Construction Techniques and Statistical Analysis of Dielectric Elastomer Actuators

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Abstract

In this study, a series of experiments were conducted to investigate and improve upon existing construction methods of dielectric elastomer actuators (DEAs). First, a proof of concept was built, which utilized a DEA as an active diaphragm to reproduce sound. Next, two electrode sizes and construction methods were compared via statistical analysis of electrode strain. In an attempt to develop an easier and more efficacious electrode construction method, the substance used for electrodes was then dissolved in six solvents. A commercially available graphite spray was compared against the solutions and determined to be the most promising on the basis of measured surface conductivity and observed particle dispersion. Finally, an actuator was tested with graphite spray electrodes; it was discovered that the spray hardens when dried and was thus not able to produce in-plane deformation.

*Keywords:* dielectric elastomer actuators, compliant electrodes, smart materials
Construction Techniques and Statistical Analysis of Dielectric Elastomer Actuators

Introduction

Broader Impact

The field of dielectric elastomers (DE) is an exciting area of research with many unexplored avenues and great potential. DEs have a plethora of potential real-world applications ranging from soft robotics, for which DEs are used as artificial muscle to various microelectromechanical systems (MEMS) such as micropumps and micronozzles (Pelrine et al., 2002; Carpi, Chiarelli, Mazzoldi, & De Rossi, 2003). Furthermore, due to their compliant nature and lack of hard edges, soft robotics are safer around humans and crops, which gives DEs abundant applications as artificial muscles for healthcare and soft-grippers for agriculture (Rossiter & Hauser, 2016).

Research Interest

A dielectric elastomer (DE) is an electroactive polymer (EAP), which undergoes large dimension transformations beyond 200% when acted upon by an electric stimulus (Pelrine et al., 2000). In this study, the construction and actuation behavior of commercially available DEs was investigated. First, a proof-of-concept loudspeaker was created using this material that could reproduce the entire frequency range of human hearing, which is approximately 20 Hz to 20 kHz. Next, a statistical analysis was performed comparing the variance and standard deviation of DE actuators (DEAs) between four total sets of actuators. The sets were developed by varying two construction parameters: electrode size (32mm vs. 64mm), and electrode application method (guide mask vs. no guide mask). Based on these results, a hypothesis is formed, and alternative
methods of electrode construction were devised to improve construction tolerance and stacked performance. Subsequently, an investigation into chemical and methodological alternatives for the creation of compliant electrodes was performed, with the goal of creating thinner, more conductive layers. A method was chosen from the tested alternatives on the basis of highest conductivity and most even dispersion and was implemented in an attempt to repeat the statistical experiments performed previously.

**Background**

**Electroactive Polymers**

A certain class of materials, commonly called smart materials, are typically defined as any matter which exhibits mechanical coupling when under the influence of thermal, magnetic, or electrical fields (Tan & Baras, 2005). These unique materials can be used as actuators (e.g., applying an electric field to induce a mechanical force), sensors (e.g., measuring mechanical strain by a change in the electric field), or even both at the same time. A subset of these is a group of materials called electroactive polymers (EAPs), which are polymers that change mechanical shape or position when an electric field or force is applied to it (Bar-Cohen, 2004). There are dozens of types of EAPs as well, and, like all smart materials, they have the potential to be both sensors or actuators; however, in this thesis, only the actuation properties of EAPs will be studied. Kim and Tadokoro (2007) divide EAPs into two main categories based on their driving forces: ionic and electric. In the following section, these two types of EAPs are discussed, and a few selected examples of each are provided; a summary is shown in Table 1.
Table 1

**Summary of differences between ionic and electric EAPs**

<table>
<thead>
<tr>
<th></th>
<th>Ionic EAPs</th>
<th>Electric EAPs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving Force</strong></td>
<td>Movement of charged particles</td>
<td>Induction of an external electric field</td>
</tr>
<tr>
<td><strong>Voltage Requirements</strong></td>
<td>Tens of Volts</td>
<td>Thousands of Volts</td>
</tr>
<tr>
<td><strong>Environment Constraints</strong></td>
<td>Liquid or gel</td>
<td>None</td>
</tr>
<tr>
<td><strong>Force Output</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td>• Ionic Polymer-Metal Composites</td>
<td>• Ferroelectric Polymers</td>
</tr>
<tr>
<td></td>
<td>• Ionic Gels</td>
<td>• Polymer Electrets</td>
</tr>
<tr>
<td></td>
<td>• Carbon Nanotubes</td>
<td>• Electrostrictive Polymers</td>
</tr>
<tr>
<td></td>
<td>• Conductive Polymers</td>
<td>• Relaxor Ferroelectric Polymers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Electrostrictive Graft-Copolymers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Liquid Crystal Elastomers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dielectric Elastomers</td>
</tr>
</tbody>
</table>

**Ionic EAPs.** This category of EAPs relies on charged particles, ions, to initiate a mechanical force (Kim & Tadokoro, 2007). These EAPs operate at an extremely low voltage requirement typically between 1-5 V. However, they often can only function within a liquid or gel electrolyte, and commonly only create bending actuation, which results in comparatively low force output.

