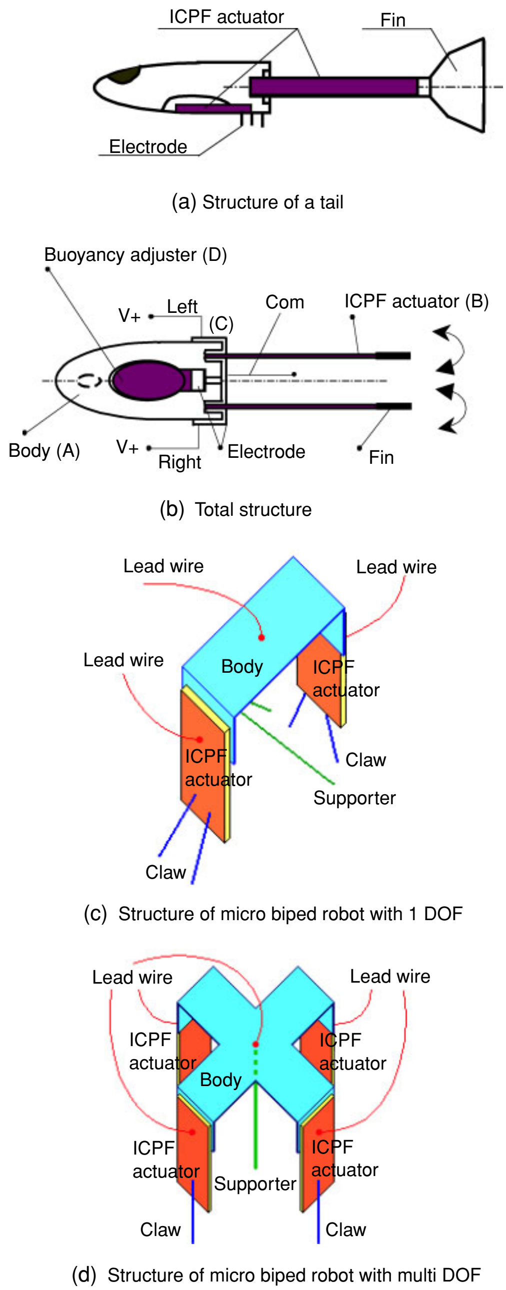

Figure 1 Structure of the micro-robot. (a) Structure of a tail, (b) total structure, (c) structure of micro biped robot with one degree of freedom, (d) structure of micro biped robot with multiple degrees of freedom.

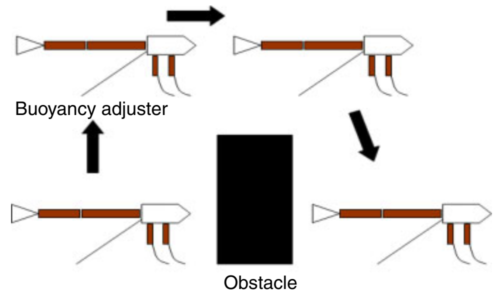

Figure 2 Hybrid underwater micro-robot.

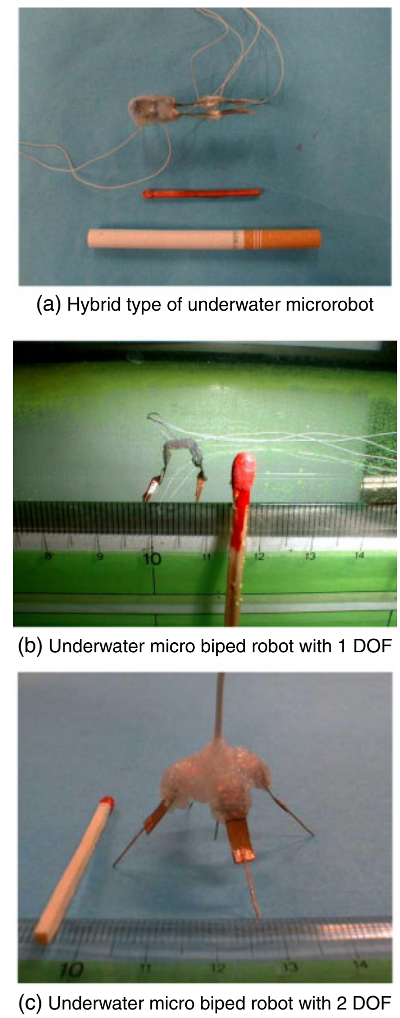

Figure 3 View of the developed micro-robot. (a) Hybrid underwater micro-robot, (b) underwater micro biped robot with one degree of freedom, (c) underwater micro biped robot with two degrees of freedom.

of the underwater micro-robot can be controlled by changing the frequency and amplitude of the input voltage.

