Micro Nafion Actuators for Cellular Motion Control and Underwater Manipulation

Michael Y. F. Kwok, Wenli Zhou, Wen J. Li, and Yangsheng Xu
Centre for Micro and Nano Systems
The Chinese University of Hong Kong
Shatin, N. T., Hong Kong
{yfkwok,wlzhou,wen,ysxu}@acae.cuhk.edu.hk

Abstract: The manipulation of biological objects is a key technology necessary for many new applications in Bio-MEMS. In this paper, we will report on our preliminary experimental work in using an Ionic Conducting Polymer Film (ICPF) to develop a biological cell robotic gripper. The ability of ICPF actuators to give large deflection with small input voltage (~5V) will allow many new applications to be developed, spanning from biology to underwater MEMS and artificial muscles. A laser micromachining process is introduced to fabricate arrays of ICPF griping devices, which can be potentially integrated onto a PCB board to develop a micro manipulation system. Individual multi-finger grippers with dimensions of 200μm x 200μm x 3000μm for each finger were realized. We will report on the design, fabrication procedures, and operating performance of these micro-grippers. Further development in the reduction of size of these actuators will enable effective control of underwater micro objects and lead to new frontiers in cellular manipulation.

1. Introduction

Many micromachined actuators now exist which operate using electrostatic, thermal, magnetic, or pneumatic control principles. However, almost all of these micro actuators cannot be used in any biological applications due to one hindrance: they must operate in a dry-environment. Although pneumatic micro grippers were ingeniously used under water to capture biological cells recently [1], slow frequency response and the inability to control individual appendages of the grippers impede these micro grippers from gaining general acceptance from the biological community. Conjugated polymers such as polypyrrole are also under investigation as aqueous microactuators (as reported in [2] and [3]) because they can change volume to deliver significant stresses and strains when electro-activated. However, an electrolyte solution is needed as an ion source or sink to activate this material, and hence, using polypyrrole will limit the medium of operation

This project was partially supported by the Hong Kong RGC Earmarked Grant (No. CUHK 4206/00E).

for these aqueous actuators. Nevertheless, polypyrrole offers certain advantages over other electro-activated materials, and should be further investigated to build underwater micro-manipulation devices.

ICPF is a sandwich of a film of perfluorosulfonic acid polymer that is between two thin layers of metal film such as gold, which serve as metallic electrodes. Strips of ICPF can give large and fast bending displacement in the presence of a low applied voltage in wet condition. However, specially coated ICPF actuators can also be made to operate in dry condition. Thus, ICPFs have a high potential to be incorporated into sensors or actuators where a large displacement is desired. ICPFs have been investigated widely in the past decade, but only as macro actuators [4][5]. There are some developmental work in progress to use ICPF for micro applications [6], but from literature survey and to the best of our knowledge, ICPF microactuators for micro-manipulation have not yet been reported. Comprehensive micromechanical studies on the motion of ICPF actuators are also non-existent at the time of this publication.

In this paper, we report on a fabrication process that uses laser-micromachining to produce ICPF actuators with width dimension less than 500µm. Hence, a new breed of micro-scale actuators is introduced to the MEMS community: actuators that can be actuated in an aqueous environment with large deflection, while consuming relatively low actuation voltage. In addition, laser-micromachining technique offers a relatively fast and inexpensive fabrication method, and will potentially give cheap and pseudo-batch-fabricable ICPF micro actuators. We have initiated an effort to create micro-cellular-manipulators by using laser-micromachining to process a commercial perfluorosulfonic acid polymer (Nafion®) [7]. Our goal is to eventually create an array of micro actuators capable of operating in biological fluids (see conceptually drawing in Figure 1). Details of the fabrication procedures and initial experimental results from our micro underwater actuators are presented in the following sections.

