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Development of a Force-Reflection Controlled Micro Underwater Actuator

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Abstract

The ability to manipulate and control biological cells with reflective-force information is a key technology necessary for many new applications in Bio-MEMS, but is currently lacking in all cellular manipulators. We report in this paper our preliminary experimental work in using an Ionic Conducting Polymer Film (ICPF) to develop a biological cellular robotic gripper with force sensing capability. ICPF actuators are able to give large deflection with small input voltage (~5V) in aqueous environments, and also able to give relatively large output voltage due to deflection by mechanical forces. Thus, ICPF actuators are investigated as possible cellular force-reflection controlled manipulators in our work. 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 our ICPF actuators in this paper. 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, ICPF actuators, ICPF sensors, force-reflection micro manipulation, 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 in the biomedical 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 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 (made of metal-Nafion-metal composite film) actuators with width dimension less than 500μm in [7], and demonstrated a new breed of micro-scale actuators to the MEMS community: actuators 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 more detailed analyses of the experimental results from varying the geometries of the manipulators to understand their dynamic behaviors. Our goal is to optimally design and fabricate micron-scale force-reflective cellular manipulators base on these experimental analyses. In addition, the Nafion composites were also tested as sensors, which were shown to be sensitive to mechanical force. This creates the potential for the development of force-reflection micro actuators.

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2 FABRICATION OF THE NAFION ICPF ACTUATORS

The fabrication of ICPF actuators consists of two primary steps: 1) fabricate a composite of metal-Nafion-metal film and 2) use laser-micromachining to cut the Nafion ICPF film into actuators of desired sizes and shapes. These procedures are briefly described below.

2.1 Fabricating the ICPF composite layers

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. We reported a simple method to overcome the peeling and cracking problem of using gold coatings in [7], which allowed us to produce Nafion ICPFs that can be actuated at ~5V. The gold-polymer-gold composites produced as described in [7] above can withstand a high voltage (20V) without the electrodes peeling off.

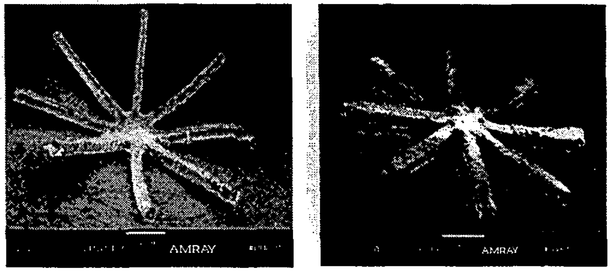
2.2 Laser Micro-machining Process

Both CO_2 and Nd:YAG lasers were explored as a micromachining tool to micro-fabricate the Nafion 117 polymer film. The Electrox CO_2 laser System, which is designed for cutting and masking organic materials, was used to process the Nafion composite. 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. We have also 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, we can consistently micromachine the Nafion polymers. A sample of a Nafion polymer structure cut by this system is also shown in Figure 1. 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.

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.

3 MECHANICAL PROPERTIES OF NAFION

In order to design functional micro underwater actuators, some fundamental studies on the mechanical behavior were performed on the Nafion composite actuators. Since these actuators are electro-activated devices made of composite materials that may undergo large deflections, close-form solutions for modelling the behavior 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. [8] are striving to produce a general workable model for ICPF actuators presently.



(a) (b)

Figure 1. (a) SEM picture of a Nafion structure laser-fabricated by a CO_2 laser system. The width of each arm is ~200 μm. (b) SEM picture of a Nafion structure processed by a Nd:YAG laser system.

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 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 composite actuators (24mmx1mmx200μm) were experimentally obtained by using this setup to monitor tip-deflection versus applied force in-situ, and was determined to have an average value $1.32 \times 10^8 N/m^2$, which is close to the value of $2.2 \times 10^8 N/m^2$ given by Kanno et al. [8] obtained using laser deflection measurements for ICPF with dimensions of 10 mmx2mmx184μm.

