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Manufacturing of ionic polymer-metal composites (IPMCs) that can actuate into complex curves

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ABSTRACT

Ionic polymer-metal composites (IPMC) are soft actuators with potential applications in the fields of medicine and biologically inspired robotics. Typically, an IPMC bends with approximately constant curvature when voltage is applied to it. More complex shapes were achieved in the past by pre-shaping the actuator or by segmentation and separate actuation of each segment. There are many applications for which fully independent control of each segment of the IPMC is not required and the use of external wiring is objectionable. In this paper we propose two key elements needed to create an IPMC, which can actuate into a complex curve. The first is a connection between adjacent segments, which enables opposite curvature. This can be achieved by reversing the polarity applied on each side of the IPMC, for example by a through-hole connection. The second key element is a variable curvature segment. The segment is designed to bend with any fraction of its full bending ability under given electrical input by changing the overlap of opposite charge electrodes. We demonstrated the usefulness of these key elements in two devices. One is a bi-stable buckled IPMC beam, also used as a building block in a linear actuator device. The other one is an IPMC, actuating into an S-shaped curve with gradually increasing curvature near the ends. The proposed method of manufacturing holds promise for a wide range of new applications of IPMCs, including applications in which IPMCs are used for sensing.

Keywords: IPMC, artificial muscle, complex curve, arbitrary shape, reversing polarity, electrical connection, variable curvature.

1. INTRODUCTION

Ionic polymer-metal composites (IPMCs) are a type of actuators, which due to their softness hold promise as artificial muscles for the fields of bio-medical engineering and biologically inspired robotics. Softness is advantageous for bio-medical applications because hard objects may damage biological tissue. For bio-mimetic robotics softness provides a means to achieve curved body or limb shapes without the need of a large number of independently controlled actuators and joints. It also provides a compliant interface to the environment.

Typically, an IPMC is manufactured as a thin strip of soft ionic polymer, coated with metal electrodes, which bends with approximately constant curvature when voltage is applied to it. Because it has no moving parts, an IPMC is silent, and because it is polymer-based, it is lightweight and can be cut out easily in any shape. In fact, IPMCs can be easily pre-formed or cast in any shape, including three dimensional shape [1]. If the pre-shaped curve has segments with opposite curvature, on application of a voltage one side will open, while the other will close. For many applications this may be an undesired result and a serious limitation.

One approach to overcome this limitation is to create several separately actuated segments on the IPMC, by removing the top metal electrode layer at the boundary between segments and thus segmenting the electrodes. Then each segment can be powered and controlled individually by external wires. This approach was used successfully to create an

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undulating swimming robot [2-4]. Another application of a segmented IPMC actuator, this time with power lines running along each segment is the soft 3-link manipulator with visual feedback introduced in [5].

There are many applications, however, for which the use of external wiring is objectionable and at the same time fully independent control of each segment of the IPMC is not required. One example of such an application is the self-actuated bi-stable buckled beam introduced in our previous work [6,7]. For such applications it would suffice if each segment of an IPMC could be tailored to respond in a different manner to the same excitation signal. In this way complex curves of the actuated IPMC can be achieved by a control signal from only one source.

In this paper we propose two key elements needed to create an IPMC, which can actuate into a complex curve. The first is a connection between adjacent segments, which enables opposite curvature. This can be achieved by reversing the polarity applied on each side of the IPMC, for example by a through-hole connection. Some work in this direction is mentioned in passing by Shahinpoor and Kim [8], however their results were not very encouraging. Eamex Corp. has shown [9] a device that bends with opposing curvature, which is made from several separate IPMCs held together by an external metal clip, which alters the natural shape and is not very reliable. The second key element is a variable curvature segment. The segment is designed to bend with any fraction of its full bending ability under given electrical input by changing the overlap of opposite charge electrodes. The devices can be manufactured so that the electrodes carry the signal from one segment to the next, thus making the application of external wiring unnecessary.

2. MANUFACTURING METHOD

In order to be able to actuate into complex shapes an IPMC should consist of segments, each of which is able to bend with arbitrary curvature when voltage is applied. Here we describe the two elements which would allow this and how to manufacture them. The first element is an electrical connection between adjacent segments, which allows them to bend in opposite directions under the same voltage source. The second is the pattering of the electrodes on each side of the IPMC, to achieve different overlapping area of similar charged and opposite charged electrodes.