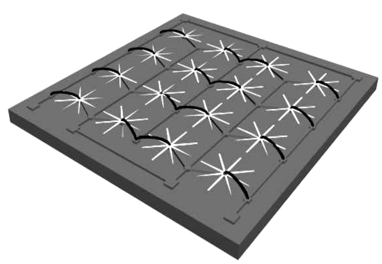


Figure 1. Conceptual illustration of an array of micro actuators that will operate in an aqueous solution. The wirebonding wires and electrical connections will be coated before aqueous operations.

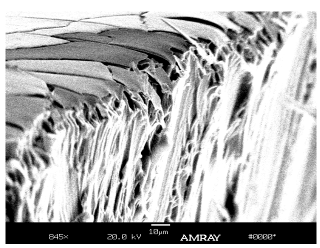
2. Fabrication Process for the Nafion ICPF

The development of ionic polymer-metal composites actuators requires an interdisciplinary study in chemistry, materials science, controls, and robotics. For fabrication, the poor surface adhesion of any metal coating sandwiching the polymer was an obstacle in making controllable and stable Nafion actuators. Metal deposited on the polymer surface will easily crack and peel off if there is no appropriate surface pre-treatment. Bar-Cohen et al. [8] reported workable solutions by using a chemical etchant (*Tetra-etch®*) to etch the surface or by introducing a seed layer between the metal and the polymer. For our work, we have developed an alternative and simpler method to over come the peeling and cracking problem of using gold coatings.

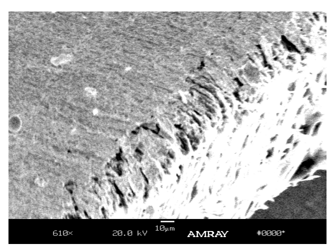
2.1 Metal Deposition

We chose the Nafion 117 produced by Dupont to create our ICFP actuators. Chromium, platinum and silver coating compounds were tested as a seed layer. However, due to the residual stress between the seed layer and the gold electrodes, cracks generally exist when these seed layers were used. Also, when actuators fabricated with these seed layers were tested, the metal electrodes generally peeled off after a sufficiently high voltage was applied, i.e., ~7V. This led us to shift to another process, which is described below.

The following process was used in our laboratory to produce reliable Nafion actuators. First, the Nafion should be roughed by fine sand paper (Class 1500). Then, the sample should be cleaned with HCl to remove impurities, followed by DI water rinse and Nitrogen drying. Then, a seed layer (about 0.4μm) of gold should be deposited on both sides of the polymer film using E-Beam evaporation. Then, about a 2μm thick of gold should be deposited on top of the seed layer by chemical electroplating (see Section 2.2). A satisfactory adhesion could be achieved between the Nafion and Au layers based on the above fabrication procedures in our laboratory. These gold-polymer composites can withstand a high voltage (20V) without the electrodes peeling off. The results of using E-beam evaporated Cr seed layer and Au seed layer are compared in Figure 2.



(a)



(b)

Figure 2. (a) SEM photo showing cracks due to residual stress between seed layer (film of Cr) and film of Au on the Nafion 117 polymer surface. (b) Au thin film with good adhesion on the surface of Nafion 117 polymer film. The Nafion polymer surface has already been processed with Class 1500 sand paper.

2.2 Electroplating Au on Nafion Polymer

After depositing a thin seed layer of Au by E-beam evaporation, the sample was processed to further increase the thickness of Au by chemical electroplating. A thicker Au layer is needed to increase electrical conductivity. Using *Gold Elconac 138* electroplating solution provided by Chartermate International Ltd., the deposition rate of Au could be calibrated with respect to time. The Nafion with Au seed layers were pre-cleaned with *Copper Wet-1150* surface cleaning solution to remove any dust or oil on the surface to ensure good adhesion with the electroplated Au. Identical metal alloy strips were used to serve as a calibrating medium. Each strip was partially covered with an electrically insulating tape and electroplated in the *Elconac 138* with different time durations. Afterwards, the step-height between the electroplated Au and the original alloy surface was measured using an *Alpha-Step® 500* surface profiler. We have consistently produced reliable actuators after 10min (~2.25um) of electroplating using the following parameters:

- Stirred 400ml of *Elconac 138* solution at room temperature.
- 10cmx7cm wire grid plated with 2.5μm platinumized titanium as anode.
- Apply 2.5V input at 20mA between and anode and cathode.

