IPMC Microgripper Research and Development

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Abstract. Described are the state of the art on designing and developing a microgripper using ionic polymer metal composites (IPMCs), an electroactive material, as an actuator to grasp and manipulate micro-sized flexible and rigid objects and yet also serve as a sensor for position feedback control. IPMCs, as a material, are compliant and can work in both wet and dry environments. This makes it ideally suited for both industrial operations, e.g., building micro-systems from MEMS components, as well as for a variety of bio-micromanipulation tasks, e.g., bacterium and cell handling. We derive a theoretical force model for the microgripper. The model estimates that an IPMC finger of dimensions 5mm x 1mm x 0.2mm exerts a force of 85 \(\mu\)N when grasping a solder ball of 15mg. We experimentally measure the load carrying capacity of the IPMC microgripper. Furthermore, we show empirically that the relationship between load carry capability and the length of microgripper fingers is linear. Experiments with three different microgripper finger shapes show that load carrying performance is related to the area of the finger rather than the shape. This implies that manufacturing ease favours microgrippers with tapered fingers. Finally, we show how flexible objects (hydrogel crystals in this case) are grasped with this IPMC microgripper.

1. Introduction

Microgripping finds applications in many areas such as assembly of microsystems and bio-micromanipulation. Assembly and testing of microsystems requires handling of MEMS components while bio-micromanipulation requires handling of flexible and fragile biological micro-objects such as cells and bacteria. There is great potential in developing a micro-robotic wetware system in the form of an integrated robotic microgripper/sensor array for active biological detection and robotic manipulation of micro-organisms such as bacteria, pathogens, metabolites, viruses, fungi, protozoa, lichens, slime molds, etc in a wet water environment. In the Phase I effort, small sub-millimeter samples of swollen polyacrylamide hydrogel were used for the simulation of soft microorganisms in a wet (water) environment. The micro-robotic wetware system was fabricated by an array of soft microgripper fingers made with ionic polymeric artificial muscles in sheets of less than 10 microns in thickness. Various microgripping solutions have been presented for assembly of MEMS components [1-11]. However only few microgripping technologies are suited for bio-micromanipulation [7], [12], [13]. Bio-micromanipulation has become a great technological challenge for the future of bioengineering, microbiology and genomics [14]. To get a better understanding of biological elements, it is necessary to analyze the properties of individual cells rather than averaged properties over a

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population. This requires operations such as positioning, grasping and injecting materials into a cell. Existing bio-micromanipulation techniques are mostly of non-contact type such as laser trapping, [15-16], electro-rotation, [17-18], and dielectrophoresis [19-20]. When laser trapping is used for bio-micromanipulation, a laser beam is focused through a large numerical aperture objective lens, converging to form an optical trap for the cell. However, in this process the high energy laser beam can damage or create abnormalities in the cell. Electro-rotation has also been used for micromanipulation of cells. In this technique electric fields of different magnitude and phase are applied to manipulate the cells. However, since the magnitude of the electric fields has to be kept low to ensure viability of cells, this technique cannot be used to hold the cell at a fixed position. These limitations of non-contact type micromanipulation make mechanical contact type micromanipulation desirable. Micropipettes have been used for microinjection of a transgene into a mouse embryo, [21]. However this method relies on bulky and expensive set-ups. Alternatively, the use of microgrippers for mechanically gripping and manipulating micro-objects to a desired position will be a promising solution to the above limitations. Since bio-micromanipulation is often carried out in a wet environment, the microgripper must be able to tolerate it. Cells, bacteria and embryos are flexible and fragile objects and hence the microgrippers should not exert large forces while handling them. For the same reason, the material for the fingers of the microgripper should be compliant rather than stiff so that the micro-objects are not damaged during handling.

This paper describes the design and test of a microgripper using an ionic polymer metal composite (IPMC), an electroactive material, as an actuator to grasp and manipulate micro-sized flexible and rigid objects. IPMC, as an ionic polymeric material, is compliant and can work in both wet and dry environments. Due to these advantages, an IPMC microgripper will be ideally suited for both industrial operations, e.g., assembly of micro-systems from MEMS components, as well as for a variety of bio-micromanipulation tasks, e.g., micro-organisms, bacterium and cell handling and manipulation.

