Electrostatic actuation in ionic polymer-metal composites

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ABSTRACT

Materials engineering has greatly contributed to improving the performance of soft active materials, but these improvements have seldom met the compelling needs of science and engineering applications. Here, we demonstrate, for the first time, a new approach to the design of soft active materials, which embraces the complexity of multiphysics phenomena across electrostatics and electrochemistry. Through principled experiments and physically-based models we investigate the integration of electrostatic actuation in ionic polymer-metal composites (IPMCs).

Keywords: contactless actuation, enhanced actuation range, pull-in instability, reduced-order modeling, soft actuators

1. INTRODUCTION

In the context of soft electroactive polymers, ionic polymer-metal composites (IPMCs) have gained considerable research interest in the last three decades as soft actuators.[1,2] In particular, their high compliance together with the small driving voltage, and the possibility of using them in aqueous environments make them promising candidates for biomimetic soft robotics and for biomedical purposes.[3–5]

An IPMC, in its most basic form, is composed of an ionomeric membrane, soaked with mobile counterions, which is sandwiched between two noble metal layers, usually deposited through an electroless plating process.[6] When a relatively small voltage is applied across electrodes, the redistribution of charges in the ionomer elicits a complex series of electrochemical phenomena, which, in turn, yields the macroscopic deformation of the IPMC.[7–9] Vice versa, IPMCs can be used as sensors and energy harvesters,[1] where a voltage is generated across the electrodes when IPMCs are deformed.

Despite the fact that their large deformation range is commonly recognized as one of their main advantage, the dielectric breakdown of the solvent at moderate voltages,[10,11] in practice, limits this range. Such a constraint is critical in certain applications which require a considerably large deformation range and fast actuation. In an effort to increase IPMCs' deformation range, we propose an innovative actuator design grounded in the multiphysics behavior of electroactive polymers. Instead of tailoring the microstructure of the material to achieve the desired performance, we integrate the internal actuation of IPMCs with electrostatic actuation through external electrodes.

While electrostatic actuation of bare ionomer membranes was proposed by Kim et al.,[12] electrostatic actuation of IPMCs has remained untapped until our recent study.[13] Here, we summarize some of the design and experimental aspects from Ref. 13. More specifically, we first describe the design of the actuator and then we put forward a series of ad-hoc experiments, illustrating the effect of electrostatic actuation on the actuator. Through experiments, we demonstrate our novel approach for the enhancement of the performance of electroactive polymers, based on the exploitation of their multiphysics nature.

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Nano-, Bio-, Info-Tech Sensors and 3D Systems III, edited by Jaehwan Kim, Proc. of SPIE Vol. 10969, 1096910 · © 2019 SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2514277

2. EXPERIMENTAL DEMONSTRATION

2.1 Experimental setup

To prove the feasibility of utilizing electrostatic actuation in IPMCs, we put forward a novel actuator design, taking inspiration from comb drive actuators, which have been widely studied for microelectromechanical systems (MEMS).[14] We place an IPMC between two external electrodes, which are charged at the same high voltage with respect to the common ground, as shown in Fig. 1. If the IPMC is perfectly positioned in the middle of the external electrodes, no net electrostatic pressure is generated on the actuator. When the IPMC is internally actuated by applying a small voltage across its electrodes, Coulomb forces on the charges piled-up close to the IPMC electrodes are generated. This forces will sum up to the internal actuation, enhancing the overall deformation.

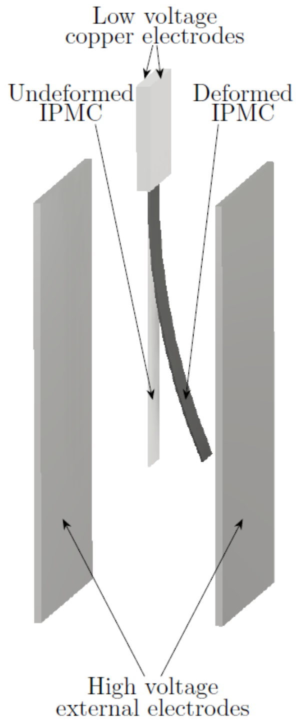

Figure 1. Schematics of the proposed actuator.

In our experiments, conducted in air, we tested a 45 mm long IPMC*, with a width of 9 mm and a thickness of 0.27 mm. The IPMC was clamped with a free length of 40 mm and positioned between two copper electrodes through a sliding mechanism. The nominal distance g_0 between the IPMC and each of the external electrodes is 12.5 mm. These external electrodes were covered with a thin anti-static plastic layer, to avoid direct contact of the IPMC with the high voltage electrodes and the unwanted effect of residual charges. The low voltage on the IPMC was applied through copper bands on the clamps. The high voltage was applied both across the IPMC sample and on the external electrodes through a driving circuit, controlled by an Arduino Uno, which set the voltages required through the Arduino serial monitor on a laptop.

