ABSTRACT

With low driving voltage (<5V) and the ability to be operated in aqueous environments, ionic polymer-metal composite (IPMC) materials are quickly gaining attention for use in underwater applications. There are, however, drawbacks to IPMCs, including the “back relaxation” effect. Specifically, when subjected to a DC input (or an excessively slow dynamic input), the IPMC actuator will slowly relax back toward its original position. There is debate over the physical mechanism of back relaxation, although one prevalent theory describes an initial current, caused by the electrostatic forces of the charging electrodes, which drives water molecules across the ion-exchange membrane and deforms the IPMC. Once the electrodes are fully charged, however, the dominant element of the motion is the osmotic pressure, driving the water molecules back to equilibrium, thus causing back relaxation. A new method to mitigate back relaxation is proposed, taking advantage of controlled activation of patterned (sectored) electrodes on the IPMC. Whereas previous approaches to correct back relaxation rested on an increase of input voltage which can lead to electrolysis, subsequently damaging the material, this method involves only proper control of isolated electrodes to compensate for the back relaxation and does not require sensor feedback. An electromechanical model of the actuator is used to guide the design of these input signals, and the feasibility of using electrode patterning to mitigate back relaxation is demonstrated. Without reaching electrolysis, an IPMC is able to maintain its position for approximately 30 seconds. Compared to a simple step response, the rate of relaxation is reduced by 94% and the maximum error is reduced by 64%.

1 INTRODUCTION

The ionic polymer-metal composite (IPMC) material is a class of innovative electroactive polymer that offers combined sensing and actuating ability in a lightweight and flexible package. Setting IPMCs apart are low driving voltage (<5V) and the ability to operate in aqueous environments. These traits make IPMCs very attractive for underwater robotics [1–3]. Biomedical applications are also possible, including artificial muscles [4] and endoscopy [5]. IPMCs are typically used for bending in a simple cantilever configuration, however patterning of the IPMC electrodes has been explored to alter the bending behavior. By applying different driving signals to different sectors of the IPMC, complex motion, specifically twisting, can be created [6, 7].

In certain applications, the benefits of IPMC actuators are overshadowed by unwanted dynamic effects and nonlinearities [8], the most obvious of which is “back relaxation,” which can cause significant positioning error when left uncorrected. Under a constant voltage input, a Nafion®-based IPMC in the traditional cantilever configuration experiences a relatively quick deflection toward the anode, followed by a slow period of relaxation toward the cathode. It is widely accepted that the so-called back relaxation effect is due to diffusion forces acting on the solvent within the ion exchange membrane. It has been shown
that this behavior can be eliminated by using a different membrane. Flemion-based IPMCs experience the opposite effect. After a fast deflection, the IPMC continues to slowly bend in the same direction [9]. Of suitable membranes for IPMCs, however, Nafion® is the most commercially available, making it the material of choice. The effect of solvents has also been explored, and it has been shown that the proper combination of solvent and cation can eliminate back relaxation [10]. Unfortunately though, most practical IPMC applications would require that the actuator be immersed in water, meaning the IPMC would have to be sealed to retain a different solvent. Different electrode development processes, for example the insertion of a palladium buffer between the ion exchange membrane and platinum, have shown promise in reducing back relaxation [11]. Sensor-based feedback control has also been used to counter back relaxation [12, 13]. With traditional feedback, however, the input voltage must be constantly increased to maintain a position. This is undesirable primarily because a voltage threshold will eventually be crossed at which the solvent in the actuator will undergo electrolysis. As this can permanently damage the actuator, it is best to keep the input below the electrolysis point. The typical potential associated with electrolysis of water at 25°C and a neutral pH is 1.23 V. For IPMCs, however, this potential might be larger, as dictated by the experimental conditions and material properties. In [14] the electrolysis potential for an IPMC was identified as 1.8 V. Past this point the resulting reaction splits water into hydrogen and oxygen and results in a higher current draw than is necessary for IPMC actuation. This is essentially wasted current, and leads to inefficient actuation. The degree to which electrolysis occurs in the actuation cycle is determined by the magnitude of the applied voltage and the shape or dynamic properties of the input.