** Ionic polymer-metal composites.** An example of this type of EAP is a group called ionic polymer-metal composites, or IPMCs (Brochu & Pei, 2010). These are made primarily of a semi-solid material which has significant free ions that are free to move...
about the pores. This material is sandwiched between two electrodes, typically made of thin metals, that can generate a voltage potential. Once generated, charged ions flood to one electrode, pooling there, and cause a swelling that results in the actuator bending.

**Carbon nanotubes.** Carbon nanotubes use a similar concept of actuation to the IPMCs described above. A voltage differential applied to individual tubes submerged in an electrolyte causes ions to rearrange and create charged clusters, which can then cause actuation due to Coulombic forces (Brochu & Pei, 2010).

**Conductive polymers.** The third subcategory of ionic EAPs is conductive polymers. These actuators are triggered by electrochemical redox reactions rearranging polymer chains (Lai, 2011). Then, when a voltage potential is applied between multiple sheets of this material, a bending actuation occurs.

**Electronic EAPs.** The second category of EAPs which Kim and Tadokoro (2007) describe is that of the electronic EAPs. This class of actuators uses strong electric fields as the mechanical driver, which requires upward of 150 V/um. The high voltage requirement of these devices is a challenge, but they are capable of holding their actuated position for a longer time than their ionic counterparts. This, combined with high force output, make electronic DEAs very desirable for applications in soft robotics. Though there are dozens of examples of electronic EAPs, only a few more common ones will be presented here.

**Ferroelectric polymers.** These EAPs work similarly to a ferromagnet, where polarized regions are aligned under the influences of an electric field (Madden et al., 2004; Lai, 2011). Their ability to remain polarized even after removing the electric field
is a tremendously advantageous aspect of ferroelectric polymers over other EAPs. This material, however, is difficult to find or synthesize due to its unique molecular properties: the molecules must contain polar side groups, be in static configurations, and not be aligned in such a way that the polarization cancels out (Brochu & Pei, 2010).

*Electrostrictive polymers.* This form of electric DEA uses polarized molecules or nanocrystalline structures which rearrange spontaneously towards a pole (Brochu & Pei, 2010). This causes an uneven material density, which then results in actuation.

*Dielectric elastomers.* Introduced in 1998 by Pelrine, Kornbluh, and Joseph a dielectric elastomer is made of a flexible, incompressible dielectric membrane sandwiched between two compliant electrodes. When a sufficiently high voltage, to the order of several thousands of volts, is applied across the electrodes, the device actuates by contracting in the direction perpendicular to the membrane and expanding parallel to the membrane to conserve volume. This contraction is a manifestation of Maxwell stress caused by the Coloumbic forces across the dielectric, which squeezes the electrode plates together (Kim & Tadokoro, 2007; Lai, 2011). This construction and actuation can be seen in Figure 1. These actuators show great promise due to their notably high strains of sometimes over 100% (Zhao & Suo, 2010). In addition, they can be—and have been—constructed effectively by hand, and with commercially available materials.

**DEA Configurations**

*Pre-strain.* Though not technically a configuration in and of itself, pre-straining is often an important element in implementing other configurations. The basic idea is that the dielectric membrane is stretched out over a rigid frame and held in place during
Figure 1. DE construction and actuation. Pictured is actuator model at rest (left) and actuated (right); arrows represent the direction of applied force.

actuation (Brochu & Pei, 2010). The pre-strain is commonly around 300% and reduces the viscoelastic nature of the material. This process then increases actuation strain and improves frequency response. Nonsymmetrical pre-strain has also been used to create uneven actuation (Pelrine et al., 2000). Though the improved performance is very desirable, it is also a challenge to implement pre-strain in many configurations.

