Development of an ionic polymer–metal composite stepper motor using a novel actuator model

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A novel ionic polymer–metal composite (IPMC) actuated stepper motor was developed in order to demonstrate an innovative design process for complete IPMC systems. The motor was developed by utilizing a novel model for IPMC actuators integrated with the complete mechanical model of the motor. The dynamic, nonlinear IPMC model can accurately predict the displacement and force actuation in air for a large range of input voltages as well as accounting for interactions with mechanical systems and external loads. By integrating this geometrically scalable IPMC model with a mechanical model of the motor mechanism an appropriate size IPMC strip has been chosen to achieve the required motor specifications. The entire integrated system has been simulated and its performance verified. The system has been built and the experimental results validated to show that the motor works as simulated and can indeed achieve continuous 360° rotation, similar to conventional motors. This has proven that the model is an indispensable design tool for integrated IPMC actuators into real systems. This newly developed system has demonstrated the complete design process for smart material actuator systems, representing a large step forward and aiding in the progression of IPMCs towards wide acceptance as replacements for traditional actuators.

Keywords: ionic polymer–metal composite (IPMC); stepper motor; mechanical design; model application

1. Introduction

Ionic polymer–metal composites (IPMCs) are a type of electroactive polymer (EAP) that inherently couple the electrical and mechanical domains, and hence can be used as both sensors and actuators [1]. IPMC technology is rapidly evolving as a result of continually increasing research and industrial interest, mainly due to their significant potential in a wide range of applications, including robotics, biomimetics, medical devices as well as replacements for traditional actuators such as motors and linear actuators [2]. IPMC materials have a number of properties making them attractive when compared to traditional actuators, including very low mass and geometries that can be tailored to demand, low power consumption and biocompatibility [3]. However, there are still a number of key issues that need to be overcome before they are widely accepted as viable alternatives to traditional sensors and actuators [2].

Although there has been a large amount of research into the material behavior and actuation mechanisms of IPMCs, much work is still needed before they will be considered as viable alternatives for traditional actuators like motors, pneumatics and linear actuators. This
research demonstrates the ability of IPMCs to operate in real applications, outside of laboratory conditions. A traditional stepper motor has been developed that can operate in air and works by converting the bending actuation of IPMCs into a rotational motion of the motor. The motor is designed with the view to miniaturization and use in micro-robotics where the force output requirements are low, but other advantages of IPMCs are important, such as weight and power availability for remote and embedded systems.

In order to facilitate the successful implementation of this device, and others, an accurate IPMC model must be developed so engineers can simulate and evaluate the [integrated system performance in a real operating environment.

Despite the amount of research into the material behavior and actuation mechanisms of IPMCs, no complete and widely accepted model has been developed to predict the current drawn as well as the mechanical output; this is mainly due to the very unrepeatable nature of the composite material [4–6]. A model that takes into account the interaction of the IPMC with any type of external load or mechanism is needed in order to design a system that will successfully achieve a desired response. The design can then be fully simulated and evaluated before implementing it in real life. A model that can achieve this is described in Section 2 and has been used because of the power it has in simulating such IPMC-actuated systems. This model was originally proposed by McDaid et al. in [5] and expanded on in [6]. The model serves as an essential design tool in the development of complete mechanical systems with integrated IPMC actuators. Use of this model has allowed the authors to successfully design a stepper motor that can achieve 360° motion using two IPMCs. An extension of this design is also proposed, which includes four IPMCs to improve the performance of the device.

This paper describes the development of a completely novel and innovative design for a traditional device using non-traditional actuators. This is a completely new way of thinking and designing systems using smart materials. No such work has been carried out, to the author’s knowledge, which takes a novel scalable model of an IPMC actuator and goes through a complete design using the model to develop a fully integrated system. This will not only demonstrate the usefulness of the developed model in designing IPMC systems but also show the design for a completely new type of actuator, which converts a cantilever bending into continuous rotational motion, similar to a conventional motor. The developed motor presents an excellent application to prove the worth of such a design process and serves as a platform to build on current research in advancing IPMCs into real world applications.

2. Electromechanical IPMC model

An accurate model describing the behavior of IPMC actuators is an essential tool for engineers designing systems incorporating IPMCs, to allow simulation and evaluation of the performance in the real world. There have been a number of different IPMC models proposed in the literature, and based on their architectures they can generally be categorized into three types: white box (physical models), black box (empirical models) or gray box models. Gray box models are a middle ground, taking well known physical phenomena of the polymer and representing them as a simple lumped parameter model [7]. The model used in this research is of a gray box design to incorporate sufficient information about the physical polymer operating mechanisms to ensure accuracy over a number of different operating conditions and inputs, yet concurrently keeping the model complexity low to remain practical for engineering design. The model was originally proposed in [5] and is described here to give the reader insight on the development of the model and the physical
phenomena on which the model is based as well as why the model is so useful in the mechanical design of systems.

