Development of force-feedback controlled Nafion micromanipulators

Wenli Zhou*[a], Wen J. Li*[a], Ning Xi**[b], and Shugen Ma***[c]
[a]Center for Micro and Nano Systems, The Chinese University of HongKong
[b]Dept. of Electrical and Computer Engineering, Michigan State University
[c]Dept. of Systems Engineering, Ibaraki University

ABSTRACT

The ability to manipulation of biological cells while having reflective-force information from the cells is a key technology necessary for many new applications in Bio-MEMS, but is currently lacking in all cellular manipulators. We will report on our preliminary experimental work in using an Ionic Conducting Polymer Film (ICPF) to develop a biological cell robotic gripper with force sensing capability. ICPF actuators are able to give large deflection with small input voltage (~5V), and also able to give relatively large output voltage due to deflection by a mechanical forces, thus are investigated as a possible material to make force-feedback controlled cellular manipulators in our work. A laser micromachining process is introduced to fabricate arrays of ICPF griping devices, which can be potentially integrated onto a substrate 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 force-feedback control of underwater micro objects and lead to new frontiers in cellular manipulation.

Keywords: micro aqueous actuators, Nafion actuators, Nafion sensors, force-feedback micro manipulators, 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 [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 stress and strain 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 for these aqueous actuators, and it has not been demonstrated as a sensing material. 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.

We have reported a fabrication process that uses laser-micromachining to produce ICPF actuators with width dimension less than 500µm in [7] and [8], and demonstrated a new breed of micro-scale actuators to the MEMS community: actuators

* {wlzhou,wen}@acae.cuhk.edu.hk; phone +852 2609-8475; fax (852) 2603-6002; http://www.acae.cuhk.edu.hk/~cmns, Rm. 413, MMW Bldg., CUHK, N. T., Hong Kong SAR. ** xin@msurobot-egr.msu.edu; phone +1 517 432-1925; fax +1 517 353-1980; 2120 Eng. Bldg., East Lansing, MI 48824-1226, USA. *** shugen@dse.ibaraki.ac.jp; phone +81 294 38 5209; fax +81 294 38 5272; 4-12-1 Naka-Narusawa-Cho, Hitachi, Ibaraki 316, Japan.

+ This work was partially funded by the Hong Kong Research Grants Council (RGC Earmarked Grant: CUHK 4206/00E).

that can be actuated in an aqueous environment with large deflection, while consuming relatively low actuation voltage. In this paper, we will report on our current effort to create micro-cellular-manipulators by using laser-micromachining to process a commercial perfluorosulfonic acid polymer (Nafion®). Results from our experiments on the dependence of actuator motion due to input voltage and voltage output versus mechanical deflection are presented. Our goal is to optimally design and fabricate micron-scale sized force-feedback cellular manipulators base on these experimental results.

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. [9] 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. We reported an alternative and simpler method to over come the peeling and cracking problem of using gold coatings in [8], which summarized in this section.

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 Nafion should be roughed by fine sand paper (Class 1500).
- The sample should then be cleaned with HCl to remove impurities, followed by DI water rinse and Nitrogen drying.
- A seed layer (about 0.4μm) of gold should be deposited on both sides of the polymer film using E-Beam evaporation (see Section 2.2 below).
- A 2μm thick of gold should be deposited on top of the seed layer by chemical electroplating.

These gold-polymer composites produce as described above can withstand a high voltage (20V) without the electrodes peeling off.

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 (~2.25μm) 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-MACHINING PROCESS

Both CO_2 and Nd:YAG lasers were explored as a micromachining tool to micro-fabricate the Nafion 117 polymer film as described in [8]. CO_2 laser will cut the Nafion ICPFs without much difficulty, however it will not give as good a resolution as Nd:YAG laser. The trade-offs are presented below.

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 cuts Nafion ICPFs consistently if 7.5 W of power is applied. However, fibre-like residue usually accompanies the laser-processed polymer structures (see Figure 1). Nonetheless, this CO_2 laser system can be used to reliably micromachine Nafion structures with minimum feature size of ~200 μm at this time.

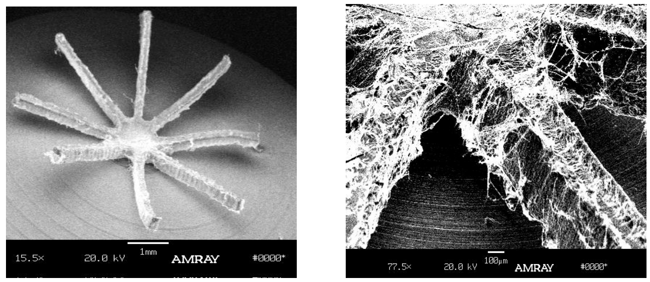


Figure 1. SEM pictures of Nafion structures laser-fabricated by a CO_2 laser system. The width of each arm is ~200 μm.

