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Precision Position Control of Ionic Polymer Metal Composite

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***Abstract*—The ionic polymer metal composite (IPMC) is a novel smart polymer material. It shows significant potential in the application for low-mass high-displacement actuators. The IPMC behavior in open loop is not repeatable and also it is difficult to maintain its tip displacement constant at a specified position in open loop. Hence closed-loop control of IPMC is important. In this paper model-based precision position control of an IPMC strip in a cantilever configuration is demonstrated. After implementing the closed-loop position control the overshoot decreased to 20% from 205.34 % in open loop, and the settling time reduced to 1 s from 27 s in open loop. Precision micro-scale position-control capability of the IPMC was also demonstrated. A 20-μm position resolution was achieved with a position noise of 7.6-μm rms.**

I. INTRODUCTION

Ionic polymer metal composites (IPMCs) are novel polymer materials belonging to the class of electroactive polymers (EAPs). Fig. 1 shows the chemical structure of Nafion based IPMC [1]. Sadeghipour, et al., Shahinpoor, and Oguro, et al. first characterized the bending property of the IPMC in 1992 [2–4]. The bending response of IPMC is due to the internal stress generated by migration of mobile cations and water molecules after the application of voltage across the thickness of polymer [5].

$$(\text{-}CF_2\text{-}CF_2)\ n\text{-}\ (CF\text{-}CF_2)\ m\text{-}$$
$$O\text{-}CF(CF_3)\text{-}CF_2\text{-}O\text{-}CF_2\text{-}SO_3^- \ldots M^+$$

Fig. 1. Chemical structure of IPMC

IPMCs have many advantages. They (1) require low drive voltage (less than 3 V); (2) produce high displacement; (3) can operate very well in wet environment; and (4) can be cut into small strips and lack moving parts. Therefore, IPMCs show significant potential in low-mass high-displacement actuation and other applications. Bar-Cohen, et al. have developed an EAP dust wiper for space rover applications [6]. Shahinpoor has suggested applications in artificial muscles [7]. Sadeghipour, et al. have developed smart dampers [1], Tadokoro, et al. have developed a distributed actuation device [8].

Consider an application like a robotic manipulator, which has to move from one specified position to another, and has to maintain the position constant. In open-loop operation, on the application of a dc voltage, it is difficult for the IPMC to maintain its position at a constant value. This is because the open-loop response of IPMC is characterized by fast bending towards the anode followed by slow movement towards the cathode and finally bending towards the initial position. In addition, the open-loop overshoot can be very large on the order of 100 to 200% for a typical IPMC strip while its open-loop settling time can be on the order of 10 to 30 seconds. Hence closed-loop precision position control becomes of critical importance in such applications to ensure proper functioning, repeatability, and reliability.

Previous research on the control of IPMC actuators focused on position control using linear quadratic regulator (LQR), proportional integral and derivative (PID) and impedance control scheme [9–11].

In this paper precision micro-scale position control is demonstrated for the IPMC by applying a position control scheme based on the lead-lag methodology. Different performance characteristics like dynamic position range, actuator speed, and ability to track different commanded position reference signals is also presented.

This paper is organized as follows. In Section II, the experimental setup developed is presented. In Section III, the empirical position model is presented while Section IV presents the precision position controller development. In Section V, different experimental results obtained after implementing the closed-loop position control on the IPMC strip are presented.

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II. Experimental Setup and Open-Loop Behavior of IPMC

An IPMC strip with dimensions of 23 mm × 3.96 mm × 0.16 mm was used in this research. Fig. 2 shows the experimental setup being used for the modeling and precision position control. It consists of a modified clamp with copper electrodes and laser distance sensor (Model OADM 20144/404790) from Baumer Electric to sense the tip position. The laser distance sensor has a resolution of 5 µm and its operation range was 10 mm with a standoff of 15mm. The response time is less than 10 ms. This sensor works on the principle of optical triangulation. The sensor can detect position up to a bending angle of 30° [12]. The tip displacement indicates the deflection of the free end of the IPMC strip. The output of the laser distance sensor was fed to a 16-bit analog-to-digital (A/D) converter of a DSP (digital signal processor) Controller Board (Model DS1102 from dSPACE Inc). The controller board has a Texas Instruments' TMS320C31 floating-point DSP.