The IPMC is modeled in cantilever configuration in air, with one end clamped in copper electrodes (Figure 1). A list of the relevant geometric parameters is given in Table 1. In order for the model to be completely scalable for different sizes of IPMC, all parameters throughout the model must be expressed in terms of these geometric quantities. All other model parameters will be introduced and explained when they are defined in the text.

The actuation of the IPMC has been modeled in three stages, mimicking the real physical mechanisms that cause the actuation. A schematic overview of the newly proposed model is shown in Figure 2.

A lumped parameter nonlinear electric circuit is used to predict the current absorbed by the polymer and hence the ion flux through the polymer, which is the major mechanism for actuation. The IPMC model is split geometrically in two parts, as shown in Figure 3, to represent the section clamped by the electrode and the free ‘beam’ section. A large number of experiments have been undertaken and the results have been used to develop and validate this model. IPMC strips with dimensions ranging from 15 to 40 mm long, 10 and 5 mm wide and also 0.2 mm and 0.7 mm thick have been experimented within our lab and limited results will been presented in this paper.

Table 1. Geometric model parameters.

| Parameter | Definition |
|-----------|------------|
| $L_C$     | Length of IPMC clamped in electrodes |
| $L_B$     | Length of the free ‘beam’ section |
| $L_T$     | Total length of IPMC |
| $w$       | Width of IPMC |
| $t$       | Thickness of IPMC |
| $\theta_T$ | Tip angle |
| $\tau_T$  | Tip torque |

Figure 1. Schematic diagram of IPMC and model geometric parameters.

Figure 2. Schematic diagram of electromechanical IPMC model.
2.1. Nonlinear electric circuit

It has been widely reported that the main mechanism for mechanical actuation of an IPMC is due to ions and hence water molecule diffusion through the polymer. It is therefore extremely important to model the current flow in the IPMC. Also, due to their low power consumption IPMCs have major potential in remote and embedded applications so the ability to accurately predict current draw is necessary for engineers when designing for power source availability [4]. Due to the nature of the material, resistance, capacitance, etc., it makes sense to model the current draw using an equivalent electric circuit. The electrical response is characterized by a dynamic and steady state response. The steady state response is a nonlinear function of the input voltage. The dynamic response, can be accurately characterized by a number of resistor–capacitor (RC) networks, and even shown by Newbury in [8] that two RC branches are sufficient to model the dynamic response of the IPMC. It is evident that this capacitive dynamic response gives rise to the back relaxation phenomena as well as hysteresis in the polymer, so is sufficient in modeling these behaviors.

The proposed nonlinear electric circuit is shown in Figure 4. Researchers have proposed models using a similar approach previously [4,8,9], but this circuit presents a number of advances over these existing models. The model divides the IPMC into two different parts based on its physical configuration, the clamped section and the free beam section. Both of these parts of the IPMC will have a different dynamic response. The steady state absorbed current is modeled using a third-order polynomial dependant on the input voltage signal. A variable resistor, $R_{ss}$, is used to model this relationship. To account for the change in dynamic response of the IPMC at different input levels, the RC branches are also variable depending on the on the level of input signal. As a result of characterizing both the steady state and dynamic response of the IPMC as a function of input signal, the current can be accurately predicted in the nonlinear region of operation, i.e. at low frequencies, as well as accurately predicting the back relaxation and hysteresis inherent in the polymer.

![Figure 3. 3D representation of IPMC and model parameters.](image1)

![Figure 4. Nonlinear electric circuit diagram used to predict the current drawn by the IPMC and the ion flux associated with the mechanical actuation.](image2)
All of the model parameters are based on real physical phenomena in the material and as such are geometrically scalable. The model also gives some insight for users into the internal working mechanisms of the IPMC, yet it is not too complex for design and simulation. The RC branches 1 and 2 represent the dynamic response of the polymer through the clamped section, whereas branches 3 and 4 represent the dynamic response through the free section of the IPMC. The two shunt resistors, $R_e/2$, represent the electrode surface resistance and is the average of the ohmic resistance of the surface of the IPMC electrodes. $V_e$ represents the average voltage through the polymer thickness in the free beam section, i.e. after the half the ohmic loss along the electrodes. The electrode resistance $R_e$ has been measured experimentally using a four-point probe technique, and using the appropriate correction factor and IPMC dimensions, the $R_S$ (‘ohm/square’) or sheet resistance value can be calculated. $R_e$ can then be expressed in terms of the geometry of the IPMC only and hence can be scaled for different sized actuators using

$$R_e = R_S \frac{L_B}{w}.$$  \hspace{1cm} (1)