2.1. Reversing electrical connection between adjacent segments

In the following we describe a method by which the adjacent segments of an electro-active transducer can be connected in reverse polarity to the same voltage source without the need for external wires. First we divide the electrode layer on the top and the bottom of the IPMC into two separate islands, which when viewed from the top would overlap as shown in Fig. 1. The gaps between the electrode islands are made by removing of the top layer of the IPMC by micro-cutting. Any other suitable material removal process e.g. scratching or laser cutting can be used. Sometimes, the process of making the gaps between regions on the electrode surface is termed “patterning” of the electrodes. The connection is realized by a through hole in the polymer material, which is coated on the inside or filled with electrically conductive material. Fig.2 (a) shows the IPMC with drilled holes and the electrode gap between them. The dashed line in Fig. 2 illustrates the location of the electrode gap on the reverse side of the IPMC. Fig. 2 (b) shows the same IPMC after the holes were filled with commercially available conductive silver paste material (Chemtronics “conductive pen”).

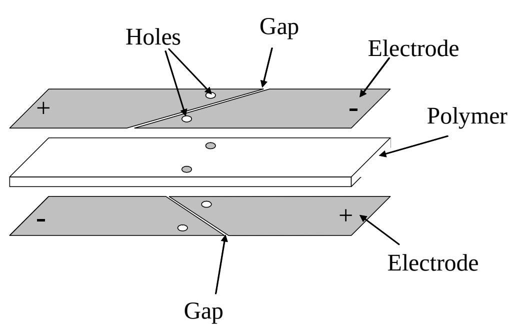
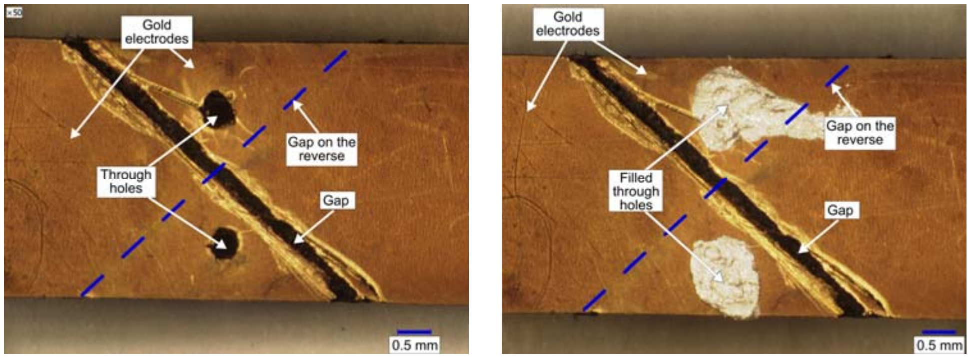


Fig.1. Patterning of electrodes and reversing connection between adjacent segments.



(a) (b)

Fig. 2. Manufacturing of a through hole reversing connection with conductive filler material. IPMC film with holes and a gap between the electrodes (a). The holes are filled with conductive material (b).

Sometimes the conductive filling material would not adhere well to the inner surface of the hole and in operation may fall off. This can be improved if the connection between the adjacent segments is done simultaneously with the electrode plating of the polymer. Additional advantage is that the number of manufacturing operations and the manufacturing time can be reduced. Fig. 3 shows the isometric view (a) and cross-section view (b) of the steps involved in the manufacturing of electrical through-hole connections in an IPMC at the same time as the electrodes. The first step is making the holes in the polymer material. In our case we used a 0.3 mm drill to drill the through holes in the polymer (Nafion 117). The second step is to plate it with the metal electrodes. The method we used is the impregnation-reduction method, a.k.a. chemical plating. In this commonly used method the electrodes are made by populating the polymer with metal ions by soaking in appropriate metal salt solution and subsequently reducing it, so that the metal precipitates on the surface of the polymer as a thin metal layer. In this process we used a gold complex as the metal salt and repeated the impregnation-reduction cycle five times before finally populating the IPMC with Na-counterions. The method that we used is described in detail by Oguro et al. in [10]. Top view of the gold-plated holes is shown in Fig. 4 (a) and the gold plating inside the hole can be seen in Fig. 4 (b). Finally, by making the electrode gaps on the electrode surface on both sides, as before, we can have a two segment actuator with each segment bending in opposite direction.