Stacked Actuators. A stacked actuator takes advantage of DEA’s compressive displacement by stacking them layer-upon-layer to create a larger contractile displacement, much like a bicep when folding one's arm (Kovacs, Düring, Michel, & Terrasi, 2009). Figure 2 illustrates this concept.
Figure 2. Stacked actuators. Pictured is a top-view of a single actuator layer (left) and a side view of several layers together in this configuration (right).

This type of structured arrangement shows great promises for soft robotics, prosthetics, and MEMS devices alike (Kovacs et al., 2009). In this configuration, electrodes are used alternatingly as anodes and cathodes, and are associated with two dielectric layers each; as shown in Figure 3, where dielectric layers (white) are sandwiched between electrode layers (gray), which alternate positive and negative charge. In this configuration, it is vital that electrodes are much thinner than the dielectric. Figure 3 also shows an intra-electrode tensile stress (orange arrows) that can be caused by having an overly-thick electrode and counteract the inter-electrode forces (green arrows) that are desirable in stacked actuators. This wastes energy and can counteract the contractile actuation strain or even weaken the adhesion of the dielectric layers; for these reasons, it is desirable to have maximally thin electrodes for this
configuration. Due to the nature of the actuation, this configuration is often built without pre-strain and relies mostly on the compressive force exerted by the electrodes upon one another.

![Diagram of multilayer construction of stacked actuators with inter-electrode forces.](image)

\textit{Figure 3.} The multilayer construction of stacked actuators with inter-electrode forces. A close-up of the layers is provided on the right (layers not to scale).

**Spring Roll.** In 2004, a novel configuration was presented by Pei, Rosenthal, Stanford, Prahlad, and Pelrine, which is often colloquially called the Spring Roll. This configuration takes a standard DEA and rolls it around a coiled metal spring. This allows for several degrees of freedom, as well as different bending or compressing motions based on how and where the voltage is applied. Spring rolls provide an interesting example of the potential versatility of DEAs. These and similar actuators have been used to make biomimetic crawling devices, again reinforcing the potential applications of DEAs in soft robotics and artificial muscle (Pelrine et al., 2002).
Dielectric Materials

A number of different materials have been proposed and tested for use as a dielectric in DEAs. In 2010, Brochu and Pei claimed that silicone, polyurethane, polyisoprene, fluoroelastomer, and acrylic material were the most commonly used, with silicone and acrylic dominating. A commercially available, acrylic-based material called 3M VHB tape has been shown to be one of the most effective dielectric layers (Pelrine et al., 2000). Specifically, model numbers VHB 4905 (0.5 mm thick) and VHB 4910 (1 mm thick) have been used frequently. Furthermore, this material’s inherent adhesive properties make it ideal for manufacturable and simple hand-construction methods alike. This study employs the use of VHB 4910 exclusively, the thicker of the two.

Electrode Materials

Just like dielectric materials, dozens of different electrode materials have been experimented with in the field of DEAs including the following: carbon grease, graphite powders, graphite spray, thickened electrolyte, patterned metallic, corrugated metallic, sputter gold, silver paste, conductive polymer, and platinum salt (Biddiss & Chau, 2008). Each has their own advantages and applications, but, of these, electrolyte solution, graphite powder, graphite spray, and carbon grease are perhaps the most widespread. For hand construction, carbon grease is still frequently used due to its simple application (Holland, Park, Polygerinos, Bennett, & Walsh, 2014). In this study, carbon grease will be used as the baseline for experimentation, but graphite spray and novel solutions will be explored as alternatives.
Building the actuator

For this research, an actuator was created using 3M VHB tape as a dielectric and carbon grease for compliant electrodes. This was done to repeat an experiment originally performed by Keplinger et al. (2013). The VHB was pre-stretched in a 3:1 ratio over a circular acrylic frame; the VHB tape’s natural adhesive properties were sufficient for adhesion to the frame. Two different arbitrary sizes of actuators were made; the outer diameter of the two frames measured six inches and twelve inches. The result of the twelve-inch actuator can be seen in Figure 4. Two small strips of copper tape on opposites sides of the frame were used as a connection point to the electronic circuitry and were electrically connected to the electrodes via thin lines of carbon grease—one on either side of the membrane. This device is electrically symmetrical, meaning the cathode and anode can be switched without any effect on performance.