This paper considers a new method to mitigate the back relaxation effect in IPMC actuators through controlled activation of multiple electrodes patterned on the surface of the ion exchange membrane. It is believed that actuation of an IPMC is heavily dependent on the charge rate of the electrodes, and once the charge reaches steady state, the actuator will begin to relax. The intuitive solution is to continue the addition of charge, but as previously discussed, this may involve an increase in voltage, which is unacceptable. If a sectored IPMC is used, the concept is that one portion of the actuator is driven, and before back relaxation sets in, the input to this sector is phased out as a second sector is powered up. In this way, the sectors trade off the responsibility of maintaining the IPMC’s configuration and sensor feedback is not required. When properly tuned, this method of control helps to keep the surface charge transient and reduces the rate at which the input voltage must be increased, while minimizing or preventing back relaxation.

The remainder of the paper is organized as follows. Models for the electrical and mechanical responses are discussed in Section 2. These models are exploited in the design of the appropriate inputs to control the IPMC. The simulations and experiments are described in Section 3. Finally, preliminary results are given in Section 4 and concluding remarks are made in Section 5.

2 ACTUATION MODELS

Input-output models are presented and then used to guide the design of the inputs to the patterned IPMCs. In the modeling of IPMCs, it is convenient to separate the electrical and mechanical characteristics of the material. As depicted in Fig. 1, the electrical model (G) can be used to convert input voltage to an intermediate output, charge, and then a separate electromechanical model (H) which takes charge as an input can produce the final output, curvature.

Simple resistive-capacitive (RC) models have been used to describe the electrical response of IPMCs [1, 15]. More advanced models have also been developed representing the IPMC as a series of RC circuits to take into account the voltage drop down the length of the IPMC [16, 17].

A thorough nonlinear model was developed by Chen and Tan [18] and reviewed here for convenience. This model does not account for back relaxation, but the nonlinear charge dynamics are explored in great depth. According to the nonlinear model [18], if the range from \( x = -h \) to \( x = h \) represents the thickness of an IPMC, charge can be given by

\[
Q = \int_{x_0}^{h} \rho(x) S dx = [E(h) - E(x_0)] S \kappa_e, \tag{1}
\]

where \( \rho \) is the charge density, \( S \) is the IPMC surface area perpendicular to the thickness direction, \( E \) is the electric field, \( \kappa_e \) is the dielectric constant of the ion exchange membrane, and \( x_0 \) is the neutral axis of charge, where \( \rho(x_0) = 0 \). Based on the boundary conditions of the IPMC, Eq. (1) can be rewritten as

\[
Q = S \kappa_e \sqrt{2 \Gamma(V)}, \tag{2}
\]

where

\[
\Gamma(V) = \begin{cases} \Gamma(V), & V > 0 \\ 0, & V = 0 \end{cases} \tag{3}
\]

and

\[
\Gamma(V) = \frac{b}{a^2} \left[ \frac{aV}{e^{aV} - 1} - \ln \left( \frac{aV}{e^{aV} - 1} \right) - 1 \right]. \tag{4}
\]

Here, \( V \) is the voltage drop over the ion exchange membrane, \( U \) is the total applied voltage, and \( a \) and \( b \) are defined as

\[
a = \frac{F(1 - C^- \Delta V)}{RT}, \quad b = \frac{F^2 C^- (1 - C^- \Delta V)}{RT \kappa_e},
\]

where \( F \) is Faraday’s constant, \( C^- \) is the anion concentration, \( \Delta V \) is the volumetric change, \( R \) is the gas constant, and \( T \) is the absolute temperature.

Viewing the IPMC as a circuit, the model breaks down into nonlinear capacitance, pseudocapacitance due to adsorption, ion
The equivalent circuit is given as \( R_{IPMC} \), while the DC resistance is shown in Fig. 2 [15]. In this representation, the motion of the actuator is modeled by the following equation:

\[
\frac{dV}{dt} = \frac{U - V}{C_1(V) + C_a(V)}. 
\]

(10)

Using this relationship, \( V \) can be plugged into (2) to find the charge, and the time derivative is easily solved.

A simpler RC model for the electrical response of the IPMC is shown in Fig. 2 [15]. In this representation, \( V \) is the driving voltage and \( R_0 \) is the internal resistance of the voltage source. The \( R_1-C \) branch accounts for the capacitive behavior of the IPMC, while \( R_2 \) accounts for the current that continues to flow even after an electrical steady state is reached. The net resistance of the equivalent circuit is given as

\[
R = R_1 + \frac{R_0R_2}{R_0 + R_2},
\]

(11)

which can be used in the following equation to determine the charge on the IPMC surface:

\[
\frac{dQ}{dt} = V - \frac{Q}{C},
\]

(12)

Assuming \( V \) is a step voltage, the surface charge \( Q \) is given by

\[
Q = VC(1 - e^{-\frac{Q}{C}}),
\]

(13)

where \( \tau = RC \) is the time constant of the circuit.