2.2 Experimental campaign

To study the effect of electrostatic actuation, we performed a series of experiments in which we varied both the voltage applied across the IPMC electrodes and the voltage applied to the external electrodes. In particular, we considered, respectively, voltages from 1.3 to 1.7 V, in steps of 0.1 V, and from 0 to 4 kV, in steps of 1 kV.

*The sample was produced by the Active Materials and Smart Living Laboratory at the University of Nevada Las Vegas.

Therefore, we examined a total of 25 voltage combinations. For all these combination, we also considered the orientation of the IPMC and the polarity of the voltage applied across the IPMC to eliminate experimental bias. To mitigate hysteresis effects, we randomized the order of application of the voltage across the IPMC electrodes, the orientation of the IPMC, and the polarity of the voltage. The voltage applied across the external electrodes, instead, was not randomized, to reduce the effect of residual charges.

The IPMC sample was stored in deionized water. Before each trial, the sample was installed in the clamp and positioned between the two external electrodes. To prevent shortening of the copper bands in the clamp due to excessive water on the IPMC surface, the sample was slightly dabbed and the part not in contact with the clamp quickly hydrated again. Once the IPMC was in the correct position, the voltage across the IPMC and the voltage on the external electrodes were applied for five seconds, during which the trial was recorded. As a measure of the extension of the deformation range, we scored the number of trials in which the IPMC touched one of the electrodes. To prevent excessive dehydration of the IPMC, at the end of each trial the sample was kept soaked in water for one minute, before the next trial, and after 20 trials we left the IPMC in water for a five minutes resting period.

2.3 Image postprocessing

In order to analyze the deflection and the shape of the IPMC sample, half of the trials (five complete sequences of 100 trials) were recorded with a Nikon D90 DSLR. Image postprocessing for tracking and shape fitting is performed through a custom-made software, based on the image processing toolbox in Matlab, allowing for a resolution of 60 μm. Once a particular frame was selected, first of all, it was binarized and then dilated and eroded. These two operations, made on a 4 pixel wide window, assured that the black pixels in the processed image would correspond to the IPMC. To identify the position of the IPMC, we computed the average over each row, which would identify the mid-axis of the IPMC, wherever it was present. In this way, we obtained a vector of position of the IPMC mid-axis, extended until the tip. As a consequence of dilation and erosion, no black pixel could be present in rows that effectively should contain at least one, resulting in gaps in the IPMC mid-axis position vector, which could be easily identified. In order to remove these gaps, a fitting procedure of the values which were present in the vector was utilized. This whole procedure was repeated for each frame of the trial, so that the position in time of each point of the free length of the IPMC was available.

3. EXPERIMENTAL RESULTS

By computing the probability of contact for each voltage combination, that is, dividing the number of contacts for each voltage combination by the number of experiments per combination (40), we obtain Fig. 2. The number of contacts is higher as the voltage on the IPMC is increased, since the curvature of the IPMC is directly proportional to the applied voltage. More interestingly, the probability of touching the electrodes increases with the voltage applied across the external electrodes, while maintaining the voltage applied across the IPMC constant. This result demonstrates the possibility of enhancing the deformation range of IPMCs through electrostatic actuation.

The effect of electrostatic actuation of IPMCs can be better understood by considering two trials, with the same voltage applied across the IPMC, and two different voltages applied across the external electrodes (Fig. 3). Through image processing, it is possible to reconstruct the tip displacement for each frame, and therefore obtain its time trace. In the case in which the external electrodes were grounded, the IPMC bends without reaching the external electrodes when a small voltage is applied across its electrodes. After achieving the peak displacement, the sample shows a gentle back-relaxation.[15,16] When the external electrodes are at a high voltage, instead, the IPMC is attracted by the nearest electrode due to the electrostatic forces generated on its depleted charges and, if the voltage is large enough, the actuator eventually sticks to it. This phenomenon, called pull-in instability and extensively explored in the MEMS domain,[17,18] limits the positioning capabilities of the proposed IPMC actuator. A careful design of the actuator and of its voltage range is required in order to avoid this instability.