2. Literature Review

Various actuator materials and microgripping mechanisms have been developed for micromanipulation applications. Zhang et al. [1] illustrate a shape memory alloy (SMA) microgripper used for tissue engineering. Shape memory alloys exhibit a limited bandwidth restricted by the heating and cooling cycles and hence have a slow response. A Microgripper using a piezo-actuator, reported by Goldfarb and Celenovic [2], requires high voltage for actuation and also results in a stiff microgripper and hence cannot be used for biological applications. Sun et al. [11] use an electrostatic actuator for microgripping. The resultant microgripper is found to be stiff and also cannot be actuated in an aqueous medium. Menciassi et al. [4] have proposed a microgripper using an electromagnetic moving coil actuator. This technology also yields a stiff microgripper and also cannot work in a wet environment. Kim et al. [5] have used Lorentz force-type actuators like voice coil motors for generating the microgripping action. However, use of this microgripper in wet environment has not been demonstrated. Zesch et al. [6] use a glass pipette with controllable vacuum tool to grasp and release micro-objects [6]. This system was demonstrated by placing micro diamonds. The vacuum mechanism provides very little flexibility in control and also yields a fragile micro-gripper. Arai and Fukuda [7] have proposed a method for micromanipulation that utilizes pressure change based on temperature change inside the micro holes made on the end effector surface. The temperature cycling effects limit the speed at which objects can be manipulated. Also this method will not work in liquid medium. Chan and Li [8] propose a thermally actuated polymer based microgripper that is actuated in a liquid medium. This microgripper works like a trimorph due to the difference in the coefficient of thermal expansion of the layers of different materials. However, the trimorph requires an actuation temperature of at least 60°C, which might damage biological cells. Haliyo [9] presents an approach to manipulate micro-objects using adhesion forces and dynamical effects. In this system, the grasping is effected by adhesion between the end-effector and the object, while dynamic effects such as inertia are
used to carry out the release operations. However, experimental results regarding manipulation of flexible objects with this technique have not been reported.

For secure manipulation of objects, researchers are working towards the development of a force and position sensing mechanism for microgrippers. The piezoelectric microgripper by Goldfarb and Celanovic [2] uses strain gauges to measure the gripping force. Sun et al. [3] propose a position controlled microgripper with electrostatic actuators using capacitive sensing for position feedback. The voice coil motor (Lorentz force type actuator) actuated microgripper uses a piezoelectric polymer PVDF (polyvinylidene fluoride) film to sense the force (Kim, et al., [13]. Shen et al. [11] have also used PVDF film as sensor for assembly of micro-mirrors. Keller [12] describes micro tweezers manufactured by the helix process. He used piezoresistive strain gauges to obtain tactile feedback during grasping. Unfortunately these tweezers are particularly fragile. Corrozza et al. [22] present a LIGA fabricated force controlled microgripper by mounting semiconductor strain gauge sensors at flexure joints of the gripper. However, the strain gauge sensors will not work when manipulating in a wet environment.

Most of the microgrippers discussed above are either stiff, fragile or do not work in wet environment and therefore have limitations in handling delicate micro-objects. Stiff microgrippers damage fragile and flexible micro-objects during handling and fragile microgrippers lack longevity. We previously developed a prototype IPMC microgripper and preliminary manipulation experiments with flexible objects were demonstrated. The motivation behind this research work is to develop a microgripper using IPMC artificial muscles that will be able to grasp and manipulate micro-sized flexible as well as rigid objects. The paper describes the design and fabrication of the microgripper, theoretical force model for the microgripper and several manipulation experiments with rigid and flexible objects.

3. Review of IPMC Material

Ionic Polymer Metal Composites (IPMCs), that are actually nano-composites because of molecular plating of electrodes, is a novel material belonging to the class of ionic electroactive polymers. An ionic polymer can absorb a polar solvent such as water, which serves as the ion transport medium. This polymer exhibits large deformation when voltage across its electrodes produces an electric field (Shahinpoor, et al. [23-26]). The voltage required for actuation of IPMC actuators is very low, often less than 5V. The displacement shown by an IPMC membrane on application of 3V of actuation voltage can be seen in figure 1(Shahinpoor, et al. [23-26]).