STRUCTURE OF THE MICRO-ROBOT

Overall structure of the micro-robot

Figure 1 shows the basic structure of the developed underwater micro-robot using an ICPF actuator. The body of the micro-robot is made of wood, which is shaped like a fish (A); a pair of tails each with a fin driven independently by ICPF actuators (B), which are installed in a parallel structure for generating a large propulsive force; leads supplying electric energy to the ICPF actuators (C); and a buoyancy adjuster underside of the micro-robot body driven by a similar ICPF actuator (D). Figure 2 shows the structure of the developed micro-robot, which can realize both the walking motion and the swimming motion by changing the electri-

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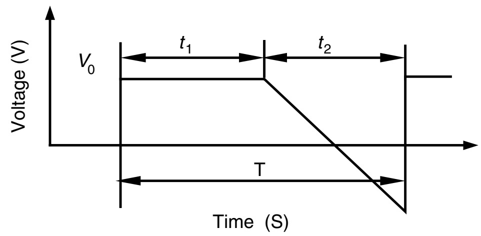

Figure 4 Driving electric voltage.

Table 1 **Moving motion of the micro-robot**

Forward[a]	Right turn	Left turn
$f_1 = f_2$	$f_1 > f_2$	$f_1 < f_2$

[a] f_1: right ICPF actuator frequency; f_2: left right ICPF actuator frequency.

cal frequency. The photo of the developed micro-robot is shown in Figure 3.

ICPF actuator

The ICPF actuator is made from a film of perfluorosulfonic acid polymer (Nafion 117, DuPont) chemically plated on both sides with platinum (of 0.003 mm thickness). It is known as an ion-exchange membrane. It is a type of high-polymer gel actuator that works only in water and in wet conditions. The ICPF bends toward the anode when a voltage of about 1.5 V is applied onto its surfaces. The displacement of the ICPF is proportional to the electrical voltage input on its surface as the swelling of polymer gels. The other characteristic of the ICPF actuator is that when the frequency of the applied voltage is low, less than 0.3 Hz, the water around the ICPF surface is electrolysed, so water blebs are generated on both sides of the ICPF surface. As a result of this change in body volume, the buoyancy of the micro-robot can be controlled. To drive the fin for propulsion the ICPF actuator ($0.2 \times 3 \times 15$ mm) is cut in a strip, and in the buoyancy adjuster the ICPF actuator ($0.2 \times 4 \times 6$ mm) is used as shown in Figure 1.

MECHANISM OF MOTION OF THE MICRO-ROBOT

The developed micro-robot has two tails each with a fin driven by an ICPF actuator as shown in Figure 1. The fins are offset at a distance d, and driven independently by electric voltage of frequencies $f1$ and $f2$, respectively, as shown in Figure 4. The motion of a fin can be described by a combination of two kinds of motion, feathering (motion in the direction parallel to the surface of water) and heaving (motion in the upward and downward directions). When a proper phase difference is established between heaving and feathering, the fin generates an effective force, as shown in Figure 5. The propulsive force is the sum of drag force vectors in the direction of motion (Equation (1)). By changing the frequencies $f1$ and $f2$ of the electric voltage applied on the ICPF actuators, the micro-robot can be made to

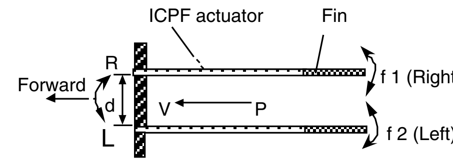

Figure 5 Mechanism of micro-robot using ICPF actuators.