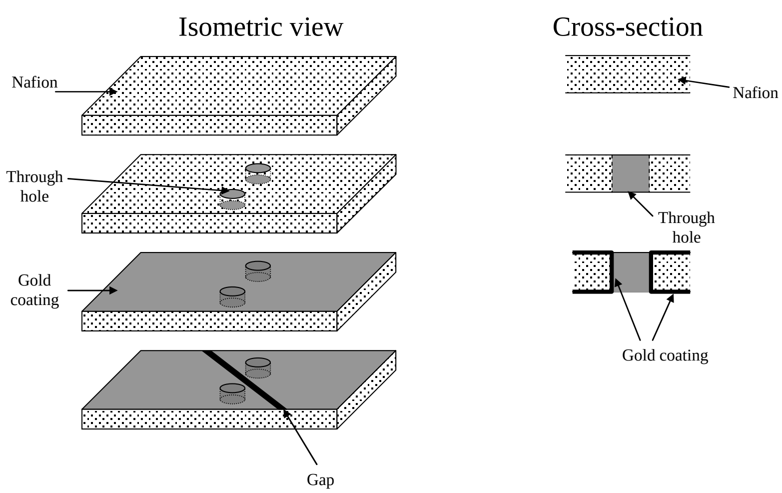
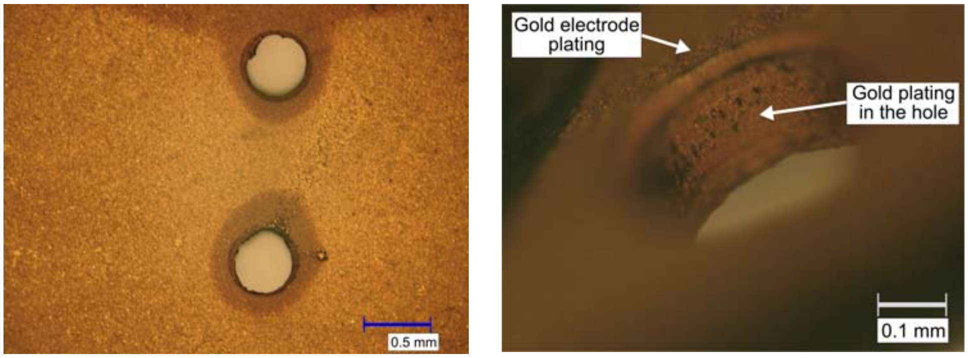


Fig. 3. Manufacturing of a through hole reversing connection as part of the electrode plating process.



(a) (b)

Fig. 4. Reversing connection done simultaneously with electrode plating: (a) top view;(b) view of plating inside the hole.

2.2. Variable curvature segment

If it would only be possible to have multi-segment IPMC actuators, with each segment bending with opposing but equal curvature, the range of applications would not be that wide. If each segment could be made to have different curvature given the same voltage, it would enable much wider range of applications.

For a typical IPMC, when an electrical potential is applied across it, it bends into a curve with approximately constant curvature Fig. 5 (a). If, on the other hand, there is no potential difference across the device, it does not bend Fig. 5 (b). If only a portion of the available electrode area is used for active bending, the amount of curvature achieved during actuation for the same voltage input is reduced. In Fig. 5 (c) it is shown how the active area can be changed by varying the amount of electrode overlap. Fig. 5 (d) is an illustration of how to achieve variable curvature within a single segment by an electrode overlap that varies along the segment. In the illustration the electrodes are patterned in triangular shapes, but other shapes are also possible. Fig. 5 (e) illustrates how a segment can be used to carry current and voltage to the next segment, without itself bending.