![Figure 1. Displacement of an IPMC actuator (1cmx4cmx0.2mm) on application of 3V signal](image)

Recent research has shown that IPMC membranes exhibit electroactive behaviour in both dry and wet environments (Shahinpoor, et al. [23-26]). The electroactive characteristics of IPMC membranes can be modelled by an equivalent electronic circuit (Paquette, et al., [27], Leary et al. [28] and Deole, et al., [29]), where the IPMC membranes are mostly capacitive at low frequencies and resistive at
higher frequencies. Deole et al. [29] have reported the change in the impedance properties of an IPMC with size. It is observed that when an IPMC membrane is cut into smaller sizes its impedance increases. (970Ω for a membrane of size 35mm x 17mm x 0.2mm; 4320Ω for 35mm x 5mm x 0.2mm and 13000Ω for 6mm x 20mm x 0.2mm, at a frequency of 5Hz). It is seen that the response of an IPMC membrane to an electric signal depends upon its inherent impedance properties. Since these impedance properties are present at a micro-scale level within the material, an IPMC membrane shows electroactivity even at that size (Shahinpoor, et al. [23-26]). The various advantages of IPMC actuators can be summarized as follows:

i) Low actuation voltage (less than 5V for larger actuators, less than 1 V for microactuators) and relatively large displacement.

ii) Flexible and compliant material. (Young’s Modulus ~ 200MPa)

iii) It can be cut to micro size without loss in actuation and sensing properties.

iv) Fast response (microsecond to second).

v) Lightweight.

vi) Comparatively inexpensive. ($20 per cm$^2$)

vii) Excellent longevity (~ 10 million cycles of vibration)

viii) Large force density (40 gmf/gm of actuator mass for a cantilever actuator)

It is clear that an IPMC membrane does not produce extremely large forces due its compliant nature. At the micro-scale, however, this actually becomes an advantage because objects will not be damaged when handled by an IPMC microgripper. This is especially important for bio-micromanipulation.

4. Design and Fabrication of IPMC Microgripper

4.1. IPMC microgripper configuration and design criteria

Following the work of Deole, et al., [29-32] and Lumia, et al., [33-34], figure 2 shows the IPMC artificial muscles in the microgripper configuration. In this configuration, the two IPMC fingers, cut from a sheet of IPMC material, are carried by a support structure and then actuated in such a way that the fingers work in tandem as a microgripper.

![Figure 2. Basic configuration of artificial muscle microgripper](4th World Congress on Biomimetics, Artificial Muscles and Nano-Bio IOP Publishing Journal of Physics: Conference Series 127 (2008) 012002 doi:10.1088/1742-6596/127/1/012002)

Based on this basic configuration, the design criteria of the IPMC microgripper are discussed below. To achieve coordinated opening and closing of the microgripper fingers, both electrical connectivity and mechanical rigidity between the IPMC fingers and the electrodes must be maintained. The actuation of the fingers requires a high quality electrical contact between the wires and the electrodes, which becomes increasingly problematic as the size of the structure decreases. Uniform
bending, which requires a uniform electric field, will ensure that the fingers remain aligned correctly so as to close around an object. To achieve this, the structure of the microgripper must prevent any finger slippage. Once again, as the size of the microgripper decreases, the mechanical structure that holds the fingers in place becomes difficult to fabricate.

The load carrying capacity of the IPMC microgripper depends on two parameters: the force the fingers exert and the length to width ratio of the fingers. Since the force density of the IPMC material remains constant, it is not surprising to find that fingers with larger area are needed for manipulating heavier objects. The mechanical structure that holds the fingers must accommodate a variety of IPMC fingers that depend on the size and weight of the objects that are grasped. Based on these needs, we designed and fabricated the microgripper structure that we call the “Pincher.”

4.2. Pincher design
Figure 3 illustrates the assembled and the exploded view of the pincher design for the microgripper. The pincher eventually is attached to a gross manipulator that moves the IPMC fingers near a desired object. Each component of the pincher is described in the following sections.

1) Pincher
The pincher opens and closes by squeezing a spring. It has two arms made of an acrylic material. These two arms have metal electrodes that are used to actuate the IPMC fingers. The spring force helps to maintain a rigid mechanical contact as well as a good electrical connection between the electrode and the fingers.

