Exploring and Evaluating Methods of Actuating an Active Lens

by

Christopher Kwok

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Abstract

Active lenses today have a variety of uses from photographic capabilities in small mobile devices to applications in engineering. They provide faster response times and higher portability and efficiency when compared to their traditional lens assemblies. For this project, I have evaluated two different methods of active lens actuation: using an electromagnetic actuator and using an electroactive polymer. From testing each method’s abilities, it was found that the electromagnetic actuator, though robust in design poses issues over long-time use. The electromagnetic actuator was able to generate a focal power range of 11.9 to 19.2 diopters (52 to 84mm focal length range), but a high power consumption led to problems with heating the internal components of the active lens assembly. In the EAP method, a lower power consumption proved to be a viable option for actuation, and through testing and calculation, it was determined to be useful in application. However, a proposed efficient design must be further explored.

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1. Introduction

An active lens, also named adaptable lens, is a type of lens that can alter its shape and change its optical properties such that a different focal length can be achieved. It does so through some means of actuation that adjusts the lens' radius of curvature. Active lenses differ from traditional lenses in that they do not specifically require any fixed lenses and they adjust focus not by mechanically displacing a lens in relation to another, but by manipulating a soft optically clear material. The benefits over traditional lenses include efficiency, portability, and faster actuation speeds.

These experiments were part of a larger research project that attempts to combine depth mapping, a type of image processing, and active lenses to produce a reliable and cost-effective collision avoidance system for next generation automobiles. The commercially manufactured active lenses used in prior testing with our integrated system did not meet the criteria for depth mapping processes. They lacked the proper focal length range, aperture size, and efficiency. In order to proceed with this project as a whole, other avenues had to be explored.

The objective of this research was to determine an effective method of actuating an active lens that would meet the criteria of our project. Though many methods were considered, the scope of this project centers around using an electromagnetic actuator and an electroactive polymer, each having their own benefits and drawbacks. An evaluation of each type and their experimental process proceeds in the following pages.

2. Background

Although the experiments described in the following are heavily focused on the construction and design of actuators, the equations and figures in this section are intended to compliment design considerations and serve to assist in experimental testing. The following should give a good understanding of the principles governing each device.

2.1 Electromagnetic Actuator

An electromagnetic actuator is essentially a device that provides a linear force or rotational torque by applying current to an armature and using its established magnetic field to produce a force against some ferrous material--most often times a permanent magnet(s). In fact, this type of actuation lends itself to many commercially manufactured products used in industry
today; some include: voice coils, valve controllers, motors, and linear actuators, which is the case used in this experiment.

Moreover, in this experiment a linear actuator designed around a lightweight solenoid is used. Figure 1 illustrates the magnetic field established when a current is supplied to the coils. The field is the strongest at the center of the coils and weakest on the outside as shown below.

![Fig 1: A schematic showing a cross-section view of a solenoid with its magnetic field.](image)

The equation for a solenoid's magnetic field is given by

\[ B_{\text{solenoid}} = k \mu_0 n I \]

Eq. 1

where \( \mu_0 \) is the permeability of free space, \( k \) the relative permeability of the solenoid core, \( n \) the turn density or number of turns per unit length, and \( I \) the current supplied to the coils. The equation for the force between a solenoid and a permanent magnet where the magnetic field acts perpendicular to the direction of the coils is given by

\[ F = B_{\text{magnet}} l (2\pi r) N \]

Eq. 2

where \( B_{\text{magnet}} \) is the magnetic field of the permanent magnet, \( l \) is the current supplied to the solenoid, \( r \) is the radius of the coils, and \( N \) is the number of turns present in the solenoid.
2.2 Electroactive Polymer

The electroactive polymer (EAP) is a common source of actuation in robotics applications\(^2\), and has been explored in other fields such as optics\(^3\). An EAP essentially acts as a capacitor when supplied with a voltage. In this experiment the EAP is designed similarly to a parallel plate capacitor that consists of a soft dielectric polymer sandwiched between a conductive material that is applied on both sides of its surfaces. During actuation, charges on opposite sides align establishing an electric field throughout the membrane. Because the polymer is soft, it will compress as the electric field causes both sides of the conductive material to attract towards each other. The magnitude of the electric field, represented by \( \varphi \):

\[
\varphi = \frac{V}{d}
\]

Eq. 3

is directly related to \( V \), the voltage applied, and inversely related to \( d \), the thickness of the dielectric membrane. The established electric field causes a compressive Maxwell stress in the same direction on the membrane, represented by the stress equation

\[
\sigma_M = \varepsilon \varphi^2
\]

Eq. 4

where \( \varepsilon \) is the permittivity of the dielectric material and \( \varphi \), the electric field. This stress causes the membrane's conductive surface area to increase, while decreasing the same portion in thickness. The membrane in its actuated state is, essentially, both stretched and flattened.

