A Proposal for Manipulating Nafion Micro Actuators Using Neural-fuzzy Based Control

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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. However, an universally accepted or accurate dynamic model for ICPF actuators does not exit yet due to the complex interdependent physical mechanisms which govern their actuation behavior – electrical, chemical, and mechanical. This makes grasping control and manipulation hard to achieve, especially if the ICPF actuators are to be used in manipulating moving biological targets. In this paper we propose a neural-fuzzy based scheme to control the movement of ICPF micro actuators.

Keywords: micro aqueous actuators, ICPF actuators, cellular manipulation, neural-fuzzy control.

I. INTRODUCTION

Recent advancements in biology indicate that increasingly complex micromanipulation techniques for motion-control of biological cells are needed. The ability to study individual cells rather than averaged properties over a population is critical in unraveling the fundamental knowledge of biological systems. Many micromachined actuators now exist but 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 cells [1], slow frequency response and inability to control individual appendages of the grippers impede them from gaining general acceptance in the biomedical community. Conjugated polymers such as polypyrrole are also under investigation as aqueous microactuators [2] 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.

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. Thus, ICPFs have a high potential to be incorporated into actuators where a large displacement is desired. ICPFs have been investigated widely in the past decade, but only as *macro* actuators [3]. There is some development work in progress to use ICPF for micro applications [4], 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.

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 [5], 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. Some initial experimental results of actuating these actuators are given in [5]. In this paper, we will present a more detailed analysis of the dynamical behavior of ICPF. In actuating these actuators, it was found that the actuation voltage would affect the frequency response and displacement of the 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. Therefore, we propose to use a generalized neural network algorithm to controlling these actuators.

II. FABRICATION OF NAFION MICRO ACTUATORS

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. Nafion ICPF actuators were fabricated successfully using CO_2

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and Nd:YAG laser systems by our group [5]. Features as small as 200µm were micro-fabricated successfully with a Nd:YAG laser system (see Figure 1), and actuators with dimensions of w=300µm, l=3000µm, t=200µm were successfully actuated under water with 15V DC voltage.

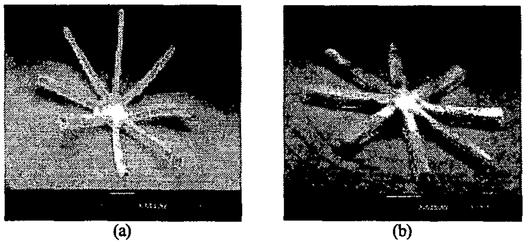

(a) (b)

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

III. Experimental Results of Nafion Actuation

An in-situ measurement system was set up to observe and quantify the deflection of the laser fabricated Nafion structures (Figure 2). 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, 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.

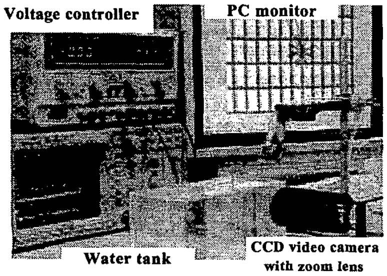


Figure 2. Picture of the in-situ monitoring setup for observing the motion of Nafion actuators.

A. *Two-Arm Grippers*

The smallest actuators tested underwater 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. A lithography-based fabrication process is under development to improve the geometrical resolution and reduce the minimum feature size of the Nafion actuators.

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.

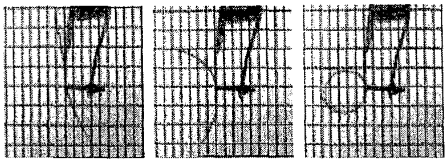


Figure 3. A 2-arms ICPF actuator which can be controlled using 4.5V to undergo a grasping motion in water.