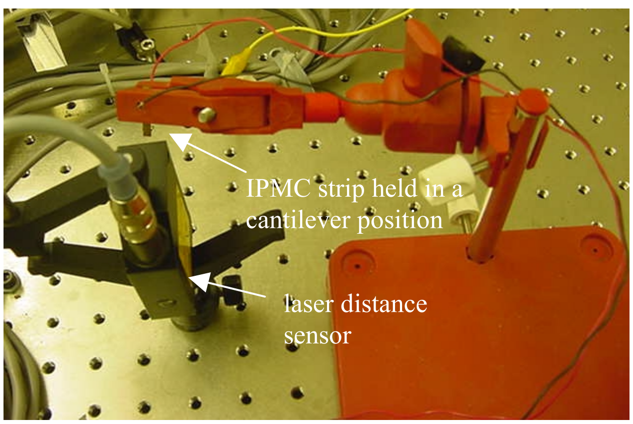


Fig. 2. Picture showing the experimental setup.

The IPMC strip, upon application of a step voltage, first bends towards the anode, and then towards the cathode. This is because on the application of voltage, mobile cations (lithium in the case of our sample) migrate towards the cathode, and water molecules migrate towards the cathode, causing a net reaction force towards the anode [5]. After that, it reaches its steady-state value. During the position control experiments the IPMC strip was so held that the laser beam from the laser distance sensor was incident on the free end. Figure 3 shows the open-loop position response of the IPMC strip to a 1.2 V step input. Open-loop step response showed a percent overshoot of nearly 205.34% and settling time of 27 s.

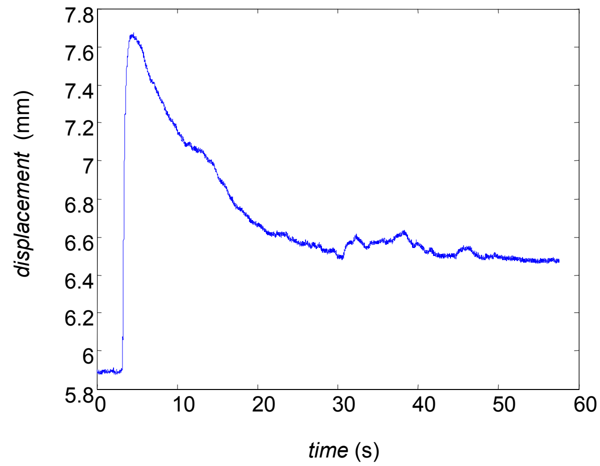


Fig. 3. Open-loop position response of the IPMC strip to a 1.2-V step input.

III. Modeling

A model-based control system was designed for the IPMC actuator. A similar methodology as done by Kanno, et al [13] was followed to derive a model between the step input and the position output of the IPMC strip. A 1.2-V step input was given continuously to the IPMC strip for a period of about 55 s at a sampling rate of 250 Hz, and an open-loop step response of IPMC was obtained (Fig. 3). For the model development a Matlab toolbox for non-linear curve fitting was used [14]. It solves non-linear curve-fitting problems in least-squares sense. The step response showed an exponential decay after its peak value, so various exponential decay terms were used to fit the data. The step response data was fitted to be

$$y(t) = y_1 e^{-at} + y_2 e^{-bt} - y_3\left(e^{-ct} - e^{-dt}\right) + C, \quad (1)$$

where C is the steady-state value which was observed to be around 0.58 mm. With the least-square curve fitting methodology the values of y_1, y_2, y_3, a, b, c, and d were obtained to be

$y_1 = -1.9313$
$y_2 = 1.4155$
$y_3 = -0.0507\,i$
$a = 1.4155$
$b = 0.1083$
$c = 5.0364 - 14.3825\,i$
$d = 5.0166 + 14.3416\,i$.