3. Laser Micro-Fabrication Process

Both CO_2 and Nd:YAG lasers were explored as a micromachining tool to micro-fabricate the Nafion 117 polymer film. Lasers provide a fast and convenient way to produce small-scale Nafion actuators for mechanical testing. Since the Nafion is a polymer, our initial concern was that it would not absorb enough Nd:YAG laser energy to allow laser ablation, as CO_2 lasers are normally recommended to cut polymers. Nevertheless, we wanted to explore the possibility of using Nd:YAG lasers as a micromachining tool for polymers due to the fact that it has a shorter beam wavelength (1.06μm compare to 10.6μm of CO_2 lasers), which will allow more focused beam spot and higher energy density to enable a more precisely cutting process.

3.1 CO_2 Laser-micromachining

We have used the Electrox CO_2 laser System, which is designed for cutting and masking organic materials, to process the Nafion polymer. The system can definitely be used to cut Nafion consistently if 7.5W of power is applied. However, fibre-like residue usually accompanies the laser-processed polymer structures (see Figure 3). Nonetheless, this CO_2 laser system can be used to reliably micromachine Nafion structures with minimum feature size of ~200μm at this time.

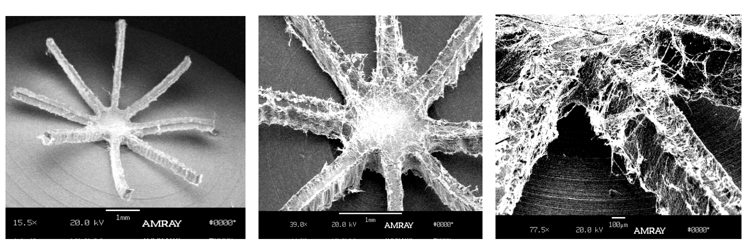


Figure 3. SEM pictures of Nafion structures laser-fabricated by a CO_2 laser system. The width of each arm is ~200μm.

3.2 Nd:YAG Laser-Micromachining

The melting point of Nafion is lower than that of metals, so its damage threshold is lower than that of metals. This means that lower laser energy intensity is required for cutting the polymer. However, Nafion is a transparent material for Nd:YAG laser beam, which means that Nafion has a very low absorptivity to Nd:YAG laser energy. Therefore, higher power is required from the laser system to cut this polymer than cutting metals such as copper. On the other hand, Nafion has lower thermal conductivity than metals so that the thermal diffusion in Nafion during laser cutting is slow, causing possible burning of the polymer if the power is set too high. Consequently, an appropriate power level had to be found that will cut the Nafion but will not burn it during the laser micromachining process.

We have used the Electrox Nd:YAG Laser system successfully to micromachine the Nafion polymers. We have found that using an aperture size of 1.5mm and ~5W of laser power (70% input power), we can consistently micromachine the Nafion polymers. A sample of a Nafion polymer structure cut by this system is shown in Figure 4. Clearly, the fibre-like residues are not visible as in the case for CO_2 laser processing. Also, the edges can be more precisely laser-machined (compare to Figure 3).

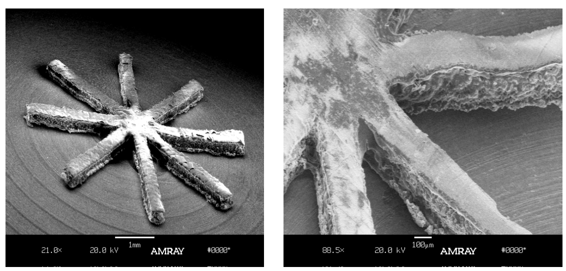


Figure 4. SEM picture of a Nd:YAG laser processed Nafion structure with each leg-width of 200μm.