Figure 4. Pre-stretched DEA with 12-inch diameter at rest (left) and activated under ~4.5kV across the membrane (right).
Powering the Actuator

Visible movement of the DE begins at approximately 2 kV across the membrane and becomes significant around 4 kV. In order to achieve these high voltages, a high voltage transformer was necessary. An EMGO AG-60 surface-mount transformer was selected which has a 1:1000 voltage input/output ratio. The AG-60 is rated at a maximum of 6 kV, but the specific device that was received showed signs of arcing at ~5.5 kV, so the voltage was kept at or under 5.5 kV for safety. This transformer worked well for DC applications using an Agilent DC power supply as a source. However, this device is load-dependent and required too much current draw for an Agilent waveform generator to supply for AC applications. A solution to this was to use the DC power supply to source current into Pin 2 while using the waveform generator as an input into Pin 5 as a control.

Reproducing Sound

The AG-60 high voltage transformer had a significant shortcoming in terms of bandwidth: the device is rated at 100 Hz, but humans can typically hear sound all the way up to 20kHz. This considerable discrepancy proved problematic when attempting to reproduce sound, for when a higher frequency wave, e.g. 5 kHz, was fed into the control, the transformer wouldn’t have time to react to the change in voltage level due to its low slew rate, thus causing a significantly mitigated voltage swing and subsequently mitigated displacement. Though a frequency sweep was still able to be produced, it was nearly imperceptible without post-amplification.

A partial solution to this problem was developed by means of adding a small weight onto the middle of the actuator. The theory is that sound is produced by moving
air, and, the more air moved, the louder the sound will be. The air movement from the original actuator was solely produced by the contractile motion in the direction perpendicular to the membrane, and, since the membrane is less than a millimeter thick, the net motion was extremely small. This small displacement was only made worse by the signal mitigation. By placing a weight perpendicular to the membrane a cone shape was created, and actuation caused the weight to be lifted in a direction perpendicular to the floor, thus using the entire membrane surface area to move air—significantly improving sound pressure. A spool of solder was used as a weight in this experiment but has nothing to do with operation otherwise. An image of this configuration can be seen in Figure 5, and a video of actuation and frequency sweeping can be seen in Video 1 of Appendix B.

*Figure 5.* A spool of solder is used as a weight to add a new axis of motion; pictures is the 12-inch diameter DEA.
Reproducing Music

An audio signal was then fed to the transformer in order to reproduce music. Multiple household audio devices were tested, and a laptop aux output was selected as the device that had the highest voltage swing, which was measured as ±1.5V. This voltage swing was still too small to drive the transformer effectively, however. Therefore, the signal was passed through a non-inverting pre-amplifier to boost the signal to ±5V. From there, the signal was passed through a 5V DC Bias circuit, so the voltage swing was between 0 - 10V providing the maximum voltage swing. The circuit schematic can be seen in Figure 6. Using this method along with the weighting technique discussed in the previous section, an audible reproduction of music was achieved. Samples of this were recorded and can be heard in Audio Sample 1 in Appendix B.

![Figure 6](image_url)

*Figure 6. Schematic of audio amplification and DC bias circuit feeding into the AG-60.*
Results

Despite limitations with the transformer, the dielectric elastomer was able to reproduce the entire audible frequency spectrum in a signal generator sweep as well as play music. This was achieved thanks to the addition of a weighting system as well as signal pre-modification. The smaller of the two actuators (6-inch outer diameter) was used for music playback as it proved to be the louder of the two. The volume output was still very low, however, so the audio sample was captured using a high sensitivity microphone. The recording setup, as well as the laptop audio setup, can be seen in Figure 7. Appendix B includes these results as publicly available audio and video file download links.

*Figure 7. Music playback and recording setup for the DEA soft-speaker proof of concept.*
Discussion

The addition of a weight on the actuator increased the sound output. This weighting system changes the geometry and the actuation pattern without adding significant complexity to the system. This configuration, and the concept behind it, considerably increases the displacement of the actuator and thus has many potential applications to be explored such as pumps or low distortion speakers. This proof-of-concept demonstrates the potential of dielectric elastomers as a compliant speaker but also emphasizes the lack of useful performance with the available equipment. The limitations experienced due to the by-hand construction call for more research in the efficacy or constancy of hand-constructed actuators, and how improvements might be made.

Statistical Analysis

It was hypothesized that hand-constructed actuators have a large degree of variance in their voltage-strain performance between individual devices. This hypothesis was tested, and an alternative method of constructing the electrodes with a stencil-like mask was compared in an attempt to improve the variation of hand-constructed actuators.