Although many models have been developed to describe the actuation of IPMCs, most do not account for the back relaxation behavior. Models have been developed using differential equations to predict back relaxation with reasonable accuracy [5], however, the structure is best suited for FEA simulation. A simple description of back relaxation is given in [15]. In this model, the IPMC motion is governed by three factors: (1) the charge accumulated on the electrodes, (2) the rate of change of surface charge, and (3) the curvature. If an IPMC is subjected to a step voltage, there is a quick initial forward motion which is dominated by the ionic flux through the IPMC. Mobile cations are drawn to the charging cathode, and carry water molecules across the membrane. This leads to swelling on the cathode side of the IPMC and bending toward the anode. This ionic current is related to the surface charge rate, and as such, the forward motion fades as the electrodes become fully charged. At this point, back relaxation sets in, caused by the pressure gradient due to the water imbalance inside the IPMC. The water pressure lessens as the curvature decreases and the water molecules move closer to equilibrium. The back pressure is opposd by the lingering electrostatic force of the surface charge acting on the hydrated cations. When the electrostatic force balances the water pressure, motion ceases. This is one reason why the steady state position of the IPMC is rarely the same as the starting position. In this description, the motion of the actuator is modeled by the following equation:

\[
\frac{dk}{dt} = K_1\frac{dQ}{dt} - \frac{1}{\tau_2}(k - K_2Q),
\]

(14)
where $k$ is the IPMC curvature, $\tau_2$ is the time constant of the relaxation, and $K_1$ and $K_2$ are coefficients weighting the effects of the surface charge rate and of the surface charge, respectively. This single equation effectively describes the IPMC’s actuation behavior, and needs only the surface charge and charge rate as inputs. Referring to the simple block diagram in Fig. 1, (14) represents the electromechanical model, $H$. The electrical model, $G$, needs only to convert input voltage to surface charge, and as such, either the nonlinear model [18] or the linear model [15] could be used. For purposes of simulation, both models are used. However, for input selection, as described in Section 4, only the linear model is used. Although it would be ideal to use a nonlinear model, a linear model is much more amenable to the necessary inversion process.

Substituting the linear charge solution (13) into (14), and assuming $k(0) = 0$, the solution of the curvature is

$$k = V \left( K_{V2} \frac{K_{V1} \tau_2 - K_{V2} \tau_1}{\tau_2 - \tau_1} e^{-\frac{\tau_1}{\tau_2}} \right) + V \left( \frac{\tau_2(K_{V1} - K_{V2})}{\tau_2 - \tau_1} e^{-\frac{\tau_1}{\tau_2}} \right), \quad (15)$$

where $K_{V1} = CK_1$ and $K_{V2} = CK_2$. Using this relationship, the entire response, from voltage to curvature, can be grouped into one transfer function.

For sectored IPMCs, it is assumed that each sector can be modeled independently. Although the curvature of the whole IPMC must physically be the same if simple bending is assumed, a “virtual” curvature can be obtained for each individual sector. The sum of the virtual curvatures simply need to be added to get the net response of the complete IPMC. For example, Fig. 3(a) shows an example of a sectored IPMC, with basically two effective sectors, one driven by input $u_1$ (Sector 1) and the other by input $u_2$ (Sector 2). The IPMC’s tilt displacement is denoted by $\delta$. The electrodes are patterned such that the surface is symmetric about the longitudinal axis. For the IPMC shown, the outer portions are used as one sector (Sector 1), while the middle portion is used as a second sector (Sector 2). When each sector is activated, the sum of the virtual curvatures simply need to be added to get the net response of the complete IPMC, as is depicted in the model shown in Fig. 3(b). In this diagram the final block, $I$, represents the conversion from curvature to tip displacement. Another transfer function could be used here, however in this study, the relationship was assumed to be linear, and the gain parameters in the electromechanical model ($H$) were tuned to produce tip displacements.