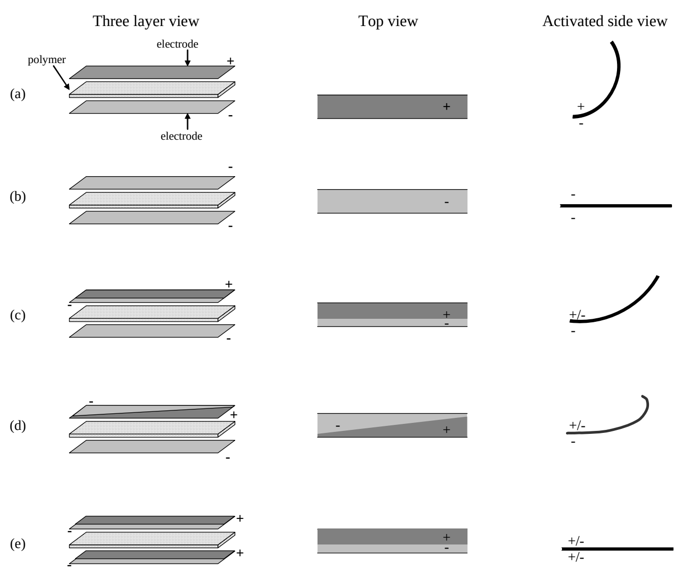
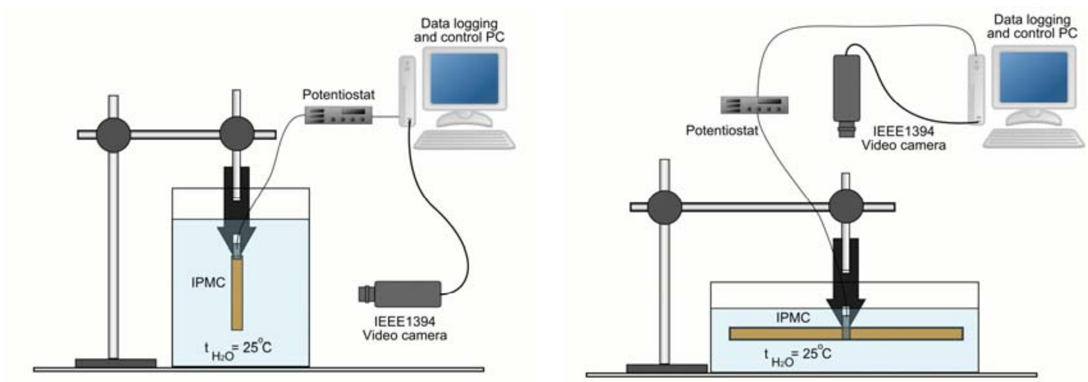


Fig. 5. Various configurations of electrode overlap: (a) conventional IPMC – 100 % overlap; (b) IPMC carrying similar charge on both sides – 0% overlap; (c) IPMC with partial overlap – large active bending portion and small portion which carries current to the next segment; (d) IPMC with gradually increasing overlap; (e) IPMC with 0% overlap configured to carry electric power to the next segment without itself bending.

Thus, by varying the electrode overlap, individual segment curvature can be changed to any fraction of the full bending ability of the segment under given electrical input. When combined with the reversing connection described above a wide range of devices become possible.

3. EXPERIMENT AND RESULTS

First we verified that our basic building blocks work as expected and then we applied it to two different IPMC devices. Each of the devices would not be possible or would be difficult to realize without utilizing the through hole reversing connection between adjacent segments or without varying the electrode overlap. We designed a bi-stable buckled beam, which flips from one stable state to the other under voltage and an S-curve with varying degree of curvature at the ends. The experimental setup used to acquire the data is shown in Fig. 6 (a), which was used for short actuators and in Fig. 6 (b), which was used for long IPMC actuators. IPMCs were driven from the PC DAC-board through a potentiostat. The motion of the IPMCs was recorded by a SONY XCD-X710CR video camera, directly connected to a data logging PC through IEEE 1394 interface, which allowed the entire image sequence to be recorded without compression at the frame rate of 30 fps. Selected frames from the acquired video stream were later digitized manually and the data was analyzed in MATLAB.



(a) (b)

Fig. 6. Experimental setup used to record IPMC motion: configuration (a) was used for relatively short IPMCs, while configuration (b) for longer IPMCs, which produced more complex shapes.

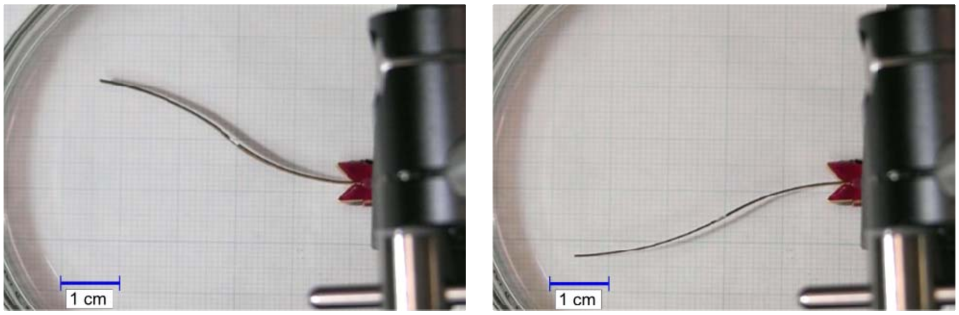
3.1. Reversing electrical connection between adjacent segments

The effectiveness of the reversing electrical connection was verified by using an IPMC with electrode pattern shown in Fig. 1. With this pattern the two adjacent segments of the IPMC are electrically connected so that the voltage applied to each segment is equal in magnitude but with opposite polarity. The bending moment in each segment also acts in opposite directions. Thus, under actuation the IPMC would bend in an S-like shape. In the test, the IPMC was held horizontally under water with temperature 25°C. It was driven with 3V amplitude 0.5 Hz sine wave. The actuator did bend as it was expected in an S-like shape (Fig. 7) and the amplitude of the end point was more than 30 mm under the given excitation.

