Magnetoactive Elastomer Solenoid Development and Implementation in Underwater Jet Propulsion

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Magnetoactive Elastomer Solenoid Development and Implementation in Underwater Jet Propulsion

Eric Damm
Magnetoactive Elastomer Solenoid Development and Implementation in Underwater Jet Propulsion

Master’s Thesis

Eric Damm

8/6/2019

Rochester institute of Technology

Under Guidance of Dr. Kathleen Lamkin-Kennard

For Partial Fulfillment of the Requirements of the Degree of Master of Science in

Mechanical Engineering
Abstract

The objective of this research was to develop and implement an elastomer solenoid capable of generating underwater jet propulsion for soft robot actuation. This is significant in pushing forward the progress of soft robotics by proving the viability of a new soft actuation method in addition to proving the viability of using silicone and magnetic particles as the driving mechanism for a soft actuator.

The two primary aims were to effectively manufacture an elastomer solenoid core and to incorporate that core with a flexible diaphragm that actuates when a voltage is applied. This combination creates a pulse of water that is pumped out of an orifice. In practice, this was a success. The propagated magnetic field in the elastomer core was very apparent in air and displacements of 2.7 cm could be achieved for a 100 mm wide diaphragm. Underwater, the added damping force of the fluid limited the displacement of the diaphragm, however; the final device was able to pump water at 250 ml/min out of an orifice.
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Nomenclature

MMP: Magnetic Microparticle

d_{orifice}: Diameter of jet orifice (m)

d_{chamber}: Diameter of jet chamber (m)

d_{disk}: Diameter of rigid disk attached to the diaphragm (m)

δ: Maximum diaphragm displacement (m)

U_m: Velocity of diaphragm (m/s)

U_P: Intermediate velocity (m/s)

U_c: Velocity at the orifice exit (m/s)

RE: Reynolds number

ρ: density (kg/m³)

L: Length of expelled water slug (m)

P_0: Pressure (N/m²)

a: Area of plate (m²)

D: Diameter of plate (m)

r: radius of plate (m)
E: Young’s Modulus (N/m$^2$)

v: Poisson ratio

t: Thickness of plate (m)

k: Spring Constant (N/m$^2$)

$\omega_0$: Resonant Frequency (Hz)
Chapter 1 – Introduction

1.1 Motivation

In the young and emerging field of soft robotics and biomimetics, the most widely used method of actuation is pneumatics. Pneumatic actuators require an air compressor, air tubes, and valves, which are made of metal or stiff plastic. The best example of a pneumatic actuator is a McKibben Muscle, which uses compressed air to create pressure in surgical tubing, causing it to contract like a bicep. The muscles react quickly and accurately, but there are a lot of extra components that limit the utility of the actuator for soft robotics.

Another, newer actuator being explored is called a DEA, or Dielectric Elastomer Actuator. DEAs have great promise as actuators, as they do not require any compressors or tubes to move fluids. The issue, however; is that they are very inefficient with the amount of force produced compared to the input power. In the early stages of their research and development, DEAs are not a particularly viable method of soft actuation for most applications.

This research proposes a new type of soft actuator; one that combines iron oxide nanoparticles with cross-linked silicone polymers. The goal is to use soft, flexible silicone rubber as the primary material in a mode of actuation. The motivation to use silicone is that it has many benefits over other rigid options, such as iron or nickel. Silicone is also useable in a wide range of temperatures, has low chemical reactivity, and is electrically insulating, waterproof, and flame retardant. Silicone rubber has also been used in biomedical applications due to its inertness in the body. The second material, iron oxide microparticles, was chosen because of the small size, the ease of use, and good magnetic properties of the particles. There has been limited research done involving mixing silicone and magnetic particles, but no substantial use has come to fruition in
the field of soft robotics. Additional motivation for this work is to expand the field of incorporating magnetic particles with soft robotics, in order to broaden the options for actuators for future researchers interested in soft robotics.

