Validating Usability of Ionomeric Polymer-Metal Composite Actuators for Real World Applications

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Abstract **– Ionomeric polymer-metal composites (IPMC) are electroactive polymer (EAP) materials that bend when electrically stimulated. As IPMC is a relatively new material, proper control methods have not yet evolved.**

In this paper the usability of IMPC actuators in real world applications is examined from the point of view of precision control. We propose a classical inverted pendulum control problem as a testbed. We suggest that if the pendulum can be balanced, then we have proven the usability of IPMC actuators for precise control tasks. In this paper we describe an inverted pendulum system driven by an IPMC actuator with PC-based control and a camera in the feedback loop. We report the preliminary experimental results in controlling the pendulum and discuss further improvements.

To our knowledge this is the first attempt to control a system or manipulate an object with IMPC actuators in a feedback loop.

Index Terms – electroactive polymers, soft actuators, IPMC, inverted pendulum control

I. Introduction

Ionomeric polymer-metal composites (IPMC), also known as ionic conducting polymer gel films (ICPF), are a type of electroactive polymer (see [1] for an overview). These materials react to an electric field or current. An IPMC is typically a thin elastic strip. Both sides of the strip are covered with metal which serve as a contact. When electric voltage is applied, the strip bends toward the anode(+).

IPMC is characterized by relatively large displacements but slow reaction. Its properties are rather similar to biological muscles which make them an attractive technology for building biologically inspired robots [2]. However, there are also dissimilarities between IPMCs and biological muscles. IPMC bends while biological muscles contract. Biological muscles consist of a large number of muscle fibres, while an IPMC actuator is one piece of material and there is no easy way to bundle IPMC strips compactly. IPMC actuators can apply force in one direction for a short time only and therefore they are best suited for reciprocating motion. In order to utilize IPMC actuators one has to find a way to benefit from their unique shape and behaviour. There are also many other issues concerning the use of IMPC actuators in real world applications. For example, IPMC actuators need a specific fluid environment (deionized water for instance).

IPMC actuators have a low metal concentration, and their operation is noiseless. This makes them hard to detect and therefore ideal for scout robots. Because of their small size and poor scalability, IPMC actuators have so far been used in small devices such as an active catheter system [3], a distributed actuation device [4], micromanipulators [5], a miniature robotic arm [6], a micropump [7], a facetype actuator [8], a wiper for an asteroid rover [9] and a ray-like underwater robot [10].

In this paper the usability of IMPC actuators in real world applications is examined from the point of view of precision control. Many applications, such as robotic arms, require great precision from actuators. Precision control of IPMC actuators is problematic and no fundamental solution has yet been found. The actuation principle of IPMC is very complicated. Proposed non-empirical models [11, 12, 13] tend to be complex, inaccurate and computationally expensive. But even in the case of a perfect model, it would be difficult to identify the parameters of an IPMC strip. The parameters of different strips (even if produced by the same manufacture and even if cut from the same IPMC sheet) vary greatly and also change over time.

Several attempts to control a strip have been described [14, 15, 16, 17]. These attempts make use of simple empirical models of the actuator and use feedback to correct model error. A uniform framework for controlling EAP materials has been proposed by Otake et al. [18], [19]. N. Bhat and W.-J. Kim [17] controlled a strip of IPMC in a cantilever configuration and achieved high precision in controlling its tip force and position. However, they only controlled the position with no load and force was controlled only in certain position with the tip fixed against a load cell. They also assumed that both position and force can be measured directly and accurately. In real life applications these constraints are not necessarily satisfied.

This paper proposes an inverted pendulum system as a testbed for validating the usability of IPMC in real world applications. The inverted pendulum control task is a classical benchmark for controllers and actuators and therefore makes it possible to compare the performance of IMPC actuators with each other and also with other types of actuators. It is also the kind of a task that could presumably be solved using IPMC actuators. In our case the inverted pendulum is attached to a moving cart by a joint. The task would be to prevent the pendulum from falling over. The authors maintain that if the pendulum can be balanced, then the usability of IPMC actuators for precision control tasks is proven. We propose an experimental system and describe a preliminary approach to controlling the pendulum. The experimental results prove that the inverted pendulum task is a plausible testbed for validating the usability of IPMC actuators. Currently we are able to control the pendulum for a short amount of time but the results can be improved using equipment with a faster sampling rate.