4. Mechanical Properties of Nafion

In order to design functional micro underwater actuators using Nafion 117, some fundamental studies on the mechanical behaviour were performed for these polymers. Since these actuators are electro-activated devices made of composite materials that may undergo large deflections, close-form solutions for modelling the behaviour of ICPF actuators are very complicated, and consequently, there is currently no generally accepted model to describe the motion of Nafion actuators as a function of voltage. Nevertheless, Shahinpoor et al. [5], and Kanno et al. [9] are striving to produce a general workable model for ICPF actuators presently.

Since no micro-scale mechanical properties of Nafion polymers have been reported (to the best of our knowledge) we have set up an in-situ measurement system to observe and quantify the deflection of the laser fabricated polymer structures. A CCD camera was linked to Snapper®, which was then connected to the computer graphics interface card of a

PC. In a water tank with transparent wall, we attached a transparency with predefined position grids, which allowed the motion of the polymer actuators to be quantified if images of the actuators could be captured with the superposition of these grids. The setup is shown in Figure 5. The motion of the actuators were digitally recorded with the grids superimposed in the background. The recorded files were then played back to find the tip deflection and velocity of the actuators.

To find the Young's modulus of our Nafion 117 actuators, we applied different forces to Nafion cantilevers and measured the tip deflection as a function of force. Forces were applied using magnet cubes (1mmx1mmx1mm) with mass of 7.4x 10^{-3}g each. So, by counting the number of magnets attached we know the force applied at the tip each cantilever. Using the predefined grid scale from the captured image, we calculated the Young's modulus (E) for these actuators by noting that, for a cantilever clamped at one end, the deflection δ of the suspended end can be related to the applied force F at the suspended end and E by $E = Fl^3 / 3I\delta$, where l is the beam length and I is the moment of inertia about the neutral axis, which is equal to $wt^3/12$ for a rectangular cross-sectional beam (w is the width, and t is the thickness of the beam). The average E is 1.32×10^8N/m^2 for our Nafion actuators with 2µm Au layers on each side, which is close to the value of 2.2×10^8N/m^2 given by Kanno et al. [9] using laser deflection measurements for ICPF with dimensions of 10mmx2mmx184µm. In calculating E, the linearity between the loading and deflection of the beam obeys Hooke's law as shown in Figure 6 (3mmx14.5mmx180µm cantilever).

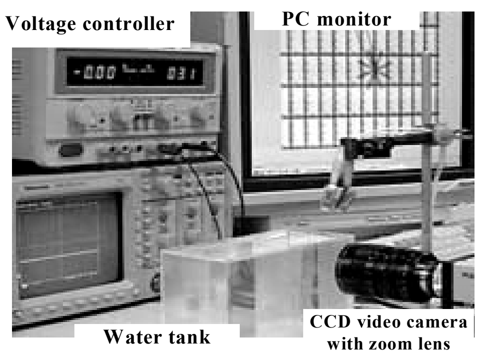


Figure 5. Picture of the in-situ monitoring setup for observing the motion of Nafion actuators.

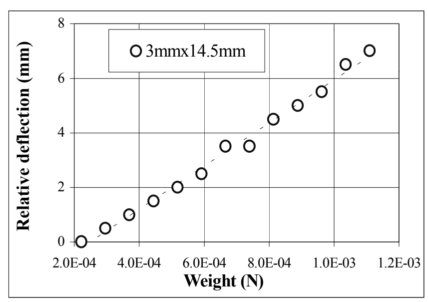


Figure 6. Experimental results of the cantilever tip deflection due to loading (Nafion with ~2µm Au on both sides).

5. Performance of Nafion Actuators

Experimental results from testing Nafion actuators with various geometrical variations are presented below. For actuation of the Nafion actuators, we applied a voltage across the electrodes on the polymer, and the actuator will bend towards their anode side.

5.1 Actuation of Nafion Actuators

The typical motion of Nafion actuators is shown in Figure 7 and can be described as a circular path if its tip deflection is traced from the unactuated vertical position. In this paper, “deflection” is defined as the path distance measured from the original unactuated tip position to a new tip position of interest.

