Enhanced IPMC actuation by thermal cycling

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ABSTRACT

IPMCs are bi-polar actuators capable of large, rapid actuation in flexural configurations. The limit of actuation is defined by the maximal voltage that can be applied to the IPMC, above which electrolysis of the electrolyte and damage to the IPMC may occur. In this paper we present preliminary results that indicate how this actuation limit could be tuned and even exceeded through controlled thermal cycling of gold-plated Nafion IPMCs. Thermal cycling is used to move the centre point of the actuation stroke. Subsequent voltage stimulation actuates the structure around this new centre point. It is shown that by further thermal cycling this centre point naturally returns to its initial position. By exploiting this shape memory characteristic as part of a control system it is expected that more sophisticated IPMC actuation will be achievable.

Keywords: IPMC, shape memory, thermal cycling, enhanced actuation.

1. INTRODUCTION

Ionic polymer metal composites (IPMCs) are electroactive polymers (EAPs) that exhibit very large bending strains in response to low stimulating voltages, typically in the range [0,3V] [1]. They are triple-layer flat composites with a central polymer membrane sandwiched by two highly conductive, and yet compliant, electrodes. The majority of IPMCs employ hydrated electrolytic polymers such as Nafion or Flemion as their central membrane. Although these membranes can be highly hydroscopic in humid environments and have even been used as dehumidifying elements (such as those manufactured by Perma Pure) they also dehydrate rapidly in low-humidity environments. This limits their application to wet environments and pre-disposes them for use, for example, in swimming robots [2]. Recent advances in alternative ionic polymers have led to new flexing actuators using ionic liquids [3]. These are far more robust to humidity changes and therefore are suitable for in-air applications. Unfortunately these actuators typically exhibit lower and/or slower strain responses. Wet IPMCs therefore remain those with the greatest, and hence most immediately applicable, response.

IPMCs are bipolar devices that bend in one direction in response to a positive voltage and in the opposite direction in response to a negative voltage. Actuation is always around a central rest position which is set by the equilibrium of mechanical forces arising from the fabrication process and from intrinsic material properties [1]. This bipolar actuation around a fixed point is a severe limitation of these composites. Currently there is no way to change the rest position of an IPMC after manufacturing and other methods must be used to customise actuation functionality. These include changing the cation type [4], electrically segmenting the surface electrodes [5], or by mechanically constraining the actuation, for example by using a custom mount or mechanical end-stop.

A far better solution would be to have some way to change the rest position of the IPMC in its post-manufacture state. This would open up a new range of actuation and customisation possibilities. Considering the simple cantilever IPMC shown in Figure 1a, which has a rest position at R_0, under a voltage stimulation in the range [-V,+V] the IPMC moves between the limits of actuation defined by R_a and R_b. If we could change the actuator rest position to R_1 we would

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expect actuation to then be in the range $[R_c,R_d] = [R_a-R_0+R_1,\ R_b-R_0+R_1]$, as shown in Figure 1b. Likewise if we change the actuator rest position to R_2 we would expect the actuation range to change to $[R_e,R_f] = [R_a-R_0+R_2,\ R_b-R_0+R_2]$, as shown in Figure 1c. Therefore if we can deterministically switch between rest positions R_1 and R_2 we can increase the total actuation range to $[R_c,R_f] = [R_a-R_0+R_1,\ R_b-R_0+R_2]$ as shown in Figure 1d with a range of rest positions between R_1 and R_2.

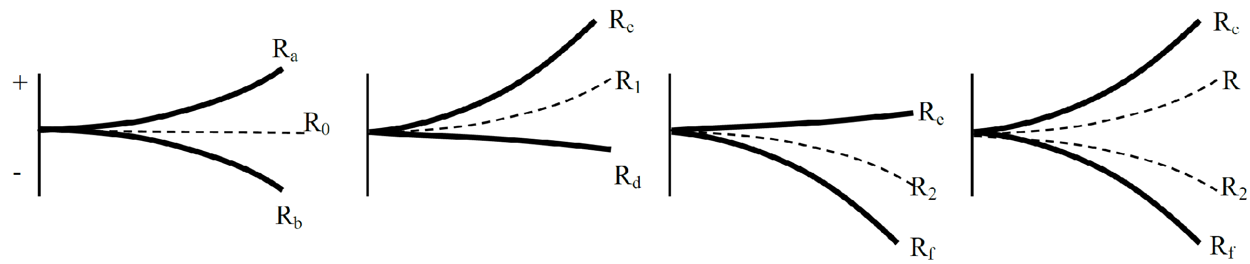

Figure 1. Increase in overall actuation by changing the rest position

In this paper we consider how the central rest position of IPMCs can be changed using a process of thermal cycling. This process is presented for the simple cantilever beam but is also applicable to more complex actuators such as multi-segment IPMCs. It is important to state here that any one-segment actuator will still only have a single degree of freedom of actuation under electrical stimulus, but that this degree of freedom can be reconfigured through the proposed thermal cycling. It is also possible to use this method to reversibly convert between an actuator that operates in a plane to one which operates though a three-dimensional trajectory.