Methods

Making the Actuators. Ten actuators were hand-made using the process described previously. Each actuator was made using a six-inch diameter frame and 300% pre-strain for the VHB dielectric. Two different sizes of electrodes were made—five of each size—with approximately 32 mm and 64 mm diameters, respectively. The electrodes were hand-painted with the carbon grease, which was applied with a pencil eraser. The sizes were approximated by traced guide-rings on the VHB dielectric before
pre-stretching; the electrodes were then painted as accurately as possible within the traced rings. The 10 actuators were then exposed to a series of ascending voltage steps and measured the strain at each step to develop a voltage-strain characteristic curve for each individual actuator.

This method of construction caused variation, both in size, shape, and thickness. Carbon grease is very viscous, so it is challenging to spread it consistently—as if trying to make a perfectly round, thin circle of peanut butter on a piece of cellophane. In an attempt to improve upon this, acrylic masks were cut and used as guides for painting the carbon grease. This method also helped spread the grease thinner and more consistently, both within a single electrode and between multiple electrodes. Masks of both the small (32 mm) and large (64 mm) sizes were used to approximately match the experiments described above; these frames are pictured in Figure 8. A matching set of five actuators was then created with this method for both sizes and voltage-strain characteristic curves for each were developed. Figure 9 shows an example of two actuators made with the masks. These two construction methods were then compared in terms of their statistical variability as well as their performance as actuators. A series of abbreviated IDs were used to keep track of the actuators; the IDs and brief descriptions of each can be referenced in Table 2.

**Recording the Data.** To record the data consistently, a camera was set up on a tripod pointing directly downwards. A ruler was then laid underneath the actuators, and a picture was taken at each voltage interval. Since the VHB dielectric is clear and the electrodes are opaque, it is easy to look through the actuator to measure the diameter of
Figure 8. 32mm (left) and 64mm (right) masks used as guiding stencils for painting, and later spraying, compliant electrodes onto the VHB dielectric.

Figure 9. Pictured are the 32mm (left) and 64mm (right) painted electrodes at rests; both were made with the use of a guide mask.
Table 2
Abbreviations and descriptions of all actuator sets tested

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Number of Samples in Set</th>
<th>Description of Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS32_1-5</td>
<td>5</td>
<td>Actuator with a 32 mm diameter electrode, made without the use of a guide mask.</td>
</tr>
<tr>
<td>AM32_1-5</td>
<td>5</td>
<td>Actuator with a 32 mm diameter electrode, made with the use of a guide mask.</td>
</tr>
<tr>
<td>AS64_1-5</td>
<td>5</td>
<td>Actuator with a 64 mm diameter electrode, made without the use of a guide mask.</td>
</tr>
<tr>
<td>AM64_1-5</td>
<td>5</td>
<td>Actuator with a 64 mm diameter electrode, made with the use of a guide mask.</td>
</tr>
</tbody>
</table>

The electrode. Images were taken at voltage step-sizes of 0.5 kV, from 0 kV to 5.5 kV. The images were later evaluated one by one, and the size of the electrode was recorded. The ruler used had tick marks of 1 mm, so results were recorded in increments of 0.5 mm, and thus the error is assumed to be ±0.25 mm. The strain was then calculated by comparing the diameter of the pictured electrode with the 0 V rest diameter. Figure 9 shows two images that were taken during the experiments and used to collect data.

Results

Figure 10 and Figure 11 show the strain-voltage behavior for small (32 mm) and large (64 mm) actuators, respectively. The left plot of each figure shows the results of specimens without a mask, while the right plot shows the results of specimens with a mask. Each colored line represents an individual actuator, with the ‘_#’ suffix representing the actuator number in the series. Each series abbreviation can be referenced in Table 2. The variance and standard deviation of these datasets are plotted in Figure 12 for the set of small actuators, and Figure 13 for the set of large.
Figure 10. Best fit lines for the voltage-strain characteristic results from the 32 mm actuators without mask (left, AS32_1-5) and with mask (right, AM32_1-5).

Figure 11. Best fit lines for the voltage-strain characteristic results from the 64 mm actuators without mask (left, AS64_1-5) and with mask (right, AM64_1-5).
Figure 12. Variance (left) and Standard Deviation (right) of the strain of the 32 mm actuators depending on voltage.

Figure 13. Variance (left) and Standard Deviation (right) of the strain of the 64 mm actuators depending on voltage.
Discussion

The initial observation of Figure 10, the small actuator characteristic curves, shows that, while the with-mask data set as a whole may not be noticeably less variant, the lines tend to follow a smoother, more consistent path as the voltage increases as compared to the without-mask data sets up to about 5 kV. For the large actuator comparison in Figure 11, there is, in fact, a visually observable decrease in variation between actuators within the with-mask set as compared to the without-mask set. This lower variation is observed across the entire spectrum of voltages.