$R_s$ accounts for the nonlinear phenomena, which occurs in the IPMC at very low frequencies and steady state. $R_{ss}$ also incorporates the equivalent ‘through-resistance’ of the hydrated Nafion membrane. These two material properties cannot be directly experimentally measured so are consequently combined and an equivalent resistance, which is dependant on the input voltage, can be found empirically through the steady state relationship between absorbed current and input voltage. The steady state current, when all dynamic response has died out is approximated as a third-order polynomial, with reference to input voltage

$$I_{ss} = a V_{ss}^3,$$  \hspace{1cm} (2)

and hence the value of $R_{ss}$ can be calculated from

$$R_{ss} = \frac{V_e|_{ss}}{I_{ss}},$$  \hspace{1cm} (3)

where $V_e|_{ss}$ is the voltage across $R_{ss}$ at steady state. This resistance is converted to an equivalent resistivity, $\rho_{ss}$ in $\Omega \ m V^2$, which can be scaled and used with all IPMC dimensions, i.e.

$$R_{ss} = \rho_{ss} \frac{t}{L_T W} \cdot \frac{1}{V_{in}^2} - R_e.$$  \hspace{1cm} (4)

A plot of the real experimental and approximated steady state response for voltages from $-4 \ V$ to $+4 \ V$ is given in Figure 5 for a 30 mm long by 10 mm wide by 0.7 mm thick IPMC.

$R_1$, $R_2$, $R_3$ and $R_4$ represent the resistance against charges flowing through the IPMC that are involved in the dynamic response. They are expressed in terms of the IPMC geometry and an equivalent resistivity in order to enable them to be scaled for different sized actuators. The parts of IPMC in the clamped and free sections have the same material properties and therefore are represented with matching resistivities, $\rho_f$ and $\rho_s$, as in
where $\rho_f$ represents the resistance against fast flowing charges and $\rho_s$ represents the resistance against the slow flowing charges through the polymer material.

Similarly capacitors $C_1, C_2, C_3$ and $C_4$ govern the time constants for the charges flowing through the IPMC that are involved in the dynamic response. They are expressed in terms of the IPMC geometry and an equivalent permittivity in order to enable them to be scaled. The parts of IPMC in the clamped and free sections have the same material properties and therefore are represented with matching permittivities, $\varepsilon_f$ and $\varepsilon_s$, as in

$$C_1 = \varepsilon_f \frac{L_{CW}}{t},$$

$$C_2 = \varepsilon_s \frac{L_{CW}}{t},$$

$$C_3 = \varepsilon_f \frac{L_{BW}}{t},$$

$$C_4 = \varepsilon_s \frac{L_{BW}}{t},$$
where $\varepsilon_f$ controls the time constant for the fast flowing charges and $\varepsilon_s$ controls the time constant for the slow flowing charges through the polymer material.

Now all the parameters for the electric circuit have been defined, the circuit can be analyzed and the current absorbed by the IPMC predicted. Also the average current flow that is responsible for the mechanical response of the IPMC through both the clamped section $I_C$ and the beam section $I_B$ can be found. $I(x)$ is the current as a function of length along the polymer strip; this is then integrated to calculate the charge per unit length, $Q_x(s) = \frac{1}{s} I(x).

2.2. Electromechanical coupling transfer function

This model proposes that the net amount of charge or number of ions/water mass that is transferred at any point along the length of the beam is linearly related to a longitudinal induced stress of the IPMC beam at that point. This can be physically interpreted as the amount of mass of water that flows being directly proportional to the amount of swelling and stress in one side of the IPMC. A number of different forms for the linear electromechanical coupling transfer function, $C_{EM}(s)$, were considered and tested. Based on these tests and work in [4] by Bonomo et al., the best response was achieved with the form

$$C_{EM}(s) = K \frac{s + Z}{(s + P1)(s + P2)}.$$  \hfill (13)

The values $K$, $Z$, $P1$ and $P2$ are found empirically. The stress as a function of length along the IPMC can then be calculated using

$$\sigma_x(s) = C_{EM}(s) Q_x(s).$$  \hfill (14)

