Aquatic Ionic-Polymer-Metal-Composite Insectile Robot With Multi-DOF Legs

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***Abstract*—Ionic polymer-metal composite (IPMC) is used in various bioinspired systems, such as fish- and tadpole-like robots swimming in water. The deflection of this smart material results from several external factors, such as water distribution and concentration. IPMC strips with a variety of water concentration on the surfaces and the surface conductivity show various deflection patterns. In this paper, IPMC strips in four initial wetness conditions (100%, 50%, 0% wet on the anode surfaces but 100% wet on the cathode surfaces, and the last one submerged in deionized water) were tested. Even without any external excitation, the strips can bend due to nonuniform water distribution. In order to understand the effects of surface conductivity in an aquatic environment, an IPMC strip with two wires connected to two distinct spots was used to demonstrate the power loss due to the surface resistance. Three types of input signals, sawtooth, sinusoidal, and square waves, were used to compare the difference between the input and output signals measured at the two spots. Thick (1 mm) IPMC strips were fabricated and employed in this study to sustain and drive the robot with sufficient forces. Finally, an aquatic walking robot (102 × 80 × 43 mm, 39 g) with six 2-degree-of-freedom (2-DOF) legs has been designed, implemented, and walked in water at the speed of 0.5 mm/s. The average power consumption is 8 W per leg. Each leg has a thigh and a shank to generate 2-DOF motions. Each set of three legs walked together as a tripod to maintain the stability in operation.**

***Index Terms*—Aquatic walking robot, biomimetic robot, ionic-polymer-metal composite (IPMC), 2-degree-of-freedom (DOF) leg.**

I. INTRODUCTION

SMART materials are employed in robotic actuators in lieu of metals and alloys due to the following advantages.

1) Lightweight: Traditionally, steel, aluminum, and their alloys are used in the robot structures. Their heavy weight leads to high power consumption in robot locomotion. Light smart materials do not need large power supplies.
2) Easy actuation: High-power and high-speed motors are commonly used to actuate robots. However, motors and robot frames are structurally separate, so they further increase weight. Smart materials can act as both structures and actuators simultaneously.
3) Flexible shapes and sizes: In many applications, robots should be designed to be tiny or in complex shapes. Smart materials can meet the demand because they can be cut in various shapes.

Smart materials can be excited by various external stimuli, such as temperature, electric field, magnetic field, and pH, according to their working principles [1]. Electroactive polymers (EAPs) are a kind of materials producing deflection or force by an external electric field. They can be categorized into electronic EAPs and ionic EAPs. Dielectric elastomer is a typical electronic EAP and requires a high electric field (about 100 V/μm) [1]. High electric fields distort the structures, so electronic EAPs exhibit small deflection but large force in performance. Ionic EAPs can generate large deflection by a low external voltage (about 5 V, depending on the thickness). However, these EAPs typically cannot produce large force. Therefore, ionic EAPs have been applied in small fish-like robots that do not need substantial locomotion [2].

Ionic polymer-metal composite (IPMC), a kind of ionic EAPs, exhibits conspicuous deflection in response to an external voltage. The structure of IPMC is a Nafion membrane with a layer of metal electrodes coated on both sides. Nafion, the basis membrane of IPMC, manufactured by DuPont, is a polymer and has been used as the cation-exchange film in fuel cells for a long while [3] because only cations can move freely inside. Nafion tends to swell by water molecules [4], so its size is changeable and dependent on the water concentration. Water molecules are bonded with cations, so the deflection of IPMC takes place when there is a difference in water concentration between both sides. The surface metal electrodes are used to move the cations by attractive and repulsive coulomb forces generated by the surface voltage. When the external power is OFF, the cations and water molecules are evenly distributed inside. When the power is ON, the cations with attached water molecules move to one side by coulomb force, and the water molecule concentration becomes nonuniform. This swelling and shrinking makes the IPMC bend [5]. The bending angle depends on the gradient in water molecule concentration, which can be controlled by the external voltage source.

IPMC has attracted much interest in the past decade because of its notable advantages: 1) Lightweight: The density of IPMC is around 2.25 g/cm^3 and it is much lighter than prevalently used metals, such as steel (7.85 g/cm^3) and aluminum (2.70 g/cm^3). 2) Easy fabrication process: IPMC is fabricated by chemical metal coating on the surface of Nafion (see Section II). (3) Easy use: IPMC just needs external voltage via two metal electrodes on both surfaces without complicated circuits and devices. In addition, it can be cut in various sizes and shapes in order to apply and fit in a variety of environment. 4) Low working voltage (1−5 V, depending on the thickness): Unlike other smart

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materials such as piezoelectric materials, IPMC can work with low external voltage instead of hundreds of volts [6]. 5) Can work in an aquatic environment: IPMC needs water in operation and works in water without being destroyed. 6) No noise and pollution: The working principle of IPMC is the movement of cations with water molecules inside, so no noise and pollution is generated in operation. 7) High working frequency (about 10 Hz, depending on the stiffness): IPMC exhibits the same performance whether the hydraulic pressure is 0.1 or 100 MPa with the same input voltage [7]. Hence, an aquatic robot can walk in water without any loss of water molecules inside.

