Electroactive polymer for artificial muscle application

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ABSTRACT

As technology advances, there was a need for new motors that could generate force efficiently, which could be achieved by mimicking the ability of biological muscles. Artificial muscles using electroactive polymers had been researched and developed in the recent years due to the great potentials in areas like robotics, toys, medical industry and prostheses, biomimetic device and electromechanical systems (MEMs). Dielectric elastomers, an electronics type of electroactive polymer, had been widely studied due to the large strain and force that could be induced under a DC electric field. In this project, a single unit actuator was first created using the dielectric elastomer and different assembly configurations could then be explored to produce a larger force which was compatible to that of biological muscles.

BACKGROUND

One of the potential applications of electroactive polymers (EAP) is artificial muscle as they can expand and contract repeatedly upon activation by electrical means. These materials mimic the actions of biological muscle such that they can move and restore their original positions after activations except that biological muscle contract instead of expand upon stimulation. In addition, these materials can perform as well as the biological muscles or even better in some aspects such as resilience, vibration damping, quiet operation, high fracture toughness, damage tolerance, and actuation strains as high as 380% (Bar-Cohen, 2004). In comparison, the biological muscles produced a typical strain of 20% and maximal value of 40% (Madden, 2007). Hence, these EAP materials have the possibility to create more lifelike aesthetics and flexible actuator configurations which can be used in robots and mechanical devices where the use of gears and bearings can be avoided due to their expenses, heavy weight and premature failures (Bar-Cohen, 2004). In 1999, the “Armwrestling Match of EAP Robotic Arm against Human (AMERAH)” was initiated by the JPL's Nondestructive Evaluation and Advanced Actuators (Armwrestling, n.d.) Technologies lab established by Dr. Yoseph Bar-Cohen to promote advances in the EAP field and increase public awareness on this (Armwrestling, n.d.).

EAP can be divided into 2 broad categories based on the activation mechanism – electronic and ionic. Each group has its advantages and disadvantages, and hence the targeted applications vary.
The electronic EAP is actuated by an electric field. Some examples are dielectric elastomers, electrostrictive graft elastomers, electrostrictive paper, electro-viscoelastic elastomers, ferroelectric polymers and liquid crystal elastomers. This class of EAP is able to generate huge displacement and hold its displacement when actuated under DC electric field. These electronic EAPs have high electromagnetic coupling coefficients and are capable of high work densities, 100 times that of muscle (Madden, 2007). Hence, these materials can be considered for robotic applications. However, high electric field is needed for actuation, approximately 10 MV/m, so high voltage had to be used, generally >1kV (Madden, 2007). To overcome this problem, a smaller film with higher dielectric constant can be used. One of the most widely studied EAP is the dielectric elastomer, which has applications for electroactive fluid pumps, acoustic speakers, electrostatic MEMS actuator, conformal skins for Braille screens as an aid to visually impaired and blind, and Artificial Muscles' autofocus lens positioner (Fig. 1) that can focus a camera by moving the lens by as much as 350 µm (Madden, 2007).

![Fig. 1. (a) Artificial Muscles' DLP-95 autofocus lens positioner and (b) cutaway drawing of the diaphragm mechanism in which bottom and top ring actuators alternately push or pull. (Courtesy of Artificial Muscles, Inc.)](image)

On the other hand, ionic EAP is actuated by the movement of ions, in which an electrolyte phase, usually liquid, is required. Some examples are ElectroRheological fluids, ionic polymer gels, conducting polymers, ionic polymer metal composites (IPMC), and carbon nanotubes (CNTs). The main advantage of this class is the ability to actuate under low electric field, as low as 1-2 V (Bar-Cohen, 2004). These EAPs can exhibit large bending displacement, however, the force or torque induced is low. Another disadvantage is that these materials cannot hold the induced displacement under DC voltage. In addition, it may be troublesome to keep the EAP wet in order to actuate. Therefore, this class is unsuitable for robotic actuation, instead, the ionic EAPs can be employed in auto-focus device for mobile phones, transducer, sensor and biomedical engineering and medical applications such as angioplasty steering mechanism (Bar-Cohen, n.d.).