2.3. Mechanical beam model

The stress generated along the length of the IPMC, as a result of a voltage input, can be converted to a bending moment, or electrically induced moment (EIM) using the flexure formula, $\sigma = \frac{My}{I}$, where $y$ is the distance from the neutral axis ($x$) in the $y$-direction and $I$ is the moment of inertia about the neutral axis. It has been reported in literature that the electromechanical conversions occur at the interface between the electrode and the polymer membrane [8,10] as such $y$ is taken as $t/2$. Now the EIM can be calculated as a function of length in the S domain $EIM_x(s) = \frac{2\sigma_x(t)l}{t}$. The EIM and any other moment that is induced in the beam as a result of externally applied forces or loads, $X_M$, are plotted on opposite sides of a bending moment diagram, as shown in Figure 6, to calculate the resultant bending moment. In this way the proposed model can accommodate for any external force/moment or load that acts anywhere along the length of the IPMC, making the model extremely useful in mechanical design. This functionality will be utilized in the design of the stepper motor which follows.

Now using an adaptation of the standard beam equation, $EI \frac{d^2v}{dx^2} = M$, the mechanical output can be calculated, where $EI$ is the product of the modulus of elasticity and moment of inertia of the IPMC. In order to better model the mechanical response of the IPMC, the modulus of elasticity can be extended to model a viscoelastic material by approximating it
with the Golla–Hughes–McTavish (GHM) parameter model \cite{11}, as used in \cite{4,8}. This takes into consideration the resonance, which makes the model accurate as the IPMC approaches higher frequencies.

3. Model parameter identification and results

All the parameters were identified using a Nafion-based IPMC actuator 30 mm long, 10 mm wide and an average thickness of 0.7 mm. The clamped length was 5 mm. The electrical parameter $R_S$ was measured experimentally using a four-point probe technique and found to be 21.6 $\Omega$. Next the steady state current for different input voltages from $-4$ V to $+4$ V was measured and using a third-order polynomial fit, the $\rho_{ss}$ value was then found as 562.6 $\Omega$ m V$^2$.

To identify the parameters associated with the dynamic, electrical and mechanical response of the IPMC step voltages from $-4$ V to $+4$ V were applied for 100 seconds to ensure the IPMC reaches steady state, and the current and displacement were measured. A 0.1 $\Omega$ current sensing resistor was used to measure the absorbed current, and a Banner LG10A65PU laser sensor with a 3 $\mu$m resolution was used to measure the deflection of the IPMC with no external load applied. The electrical circuit model is simulated for 100 seconds (note the electrical and mechanical models can be analyzed independently) with the measured values of $R_e$ and $R_{es}$ and nominal values for the parameters associated with the dynamic response $\rho_f$, $\epsilon_f$, $\rho_s$ and $\epsilon_s$. These parameters are then optimized by minimizing the cost function

$$J = \sqrt{\frac{\sum_{i=1}^{n} (ExperimentalData - SimulatedData)^2}{\sum_{i=1}^{n} (ExperimentalData)^2}},$$

which is the error between the simulated absorbed current and the experimental absorbed current at each time step, $i$ to $n$. 

Figure 6. Bending moment diagram of IPMC. Model accounts for the EIM$_x$ as well as any external moment XM$_x$ as a result of external loads and forces.
Optimal parameter values are found for $-4$ V to 4 V in 1 V increments and there is a clear linear relationship between all the electrical parameters and the input voltage, demonstrating the dependence of the dynamic behavior of the circuit on the input voltage level. The optimized parameters are given below as a function of input voltage. An interesting observation is that the two parameters governing the fast response are fairly constant, whereas the parameters governing the slow response are quite reactive to voltage input level:

\[
\rho_f = -0.0606|V_{in}| + 1.7062, \quad (16)
\]

\[
\varepsilon_f = 0.0032|V_{in}| + 0.4428, \quad (17)
\]

\[
\rho_s = -6.2988|V_{in}| + 28.013, \quad (18)
\]

\[
\varepsilon_s = 0.7726|V_{in}| + 0.029. \quad (19)
\]

The modulus of elasticity of the composite material cannot be calculated accurately based on theoretical material properties, so it was measured experimentally. A SS-2 Precision Force Sensor (range $\pm 30$ gf) was used to measure blocked force at varying displacements, with $V_{in} = 0$, to measure a passive stiffness, then this was scaled to give a modulus of elasticity of 0.06324 GPa. The moment of inertia was calculated using the IPMC geometry as $0.2858 \times 10^{-12}$ m$^4$. Once the mechanical circuit was developed, the EIM, was then calculated. Using the formula from Equations (13) and (14), the electromechanical coupling transfer function $C_{EM}(s)$ can be optimized. The $C_{EM}(s)$ parameter values that minimize the cost function $J$ in Equation (15) are $K = 2.633 \times 10^5$, $Z = 0.01169$, $P_1 = 20.241$ and $P_2 = 0.06548$.