Actually c and d should be a complex conjugate pair, but there was a small difference in the values obtained due to the rounding-off error in Matlab. Taking the Laplace transformation of the output and input equations we get

$$Y(s) = \frac{y_1}{s+a} + \frac{y_2}{s+b} - y_3\left(\frac{1}{s+c} - \frac{1}{s+d}\right) + \frac{C}{s} \quad (2)$$

$$U(s) = \frac{\text{step voltage}}{s}, \tag{3}$$

where the 'step voltage' is the 1.2-V step input. After substituting the values of y_1, y_2, y_3, a, b, c, and d obtained previously and taking the ratio of $Y(s)$ and $U(s)$, the transfer function from the input voltage and the output tip displacement of the IPMC was found to be

$$\frac{Y(s)}{U(s)} = \frac{0.06464\,s^4 + 5.647\,s^3 + 75.02\,s^2 + 1496s + 48.1}{1.2\,s^4 + 16.16\,s^3 + 319.5\,s^2 + 953.7s + 99.53}. \tag{4}$$

Fig. 4 shows the modeled and actual step response. From the figure it is observed that the modeled response matches the actual response well.

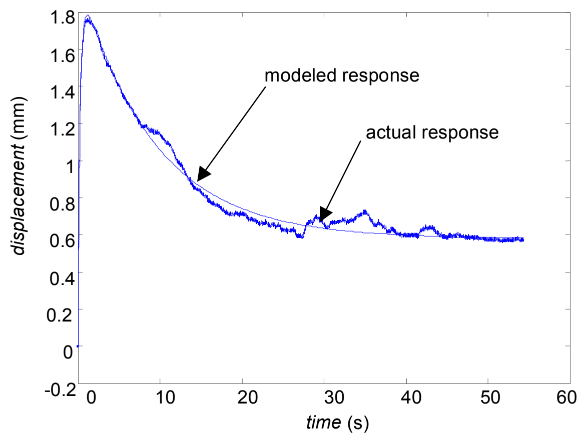


Fig. 4. Modeled versus actual position responses of the IPMC strip to a 1.2-V step input.

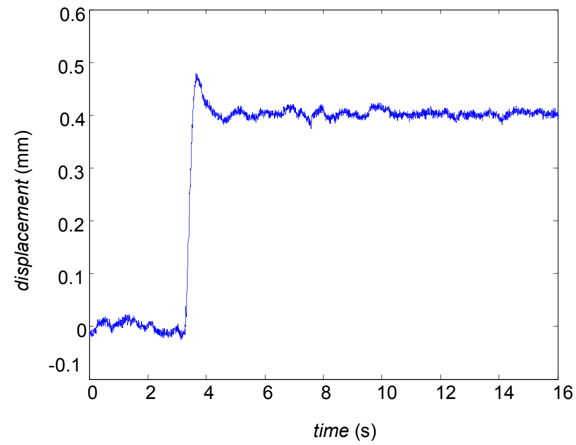
IV. Control System Design

The control objectives were to reduce the percent overshoot, to track the commanded input position and to decrease the settling time and the steady state error. The voltage applied to the IPMC strip was limited to ±2 V, which restricted the voltage swing of the controller. It is generally recommended to apply voltages no greater than 3 V to prevent damage of the IPMC strip.