Furthermore, the development of soft magnetic actuators provides a novel contribution to the field of soft robotics. Although promising, there has yet to be substantial research into the use of elastomer solenoid cores as primary sources of actuation. The work illustrated here further strengthens the viability of using silicone as a solenoid core.
1.2 The Research Question

A common actuator used in conventional robotics is the solenoid, which is an electrical component driven by a current sent through a coil of wire. Solenoids are widely used since these actuators are robust and can be used in a variety of applications. However, little work has been done to bring this technology into the field of soft robotics, which leads to the research question: Can a solenoid be effectively made from an elastomer and successfully utilized for soft robot actuation? Furthermore: How viable is a magnetoactive elastomer for use in solenoid actuation?

This thesis seeks to address these questions through the following aims:

- Develop an elastomer solenoid core using iron oxide microparticles in combination with a cross-linked silicone polymer.
- Create an elastomer diaphragm capable of pulsing when an external force is applied.
- Implement the elastomer solenoid core with the diaphragm in a soft actuation device capable of pumping 500 ml/min of water.
Chapter 2 - Background

2.1 Literature Review

The field of soft robotics has expanded greatly in recent years. However, there are currently few soft actuators that are viable for soft robotic applications. Furthermore, many of the examples that use magnetic fields or magnetoactive elastomers fail to provide potential applications for the research. Other examples that do give applications tend to be incredibly specific, which limits future research to a very small branch of pathways.

To give context to the goal of the research and to set a baseline of the knowledge around the topic, a literature review was performed. The following papers are presented for their relevance to elastomer actuation using magnetics and soft underwater pumping. The current research seeks to address the voids identified in the existing literature through creation of an elastomer solenoid actuator.

2.1.1 Magnetoactive Elastomer Diaphragms

Jayaneththi et al. [3] manipulated a ferrous elastomer diaphragm with an exterior electromagnet. Figure 1 demonstrates that pulsing motions can be achieved using a magnetic polymer composite. The diaphragm was 65 mm in diameter and 1.5 mm in thickness. They achieved a maximum displacement of 2.5mm with an input of 1.5 amps. The study presents a method for creating the diaphragm and proposed ratios of Ecoflex to Fe₃O₄ (20% magnetic filler by weight). The gap in this research is the lack of any clear application of the technology. The authors propose implanting the diaphragm inside the body and pulsing it with an exterior electromagnet, but no specific applications are discussed or implemented.
More in depth methods for diaphragm creation are outlined by Marchi et al. [4]. To manufacture the diaphragm films, 10 – 50% by weight of magnetic particles were placed in an Ecoflex mixture. The mixture was then placed in an ultrasonic bath for a few minutes at a frequency of 59 kHz. The mixture was then coated on a Teflon substrate and spin-coated at 500 RPM for 30 seconds. Some of the films were subjected to a magnetic field normal to the face of the samples. A 30% mixture of particles to silicone was determined to have the best physical and magnetic properties.

2.1.2 Magnetic Alignment of Iron Oxide Inside a Silicone Matrix

In the work done by Marchi et al. [4] iron oxide particles were magnetically aligned inside a silicone matrix in order to achieve a better magnetic response. Figure 2 shows the effect of magnetic alignment. On the left side of the image, there is an illustration of what the particles look like with or without magnetic alignment. The right side shows the difference in displacement described by Marchi et al. [4].

Figure 1: Elastomer Diaphragm Literature Design [3]
According to Marchi et al. [4] the magnetic alignment procedure involved subjecting curing films to an external magnetic field of 200 mT produced by a cylindrical neodymium static magnet (diameter, $D$, of 25 mm, thickness, $t$, of 10 mm) and directed along the normal to the surface of the films. The films were then placed in an oven at 80 °C overnight. [4].

