IPMCs as EAPs: Applications

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Abstract

IPMC actuators have number of advantages for the applications such as low drive voltage (less than 3 V), relatively high response (100 Hz), large displacement, soft material, capability of activation in water or in wet condition, possibility to work in dry condition, durability, and easy to miniaturize. In recent years, a great number of applications based on the IPMCs have been carried out by many workers. In this chapter, IPMC research on biomedical applications, biomimetic robotics, sensor/actuator integration, and energy harvesting is reviewed.

Keywords

Ionic Polymer-Metal Composite • IPMC • Biomedical Applications • Biomimetic Robot • Sensor/Actuator Integration • Energy Harvesting

1 Biomedical Applications

IPMC actuators are soft, flexible, and low drive voltage. Hence, they are very safe for humans. In addition, they are easy to deform in any shape and to miniaturize. Thanks to these advantages, many researchers have tried to apply them to many biomedical applications. In this section, applications of IPMC actuators to biomedical applications such as micro-catheter, micro-pump, and human-affinity tactile devices such as Braille displays are reviewed.

1.1 Active Micro-catheter

Micro-catheter-based diagnosis and therapy for intravascular treatment have become increasingly popular. By using conventional micro-catheters that are only soft polymer-based tubes and are not capable of moving actively, it needs certain skill for surgeons to control the tip of the catheter by using guide wires for the operations. Hence, actively controllable micro-catheter and guide wires from outside of the human body – "active micro-catheter" are very useful for catheter-based diagnosis and therapy. In order to develop micro-active catheters, a micro-actuator for controlling the tip of the catheter is a key technology. From the viewpoint of the previously mentioned advantages of IPMC actuators, such as soft, low drive voltage and easy to miniaturize, the IPMC actuator was applied to the active micro-catheter for aneurysm surgery on the brain.

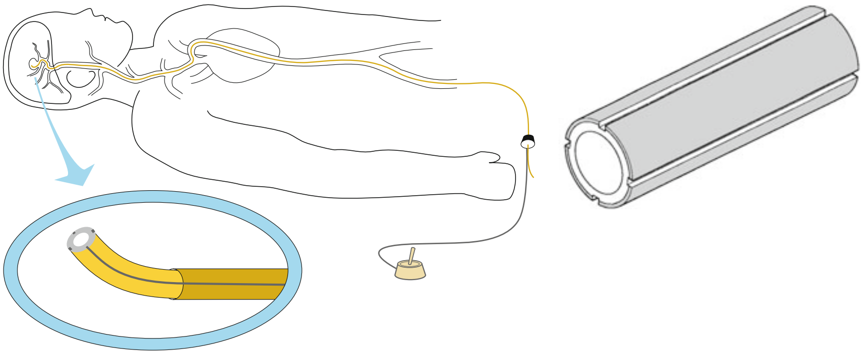


Fig. 1 Schematic view of a micro-active catheter for aneurysm surgery (*left*) on the brain based on a tubular IPMC actuator (*right*) (Reproduced from Oguro et al. 1999)

Guo et al. firstly developed the active guide wire for the micro-catheter based on the IPMC actuator (Guo et al. 1995). They proposed a prototype model of micro-catheter with active guide wire using IPMC actuator (Pt-plated Nafion film) which has two bending degrees of freedom. By using this prototype, they carried out "in vitro" experiments based on blood vessel simulator system composed of a glass blood vessel simulator, a pump for circulating physiological saline, an instrument for measurement, and a heater. They confirmed the inserting motion of the prototype into aneurysm under various experimental conditions such as temperatures, flow rates of circulating saline, diameters of blood vessel simulator, etc. Therefore, they concluded that the proposed catheter system with guide wire works properly and that it can improve the effectiveness of conventional procedure for intravascular operations.

Oguro et al. developed micro-active catheter system without guide wire based on a tubular IPMC actuator with four electrodes around the tube that can drive tubular ionic polymer to bend to multiple directions (Fig. 1) (Oguro et al. 1999). The tubular IPMC actuator of 0.8 mm in outer diameter for the active catheter was successfully developed by applying the sequential plating of gold electrodes around the Flemion (perfluorocarboxylic acid polymer) tube; fabricating four electrodes around the tube by laser ablation cutting after plating. In order to bend the tubular actuator of 0.8 mm in outer diameter for more than 90°, Flemion, which is softer than Nafion, was used as an ionic polymer.

The motion of the tube to all directions can be controlled with combined signals applied to four electrodes around the tube. For the practical usage of the tip of the micro-active catheter for intravascular neurosurgery as shown in Fig. 1, the tubular actuator of external diameter of 0.8 mm in the swollen state was attached to the end of catheter. The actuator is 2 cm and the total length of the catheter is 1.5 m. The tip of the active catheter can be controlled from outside of the human body with a small joystick bent more than 90° within 10 s in physiological saline without gas evolution. Intravascular in vivo tests of the micro-catheter with an animal were also carried out.

Fang et al. proposed the sensing/actuating IPMC for active guide wire in checking the bifurcation of blood vessels without integrating a bulky sensor or adjusting the curvature of IPMC-based active guide wire (Fang and Lin 2010). They developed a prototype of micro-catheter with active guide wire using a gold-plating Nafion IPMC that has a sensing and actuating function. The sensing is based on an amplitude modulation–demodulation technique to obtain deformation-sensing signal converted from the variation of the electric resistances in the IPMC electrodes.

1.2 Micro-pump

In microfluidic systems or lab-on-a-chip technology, the micro-pump is an essential element. Among many types of micro-pumps proposed, they fall into two categories: mechanical micro-pumps and nonmechanical micro-pumps. In order to generate stroke volumes of mechanical micro-pumps, diaphragms are widely used. Previously, piezoelectric, thermopneumatic, electrostatic, and electromagnetic actuators have been used for the diaphragms for micro-pumps. The IPMC is a new promising actuator used for this application since it has an ability to generate a larger bending deformation (more than 1 %) under a low voltage (less than 1 V) and to operate not only in liquid, but also in air, as compared to previously used actuators.

