Ionic polymer–metal composite applications

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In this paper, the authors present a comprehensive review of ionic polymer–metal composites (IPMCs) covering their fundamentals, fabrication processes, characterization and applications. IPMCs are becoming increasingly popular among scholars, engineers and scientists due to their inherent properties of low activation voltage, large bending strain – that is, the transformation of electrical energy to mechanical energy – and properties to be used as a bidirectional material – that is, they can be used as actuators and sensors. Among the diversity of electroactive polymers, recently developed IPMCs are good candidates for use in biorelated applications because of their biocompatibility. The applications of IPMCs have been growing due to the progression in their manufacturing techniques, development of more accurate control models and recently demonstrated sophisticated IPMC actuator applications. This indicates that IPMC actuators hold potential for more sophisticated applications in control. Several recently reported IPMC fabrication processes, mechanical characteristics and performance and a number of recent IPMC applications have been reported in this paper. Extensive references are provided for a more in-depth explanation.

1. Introduction

The research on electroactive polymers (EAPs) for smart materials and structures has become a rapidly growing trend in recent years. With the characteristics of low weight, high strain, cost-effective manufacturing and flexible structure, EAPs have a significant potential in various fields and have gradually become more realistic. EAPs have been utilized as actuators and sensors because they are capable of converting electrical energy into mechanical energy and vice versa, and they are available in various shapes and dimensions. The study of EAPs includes the following two major areas: (a) electronic EAPs and (b) ionic EAPs.¹ Ionic EAPs such as gels, polymer–metal composites and conductive polymers are operated by the diffusion of ions. Thus, an electrolyte for actuation is required. One advantage of ionic EAPs is that the actuation voltage can be relatively low (e.g. <10 V). Among the various ionic EAPs, ionic polymer–metal composites (IPMCs) have been broadly studied because of their promising biomechanical and biomimetic applications.² A typical IPMC consists of a polyelectrolyte membrane (usually Nafion or Flemion) plated on both faces by a noble metal (palladium, silver, gold and copper) and is neutralized with certain counterions that balance the electrical charge of the anions covalently fixed to the backbone membrane. The transport of hydrated cations within an IPMC beam under the applied voltage and the associated electrostatic interactions lead to the bending of an IPMC beam, as illustrated in Figure 1.³ Aside from other active materials, IPMCs possess soft properties and can be constructed as flexible structures that can be driven by low voltages for operation in

aqueous environments. Thus, IPMCs are highly appealing for studies in underwater robotics.⁴ Biomedical applications are also possible, including artificial muscles and endoscopy.^{5,6}

IPMC manufacturing starts by selecting the base ion exchange polymers, which are typically manufactured from organic polymers that contain covalently bonded fixed ionic groups. The copolymers of styrene and divinylbenzene are most the popular ion exchange material because of their ion exchange capabilities and water uptake. Other popular ion exchange materials are perfluorinated alkene: with short side chains terminated by ionic groups. The large polymer backbones determine their mechanical strength. Short side chains provide ionic groups that interact with water and allow passage of appropriate ions. Therefore, they can create hydrophilic nanochannels, called cluster networks. These configurations are completely different in other ionic polymers such as styrene/divinylbenzene families that are primarily limited by cross-linking, the ability of the ionic polymers to expand (due to their hydrophilic nature). There are several commercially available ion exchange material manufacturers; among them, Nafion from DuPont, Aciplex from Asahi Chemical and Flemion or Selemion from Asahi Glass are a few of the popular names. IPMC fabrication is lab-intensive work, and safety requirements should be taken into consideration during chemical processing. There are two distinct IPMC fabrication processes, the initial compositing process and the surface electroding process. Depending on the preparation processes, the morphologies of the precipitated metal will be significantly different.

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Figure 1. IPMC actuation mechanism³