A popular application of IPMC is biomimetic robots that can imitate the locomotion of insects and fishes with its repetitive and bidirectional bending. Fish-like robots were developed that could swim in an aquatic environment by undulating an IPMC tail fin [2], [8]. A worm-like robot, made of a segmented IPMC strip, crawled with appropriate input signals for each segment [9]. The application on a series of IPMC strips working in various phases has been reported in other fields. For example, Takagi *et al.* designed a rajiform swimming robot with two pieces of skate's fins on both sides [10]. Each fin consists of eight IPMC strips with a thin and transparent cover and works by sequential deflection of all IPMC strips. Various types of biomimetic robots using IPMC strips were developed, such as walking, climbing, and swimming robots [11], [12]. Yun and Kim implemented a three-finger microgripper of a robotic manipulator with three IPMC strips [13], [14]. With three laser distance sensors on each finger, all strips could be actuated by independent feedback controllers with an antiwindup scheme.

The objective of this study is to design and implement an aquatic walking robot based on our fundamental design principles with the IPMC strips that we fabricated. Most of the robots [2], [8]–[12] were made of thin (about 0.2 mm) IPMC strips, fabricated with Nafion 117. They exhibit conspicuous deflection but no sufficient force output and low current [15]. It is not problematic for fish- and tadpole-like robots because they can swim in water by buoyancy without other supports. In this study, 1-mm Nafion was used to be the basis to generate sufficient force for a walking robot. A simple IPMC strip has only one bending degree of freedom (DOF). Walking robots need at least two DOFs per one leg to perform walking locomotion. Therefore, most walking robots have two kinds of legs, a driver and a supporter, to activate and support the body [11]. To imitate a real-life insect more closely, one leg with two DOFs is designed in this study.

This paper consists of six sections. Section II describes the fabrication process and properties of our own IPMC. Section III shows the results of fundamental experiments of our IPMC strips. This section has two sets of experiments on different aspects of deflection. Section IV discusses the design and implementation of our aquatic robot in detail, including power transmission. The walking procedure and the driving signal sequences to generate smooth walking motions in water are also presented. Section V exhibits the implementation of our robot and describes the experimental results. The appropriate working environment and input signals are determined according to the experiments in Sections III and IV. Section VI presents the conclusions.

II. Enhanced IPMC for Robotic Applications

A. Fabrication of IPMC

In order to fabricate the IPMC strips for our robot, Nafion and platinum were chosen as the basis and surface electrodes, respectively, because platinum is electrically conductive and chemically stable. There are a variety of coating methods for metal electrodes. For IPMC, however, the basis, Nafion, is electrically nonconductive so only electroless coating methods are feasible. For the chemically reducing coating, we prepared Nafion membranes with Tetraammineplatinum(II) chloride monohydrate ($Pt(NH_3)_4Cl_2{\cdot}H_2O$, from Alfa Aesar), sulfuric acid (H_2SO_4), and sodium borohydride ($NaBH_4$, from MP Biomedicals) as a reducing agent. The fabrication procedure we took is based on [16] and improved by us.

The following procedures are corresponding to those in Fig. 1, which illustrates the IPMC fabrication procedure in detail.

1) Roughening the surface of Nafion on both sides manually applying sandpapers in the same direction. Roughened surface can easily attach more platinum particles [17]. In addition, plasma is prevalently used for fine and uniform roughening. The strips roughened by different plasma such as argon or oxygen show different responses mainly because the etched depths are different [18], [19].
2) Cleaning Nafion using deionized (DI) water with an ultrasonic machine for 30 min to remove the dust on the surface after roughening [16].
3) Removing the organic impurities on Nafion using 1.0-M boiled sulfuric acid for 30 min [16]. Nafion will swell and be softened in this step, so it must be kept flat.
4) Cleaning the residual sulfuric acid using boiled DI water for 30 min [16].
5) Soaking in platinum solution for 48 h to keep platinum particles attached onto Nafion [16].
6) Reducing platinum layer by $NaBH_4$ solution, keeping the temperature around 40 °C in order to get a stable reducing speed [16]. The reaction equation by using $NaBH_4$ as a reducing agent is

$$\begin{aligned} &\mathrm{NaBH_4} + 4[\mathrm{Pt(NH_3)_4}]^{2+} + 8\mathrm{OH^-} \\ &\quad \rightarrow 4\mathrm{Pt} + 16\mathrm{NH_3} + \mathrm{NaBO_2} + 6\mathrm{H_2O}. \end{aligned} \tag{1}$$

7) Cleaning residual reducing agent with 60–70 °C DI water for an hour [16].
8) Repeating steps 5–7 for five times in order to get thicker metal electrodes, which can improve the performance because of better conductivity.
9) Soaking in concentrated salty water (3.5%) for one day and then DI water for two days to improve the performance by replacing counter ions insides by sodium ions (Na^+).
10) Cleaning the surface and soaking in DI water for 48 h to remove residual sodium ions.