Guo et al. developed the micro-pump using the IPMC actuator, which has a size of 10 mm in diameter and 20 mm in length (Guo et al. 1997). They successfully obtained the flow 4.5 ml/min ~ 37.8 ml/min of the micro-pump by changing the frequency of the applied voltage (Fig. 2). The micro-pump using the IPMC actuator is able to make a micro-flow and silent for driving, which is suitable for the

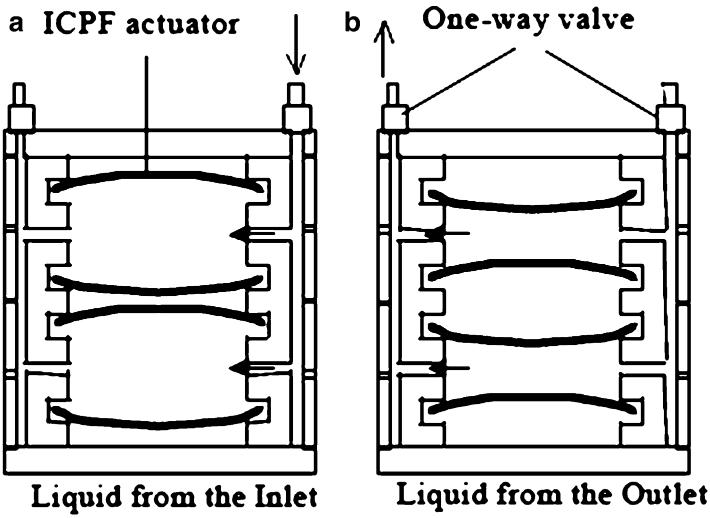


Fig. 2 Micro-pump using the IPMC (ICPF) actuators as diaphragms (Reproduced from Guo et al. 1997)

biomedical uses. Nguyen et al. also developed micro-pump using the IPMC actuator as the diaphragm (Nguyen et al. 2008). By using Nafion/silica-nanocomposite-based IPMC actuator, they developed a prototype of a micro-pump composed of the IPMC diaphragm with a flexible structure fabricated from polydimethylsiloxane (PDMS) material, which has a size of 20 × 20 mm (area) × 5 mm (height). A maximum flow rate of 0.76 ml/min and a maximum back pressure of 1.5 kPa were recorded at an applied voltage of 3 V and a driving frequency of 3 Hz. Lee and Kim studied the design of IPMC actuator-driven micro-pump (Lee and Kim 2006). In order to design an effective IPMC diaphragm for a valveless micro-pump, they studied the optimum electrode shape of the IPMC diaphragm and the estimation of its stroke volume by using a finite element analysis (FEA). Based on the analysis, they concluded that the mean output flow rate of the IPMC actuator-driven valveless micro-pump was estimated at a low Reynolds number of about 50.

1.3 Human Affinity Tactile Devices

The IPMC actuator is soft and flexible and has a low drive voltage. Hence, it is very safe for human. If the IPMC film can be successfully patterned and integrated, and each micro-actuator strip can be controlled separately, human-affinity tactile information communication system can be developed.

A flexible and light page-type Braille display of which the effective size is 4×4 cm^2 and consists of 144 dots and 24 Braille letters as shown in Fig. 3 has been developed by Kato et al., by integrating the IPMC actuator array with organic transistors developed by them (Kato et al. 2007). The IPMC actuator array composed of 12×12 rectangular actuators whose size is 1×4 mm^2 was mechanically processed using a NC cutting machine from one IPMC actuator film. Each Braille dot is controlled by the up/down motion of a small semisphere that is attached to the tip of each rectangular IPMC actuator under the rubberlike surface of the display. The total thickness and the weight of the entire devices are 1 mm and 5.3 g, respectively. The readability of the sheet-like Braille display using the IPMC actuator was tested by the reading tests in which four visually impaired persons participated. All persons that attended were able to recognize the Braille format which this Braille display showed. This result shows that the generating force and the displacement of this device are sufficient to facilitate reading by the visually impaired persons.

The issue that remains to be addressed is the stability of the device. The IPMC actuator used was water-swollen gold-plating Nafion, which is usually operated in wet condition. On the contrary, organic transistors degrade easily in moisture and/or oxygen. In order to solve this issue, based on ionic-liquid-based bucky-gel actuator with organic transistor, ultra-thin and light Braille display that is operable in air for long time has been developed (Fukuda et al. 2011).

Konyo et al. developed the tactile display using the IPMC actuator (Konyo et al. 2007). The IPMC actuator has many advantages including high spatial resolution, wide frequency range, an ability of generate stimuli in multiple directions, wearability, and safety, as compared to the conventional actuators used for the

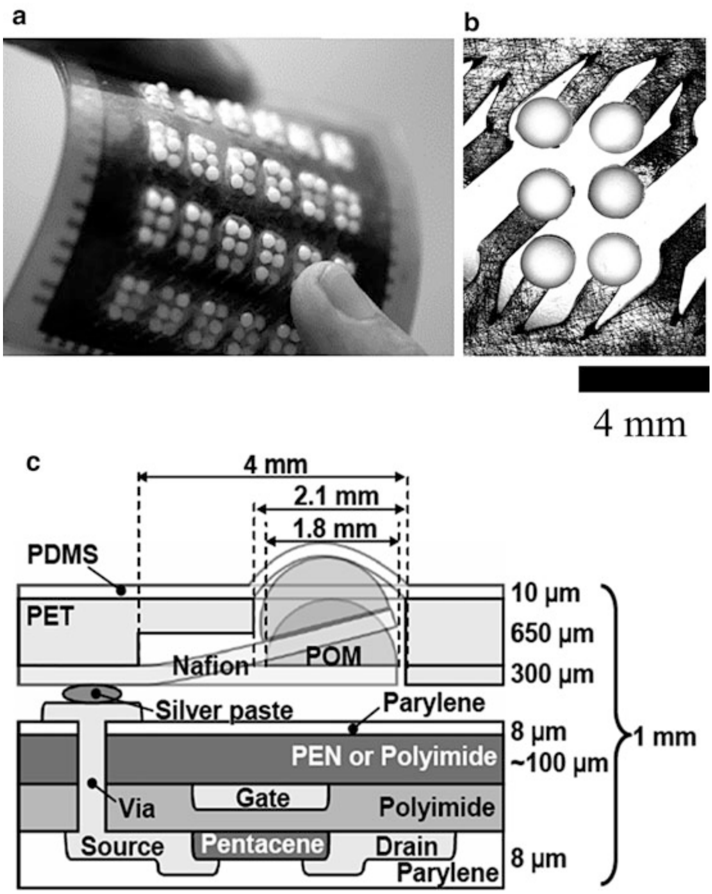


Fig. 3 Sheet-type Braille display based on the IPMC actuators: (**a**) photograph of the Braille display, (**b**) photograph of one Braille cell composed of six dots attached with IPMC actuator films, (**c**) a cross-sectional illustration of one Braille dot. The IPMC actuator is driven by an organic transistor. (Reproduced from Kato et al. 2007)

tactile display such as magnetic oscillators, piezoelectric actuators, shape memory alloy actuators, pneumatic devices, etc. They successfully produced total textural feeling related to the physical properties of materials by focusing on the following three sensations: roughness, softness, and friction.