As expected per the hypothesis, Figure 12, with the small sized actuators, shows decreased variation and standard deviation of the mask group as compared to the no-mask group up to about 4 kV, after which the no-mask group has an unexpected drop in the metrics. The larger actuator data set in Figure 13 shows that the mask group had decreased variation and standard deviation across the entire tested voltage range.

Interestingly, Figure 12 also shows what appears to be an exponential correlation between voltage, standard deviation, and variance for the actuators made with a mask where a higher voltage results in a higher standard deviation and variance between actuators. No such correlation seems to exist for data based on actuators prepared without masks; instead, a seemingly-linear, but very erratic correlation is observed. Figure 13 similarly shows a more consistent relationship between voltage, standard deviation, and variance for actuators constructed with a mask than those constructed without. This gives further evidence that constructing these actuators using a mask creates more predictable devices than doing so without a mask; this increased consistency could assist with both
modeling as well as attempting to implement these devices. The improved performance consistency when using a mask is likely due to both the increase in the consistency of electrode size and shape (how close to a perfectly round circle of the desired diameter it is), as well as electrode thickness (how evenly the electrode can be spread) that using a mask allows.

**Electrode Composition**

Based on the previous results, improvements on the consistency of electrodes were attempted for hand-construction methods. The carbon grease has already been noted as being extremely viscous, and thus difficult to apply evenly when making electrodes; furthermore, it has been shown that adding a guide mask to apply a thinner layer of carbon grease with more consistent thickness and shape can decrease the variation between individual actuators. Therefore, a hypothesis was derived that thinner, more easily spreadable electrode materials will result in even greater construction and performance consistency. To test this hypothesis, the carbon grease was dissolved in six different chemical solvents to decrease viscosity. This method was then compared to a commercially available conductive graphite lubricant spray as another alternative method of achieving the same result of a thinner, more easily applicable electrode. These were then compared by using several methods to determine which alternative was most promising for a second set of experiments like those described earlier. Finally, based on the results of these experiments, a new actuator with graphite spray electrodes was built with the intent to compare its strain performance and construction variance to the original carbon grease actuators.
Methods

Solutions. Carbon grease is made up of carbon black particles suspended in dimethylpolysiloxane, a silicone lubricant in an approximate 20:80 ratio (MG Chemicals, n.d.). The first attempt was to dissolve this substance in a chemical solvent, after which it could be painted onto the dielectric in a much thinner layer, and the solvent would evaporate out leaving a thin layer of carbon grease behind. In order to do this, 1±0.01 g of carbon grease was dissolved into 2 mL of the following six solvents in vials:

- Acetone
- Ethyl Acetate
- Hexane
- Methyl Ethyl Ketone (MEK)
- Methylene Chloride
- Tetrahydrofuran (THF)

The solutions were left to sit for 65 hours in closed vials before being opened and painted with a foam paintbrush on untreated glass slides, shown in Figure 14, for evaluation under a microscope. The first layer was allowed to dry, and a second layer was applied to all slides. See Appendix A for images of the solutions over time.

Graphite spray. Later, a second method of creating an alternative electrode was found in the use of commercially available, graphite-based dry lubricant in a spray form. This spray was made from graphite particles suspended in chemical solvents and pressurized for easy spraying (The Blaster Corporation, 2016). The off-the-shelf, commercially available Blaster 8-GS was chosen for the experiment.
Data gathering. Microscopic images of the materials left after solvent evaporation were taken at 100x and 400x magnification and were used to optically judge the effectiveness of the solvent at dissolving the carbon grease and the graphite spray by means of the dispersion pattern of the dry solute. Following this test, an ohmmeter was used to measure surface conductivity along the surface of the material. For consistency, the ohmmeter probes were strapped together with an inch separating them.

Results

Microscopic images of the six dried solutions at 100x and 400x magnification are shown in Figure 15 and Figure 16, respectively. Two magnification levels are shown for the one-layer graphite spray slides in Figure 17.

The results of the surface resistivity tests are presented in Table 3. Multiple coats of graphite spray were then applied to a piece of paper to explore the effects of several layers. The results of this subsequent test can be seen in Table 4.
Figure 15. Two layers of dried carbon grease solution under 100x magnification.

Figure 16. Two layers of dried carbon grease solutions under 400x magnification.