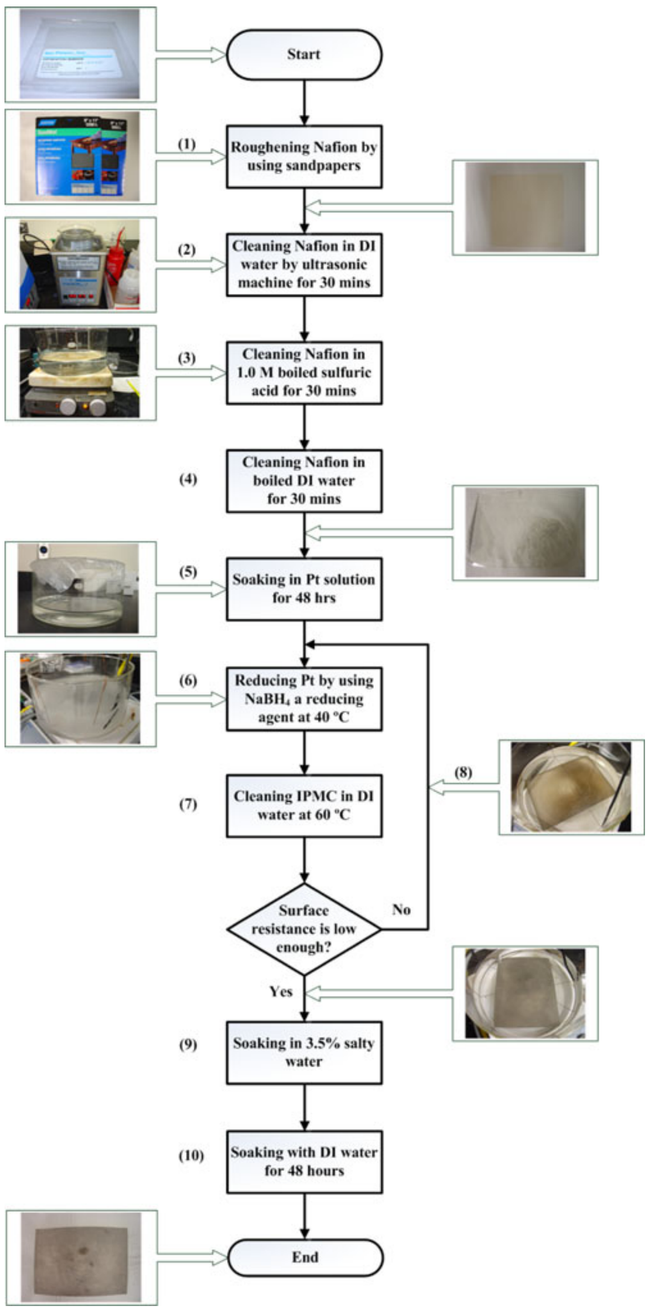

Fig. 1. Flowchart of IPMC fabrication.

The free cation, counter ion, can be replaced by alkali metal such as Li^+, Na^+, K^+, Rb^+, Cs^+ as well as alkyl-ammonium cations such as tetramethylammonium (TMA^+) and tetrabutylammonium (TBA^+) [20]. According to [20], IPMC with various counter ions have different magnitudes in performance. In Step 9, after replacing counter ions by sodium ions, the deflection can get improved significantly and instantly but shows a significant back relaxation right after bending up to the crest. If the counter ion is TMA^+, it will take longer time to bend up to the maximum, but no back relaxation takes place before the strip is dried [20]. Besides, counter ions are not easy to be removed because of the powerful ionic bonding force. Therefore, in Step 10, the counter ions are still bonded inside Nafion instead of being replaced by other cations. In this study, it is desirable that IPMC can show a rapid deflection because the frequency of driving signals is 0.2 rad/s, so sodium ion is an appropriate candidate to replace the counter ion.

The fabrication was improved in both preprocess and postprocess. The contact area between the Nation and surface metallic electrodes was enlarged by wiping with sandpapers to attach more platinum powders. In addition, the amount of platinum powders and the cost of time were decreased, but exhibiting similar performance. Finally, counter-ion replacement was done by soaking in salty water to get Na^+ inside the IPMC.

Transparent Nafion became gray because of the reduced platinum particles. Five or six times of reduction can generate a highly conductive metal layer, but the conductivity still depends on the concentration of the metallic solution.

B. *Properties of IPMC*

An IPMC actuator is a highly nonlinear system, and its dynamic responses are affected by various factors as follows.

1) *Driving signals:* It follows that the deflection will be enhanced by a higher input voltage. However, there is a limitation (about 10 V) because high voltage may burn and damage the surface electrodes.
2) *Size:* Size can affect the deflection due to stiffness. For IPMC strips in the same shape, thickness plays an important role on deflection because of stiffness. Strips with high stiffness can generate large force but small deflection. On the other hand, thin IPMC strips cannot generate sufficient force but rapid and large deflection. Thus, depending on the thickness, IPMC can be used in various applications [21]. Stiffness is affected by not only thickness but external environment such as temperature [22].
3) *Surface resistance/conductivity:* The deflection of IPMC is generated by cations attracted and repelled by the surface voltage. The best performance can be shown if there is no power or voltage loss on the surface electrodes. The surface gets more conductive as the thickness of the metal layer increases because the surface condition is directly related to how much metal is attached on the surface. In most cases, other researchers made IPMC with an around 10-μm metal layer to reduce the resistance by repetitive coating [7]. For our strips, the thickness of surface metal layers also increased up to 10 μm. In addition, the surface resistance of our strips is about 0.3 Ω/mm when the width is 10 mm.
4) *Water concentration:* IPMC needs water for bending, but water molecules in an oversaturated strip hinder cations from moving freely. In addition, water increases the surface and internal resistance by expanding IPMC. Therefore, the water concentration must be set right for the best performance.