2 Biomimetic Robots

The second section in this chapter briefly reviews biomimetic robots using IPMC actuators. Fishlike robots are reviewed firstly. In the experiment of a snake robot, the wave motion grows from the head to the tail even without feedback control. This interesting phenomenon may support a hypothesis that living animals utilize the elasticity of their bodies or muscles when they swim. Walking robots and other types of robots using IPMCs are also reviewed briefly in the latter part of the second section.

2.1 Introduction

Biomimetics is the development of novel technologies through the distillation of principles from the study of biological systems (Lepora et al. 2013). Because ionic polymer–metal composites (IPMCs) can be driven by low voltage and usually require water for work (Shahinpoor et al. 1998), it is an attractive idea to use IPMCs for biomimetic robots (Bar-Cohen and Breazeal 2003; Roper et al. 2011; Chu et al. 2012; Kim et al. 2013).

In this section, biomimetic robots using IPMCs are briefly reviewed. Firstly, some fishlike robots are introduced. Especially for a snake robot, it was found that the wave motion increased from the head toward the tail even without feedback control (Takagi et al. 2006a). A mathematical model can predict the phenomenon of growing wave of the robot. Interestingly, similar phenomena can be observed in the swimming of living snakes and slender fishes (Azuma 1992). A brief discussion is presented for the phenomena observed in both the robot and the living animals. In the latter part of this section, walking robots and other types of robots are briefly reviewed.

2.2 Brief Review on Fishlike Robots

Many researches on fishlike robots using IPMC actuators have been conducted. In the early stage of the researches on IPMCs, Mojarrad and Shahinpoor developed a biomimetic underwater robot (Mojarrad and Shahinpoor 1997a). The first commercial product using IPMCs in the world was a goldfish-like robot developed by EAMEX company in Japan (Bar-Cohen 2003). The fish robot of EAMEX could swim in a water tank by wireless power supply. The methods of wireless powering of IPMCs have been also discussed by some researchers (Lee et al. 2012; Abdelnour et al. 2012).

Guo et al. developed a fishlike robot (Guo et al. 2003). They measured the swimming speed and the propulsive force of the robot. Aiming at autonomous robots, some researchers have developed battery-powered robots without tethers, e.g., a tadpole robot (Kim et al. 2005) and fish robots with a caudal fin (Chen et al. 2010; Aureli et al. 2010a).

Another direction of the research is increasing the degrees of freedom of the fin(s) of a biomimetic robot. Nakabo et al. developed a snake robot from an IPMC strip by segmenting the electrodes into some parts (Nakabo et al. 2007). The snake robot swims by applying the appropriate distributed voltages. Takagi et al. discovered that the amplitude of the traveling wave on the flexible snake robot grew from the head to the tail (Takagi et al. 2006a). This interesting phenomenon will be briefly discussed in

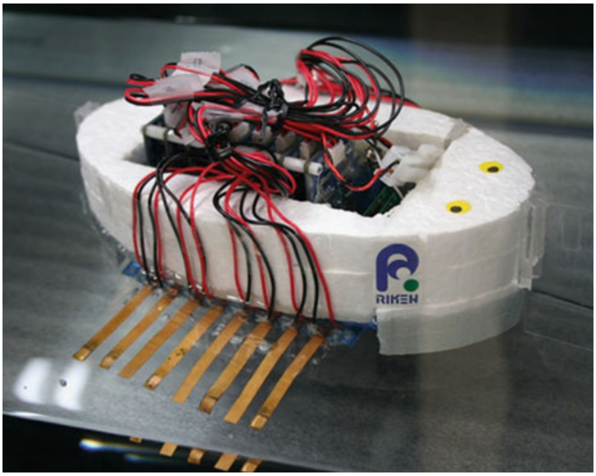


Fig. 4 Autonomous raylike robot (Takagi et al. 2006b)

the next subsection. Kamamichi and Yamakita developed a three-link snake robot (Yamakita et al. 2007). They also proposed a self-excitation control method to generate oscillating motion (Kamamichi et al. 2006).

Robots with more complex shapes have been also reported. Punning et al. proposed a raylike robot using IPMCs (Punning et al. 2004). Takagi et al. developed an autonomous raylike robot (Takagi et al. 2006b) shown in Fig. 4. The robot consisted of a plastic body, 16 IPMCs, a microcontroller, amplifiers, and a battery. Chen et al. also developed a manta ray robot (Chen et al. 2012). Palmre et al. discussed the design of a fin (Palmre et al. 2013). They set some IPMC actuators into a soft boot material to create an active control surface. As other unique fishlike robots, jellyfish robots have been proposed (Yeom and Oh 2009; Najem et al. 2012).

2.3 Phenomenon of Growing Wave of a Swimming Snake Robot: Do Living Fishes Utilize Their Elastic Bodies for Efficient Swimming?

Figure 5 shows the snake robot developed by Nakabo et al. The electrodes of the IPMC are segmented into seven parts. Therefore distributed voltages can be applied to the IPMC. The snake robot can swim by applying traveling-wave voltages of the appropriate frequency and wavelength. In the experiment of the snake robot, the amplitude of the wave motion increases from the head toward the tail even though the amplitudes of the applied voltages are constants.