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 2. 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 1).

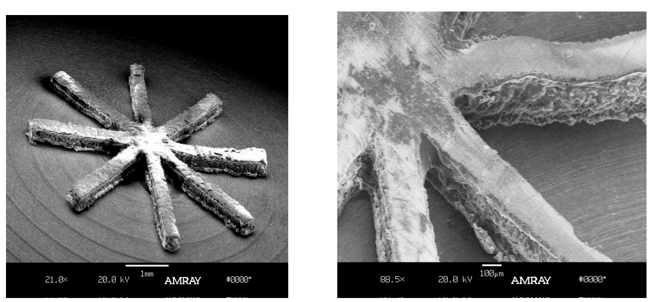


Figure 2. SEM picture of a Nd:YAG laser processed Nafion structure with each leg-width of 200 μm.

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. [10] are striving to produce a general workable model for ICPF actuators presently.

An in-situ measurement system was set up 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 3. 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.

The Young's modulus of our Nafion 117 actuators were experimentally obtained by using this setup to monitor tip-deflection versus applied force in-situ, and was determined to have an average value $1.32 \times 10^8 N/m^2$ [7,8], which is close to the value of $2.2 \times 10^8 N/m^2$ given by Kanno et al. [10] using laser deflection measurements for ICPF with dimensions of 10 mmx2 mmx184 μm.

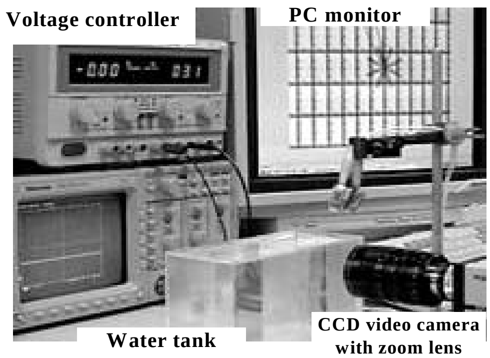


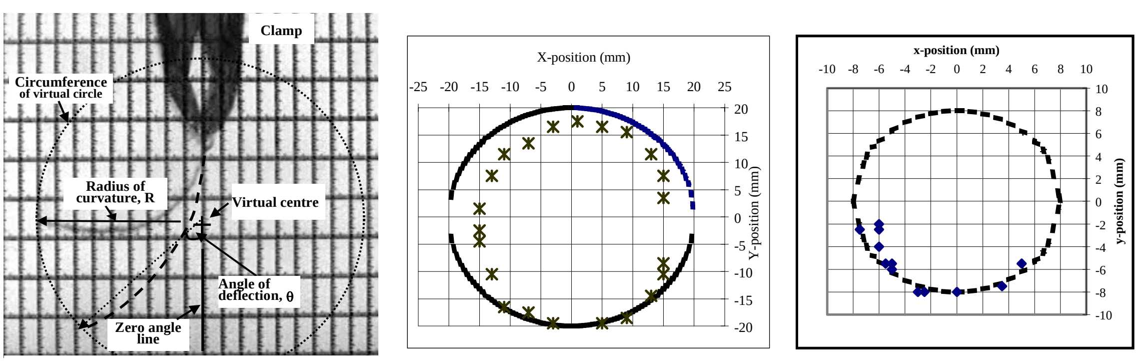
Figure 3. Picture of the in-situ monitoring setup for observing the motion of Nafion actuators.

5. PERFORMANCE OF NAFION ICPF ACTUATORS AND SENSORS

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 4 and can be described as an oval 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.



(a) (b) (c)

Figure 4. (a) Definitions of parameters used to quantify the deflection of an ICPF strip actuator. (b) Tip position of a 20mmx1mmx200μm ICPF strip during actuation. (c) Tip position of a 8mmx1mmx200μm ICPF strip during actuation.