III. Effect of an Aquatic Environment

The IPMC strips in this research are of 1 mm in thickness and operate at about 8 V and 500 mA. In this experiment, the external

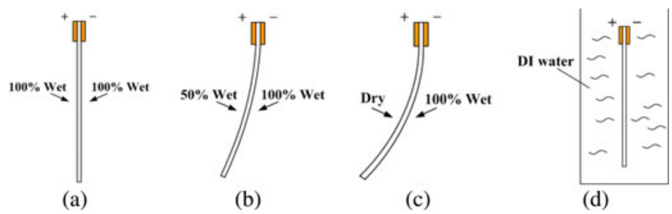

Fig. 2. Four testing conditions for IPMC: (a) fully wet, (b) half wet, (c) dry on one side, and (d) submerged in water.

voltage was applied, but the initial surface water concentrations were different in each test. The surface water, however, was dried by the raised surface temperature in operation.

Fig. 2 shows the four conditions, which have different initial wetness. It was defined by the length, which results from the property of Nafion. Nafion swells if saturated with water, so the wetness can be attained by the difference in length between two sides. For example, our IPMC strip is 40 and 46 mm when thoroughly dry and wet, respectively. It means 50% wet if one side is 43 mm. The four conditions were as follows: 1) The first condition is the IPMC strip with completely wet on both sides as shown in Fig. 2(a). This strip was soaked in DI water for 10 min before testing. 2) The second condition shown in Fig. 2(b) is to reduce the wetness on the anode side to approximately 50%. 3) Fig. 2(c) illustrates the third condition, which is an IPMC strip with completely dry and wet on the anode and cathode surfaces, respectively. For these three conditions, all strips were tested in air so the anode surfaces could be dried. It would affect the deflection when the surface water concentration is not uniform in operation. As a consequence, several states, such as initial, speed-up, and back relaxation, show up as in Fig. 3. Initial state is the time duration before the response increases significantly for dried surfaces. Back-relaxation state, a special phenomenon in IPMC testing, shows a backward bending motion although the positive input signal has been provided continuously. Speed-up state is the time duration between the initial state and back relaxation and shows up when the anode surface is dried, which causes the surface to shrink and then improve the surface conductivity. Therefore, an instant rising-up manifests this state, and the maximum deflection takes place. 4) In the last condition, shown in Fig. 2(d), the strip was tested in water and completely wet without any surface water molecules evaporated. Therefore, the result is not similar to these in the previous three conditions.

Fig. 3(a) shows the deflection under condition 1. The testing began when the strip was fully wet on both surfaces. This figure shows a very steady and slow deflection initially but rapid rising after 80 s because the anode surface was almost dried after 80 s. The initial state appeared before 80 s when the anode surface was not dried yet. After 80 s, the deflection sped up until an upper limitation because the surface conductivity got better than that in the previous state. In this case, the maximum deflection reached around 25 mm at 260 s. After that, the strip exhibited back relaxation and bent toward the cathode side when a positive voltage was applied.

Under condition 2, the strip was 50% and 100% wet on the anode and cathode sides, respectively. Fig. 3(b) shows that the initial state was shortened because it took less time to dry the anode surface. It showed almost no change for the first 10 s without any input signal. From 10 s, it showed a conspicuous deflection when the external voltage was applied. The speed was faster than the previous one because of the lower water concentration. Then, the speed-up state began at 60 s when the anode surface was dried. Finally, the back relaxation toward the cathode side appeared. Compared with the previous test, this showed shorter initial, speed-up, and back-relaxation states. In addition, the maximum of the deflection was around 25 mm, which was larger than the previous test, too.

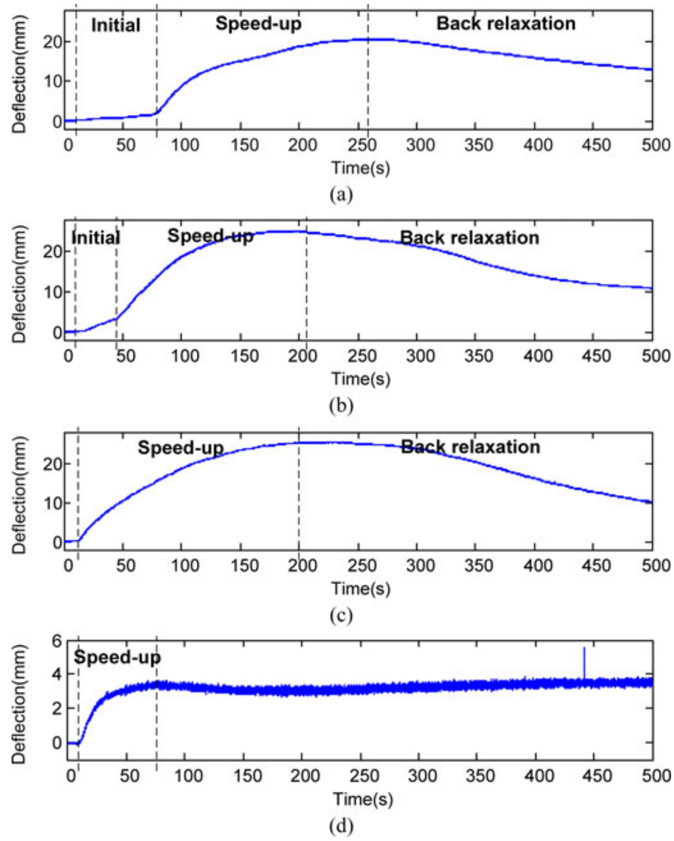

Fig. 3. Responses of the IPMC strip under the four testing conditions: (a) fully wet, (b) half wet, (c) dry on one side, and (d) submerged in water.