This paper is organized as follows. In Section II ionic polymer metal composites are described in more detail. The primary phenomenon behind bending is discussed and the behaviour in response to electric current is described. Section III discusses the inverted pendulum control task, adapted to IPMC actuators. In Section IV our setup is presented. Section V describes the controller used for pendulum control and experimental results are presented in the section that follows. Conclusions are drawn in Section VII and improvements to the controller are suggested in Section VIII.

II. Ionic Polymer Metal Composites

IPMC is a three-layered sheet with a 0.2 mm thick polymer membrane in the middle and 5-10μm thick metal layers on both sides. Therefore this material is called a polymer metal composite. The polymer membrane is filled with liquid and contains free cations or anions. Therefore the polymer is called ionic. In our experiments we use platinum coated Musclesheet™ produced by Biomimetics Inc. with Na+ ions for cations. There are also other types of polymers, metals and ions, that could be used [1]. An IPMC reacts to electric simulation.

A strip of IPMC, when stimulated with low (1-5V) voltage, undergoes three phases (Fig. 1.):

1. The strip bends quickly towards the anode(+), then slows down until finally stopping.
2. The strip starts slowly bending back towards the cathode(−) passing the initial position.
3. The strip relaxes slowly to nearly the initial position.

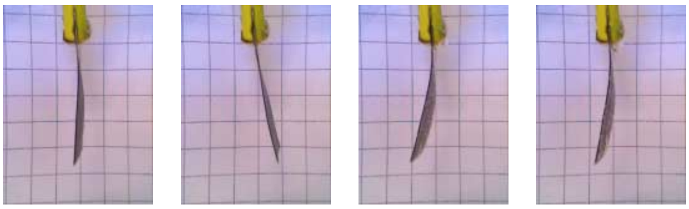

Fig. 1. The behaviour of IMPC strip stimulated with 2V.

The bending mechanism itself is very complex. Physical phenomenon such as the motion of ions in the polymer, applied electrostatic force, the gradient of the concentration of the ions, etc. have been considered to be some of the factors causing the bending of the actuator [1].

The main phenomenon causing the bending movement of IPMC in the first phase is the changes in the concentration of water molecules across the thickness of the polymer layer. In the initial state, water molecules are equally distributed in the material (Fig. 2.). When electric potential is applied, the cations(+) move towards the catode(−) together with the water molecules attached to them. This causes expansion of the material along one side and contraction along the other side. As a result, the strip bends (Fig. 3.). The bent state is an imbalanced situation because the water diffuses back (Fig. 4.).

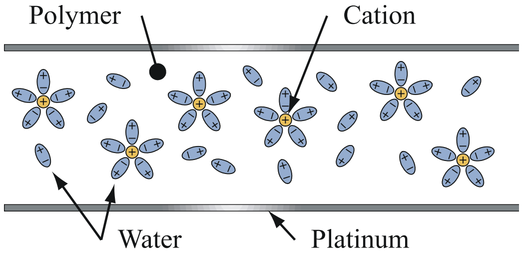

Fig. 2. IPMC in an initial state.

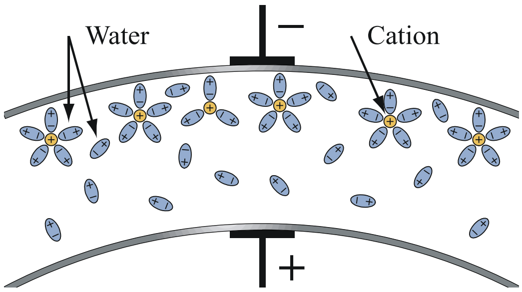

Fig. 3. IPMC in a bent state.

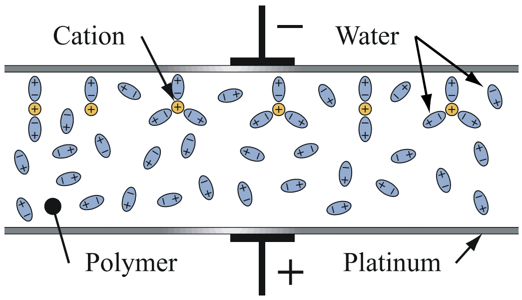

Fig. 4. IPMC in a relaxing state.