This flattening of the EAP causes some of its electrical properties to change. The equation for a parallel plate capacitor is

\[
C = \frac{k \varepsilon_0 A}{d}
\]

Eq. 5

where \( k \) is the relative permittivity of the membrane, \( \varepsilon_0 \) the permittivity of free space, \( A \) the surface area of which the conductive material is applied, and \( d \) the thickness. However, Equation 5 is no longer valid since it does not remain constant throughout actuation. Both the surface area and the thickness change as the EAP is actuated. To account for this geometric
change, the capacitance of the EAP must be derived as a function of applied voltage, \( C(V) \). In order to do so, the changing parameters of the capacitance equation, thickness and area, must also be derived as functions of applied voltage.

The thickness as a function of voltage is derived from the strain equation in the thickness direction

\[
\varepsilon_d = \frac{d(V) - d_0}{d_0} = \frac{\sigma_d}{E}
\]

Eq. 6

where \( d_0 \) is the initial thickness of the membrane, \( \sigma_d \) is the stress in the thickness direction, and \( E \) is the Young's modulus of the membrane. By substituting \( \sigma_d \) for Equations 3 and 4 and by rearranging, we obtain an equation for thickness as a function of applied voltage.

\[
d(V) = d_0 \left(1 - \frac{eV^2}{E d_0^2}\right)
\]

Eq. 7

We assume that the electric field remains constant throughout the entire membrane because of the uniformly applied conductive material and the small deviations in thickness during actuation in comparison to the deviation in surface area. Therefore, the EAP in its transverse plane can be modeled as a cantilever fixed at one end with a uniformly distributed load on both sides. The boundary condition is ignored and thickness is assumed to be uniform along the membrane. A schematic of this model is shown in Figure 2.

Fig 2: (a) Illustration of cantilever model showing strain in its longitudinal direction. The red line indicates where the boundary condition is ignored. (b) Schematic showing fixed outer radius and direction of strain of EAP.
The EAP in this particular application was created by applying conductive material within an annular region of the membrane with inner radius, $r_i$, and outer radius, $r_o$, where the outer radius remains constant, bounded by a rigid frame. The inner radius, however, changes according to applied voltage. We relate the radius with the thickness using the Poisson's ratio where

$$\gamma = -\frac{\varepsilon_d}{\varepsilon_r}$$

Eq. 8

where

$$\varepsilon_r = \frac{\Delta r}{r_0 - r_i}$$

Eq. 9

and

$$\Delta r = r_i - r_i'(V) = \int_{r_i}^{r_o} \varepsilon_r(V) \, dr = (r_0 - r_i) \frac{d(V) - d_0}{d_0 \gamma}$$

Eq. 10

By substituting for thickness and rearranging, we obtain

$$r_i'(V) = r_i - \frac{(r_0 - r_i)\varepsilon V^2}{\gamma E d_0^2}$$

Eq. 11

Figure 3 shows a circumferential element taken at radius, $x$ (indicated in red), with an area of $A = 2\pi x \, dx$ along with the dimensions, $r_i$ and $r_o$.  

Fig 3: An annular region showing inner and outer diameter with a circumferential element with thickness $dx$.

By substituting the equations for area and thickness into Equation 5, a definite integral for capacitance as a function of voltage

$$C(V) = \int_{r_i(V)}^{r_o} k \varepsilon_0 \frac{2\pi x}{d(V)} dx$$

Eq. 12

is given, where the area is integrated by $r_i(V)$, the surface area component dependent on voltage, and the outer radius. The resulting equation

$$C(V) = \frac{k \varepsilon_0 \pi}{d(V)} \left[ r_o^2 - r_i'(V)^2 \right]$$

Eq. 13

is then obtained. Capacitance can now be calculated for the EAP, given an applied voltage.

In order to control the actuation of the EAP, input voltage must be controlled by some function (i.e. a sine wave). Also, in order for the membrane to behave as expected (i.e. to contract and relax in phase with the control function), a parallel resistance must be added. This resistance provides a pathway for discharge during actuation such that the EAP does not remain in its actuated state. Without this resistance, the EAP will discharge over a longer time nullifying the purpose of a control function. A schematic for the RC circuit is shown in Figure 4.
Fig 4: A circuit diagram with a capacitor and resistor in parallel with each other supplied with an alternating current\(^4\).