Figure 6 shows the captured swimming motion of the snakelike robot in the experiment. The solid lines are the obtained shapes by image processing. The dotted lines are the envelope of the traveling wave. Clearly the amplitude of the tail side is

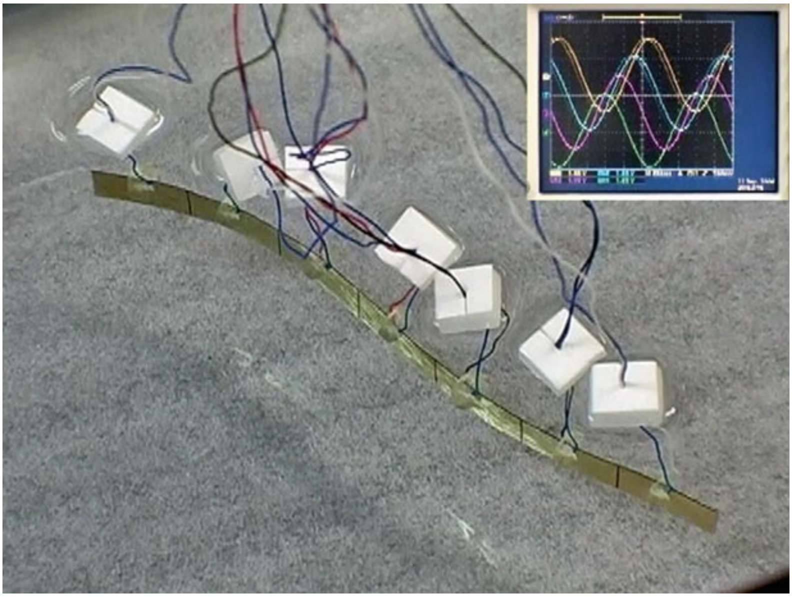


Fig. 5 Snakelike robot (Reproduced from Takagi et al. 2006a)

greater than that of the head side. Note that this shape of the envelope is generated by itself and without control. Although the input voltage is uniformly applied to the robot, the resultant deflection is not uniform and growing from the head to the tail, as shown in Fig. 7. It should be noted that the similar growing wave can be observed in the swimming of living snakes and slender fishes (Azuma 1992). The growing wave on the body of a fish is known to increase the efficiency of the swimming (Lighthill 1960). The phenomenon observed in the robot may indicate that the living aquatic animals utilize the elasticity of their bodies and muscles when they swim.

The envelope can be predicted by a simple mathematical model based on Euler–Bernoulli beam (Takagi et al. 2006a). Conversely, as a relation between the forward dynamics and the inverse dynamics, Cheng et al. estimated muscle force of a living fish using a simple beam model (Cheng et al. 1998). According to the reference (Takagi et al. 2006a), the envelope function denoted by $A(x)$ is given by

$$A(x) = \sqrt{\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_m A_n \phi_m(x)\phi_n(x)\cos(\theta_m - \theta_n)}$$

where A_i and θ_i are parameters depending on the material constants, the boundary condition, the frequency ω, and the wavelength λ. $\phi_i(x)$ is the eigenfunction (mode shape function) of bending deflection of a beam with free–free ends. We can show the function $A(x)$ becomes an increasing function by the parameter estimation of the experimental data. See the reference (Takagi et al. 2006a) for the details.

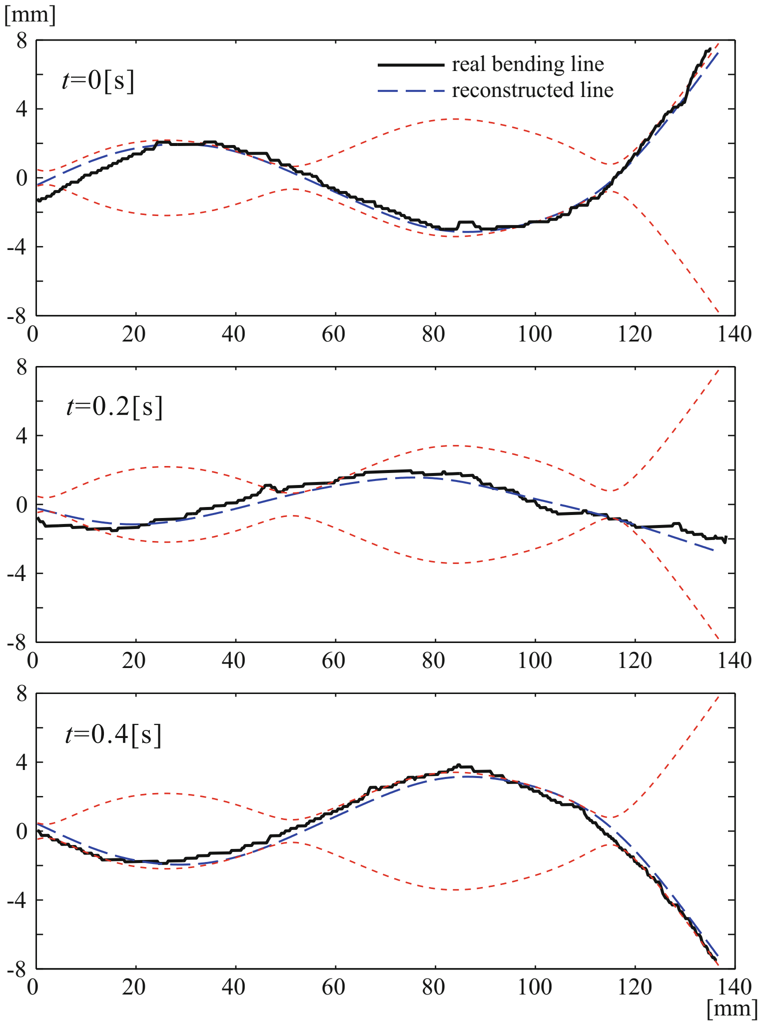


Fig. 6 Captured motion of the snakelike robot in the experiment (Reproduced from Takagi et al. 2006a). The head of the robot is located in the left hand side. *Dashed lines* show the fitted shapes, and *dotted lines* show the envelopes

2.4 Brief Review on Walking Robots and Others

Compared with the fishlike robots, other types of biomimetic robots are not so much reported. Some walking robots are studied, such as biped, quadruped, and multi-legged robots.

Yamakita and Kamamichi developed a biped robot (Yamakita et al. 2004). They also proposed a mechanism to convert the bending motion into the linear motion.