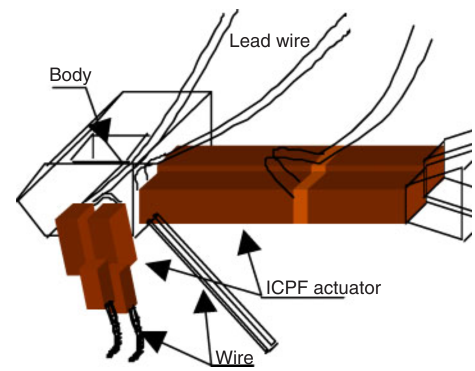

Figure 6 Adjusting mechanism of hybrid micro-robot.

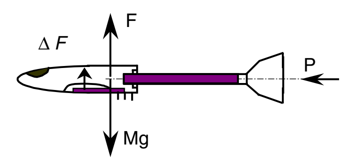

Figure 7 Floating mechanism of the micro-robot.

move in the forward, right turn, and left turn directions (Table 1).

The micro-robot has a solenoid and two permanent magnets. It can change the body posture by adjusting the position of the barycentre, as shown in Figure 6.

$$P = -\tfrac{1}{2} C_{\mathrm{d}} \rho A \, |V_k| \, V_k, \tag{1}$$

where C_{d} is the drag coefficient based on the wetted surface area A, ρ is the density of water, and V_k is the speed in the direction of motion.

The micro-robot has a buoyancy adjuster driven by an ICPF actuator. The ICPF actuator has the characteristic that when the frequency of the applied voltage is less than 0.3 Hz, the water around the ICPF surface is electrolysed, so water blebs are generated both sides of the ICPF surface. As a result of this change in body volume, the floatage of the micro-robot can be controlled. The floating mechanism of the micro-robot is shown in Figure 7. We know that the floatage of the micro-robot is

$$F = \rho \times V_{\mathrm{a}}, \tag{2}$$

where V_{a} is the total volume of the micro-robot. At first, when the weight Mg is a bit higher than the floatage F, the micro-robot sinks downward in water. When the water around the ICPF surface is electrolysed, the generated bleb adsorbs on both side of the ICPF actuator and it increases the total volume of the micro-robot by ΔV. It also increases the flotage by ΔF.

$$\Delta F = \rho \times \Delta V. \tag{3}$$

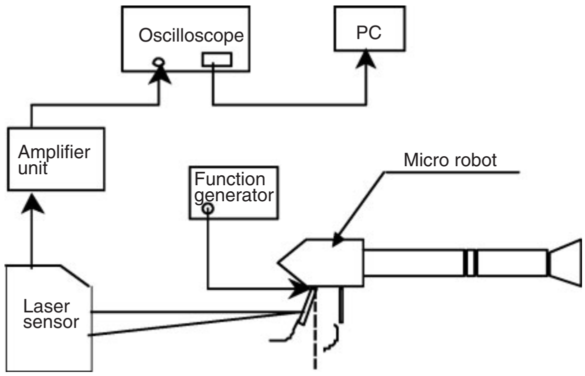

Figure 8 Measurement system.

We observed that the volume of the generated bleb can be controlled by changing the frequency and the amplitude of the applied voltage. When

$$\Delta F = Mg - F, \tag{4}$$

it stops sinking and gets suspended in water. When

$$\Delta F > Mg - F, \tag{5}$$

it begins to float upward; this happens when the frequency of the applied voltage is less than 0.3 Hz. Electrolysis begins to be obvious, and the larger the amplitude of voltage applied, the higher the volume of the bleb generated.