It is interesting to note that IPMCs are nearly resistive ($>50\ \Omega$) in the high-frequency range and fairly capacitive ($>100\ \mu\text{F}$) in the low-frequency range.⁷ The electrical behavior of IPMCs strongly depends on the frequency that means a distinct response to a driving voltage with a frequency less than 10 Hz (actuating frequency) and a high frequency (typically above 1 kHz). In the high-frequency range, hydrated ions cannot follow the fast direction variation of the applied electric fields and mostly react as an immobile charge particle. In this range, only the electrons contribute in the electrical properties of the sample without any actuating effect. The distinctive response of the ions and the electrons to the electric field in addition to the capacitor-like structure of IPMC results in a non-linear and frequency-dependent relation between the current and the voltage. By increasing the frequency, the non-linearity decreases until it vanishes entirely, and Ohm's law can be used to describe the IPMC resistance behavior. Thus, apart from the ion concentration and the sample dimension, the resistivity of IPMC across the membrane also depends on the frequency, and one can use this property to design a self-sensing sensor, which can detect an external disturbance. The mechanical characteristics of IPMC also depend on the frequency; generally, as the frequency increases, there is a corresponding decrease in displacement. At low frequencies and an imposed voltage, the effective elastic modulus of the IPMC cantilever strip is small, while at a higher frequency, the elastic modulus is high and the displacements are smaller; this is due to the simple fact that during low frequency, the hydrated ions have time to gush out of the surface electrode, while in the high frequency, they are rather contained inside the polymer. These singular characteristics have motivated researchers to model IPMCs as both capacitive and resistive element actuators that behave like a biological muscle and provide an attractive means of actuation as the artificial muscles for biomechanics and biomimetics applications. In the energy-harvesting and sensing

modes, they appear to have a very good bandwidth to sense low as well as high frequencies despite the piezoelectric materials such as lead zirconate titanate that are only suitable for high-frequency sensing. Shahinpoor and Kim⁸ have reviewed some of these recent applications such as mechanical grippers, metering valves, diaphragm pumps, electrochemical relay switches and composite wing flaps. Being biocompatible materials, IPMCs have been used in many novel biomedical, rehabilitation and surgical devices such as heart compression devices, biomedical microrobots for intravascular therapies, ultrathin scanning endoscopes and surgical robotic instruments.^{9–13} Linear and three-dimensional (3D) actuators, made of IPMCs, have been used in many robotic systems including snake-like swimming robots, microoctopod robots and undulatory tadpole robots.^{14–16} IPMCs, with non-traditional shapes, such as disk-like structures, helical structures and cylindrical designs, have been investigated for applications that range from energy harvesting to active catheters in minimal invasive surgeries.^{17–19}

The actuation characteristics of IPMC, including a suitable response time, high bending deformation and long life, show significant potential for the backward and forward propulsion of underwater microrobots.^{20–24} They are mainly used as oscillating or undulating fins for swimming microrobots when fast response is required.^{25–32} The patterning approach creates isolated electrodes on the IPMC membrane where, by applying different driving signals to different sectors of the IPMC, complex motion, specifically twisting, can be created.^{33,34} At the same time, other regions can be patterned for sensing fin deformation and responses to external stimulation.³⁵

Recently, the application of IPMCs in various biomedical systems has been investigated.³⁶ An active guide wire for the microcatheter based on the IPMC actuator has been developed.^{37–39} With the development of IPMC fabrication technology, tubular and cylindrical IPMC actuators with four separated electrodes have also been developed for active catheters.^{40,41} Many surgical applications are already being researched using IPMCs as actuators, which have proved their viability as a good material for surgical robots; some of these include a fragment capturer to collect the plaque generated in surgery to remove a thrombus, 3D tweezers developed using arbitrary-shaped IPMC, an active catheter and a system for endoscopic surgery.^{42–45} IPMCs are inherently compliant and would therefore have low tip mechanical impedance making the tools inherently backdrivable, which will ensure the safety during surgery, and can also be designed to be easily miniaturized.⁴⁶ Although all these show promise, much work is still required to overcome some of the drawbacks of IPMCs, including hysteresis and non-repeatability, in order to advance them into real-world systems. One promising new application of IPMCs is in drug delivery systems. IPMCs lend themselves well to miniaturization, and they can be used as an integrated actuator in the dispensing system for an embedded pump reservoir system, which can operate for long periods of time due to low power consumption. Because of low-driven voltage, large deformation, flexible operation and

self-sensing ability, the IPMCs promise an attractive actuation choice for the diaphragm of micropumps. IPMCs can be used to couple high precision with high compliance to create a safe and accurate micromanipulation system.^{47–55}

IPMCs have built-in sensing and actuation capabilities.^{46,56} In particular, they hold strong promise for versatile sensing applications because of their high sensitivity, inherent polarity and direct mechanosensory properties, which minimize the complexity in both the sensor construction and the signal processing. Furthermore, they are biocompatible and amenable to fabrication.^{57–60} Recent applications of IPMC sensing capabilities span the measurement of force, flow, shear loading, curvature, structural health monitoring and energy harvesting.^{61–69}