Figure 17. One layer of dried graphite spray at 100x (left) and 400x (right) magnification.
Table 3
Resistivity of dried solutions on untreated glass

<table>
<thead>
<tr>
<th>Solution</th>
<th>1 Layer Surface Resistivity (kΩ)</th>
<th>2 Layer Surface Resistivity (kΩ)</th>
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<tbody>
<tr>
<td>Carbon Grease*</td>
<td>between 10 - 30</td>
<td>between 10 - 30</td>
</tr>
<tr>
<td>Acetone</td>
<td>inf</td>
<td>500</td>
</tr>
<tr>
<td>Ethylene Acetate</td>
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<td>200</td>
</tr>
<tr>
<td>Hexane</td>
<td>300</td>
<td>140</td>
</tr>
<tr>
<td>MEK</td>
<td>1700</td>
<td>230</td>
</tr>
<tr>
<td>Methylene Chloride</td>
<td>210</td>
<td>80</td>
</tr>
<tr>
<td>THF</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>Graphite Spray</td>
<td>93</td>
<td>46</td>
</tr>
</tbody>
</table>

*Variable thickness

Table 4
Resistivity of graphite spray on thick printer paper

<table>
<thead>
<tr>
<th>Layers</th>
<th>Surface Resistivity (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
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<td>4</td>
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<td>5</td>
<td>9</td>
</tr>
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<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Discussion

**Solutions.** The microscopic images of the dried solutions were used to gain insight into which solvents were most effective at dissolving dimethylpolysiloxane. To do this, the dispersion pattern was optically examined. Dried solutions that were more evenly distributed and more generally connected were considered better since they maintained the most conductive pathways. The clearest result is that ethyl acetate is a
poor solvent. At 400x magnification, it seems evident that acetone was also not very effective, but the other four dried solutions looked well distributed.

The results of the surface resistivity tests were compared. For the solutions, 1 and 2 layers refer to how many coats were put down before the measurements. Carbon grease, on the other hand, is viscous enough that it was difficult to get a consistent resistance measurement when smeared on the glass due to inconsistencies in thickness. For this reason, a range of values is given based on five measurements of a single sample. Lower values indicate higher conductance and are thus preferable in this case. The data here support the assertion that acetone and ethyl acetate were least effective. MEK was also found to be ineffective. Methylene chloride and THF are the most effective, with hexane being a close third. The highest scoring single test was two layers of methylene chloride, which registered 80 kΩ. This value is the minimum resistance datum in the group of dried solutions, yet still more than double even the highest measurements of carbon grease. Thus, due to carbon grease’s lower resistance values, grease is still the best conductor in the group.

**Graphite Spray.** As can be seen in Figure 17, in comparison with the solution-based samples in Figure 15 and Figure 16, the graphite spray was very evenly spread, and closely packed. This, of course, is mainly due to its spray application. The surface resulted in a two-layer reading of only 43 kΩ, nearly halving that of methylene chloride (see Table 3).

An additional experiment was performed in which one to six layers of graphite spray were applied onto pieces of thick printer paper and again surface resistivity was
measured. Six layers registered 5 kΩ, which is half of the best results with carbon grease, while still being considerably thinner and more evenly spread. This result combined with the relatively inexpensive price, availability, and ease of application made graphite spray an extremely promising method for creating electrodes, and thus the subject of the next experiment in this study.

Implementing an Electrode Alternative

The construction process using graphite spray was very similar to that described earlier. The leads from the main graphite electrodes to the copper tape were still painted on with carbon grease to ensure an even and well-conducting path. Furthermore, it removes a potential variable. The carbon grease was also spread in a small semi-circle to increase the surface area of contact between the grease and the spray; the two semi-circles on either side did not overlap. The grease leads were applied prior to mounting the main electrodes, unlike the method described earlier. Finally, the acrylic masks were reused to act like a stencil for the spray. The spray was applied in short bursts about three inches from the surface of the stencil, which was laid on top of the pre-stretch VHB dielectric. Two six-inch actuators were made using one and three layers of graphite spray, respectively, and 32 mm electrode diameters. The spray was given approximately five minutes to dry before it was connected to the same power system as used earlier for testing. Figure 18 shows a picture of the completed actuator with three layers after drying.

Up to 5.5 kV of potential was applied across the electrode. The experiment resulted in no visual in-plane actuation, and eventually in dielectric breakdown across the
VHB membrane. Upon investigating the lack of actuation strain, it was found that the graphite spray was non-compliant once dry. Rather, while drying, the graphite particles tended to stick together and form into small subsections, which caused the formation of small cracks in the electrode. For this reason, the original hypothesis that applying an evaporative carbon black solution for electrodes would decrease variability as compared to carbon paste was unverifiable. The effect can also be seen in Figure 18.