3.2. Variable curvature by electrode overlap

The dependence of bending deflection on the electrode overlap is verified by using an IPMC with electrode pattern shown in Fig. 8. The electrode on the reverse of the device is not patterned, while the front side electrode is patterned (divided) into seven equal sized areas (electrode islands). The area of overlap between the front and back electrodes is set by the number of electrode islands on the front side connected to a voltage of opposite polarity to the back side. The IPMC is held vertically under water with temperature 25°C. The digitized traces of the actuator bent by application of a

2 V step voltage are shown in Fig. 9 (a). Larger area of electrode overlap results in larger bending and the relationship between the endpoint deflection *d* and electrode overlap is close to linear as seen in Fig. 9 (b).



(a) (b)

Fig. 7. IPMC designed to achieve S-shaped curve under actuation. Input signal: 3V amplitude 0.5 Hz sine wave. (a) maximum upward bending; (b) maximum downward bending. End amplitude is more than 30 mm.

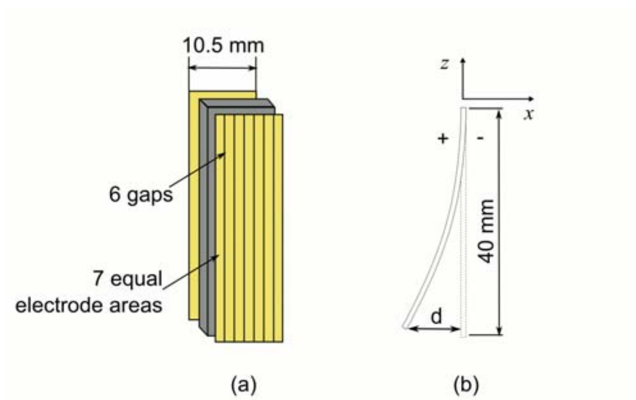
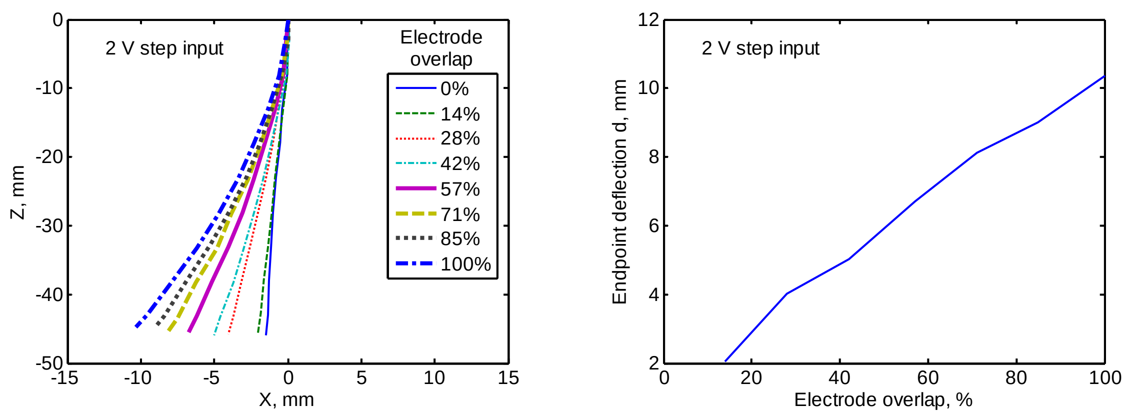


Fig.8. IPMC specimen used in testing the overlap effect with: (a) division into equal electrode areas; (b) diagram explaining the coordinate system and endpoint deflection graphed in Fig. 9(b).



(a) (b)

Fig.9. Effect of varying electrode overlapping area under 2V step input: (a) deflected shapes of the IPMC specimen shown in Fig.6(a); (b) endpoint deflection as a function of electrode overlap.