INTRODUCTION

The objective of this project was to design an EAP actuated robotic arm for the arm wrestling competition organized by Dr. Yoseph Bar-Cohen. Hence, dielectric elastomer was chosen as the
actuator since the electronic class could generate higher force and mechanical energy density, and normal operation in air. In a recent review by Madden, electromechanical coupling for the acrylic and silicone dielectric elastomers was 60–80% and 90% respectively (2007). The great actuation strains (>40%) resulted in large work per unit volume per stroke, with a maximum of 3.4 MJ/m$^3$ that is 400 times that of biological muscle (Madden, 2007).

There are several ways to increase the actuation force generated. Dielectric elastomers behave like capacitors with compliant dielectrics and electrodes such that when a voltage is applied across the electrodes, the electrostatic attraction compresses and elongates the dielectric. This Maxwell stress generated is proportional to the dielectric constant and also to the square of the applied field (Madden, 2007). In order to obtain large strain, the electrodes and the elastomer should be highly compliant with high dielectric strength and conductivity. Conductive carbon or silver grease can be used as the compliant electrodes. Dielectric strength can be improved by pre-straining the elastomers while the dielectric constant of a silicone or acrylic elastomer can be increased by incorporating heavy particles such as titanium oxide (TiO$_2$). To achieve maximum mechanical energy density and electromechanical coupling, voltage which is near to the breakdown voltage of the material can be used. Also, multiple layers of EAP can be stacked or rolled into tubes to generate a larger force.

The approach suggested for this project is to come up with a rolled configuration using the acrylic elastomer and carbon conductive grease as the single unit actuator. After which, many units can be assembled to produce a bigger force.

**PROCEDURE**

1. A piece of 3M VHB 4910 acrylic tape, 6 x 2.5 cm, was pre-strained in both directions by stretching over a flat hollow rectangular acrylic frame, 27 x 5 cm.
2. Carbon grease, which acted as the compliant electrode, was applied on the top and bottom surface of the stretched EAP, 20 x 1 cm and 10 x 1 cm respectively (Fig 2). Thin aluminium strip was inserted at each electrode layer to aid connection to the volt meter. After which, a second piece of EAP is stretched and stacked above the greased EAP.

![Figure 2. Top view (left) and side view (right) of stacked polymers with grease applied.](image-url)
3. A spring was fitted between 2 acrylic end caps, each has a height of 1.5 cm, and compressed to 5 cm on a steel rod. The 2 layers of polymers were then rolled around the compressed spring together with its end caps. Upon completion, the compressed spring was released from the rod, making sure that the spring did not extend to its free length before the actuation force and displacement could be measured.

![Image of end caps and rolled EAP](image)

**Figure 3.** End caps (left) and Rolled EAP remaining in a compressed state (right)

4. The force generated was recorded by the Materials Testing System (MTS) with the distance between the 2 wooden adaptors fixed.

![Image of setup on MTS](image)

**Figure 4.** Set up on the MTS.

5. The above procedure was repeated using springs with different spring constant.

6. The experiment was then repeated with the active area of grease doubled, from 1 cm width to 2 cm width, using another acrylic frame with a thinner border and 2 thinner end caps with a height of 1 cm.

**RESULT AND DISCUSSION**
<table>
<thead>
<tr>
<th>Spring Constant, k (N/mm)</th>
<th>Force obtained for small active area (N)</th>
<th>Force obtained for big active area (N)</th>
<th>Observation/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>Rolled EAP was very ‘bent’. Shortcircuit at 5 kV implied EAP broke.</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
<td>Rolled EAP was bent.</td>
</tr>
<tr>
<td>1.0</td>
<td>1.8</td>
<td>1.9</td>
<td>-</td>
</tr>
<tr>
<td>3.0</td>
<td>1.6</td>
<td>1.5</td>
<td>The edge of EAP was slipping fast at the end caps.</td>
</tr>
<tr>
<td>10.0</td>
<td>-</td>
<td>-</td>
<td>Spring extended fully to its free length upon release from rod.</td>
</tr>
</tbody>
</table>

Table 1. Force generated by EAP with different spring constants and active areas at 9 kV.