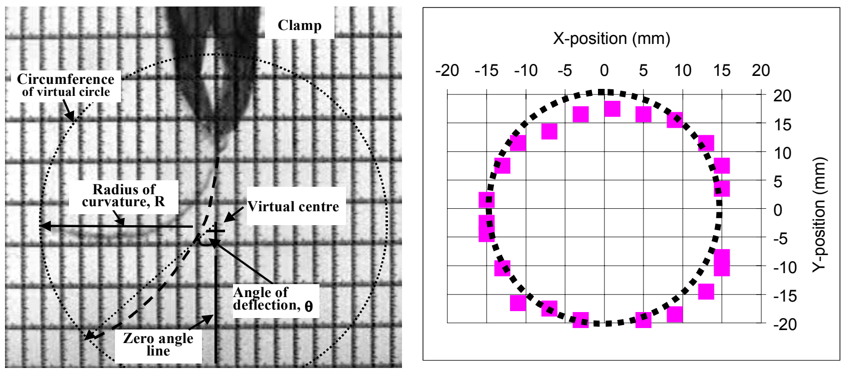


Figure 7. (Left) Definitions of parameters used to quantify the deflection of an ICPF strip actuator. (Right) Tip position of ICPF strip during actuation.

5.2 Parametric Experimental Study of the Nafion Actuators

Several experimental studies were performed to understand the motions of the Nafion actuators. We have varied the geometries of the actuators and also the applied potential across the electrodes to examine the deflection rate of the actuators.

Keeping the length of the actuator to 24mm and applied a constant voltage across the electrodes, the time needed to complete a deflection cycle decreases with the reduction of width dimension. The experimental result is shown in Figure 8. A *complete cycle time* is defined as the time required for the actuator tip to move from its original position to a maximum deflection position to the left ($\theta \sim 180^o$ as defined in Figure 7), and then move to its maximum deflection position to the right ($\theta \sim -180^o$), and finally back to its original unactuated position ($\theta = 0^o$). Experimentally, 4.5V DC was applied across the electrodes on the Nafion strip surface, which caused it to eventually bend to a maximum position on the anode side (left-hand side in this case). Then by reversing the polarity of the electrodes, thus, previously positive anode now becomes the negative cathode, a maximum right deflection is eventually obtained. Finally, voltage is shut off and the strip bends back to its original position to complete one bending cycle.

As shown in Figure 8, the response of the actuators clearly is not a linear function of the width of the actuators, although small widths do give faster response. However, it seems as if an optimal width can be found to maximize time response and bending deflection for given fixed parameters of voltage, length, and thickness, because reducing the width from 1mm to 0.5mm did not yield much improvement relative to width reduction from 1.5mm to 1mm. It should be noted that commercially available Nafion films are ~180µm thick, so scaling the width below 180µm would not be a good mechanical design for ICPF actuators made using commercial Nafion films.

Experiments with varying lengths were also carried out. As shown in Figure 9, rate of actuation for strips of ICPF with lengths of 8mm, 16mm and 24mm were tested (each strip was 1mm wide, and a 4.5V DC potential was applied across the electrodes). As indicated in the figure, for 8mm long strip, the maximum deflecting angle was 110° (13mm); for 16mm long strip, the maximum deflecting angle was 140° (28mm); and finally, for 24mm long strip, the maximum deflecting angle was 155° (48mm).

Apart from the length, actuating voltage can also affect the maximum deflection angle as well as the rate of actuation for the actuators. Voltage tests were carried out and the results are shown in Figure 10. The frequency response and maximum tip deflection of the Nafion actuators are both affected by the input voltage as shown in the Figure. The tip deflection as a function of driving voltage frequency is shown in Figure 11. Note the results are still inconclusive for deflection response versus driving frequency, as the effects of different geometric parameters and driving potentials need to be investigated.