3.3. Bi-stable buckled IPMC beam

In previous papers [6,7] we have proposed a new bi-stable device which is made of IPMC and can switch between stable states when voltage is applied to it. An advantage of this kind of device is that even when the electrical supply is removed the device will remain in the last stable state that it was actuated into. Using a reversing connection would simplify significantly the device as no external wiring would be necessary. Fig. 10 (a) shows the segmentation of the straight actuator, into three segments. When the actuator is buckled (Fig. 10 (b)) the curvature of the middle segment and the end segments has opposite sign. To flip the beam to the other stable state the generated bending moment in the middle and end segments must have opposite sign (Fig. 10 (b)). This is achieved by connecting the segments with the reversing electrical connection described above. When the applied voltage exceeds a certain threshold the device flips to the other stable state. This motion sequence as captured by the camera is shown in Fig 11. In this case the device was actuated by a 2.5 V amplitude 0.5 Hz square wave.

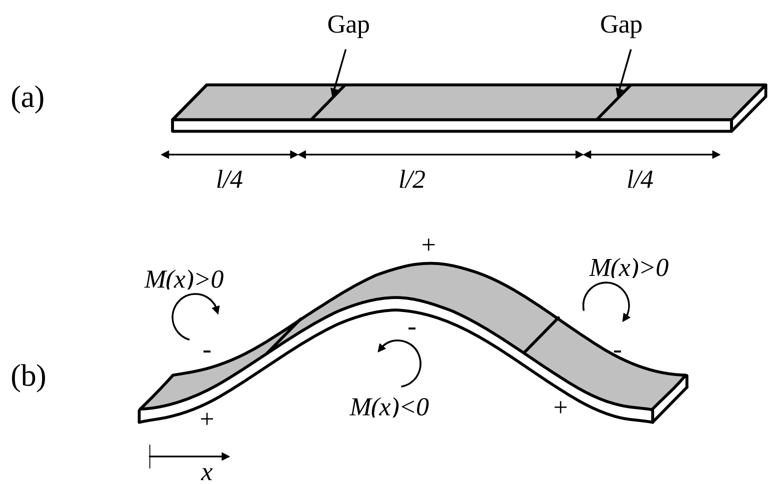
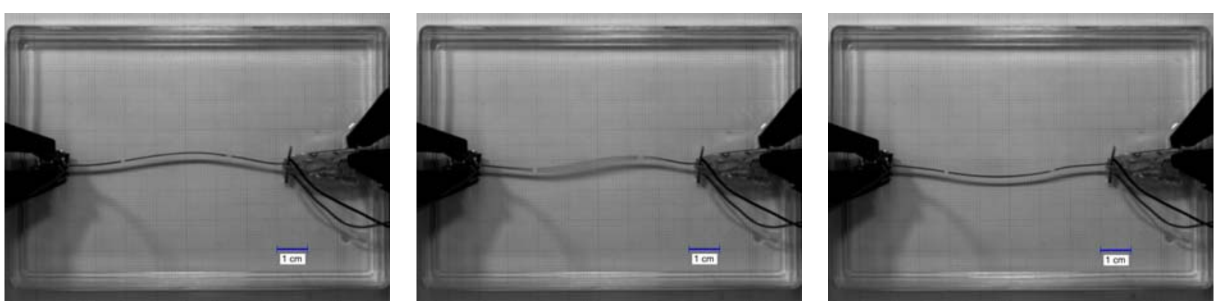


Fig. 10. Bi-stable IPMC actuator: (a) segmentation. (b) one of the stable states when IPMC is buckled and the necessary actuation and moment sign for switching the state.



(a) (b) (c)

Fig. 11. Three-segment bi-stable IPMC actuator in one of the stable states (a), during transition (b), and in the other stable state (c). Actuation by 2.5 V amplitude 0.5 Hz square wave signal.

3.4. S-shape curve with varying curvature of the end segments

By combining the two elements – reversing electrical connection and electrode overlap, we can create IPMC actuators, which can actuate in different complex shapes. Here we consider a 3 segment device, which when actuated forms an S-shape curve, consisting of three segments: curved segments at both ends, that have gradually increasing, opposite sign curvature, and a middle segment, that remains straight under actuation. Fig. 12 shows the pattern of overlapping and interconnected electrodes suitable for obtaining the predetermined S-like shape in actuated state. The electrodes carrying voltage with the same sign on the opposite sides of the device are interconnected with through-hole connections as described above. In the middle segment of the device, the electrode layers are patterned so that electrodes carrying opposite charges do not overlap. At each end of the device, the overlap of the electrodes carrying opposite charges gradually increases to full 100 % overlap.

The device was actuated with a 3 V 0.05 Hz square wave and the captured frames of two extreme positions are shown in Fig. 13. The images were digitized for further analysis of the curvature and the traces are shown in Fig. 14 (a). Data sets representing each curved segment was divided into two halves – one half closer to the center of the device and the other – near the end. Then a best circle fit was performed on the total of four data sets. The result of the fit is as expected - curvature increases toward the end of the segments, together with the increase of electrode overlap (Fig. 14 (b)).