![Figure 2: Magnetic Alignment Literature Sample [4] The left shows the particle alignment (top: unaligned, bottom: aligned). The right shows an image of the corresponding experimental result.](image)

Ijaz et al. [5] describe using a 30% ratio of particles to Ecoflex by weight and mixing for five minutes. The authors spin coated the material onto a glass microscope slide at 600 RPM for 30 seconds. The sample was then immediately placed between the poles of an electromagnet at 1000 Oe horizontal magnetic field (equivalent to 0.1 Tesla magnet). Figure 3 illustrates the

![Figure 3: Film Creation Literature Method [4]](image)
process [5]. The particles aligned as shown in Figure 4. The authors then cured the mixture in an oven at 80 degrees Celsius for 3 hours.

Two methods were used for analysis of the magnetic alignment. The first method was a visual method with a scanning electron microscope at 500x magnification and an acceleration voltage of 3kV. The results from this analysis are shown in Figure 4. The left side shows the chained particles and the right shows normally distributed particles. The second method used a vibrating sample magnetometer to measure the magnetic response from the different samples. The findings obtained using the second method showed that the higher concentrations led to a larger displacement during testing.

Song and Cha [6] analyzed how magnetic microparticle concentrations in silicone influence the magnetic response of the material. Concentrations were determined using field-emission scanning electron microscopy. Samples were then cooled in liquid nitrogen to preserve the internal structures. The frozen samples were then broken in half, fixed to the SEM sample holder using carbon tape, and observed in back-scattered electrons mode in order to analyze the iron oxide distribution.
2.1.3 Liquid Metal Wire Windings for a Soft Electromagnet

Lazarus and Meyer [7] focused on using a liquid, ferrofluid core in addition to liquid metal windings as wire for development of a fully soft electromagnet with a liquid magnet core and windings. The authors then analyzed the physical and magnetic characteristics of the coil and liquid core. Figure 5 shows the flex testing of the setup. As can be seen in Figure 5, the liquid windings and core successfully stretched together and proved the viability of this idea.

![Figure 5: Soft Windings](image)

*Figure 5: Soft Windings
Literature [6]*
2.1.4 Soft, Octopus Inspired Pulsing Robot

Serchi et al. [8] designed a device to mimic that of the mantle in octopus. The aim of this work was to develop an innovative kind of soft underwater robot capable of propelling itself underwater. Figure 6, from Serchi et al. [8], shows the final design for the mantle in the soft robot. The most notable parts are number 4, the cables, number 7, the gearmotor, and number 6, the output nozzle. The driver for this device is the gear motor, which pulls the cables and compresses the body. The compression pushes water out of the nozzle and creates jet propulsion. Results from the study suggest that a soft mantle can create enough pressure to propel itself. Perhaps even more significant is the proven viability of the use of an orifice, instead of a valve, for creating propulsion.

![Figure 6: Soft Mantle Literature Design](image_url)
Figure 7 is an image from Serchi et al. [8] showing the rear and frontal view of their robot.

![Figure 7: Rear and frontal view of the robot from Serchi et al [8]](image)

One issue with this study is that a motor was used to cause the pressure increase inside the vessel. Motors are heavy, metal, and certainly not soft. A secondary issue is that the setup seems very fragile. There are a lot of moving parts that could be damaged if the device propels itself into a hard surface and the cable detaches.
2.1.5 Underwater Jet Propulsion Via an Orifice

Thomas et al. [9] proposed a new idea for underwater jet propulsion, specifically for low speed vehicles. The authors based their inspiration on locomotion methods from organisms like jellyfish and squid. Figure 8 shows the actions the authors were attempting to analyze.

![Diagram of synthetic jet](image)

*Figure 8: Synthetic jet proposed by Thomas et al. [7]. (A) The initial in-stroke sucks water into the chamber. (B) The out-stroke causes fluid to roll up into a ring. (C) The vortex ring pinches off. (D) During subsequent in-strokes, water is sucked in from around the departing vortex ring. [Reproduced from [7]].*
The authors further broke down the calculations used to optimize the design of their jet device. Figure 9 and Figure 10 illustrate the geometries used for the calculations [9].