A lag compensator was designed to meet the control objectives. Matlab tool 'rltool' was extensively used to design the compensator. The compensator, which was designed and implemented at a sampling frequency of 250 Hz, is given below

$$G_C(z) = 0.024 \times \frac{(z+0.904)}{(z-1)}. \tag{5}$$

To decrease the steady state error a free pole was placed at the origin. This control system has a phase margin of 34.5° at a crossover frequency of 0.84 Hz. Fig. 5(a) shows the closed-loop response to a 0.4-mm step input. The overshoot decreased to 20% while the settling time reduced to 1 s. Fig. 5 (b) shows the control voltage generated by the controller.



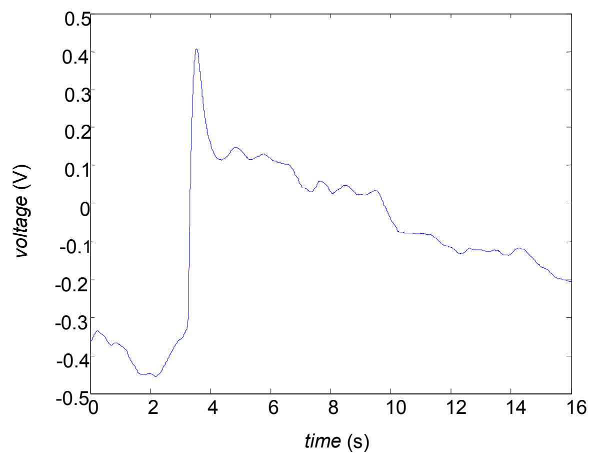


Fig. 5. (a) Closed-loop response of the IPMC strip to a 0.4-mm step input after implementing the digital lag compensator. (b) Control voltage profile generated by the lag compensator to achieve this closed-loop position response.

V. Experimental Results

To use IPMC in next-generation, micro- or nano-manipulation devices, micro-scale control of tip displacement of the IPMC becomes of primary importance. Fig. 6 shows the 20-µm step response of the IPMC strip under closed-loop position control. 20 µm was the finest tip displacement achieved with a position noise of 30 µm peak to peak or 7.6 µm rms.

The maximum controlled tip displacement, which was achieved by using the IPMC strips under closed-loop control, is also important in deciding the dynamic range of IPMC. The dynamic position range for the IPMC strip was determined as 20 µm to 4 mm. Fig. 7 shows the 4-mm position response of the IPMC strip under closed-loop control.

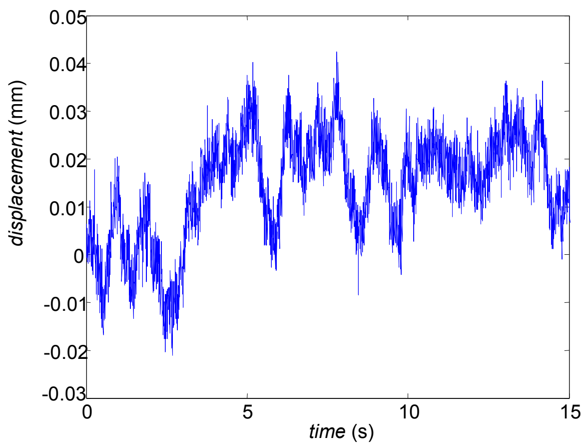


Fig. 6. 20-μm step response of the IPMC strip under closed-loop control.

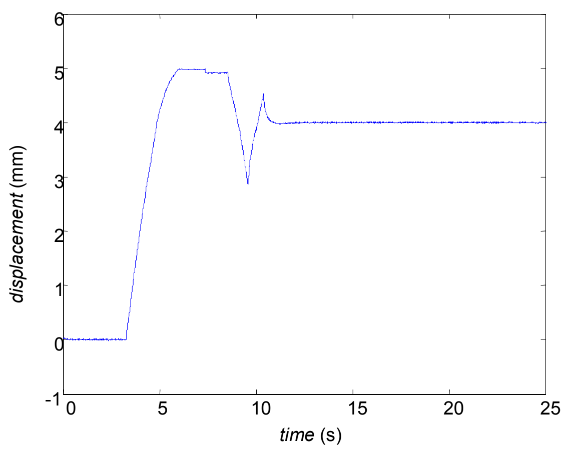


Fig. 7. 4-mm step response of IPMC strip under closed-loop position control.