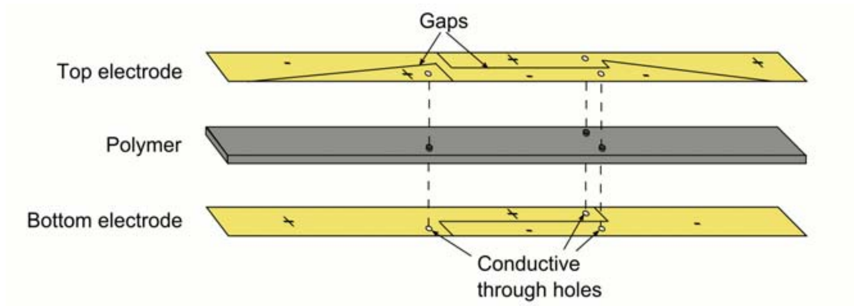
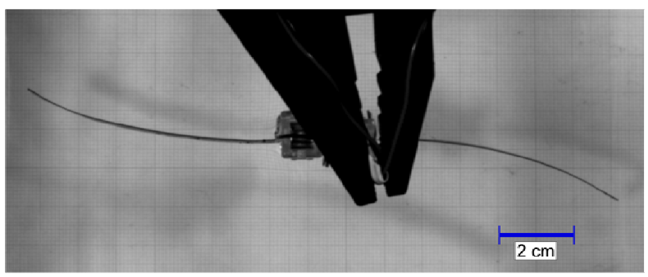
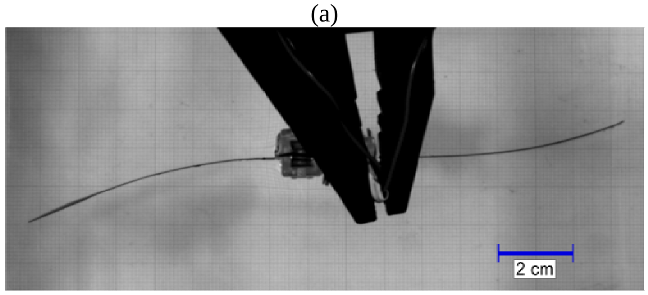


Fig.12. Electrode pattern design for achieving an S-curve with gradually increasing curvature at the both ends.

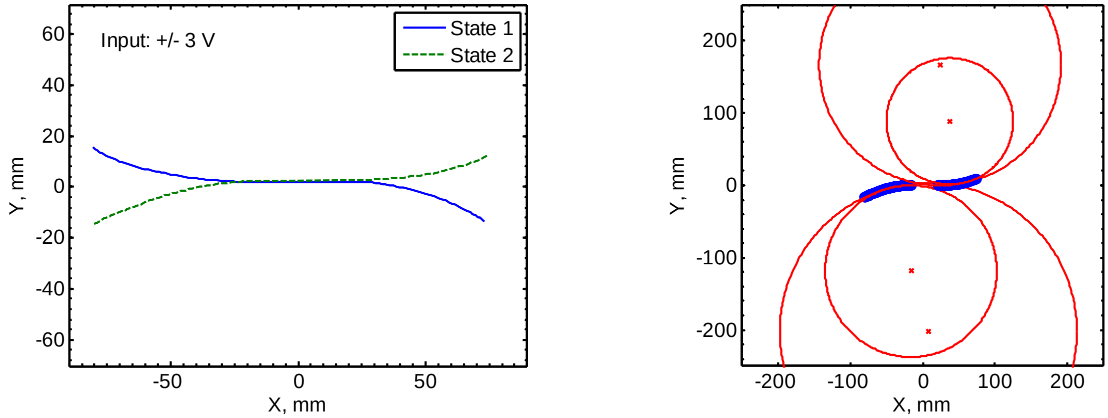


(a)



(b)

Fig.13. IPMC forming an S-curve with gradually increasing curvature at the both ends. Actuation signal 3 V 0.05 Hz square wave.



(a) (b)

Fig.14. (a) Traced shapes of the IPMC in Fig 13. (b) Radius of best fitting circle decreases toward the end as expected.

4. DISCUSSION

The above results confirm that IPMCs can be manufactured to produce complex curves when actuated. Let us now consider what kind of applications would benefit from this new feature.