B. *Nafion Structures as Sensors*

A beam with dimensions of 24mmx1mmx200µm was deflected to study the basic sensing characteristics of Nafion ICPFs as a sensing material. A force was loaded on the tip of the beam 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. The beam mechanical vibration versus its 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: 1) voltage output is proportional to sensing element deflection; 2) mechanical damping characteristics are very consistent for sensing elements of this scale; 3) voltage output of the beam is polarized according to the direction of bending; 4) a maximum saturation output voltage exists, i.e., beyond a certain loaded force, the voltage output will no longer increase.

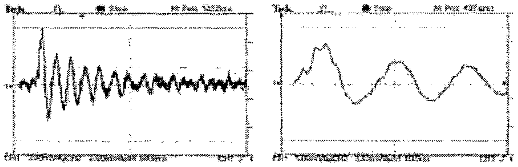

(a) (b)

Figure 4. (a) Transient response of a Nafion sensing element. A force was applied to the tip of a beam to obtain a tip deflection, and then the beam was unloaded to allow it to freely vibrate. (b) Output of a beam bend close to $\theta = 180°$ (as defined in Figure 5) and then allowed to freely vibrate.

IV. Parametric Experiments on Nafion Actuation

Parametric experiments were performed 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 (Figure 5).

Nafion actuators deflect at different rates depending on their structural geometry and actuation voltage. For instance, an actuator with a larger length/width ratio will deflect to a prescribe position faster than an actuator with smaller ratio, under the same applied voltage. Also, when the geometry is fixed, they respond faster under greater applied voltage. Experimental results to determine the deflection as a function of time with varying actuator lengths are shown in Figure 6a. 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). The tip trajectories for each of these actuators are shown in Figure 6b. It is interesting to note that each trajectory closely resemble a circle, with the radius defined by the actuator length.

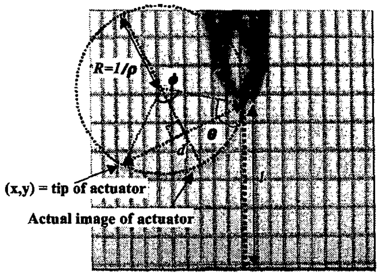


Figure 5. Definitions of parameters used to quantify the deflection of an ICPF strip actuator. Tip position and arm curvature of a 22mmx1mmx200μm ICPF strip during actuation is shown in the picture.

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.

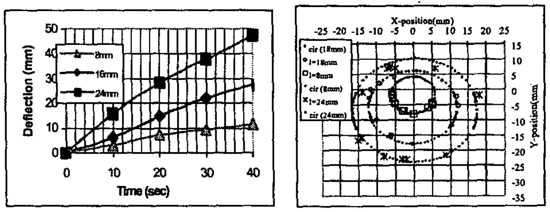
From Figure 5, if the angular speed ω for an actuator is defined as $\Delta\theta$ over a time span Δt, then from our experimental data, ω is constant through the entire range of motion of the actuator, as along as the applied voltage remains constant through out the actuation. (Our experimental data 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

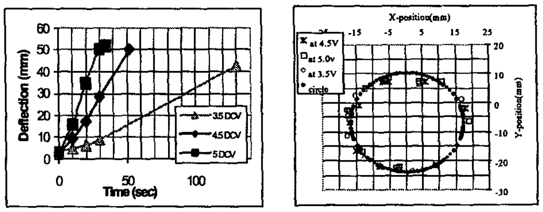
$$d = 2R(\sin\theta) \tag{2}$$

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 6. 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.



(a) (b)

Figure 6. (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 7. (a) Tip deflection as a function of voltage (24mmx1mm). (b) Trajectory traveled by the different actuators.

We are currently rebuilding our experimental setup to allow actuation of the actuators beyond 180°, so that we can further validate our model.

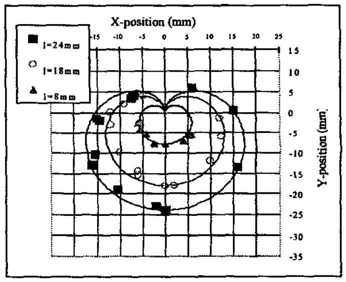


Figure 8. Comparison of the modelled trajectory to experimental observations.