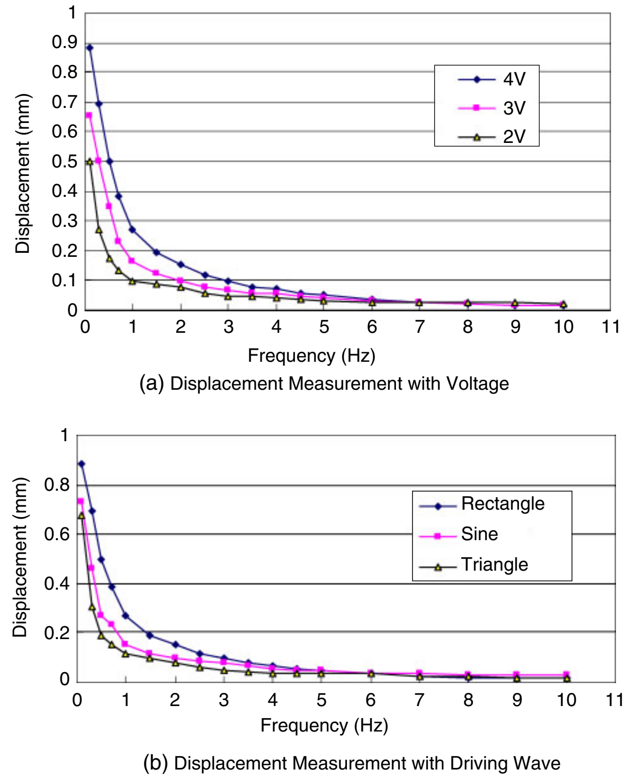

Figure 9 Experimental results of the displacement (in air). (a) Displacement measurement with voltage, (b) displacement measurement with driving wave.

CHARACTERISTIC MEASUREMENT

Measurement system

A computer can control the electric voltage applied to the ICPF actuators. The electrical current is measured by a galvanometer. The bending displacement of the fins at the point of the front end is measured using a laser displacement sensor. The bending amplitude of the fins can be measured in terms of the input voltage as shown in Figure 4. Measurement system is shown in Figure 8.

Characteristics of the fin

By using the measurement system shown in Figure 8, the following characteristics were measured. First, we measured the maximum displacement at the center point of a fin in air by changing the frequency of the input voltage (Figure 4). Second, the maximum current is also measured by changing the input voltage.

The experimental results are shown in Figures 9 and 10, which show that the maximum displacement is in inverse proportion to the frequency of the input voltage and the maximum current is nearly proportional to the input voltage respectively.

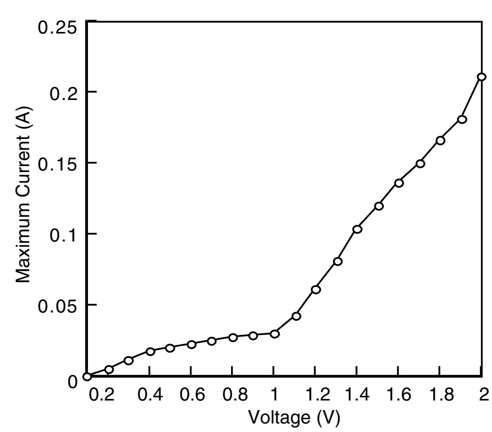

Figure 10 Maximum electric current (in air).

PROTOTYPE FISH-LIKE MICRO-ROBOT

The prototype developed is shown in Figure 3. It is 10 mm in width and 45 mm in length (body 15 mm without tail), as shown in Table 2. The body of the micro-robot is mainly made of wood as it is lightweight. In order to verify the mechanism of the micro-robot, we carry out the swimming experiments in three directions with three degrees of freedom in water by changing the voltage frequency. Figure 11 shows the walking motion underwater. Figure 12 shows the floating motion in the vertical direction for avoiding obstacles in the water by changing the buoyancy of the micro-robot in reaction.

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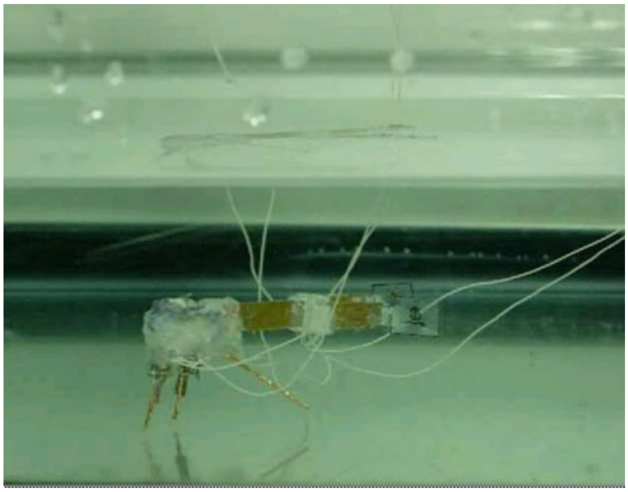

Figure 11 Walking motion underwater.