Although IPMCs can also be used as sensors [20] this paper focuses on the use of an IPMC as an actuator. As described above, the behavior of IPMC in an electric field is complex and not thoroughly understood. Some facts and observations that must be considered when controlling the IPMC actuator are listed below:

- There is no functional relationship between the applied voltage and output force. The force depends on the previously applied voltages.
- The actuator can apply force in one direction for only a short time (a few seconds).
- Under constant voltage, force increases at first but after a while starts to decrease exponentially.
- The voltage would have to be increased continually to keep the force constant.
- When the voltage is decreased, the direction of the output force is reversed.

Other factors that must be considered when using IPMC strip as an actuator are the following:

- An IPMC actuator works only if it is humid. A dried actuator has to be specially processed in order to make it work again.
- While working in air, the hydration level of the material can change and this in turn causes changes in its behaviour [14]. A solution to the problem was introduced in [21] - water was encapsulated within the membrane by a covering material. However the covering material will increase the stiffness and thereby lower efficiency.
- Applying more than 1.23V to the strip causes water electrolysis which can lead to problems. First of all, electrolysis consumes energy. Also, if the strip operates in air, the area of electrolysis dries very quickly. If the strip operates in a closed environment, the emission of oxygen and hydrogen will pressurize the environment.
- An IPMC actuator exhibits shape hysteresis. This means that its relaxed position changes during its operation [Fig. 4.].
- The metal coating of an IPMC strip has relatively high resistance because it is very thin and cracked. For that reason, the strip bends more at the contacts and less towards the tip. There is a trade-off between conductivity and elasticity. If the metal layer is too thick the strip will no longer bend.

III. INVERTED PENDULUM CONTROL TASK

An inverted pendulum is inherently unstable. Assessing whether the system has been successfully controlled is therefore a trivial question. There is a wide variety of inverted pendulum systems. The joint can be stationary or can be located on a moving platform. There can be just one pendulum or several pendulums on a top of each other. For videos of how pendulums with different numbers of links are balanced, see [22].

All kind of variations were considered, when choosing a system to test the performance of IPMCs. The simplest of all tasks – the system where a single pendulum rotates about a stationary axis – was first eliminated. The solution for that task is too trivial. Even a plate spring could balance that system. Also the multi-link versions of inverted pendulum tasks were eliminated as too complicated to build and control.

The system proposed for validating IPMC usability has a single inverted pendulum attached to a platform. An IPMC strip in cantilever configuration pushes and pulls the platform with its tip. The state of the platform and pendulum can be represented by four variables: the position and velocity of the platform, the angle (0 if vertical) and angular velocity of the pendulum. The pendulum would naturally tend to fall down from the vertical position, which is a position of unstable equilibrium. The goal is to make all four variables converge to zero as quickly as possible.

Like most of real world applications, the task is challenging because the conditions are not ideal. To apply closed-loop force control we need to know exactly the force that was applied by the IPMC strip to the platform. It is difficult to measure this force directly. Therefore the force has to be estimated based on the reaction of the system. The task is also challenging because achieving the goal is not straightforward. To achieve the goal one has to occasionally move away from it. An example of such a situation is given in Fig. 5. – Fig. 7.

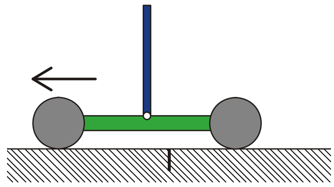

Fig. 5. The pendulum is in the vertical position but the platform is not in the initial position. In order to achieve a correct angle for approaching the initial position, the platform has to be moved further away from the initial position.

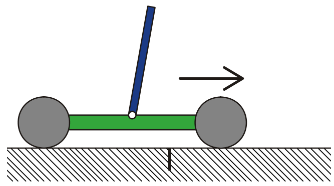

Fig. 6. The pendulum has the correct angle and the platform can start moving toward the initial position. The platform has to be moved so that the pendulum will end in the vertical position, when the initial position is reached.

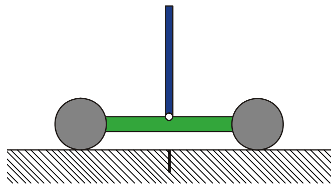

Fig. 7. The pendulum is in the vertical position and the platform is in the initial position. The goal is reached.

Due to their properties IPMC actuators are not suitable for all kinds of applications, but presumably they are suitable for controlling the inverted pendulum. The actuator has a constrained actuation range, but as the platform operates only in a close range around the initial position, this is not a problem. An IPMC strip cannot apply force in one direction for more than a few seconds. Fortunately when balancing inverted pendulum one does not have to apply force in one direction for a very long time. The IPMC actuator can relax when the pendulum is in its equilibrium state.