Though the fact that the graphite spray hardened when dry prevented any in-plane strain data to be gathered or compared, this does not rule out graphite spray as a potentially effective electrode material for creating certain dielectric actuator configurations. Presumably, in the experiment, there still existed a transverse-plane actuation, as the two electrodes compressed the dielectric directly between them under the influence of the electric field. This strain, then, could still be used in any configuration that relies on transverse-plane actuation, such as a stacked actuator. This
new hypothesis was untestable using the current apparatus due to an insufficient power supply to drive an actuator with a thicker dielectric necessary to create measurable transverse-plane strain.

**Summary and Conclusions**

To investigate the functionality of hand-constructed dielectric elastomer actuators, a series of experiments were performed. Carbon grease was painted onto commercially available VHB tape pre-stretched over a frame to create the actuators, which were then subjected to a series of tests in order to evaluate construction consistency. Two electrode diameters were tested, as well as the inclusion or exclusion of guide masks to paint the electrodes. Finally, evaporative solutions were tested alongside commercially available carbon solutions to find material alternatives for the electrodes.

The statistical data set showed that actuators made by applying carbon grease with the use of a mask operated more consistently, both as a single actuator over a range of 0–5.5 kV, as well as across a set of five actuators. These results could serve as a baseline for which to carry out research on the comparison of construction methods.

For the experiments concerning electrode composition, it was found that methylene chloride, tetrahydrofuran, and hexane were all effective for use as electrode materials when solutions made with these solvents and dimethylpolysiloxane-suspended carbon were allowed to dry. Conversely, acetone, MEK, and ethyl acetate were not as effective. Furthermore, it was found that off-the-shelf graphite-based aerosol lubricant has much promise, as it provides an easy means of application and surpassed carbon grease in terms of conductivity by a factor of six. A DEA made with graphite spray
electrodes was unable to verify the hypothesis, however, since the dried graphite spray was unable to expand in the axial direction.

**Future Work**

Though the results of the final experiment were incapable of demonstrating improvements to the statistical data sets developed earlier, there still exists potential applications of using graphite-spray to construct DEAs. The non-compliant nature of the dry lubricant means that the electrode cannot effectively actuate in the axial direction (parallel with the VHB dielectric), but that does not mean it cannot actuate in the transverse direction (perpendicular to the VHB dielectric). This means this method of DEA construction could still be useful in any configuration that takes advantage of transverse actuation such as stacked actuators, and, as was discussed in the background subsection, having a thin electrode is vital to creating a stacked actuator. More work is thus needed in the application and performance of graphite spray electrodes.
References


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Mechatronics, 16(1), 58–66. https://doi.org/10.1109/TMECH.2010.2090164


Appendix A

Pictures of Test Tubes Containing Carbon Grease Solutions

*Figure 19.* Carbon grease solute in vials before adding solvents. Solutions from left to right: acetone, ethyl acetate, hexane, MEK, methylene chloride, THF.

*Figure 20.* Carbon grease solutions after two (2) minutes. Solvents from left to right: methylene chloride, acetone, ethyl acetate, MEK, hexane, THF.
Figure 21. Carbon grease solutions after twenty (20) minutes. Solvents from left to right: methylene chloride, THF, acetone, ethyl acetate, MEK, hexane.

Figure 22. Carbon grease solutions after twenty (20) hours. Solvents from left to right: methylene chloride, MEK, ethyl acetate, acetone, hexane, THF.
Figure 23. Carbon grease solutions after sixty-five (65) hours. Solvents from left to right: hexane, acetone, methylene chloride, THF, ethyl acetate, MEK.
Appendix B

External Media Resources

https://goo.gl/photos/jhJNhxo3hXDGbcs26
Video 1. Frequency Sweep, 6-inch actuator

https://goo.gl/photos/r2Svjd9iJd6zK6N38
Video 2. Unweighted Actuation, 12-inch actuator

https://goo.gl/photos/QKN93Quo84YkFZY27
Video 3. Weighted Actuation, 12-inch actuator

https://www.dropbox.com/s/p8vjsnuor844vh5/MC_OHN.wav?dl=0
Audio Recording 1. Mariah Carey, Oh Holy Night

https://www.dropbox.com/s/1xzepf3dybu9p4/SNA.wav?dl=0
Audio Recording 2. The White Stripes, Seven Nation Army
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