There are many applications where reconfiguration of the rest position of an actuator is extremely useful. This is especially important for devices where manufacturing tolerances result in a rest position that is outside specification. Movement of the rest position may also occur as the actuator ages. Take for example a micro-mirror which is actively positioned by an IPMC actuator in order to overcome vibration in a remote laser transmitter as shown in Figure2. Here we desire the rest position of the IPMC to be at R_0 so that when the actuator is off and there is no vibration in the laser emitter L, the light beam from L is directed to the light sensor D. Unfortunately manufacturing variations mean the actuator has rest position R_1, resulting in a redirection of the laser beam along towards B. To overcome this undesireable offset we would conventionally redesign the mounting of the IPMC, but this would be expensive and would have to be customised for each different IPMC. Alternatively we could apply a constant offset voltage to the actuator to force it back to R_0, but this would be extremely wasteful of electrical energy and would shorten the life of the actuator. Alternatively if we can move the rest position to R_0 using simple thermo-mechanical methods the resulting actuator will direct the laser to the sensor and will require zero electrical energy to maintain this rest position.

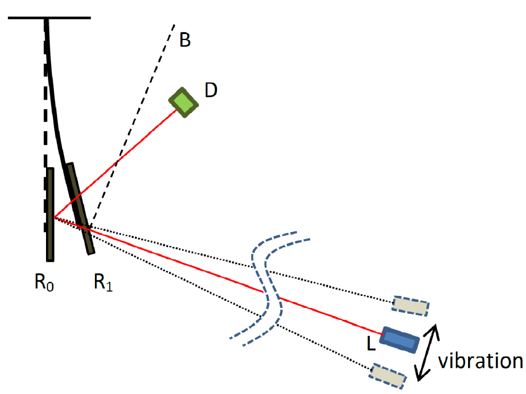

Figure 2. Correction for manufacturing tolerances in a laser steering mirror

The ability to change the rest position of an IPMC can also be interpreted as changing between stable mechanical states. In effect we have a multi-stable electroactive polymer where stable states require zero energy. This notion of zero-energy fixity in EAPs has been addressed previously in dielectric elastomer actuators [6][7] with particular application to braille displays. The reconfiguration of IPMC rest positions discussed here may also be used for such tactile display applications.

In this paper we hypothesis that Nafion-based IPMCs can exhibit shape memory effects which are consistent with prior research on raw Nafion. These shape memory effects satisfy our requirements for mechanical reconfigurability and hence enable the adjustment of the rest position of IPMCs presented above. Subsequently we present preliminary results for thermo-mechanically re-programmed IPMCs and show that actuation range is increased for the same applied voltage. Results provide the first indication of the presence of shape memory effects in IPMCs and provide the first step toward their application.

2. SHAPE MEMORY EFFECTS IN NAFION

Xie et al. has been shown in [8] that dry Nafion 117 can be programmed to memorise more than one shape and can recover these shapes through thermo-mechanical cycling. These shape memory effects follow the typical programming and recovery cycle as shown in the time domain in Figure 3 where the stress is applied mechanically, resulting in induced material strain [9]. Here four distinct states are shown; A: The shape memory material is at its neutral position, typically having been thermally cycled to remove any prior shape programming. B: The temperature is increased to the programming temperature T_p. C: Stress is mechanically applied, resulting in strain in the material. D: Temperature is reduced while maintaining the mechanical stress, thereby fixing the induced strain. E: Stress is removed, but material strain remains, i.e. the material has been shape-programmed. F: At some later time the temperature is raised above the recovery temperature T_r (typically greater than T_p) and the programmed strain decreases. G: The material has fully recovered its initial shape. State E is the most significant state, where induced strain is maintained at zero energy cost. Note that in state F strain energy is released. This strain energy can be left to dissipate or may be utilised in application, for example in [10] the release of strain energy in recovery is used to close a radially contracting structure.