5.2 EXPERIMENTAL RESULTS OF THE NAFION ACTUATION

Keeping the length of the actuator to 24 mm 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 5. 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 4), 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 5, 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 1 mm to 0.5 mm did not yield much improvement relative to width reduction from 1.5 mm to 1 mm. It should be noted that commercially available Nafion films are ~180 μm 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 6, rate of actuation for strips of ICPF with lengths of 8 mm, 16 mm and 24 mm were tested (each strip was 1mm wide, and a 4.5 V DC potential was applied across the electrodes). As indicated in the figure, for 8mm long strip, the maximum deflecting angle was 110° (13 mm); for 16 mm long strip, the maximum deflecting angle was 140° (28 mm); and finally, for 24 mm long strip, the maximum deflecting angle was 155° (48 mm).

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 7. 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 8. 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 9.

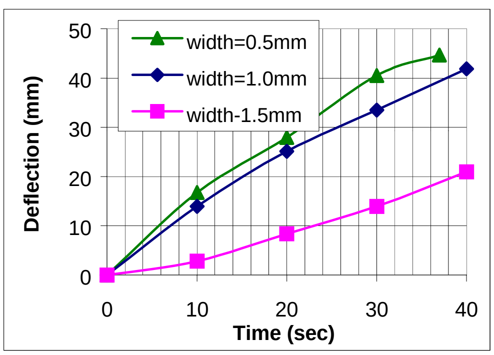


Figure 5. Rate of actuation for different widths of strip actuators (4.5V, l=24 mm).

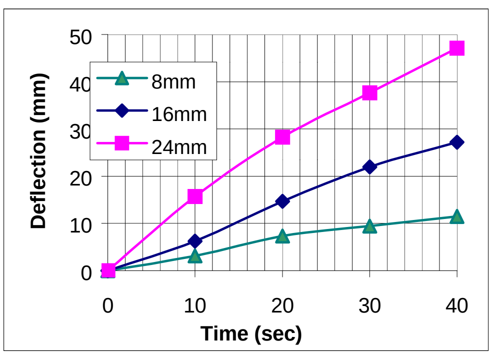


Figure 6. Rate of actuation for different lengths of strip actuators (4.5V, l=24 mm).

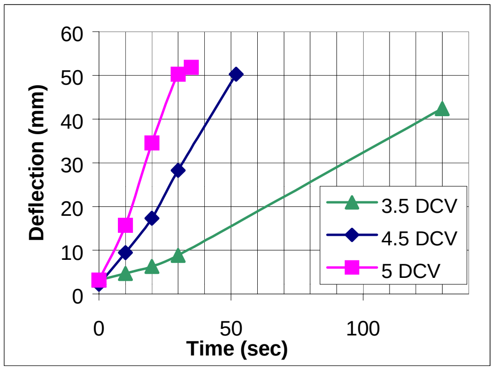


Figure 7. Deflection due to different applied voltage (4.5V, l=24 mm, w=1 mm).

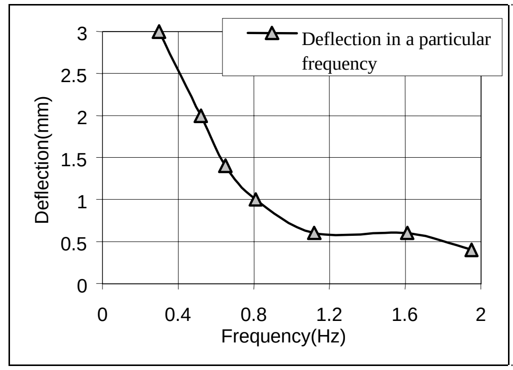


Figure 8. Actuator deflection versus driving voltage frequency (4.5V, l=24 mm, w=1 mm).

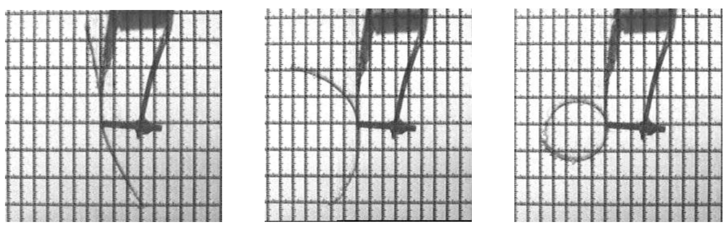


Figure 9. A 2-legs ICPF actuator which can be controlled to undergo a grasping motion under 4.5V in water.

5.3 ACTUATION OF MICRO-SCALE NAFION ACTUATORS

We have also successfully actuated actuators less than 500 µm wide under water. The smallest actuators we have successfully tested are with dimensions of *w=300 µm, l=3000 µm, t=200 µm*, using 15 V DC voltage (see Figure 10). 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.