The time constant for an RC circuit

\[ \tau = RC \]

Eq.14

is the product of the circuit resistance and its capacitance. This time constant, \( \tau \), is used to determine the behavior of the EAP and specify an actuation speed. Using Equation 14 with the equations for capacitance, we can define a specific range for resistance that would allow for steady discharge for a specific actuation frequency.

2.3 Focal Length and Lens Shape

The lensmaker's equation\(^5\)

\[
\frac{1}{f} = (i - 1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(i - 1)d}{iR_1R_2}\right]
\]

Eq.15

where \( f \) is the focal length of the lens, \( i \) the refractive index, \( R_1 \) and \( R_2 \) are the radius of curvature for both sides of the lens, and \( d \) the thickness of the lens, is used to calculate the focal length range of an active lens. As the shape of an active lens changes, so does its radii of curvature, resulting in a different focal length. A focal length range can be determined by inputting the maximum and minimum radii of curvature into the lensmaker's equation. For a plano-convex/plano-concave lens (one with a side that is flat), the radius becomes infinity, which cancels out the corresponding term in the equation, and upon actuation, the planar side does not change.
For evaluating lens geometries with regards to focal length, the volume of a lens may be approximated by that of a spherical cap. Since a single lens is actuated, the volume of said lens must remain constant. Therefore, by using the spherical cap equation, it is possible to determine whether a lens configuration is feasible for the focal length limits we require. The equation for volume of a spherical cap is given below.

\[ V = \frac{\pi h}{6} (3a^2 + h^2) \]

Eq.16

3. Experimental Design

3.1 Electromagnetic Actuator

The lens used in testing was constructed out of a Sylgard 184 silicone elastomer membrane (refractive index of 1.41) and distilled water (index of 1.33) as the lens' optical fluid. The silicone material was chosen for its ease of handling and material properties that complied with the needs of the experiment. The design was of a 0.50 in diameter aperture, slightly larger in size to the manufactured Optotune EL-10-30-Ci lens with aperture size of 0.39 in (10mm)\(^6\). A CAD of the lens piece is shown in Figure 5.

![Fig 5: A CAD representation of the lens (light blue) and frame (grey) to hold liquid and membrane. Actuator not shown.](image-url)
The actuator was made using a solenoid with a 3D-printed frame, 18-gauge copper wire, and neodymium ring magnets (1.5 in OD, 1.0 in ID). A ring mechanism was also made; this was the actual part that contacted the lens membrane. This piece had an extrusion that fit within the inner diameter of the lens piece and a disk like surface that contacted the solenoid. The assembly consisted of the magnets in-line with the solenoid and ring mechanism. Upon actuation, the ring portion of this piece would push against the outer circumference of the lens, causing a displacement of the lens fluid, which caused the non-contacted region of the lens to protrude outward. Thus, actuation resulted in a decreased radius of curvature and focal length.

![Fig 6: (From left to right) solenoid with ABS frame, ring mechanism, neodymium magnets](image)

To test the actuator strength, the actuator assembly was set up vertically and loaded with weights. The solenoid was directly connected with a DC power supply and tested varying the input current. The results were measured against estimations from Equation 2 and are detailed in Section 4.

To test the optical capabilities of this design, a collimated laser was used to measure the focal length range over the range of actuation. The laser is shone through from behind the lens onto a perpendicular surface that is a distance greater than that of the estimated focal length from the lens. The lens diffracts the beam into a larger circle that can be measured on the surface of which it hits. This measured circle diameter along with the known laser beam diameter can be used to calculate the focal length.

![Fig 7: Schematic showing test setup with collimated laser and lens.](image)
3.2 EAP

The electroactive polymer was made using 3M VHB 4905 tape (0.5mm thick) as the membrane material and graphite powder as the conductive material. The tape is a derivative of an acrylic polymer with a Poisson's ratio of about 0.35. It is stretched approximately 3 times in both directions to fit and adhere to a quarter-inch thick acrylic frame with a circular diameter of 4 inches. Graphite powder is deposited to both sides of the membrane creating an annular region, leaving 1.5 inches of clear space at the center of the membrane. Graphite powder was used for its inexpensiveness and for its ease of application as opposed to, for example, carbon nanotube which requires a more extensive application process.

![Illustration of EAP and acrylic frame.](image)

To set up and test the EAP's capabilities, a Tektronix AFG3022B function generator and Global Specialties 1301A DC power supply was used with a laboratory made buffer (gain of 1) that supplied the EMCO model Q80 high voltage converter. The high voltage unit was directly connected to the EAP. Figure 9 shows the laboratory setup.
The high voltage converter has an input voltage range from 0 to 5 volts—with a threshold voltage of 0.7 volts—and an output range from 1500V to 8000V. Because of inconsistencies experienced with the converter, a limited input range of 0.8V to 4.0V was used for actuating the EAP, resulting in an output voltage of around 1500V to 6500V.