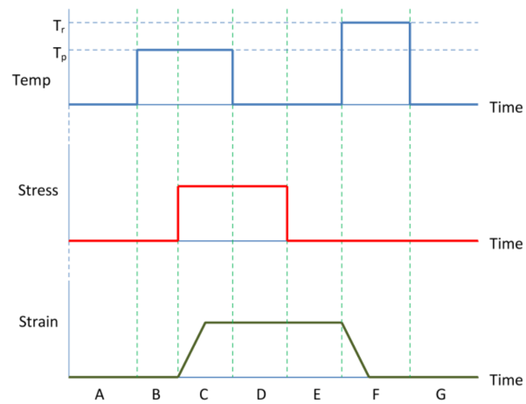

Figure 3. the typical cycle of shape memory programming and recovery

The thermo-mechanical characteristics of most shape memory polymers are captured by the response of elastic modulus to changing temperature. Figure 4 shows the prototypical modulus vs. temperature graph with a sharp transition at T_g (the glass transition temperature) from the rigid glassy state to the soft rubbery state. Note that T_p and T_r, the temperatures for programming and recovery, must be above T_g. The consequence of a sharp transition graph as in Figure 4 is that only one shape can be memorised and recovered in any one cycle. Some polymers have been identified or engineered to have more than one shape memory state, i.e. they can be programmed with two or more different shapes and these can be separately recovered [11]. Xie et al. [8] have shown that Nafion has a remarkably shallow transition graph where T_g covers a temperature range from approximately 55°C to approximately 130°C. The consequence of this is that Nafion can be programmed with, and recover from, many separate and independent states. Xie has shown in experiments that Nafion can readily memorize and recover four different shapes. It may be supposed from these thermo-mechanical properties that Nafion is able to memorise a far higher number of shapes, especially if temperature can be controlled accurately.

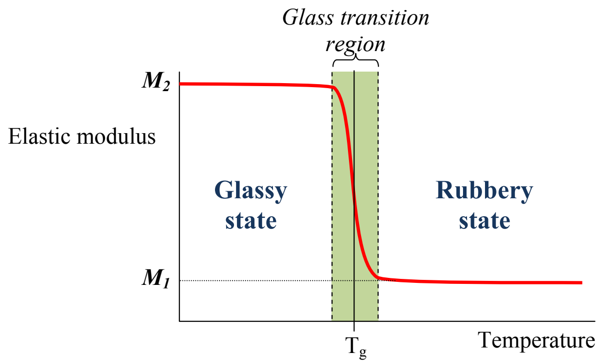

Figure 4. Typical mechano-thermal characteristics of a shape memory polymer

The question naturally arises: if Nafion has been shown to have shape memory properties, is the same true for Nafion based IPMCs? If so, can we utilise such properties to increase the range of operation of an IPMC? This is not a simple question to answer in advance of experimental study since IPMCs are significantly different to the raw Nafion upon which they are based. The raw Nafion used by Xie was stock dry membrane. It underwent an initial annealing process that markedly darkened in appearance and shrank by some 26%. It is to be expected that a significant amount of strain energy that was introduced at manufacturing was released during this process. The darkening of the polymer in response to annealing has been speculated to have been caused by thermal decomposition of the polymer chain end-groups, parts of the molecule that may well be significant in the fabrication and operation of IPMCs. In contrast, the gold-plated IPMCs used our research have undergone the chemical electro-less plating process developed by Oguro and Asaka [12]. This includes heating to 75°C in ionic solutions. This temperature is unlikely to release as much pre-strain as is shown in Xie's annealing process, and indeed the IPMC is visible unchanged by heating to 75°C in solution. The IPMCs used in our tests were kept hydrated throughout. This is in marked contrast to the dry Nafion in Xie's work. Since the Nafion swells up to 14% in water this volume change could have a large impact on shape memory effects. Further differences are due to the gold electrodes that are deposited on the surface of the IPMC. These will inevitably introduce mechanical constraints which are not present in raw Nafion, and this is shown clearly by the much greater stiffness of final coated IPMCs in contrast to the pre-coating, hydrated Nafion. Additionally, raw Nafion in [8] has not been chemically treated in any way. In contrast IPMCs undergo a relatively severe chemical process involving acid and alkali cleaning, metal-complex ion infusion and in-situ reduction. It is to be expected that such a process will affect the shape memory response of the original Nafion. Finally, the finished hydrated IPMC is doped with selected mobile cations in order to generate the desired mechanical response to applied voltage. The movement of these ions, and indeed the water that is induced to move with them, may well have an impact on shape memory effects. Adding all these differences together it is natural to be a little sceptical that any shape memory effects will be evident in electro-less plated Nafion IPMCs.