4 PERFORMANCE OF NAFION ICPF ACTUATORS

Experimental results from testing Nafion actuators with various geometrical and applied voltage variations are presented below. To actuate the Nafion actuators, we applied a voltage across the electrodes on the polymer, which bent toward their anode side.

4.1 Actuation of Nafion Actuators

We have successfully actuated actuators less than 500 μm wide under water. The smallest actuators tested were with dimensions of w=300μm, l=3000μm, t=200 μm, using 15V DC voltage. These actuators were found to have a ratio of tip-deflection/length smaller than the meso-scale (millimeter 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 working on a lithography-based fabrication technology to improve the geometrical resolution and reduce the minimum feature size of the Nafion actuators.

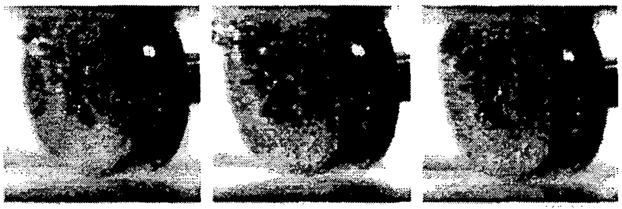


Figure 2. Time-sequence images of micro underwater Nafion actuators. The actuator shown has the dimensions of w=300μm, l=3000μm, t=200μm for each leg. The actuator was actuated with 15V input voltage at 50mA current

If a manipulator could be designed with an appropriate spring constant by choosing the correct geometric parameters, grippers can be fabricated. An example of an underwater grasp-manipulator made of a 2-arms ICPF actuator with each arm having dimensions of 16mmx1mmx200μm is shown in Figure 3.

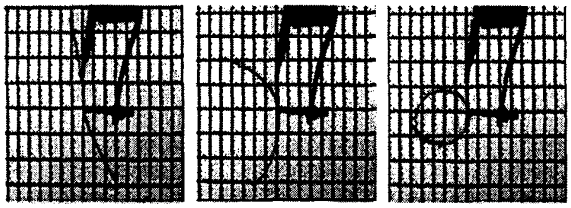


Figure 3. A 2-arms ICPF actuator which can be controlled using 4.5V to undergo a grasping motion in water.

4.2 Modelling of the Dynamic motion of the Nafion Actuators

To understand the dynamic behavior of the Nafion ICPFs as a function of their spring constant and applied voltage, experimental results were analyzed. Typical motion of Nafion actuators is shown in Figure 4. In this paper, "deflection" is defined as the distance of a trajectory traveled by the tip of an actuator as measured from the unactuated initial tip position.

Experimental results to determine the deflection as a function of time with varying actuator lengths are shown in Figure 5a. 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 the 8mm long strip, the maximum deflection angle was 13mm; for the 16mm long strip, the maximum deflecting angle was 28mm; finally, for the 24 mm long strip, the maximum deflection was 48mm. The tip trajectories for each of these actuators are shown in Figure 5b. It is interesting to note that each trajectory closely resemble a circle, with the radius defined by the actuator length.

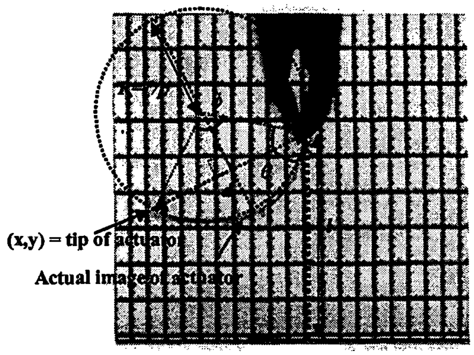


Figure 4. Definitions of parameters used to quantify the deflection of an ICPF strip actuator. Tip position and arm curvature of a 22mmx1mmx200μm ICPF strip during actuation is shown in the picture.