Table 2 **Specifications of the prototype micro-robot**

Size	10 mm × 45 mm
Weight	0.76 g
Material	Wood
Actuator	ICPF (0.2 × 3 × 15)
Power supply	Electricity (e.g., 4 V, 0.15 A)

RESULTS

We carried out the swimming experiments of the prototype micro-robot using a measurement system shown in Figure 13. The propulsive forces for various frequencies were measured using a laser displacement sensor, an electric balance, and a copper beam. The copper beam is soft enough to be bent by the propulsive force. The electric balance is used for evaluating the force. We also measured the propulsion speed for various frequencies using a high-speed camera. The average value of more than 20 measurements is used as the final test data. By changing the frequency from 0.2 to 5 Hz at 2.5 input, the experimental results of the average propulsive force and the average speed are shown in Figure 14. Experimental results

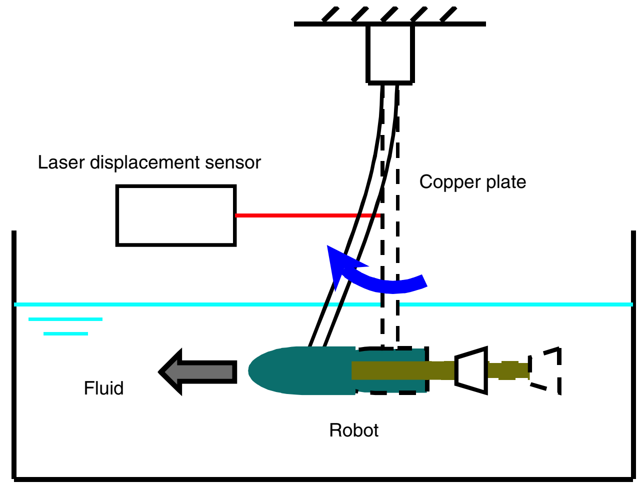

Figure 13 Measurement system of propulsion.

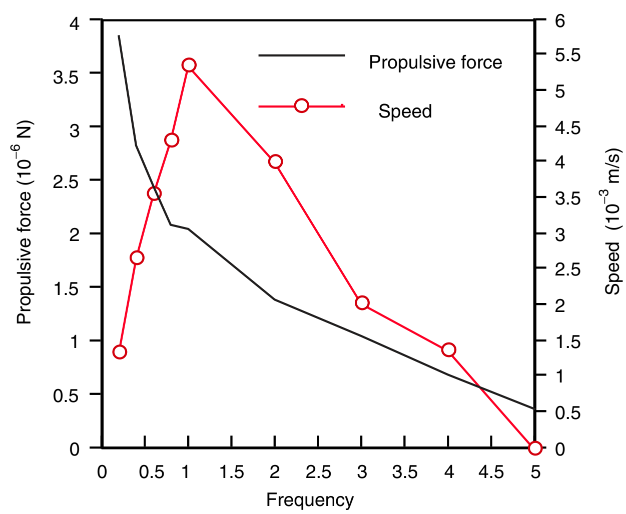

Figure 14 Experimental results (2.5 V).

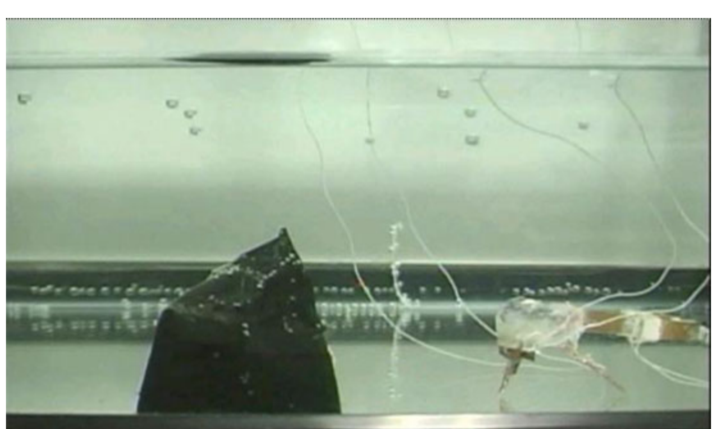

Figure 12 Floating motion for avoiding obstacles.