The behaviour of the IPMC actuator depends on the hydration level. In this initial phase of the work we have placed the pendulum in water. We thereby eliminate the parameter change of actuator due to hydration level which simplifies the control task.

A system in water acts differently than the same system in air. In the air, the force caused by the acceleration of the platform plays an important role, while the resistance of the medium is insignificant. In water the situation is reversed. The resistance of the medium becomes an important factor and the acceleration of the platform is less important. That in turn causes changes in the control strategy. In air the goal is to achieve accurate acceleration of the platform, while in water the goal is to achieve accurate velocity of the platform. In water it is easier to control the system because IPMC actuators are rather weak and can not accelerate very rapidly. Also the pendulum falls more slowly in water due the reduced weight. To amplify these effects the pendulum could be shaped as a plate and made as lightweight as possible. However the pendulum cannot be made too light because then it will float.

IV. System Setup

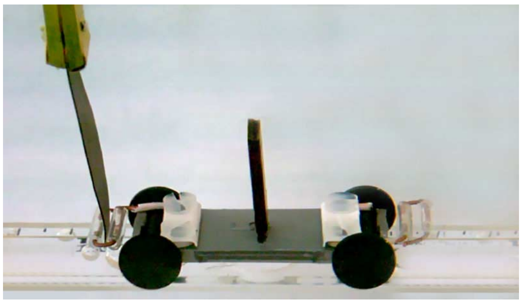

Fig. 8. The cart, the pendulum and the IPMC strip.

The inverted pendulum system is presented in Fig. 8. A cart, made from the base of a toy car, is used as a moving platform. The cart is placed on a plastic ruler that forces it to follow a fixed trajectory. A plastic plate is used as the pendulum. It is sufficiently light to make force caused by the acceleration of the cart redundant in comparison with the water resistance. To get a nearly frictionless joint, the plate is sharpened at the bottom and placed in a notch on the top of the cart. The IPMC strip is held vertically in a cantilever configuration at one end of the cart. The tip of the strip is fixed between two plastic rolls that are attached to the cart. The dimensions of the components of the system are given in Table 1. To keep the IPMC strip hydrated, the system was placed in a tank of deionized water tank (Fig. 9.).

TABLE I
The Dimensions of The Components of The System

	Strip	Pendulum	Cart
Length (mm)	24	14.5	40
width (mm)	9.5	5.9	15.5
thickness (mm)	0.2	1.5	7.4
mass (g)	0.11	0.12	1.41

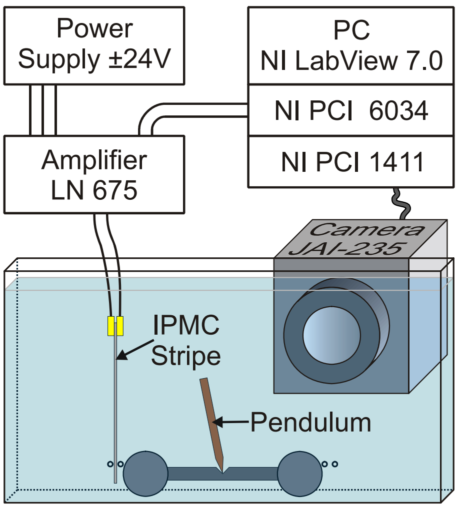

Fig. 9. The system setup.

There is also another pair of rollers for a second IPMC strip. However we used only one strip because it was strong enough to move the cart. Adding a second strip would only have complicated the control of the cart.

The system also includes components for monitoring and control (Fig. 9.). The IPMC strip is controlled by a PC running National Instruments LabView 7.0. A monochrome camera (JAI-235) is used to give feedback to the controller and to record the experiments. As the observed objects are inside a water tank the use of other type of contact free sensors like laser vibrometer would be problematic. A piece of white paper is placed behind the water tank to increase the contrast of the video image. Extracting positions of the cart and the pendulum from the video is a relatively easy task. Two rows from the picture are analyzed. One is located on the height of the wheels and the other below the tip of the pendulum. After applying a low-pass filter to the intensity graphs, the positions of the wheels and the pendulum are easily determined.

The velocities can not be measured directly, therefore they are computed. The velocity is set to be the average velocity between two consequent frames. Average velocity is computed using the last two positions. Similarly the acceleration is computed using the two most recently computed velocities. From the acceleration of the cart the force applied by the IPMC strip is estimated.