Fig. 3(c) shows the response of the strip with completely dry and wet on the anode and cathode surfaces, respectively. It showed a rapid and continuous rising up to the upper limitation without any state change. In other words, there was no initial state in this case because the anode surface was completely dry. From 10 s, the speed-up state appeared for around 200 s to the maximum deflection, 25 mm. This state took more than the previous two tests, 180 s and 160 s. The reason is that the lack of water molecules improved the stiffness of the strip and caused it not to bend easily. Therefore, dry surfaces cause the strip to shrink to improve the surface conductivity in general, but the high stiffness is problematic in deflection.

According to the previous three experiments, the IPMC strip showed no significant difference in the maximum deflection among these three results but the responding time. It seems that

TABLE I
COMPARISON OF THE RESULTS IN ALL CONDITIONS

Condition	Rise time (s)	Peak time (s)	Maximum deflection (mm)
1	230	250	21
2	200	200	23
3	180	180	25
4	40	70	4

all of the states were accelerated when the difference in surface water concentration between two sides was larger. Therefore, the internal water molecules influenced the deflection of IPMC, and our robot would work in an aquatic environment, avoiding back relaxation.

Under condition 4, the IPMC strip was tested in an aquatic environment in order to keep both surfaces wet in the entire operation. Fig. 3(d) shows the deflection lacing the initial state due to no change on the anode-surface water concentration. In other words, this strip began to keep bending toward the anode side after provided with external voltage. However, the maximum deflection was much smaller than the previous three tests due to a great number of water molecules, which might decrease the velocity of free cations. The movement of water molecules caused IPMC to swell and exhibit deflection. However, if an IPMC strip was full of water molecules inside, the crowded space limited the movement of water molecules. It might also be difficult to move all water molecules to the cathode side in a limited space. Therefore, the small difference in water molecules concentration between the two sides degraded the performance. Besides, Fig. 3(d) shows a greater noise because of the bubbles generated by water electrolysis, a peculiar phenomenon in IPMC. At around 440 s, a sizable bubble was generated and then popped suddenly, leading to an impulse-like noise. The most significant advantage under this submerged condition is that there was no back relaxation that showed in the previous three tests. Moreover, the deflection did not change much after rising up to the maximum but was kept almost steady. Therefore, an aquatic environment is more suitable than the previous three cases because of the steady deflection and no fear of lacking in water molecules. Finally, the repeatability in responses was also excellent, which will be presented in Section IV.

Table I is the summary of the results presented in Fig. 3. In the first three cases, both the rise time and the peak time get shorter as the water concentration difference between both surfaces increases. In a robotic application, it would be problematic if it takes much time to reach the maximum deflection. For example, in the first three cases, it would not be appropriate for a walking motion to take around 200 s to make a larger stroll (greater than 20 mm). In order to actuate a robot, a series of input signals is needed and IPMC strips can exhibit larger (around 10 mm) deflection with continuous signals than that in condition 4, and they will be shown in the following experiments.

The strip tested in water showed a much better response by square waves for the abrupt voltage change so that our robot could walk fast and steadily. Fig. 4 shows the deflection by inputting three types of signals and it has the best amplitude and

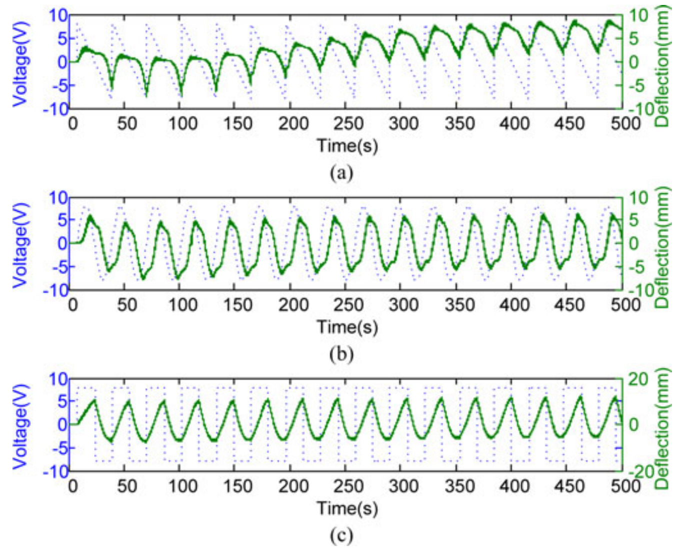

Fig. 4. Deflection (dotted lines) by providing three types of input signals (solid lines): (a) sawtooth, (b) sinusoidal, and (c) square waves. The frequencies of all signals are 0.2 rad/s.