3 EXPERIMENTAL SYSTEM

3.1 IPMC Fabrication

For this study, all IPMCs were fabricated in-house, using a platinum reduction method similar to that described by Kim and Shahinpoor [19]. The ion exchange membrane used was Nafion® (1100 EW) with a thickness of 0.5mm. To increase surface area for the reduction process, the membrane was roughened with sandpaper. All sanding was done in the transverse direction, to promote greater bending. After soaking the membrane in deionized (DI) water for several hours, it was cleaned in successive baths of hydrogen peroxide ($H_2O_2$) and sulfuric acid ($H_2SO_4$), followed by two baths in DI water. The plating process began by introducing platinum ions to the membrane by soaking it in a platinum complex solution, tetramineplatinum chloride hydrate ($Pt[NH_3]_4Cl_2$), overnight. Metallic platinum was formed on the surface via a reducing agent, sodium borohydride (NaBH₄). Ammonium hydroxide (NH₄OH) was also added during the reduction process to regulate the pH of the solution. After the reduction, the plated membrane was washed in sulfuric acid and two DI water baths. The plating process is repeated as necessary. For this work, the process was carried out 2-3 times. After plating, an ion exchange was carried out by soaking the IPMC over night in a sodium chloride (NaCl) solution. Finally, a CNC machine with a circuit board routing end mill was used to cut through the platinum layer (depth of 25 to 50 micrometers) and appropriately sector the electrode [7]. After a great amount of testing, the surface resistance of the IPMCs degraded. When this happened, the IPMCs were revitalized by adding a layer of gold over the platinum layer. While immersed in a gold solution, a low voltage was applied between the IPMC and a piece of stainless steel, leading to electroplating of gold onto the IPMC [20].

3.2 IPMC Test Setup

A custom-designed voltage/current amplifier was used to drive the IPMCs in this study [21]. To provide a strong clamping force and resist corrosion, nickel plated neodymium magnets were used to conduct power to the IPMCs [20, 22]. A mount for the magnets was designed to hold the magnets in place, contact-
In this case, the IPMC was divided into three sections, meaning six magnets were used. The outer two sections were actuated in unison, however, making them effectively one sector. A custom-designed National Instruments LabVIEW program with a 16-bit data acquisition card were used to output the voltage signals, as well as record the IPMC tip displacement, via a laser displacement sensor (SUNX Microlaser Sensor LM10).

### 3.3 Model Validation

A key assumption in modeling the sectored IPMC is that the sectors are decoupled. To validate this assumption, the sectors of an IPMC were actuated individually with a step voltage. Then, the same step input was given to both sectors at the same time. Figure 5(a) compares the tip displacement of the IPMC in both cases. The results are in good agreement, providing confidence in the decoupled assumption.

To determine the various gain parameters for the previously described model, each sector of the IPMC was subjected to a step input of 1.5V, and the displacement was recorded. Using a least squares curve fit in MATLAB, the model was tuned to fit the data. The gain parameters had to be adjusted periodically as the response of the IPMC changed, but the values used for model validation are given in Table 1. The model was then implemented in Simulink to carry out all simulations. Figure 5(b) compares experimental sectored IPMC step responses and the corresponding simulations. Finally, the decoupled assumption was further verified by comparing the sum of the model responses to the experimental IPMC response when both sectors were actuated simultaneously. As shown in Fig. 5(c), the model represents the true response reasonably well.

![Figure 4](image-url) Experimental setup, including an IPMC with two effective sectors, where \( u_1 \) controls the inner sector (Sector 1) and \( u_2 \) controls the two outer sectors (Sector 2).

![Figure 5](image-url) Model validation: (a) individual and simultaneous sector actuation, (b) individual sector responses and corresponding simulation results, and (c) simultaneous sector actuation and sum of corresponding simulations.

<table>
<thead>
<tr>
<th>Sector</th>
<th>( K_{V1} )</th>
<th>( K_{V2} )</th>
<th>( \tau_1 )</th>
<th>( \tau_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.022</td>
<td>-0.529</td>
<td>62.046</td>
<td>1.274</td>
</tr>
<tr>
<td>2</td>
<td>6.165</td>
<td>-0.226</td>
<td>40.942</td>
<td>3.619</td>
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</table>

### 4 PRELIMINARY RESULTS

As a first step in employing the model and as a demonstration of feasibility, a ramp (non-periodic) input was tested on an IPMC like the one shown in Fig. 4. Using the linear RC model, a desired trajectory was made such that it matched the modeled step response of Sector 2 until the point of maximum displacement. From this point on, the maximum displacement value was held constant. To achieve this trajectory, Sector 2 was given a step input which, when modeled, gives a perfect response until back relaxation starts. At this point, the difference between the
Table 2. Gain parameters for triangular input test.