The frame rate of the camera is 25 frames per second. The new position of the cart and the angle of the pendulum are acquired every 0.04s. Unfortunately the speed of the cart can change considerably during 0.04 s. This means that the computed velocity is not accurate. The computed acceleration and force are even more inaccurate. The camera is good enough for recording the experiments but is too slow for measurements.

V. The Controller

The task can be divided in two stages. In the first stage the force to be applied to the cart in order to balance the pendulum is found. In the second stage the electric voltage to be applied to the IMPC strip in order to achieve the desired force is found. Accordingly, the controller of the system consists of two parts (Fig. 10.).

1. The controller of the cart and pendulum determines the force applied to the cart. It is fed with system state and works in a closed-loop.
2. The controller of the IPMC strip controls the voltage applied to the IMPC actuator. Its input should be the force, actually applied to the cart. Currently it is not used, because the computed force is too inaccurate. Therefore the IPMC actuator controller works in an open-loop manner.

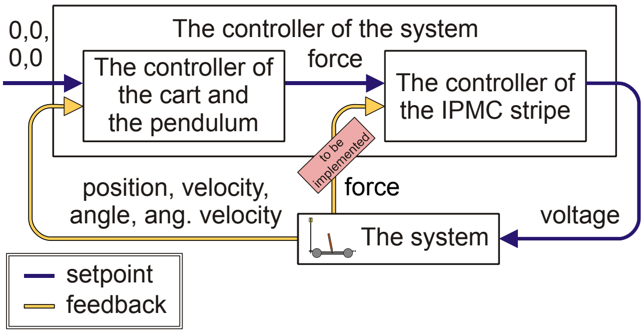

Fig. 10. Block diagram of the controller

A. *The controller of the cart and pendulum*

In water the behavior of the pendulum is mostly dependent on the velocity of the cart. The velocity is changed by applying the force to the cart. To find the force the following calculations are performed:

1. The desired velocity in the given state is computed.
2. The model of the system is used to calculate the force to be applied during the predefined time (0.04s) to obtain the correct velocity.

The velocity is calculated according to

$$v = a_1 \cdot p + a_2 \cdot p^2 + b_1 \cdot \alpha + b_2 \cdot \alpha^2 , \qquad (1)$$

where v is the velocity of the cart, p is the position of the cart and α is the angle of the pendulum (Fig. 11.).

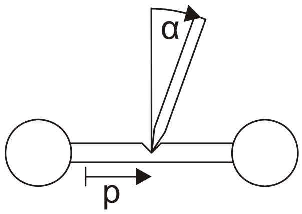

Fig. 11. The position of the cart and the angle of the pendulum.

The coefficients have the following values found by trial and error:

$$a_1 = 2.5\frac{1}{s} \ , \ a_2 = 200\frac{1}{m \cdot s} \ , \ b_1 = 0.12\frac{m}{s \cdot rad} \ , \ b_2 = 0.2\frac{m}{s \cdot rad^2} \ .$$

B. *The controller of the IPMC strip*

In the absence of precise experimental data, we had no other choice than to take an educated guess on how the model of the IPMC strip should look.

As explained in section II, the force depends on the previously applied voltages. Under constant voltage, force increases at first but after a while starts to decrease. Meanwhile the strip gets more and more fatigued. The state of the strip is represented by two variables: $-1 \leq fatique \leq 1$ and *force*. When *fatigue* equals 1 or −1, the strip is exhausted and unable to increase *force*.

The dependency of the state of the IMPC from voltage (Fig. 12.) is described by (2) and (3).

$$\frac{d}{dt} fatigue(t) = \left(\frac{voltage(t)}{\mathrm{C1}} - fatique(t) \right) \cdot \mathrm{C2} \quad , \qquad (2)$$

$$\frac{d}{dt} force(t) = \frac{d}{dt} fatigue(t) \cdot \mathrm{C3} - force(t) \cdot \mathrm{C4} \quad . \qquad (3)$$

In our experiment the coefficients have the following values: C1 = 2, C2 = 6.25, C3 = 28 and C4 = 60. The values are found by trial and error.