4. CONCLUSIONS

In this paper, we have studied the integration of electrostatic actuation in IPMCs. Through a series of experiments, we have demonstrated that electrostatic forces can be successfully used to enhance the deformation range

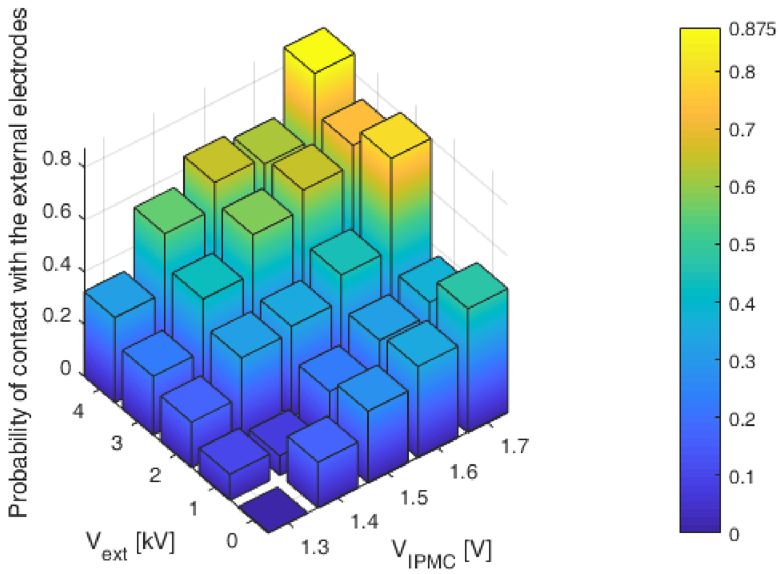

Figure 2. Probability of contact in the wall as a function of the voltage applied across the IPMC electrodes, V_{IPMC}, and of the voltage applied to the external electrodes, V_{ext}.

of IPMCs. Such electrostatic forces could be generated by placing an IPMC between two external electrodes at a high potential with respect to a common ground. This novel approach to the design of soft electroactive materials allows tailoring of performance, without requiring a complex engineering of the material structure.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation under Grant No. OISE-1545857 and by KIST flagship program under Project No. 2E29460.

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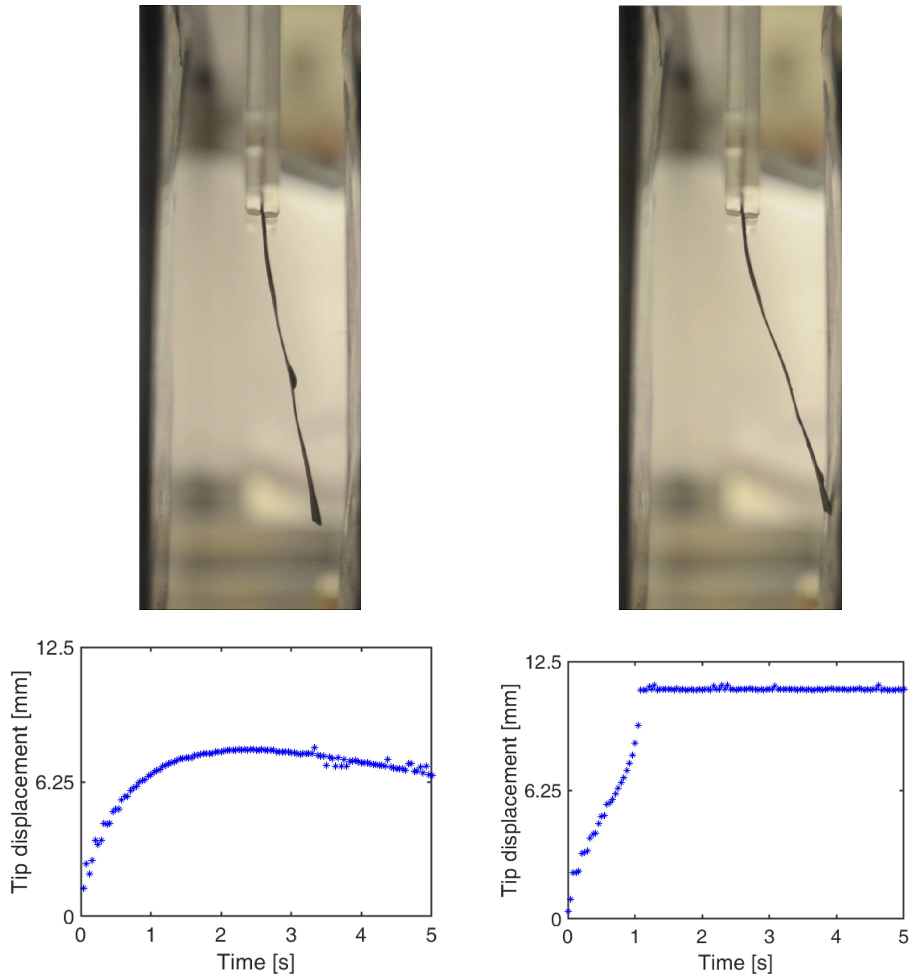

Figure 3. Pictures of the experimental setup (top) and tip displacement traces over time (bottom) for two trials with the same voltage applied across the IPMC ($V_{\mathrm{IPMC}} = 1.4$ V) and different voltage applied on the external electrodes ($V_{\mathrm{ext}} = 0$ kV on the left, $V_{\mathrm{ext}} = 4$ kV on the right).

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