In summary, although the motion of Nafion actuators are still not well understood, we can now consistently make micron-scale wide Nafion actuators of different mechanical designs using our laser-machining process. An example of an underwater grasp-manipulator made of 2-legs ICPF actuator is shown in Figure 12.

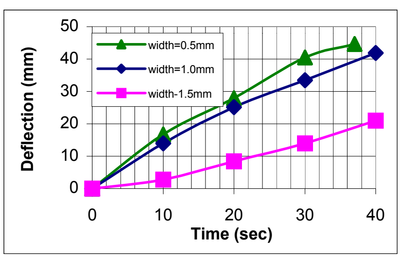


Figure 8. Rate of actuation for different widths of strip actuators (4.5V, l=24mm).

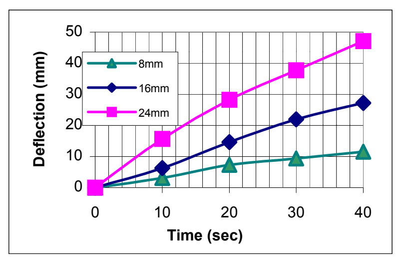


Figure 9. Rate of actuation for different lengths of strip actuators (4.5V, l=24mm).

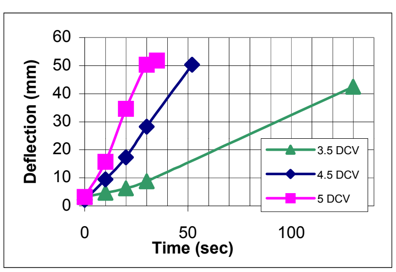


Figure 10. Deflection due to different applied voltage (4.5V, l=24mm, w=1mm).

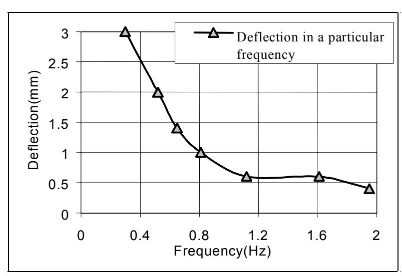


Figure 11. Actuator deflection versus driving voltage frequency (4.5V, l=24mm, w=1mm).

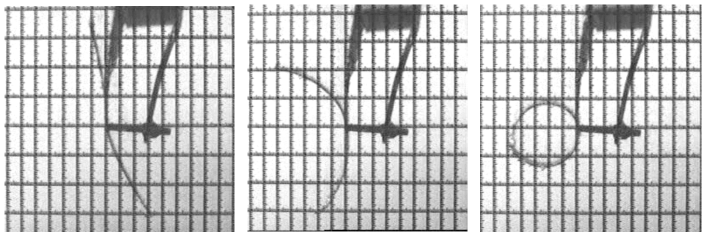


Figure 12. A 2-legs ICPF actuator which can be controlled to undergo a grasping motion under 4.5V in water.

5.3 Actuation of Micro-Scale Nafion Actuators

We have also successfully actuated actuators less than 500µm wide under water. To the best of our knowledge, these are the smallest reported underwater Nafion actuators to date. The smallest actuators we have successfully tested are with dimensions of *w=300µm, l=3000µm, t=200µm*, using 15V DC voltage (see Figure 13). We have found that these actuators have a ratio of tip-deflection/length smaller than the meso-scale actuators. This is due to the greater spring constant *k* presented by the shorter length dimensions, i.e., *k* scales with w/l^3. Hence, *w* must be reduced significantly if a micro-scale Nafion actuator is to have large deflections. We are currently developing a new in-situ monitoring system to observe and quantify these Nafion actuator motions. Also, we are calibrating our laser system to improve the cutting resolution and hence reduce the minimum feature size of the Nafion actuators.