3. EXPERIMENTAL INVESTIGATION

To test the shape memory properties of IPMCs we designed a simple experiment based on the standard therm-mechanical cycle of a shape memory polymer, but adapted to the properties of hydrated IPMCs. Figure 5a shows the schematic of the experimental setup. The sample IPMC is held vertically in a water bath. The mounting clip also provides electrical connection to control signal V_{ipmc}. Water can be added to the bath from three supplies at temperatures T_p (programming temp), T_r (recovery temp) and T_0 (operating temp). Water can be removed via a tap at the bottom of the water bath. The horizontal displacement of the tip of the IPMC is monitored by a laser displacement meter (LDM). To provide mechanical input during shape programming the metal block B is used. By moving the block against the IPMC we can impose a controlled mechanical displacement or can withdraw it completely to enable free movement of the tip, as shown in Figures 5b and 5c.

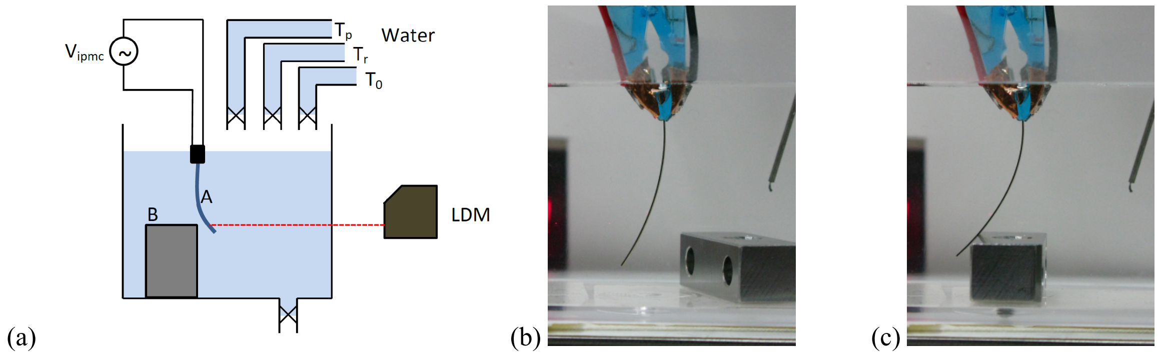

Figure 5. Experimental setup (a) for assessing thermo-mechanical properties of IPMCs, and photographs of the IPMC at rest (b) and mechanically deformed using a metal block (c)

The temperatures T_p, T_r and T_0 were fixed at 60°C, 80°C and 28°C respectively. These temperatures were chosen to be approximately within the temperature range that the IPMC had been exposed to during manufacturing. The difference of 20°C between T_p and T_r was estimated to be sufficient to enable significant recovery after programming. For a typical shape memory polymer, if T_r is close to T_p then shape memory recovery may not be complete. All IPMCs were 30mm×4mm and were fabricated from Nafion 117 (175µm thick) membrane, electro-less plated with gold using the Oguro/Asaka method.

The experimental process was as follows (T_w is the current temperature of the water bath). The process involved two cycles of shape memory fixing, one with positive mechanical deformation and one with negative mechanical deformation:

1) T_w=T_0, Pre-programming actuation test undertaken (square wave approx. 0.5Hz, +/-1.5V)
2) T_w=T_0, The metal block B was moved in order to impose a 4mm mechanical deformation approximately 10mm from the tip.
3) T_w=T_p, The IPMC was heated to T_p and held at that temperature for approximately 5minutes.
4) T_w=T_0, The IPMC was cooled to T_0 to fix the programmed shape (i.e. the mechical deformation)
5) T_w=T_0, The block B was removed, and no longer touched the IPMC
6) T_w=T_0, Post-programming actuation test undertaken (square wave approx. 0.5Hz, +/-1.5V)
7) T_w=T_r, The IPMC was heated to its recovery temperature T_r and keep at that temperature for approximately 2 minutes.
8) T_w=T_0, The IPMC was cooled after shape recovery to T_0 in order to re-fix its pre-programmed shape.
9) T_w=T_0, Post-recovery actuation test undertaken (square wave approx. 0.5Hz, +/-1.5V)
10) T_w=T_0, The metal block B now was moved in order to impose a -4mm mechanical deformation approximately 10mm from the tip.
11) T_w=T_p, The IPMC was again heated to T_p and held at that temperature for approximately 5minutes.
12) T_w=T_0, The IPMC was cooled to T_0 to fix the programmed shape (i.e. the mechical deformation)
13) T_w=T_0, The block B was removed, and no longer touched the IPMC
14) T_w=T_0, Post-programming actuation test undertaken (square wave approx. 0.5Hz, +/-1.5V)
15) T_w=T_r, The IPMC was heated to its recovery temperature T_r and keep at that temperature for approximately 2 minutes.
16) T_w=T_0, The IPMC was cooled after shape recovery to T_0 in order to re-fix its pre-programmed shape.
17) T_w=T_0, Post-recovery actuation test undertaken (square wave approx. 0.5Hz, +/-1.5V)