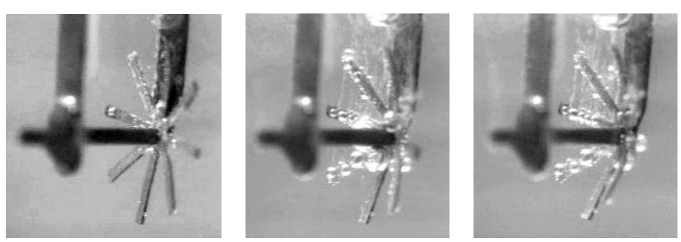


Figure 10. Time-sequence images of micro underwater Nafion actuators. The actuator shown has the dimensions of w=500mm, l=4000 mm, t=200 mm for each leg. The actuator was actuated with 15 V input voltage with 50 mA current to a tip deflection of ~1 mm.

5.4 EXPERIMENTAL RESULTS OF THE NAFION SENSING ELEMENTS

A beam of 24mm*1mm*200µm was deflected to understand the basic sensing characteristics of Nafion as a sensing material. The experimental results shown below were performed in air. A force is loaded on the tip to cause a displacement and then unloaded. Immediately, the beam vibrates and voltage output (without any signal processing) could be observed on an oscilloscope as shown in the figures below. In general, the following observations were made from several rudimentary experiments on Nafion sensing elements:

- Voltage output is proportional to sensing element deflection – detailed experiments are needed to quantify their relationship (compare Figure 11 and Figure 12).
- Mechanical damping characteristics are very consistent for sensing elements of this scale, i.e., if the same force were loaded on sensing elements of same dimensions and then unloaded, the vibration of the beam will damp out after the same number of oscillating cycles.
- The voltage output of a single sensing beam is polarized according to the direction of bending (compare Figure 11 and Figure 13).
- There exists a maximum saturation output voltage, i.e., beyond a certain loaded force, the voltage output will no longer increase (Figure 14).

We are currently performing much more detailed analyses on Nafion sensing elements to gain a much better understanding of their characteristics. We will then predict the sensitivities of Nafion sensors by scaling down the mechanical dimensions to determine their sensitivities at the micro-size scale.

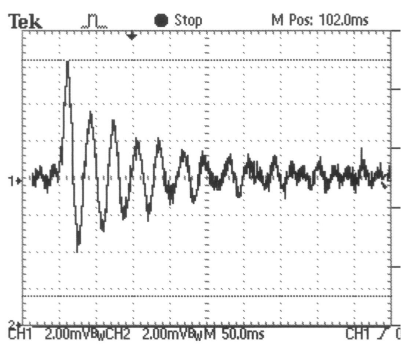


Figure 11. Transient voltage response of a Nafion sensing element. A force F1 was applied to the tip of a 24mm*1mm*200µm Nafion beam to obtain a tip deflection D1, and then F1 is unloaded to allow the beam to freely vibrate.

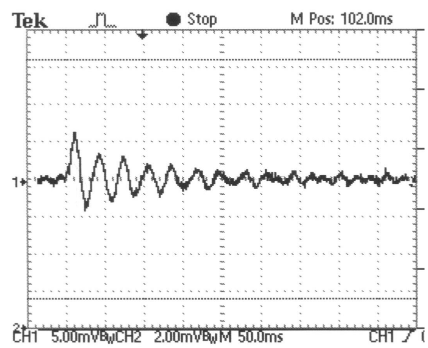


Figure 12. Same as the experiment performed in Figure 11, except that a force of F2 < F1 is used in this case.

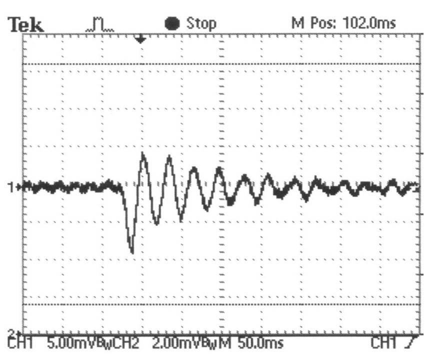


Figure 13. Same as the experiment performed in Figure 11, except that the beam was bend initially in the opposite direction as in the previous case. Note that the voltage output is asymmetric from the results shown in Figure 11.