IPMCs generate charges when experiencing a mechanical load or deformation. If the polymer is not deformed, the distribution of cations inside the polymer is uniform and no output voltage is detected. An output voltage is therefore generated, proportional to the experienced strain. Since the IPMC sensing response depends on the hydration level, IPMCs work well in water and do not need to be waterproofed. IPMCs have been recently considered in several energy-harvesting applications.⁷⁰ Due to their light weight, large compliance and long service life, IPMCs represent a possible alternative to traditional powering systems and can compete with other classes of active materials.^{71,72} IPMCs have been proposed for energy extraction from the tail beating of a biomimetic fishtail and from flutter of a heavy flag.^{68,73}

IPMCs are a good choice for researchers to design and develop efficient biomimetic sensory systems for aerial and underwater robots to perform complicated and sophisticated tasks. IPMCs are suitable for several reasons. First, the direct mechanosensory property of IPMCs minimizes the complexity in sensor construction. Finally, the softness of the material allows IPMC sensors to respond to small flows. These sensors also demonstrate promises to react to different types of fluid media and provide output signals that can differentiate the fluids accordingly. Several studies have demonstrated the use of IPMCs to sense shear, tensile and bending stresses.^{65,74–77} All these studies focus on flat IPMCs due to current limitations on IPMC fabrication techniques, which primarily rely on metal plating on a flat polymer.⁷⁸ However, recent efforts have proposed novel fabrication methods, which allow for more complex shapes and patterns.^{19,79–81} Disk-shaped IPMCs are fabricated by hot-press Nafion granules to study energy harvesting.⁷⁹

2. Biomedical applications of IPMCs

Instead of sealing the actuator, it can be encapsulated with the surrounding water because the proposed catheter scope design in reference has sufficient space inside as shown in Figure 2.⁸² The two-dimensional functional capability of a cylindrical IPMC actuator makes it a promising candidate to be used as an active catheter in different specialized medical scanning applications such as endoscopy.⁸³ This can be achieved by the interdigitation of four

surface electrodes and their sequential excitation by appropriate signal combinations as shown in Figure 3. A novel flexible IPMC actuator with integrated electrically controlled clamping and feedback functions for biomedical applications such as minimally invasive surgery (MIS) is proposed as shown in Figure 4.⁸⁴ IPMC actuators include two major features: two clamping fingers and a handle. The working electrodes located on the surfaces of the clamping fingers control the bending motion of the fingers. Because the effective motion is either opening or closing, the inner electrodes of both fingers can be functioned as a single electrode, and the outer electrodes of both fingers can be functioned as another electrode. A soft strain gage has been developed to be integrated with the intrinsic IPMC actuator. A novel synthesis technique to fabricate a soft, lightweight and active IPMC-embedded tube capable of creating multiple degree-of-freedom (DOF) motions for MIS applications has been developed.⁸⁵ The actuating tube is characterized in terms of bending deflection and response speed, which are the key factors in the design of MIS robotics. A novel IPMC actuated intraventricular device (VAD) for end-stage heart failure patients is presented in Figure 5.⁸⁶ The membrane and the vertical actuators are made of combined sets of shape-memory alloy wires and IPMC actuators. Nafion is used as an interconnecting material between adjacent pieces in order to give them more DOFs. The polarities of the electrodes of all the pieces are chosen in such that they bend toward each other for closing the membrane and away from each other for opening it. Mimicking the natural motion of the heart requires almost no shear stress on the blood cells and leaves no stagnant points; hence, it reduces the risk of hemolysis and thrombosis.

Namb and Ahna⁸⁷ aimed to study an optimal design for the IPMC diaphragm of a micropump to increase its deformation capability and operating durability by presenting a novel design technique, which is based on several IPMC actuators covered by two elastic thin films. To solve the problem of edge constraints, Namb and Ahna⁸⁷ used a flexible support structure for an IPMC diaphragm. The contribution of McDaid *et al.*⁸⁸ is to design and validate a force feedback system on the IPMC micromanipulator for the safe and reliable manipulation of cells and microbiological materials. Although the IPMC actuators ensure that the device is inherently compliant, the system is not guaranteed to be safe throughout the operation with only position control. The operating environment during cell manipulation, as well as the physical properties of the cells themselves, is likely to be unknown or at least have a large degree of uncertainty, and as such, force feedback and control are essential to ensure safety.