<table>
<thead>
<tr>
<th>Sector</th>
<th>$K_{V1}$</th>
<th>$K_{V2}$</th>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.256</td>
<td>-1.082</td>
<td>56.518</td>
<td>4.727</td>
</tr>
<tr>
<td>2</td>
<td>11.918</td>
<td>-0.406</td>
<td>64.406</td>
<td>4.155</td>
</tr>
</tbody>
</table>

desired trajectory and that of Sector 2 was taken and used as the desired response for Sector 1, as shown in Fig. 6(a). Feeding this through the inverse of the transfer function model for Sector 1 provided a constantly increasing voltage signal to compensate for the back relaxation of Sector 2 [see Fig. 6(b)]. The inversion was computed using the approach described in [23], and the gain values as shown in Table 1 were used again. As can be seen in Fig. 6(c), the response is greatly improved, even before Sector 1 is given a voltage exceeding the 1.5 V input given to Sector 2. In the range shown, the uncompensated displacement decays at an average rate of 15.0 $\mu$m/s after the maximum displacement is reached. On the same interval, the compensated response decays at an average 2.8 $\mu$m/s, an improvement of 81%. Furthermore, the maximum displacement error from the desired trajectory in the uncompensated case was 74%, compared to 26% in the compensated case, a 64% improvement.

Next, a continuously alternating input was explored. A triangle-like signal of constant amplitude was used to power Sector 1, while the responsibility of compensating was left to Sector 2. To determine the ideal frequency of the waveform, step responses measured just before this test were considered. Each sector reached maximum displacement in approximately 10 seconds, representing the fastest possible response time. It was decided that each movement should be allotted 10 seconds, meaning the period of the input wave should be 20 seconds, and the frequency should be 50 mHz. Passing the triangle-like wave through the model for Sector 1 provided the corresponding desired output for that sector. To determine the desired output for Sector 2, the output for Sector 1 was subtracted from the total desired trajectory. Finally, the output for Sector 2 was passed through the appropriate inverse model to produce the necessary input voltage. The desired trajectories and required input voltages are given in Fig. 7, and the gain parameters used for this test are given in Table 2.

The next step was to actuate a sectored IPMC, one sector at a time, using these inputs. As can be seen in Fig. 8, the individual response of each sector matched fairly well with the simulation. The inputs were then applied to both sectors simultaneously. The result is shown in Fig. 9(a), as well as the response to a 0.6 V step input, for comparison. Although the linear RC model was used in the construction of the inputs, both the linear and nonlinear simulation results are presented for reference. Though not perfectly smooth, the response is reasonably steady for the period shown. As shown in Fig. 9(b), the error is much improved in the compensated case, as compared to the uncompensated step response. For the reference step input, the displacement decays at an average rate of 8.2 $\mu$m/s after maximum displacement is reached, whereas the compensated displacement experiences a slight rise over the same interval (0.5 $\mu$m/s). Comparing absolute values of these rates indicates a 94% improvement when using the alternating inputs. Compared to the desired trajectory, the step response produced a maximum error of 52%, whereas the response to alternating inputs yielded a maximum of 19% error, an 64% improvement. All results are summarized in Table 3.

5 CONCLUSIONS AND FUTURE WORK

This paper explored controlled activation of patterned electrodes on IPMCs to mitigate back relaxation. Models were dis-
Table 3. Improvements over uncompensated response.

<table>
<thead>
<tr>
<th>Method</th>
<th>Decay (µm/s)</th>
<th>Improvement (%)</th>
<th>Max. Error (%)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncompensated</td>
<td>Compensated</td>
<td>Uncompensated</td>
<td>Compensated</td>
</tr>
<tr>
<td>Ramp input</td>
<td>15.0</td>
<td>2.8</td>
<td>81</td>
<td>74</td>
</tr>
<tr>
<td>Alternating</td>
<td>8.2</td>
<td>0.5</td>
<td>94</td>
<td>52</td>
</tr>
</tbody>
</table>

Figure 7. Triangle-like signal: (a) desired trajectories and (b) required input voltages.

Figure 8. Responses for (a) Sector 1 and (b) Sector 2.

Figure 9. Simultaneous sector actuation: (a) response and (b) error.

Preliminary experiments were conducted to demonstrate feasibility for the approach. Through a simple illustrative example, the back relaxation of an IPMC under step input was reduced by 94%, while the maximum error between the measured and desired responses was reduced by 64%. Future work will include further refinement of the input shaping process. The nonlinear model described [18] will be studied in greater depth and feasibility of using this model for input selection will be explored. The ultimate goal is the development of a feedforward/feedback controller to fight back relaxation in real time, with a minimal increase in input voltage.

6 Acknowledgements

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