As shown in Figure 6a, the response of the actuators clearly is not a linear function of the width of the actuators, i. e., reducing the width from 1mm to 0.5mm did not yield much improvement in speed relative to width reduction from 1.5mm to 1 mm. 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. It should be noted, again, that the tip trajectories are circular, as shown in Figure 6b. However, the trajectories do not depend on the width of the actuators.

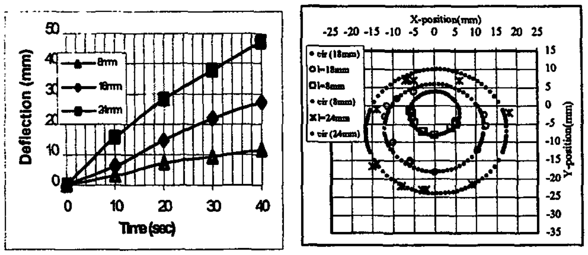
Apart from the length, actuating voltage can also affect the maximum tip deflection as well as the rate of actuation for the actuators. Voltage tests were carried out and the results are shown in Figure 7a. As shown, the frequency response and maximum tip deflection of the Nafion ICPF actuators are both affected by the input voltage. Also, again, the tip trajectories do not depend on the actuation voltage, as shown in Figure 7b.

From Figure 4, if the angular speed ω for an actuator is defined as $\Delta\theta$ over a time span Δt, then from our experimental data, ω is constant through the entire range of motion of the actuator, as along as the applied voltage remains constant through out the actuation. (Our experimental data also show the dependence of ω on w and the applied voltage, hence, we are currently performing a more thorough analyses.) Therefore, the tip position (x,y) as referenced from the origin, which is located at the fixed end of the actuator, can be calculated as:

$$x = d(\sin\theta), \qquad y = d(\cos\theta) \tag{1}$$

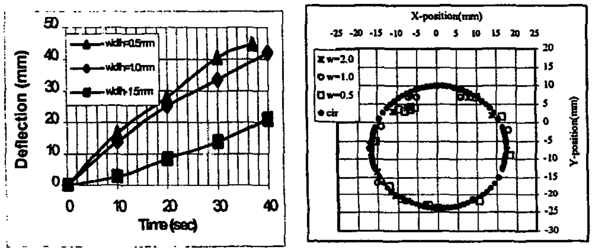
where

$$d = 2R(\sin\theta) \tag{2}$$



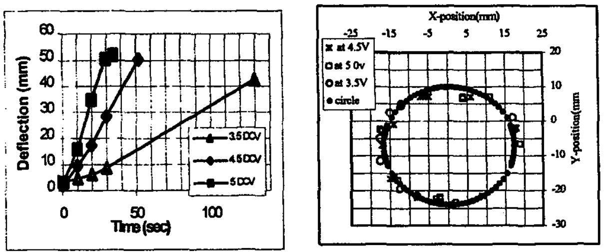
(a) (b)

Figure 5. (a) Tip deflection as a function of time for different lengths actuators. Each actuator was 1mm wide and 4.5V was applied to actuate the actuators. (b) The trajectory traveled by each of the actuators.



(a) (b)

Figure 6. (a) Tip deflection as a function of actuator width (24mm length at 4.5V). (b) Trajectory traveled by each actuator as a function of width.



(a) (b)

Figure 7. (a) Tip deflection as a function of voltage (24mmx1mm). (b) Trajectory traveled by the different actuators.

In (2), R is related to the radius of curvature of the actuated Nafion beam, or approximately equals half of the length of the actuator l. (1) and (2) are true only for $\theta > 0$, as the radius of curvature of the actuator ρ will approach ∞ when θ is zero. Based on (2), the tip trajectory of an actuator with any length l of fixed width and applied voltage can be predicted. Figure. 8 shows the modelled trajectories of the same actuators shown in Figure 5. Our current experimental setup prevented us from collecting tip trajectory data beyond a certain θ close to 180° due to the clamp used to apply the voltage across the electrodes to actuate the actuators. We are currently rebuilding our experimental setup to allow actuation of the actuators beyond 180°, so that we can further validate our model.