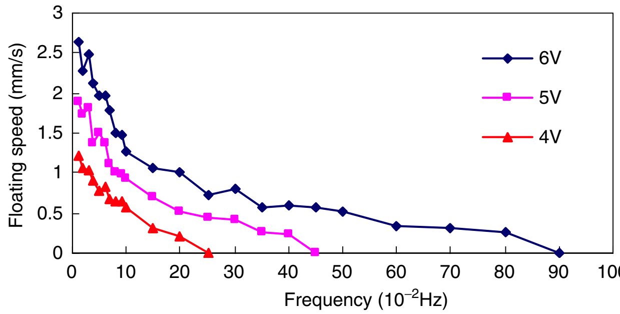

Figure 15 Experimental results of floating speed.

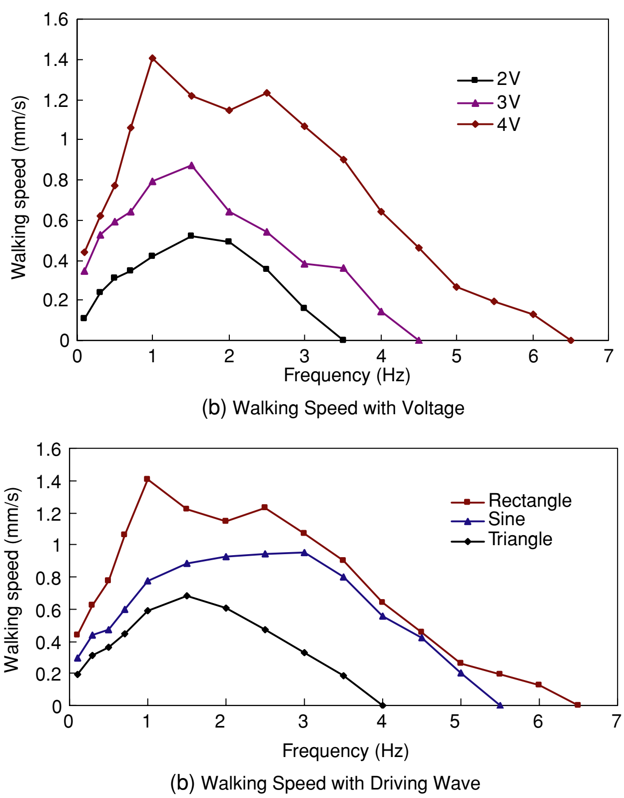

Figure 16 Experimental results of the micro-robot with one degree of freedom. (a) Walking speed with voltage, (b) walking speed with driving wave.

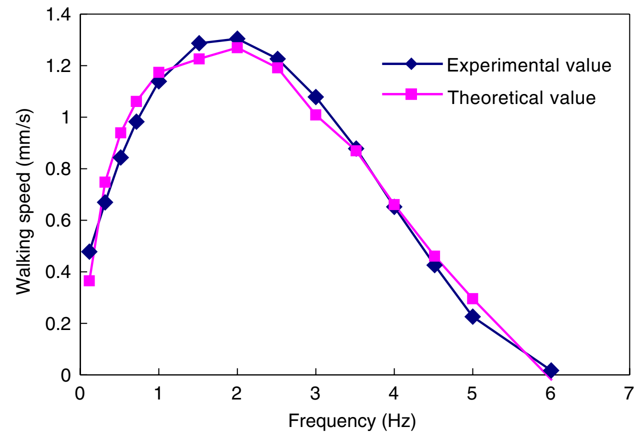

Figure 17 Relationship between calculation results and experimental results with one degree of freedom.