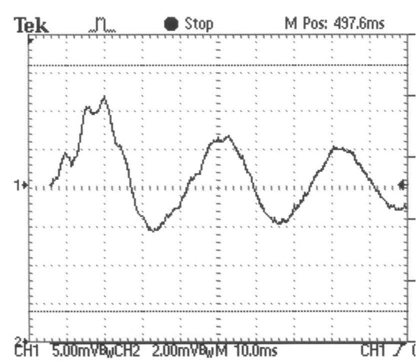


Figure 14. Output of a beam bend close to 180^o (as defined in Figure 4) and then allowed to freely vibrate.

6. FORCE FEED-BACK CONTROL EXPERIMENT OVER THE INTERNET

Since Polyvinylidence fluoride (PVDF) as a piezoelectric sensing material has similar electrical output characteristics as the Nafion sensing elements, i.e., Nafion ICPF sensors behave like piezoelectric sensors, we have initiated force-feedback experiments using PVDF micron-sized sensing structures. PVDF micro structures are much easier to process and has better voltage output sensitivity than Nafion ICPFs (from comparing our experimental results), they allow us to independently develop a force-feedback manipulation technology which can be used later even if the Nafion-sensing sensitivities are not sufficient for micro-cellular force-sensing-feedback manipulation. We have proved that piezoelectric voltage output characteristic can be used for force-reflection information over the Internet in [11]. This section summarizes the results of our findings.

The experimental results presented here relate to the testing of force-feedback control of an x-y stage using a PVDF tip-sensor between Hong Kong, China, and Michigan, USA. The computer codes for controlling the x-y stage can easily be converted to controlling micro Nafion manipulators in the future. During the experiment the operator from the Robotics and Automations Laboratory (RAL) of Michigan State University sends position increment commands and receives force feedback from an PVDF sensing element attached to an x-y positioning stage, which is located at the Advanced Microsystems Laboratory (AML) of The Chinese University of Hong Kong. The position increments are sent for both x and y axes while the force is sensed only in the y axis.

To emphasize the delay problem over the Internet Figure 15 shows a sample of round trip delay between the operator and the sensor. It is clear that the delay is random with no specific pattern or model. If not dealt with, this delay might cause instabilities and desynchronizations. However, as will be seen in the experimental results, we have used an "event-based" feedback control scheme to give a stable and synchronized system.

Figure 16 presents plots of the force felt by the operator, the force sampled from the PVDF sensor and the error between them. As seen, the force felt is closely following the one sampled from the sensor. Although this is not occurring at the same time instant, since both plots are with respect to local and not global time, the system is still stable and event synchronized. Despite the random time delay experienced between Hong Kong and Michigan Sate, the system performance is stable as seen from the error, which is constantly converging to zero and has a small value at all times. This implies that, for the given sampling frequency, the system is transparent. Meaning that in case the operator was controlling the sensor from a local machine a similar force profile would have been experienced.

Eventually, we hope to realize a complete system encompassing force, temperature, audio, and visual (which we termed *Supermedia*) information that can be supplied to a remote operator, and link and couple a human operator to the micro-cellular environment. This coupling will increase the efficiency and safety of manipulation at microscopic levels.

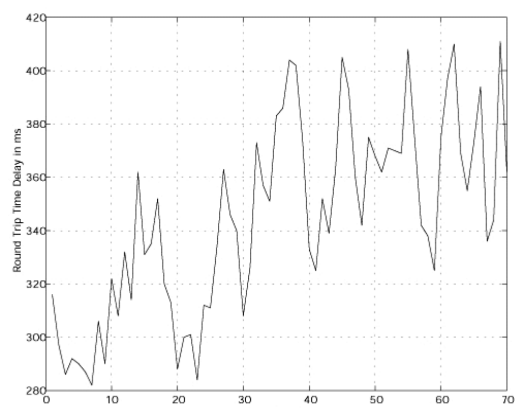


Figure 15. A sample of round trip delay between Hong Kong and Michigan.