2) Common Electrode
It is basically a gold plated metal piece and forms the common electrode for the two fingers, as shown in Figure 3b.

3) IPMC finger design
As mentioned earlier the fingers are cut from a sheet of IPMC material. The shape of each finger, as shown in figure 4, has a large base leading to the actual microgripper finger. Keep in mind that for the
smallest objects we hope to grasp, the finger might approach 25 x 125 microns with a base of perhaps 100 x 150 microns. This particular configuration is advantageous because:

1) It will be possible to see the base with a naked eye, thus facilitating assembly of the fingers into the pincher.
2) The base makes it possible to attach a wire to the finger. The smallest wire that we use has a diameter of 200 microns.

Each of these fingers is assembled in the pincher in such a way that it connects with one of the electrodes of the pincher on one side and with the common electrode on the other side. The exploded view (figure 3 (b)) illustrates the assembly procedure for the IPMC fingers in the pincher.

5. Microgripper Force Model
A microgripper force model is developed to estimate the force exerted by the IPMC fingers when grasping an object. The input for the model is the weight of the object being lifted and the output is the amount of force that needs to be exerted by the IPMC fingers to grasp that object securely. We have the following assumptions:

- The object is spherical in shape.
- The object and the IPMC fingers contact at the tip of the IPMC fingers (figures 5 and 6).
- The tip displacement curve (figure 7), showing the tip deflection of IPMC fingers of various lengths (depicting the shape of an actuated finger), does not change substantially when in contact with the object.
Figure 5—Microgripper Grabbing an Object with Axial Force \( F \)

\[ F = \text{Frictional force} \]

\[ N = \text{Normal reaction} \]

\[ \mu = \text{Coefficient of friction between platinum and solder ball} = 0.3 \]

\[ \theta = \text{Angle of contact between IPMC finger and solder ball} \]

\[ m = \text{mass of the micro-object} \]

\[ g = \text{acceleration due to gravity} \]

By using the static equilibrium condition for the free body diagram shown in Figure 6, we obtain

\[ 2F \cos \theta = 2N \sin \theta + mg \]

(1)

Since the friction is proportional to the normal force, i.e., \( F = \mu N \), we can derive the normal force that the microgripper finger must exert.

\[ N = \frac{mg}{2\mu \cos \theta - 2 \sin \theta} \]

(2)

\( N \) is the normal reaction exerted by the solder ball and is equal and opposite to the force exerted by each IPMC finger. Therefore, equation (2) computes the force that an IPMC finger exerts to grasp a sphere of known weight.
Angle of Contact: figure 7 shows the displacement of the tip of the IPMC fingers of various lengths on application of a 2V signal. The equation for the curve is

\[ y = 0.0266x^2 + 0.1293x \]  

The displacement plotted in figure 7 is the free end deflection of the IPMC fingers. For modelling purposes, it is assumed that the tip displacement curve of the IPMC finger is the same for free space motion and when the tip is in contact with the sphere. The angle of contact clearly varies with the length of the IPMC finger. We can find this angle by taking the derivative of the equation of the curve in figure 7.

\[ \frac{dy}{dx} = 0.0532x + 0.1293 = \tan \theta \]  

By substituting the finger length, \( x \), into equation (4), we compute the angle of contact (figure 8) between the object and the IPMC finger. Substituting the angle of contact into equation (2), the force exerted by the IPMC fingers for securely gripping the sphere is computed. This theoretical gripping model helps to estimate the amount of force exerted by the IPMC fingers for gripping a spherical object of known weight. This model can also be used to determine the appropriate finger size for manipulating a micro-object of known weight.
6. Micromanipulation Experiments
The main objectives of the micromanipulation experiments were to:
1) Measure the performance of the microgripper in terms of ability to grasp and release flexible and rigid micro-objects.
2) Measure the load carrying capacity of a microgripper and find the relationship between the finger lengths and load carrying capacity.
3) Understand empirically the effect of finger shape on the load carrying capacity of the microgripper.