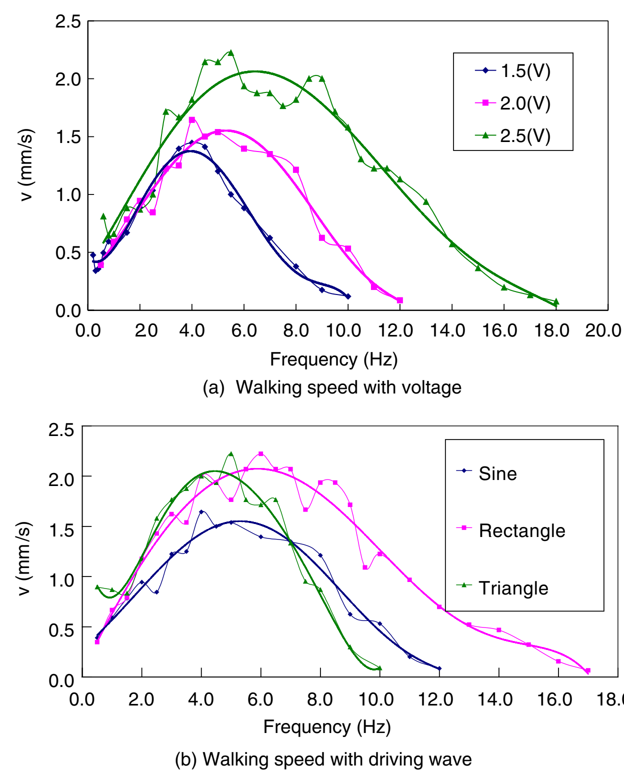

Figure 18 Experimental results of the micro-robot with two degrees of freedom. (a) Walking speed with voltage, (b) walking speed with driving wave.

show that the speed can be varied from 1.3 to 5.21 mm/s by changing the voltage frequency. Figure 15 shows the floating speed for the micro-robot by changing the voltage frequency and amplitude of the input voltage.

Figures 16 and 17 show the experimental and theoretical results, respectively, of the walking speed obtained by changing the voltage frequency for the micro-robot with one degree of freedom. Figures 18 and 19 show, respectively, the experimental and the calculated values of the walking speed by changing the voltage frequency for the micro-robot with two degrees of freedom. The results show that by changing the voltage frequency and the amplitude of the input voltage, we can control the walking speed for the micro-robots, and the walking speed can be calculated using the displacement of the ICPF actuators and the voltage frequency. It is very useful for the optimization design of the micro-robot.

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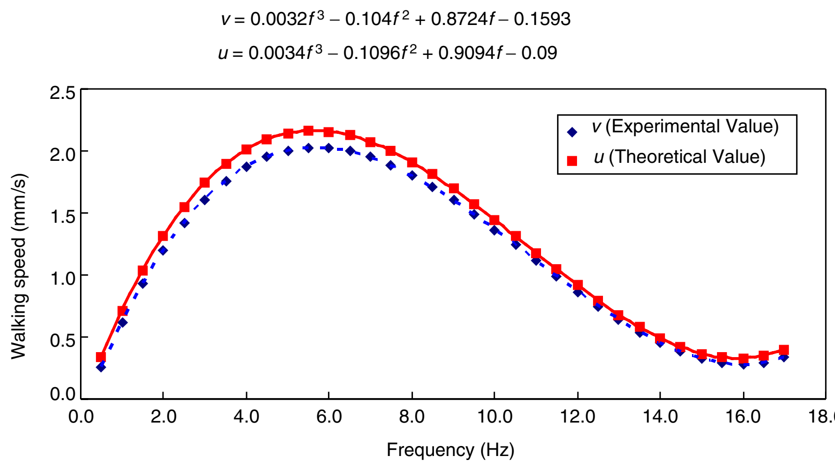

Figure 19 Relationship between calculation results and experimental results with two degrees of freedom.

CONCLUSIONS

This article describes the structure and mechanism of motion of a novel hybrid underwater micro-robot with ICPF actuators, and discusses the swimming and floating characteristics of the micro-robot in water. The mass center of the micro-robot can be controlled by an electromagnetic actuator. So the floating motion in the vertical direction has been realized easily. There are two pairs of fins, a mass center adjuster and a floatage adjuster. Characteristic of the underwater micro-robot is measured by changing the voltage frequency and amplitude of the input voltage. The experimental results indicate that the swimming speed of the proposed underwater micro-robot can be controlled by changing the frequency of input voltage, and the moving direction (upward or downward) can be controlled by changing the voltage amplitude and the frequency of the input voltage.