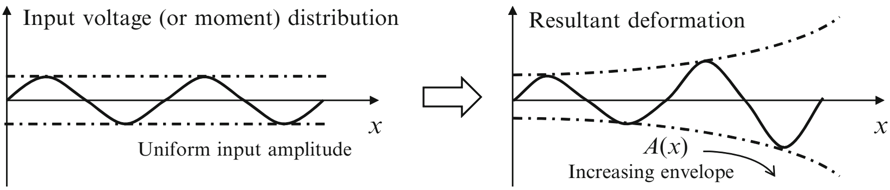
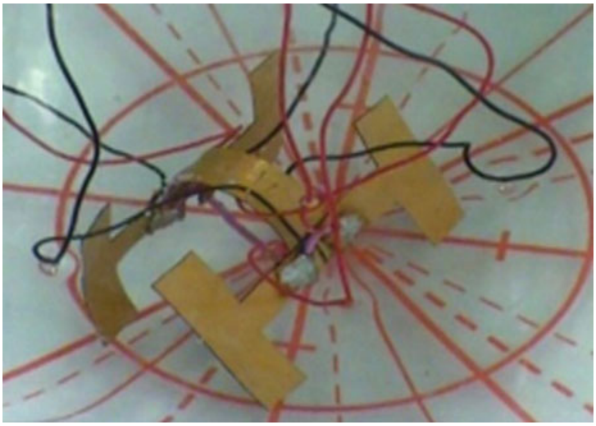


Fig. 7 Schematic illustration of the uniform input (*left*) and the resultant deformation with the increasing envelope (*right*)

Fig. 8 Quadruped underwater robot with fully IPMC body (Reproduced from Tomita et al. 2011)



There also exists another mechanism to convert the bending motion into the rotational motion (Takagi et al. 2005).

Guo et al. proposed a multi-legged robot (Guo et al. 2012). Chang and Kim also developed a multi-legged robot (Chang and Kim 2013). Tomita et al. proposed a quadruped robot directly made from an IPMC sheet shown in Fig. 8 (Tomita et al. 2011). Takagi et al. discovered that copper electrodes can enhance the deformation of IPMCs by unintended ion exchange (Takagi et al. 2014) in the experiment of the quadruped robot.

Shahinpoor et al. showed an idea of flapping flying machine (Shahinpoor et al. 1998). Arena et al. proposed a wormlike robot (Arena et al. 2006). As a robot similar to the snake robots, however, much smaller, Sareh et al. proposed artificial cilia (Sareh et al. 2012).

2.5 Conclusions on Biomimetic Robots

IPMCs are attractive actuators for biomimetic robots due to its softness and usability in water. Some researches on biomimetic robot have been briefly reviewed in this section, such as fishlike robots, walking robots, and other types of robots.

This section also introduced a notable phenomenon of growing wave of a snake robot. The living animals may utilize the elasticity of their bodies and muscles, as the phenomenon observed in the robot. As well as mimicking functions of living animals, the future direction of the researches on biomimetic robot are expected to reveal the energy-efficient motions of living animals.

3 Sensor/Actuator Integrated (Feedback) Systems

Some of the EAP materials can be used as a sensor and an actuator in same devices. IPMC is a typical example of such materials. In this section, the sensor function of the IPMC and its application to the sensor/actuator feedback systems are explained.

3.1 Sensor Function of IPMCs

It is known that IPMC can be used as a sensor, as the IPMC generates electromotive force when it is deformed (Mojarrad and Shahinpoor 1997b; Shahinpoor et al. 1998). Figure 9 shows the sensor response of IPMC, where the strip of the IPMC was deformed and the output voltage was observed by an oscilloscope. Depending on the size or the composition of the strips, the electromotive force of several millivolts can be observed, and IPMC can be used as sensors sufficiently.

In order to realize the control and soft actuation of IPMC actuators, a "soft" and "light" sensing device is needed. The most effective device is the IPMC itself. IPMC has important advantages for utilization as a sensing device:

- It is highly sensitive and outputs voltage of millivolt order.
- It is usable over a wide range of deformation.
- It is flexible and can be integrated into a soft actuator system.

Figure 10 shows the verification result of the sensor function. The strip of the IPMC was fixed as a cantilever and was deformed manually. Its deformation was measured by a laser displacement meter, and the output voltage was pre-amplified and measured. The size of the strip used in the experiment was 20 × 2 mm and 0.2 mm of thickness. From the result, the output signals arise through the deformation of the strip, and the magnitude of the output signals is related to that of the

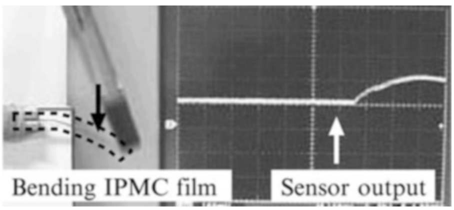


Fig. 9 Output response of IPMC sensors

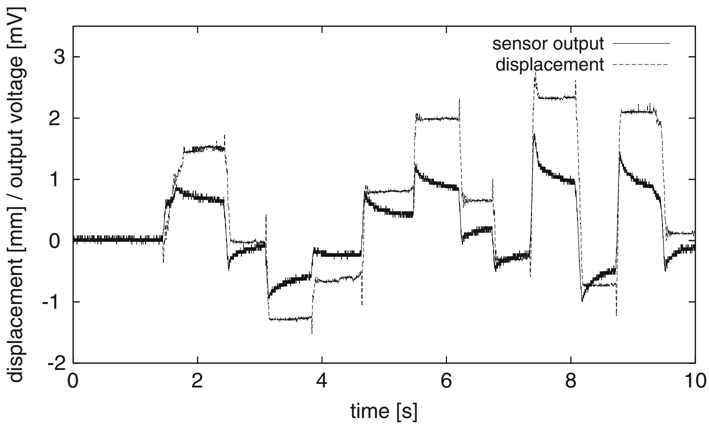


Fig. 10 Experimental result of the IPMC sensor response

deformation. It is also confirmed that the sensor characteristics are dynamical as the slow decay of the output signal exists in a constant deformation.

For system applications of soft materials, it is important to analyze and model the responses. Some models of the sensor function of IPMCs were studied from the viewpoint of the black/gray box modeling (Newbury and Leo 2003; Bonomo et al. 2006) and the white box (physical and chemical) modeling (Farinholt and Leo 2004).

3.2 Sensor Systems and Application to Feedback Control

Since the characteristics of the sensor output are dynamical, we should compensate the dynamics to estimate the deformation of IPMC from the sensor signals. In this section, an estimation method and an example of feedback controls based on the estimation results of the sensor systems are described (Yamakita et al. 2008).

3.2.1 Estimation Method

To estimate the deformation from the sensor output, we identify the dynamics using input–output data as a linear time-invariant (LTI) system and construct a sensor system using an observer based on the linear system control theory.