3. IPMC underwater applications

A compact structure with efficient and precise locomotion and multifunctionality, in the form of a new inchworm-inspired microrobot with ten IPMC actuators used as legs or fingers, has been developed as shown in Figure 6.⁸⁹ This unit employs four of its actuators to walk, rotate and float. The other six actuators have been utilized to implement grasping. Also, the microrobot can detect the direction and the distance of an object and avoid an

Figure 2. IPMC-actuated active catheter tube⁸²

Figure 3. A cylindrical IPMC with four interdigitated electrodes (top) and illustrated actuation (bottom)⁸³

obstacle while walking, using three short-range proximity sensors. The developed underwater microrobot is driven by a low voltage, which is safe and economical, so it can be used for the amusement application, such as toys, or used in the aquarium. It can also be used for underwater exploration in limited underwater environments. In addition, it shows significant potential for monitoring ocean currents and chemical agents and studying animal migration, depth measurements and military functions. A simple IPMC strip has only one bending 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. In order to more closely imitate a real-life insect, a microrobot with one leg with two DOFs has been designed and demonstrated.⁹⁰ A microrobot for underwater application has been constructed and demonstrated using the proposed legs having IPMC thighs and shanks. A compact, flexible and multifunctional lobster-like microrobot, as shown in Figure 7, has been constructed and demonstrated.⁹¹ A series of experiments have been carried out to evaluate its walking, rotating, floating and grasping motions. A compact monolithic control surface with integrated sensing has been developed by an IPMC fin with patterned electrodes.⁹² The surface electrode material of proposed IPMC fins is sectored into different electrically isolated regions for generating complex deformations. The surface electrode pattern on the IPMC has been created using a simple surface machining process. By selectively activating specific regions of the IPMC, bending, twisting, flapping and other bioinspired locomotive behaviors can be achieved. Due to their ability for mechanoelectrical transduction, with careful design of the electrode pattern, certain areas of the IPMC can be used to create a highly deformable control surface, while at the same time, other regions can be patterned for sensing fin deformation and responses to external stimulation. The result is a compact monolithic control surface with integrated sensing for multifunctional applications. A novel synthesis technique is developed to fabricate a hybrid IPMC membrane actuator capable of generating 3D kinematic motions.³ The actuator consists of separated IPMC beams bonded with a soft polydimethylsiloxane (PDMS) membrane, as shown in Figure 8. By controlling each individual IPMC beams, complex 3D motions such as oscillation and undulation can be generated. Complex deformations can also be realized by integrating IPMC actuators into soft boot material additionally serving as a coating material for prolonged operation as shown in Figure 9.⁹³ One unique advantage of the proposed structural design is that custom-shaped fins and control surfaces

Figure 4. Motivation and working functions of the novel self-strain feedback IPMC clamping actuator with electrical control ability⁸⁴

Figure 5. An embodiment of the actuator⁸⁶

can be easily created without special materials processing. The molding process is relatively inexpensive and does not require functionalizing or activating the boot material, similar to manufacturing IPMCs. The result is a significant cost reduction by avoiding the need for electroless plating of platinum and electrode patterning or machining. Furthermore, the integrated IPMCs are protected from the surrounding environment. The concept has been experimentally validated through extensive experimentation for underwater applications.

Smaller IPMC actuators are used to replicate the bell deformation of jellyfish with 70% power reduction compared to previous models as shown in Figure 10.⁹⁴ Different methods of

implementing the actuators, underneath the bell with smaller IPMC actuators, are investigated to replicate the natural jellyfish's bell deformation. The results demonstrate that the proper placement of the IPMC actuators results in a bell configuration that more accurately represents the deformation properties of the natural jellyfish. Smaller IPMC actuators are used to achieve the desired deformation, and thus, the power consumption is reduced by 70% compared to previous generations. An IPMC-actuated water jet thruster for underwater microrobots that generates thrust from fluid mass at a certain contraction frequency is presented.⁹⁵ The thrust characterization of the contractile water jet thruster (CWJT) is provided against two input parameters, input current to actuators and nozzle opening area.

Figure 6. Inchworm-inspired IPMC microrobot:⁸⁹ (a) initial position; (b) walking motion; (c) grasping motion; (d) floating motion

4. IPMC applications as sensor

A sensor fabricated from the integration of a polyvinylidene fluoride film into an IPMC actuator fulfils the robotic industry requirement of localization and shape estimation as shown in Figure 11.⁹⁶ The curvature-sensing mechanism can also perform a scanning motion by using the electrically controlled IPMC actuator. Recently, Abdulsadda and Tan⁹⁷ reported an artificial lateral line, shown in Figure 12, based on the sensing capability of IPMCs. IPMCs are suitable for developing artificial lateral lines for several reasons. First, the direct mechanosensory property of IPMCs minimizes the complexity in sensor construction. The softness of the material allows an IPMC sensor to respond to small flows. While the feasibility of an IPMC lateral line has been demonstrated, the prototype has been manually constructed with each of the four IPMC sensors measuring 8 mm long, 2.5 mm wide and 200 μm thick. These sensors are cut from a larger IPMC sheet and fabricated with a planar process.