5. EXPERIMENTAL RESULTS OF NAFION ICPFS AS SENSING ELEMENTS

A beam with dimensions of 24mmx1mmx200µm was deflected to understand the basic sensing characteristics of Nafion ICPFs as a sensing material. The experimental results shown below were performed in air. A force was loaded on the tip to cause a displacement and then unloaded. Electrical signal was measured across the metal layers sandwiching the Nafion at the clamped end of the beam. Immediately, the beam underwent vibration and output voltage (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:

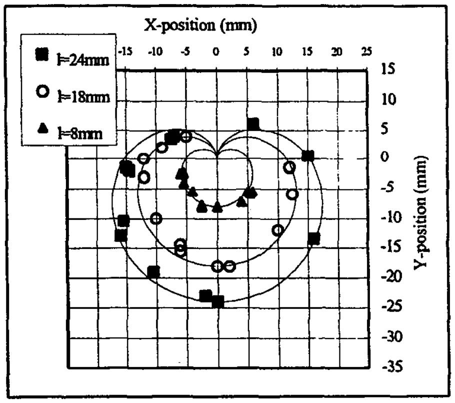


Figure 8. Comparison of the modelled trajectory to experimental observations.

- Voltage output is proportional to sensing element deflection – detailed experiments are needed to quantify their relationship (compare Figure 9 and Figure 10).
- Mechanical damping characteristics are very consistent for sensing elements of this scale.
- The voltage output of the beam is polarized according to the direction of bending (compare Figure 9 and Figure 11).

- There exists a maximum saturation output voltage, i.e., beyond a certain loaded force, the voltage output will no longer increase (Figure 12).

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 geometric dimensions to determine their sensitivities at the micro-size scale.

6. FORCE-REFLECTION CONTROL EXPERIMENT OVER THE INTERNET

We have initiated force-reflection experiments using Polyvinylidence fluoride (PVDF) sensing structures. PVDF (a piezoelectric material) structures are much easier to process and have similar output response characteristics as Nafion ICPFs but with much better unprocessed voltage output sensitivity than Nafion ICPFs. They allow us to independently develop a force-reflective manipulation technology in parallel with developing Nafion ICPFs as actuation and sensing devices. Although PVDFs are good sensors, very high voltages are required to actuate them through micron-level deflections, and hence, they are not suitable for manipulation applications.

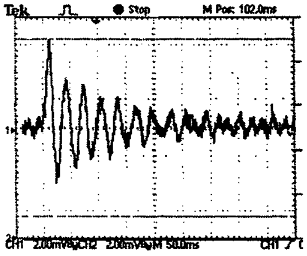


Figure 9. Transient response of a Nafion sensing element. A force F_1 was applied to the tip of a beam to obtain a tip deflection D_1, and then F_1 was unloaded to allow the beam to freely vibrate.

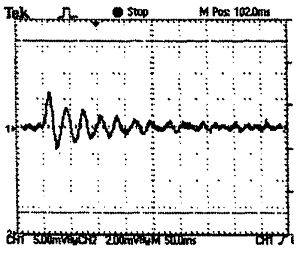


Figure 10. Same as the experiment performed in Figure 9, except that a force of $F_2 < F_1$ was used in this case.

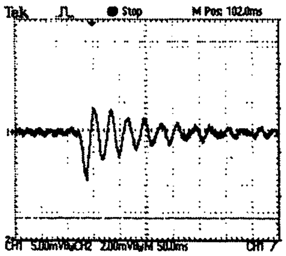


Figure 11. Same as the experiment performed in Figure 9, except that the beam was bend initially in the opposite direction as in the previous case.

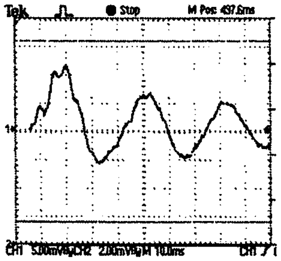


Figure 12. Output of a beam bend close to $\theta = 180°$ (as defined in Figure 4) and then allowed to freely vibrate.