The model of the sensor is assumed to be represented by a LTI model as

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}, \tag{1}$$

where y is an output of the system which is the output voltage, u is an input of the system which is the deformation of the IPMC, and x is a state variable of the system.

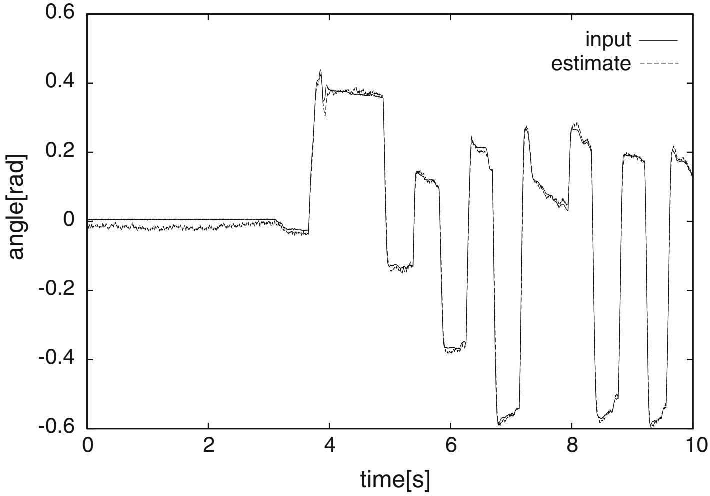


Fig. 11 Estimation result of the sensor system

Assume that the variation of the input is not fast, i.e., $\dot{u} \approx 0$, then the augmented system can be defined as

$$\begin{cases} \dot{\bar{x}} = \bar{A}\bar{x} \\ y = \bar{C}\bar{x} \end{cases}, \tag{2}$$

where $\bar{x}$ is the state of the augmented system, and

$$\bar{x} = \begin{bmatrix} x \\ u \end{bmatrix}, \ \bar{A} = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}, \ \bar{C} = [C \quad D].$$

If the system of Eq. 2 is observable, the input u can be estimated by the observer, which is a part of the state of the augmented system. The observer system based on the stationary Kalman filter is represented as

$$\dot{\hat{x}} = (\bar{A} - K\bar{C})\hat{x} + Ky, \tag{3}$$

where K is a gain matrix of the optimal observer.

Figure 11 shows the estimation result of the sensor system based on the observer as above procedure. By utilizing the identified linear model and the observer, the deformation of the film can be measured with high accuracy.

3.2.2 Feedback Control Based on the Sensor Signal

In order to confirm the validity of the sensor system, we demonstrate an experiment of feedback control using IPMC sensor/actuator. In the experiments, a pair of IPMC strips is connected in parallel. One of the IPMC strips is used as an actuator, and

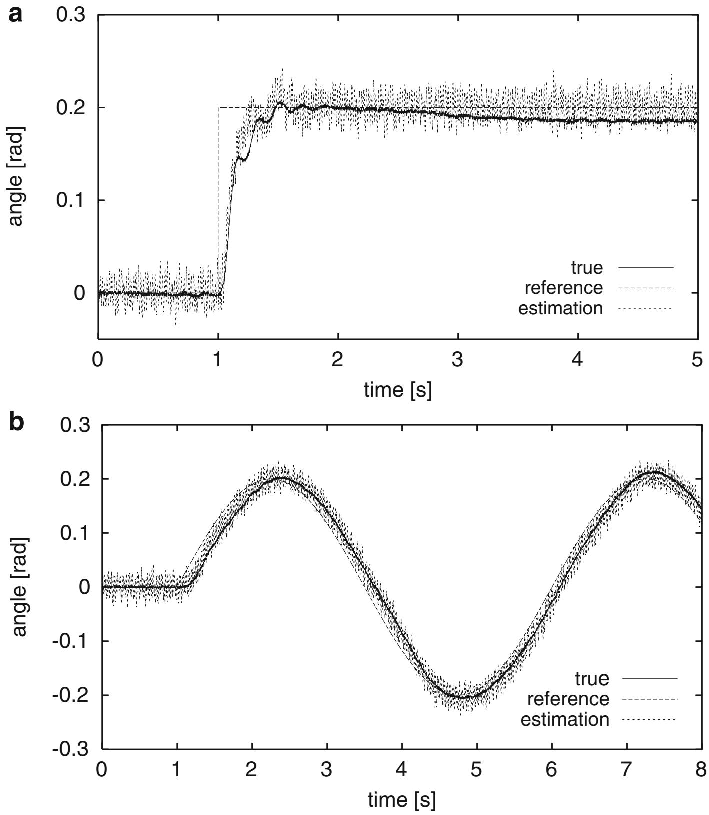


Fig. 12 Experimental results of feedback control based on the sensor signal. (**a**) Feedback control to the fixed value. (**b**) Feedback control to the sinusoidal wave

another is used as a sensor. Then the deformation of the strips is controlled using the estimated value by the sensor system.

Figure 12 shows the experimental results of feedback control by using the signals of the IPMC sensor system. We applied PID controller based on the estimated deformation. The figures plot the reference, estimated, and real deformation over time, and the reference trajectories were step and sinusoidal signals, respectively. The estimation of the deformation and the feedback control were realized sufficiently with only some errors of the estimation.

Several researchers have also attempted to realize self-sensing actuations of IPMCs. The term “self-sensing” means the realization of sensing without attaching the sensing device. One of the methods is construction of the sensor/actuator integrated device with patterned electrodes, which separates the actuating and sensing parts on one strip of IPMCs (Nakadoi et al. 2007). The patterned device can be constructed by removing electrodes with a laser ablation or a mechanical cutting and also constructed by partial electrode formation with chemical treatment. Another method is an estimation approach based on measurements of electrodes resistance (Kruusamae et al. 2011; Punning et al. 2007; Nam and Ahn 2014) and impedance (Cha et al. 2013c; Cha and Porfiri 2014). The electrode resistance of both surfaces changes according to the deformation. The deformation can be estimated by measuring the voltage signals related to the resistance variations. Although the improvements in the performance are needed for practical use, IPMCs have a great potential in applications of soft robots and controlled devices.