The nonlinear model is now complete with all parameters calculated and presented in terms of actuator geometry so the model is completely scalable and can be used for mechanical design and optimization.

The proposed model with the parameters identified above was simulated for 100 seconds and both absorbed current and free deflection compared with actual measured values to evaluate their correlation. Figure 7a shows the predicted current draw and the actual measured current draw for the $30 \times 10 \times 0.7$ mm IPMC. Figure 7b shows the corresponding predicted and actual displacement when no external load is applied.

From the plots above it is clear that the proposed model can predict both the absorbed current of the IPMC and the deflection with no externally applied load with reasonable accuracy. It can be seen that the tip displacement for a 4 V signal has a larger error than the all the other predicted results. This is put down to the fact that the IPMC is at the uppermost end of its operating range at 4 V and as such the displacement is non-uniform and quite unpredictable. Error may also be introduced at larger displacements due to the laser sensor measuring a linear displacement as opposed to an angular displacement. Despite this, displacements at all other lower voltage levels can be extremely accurately predicted. An example, for free deflection, is given in the surface plot below (Figure 8) which demonstrates the ability of the model to simulate the mechanical action at all positions along the beam as a function of time.

It can be seen that the model captures both the nonlinear steady state characteristics, after the system has been left for a long time to settle, as well as the fast dynamic response of the IPMC at a large range of voltage inputs (up to 4 V). The model correctly predicts the back relaxation phenomena and can therefore also model the hysteresis in the material. With the addition of GHM parameters in the mechanical model, the simulation will remain accurate from the lower frequencies up to and above the resonance of the actuator.
4. Stepper motor design

A traditional stepper motor is a brushless, synchronous electric motor which divides a full rotation of the motor into a number of ‘steps’. A stepper motor configuration (Figure 9) was chosen for achieving rotary motion using IPMCs for a number of reasons, including simple design and working mechanism to convert IPMC bending to rotary motion, very low contact area between IPMC and device resulting in low friction and also the ability to use open loop
control architecture. The IPMC stepper motor works by sending a voltage sequence to the IPMC actuators which will cause them to bend into contact with the pins attached to the motor shaft; this applies a force to the motor which will then result in controlled rotary motion. The motion, similar to a traditional stepper motor, will be in steps. Advantages of the IPMC stepper motor include low cost, lightweight design, low power and open loop control.

The pins are placed on a top and bottom layer, each corresponding to one IPMC. The pins on each layer have a 90° separation from each other and the top pins are 45° out of phase from the bottom pins. The stand is adjustable for accommodating different size IPMC strips as required. A saturated input voltage of ±3 V is used to actuate the motor. Table 2 below outlines the operation of the motor for a two step sequence, each step corresponds to 45°.
can be seen that there is a pause in the operation of the motor between steps. This is necessary in the design with two IPMCs to avoid the motor pins clashing with the IPMC that is returning to its home position.

The stepper motor has been designed using CAD tools and mathematical analysis, utilizing the developed IPMC actuator model. The motor friction is added to the system model, using a standard Coulomb and viscous friction model, to make a realistic simulation and see if the IPMC can actually move the motor shaft. The motor friction force was found experimentally to be 0.27 gf for static and 0.21 gf for dynamic motion. Using these forces the friction coefficients were calculated and input to the friction model which is integrated with the IPMC and mechanical models to create an entire system model which can accurately represent the real life situation. Different lengths of IPMC were simulated and the length of 35 mm long (clamped length 5mm) and 10 mm wide was found to give the desired performance, both force and deflection, that was required to actuate the motor. Designing the system in simulation first has allowed the system to be extensively tested and the performance verified before the prototype was built. This demonstrates the usefulness of the developed model for designing IPMC actuated mechanisms. The simulated performance of the system is shown in Figure 10.

The actual rapid prototyped stepper motor is shown Figure 11; this was used to test the actual performance.