4. Results and Discussion

For benchmarking purposes, we compare the results of this experiment to the functionality of the Optotune EL-10-30-Ci lens, one that the project as a whole has been utilizing for preliminary testing for image processing methods. Our goal was to determine which method was the most viable in terms of creating a lens approximately twice the aperture size of that of the Optotune, have a focal length range comparable to said lens, and have a full range actuation speed of about 4-5 Hz.

4.1 Electromagnetic Actuator

Overall, the method using the electromagnetic actuator proved to function similarly to the Optotune lens; many of the same drawbacks were present. However, what contrasted from the manufactured lens was that the prototyped lens was able to produce a much higher focal power. During the assembling of the lens, it was made with an initially small radius of...
curvature, resulting in a short focal length range during its unactuated state. Table 1 provides some perspective of the differences of the two lenses.

<table>
<thead>
<tr>
<th></th>
<th>Prototype Low Current</th>
<th>Prototype High Current</th>
<th>Optotune Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applied Current [A]</strong></td>
<td>0 (unactuated)</td>
<td>1.2</td>
<td>0 to 0.4 (max range)</td>
</tr>
<tr>
<td><strong>Focal Length [mm]</strong></td>
<td>~84</td>
<td>~52</td>
<td>~100 to 200</td>
</tr>
<tr>
<td><strong>Optical Power [m⁻¹]</strong></td>
<td>11.9</td>
<td>19.2</td>
<td>5 to 0</td>
</tr>
<tr>
<td><strong>Force Exerted [N]</strong></td>
<td>0</td>
<td>0.13</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 1**: Data table showing parameters measured from testing electromagnetic actuated lens

The results in Table 1 were obtained by testing the prototyped lens using a collimated laser pointer and compared against the data given from the Optotune specifications sheet. Please note, the manufactured lens included a concave offset lens with a focal length of ~150mm, thus shifting the range of focal length during use to ~200 to infinity to ~-600mm.

![Image of diffracted beam](image)

**Fig 10**: Images showing differences in diffracted beam diameter during collimated light test. On left: laser beam when distance from surface to lens is equal to focal length. On right: at same distance, lens at fully actuated state diffracting beam.

A major issue present in both models occurred when attempting to hold the lens at a high focal power. While drawing current near the maximum limits both lenses begin to increase in temperature. The high power consumption from the prototype led to condensation on the lens surface while also decreasing the amount of force the actuator could output. While input current was held at the maximum, the solenoid heated up and an increase in resistance in the wire upon further heating resulted in failure of the actuator. While using the Optotune interface, a damage warning is given notifying the user of excessive power and possible detrimental effects that may arise.

Figures 11 and 12 show the differences in magnification between our prototyped active lens and the Optotune lens.
Fig 11: Images showing differences in magnification from change in focal length of prototyped lens.

Fig 12: Images showing differences in magnification over range of focal length of Optotune lens.

In addition to temperature rise and power consumption, this design using an electromagnetic actuator proved difficult to produce a lens with a larger aperture. Given the resources available, a liquid lens of twice the diameter would require a much more involved assembly procedure. The amount of liquid would be difficult to manage and deposit inside the lens piece. In addition, with a larger assembly, there is more potential for leakage.

4.2 EAP

The proportionally controlled high voltage converter used in the experiments offered inconsistencies that could only be counteracted through trial and error and further research of the unit. In testing of the electroactive polymer, the expectation was that it would behave in a manner that was proportional to the input voltage, that it would charge and discharge over the course of a period of the signal supplied by the function generator. However, because the high voltage converter consisted of many inline capacitors, the unit itself would not discharge, resulting in a delayed release of charge from the EAP. A partial (for proprietary reasons the manufacturer did not share with us the full circuit diagram) schematic of the interior components of the high voltage unit is shown in Figure 13.
Fig 13: A partial diagram of the capacitors and diodes on the inside of the high voltage converter.

To enable the EAP to discharge as expected, a parallel resistance is added with the unit and EAP. The function generator was set to a 1Hz sine wave alternating between 0.8V to 4.0V and the corresponding resistance needed was calculated using Equation 14. A measured difference of 0.2in in diameter was observed at maximum actuation.