4 Energy Harvesting

Recent breakthroughs in lightweight electroactive materials have promoted major scientific and technological advancements in the area of energy harvesting for powering miniature electronic devices (Erturk and Inman 2011). In the context of underwater energy harvesting, IPMCs are receiving considerable attentions for several advantageous attributes, including their inherent ability to work in wet environments, their large electrical capacitance, and their small stiffness (Shahinpoor and Kim 2001; Jo et al. 2013). Considerable efforts have thus been placed in design and modeling of IPMC-based energy harvesting devices (Brufau-Penella et al. 2008; Tiwari et al. 2008; Aureli et al. 2010b; Anand et al. 2010; Giacomello and Porfiri 2011; Peterson and Porfiri 2012; Cellini et al. 2014a, b; Hu et al. 2014).

In particular, energy harvesting from underwater flexural vibrations of an IPMC strip excited at its base has been explored in Aureli et al. (2010b). A similar scenario has been studied in Brufau-Penella et al. (2008) to investigate IPMC-based energy harvesting for air vibrations. Energy harvesting from flexural vibrations has also been addressed in Anand et al. (2010), where a detailed analysis of the role of the electrodes' composition can be found. Flexural vibrations have been leveraged in the design of fluttering heavy flags in Giacomello and Porfiri (2011) for energy scavenging from a steady water flow as well as in Cellini et al. (2014a) to investigate IPMC-based energy harvesting from fluid-induced buckling. Underwater energy harvesting of a parallel array of IPMCs with a common base excitation has been considered in Cellini et al. (2014b). Experimental evidence of the feasibility of IPMC-based energy harvesting from different deformation modes is presented in Tiwari et al. (2008), where experimental data on cyclic bending, tension, and shear in air can be found. Moreover, IPMC-based energy harvesting from the impact of self-propagating vortex rings has been tackled in Peterson and Porfiri (2012) and Hu et al. (2014). Notably, a concise summary of some of these efforts can be found in Porfiri and Peterson (2013).

Here, we summarize some of our recent work on the integration of IPMCs in relatively unconventional underwater energy harvesting devices. Specifically, we assess the feasibility of IPMCs for energy harvesting from the undulations of a biomimetic fish tail (Cha et al. 2013a), underwater torsional vibrations (Cha et al. 2013b), and hull slamming (Cha et al. 2012).

4.1 Energy Harvesting from the Undulations of a Biomimetic Fish Tail

First, we report on energy harvesting from the bending vibrations of a biomimetic tail in a quiescent fluid (Cha et al. 2013a). This research is motivated by the evidence that fish locomotion is associated with a number of energy sources that could be tapped through IPMCs (Dabiri 2007). Figure 13 shows an IPMC attached on one side of a biomimetic tail, designed based on shark morphometric data in Kohler et al. (1995). The tail is fabricated through injection molding of silicone, and a slender stainless steel beam is inserted in the mold to increase the overall stiffness of the biomimetic fish tail. The undulations of the biomimetic tail are modeled by studying the nonlinear underwater vibrations of an equivalent beam with varying rectangular cross section, through the hydrodynamic function proposed in Phan et al. (2013). The electrical behavior of the IPMC is simply described via a lumped circuit model consisting of a resistor, a capacitor, and a voltage source connected in series and controlled by the deformation of the tail.

The harvested power from the IPMC is obtained by connecting it to a shunting resistor. We find that the power output is maximized when the shunting resistance matches IPMC internal impedance, the test structure is excited at its resonance frequency, and the IPMC is placed in the vicinity of the clamped side of the tail. The optimal harvested power is on the order of 10–100 pW per unit base angle.

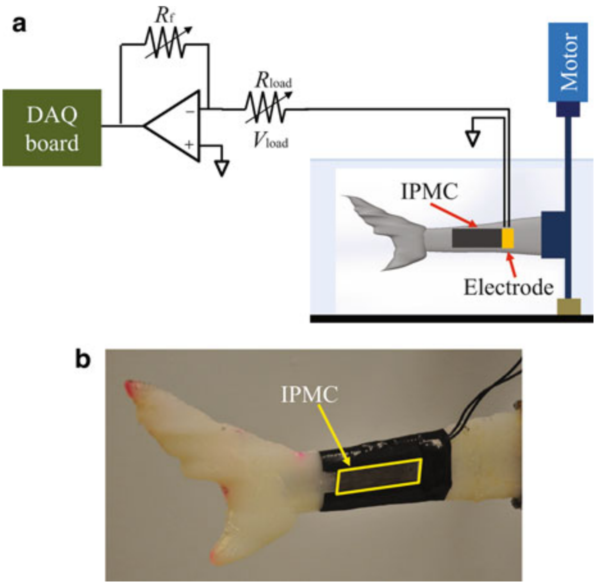


Fig. 13 (**a**) Schematic of the experimental setup for energy harvesting characterization and (**b**) detailed view of the biomimetic tail hosting the IPMC (Reproduced from Cha et al. 2013a)

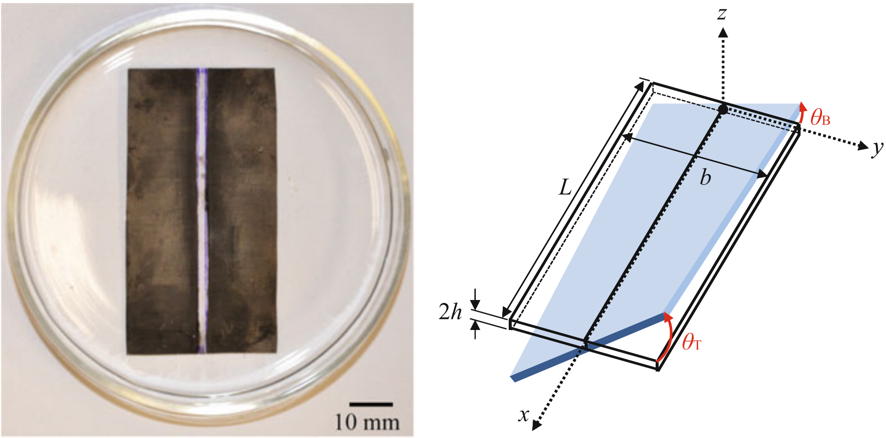


Fig. 14 (*Left*) A patterned IPMC and (*right*) schematic of the IPMC undergoing torsional vibration (Reproduced from Cha et al. 2013b)

4.2 Energy Harvesting from Torsional Vibrations

Second, we consider energy harvesting from underwater torsional vibrations of a cantilevered IPMC strip subject to harmonic base excitation (Cha et al. 2013b). The IPMC is split into two separate parts through patterned electrodes, as shown in Fig. 14, to enhance the sensitivity to torsional deformations. Ideally, the IPMC response would be zero without patterned electrodes, since the charges generated on each electrode would vanish due to the skew symmetry of the deformation with respect to the beam axis. The IPMC pattern is obtained by masking specific areas of the polymer with tape during plating (Jeon et al. 2008). The IPMC is modeled as a thin beam undergoing torsional vibrations, and the effect of the encompassing fluid is described using the hydrodynamic function developed in Aureli et al. (2012). The IPMC electrical response is described via a lumped circuit model, where the voltage source is controlled by the total twist angle.