6.1. Experimental set-up

Figure 9 shows a schematic of the experimental test set-up. A multifunction I/O board (National Instruments, AT-MIO-16E2) and corresponding SCXI devices and terminals (National Instruments, 1000, 1121, 1302 and 1321) are controlled by the NI Labview 7.0 Express. To generate the actuation signal the function generator.vi provided in the DAQ of Labview 7.0 is used. An analog voltage signal of desired amplitude and frequency is generated with the help of this program. This signal is first fed to a power amplifier (Techron model 7521) and then used to actuate the fingers of the microgripper. The analog signal from the amplifier is also fed into an oscilloscope (Nicolet 2090) for monitoring purposes.

6.2. Rigid object micromanipulation
Rigid micro-objects were made out of solder, ranging in size from 100 to 1500 microns in diameter. The solder balls were roughly spherical in shape. The microgripper was driven by a 2V signal. Figure 10 shows the microgripper manipulating a solder micro-ball. The length, width and thickness of the finger are 5mm, 1mm and 0.2 mm, respectively. Thus it can be inferred that the IPMC fingers produce enough force to grasp a spherical solder ball that weighs approximately 15mg. In the next sections, the load carrying capacity of different sized IPMC fingers is measured and a relationship between finger length and load carrying capacity is established.

6.3. Load carrying capacity
To calculate the load carrying capacity of an IPMC microgripper, a simple method using pre-weighed micro-objects was adopted. The microgripper lifted solder micro-balls of increasing weight until it failed to lift one. The weight of the heaviest ball that the microgripper is able to lift is then designated...
to be its load carrying capacity. Though the approach lacks the sophistication of using a load cell (that are very expensive at these small force levels) to measure the force that the fingers can exert, it measures the load carrying capability in precisely the way the microgripper will be employed in an application, i.e., carrying an object. Consequently, this somewhat crude approach may in fact be the best way to measure load carrying capability.

During this experiment, the actuation voltage was kept constant at 2V. The microgripper (figure 10) with fingers having dimensions- 5mm x 1mm x 0.2mm was measured to have a load carrying capacity of 15mg. The weight of each IPMC finger was measured to be 2.1mg. Thus the IPMC fingers were able to lift a weight more than seven times the weight of each finger.

Substituting x=5mm in equation (4), the angle of contact is found out to be 21.57°. Knowing the mass of the solder micro-ball, 15 x 10^-6 kg, and assuming a coefficient of friction between platinum and solder of 0.3, the force exerted by the IPMC fingers can be calculated using equation (2) to be 85 µN.

It is noticed that the IPMC fingers exert a very small force on the object. Due to such a small force, it can be concluded that IPMC fingers will not puncture flexible and fragile micro-objects during manipulation. The force exerted by the fingers is a function of finger length and hence by choosing an appropriate finger size we can easily manipulate any micro-object of known weight.
Optimum finger length
To find the optimum finger length for an IPMC micro finger, microgripping experiments were carried out with various lengths of fingers. The experimentation started with a 12mm x 1mm x 0.2mm finger and its load carrying capacity was measured by the method described earlier. Keeping the width and thickness constant, the fingers were cut to 10mm, 8mm, 6mm and 4mm and the load carrying capacity was measured for each size. As shown in figure 11, the results show a linear relationship between the load carrying capacity of a microgripper and the finger length. There is an inherent trade-off between finger length and strength. As the length of the finger decreases, the amount of tip displacement also decreases. Consequently, the microgripper with shorter fingers must be positioned more accurately with respect to an object than the microgripper with longer fingers. Since the weight and size of objects are application dependent, it is possible to tailor the finger length to satisfy the goal of carrying a range of object weights.

Figure 11. Load carrying capacity vs. finger length

Figure 12. IPMC micro fingers
i) tapered fingers ii) straight fingers iii) straight fingers of a single piece

6.4. Optimum finger length
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7. Effect of IPMC Finger Shape on Microgripper Performance
Since microgripper fingers are cut from a sheet of IPMC material using a micro-surgical scalpel, the shape of the fingers is arbitrary. The issue is whether certain shapes are inherently better than others in terms of microgripper load carrying capability. Three different shapes of fingers are shown in figure 12. The first type is the tapered finger, where the advantage is ease of fabrication. The straight fingers of figure 12 (ii) have been the traditional fingers we have used. The straight fingers of figure 12 (iii) create the fingers from a single piece of IPMC. The advantage of this approach is that the material is simply folded with a pair of electrodes placed in the middle to create the microgripper. The hope was that it would be easier to align the fingers in the pincher with a single piece of IPMC than with multiple fingers. Using the same experimental procedure as in Section 6, the load carrying capacity for each finger shape was measured. These data are shown in Table 1. Note that the total area of each finger is roughly the same.