<table>
<thead>
<tr>
<th>Input Voltage Range [V]</th>
<th>EAP tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter Difference [%]</td>
<td>-13.3</td>
</tr>
<tr>
<td>Diameter Difference [in]</td>
<td>1.5 to 1.3</td>
</tr>
<tr>
<td>Capacitance Range [nF]</td>
<td>1.0 to 1.1</td>
</tr>
</tbody>
</table>

Table 2: Results showing actuation diameter change and capacitance range

A lens design was not pursued due to extenuating circumstances including slow lead time with ordering the high voltage unit, time constraints, and issues concerning the effectiveness of this method of actuation. However, with the concepts explored in this paper's background, it is possible to evaluate whether or not the EAP is a viable option for actuating an active lens for our application. If we are to compare a potential lens with the functionality of the Optotune lens, the project hopes to be able to create one that has an aperture size that is twice as large (20mm) with approximately the same focal length range.

For the parameters specified, the same EAP, annular in geometry with the same outer diameter of 4 in, would need to have a transparent center with an initial diameter of 23.1mm (0.91 in) to achieve our specified minimum aperture size of 20mm (0.79 in) at its peak actuated state. By
using Equation 13, we can predict the capacitance of the EAP over an applied voltage range, which is shown in Figure 14. This shows a nonlinear relationship between the two parameters.

Fig 14: A graph of capacitance over applied voltage during actuation of the EAP using specified parameters

As capacitance changes during actuation, resistance must also change in order to accommodate for the time constant as explained with Equation 14, the RC circuit relationship. As the capacitance increases, the resistance must decrease in order for the actuation of the EAP to remain in phase with the control signal. Should the EAP begin to drift out of phase from an unaccommodating resistor, smooth and continuous actuation will not be realized. Figure 15 was generated by substituting Equation 13 into Equation 14 and shows how resistance must change over an applied voltage range. The outer diameter of the EAP was set to 4.0in, with inner radius of 0.91in as specified above, and the time constant used was 0.44m$^{-1}$. With this result, it is imperative to implement a controllable variable resistor within the entire assembly.
**Fig 15:** A graph of required resistance over applied voltage during actuation of the EAP using specified parameters

Because the EAP causes a change in diameter, the resulting aperture size will decrease upon actuation. To account for this, at peak voltage supplied (smallest aperture size) the diameter of the transparent area should be 20mm.

By using Equation 16, for a given lens that is made to fit our specifications and can be actuated to where the diameter decreases by 13.3%, we are able to obtain a focal length range from ~113 to 200mm, a range very comparable to that of the Optotune lens.

A schematic showing our idea of a solid-state active lens design using this method is shown in Figure 16. We envision that the lens will be first cast using some type of clear silicone material and then adhered to the transparent region of the EAP. When the EAP is actuated, the deformation of the membrane will compress the lens radially and ultimately change its radius of curvature. Our tentative design is of a lens oriented facing upwards, with the EAP parallel with the ground, such that a mirror angled above could be used to capture light from in front of the lens.
5. Conclusion

This thesis was an attempt at clarifying the benefits and drawbacks of using an electromagnetic actuator versus an electroactive polymer for an active lens featuring controllable optical power. It was determined that an electromagnetic actuator, though common in many mechanical applications, was not durable enough to withstand constant periods of actuation, especially for the demands of such a precision-seeking application as a collision avoidance system. Its high power consumption and resulting heating problems are reasons to seek other potential options. In the case of the EAP, the benefits include: low power consumption and less mechanically moving parts. For the tests and analysis conducted, it proves to be a viable and potentially superior alternative for actuating an active lens. However, it is imperative that this application includes a finely controlled variable resistor in order for the EAP to be actuated in a reliable manner.
Acknowledgements

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Appendix

Matlab Code used to generate Figures 14 and 15.

% Matlab function to plot Resistance vs. Applied Voltage
% used in conjunction with the RC time constant equation

function result = cap(V)

% Hard coded parameters for EAP
R = 2 * 0.0254; % meters
r = 0.0231 / 2;
d = 0.0005 / 3; % d_nought (thickness)
Area = pi * ((R.^2) - (rchange.^2));
k = 2.7; % for acrylic resin
epsnot = 8.8542 .* 10.^-12; % permittivity of free space
poisson = 0.35; % for acrylic resin
youngs = 1.8 * 10.^6; % Young's Modulus of membrane (though unstretched,
% still approximated throughout actuation)
tr = 0.44 / 5;

c = ((k.*epsnot.*pi.*((R.^2)-(rchange.^2))./...
    (poisson.*youngs.*(d.^2))).^2))./((d.*(1-(k.*epsnot.*V.^2))...)...
    /(youngs.*(d.^2))) ; % in Farads

timecons = tr / 2.2;
resistance = (timecons .* c).*10^-6; % in MegaOhms

% plot(V,c)
% hold on

plot(V, resistance, 'r')
end
References