Experimental results show that energy harvesting is optimized when the shunting resistance matches the overall IPMC impedance and the optimal harvested power is on the order of 10–100 pW.

4.3 Energy Harvesting from Wedge Slamming Impacts

Finally, we briefly describe the mechanics of energy transfer from the impact of an IPMC-based wedge on the free surface of a quiescent liquid (Cha et al. 2012). This wedge is composed of a rigid aluminum structure to which two IPMCs are clamped on both sides and connected to the bottom of a T-shaped mount that slides freely within the rails. During experiments, the wedge is raised to a selected drop height from 2 to 8 cm and then released to freely fall on the water. The two IPMCs are

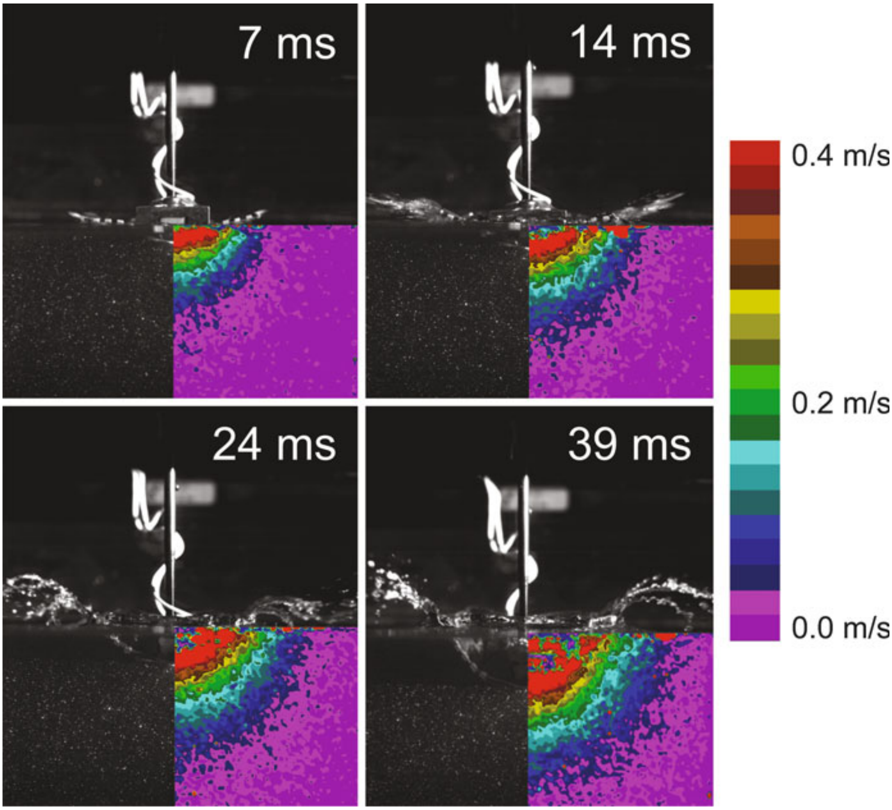


Fig. 15 Snapshots of the wedge impacting the free surface with superimposed PIV data for the *right* hand side of the wedge at the drop height 2 cm (Reproduced from Cha et al. 2012)

connected in parallel through the common aluminum clamps. The motions of the fluid and the IPMC-based wedge are recorded through a time-resolved particle image velocimetry (PIV) system. Figure 15 shows four snapshots of the IPMC-based wedge impacting the water surface, along with the corresponding velocity intensity computed for the right half of the wedge. The energy transfer during slamming can be obtained by computing the peak strain energy from the IPMC deformation. The peak energy is found at the onset of the IPMC deformation.

The energy transfer rate from the input potential energy to the strain energy during a slamming impact is on the order of 1.4−3.8 %. The output electrical energy in the IPMC can be partitioned into the contribution stored in the capacitor and the energy dissipated in the resistor. We find that the electrical energy stored in the capacitor varies from 5 to 20 pJ as the drop height varies between 2 and 8 cm, while the energy dissipated in the resistor is one order of magnitude larger. The conversion rate of strain energy to electrical energy is on the order of 0.000003−0.000036 %.

5 Conclusions

In this chapter we reviewed the latest research on the applications of IPMC actuators, including biomedical applications, biomimetic robotics, sensor/actuator integration, and energy harvesting. Since the IPMC actuators have many advantages for human-affinity biomedical applications such as soft, flexible, low-voltage drive, easy to deform in any shape and to miniaturize, many researchers have tried to apply them to many biomedical applications. The applications of the IPMC actuators to micro-catheter, micro-pump, and human-affinity tactile devices such as Braille displays have been demonstrated.

IPMCs are attractive actuators for biomimetic robots due to the softness and the ability to use in water. Fish robots, snake robots, and walking robots based on the IPMC actuators have been demonstrated. As well as mimicking functions of living animals, the future direction of the researches on biomimetic robot are expected to reveal the energy-efficient motions of living animals.

The IPMCs can be used as a sensor and an actuator in the same device. The sensor function of the IPMC and its application to the sensor/actuator feedback systems have been explored. Energy-harvesting-based IPMCs have also been explored. In the context of underwater energy harvesting, IPMCs are receiving considerable attentions for several advantageous attributes, including their inherent ability to work in wet environments, their large electrical capacitance, and their small stiffness. Energy harvesting based on the IPMCs from the undulations of a biomimetic fish tail, underwater torsional vibrations, and hull slamming has been demonstrated.

In conclusion, on the basis of the established research of materials and mathematical modeling of IPMCs described in the preceding chapters, the proposed applications of the IPMCs in this chapter are promising. In the near future, various commercial products are expected to be realized from the proposed applications in this chapter.

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