Figure 9: Literature Jet Schematic [9]

Figure 10: Left: Slug model of water exiting the orifice; Right: Slug model turning into vortices after leaving the orifice [9]
According to Thomas et al. [9], the system could be analyzed using a “slug model” that considers the expelled water as one piece. This is one of the simplest models for this type of analysis. The intermediate velocity in the small channel created by the outlet orifice can be calculated using

\[ U_p = U_m \times \frac{d_{\text{chamber}}^2}{d_{\text{orifice}}^2} \]  

[1]

where \( U_p \) is velocity through the orifice (m/s), \( U_m \) is velocity of the diaphragm (m/s), \( d_{\text{chamber}} \) is the diameter of the chamber (m), and \( d_{\text{orifice}} \) is the diameter of the exit orifice (m). The diaphragm velocity can be calculated using

\[ U_m = 2 \times \delta \times \text{frequency} \]  

[2]

where \( \delta \) is the diameter of the diaphragm (m) and frequency is measured in Hz. From here, the Reynolds number of the fluid can be calculated using

\[ RE = U_p \times \frac{d_{\text{orifice}}}{\text{viscosity}} \]  

[3]

After the Reynolds number is calculated, the exit velocity of the fluid can be found using

\[ U_e = U_p \times \left(1 + \frac{8}{\sqrt{\pi}} \times \frac{1}{\sqrt{RE}} \times \frac{\sqrt{L}}{\sqrt{D}}\right) \]  

[4]
where \( U_e \) is the exit velocity (m/s), \( L \) is the length of the slug of ejected fluid (m), and \( D \) is the diameter of the slug of ejected fluid (m). The authors then analyzed the reaction force of the vortices created from the expulsion of water (shown in Figure 10) using

\[
Circulation: \Gamma = \frac{1}{2} * L U_p
\]

[5]

The circulation is a measure of vortex strength and an indirect way of measuring thrust. Using the circulation, the Impulse can then be found using

\[
Impulse: I = \frac{\pi * D^2 * \rho}{2} * \Gamma
\]

[6]

The impulse, \( I \), is the impulse imparted on the enclosure by the slug of liquid exiting the orifice. The final simplification for the average thrust is calculated using

\[
T_{ave} = \frac{I}{t}
\]

[7]

where \( T_{ave} \) is the average thrust created per pulse of the diaphragm (N) and \( t \) is the time of a single outward push (s).
2.1.6 Calculations for physical properties of a thin circular plate

Wygant and Kupnik [10] calculated the diaphragm displacement for circular capacitive micromachined ultrasonic transducer cells. More specifically, the authors provided detail on how to calculate the useful constants for a flat plate.

First, the plate deflection is solved for as a function of radial position using

\[
\omega(r) = \frac{P_0 a^4}{64 D} \left(1 - \frac{r^2}{a^2}\right)^2 = \omega_{pk} \left(1 - \frac{r^2}{a^2}\right)^2
\]

where \(\omega\) is the deflection (m), \(p\) is the applied pressure (N/m\(^2\)), \(D\) is the flexural rigidity (N*m\(^2\)), \(r\) is the radial position on the circle (m), and \(a\) is the radius of the circle (m). Then, the Flexural rigidity is found using

\[
D = \frac{Et^3}{12(1 - \nu^2)}
\]

where \(E\) is Young’s Modulus, \(\nu\) is Poisson’s Ratio, and \(D\) is the flexural rigidity. The maximum plate deflection can be found using

\[
\omega_{pk} = \frac{P_0 * a^4}{64 * D}
\]

The spring constant can be calculated as

\[
k = \frac{192\pi D}{a^2}
\]
where $k$ is the spring constant (N/m). The resonant frequency can then be determined using

$$\omega_0 = \frac{k}{\sqrt{m}} = \frac{10.22}{a^2 \sqrt{\frac{\rho t}{D}}}$$  \[12\]

The resonant frequency equation provided by Wygant and Kupnik [10] is important because, by pulsing the diaphragm at its resonant frequency, a greater magnitude of displacement can be achieved since the momentum from each previous pulse is carried into the subsequent pulse.