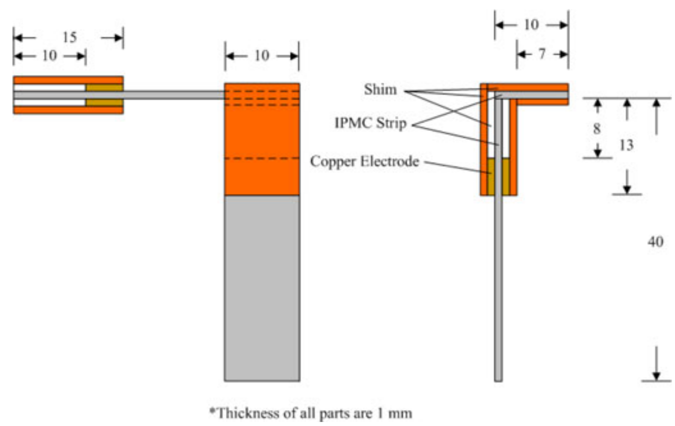

Fig. 5. Structure design of a leg (unit: mm).

no large deviation when inputting square waves. Furthermore, according to Fig. 4, IPMC exhibited no back relaxation when operated in an aquatic environment. Both deviation and back relaxation are supposed to be avoided in robotic applications. Therefore, the square-wave signal was chosen to actuate our robot in an aquatic environment.

IV. ROBOT DESIGN

A. Hardware Design

In order to provide 2 DOFs for each leg, two pieces of IPMC strips were conjoined with 1-mm plastic shims as a joint and work together. Each IPMC strip has the same size, 40 mm × 10 mm × 1 mm, as those used in all previous testing. Fig. 5 illustrates the structure and dimension of one leg. Copper electrodes with two copper wires are connected to external power. The wire used in this study is a thin magnet wire (made by MWS Wire Industries, American wire gauge (AWG) # 38 with the nominal diameter of 0.1143 mm [23]). The copper electrodes are

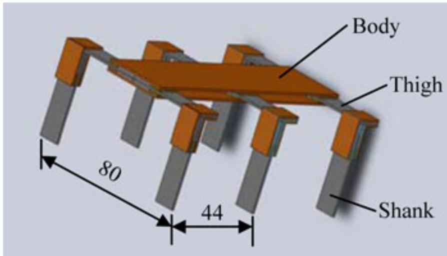

Fig. 6. Design of the IPMC robot (unit: mm).

used to transmit electric power to the surfaces of IPMC strips as uniformly as possible. It turned out to be very difficult to attach wires directly onto the IPMC surface without damaging it. We tried various methods such as using soldering, waterproof epoxy, and clips. With this joint, one leg can be divided into a shank and a thigh, which can make a step and lift the shank up. Our robot has six 2-DOF legs, and each one can support and activate the body by itself. Our final robot design is shown in Fig. 6.

The walking procedure illustrated in Fig. 7 consists of two groups of symmetrical operations. Two groups (O and E) of three legs work separately in order to make a stable stride. Four sets of driving signals are provided and defined as OU, EU, OL, and EL, which represent the upper legs of Legs 1, 3, and 5, the upper legs of Legs 2, 4, and 6, the lower legs of Legs 1, 3, and 5, and the lower legs of Legs 2, 4, and 6, respectively. Each set of strips work simultaneously in order to keep the stability. In Fig. 7, part (a) is the initial status. In part (b), the OU legs bend upward to lift their lower legs up. Part (c) shows the OL legs bend forward to prepare for making a stride. Part (d) shows the OU legs bend downward to keep the strides and balance. So far, the EU legs had not worked yet. In part (e), the OL legs bend backward to activate the body by friction on the ground and then the EU legs bend upward. In part (f), the EL legs bend forward. The EU legs bend downward to keep the strides shown in part (g). In parts (d) and (g), all legs touch the ground to keep the balance right after making a stride. In part (h), the EL legs bend backward to move the body and then the OU legs bend upward in order to prepare for the next step. Fig. 8 shows the driving signals for the four sets of IPMC strips to generate the bending motion of each leg. These signals were generated by a digital-signal-processing (DSP) board (DS1104, manufactured by dSPACE) [24].

A 44-mm gap between two adjacent legs was designed to prevent bumping with each other. The maximum deflection in water is less than 20 mm according to the previous tests, so 44 mm is sufficient not to interfere with other legs in operation. Besides, this robot always has at least three legs touching on the ground to keep the balance. Thus, this design and walking method can enhance the performance of our robot.

B. Power Electronics Design

Instead of conventional 200-μm-thick IPMC strips, those used in this study require around 500 mA to operate. The instant maximum current, around 1.5 A, occurs when the voltage