We have proved that the PVDF piezoelectric voltage output characteristic can be used for force-reflection information over the Internet in [9]. The results are summarized below.

The experimental results presented here relate to the testing of force-reflection 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 control the 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 were sent for both x and y axes while the force is sensed only in the y axis.

The round trip delay over the Internet between the operator and the sensor was shown to be random with no specific pattern or model. If not dealt with, this delay might cause instabilities and desynchronizations. To address this problem, we have used an "event-based" feedback control scheme to give a stable and synchronized system.

Figure 13 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 followed 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 manipulation system encompassing force, temperature, 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.

7 ON-GOING WORK

Initial experiments on controlling the thickness of solution-based polymer film was performed using spin-coating technique. An example of film thickness versus spin-rate achievable is shown in Figure 14. Based on this result, we have initiated our process and mechanical design of micro Nafion actuators. Using the average of the Young's modulus determined by our experiments [7] and by Kanno et al. [8] ($E_{average}=1.76*10^8$ N/m), and the spring constant obtained from our experiments ($5.09*10^1$ N/m) which allowed the actuators to undergo a complete grasping motion, we have tabulated the allowable l/w ratio for micro actuators (Figure 15), and have initiated the lithographic fabrication of Nafion actuators. We will report on these results at the conference.

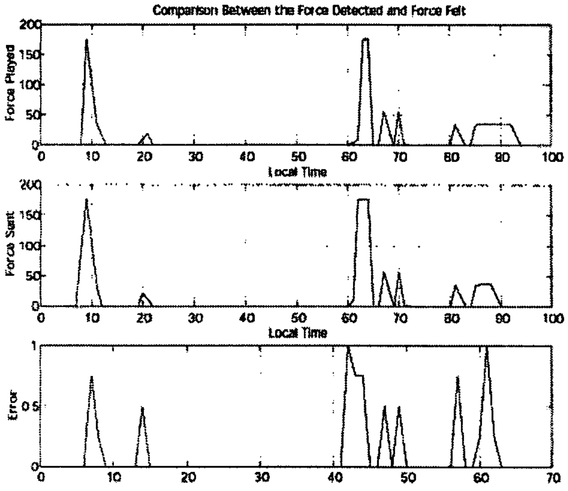


Figure 13. Comparison between the forces felt and the ones sent.

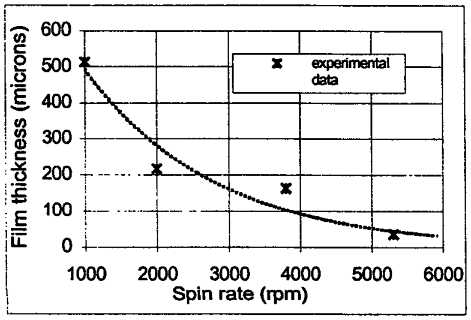


Figure 14. Comparison between the forces felt and the ones sent.

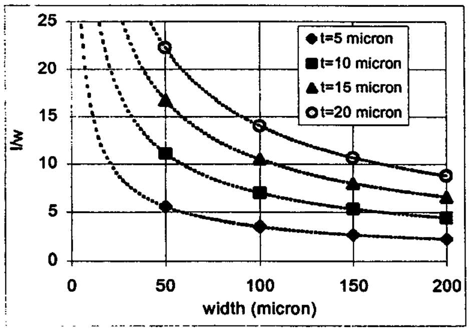


Figure 15. Comparison between the forces felt and the ones sent.

8 CONCLUSION

Nafion ICPF actuators were fabricated 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=300μm, l=3000μm, t=200μm were successfully actuated under water with 15V DC voltage. We have also performed parametric experiments to understand the behavior of Nafion actuators with variations of applied voltage and actuator geometries. A simple circular path was found to model the tip-deflection of the actuators quite well. 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 cellular-manipulation system using ICPF elements.

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