2.1.7 Gaps in the Literature

The previous studies in the literature present some information about topics surrounding the main topic of the current research, but many gaps remain. Serchi et al. [8] presented a concept, but only the mantle is made of silicone and the compression method is rather rudimentary. Jayaneththi et al. [3] proposed a flexible and magnetic diaphragm but did not present feasible applications for their work. Marchi et al. [4] discussed magnetically aligning iron oxide microparticles during the curing process in order to achieve a better magnetic response. However, similarly to Jayaneththi et al. [3], the authors do not present a clear application for the technology. Thomas et al. [9] provided useful equations for key physical characteristics of a pulsing diaphragm, but the entire proposed device is made of hard plastic and metal. This thesis utilizes aspects from all this literature to develop a novel soft pulsing diaphragm and an elastomer solenoid core.
Chapter 3 – Methods

In this chapter, the materials and methods for the research are detailed. Section 3.1 describes the early work performed, leading up to and through the design of the final water pumping device, described in Chapter 2

3.1 Preliminary Work

The objective of the study was to develop and implement an elastomer solenoid core that could be integrated into biomedical applications and applications involving harsh conditions such as environments with extreme temperatures or pH levels. One early source of inspiration for the design came from audio speakers because they can move small amounts at very high frequencies with little voltage applied. This idea was stretched into the goal of creating exaggerated pulses at lower frequencies.

3.1.1 Basic Speaker Development

A simple speaker was created by coiling wire around the bottom of a paper coffee cup, connecting those wires to the 3.5 mm jack in an mp3 player, and fastening a permanent magnet to the bottom of the cup. An illustration of this is depicted in Figure 11. This basic prototype was successful, and the rudimentary speaker projected the signal from the audio jack of the mp3 player. The key finding from this experiment was that small vibrations from a low voltage source are possible without the need for specialized speaker components.
A second source of inspiration for the actuator design was drawn from the archetypal soft creature: the octopus. An octopus uses an organ called a mantle to draw water through an inlet and squeezes it out through a nozzle in order to create jet propulsion. Serchi et al. [8] proved that a synthetic soft mantle can provide adequate propulsion in order to move itself. Robot created by Serchi et al. [8] involved using pulleys to contract the walls of a soft enclosure in order to squeeze water out of an orifice. Figure 12 shows an early concept for the jet propulsion device developed in this thesis work. This is not the final design, merely the original concept for the water pumping device. In Figure 12, there are four labeled sections of the schematic. 1: The flexible diaphragm, 2: The stiff housing, 3: The elastomer solenoid core, 4: The outlet orifice, 5: The inlet valve.
Once the concept for the device was finalized, the next step was to determine the materials and methods that would be used to develop the final prototype.

3.1.2 Magnetoactive Elastomer Development

Initial samples of magnetic elastomer materials were synthesized using different estimated ratios of silicone to iron oxide particles. Two different silicone polymers were used – Ecoflex 30 (Smooth-On; Macungie, PA) and Sylgard 184 (Dow Corning; Midland, MI). The best magnetic response was obtained with a high concentration of particles; however, the physical characteristics of the polymer, such as the Poisson’s ratio and elasticity, suffered severely. Samples made from Sylgard 184 were able to cure correctly with higher concentrations of particles than the Ecoflex 30 samples. Ratios up to 11:10 particles to elastomer by weight could be used with Sylgard 184, while the maximum ratios that could be obtained using Ecoflex were

Figure 12: An early design for the jet propulsion device. This was a stepping stone to what would be the final design (shown later in the section) 1. Displaced Diaphragm, 2. Housing, 3. Solenoid, 4. Outlet valve, 5. Inlet Valve
4:10 particles to elastomer by weight. Beyond this ratio, the samples did not cure properly. However, Ecoflex is inherently much more elastic than Sylgard.