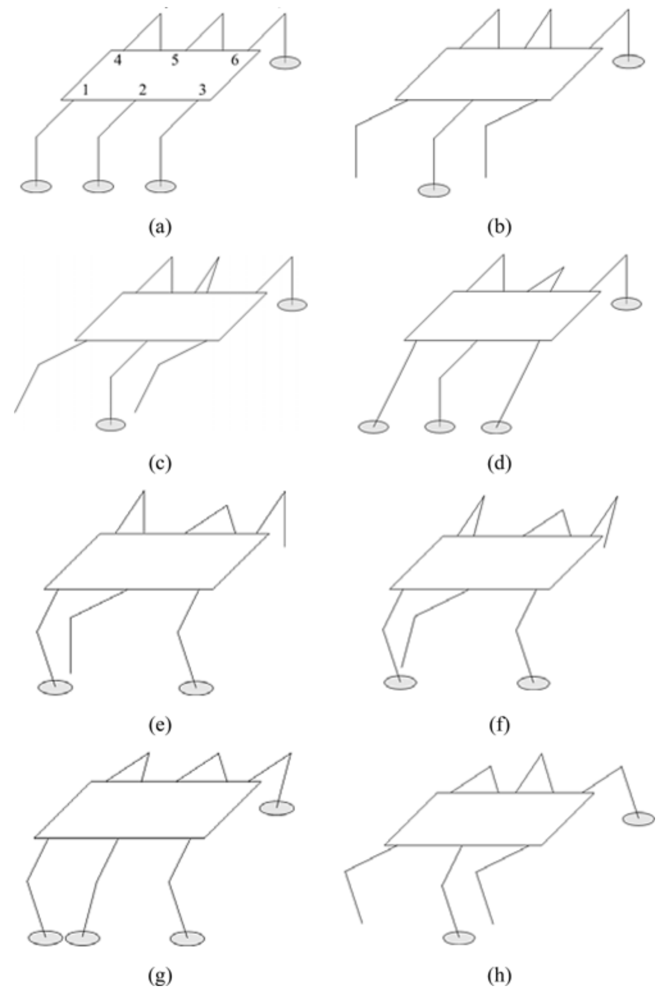

Fig. 7. Locomotion of the IPMC robot. The legs with the shaded ovals touch the floor.

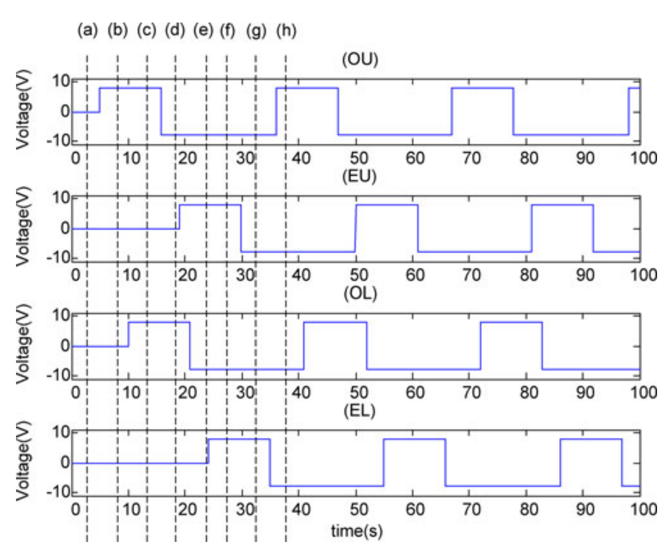

Fig. 8. Driving-voltage sequences for the four sets of IPMC legs. The letters (a)–(h) correspond to the parts in Fig. 7.

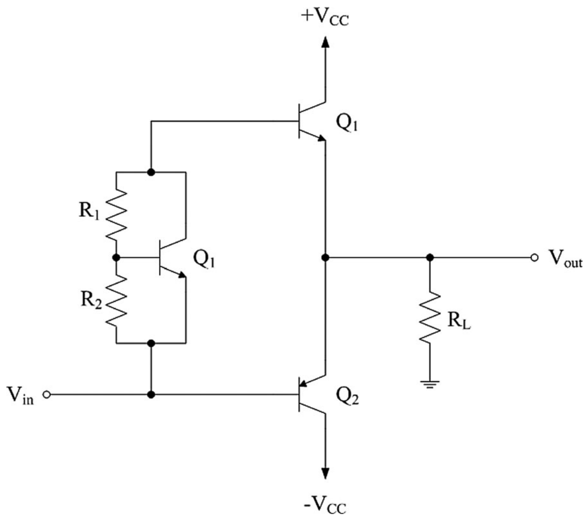

Fig. 9. Power-amplifier circuit.

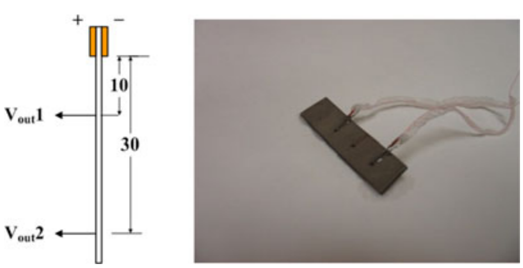

Fig. 10. IPMC strip with two wires attached.

changes abruptly in square waves. In order to provide high current, a voltage follower and amplifier was implemented as shown in Fig. 9 with an NPN (D44H8, manufactured by Fairchild Semiconductor, for Q_1 and Q_3) and a PNP (D45H8, manufactured by Fairchild Semiconductor, for Q_2) bipolar junction transistors [25], [26]. This circuit amplifies the current but maintains the voltage gain to be one. Twelve of these amplifier circuits drive 12 IPMC strips individually. In Fig. 9, $R_1 = 4.7$ kΩ, $R_2 = 1$ kΩ, and R_L is the resistance of an IPMC strip, around 300 Ω.