The presence of the plateau in Fig. 7 at around 5-mm from about 5.95 s to 8.53 s can be attributed to the IPMC strip going out of range of the laser distance sensor. The initial sensor reading was set to 5 mm, while the range of the sensor was 0-10 mm. Hence, when the IPMC strip moved 5 mm, it went out of range of the sensor. The control voltage was saturated to 2 V and no control action occurred during that period. Due to the lack of control action the IPMC strip started coming back to its initial position. Error was accumulated for the period it was out of sensor range, and integrator windup occurred leading to the sudden drop in position to about 2.86-mm at around 9.58 s and then the rise in position to 4.53-mm at around 10.4 s before reaching the 4 mm position.

To demonstrate the capability of the IPMC strip to follow position trajectories under closed-loop control, many responses were taken to various commanded trajectories. Fig. 8 (a) shows the actual and commanded closed-loop response of the IPMC strip to a sine wave of 0.5-mm amplitude and 0.25-Hz frequency. The driving frequency is less than the crossover frequency (0.84 Hz) while Fig. 8 (b) shows the actual and commanded response of the IPMC strip to a trapezoidal profile. The IPMC strip followed the commanded signals quite well as long as the driving frequency was less than the crossover frequency.

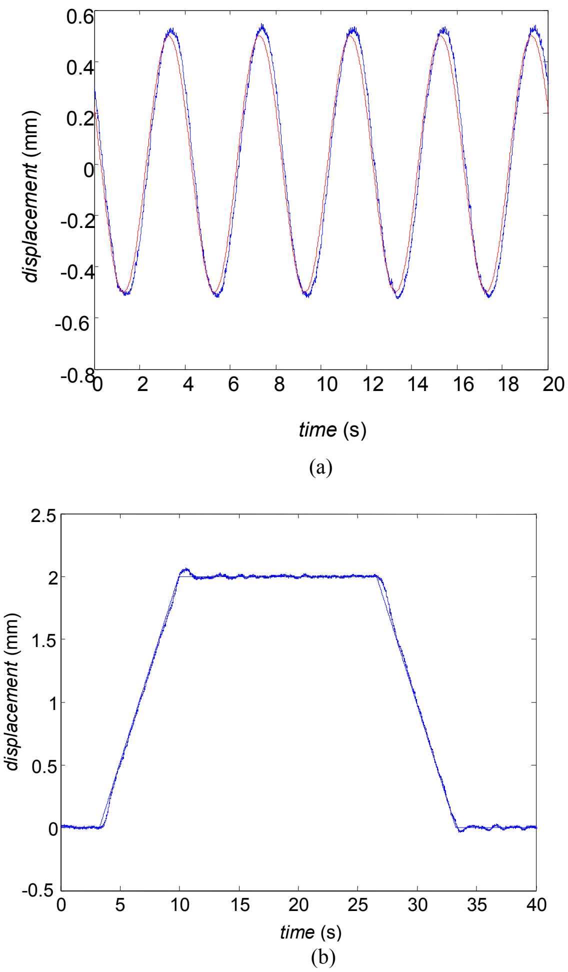
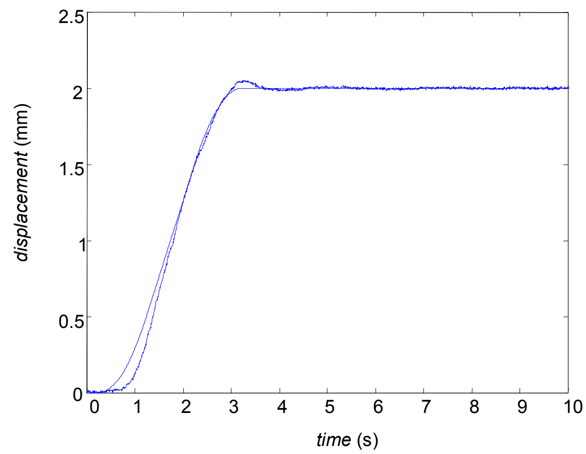