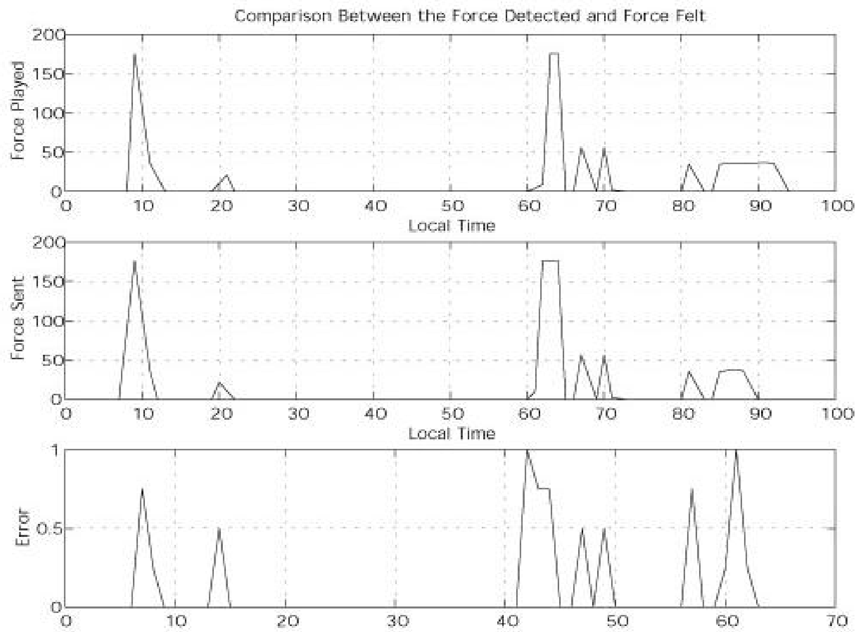


Figure 16. Comparison between the forces felt and the ones sent.

7. CONCLUSION

We have successfully micro-fabricated Nafion ICPF actuators using CO_2 and Nd:YAG laser systems. Features as small as 200μm were micro-fabricated successfully with a Nd:YAG laser system, and actuators with dimensions of w=300 μm, l=3000 μm, t=200 μm were successfully actuated under water with 15 V DC voltage. We have also performed parametric experiments to understand the behavior of Nafion actuators with variations of applied voltage and actuator geometries. Rudimentary experiments were also conducted on using Nafion ICPFs as sensing elements to sense mechanical forces. An Internet force-feedback experiment was also performed to validate that piezoelectric-type sensors can be used for force-feedback controlled haptical interface. The knowledge gained from these experiments will allow us to design and develop a *Supermedia* cellular-manipulation system using ICPF elements.

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. J. Ok, M. Chu, C. J. Kim, "Pneumatically driven microcage for micro-objects in biological liquid," *Proceedings of IEEE MEMS*, pp. 459-463, 1999.
2. E. W. H. Jager, O. Inganas, I. Lundstrom, "Microrobots for micron-size objects in aqueous media: potential tools for single-cell manipulation," *Science* **288,** pp. 2235-2238, 2000.
3. E. Smela, "Microfabrication of PPy microactuators and other conjugated polymer devices," *J. Micromech. Microeng.* **9**, pp. 1-18, 1999.
4. Y. Bar-Cohen, "Electroactive Polymer Actuators and Devices,", *Proceedings of SPIE on Smart Structures and Materials 2000*, Vol.3987, 2000.

5. M. Shahinpoor, Y. Bar-Cohen, J. O. Harrison, J. Smith, "Ionic Polymer-metal Composites (IPMCs) as biomimetic sensors, actuators and artificial muscles - a review". *Smart Mater. Struct*. **7**, No.6, pp. R15-R30, 1998.
6. S. Guo, T. Fukuda, T. Nakamura, F. Arai, K. Oguro, M. Negoro, "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*, 3, pp. 2226 –2231, 1996.
7. M. Y. F. Kwok, J. S. J. Qin, W. J. Li, "Micro Nafion actuators for cellular motion control and manipulation," *Proceedings of 3rd Asian Control Conference*, pp. 622-627, 2000.
8. Wen J. Li, Michael Y. F. Kwok, Julia S. J. Qin, and Y. S. Xu, "Micro Nafion actuators for cellular motion control and underwater manipulation", 7th International Symposium on Experimental Robotics (ISER 2000), Dec. 10-14, Honolulu, Hawaii, USA.
9. Y. Bar-Cohen, S. Leary, M. Shahinpoor, O. J. Harrison, J. Smith, "Electro-Active Polymer (EAP) actuators for planetary applications," *Proceedings of SPIE*, 3669-05 1999.
10. R. Kanno, S. Tadokoro, T. Takamori, K. Oguro, "3-Dimensional dynamic model of Ionic Conducting Polymer Gel Film (ICPF) actuator," *Proceedings of IEEE International Conference on Robotics and Automation*, 1, pp. 219 –225, 1996.
11. K. W. C. Lai, C. K. M. Fung, W. J. Li, I. Elhajj, and N. Xi, "Transmission of Hypermedia Information on Micro Environment via Internet", IEEE International Conference on Industrial Electronics, Control and Instrumentation 2000, October 22-28, 2000, Nagoya, Japan.