Table 1 shows that all the fingers have approximately equal load carrying capacity. Since this is the case, the logical approach is to use a finger shape that is the easiest to fabricate with the micro-surgery scalpel. The tapered fingers (figure 12 i) are currently the easiest to fabricate, and in the future we will be using them. The folding version (figure 12 iii) actually proved more difficult to use than the others because folding the finger and placing it in the pincher often misaligned the fingers. This shape has been abandoned.

| Shape of Finger                  | Area of Finger (mm^2) | Load carrying capacity (mg) |
|---------------------------------|-----------------------|-----------------------------|
| Tapered fingers                 | 6                     | 16                          |
| Straight fingers                | 5                     | 15                          |
| Straight fingers of a single piece | 5                   | 15                          |

8. Flexible Object Micromanipulation
This experiment assesses the performance of the microgripper in the manipulation of flexible objects. Flexible objects were made from polyacrylamide hydrogels which are hygroscopic in nature. When hydrated, the small particles of hydrogel swell to form flexible micro-objects. The microgripper was then used to grasp and manipulate these flexible objects. Figure 13 shows the microgripper gripping one. It was observed that even when the fingers are open, the flexible object would occasionally stick to the fingers. This sticking effect is due to the surface tension force generated by the wet hydrogel objects.

It is already seen that the IPMC fingers exert a very small force (85μN) while handling a microsolder ball having a weight of 15mg. Since, the IPMC microgripper exerts such a small force during gripping it can be seen that the delicate flexible hydrogel objects are not damaged during manipulation.
9. Conclusions and future work
The basic functional requirements and the related design criteria for development of an IPMC microgripper were discussed. A pincher design for an IPMC microgripper was fabricated and tested. The microgripper was able to lift an object more than seven times the weight of each finger. A theoretical force model was developed for the microgripper and the model estimated that an IPMC finger (5mm x 1mm x 0.2mm) exerted a force of 85 µN. Therefore it can be seen that the force exerted by the IPMC fingers is very small. Due to the low magnitude of forces and the compliant nature of the IPMC fingers, it is fair to conclude that the IPMC microgripper is perfectly suited for the manipulation of bio-materials. Related to the low forces exerted by the microgripper fingers, compliance is shown in figure 14 where a finger makes contact with a surface. It was also found that the load carrying capacity of a microgripper increases when the finger length is reduced (width and thickness remaining constant).

The micro IPMC fingers are currently cut using an inexpensive micro-surgical scalpel from a larger piece of IPMC material. Though this fabrication method is inexpensive as compared to other microgripper manufacturing methods such as LIGA, surface micromachining or micro-electro discharge machining, it is limited to perhaps 300-400 microns. In the future, we will use lasers to cut smaller fingers.

It was also observed that the flexible objects often stick to the fingers during release. It is not unreasonable to expect very small rigid micro-objects, e.g., less than 100 microns in diameter, to behave in a similar manner. In future work we plan to address these sticking effects. Finally, this paper examined IPMC fingers as actuators that can behave as sensors, too (see the attached list of references for the sensing properties of IPMC). We plan to make a closed loop feedback control system for a microgripper using an actuator/sensor sandwich. The sensor will measure how far the actuator moves and the control system will use this measurement to command the actuator.

Acknowledgements
This work has been supported by the NSF under the Grant IIS-0329106.

10. References
[1] H. Zhang, Y. Bellouard, T. Sidler, E. Burdet, A. N. Poo, R. Clavel, “A Monolithic Shape Memory Alloy Microgripper for 3-D Assembly of Tissue Engineering Scaufs,” Proceedings
of SPIE-Microrobotics and Microassembly III, B. J. Nelson and J-M Brugedts, 4568, Boston, MA, October 29-30, 2001, pp. 50-60.

[2] M. Goldfarb and N. Celanovic, “A flexure-based gripper for small scale manipulation,” Robotica, 1999, vol. 17, no. 2, pp. 181-188.