V. Experimental Results

In order to ensure that no part on the IPMC legs loses power, the conductivity of the surface metal electrodes were measured. An IPMC strip with two holes, at 15 and 35 mm from one end, to measure the voltages ($V_{\text{out}1}$ and $V_{\text{out}2}$), was used, and surface voltages at these two spots were compared. Fig. 10 shows the strip with two wires connected to two analog-to-digital convertor channels on the DSP board. Fig. 11(a)–(c) shows the results of the input and output voltages when the input signals are sawtooth, sinusoidal, and square waves, respectively. It is very clear that the output is smaller than the original signals so the output performance would not be as good as expected no matter what kind of input signal is. In addition, the measured output signals were distorted in the wave peaks and troughs, which might cause unsteady deflection if the signal is overdistorted.

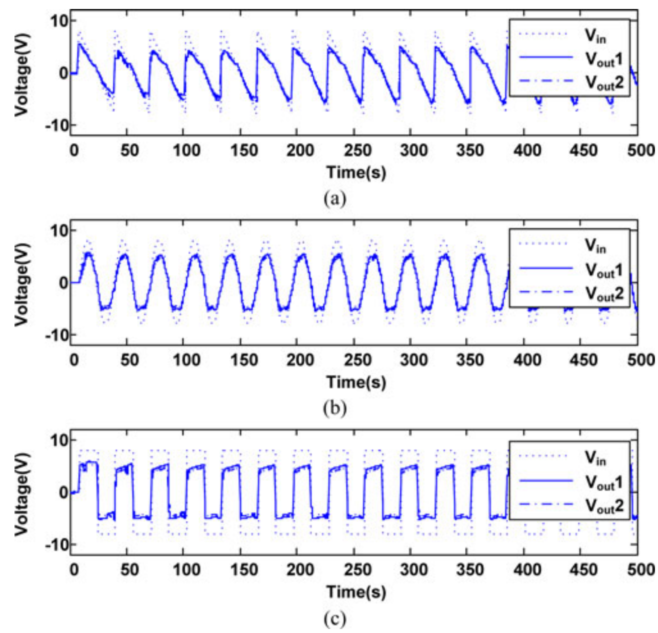

Fig. 11. Input and output signals measured at the two spots.

Fig. 12. Implemented IPMC robot placed in a fish tank.

After the testing of the IPMC properties in Section III (in Figs. 2 and 3), the working environment and input signal was decided and then an aquatic robot was constructed, as shown in Fig. 12. It is as light as 39 g with the dimension of 102 mm × 80 mm × 43 mm. The speed in water is around 0.5 mm/s with a 0.2-rad/s square-wave driving signals, which can cause larger deflection than step input by abrupt change between wave crests and troughs, as shown in Fig. 11(c). The robot walks smoothly and steadily because of each of the three legs works as a tripod for the stability, as illustrated in Fig. 7. In addition, the aquatic environment and the friction between the ground and the IPMC strips also affect the performance of our robot. For example, the speed would change if water is flowing or other surfaces instead of glass are used as the ground. Each IPMC strip exhibited nonidentical deflections due to various surface conditions, such as conductivities and shapes. In this paper, however, all strips were selected according to the deflection testing in order to let all legs can make almost the same stride. The bubbles caused by water electrolysis were generated continuously in operation but did not affect the robot's locomotion significantly. Besides, the effect of wires could be ignored due to the sufficient force generated by our thick IPMC strips.

Our robot contains 12 pieces of IPMC strips and each of them needs 500 mA on average, when provided with 8-V square waves as the input signal. The average power consumption is around 4 W per strip. In addition, our robot costs around $300 for the platinum powders and Nafion. For one robot, around 1 g of platinum powder was used as the surface electrodes.

VI. Conclusion

An aquatic walking robot has been designed and implemented in this study. Based on various fundamental experiments and tests, such as the effects of surface water concentration and an aquatic environment, IPMC strips and the design methodology for our robot were chosen in this application. Nafion is the basis membrane of IPMC, so where and how water molecules move is the key aspect of deflection. Our fabricated IPMC strips were 1 mm thick in order to sustain and drive the body. These thick IPMC strips could not bend without relatively high driving current, so a power amplifier circuit was designed for each strip to provide required current. This circuit consists of a voltage follower and a current amplifier which can generate the current in need but maintain a unity voltage gain.

Our robot has six 2-DOF legs in order to imitate a real-life insect closely. For our robot, a supporter and a driver are combined into a 2-DOF leg, which consists of a thigh and a shank, in order to replace conventional 1-DOF legs. Twelve IPMC strips were grouped into four sets, and their motions were choreographed for smooth locomotion. Each set of three shanks simultaneously touching on the ground in a tripod-fashion can keep the balance and stability. In addition, all 2-DOF legs can make a stride independently instead of two sets of 1-DOF legs. The driving signals provide the power for the four sets of IPMC strips, the thighs, and the shanks of each set of the three legs. With these driving signals, all legs of our robot can make a stride to walk in water and keep the stability at the same time.

Finally, our robot with a microcontroller, power circuits, and sensors can operate stand-alone instead of being tethered to a personal computer. Therefore, an IPMC-based robot can be used in seabed engineering and exploration because water pressure causes nothing to the deflection of IPMC. In addition, IPMC robots would be better than other underwater robots because of the availability in various shapes and sizes.

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