V. PROPOSED ALGORITHM FOR ACTUATION CONTROL

The Generalized Neural Network (GNN) proposed to control the Nafion actuators is depicted in Figure 9, which was used successfully to control the trajectory of a 4-link shape memory alloy actuation system by K. F. Lei, et. al. [8]. There are 2 layers of neuron in the proposed GNN. Denote the neurons as N_i^1 (or N_j^2), $i = 1,\ldots,n_1$ (or $j = 1,\ldots,n_2$) for layer 1 (or layer 2), and also the input and output values of N_i^1 (or N_j^2) as x_i^1 (or x_j^2) and y_i^1 (or y_j^2), respectively. In this case, the neuron output is the same as the input, $y_i^1 = x_i^1$ (or $y_j^2 = x_j^2$), $i = 1,\ldots,n_1$ (or $j = 1,\ldots,n_2$) for layer 1 (or layer 2).

The main feature of the GNN here is that the connection in between layer 1 and 2 is now inserted a one variable fuzzy logic algorithm which utilizes product-sum-gravity (PSG) for implementation. As a result, the output of the GNN is

$$y_j^2 = x_j^2 = \sum_{i=1}^{n_1} \sum_{t=1}^{m_i} \mu_{A_{i,t}}(y_i^1) b_{j,i,t}\,, \tag{1}$$

where m_i is the number of membership functions corresponding to the i-th neuron in layer 1, $\mu_{A_{i,t}}(y_i^1)$ is the t-th antecedent set, $t = 1,\ldots,m_i$, corresponding to the i-th neuron in layer 1, and $b_{j,i,t}$ is the singleton rule consequent corresponding to the t-th antecedent set of the i-th neuron in layer 1 which is connected to the j-th neuron in layer 2 The neuro-fuzzy network depicted in Figure 9 has three inputs x_1^1, x_2^1, x_3^1 and three outputs y_1^2, y_2^2, y_3^2, and with $n_1 = 3$, $n_2 = 3$, $i = 1,\ldots,3$, $j = 1,\ldots,3$ and $m_i = 4$. As mentioned before, one advantage of the GNN is the fact that it maintains the same structure even after singular value-based reduction are carried out [8].

For each cantilever Nafion actuator, the proposed method will generate 1000 data sets for training. Each data set is obtained by first recording the current tip position of the cantilever (x_a, y_a), and then commanding a voltage (v_i) to the Nafion and measuring the resulting tip position of the cantilever (x_b, y_b). The voltage inputs are generated randomly within reasonable constraints so as not to damage the Nafion materials. The data set are then used to train a 4-inputs 1-output GNN network for the Nafion actuator in concern using the back-propagation training algorithm [9]. The inputs in this case are coordinates of the current position and the desired final position of the Nafion cantilever tip, and the output is the enabling voltage to apply to the Nafion cantilever. It is envisioned that the GNN will start with 4 membership functions for each input, making a total of 256 rules overall. The outputs are assumed singleton values. Upon training of the GNN, corresponding voltage to the Nafion actuator can then be generated to command its tip to traverse in prescribed path.

VI. 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. Basic parametric experiments were performed 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. The frequency response of the dynamic behavior of the actuators were found to depend on voltage, hence making position control of the actuator difficult. A generalized 3-input, 1-output neural network algorithm is proposed to control the position of the actuator. Experiments are underway to test the algorithm.

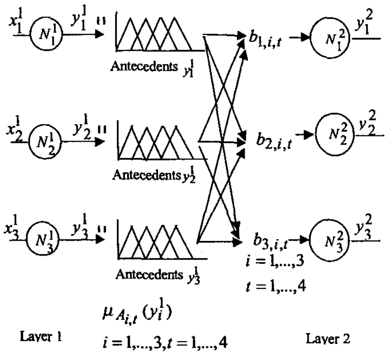


Figure 9. The GNN architecture ($n_1 = 3$, $n_2 = 3$, $i = 1,\ldots,3$, $j = 1,\ldots,3$ and $m_i = 4$).

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