Figure 7. Prototype lobster-like microrobot⁹¹

To emulate the biological lateral line, where there are hundreds of neuromasts each with a length under 1 mm, novel microfabrication methods need to be developed. A novel approach to the fabrication of micro-sized IPMC arrays that stand upright on a substrate is presented in Figure 13.⁹⁸ Forming a micro-vertical Nafion structure through casting is faced with several difficulties due to volume shrinking and capillary effects. Another challenge lies in selectively forming the metal electrodes for the IPMC beams, so that there is no short-circuiting between the two electrode surfaces. The behavior of the IPMC materials for flow-sensing situations, relevant to automotive applications, is investigated.⁹⁹ For instance, the precise metering of the air and the fuel entering into the combustion chamber is critical because it governs the fuel-air mixture formation in the combustion chamber that can directly impact the combustion efficiency and the exhaust emissions. The results reveal that an IPMC sensor exhibits a very good transient response to the dynamic flow-

Figure 8. IPMC/PDMS membrane actuator³

Figure 9. IPMCs embedded into soft boot structure⁹³

Figure 10. (a) An assembled IPMC jellyfish robot; (b) a picture of an experimental setup⁹⁴

Figure 11. Working principle of a flexible dynamic curvature sensor⁹⁶

induced stimuli. It also demonstrates promises to react to different types of fluid media and provides output signals, which can differentiate the fluids accordingly. An ongoing effort is to correlate the signal profile of the IPMC's response with the rheological properties of the fluid. This could add a potential functionality of IPMC materials as a sensing element for characterizing different fluid flow conditions. The mechanical sensing of an IPMC shell subject to uniaxial compression is investigated.¹⁰⁰ A novel methodology to fabricate shell-like IPMCs has been developed, which combines hot forming of soft polymers and electroless chemical reduction processes. Experimental findings demonstrate that IPMC buckling can be accurately sensed by way of the short-circuit current. The IPMC shell can be used for the health monitoring of shell-like structural elements under compression like columns.

Smart textiles, or a wearable embedded sensor that monitors motion, temperature, electrocardiogram, blood pressure and other parameters of the vital signs of a person, is recently investigated widely. IPMC is expected to function as a smart textile device that detects the directional motion of the outfit of a person. Since IPMCs detect angular displacement, they can be used as sensors that are embedded in smart textile units.¹⁰¹ The device can be used for the shape estimation of robotic manipulators. The concept has been experimentally validated.

Figure 12. A prototype of IPMC-based artificial lateral line⁹⁷

Figure 13. Envisioned artificial lateral line consisting of arrays of an IPMC⁹⁸

5. Conclusion

This study presents a summary of the advancements in IPMC manufacturing techniques and their availability in various shapes and sizes. This ensures widening the scope of the applications of IPMCs and their improvement in performance of the already reported applications, for instance, cylindrical actuators for active catheter systems and undulatory motion generation, IPMC-embedded tube for MIS, molding of IPMC actuators into soft boot mold material for the realization of complex deformations, circular IPMC-driven diaphragm for micropump, fabrication of micro-sized IPMC arrays for lateral line sensory system and tubular IPMC for structural health monitoring. Due to the biomimetic actuation and biocompatibility of IPMC, both bio-inspired and biomedical applications have been characterized. These include, for instance, underwater biomimetic microrobots, robotic jellyfish, micropumps, active catheter systems, micromanipulator and VAD. IPMC application as sensors and IPMC-embedded sensing devices are characterized for various applications. The development of curvature/tactile sensor devices for industrial applications, lateral line sensory system for underwater applications, IPMC application for flow sensing and liquid recognition, buckle-sensing capability of IPMC shell under compression are discussed in detail. Most of the advancement in IPMC research has been in the last two decades; thus, the development of IPMC is still far from attaining maturity. Since the actuation performance of IPMC is still not well developed to be used in varieties of application, it needs a considerable amount of research. It is believed that this paper will further help catalyze research in IPMCs and EAPs and will act as a guide for the rest of the materials science community.

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