[3] Y. Sun, D. Piyabongkarn, A. Sezen, B. J. Nelson, R. Rajamani, R. Schoch, D.P. Potasek, “A Novel Dual-Axis Electrostatic Micro-Actuation System for Micromanipulation,” Proceedings of International Conference on Intelligent Robots and Systems, EPFL, Switzerland, October 2-4, 2002, pp. 1796-1801.

[4] A. Menciassi, B. Hannaford, M. C. Carrozza, Paolo Dario, “4-Axis Electromagnetic Microgripper,” Proceedings of International Conference on Robotics and Automation, Detroit, Michigan, May 10-15, 1999, pp. 2899-2904.

[5] S. M. Kim, K. Kim, J. H. Shim, B. Kim, D. H. Kim, C. C. Chung, “Position and force control of a sensorized microgripper,” Proceedings of International Conference on Control, Automation and System, Muju Resort, Jeonbuk, Korea, October 16-19, 2002, pp. 319-322.

[6] W. Zesch, M. Brunner, A. Weber, “Vacuum Tool for Handling Microobjects with a Nanorobot,” Proceedings of International Conference on Robotics and Automation, Detroit, Michigan, May 10-15, 1999, pp. 2899-2904.

[7] F. Arai, T. Fukuda, “Adhesion-type Micro endeffectors for Micromanipulation,” Proceedings of the International Conference on Robotics and Automation, Albuquerque, NM, April, 1997, pp. 1472-1477.

[8] H. Y. Chan, W. J. Li, “A Thermally Actuated Polymer Micro-robotic Gripper for manipulation of Biological Cells,” Proceedings of International Conference on Robotics and Automation, Taipei, Taiwan, September 14-19, 2003, pp. 288-293.

[9] D. S. Haliyo, S. Regnier, “Manipulation of micro-objects using adhesion forces and dynamical effects,” Proceedings of International Conference on Robotics and Automation, Washington, DC, May 11-15, 2002, pp. 1949-1954.

[10] D. H. Kim, B. Kim, H. Kang, “Development of piezoelectric polymer-based sensorized microgripper for microassembly and micromanipulation,” Journal of Microsystem Technologies, Volume 10, 2004, pp. 275-280.

[11] Y. Shen, N. Xi, W. J. Li, “Force-Guided Assembly of Micro Mirrors,” Proceedings of International Conference on Intelligent Robots and Systems, Las Vegas, Nevada, October 27-31, 2003, 2149-2154.

[12] C. G. Keller, “Microgrippers with Integrated Actuator and Force sensors,” Proceedings of the International Symposium on Robotics and Automation, World Automation Conference, Anchorage, AK, May 1998.

[13] H. Y. Chan, W. J. Li, “A Thermally Actuated Polymer Micro-robotic Gripper for manipulation of Biological Cells,” Proceedings of International Conference on Robotics and Automation, Taipei, Taiwan, September 14-19, 2003, pp. 288-293.

[14] U. Deole, R. Lumia, M. Shahinpoor, “Grasping flexible objects using artificial muscle microgrippers,” World Automation Congress: International Symposium on Manufacturing and Applications (ISOMA), Seville, Spain, June 28 – July 2, 2004.

[15] A. Ashkin, “Optical trapping and manipulation of neutral particles using lasers,” Proceedings of National Academy of Sciences, Vol. 94, May 1997, pp. 4853-4860.

[16] F. Arai, T. Sakami, K. Yoshikawa, “Synchronised Laser Micromanipulation of Microtools for Assembly of Microbeads and Indirect Manipulation of Microbe,” Proceedings of International Conference on Intelligent Robots and Systems, Las Vegas, Nevada, October 27-31, 2003, pp. 2121-2126.

[17] S. Masuda, M. Washizu, I. Kawabata, “Movement of blood cells in liquid by non-uniform travelling field,” IEEE Transactions on Industrial Applications, 24, 1988, pp. 217-222.
[18] G. Fuhr, R. Hagedorn, T. Muller, “Linear motion of dielectric particles and living cells in microfabricated structures induced by traveling electric fields,” IEE Transactions on Micro-Electro-Mechanical Systems, 1991, pp. 259-264.