Now the system was built and constructed, experiments were undertaken to verify all the simulations. Figure 12 below shows the actual measured tip displacements of the IPMCs when they are being actuated in order to move the motor. They were measured using 2 Banner LG10A65PU laser sensors with a 3 μm resolution. It can be seen that there is a reasonable correspondence between the simulated motor and the actual experimental results. It can be seen that at the beginning the IPMC has a larger displacement and it starts to degrade in performance. This is mainly due to the fact that the motor is operating in air for a period of time and the IPMCs exhibit highly time-varying behavior in this type of environment. Despite this it can be seen that the motor does act as the simulation predicts and rotary

| Time step | $V_{\text{IPMC1}}$ | $V_{\text{IPMC2}}$ | IPMC 1 | IPMC 2 | Shaft |
|-----------|-------------------|-------------------|--------|--------|-------|
| $t_0-t_1$ | +3                | +3                | Bends in positive direction until at home position | Bends in positive direction until at home position | No rotation |
| $t_1-t_2$ | -3                | +3                | Bends in negative direction and applies force on pin along its path until it loses contact with the pin | Stays at the home position | Rotates clockwise direction as IPMC 1 pushes the pin |
| $t_2-t_3$ | +3                | +3                | Bends back until it reaches the home position | Stays at the home position | Wheel does not rotate during this time period |
| $t_3-t_4$ | +3                | -3                | Stays at the home position | Bends in negative direction and applies force on pin along its path until it loses contact with the pin | Rotates clockwise direction as IPMC 2 pushes the pin |
| $t_4-t_5$ | +3                | +3                | Stays at the home position | Bends back until it reaches the home position | Wheel does not rotate during this time period |
motion is achieved. The camera shots in Figure 13 show the motor in operation, and again it can be seen that the system does operate as predicted.

4.1. Extension to four IPMCs

It has been demonstrated that the stepper motor works as simulated and therefore it is valid to believe that this model and simulation technique can be extended to other devices. The next step to improving the performance of the stepper motor is to remove the pause in the

Figure 10. Simulated input voltage and displacement for (a) IPMC 1 and (b) IPMC 2. (c) Resulting motor shaft displacement.
Figure 11. Rapid prototyped stepper motor.

Figure 12. Laser displacement of the IPMCs driving the stepper motor.
operation to achieve continuous rotation as with traditional rotary motors. A new design incorporating four IPMCs and using the same principle as the previous design has been proposed. The IPMCs work in two pairs, with each pair acting similarly to the two IPMCs in the previous design. In simulation it is shown that the two pairs must be $90^\circ$ or more out of phase from each other to avoid the IPMC clashing when returning to the home position. The phase also has to be a multiple of $45^\circ$ to remove the pause and achieve constant motion. It has therefore been designed that the IPMC pairs are $135^\circ$ out of phase and the simulations prove that this will remove the pause in the system. The design is shown in Figure 14.

The design has been simulated using the developed IPMC model, using the same technique as the two IPMC design. The simulation results are shown in Figure 15. It can be seen that indeed the new design can achieve continuous motion.

The time step can be altered to speed up the motor, but there is a limit to the step time as the IPMCs still need to have enough time to reach their home positions. A smaller voltage could also be applied, but this would decrease the available torque output of the motor and may decrease the speed of the motor as well. Variations on the design can easily be simulated using the model to verify the design before going on to build the system.

![Figure 13. Camera shots of motor in operation (a) at initial position, (b) after step 1, (c) after step 3, (d) after step 5, (e) after step 7 and (f) after $315^\circ$ rotation completed (note the black dot).](image)

![Figure 14. Motor shaft and IPMC setup for four IPMC stepper motor.](image)
5. Conclusions

A new type of motor which uses IPMC actuators has been developed and implemented. The design and simulation of the system using the novel IPMC model has demonstrated the usefulness of modeling IPMC actuation in designing systems which implement IPMC actuators. This proves that the IPMC model does indeed work with externally applied loads and can therefore be used to design any number of IPMC systems. The model accounts for all types of external loads and is scalable for different sized IPMCs and hence is extremely useful for designing mechanical systems. The model also accurately predicts the absorbed current, which can be used for calculating power consumption, particularly important when designing for remote and embedded applications.

The stepper motor has been designed and implemented with two IPMCs and can achieve full 360° rotation, but has some pause time in between steps. An improved design has been proposed and validated in simulation which also can achieve full rotation and removes the pause time, resulting in continuous rotation similar to a traditional stepper motor. Overall the model has been shown to work for this design of a stepper motor, but more importantly than this particular design is the demonstration of the application of this model to a real world situation.

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