When the rolled EAP was released from the steel rod, the configuration should be stable and kept in equilibrium by the expansion force exerted by the compressed spring and the compressive force of the stretched EAP. Hence, the force measured during actuation was due to the extension of the compressed spring as the polymer relaxed and induced displacement. In other words, this force should be linearly proportional to the spring constant and the extension of the spring during actuation.

Various spring constants were tested, and k=1.0 showed the best result. For k<1.0, the rolled EAP tend to shrunk and prone to bending easily. In the case of the spring with k=0.03, it was too weak to resist the compressive nature of the pre-strained EAP such that it shrunk to a length of 4.4 cm on one side, and 4.7 cm on the other side. This might result in an early breakdown because the dielectric strength of the polymer was reduced. Due to the dominating force of the EAP, the rolling process had to be done with great care and accuracy as the spring was very susceptible to bending if the direction of rolling was off-centre or one side of the polymer was removed from the frame first. For k>1.0, the restoring force of the spring outweighed that of the polymer, and thus, the edge of the EAP at the end caps tend to slip and the spring may extend to almost its free length in equilibrium. Hence, the force generated would be less as the amount of possible extension from the spring decreased.

According to Kornbluh et al, the force generated by a flat piece of EAP film would increase with bigger active area (1998). However, in the rolled configuration, results showed that the difference was insignificant. This could be accounted by the roughly same amount of free space available for
expansion of the active area (Figure 5), which then determined the amount of extension of the spring and hence the force generated.

Figure 5. Side view of rolled EAP with different active areas (dimensions in cm).

Once the single unit actuator proved to work, more units could be assembled in different ways to produce a larger force. Since the spring with k=1.0 gave the optimum result, 2 arrangement, in series and parallel, were carried out using 2 rolled EAP with k=1.0 and of different active areas, A and 2A (Figure 6). For the parallel arrangement, acrylic strips were put beneath the shorter rolled EAP to ensure that both rolled EAP were at the same height such that they could touch the wooden adaptor above before the actuation force was measured.

Figure 6. Series (left) and parallel (right) of 2 rolled EAP.

The actuation force measured at 8 kV for the series and parallel arrangement was 1.6 N and 2.6 N respectively, while the individual rolled EAP with an active area 2A and A produced 1.5 N and 1.6N respectively. Hence, the parallel arrangement was better as it was capable of 83.8% efficiency while the series arrangement only had an efficiency of 51.6%. A possible explanation was that when the rolled EAPs were actuated in series arrangement, part of the restoring spring force from each spring might have cancelled out with each other. Although, the parallel arrangement was more
productive, the disadvantage was the need to ensure that all the rolled EAP involved were approximately at the same height before actuation.

CONCLUSION

In conclusion, a single actuator unit made of 3M VHB acrylic dielectric elastomer from the electronic class was able to produce a force of 1.9 N at 9 kV and hold the induced displacement and force under a DC field. Actuation under a higher voltage, optimally near the breakdown voltage of the material, yielded higher forces. Given the small and light frame of the single unit actuator, more units could be packed together in a parallel arrangement to generate a greater force that was necessary for a robotic arm. However, the robustness of the rolling process should be improved to ensure rolled EAPs that were straight with consistent height could be produced in subsequent batches. Also, to fully utilize the resources, the ratio of the width of the active area to the maximum displacement possibly induced could be tested on a polymer that was stretched over a flat hollow rectangle frame. Later, that could be used to determine the area of conductive grease to be applied for the rolled configuration, so that there would be maximum free space allowed for expansion and hence greater force produced due to the extension of the spring.

REFERENCES