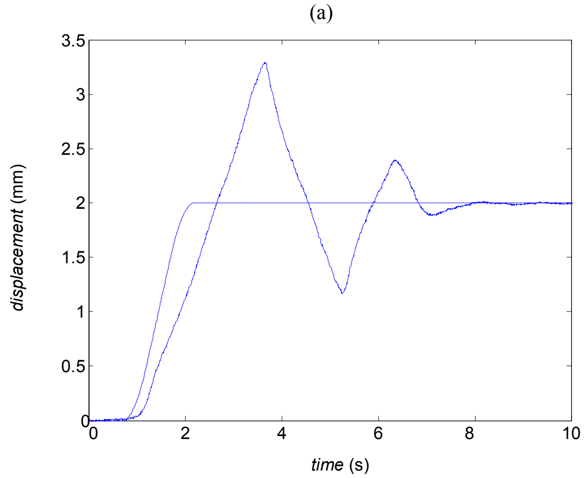
Fig. 8. (a) Closed-loop response of the IPMC strip to a sine wave of 0.5-mm amplitude and 0.25-Hz frequency. (b) Actual and commanded responses of the IPMC strip to a trapezoidal motion profile.

To check the maximum speed the IPMC can generate under closed-loop control, trapezoidal velocity profiles were generated using a combination of ramp inputs in Simulink. As the laser distance sensor could only measure the position and not the velocity, the velocity profile generated was passed through an integrator block in Simulink, and the closed-loop response of the IPMC tip displacement was compared to the commanded position profile. Fig. 9 (a) compares the actual position curve with the commanded one, for a maximum speed of 1 mm/s. The IPMC strip followed the commanded profile very well. Similar responses were obtained for other commanded speeds. Fig. 9 (b) shows the commanded profile and actual response generated to meet the maximum speed of 2 mm/s.

The IPMC strip could not achieve the 2 mm/s commanded speed. But the slope of the curve indicates the reaching of a speed of about 1.5 mm/s. The integrator windup effect similar to one in Fig. 7 is also observed in Fig. 9 (b). We have been developing an integrator antiwindup scheme to reduce this integrator windup phenomenon. Thus, presently the IPMC strip is capable of generating the maximum speed of 1 mm/s under closed-loop position control.



(a)



(b)

Fig. 9. (a) Actual and commanded position response obtained from a trapezoidal velocity profile of the maximum speed of 1-mm/s. (b) Actual and commanded position response obtained from a trapezoidal velocity profile of maximum speed of 2 mm/s.

VI. Conclusions

The IPMC is a new generation of smart materials with significant potential in the development of microdevices such as micromanipulators and microgrippers. IPMCs have several advantages. They require low drive voltage (less than 3 V) and can produce high displacement. Researchers have demonstrated different applications of IPMCs in artificial muscles, distributed actuation devices and also robotics.

The open-loop tip displacement of IPMC strip in cantilevered configuration to a 1.2-V step input showed the overshoot of 205.34% while the settling time was about 27 s. A lag compensator was developed based on the model we developed. The control objectives in this case were to decrease the settling time, the percent overshoot, and the steady state error. The phase margin with this controller was 34.5° and the crossover frequency was at 0.84 Hz. With this controller the settling time reduced to 1 s and the percent overshoot decreased to 20%.

Micro-scale precision position control was also demonstrated in this paper. The position resolution under closed-loop control was 20 µm. Reference motion tracking was demonstrated by the tracking of a trapezoidal and sinusoidal-wave profiles under closed-loop position control. The maximum speed, of this IPMC actuator under closed-loop position control was found out to be 1 mm/s.

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