Table 1 and Table 2 show the physical properties of raw Sylgard 184 and all Ecoflex products, respectively. One telling metric is the “% elongation at break”. For the Sylgard, this elongation is 140%, while the Ecoflex has a minimum of 800% elongation depending on the mixture. These two tables illustrate the reasoning behind material choices. The defining features of the Sylgard and Ecoflex are the rigidity and elasticity, respectively. These properties provide specific functionality for the water pumping mechanism that is described below.

### Table 1: Sylgard 184 Spec Table [11]

<table>
<thead>
<tr>
<th>CTM* ASTM*</th>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>As supplied</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0050 D1084</td>
<td>Viscosity at 23°C (Base)</td>
<td>mPa.s</td>
<td>5500</td>
</tr>
<tr>
<td></td>
<td>Mixing ratio by weight (Base:Curing Agent)</td>
<td></td>
<td>10:1</td>
</tr>
<tr>
<td>0050 D1084</td>
<td>Viscosity at 23°C, immediately after mixing with Curing Agent</td>
<td>mPa.s</td>
<td>4000</td>
</tr>
<tr>
<td>0055 D1824</td>
<td>Pot life at 23°C</td>
<td>hours</td>
<td>2</td>
</tr>
<tr>
<td><strong>Physical properties, cured 4 hours at 65°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0176</td>
<td>Colour</td>
<td></td>
<td>Clear</td>
</tr>
<tr>
<td>0099 D2240</td>
<td>Durometer hardness, Shore A</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>0137A D412</td>
<td>Tensile strength</td>
<td>MPa</td>
<td>7.1</td>
</tr>
<tr>
<td>0137A D412</td>
<td>Elongation at break</td>
<td>%</td>
<td>140</td>
</tr>
<tr>
<td>0159A D624</td>
<td>Tear strength - die B</td>
<td>kN/m</td>
<td>2.6</td>
</tr>
<tr>
<td>0022 D0792</td>
<td>Specific gravity at 23°C</td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>Volume coefficient of thermal expansion</td>
<td>1/K</td>
<td>9.6x10^-4</td>
</tr>
<tr>
<td></td>
<td>Coefficient of thermal conductivity</td>
<td>W/(m.K)</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Electrical properties, cured 4 hours at 65°C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0114 D149</td>
<td>Dielectric strength</td>
<td>kV/mm</td>
<td>21</td>
</tr>
<tr>
<td>0112 D150</td>
<td>Permittivity at 100Hz</td>
<td></td>
<td>2.75</td>
</tr>
<tr>
<td>0112 D150</td>
<td>Permittivity at 100kHz</td>
<td></td>
<td>2.75</td>
</tr>
<tr>
<td>0112 D150</td>
<td>Dissipation factor at 100Hz</td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>0112 D150</td>
<td>Dissipation factor at 1kHz</td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>0249 D257</td>
<td>Volume resistivity</td>
<td>Ohm.cm</td>
<td>5x10^4</td>
</tr>
<tr>
<td></td>
<td>Comparative tracking index (IEC112)</td>
<td></td>
<td>600</td>
</tr>
</tbody>
</table>

1. Brookfield LVF, spindle #4 at 60rpm
2. Time required for catalysed viscosity to double at 23°C.
* CTM: Corporate Test Method, copies of CTMs are available on request.
ASTM: American Society for Testing and Materials
Based on the higher stiffness and ability to hold a higher concentration of particles, the Sylgard 184 was chosen as the base material for the solenoid core. To create this mixture, the base and curing agent were combined at a 10:1 ratio by weight and manually mixed with a stirrer for 5 minutes. The mixture was then placed in a vacuum chamber until there were no more bubbles being released from the mixture. The magnetic particles were then placed in the mixture at the desired ratio by weight. The particles were mixed for five minutes and the mixture was placed in a vacuum chamber. Marchi et al. [4] and Ijaz et al. [5] described a mixing method utilizing an ultrasonic bath, however, these results could not be duplicated. The solution was too thick and seemed barely affected by the bath at all.

A preliminary investigation using magnetic materials was then done in order to try to develop an elastomer solenoid core. Figure 13 shows the first iteration of a solenoid core. The core was approximately 7.5 mm in diameter and 30 mm in total length. The coil had
approximately 35 turns of 30 awg magnet wire. For testing purposes, 2.5 amps were applied and could move a common wood screw across a desk.