One of the devices which were manufactured and shown in the previous part was a self-actuated (or internally actuated) bi-stable buckled beam. There are many different ways to utilize such an active bi-stable structure as a building block for more complex designs. One such design is a linear actuator realized as two coupled buckled beam IPMC actuators Fig.15, which can balance each other [11]. Even more complex structures are possible by using the linear actuator cell as a building block.

With the proposed technology, IPMCs could be used for nozzles with controllable shape which would find applications in locomotion or material forming. Fig. 16 illustrates how a gel-like substance can be formed when it is forced to pass through the nozzle. The nozzle changes shape when electrically stimulated, and the cross-section of the gel passing through it changes as a result.

One expected bio-medical application is for compression device that exerts local pressure at selected points of organs. This type of device can be used, for example, as a heart-compression device for patients with a high risk of heart failure, or as an eye compression device for patients with various eye defects. The compression device can be tailored to apply pressure locally, without compressing important blood vessels or tissues (Fig. 17). The device would not be limited to circular shape but can also be tailored to any other shape and to apply pressure along a contour.

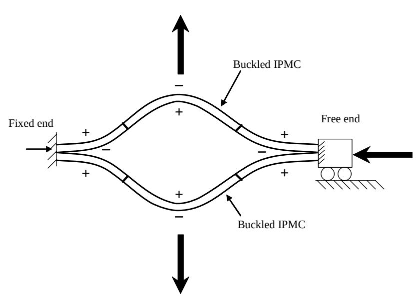


Fig.15. Linear actuator device from buckled IPMC beams.

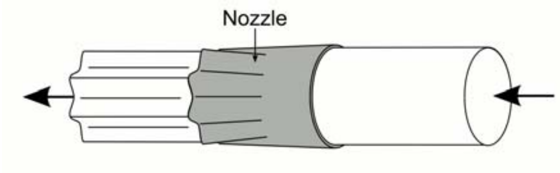


Fig.16. Forming of gel-like substance into complex shapes by IPMC nozzle.

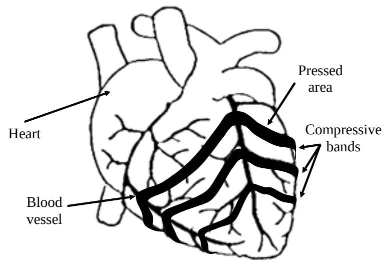


Fig.17. Heart compression device for applying local pressure.

The proposed manufacturing technology opens the way for many interesting applications not only for actuation, but for sensing as well. When used as sensors, typical IPMC devices can only detect simple bending. If bent into a more complex shape, e.g. an S-shape, the voltage and/or current generated in each segment having opposite curvature will have opposite sign and, through a cancellation effect, the resulting electrical signal generated by the device may be too small to measure. A two-segment actuator with reversing connection would generate a larger signal because, although the two segments are always bent in opposite directions, the reverse connection acts to sum the electrical signals generated by each segment. When used in a sensor configuration the multi-segmented and through-hole connected bending actuator enables a greater variety of potential applications.

The proposed technology of manufacturing IPMC devices is promising to enable a wide range of applications which were not possible with conventional IPMCs, that can only bend with approximately constant curvature. However there are still some challenges to be overcome. As the basic structure is provided by the water swelled polymer, any reduction in water content by water evaporation is likely to cause internal stress redistribution which buckles and twists the polymer. This change may be permanent and much larger than the curvature achievable by varying the electrode overlap. Some drying out of the polymer is almost unavoidable during the manufacturing of the gaps on the electrode surface. One possible way around this may be to use thicker polymer membranes which are relatively more rigid and can maintain their shape even under reduced water content. The smaller bending amplitude of the thicker IPMC, may be enhanced by introducing directional surface roughness on the membranes prior to electrode coating [12].

6. CONCLUSIONS

Typically, ionic metal-polymer composite (IPMC) actuators can only bend with approximately constant curvature when actuated. We have proposed and tested successfully two key elements needed to create an IPMC that can actuate into predetermined complex curves: 1. connection between adjacent segments, which allows them to bend with opposite curvature, and 2. variable curvature segment, designed to bend with any fraction of its full bending ability under given electrical input by defining the overlap of opposite charge electrodes.

We demonstrated the usefulness of these key elements in two devices. One of them is a bi-stable buckled IPMC beam, also used as a building block in a linear actuator device. The other one is an IPMC, actuating into an S-shaped curve with gradually increasing curvature near the ends.

The proposed method of manufacturing holds promise for a wide range of new applications of IPMCs, including applications in which IPMCs are used for sensing and this is a direction, which we will further investigate.

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