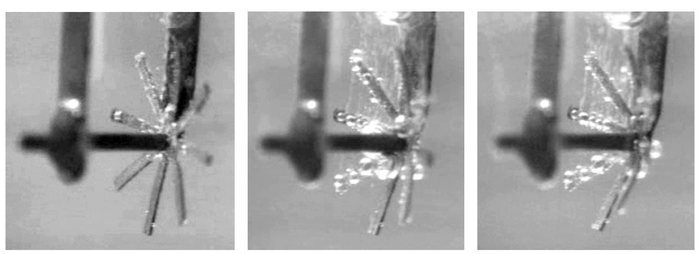


Figure 13. Time-sequence images of micro underwater Nafion actuators. The actuator shown has the dimensions of w=500mm, l=4000mm, t=200mm for each leg. The actuator was actuated with 15V input voltage with 50mA current to a tip deflection of ~1mm.

6. Conclusion

We have successfully micro-fabricated Nafion ICPF actuators using CO_2 and Nd:YAG laser systems. A simple process was also developed to fabricate these actuators using Au electroplating. Features as small as 200µm were micro-fabricated successfully with a Nd:YAG laser system, and actuators with dimensions of *w*=300µm*, l*=3000µm*, t*=200µm were successfully actuated under water with 15V DC voltage. We have also perform parametric experiments to understand the behavior of Nafion actuators with variations of applied voltage and actuator geometries. The knowledge gained from these experiments will allow us to design and develop micron scale ICPF actuators in the future.

Our future work includes designing and creating practical Nafion actuators using the laser-micromachining process developed from this work. In parallel, we will also develop other fabrication techniques to further reduce the widths and thickness of the Nafion polymer structures. The successful development of these actuators will enable effective and fast control of underwater micro objects and lead to new applications in cellular manipulation.

Acknowledgement

We would like to thank Dr. W. Y. Cheung for his help in the metal deposition and The Electronic Engineering Department of The Chinese University of Hong Kong for allowing us to use its cleanroom equipment. Appreciations are also due to A&P Instrument Co., Ltd. for assisting us in cutting the Nafion with CO_2 laser and in setting up our Nd:YAG laser system. This work was funded by the Research Direct Grant (Grant no. 2050173) of The Chinese University of Hong Kong and the Hong Kong Research Grants Committee (RGC Grant no. CUHK 4206/00E).

References

[1] Ok J, Chu M, Kim C J 1999 Pneumatically driven microcage for micro-objects in biological liquid. Proceedings of IEEE MEMS 459-463.

[2] Jager E W H, Inganas O, Lundstrom I 2000 Microrobots for micron-size objects in aqueous media: potential tools for single-cell manipulation. *Science* Vol 288 2235-2238.

[3] Smela E 1999 Microfabrication of PPy microactuators and other conjugated polymer devices. *J. Micromech. Microeng.* Vol 9 1-18.

[4] Bar-Cohen Y 2000 Smart Structures and Materials 2000: Electroactive Polymer Actuators and Devices. Proceedings of SPIE, Vol. 3987.

[5] Shahinpoor M, Bar-Cohen Y, Harrison J O, Smith J 1998 Ionic Polymer-metal Composites (IPMCs) as biomimetic sensors, actuators and artificial muscles - a review. *Smart Mater. Struct*. R15-R30.

[6] Guo S, Fukuda T, Nakamura T, Arai F, Oguro K, Negoro M 1996 Micro active guide wire catheter system-characteristic evaluation, electrical model and operability evaluation of micro active catheter. Proceedings of IEEE International Conference on Robotics and Automation Vol.3:2226 –2231.

[7] Kwok M Y F, Qin J S J, Li W J 2000 Micro nafion actuators for cellular motion control and manipulation. Proceedings of 3rd Asian Control Conference 622-627

[8] Bar-Cohen Y, Leary S, Shahinpoor M, Harrison J O, Smith J 1999 Electro-Active Polymer (EAP) actuators for planetary applications. Proceedings of SPIE 3669-05

[9] Kanno R, Tadokoro S, Takamori T, Oguro K 1996 3-Dimensional dynamic model of Ionic Conducting Polymer Gel Film (ICPF) actuator. Proceedings of IEEE International Conference on Systems, Man and Cybernetics 2179 –2184.