Figure 6 shows the tip displacement during voltage actuation for the major states of; 1. pre-programming, 2. after first (positive displacement) programming, 3. after first recovery, 4. after second (negative displacement) programming, and 5. after second recovery. Note how after programming (states 2 and 4) the rest position has moved significantly. In state 2 the new rest position is 1.62mm displaced from the start position and in state 4 the new rest position is -1.3mm displaced from the start position.

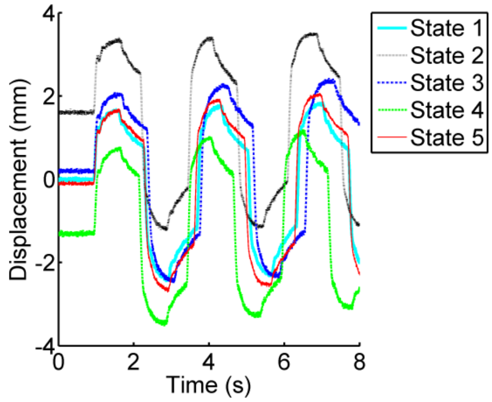

Figure 6. Displacement against time for States 1-5, encompassing two programming and recovery cycles.

Figure 7 shows the change in rest position of the IPMC for the five states shown in Figure 6. The state transitions 1-2 and 3-4 show effective shape memory programming. State transitions 2-3 and 4-5 show shape recovery. Maximum peak-peak displacements in Figure 5 is shown in Table 1. The mean of these maximum pk-pk displacements is 4.89mm.

Table 1: peak-to-peak actuation response for the five states in figure 5

State	**1**	**2**	**3**	**4**	**5**
Pk-pk displacement (mm)	4.56	4.94	5.02	4.89	5.02

The full range of rest position shown in Figure 7 is 2.92mm. This represents a 60% change in rest position with respect to the mean actuation range (4.89mm for +/-1.5V). This shows a significant change in rest position.

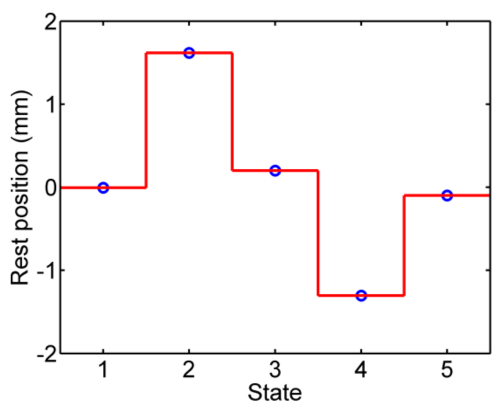

Figure 7. Reconfigurable rest position shown for the States 1-5 in figure 6.

The results above show that IPMCs exhibit shape memory effects. While it is difficult with these results to compare the effectiveness of IPMC shape fixing to the versatile shape memory effects shown for raw, dry, Nafion, these results show that the change in rest position, as a proportion of the actuation range, is significant (60% here).

4. CONCLUSIONS

We have proposed that Nafion IPMC electoactive polymers may, like raw dry Nafion, exhibit shape memory effects. That is, they can be programmed to memorise a shape and subsequently recover from that shape upon appropriate thermal stimulation. We have shown experimentally that IPMCs do indeed have shape memory properties and that these can be significant with respect to a 1.5V actuation response. These results suggest the potential of this technique and enable the future development of robotic and actuator devices that exploit this phenomenon. Likely applications include swimming robots and micro optical devices.

In this paper we have presented shape memory fixing using mechanical deformation (with a metal block). Since IPMCs deform under electrical stimulation, in follow-on research it will be natural to examine the possibility of shape memory fixing where the actuator deformation is electrically-induced. If successful this would mean that no external mechanical means would be needed to shape program a Nafion IPMC. This is an extremely attractive proposition.

In these experiments all thermal control has been via fluid exchange. In practical applications alternative heating and cooling mechanisms would need to be investigated, including Joule-heating using the surface electrodes.

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