On the basis of the experimental results, it was verified that the proposed hybrid underwater micro biped robot can realize swimming, walking, and floating motions, and the running speed of the micro bipedal robot was controllable by changing the voltage amplitude and the frequency of input voltage. The micro-robot is expected to find industrial and medical applications.

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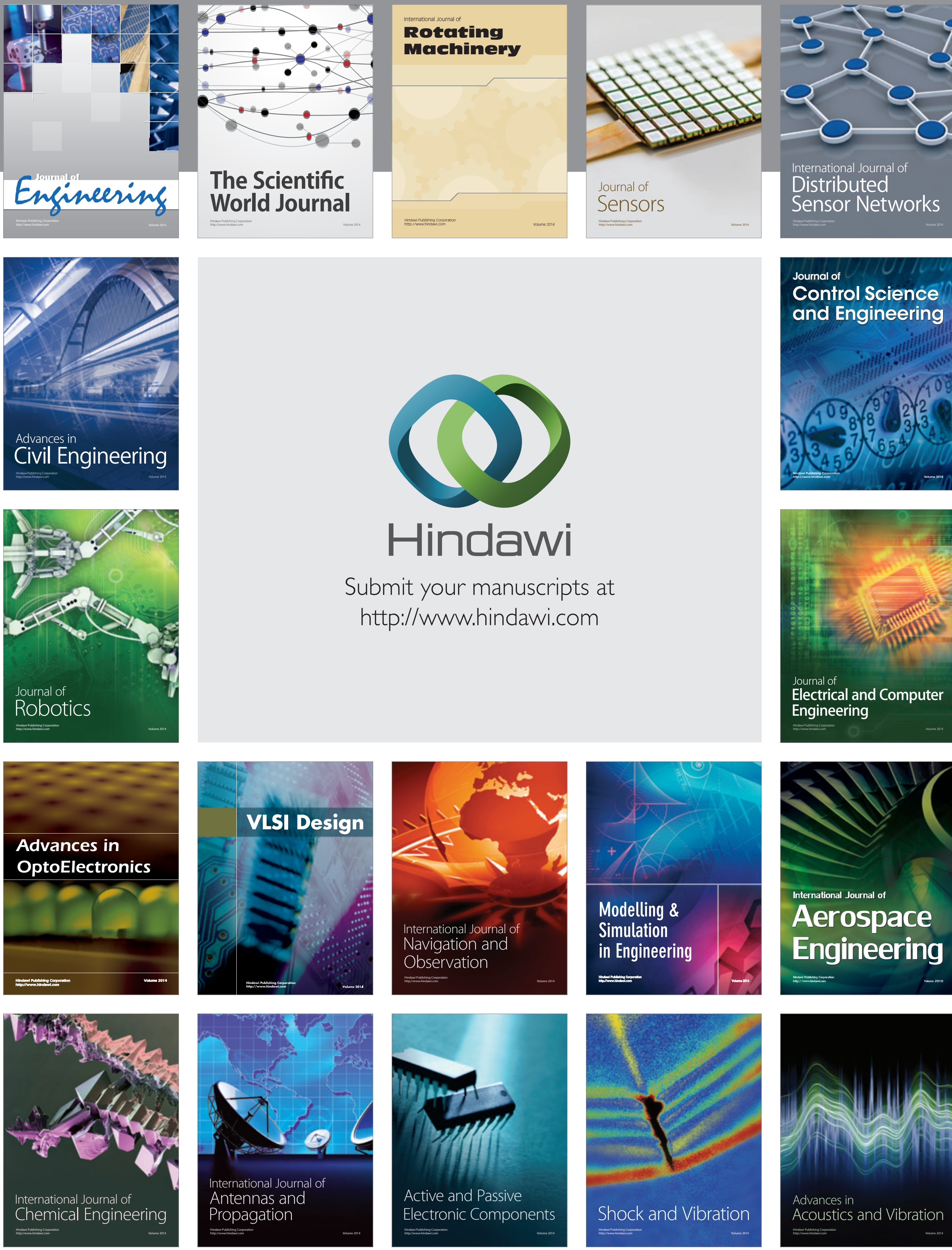
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