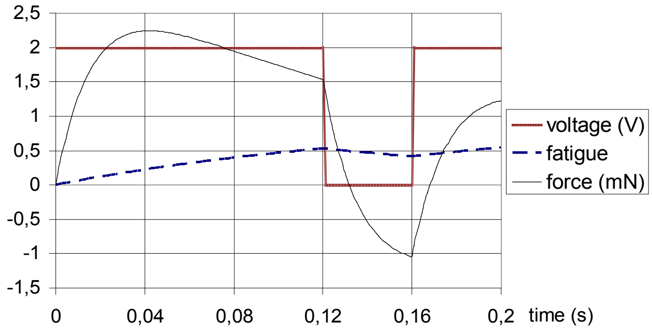

Fig. 12. Simulation results

VI. EXPERIMENTS

Video at [23] represent the a preliminary experiment with IPMC control of the inverted pendulum system described above. The pendulum could be balanced for up to 10 sec. Fig. 14 and Fig. 15 represent a snapshot and the waveform chart respectively.

As presented in Table 2 the mean absolute velocity difference is only half the mean absolute velocity. With the system changing its state so rapidly between successive samples it is very hard to estimate the state in between samples and force applied to the system. This greatly restrains the performance of the controller.

TABLE II
MEAN ABSOLUTE VALUES

	Cart	Pendulum
(angular) velocity	6.83 mm/s	0.62 rad/s
(angular) velocity difference	3.04 mm/s	0.26 rad/s
(angular) acceleration	75.93 mm/s^2	6.43 rad/s^2

The experiments also proved that the described inverted pendulum task is suitable for validating IPMC usability. Control of such a system is feasible with an actuator having the physical constraints characteristic of IMPCs. The displacement of the tip is large enough to control the position of the cart in all required locations. The reaction speed of the strip is sufficient to control such a system. However, in air the pendulum falls considerably faster and the system would be more difficult to control. Also the output force of a single actuator is large enough to control the test system. We also observed that such a control task does not require the strip to be in a fixed position for a long time, which is hard to achieve with ion-conducting materials due to water diffusion.

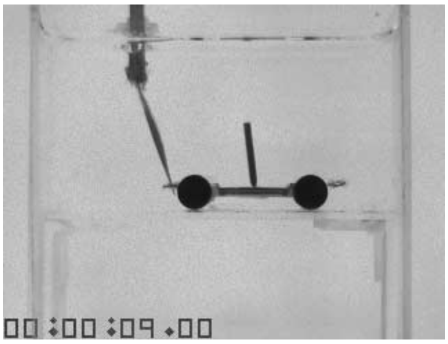

Fig. 14. A frame from the video "experiment01.mpg" 1 second before the pendulum falls.

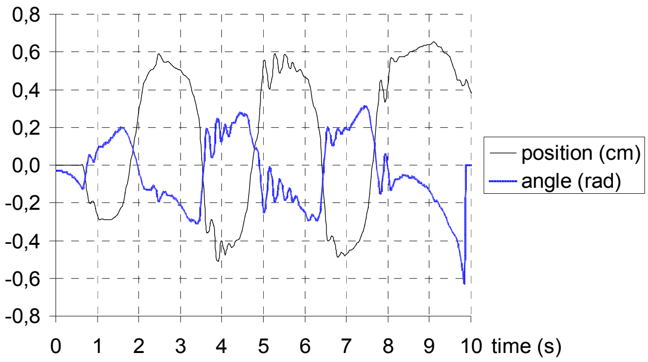

Fig. 15. Waveform chart of the position of the cart and the pendulum angle during the experiment represented in Fig. 14.

VII. Conclusion

This paper describes an inverted pendulum used to verify the performance of IPMC actuators, the controller of the system and preliminary experimental results. To our knowledge this is the first attempt to use IMPC actuators to stabilize a system.

We have shown that the inverted pendulum described in Section IV is a suitable testbed for testing IMPC actuators given the physical limitations of IPMC materials.

In our future work we are planning to find how much force and response speed is required for this experimental setup. A camera suitable for estimating velocity of the system and force applied to the system can then be acquired. This would permit us to implement closed-loop IPMC actuator control as suggested in Fig. 10. Better experimental data would enable us to derive more precise models. Also feedback control algorithms should be validated and improved.

If we succeed on controlling the system, we wish to use the system for comparing the performance of various types of IPMC-s against traditional actuators.

Our more distant goal is to show the potential of IPMC actuators in real world applications. Besides improving our control methods, we also plan to test the system with onboard sensors, in the air and with more complicated IPMC actuators.

Acknowledgment

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