[19] T. Schnelle, T. Muller, G. Gradl, S. G. Shirley, G. Fuhr, “Dielectrophoretic manipulation of suspended submicron particles,” Electrophoresis, 21, 2000, pp. 67-73.

[20] G. B. Lee, L. M. Fu, “Platform Technology for manipulation of Cells, Proteins and DNA,” Proceedings of International Conference on Robotics and Automation, Taipei, Taiwan, September 14-19, 2003, pp. 3636-3641.

[21] E.W.H. Jager, O. Inganas, and I. Lundstrom, “Microrobots for micrometer-size objects in aqueous media: Potential tools for single-cell manipulation,” Science, Vol. 288, Issue 5475, 30 June 2000, pp. 2335-2338.

[22] M. C. Corrozza, P. Dario, A. Menciassi, A. Fenu, “Manipulating Biological and Mechanical Micro-objects with a LIGA-Microfabricated End Effector,” Proceedings of the International Conference on Robotics and Automation, Leuven, Belgium, May 16-20, 1998, pp. 1811-1816.

[23] M. Shahinpoor, Y. Bar-Cohen, J. Simpson and J. Smith, “Ionic-Polymer Metal Composites (IPMCs) As Biomimetic Sensors and Actuators-A Review,” Smart Materials & Structures Int. Journal, vol. 7, 1998, pp. 15-40.

[24] M. Shahinpoor and K. J. Kim, “Ionic Polymer –Metal Composites-I. Fundamentals,” Smart Materials and Structures International Journal, vol.10, 2001, pp. 819-833.

[25] M. Shahinpoor, K. J. Kim “Ionic Polymer-Metal Composites: III. Modeling and Simulation as Biomimetic sensors, actuators, transducers and artificial muscles,” Smart Structures and Materials, Vol. 13, 2004, pp. 1362-1388.

[26] M. Shahinpoor and K. J. Kim, “Ionic Polymer Metal Composite-IV. Industrial and Medical applications,” Smart Materials and Structures, vol. 13, 2005, pp. 1362-1388.

[27] J. W. Paquette, K. J. Kim, J-D Nam and Y. S. Tak, “An Equivalent Circuit for Ionic Polymer-Metal Composites and their performance improvement by a Clay-based Polymer Nano-composite,” Journal of Intelligent Material Systems and Structures, Vol. 14, October 2003, pp. 633-642.

[28] S. Leary and Y. Bar-Cohen, “Electrical Impedance of Ionic Polymeric Metal Composites,” Proceedings of SPIE’s 6th Annual International Symposium on Smart Structures and Materials, 1-5 March, 1999, Newport Beach, CA. Paper No. 3669-09.

[29] U. Deole, R. Lumia, M. Shahinpoor, “Characterization of Impedance Properties of IPMC Actuators,” Biomimetics, Artificial Muscles, and Nano-Bio 2004, Albuquerque, NM, December 6-8, 2004.

[30] Ujwal Deole, “Artificial Muscle Microgrippers”, Master of Science, M.Sc., Department of Mechanical Engineering, The University of New Mexico, Albuquerque, New Mexico, December, 2005.

[31] Ujwal Deole, Ron Lumia, Mohsen Shahinpoor, “Design and Test of IPMC Artificial Muscle Microgripper”, Proceedings of the Third World Congress On Biomimetics, Artificial Muscle and Nano-Bio (Biomimetics and Nano-Bio 2006), May 25-28, 2006, Lausanne, Switzerland (2006)

[32] U. Deole, R. Lumia and M. Shahinpoor, “Grasping Flexible Objects Using Artificial Muscles Micro-Grippers”, Proceedings of the 2004 World Automation Conference (WAC 2004), June 28-July 1, 2004, Seville, Spain, (2004)

[33] R. Lumia and M. Shahinpoor, "Microgripper design using electro-active polymers", Proc. SPIE Smart Materials and Structures Conference, March 1-5, 1999, New Port Beach, California, Publication No. SPIE 3669-30, pp. 322-329, (1999)

[34] R. Lumia and M. Shahinpoor, “Artificial Muscle Micro-Gripper”, Proceedings of the First World Congress On Biomimetics and Artificial Muscle (Biomimetics 2002), December 9-11, 2002, Albuquerque Convention Center, Albuquerque, New Mexico, USA, (2002)