A larger core was then created to improve the magnetic properties. With the same applied current and more turns, the electromagnet was able to pick a screw up off the desk. Figure 14 shows the second iteration of the solenoid core.

One challenge faced during both trials was that, due to settling, the concentration of iron oxide particles was higher at the bottom of the cylinder than the top. As a result, the magnetic response was significantly greater at one end than the other. In later iterations, curing the Sylgard
184 in the oven led to significantly quicker curing times and very little uneven settling of iron oxide particles.

The Sylgard 184 was chosen for the base material in the solenoid core because it did not need to be as flexible as the diaphragm since it did not need to deform. The Sylgard also allowed for a higher ratio of magnetic particles than the Ecoflex (up to 11:10 as mentioned above). Although Sylgard 184 is a much stiffer material, the material can still be considered within the realm of soft actuation.

Prototypes for the diaphragm were then created by utilizing the same mixture from the second iteration of the solenoid core. This mixture was placed in a vacuum chamber and then poured on a piece of aluminum foil. A draw coater was then used to create a thin film of the mixture that was dried overnight. The thickness of the film was about 2 mm. The process led to the successful creation of a film; however, the film thickness was non-uniform. In addition, the elasticity was very low. A third issue was the amount of clumping of particles in the diaphragm. Figure 15 shows the initial prototype for the diaphragm. The features that look like bubbles are clumps of particles. These were all removed in future iterations by using a longer mixing time. Figure 16 shows a significantly improved diaphragm, although there are air bubbles still present in the mixture. This sample was improved with a longer mixing time, longer time in the vacuum chamber, and more even pouring onto the draw coater. This sample was much more elastic than the initial sample.
The first trials done to attract the magnetic diaphragm to the core were unsuccessful. The best response achieved was no more than a quiver in the material with a total displacement of less than a millimeter. However, it should be noted that the diaphragm had a very high displacement when put near a field of stronger neodymium magnets. The use of neodymium magnets offers potential for future iterations of this work. Three changes were made to address the limited displacements. The core was attached to the diaphragm causing the two components to move in tandem through the coil of wire. The wire gauge was also dropped to 17 awg from 30 awg in order to allow for a higher current to be transmitted. Finally, the iron oxide particles were
removed from the diaphragm as their contribution to the magnetic attraction was deemed negligible, and even deliterious, since the particles decreased the elasticity of the diaphragm.

3.2 Theoretical Analysis

After initial development of the actuator concept and preliminary testing of the materials was done, parameters for the enclosure were determined. A preliminary goal for the device was to move one half liter of water per minute using a diaphragm diameter of 10 cm. The diameter of the diaphragm was set to 10 cm due to the availability of the 10 cm diameter PVC piping that was used for the wall of the enclosure. Figure 15 shows a simulation of the theoretical maximum deflection of the pulsing diaphragm.

![Figure 17: Displacement simulation of diaphragm](image)

This simulation reveals that the diaphragm creates a shape called a “sphere cap”. Figure 18 depicts the sphere cap.
The volume of a sphere cap can be found using

\[
V = \frac{\pi \cdot h^2}{3} \cdot (3 \cdot r - h) \tag{13}
\]

where \(h\) is height of sphere cap (m), \(r\) is radius of sphere cap (m), and \(V\) is the total volume of the sphere cap (m\(^3\)). Using Equation 13, the theoretical volume of water displaced by a single pulse of water can be found.
3.2.1 Magnetic Field Force

While there are equations to solve for the strength of the magnetic field, it is difficult to calculate of the force imparted on an object in Newtons. As a result, the value was determined experimentally.

In order to find the force imparted on the core by the magnetic field, the core was placed inside the windings unsecured and allowed to move freely. Next, pulses were sent through the coil causing a magnetic field to propagate and act on the magnetoactive core. The total vertical displacement of the core was recorded and used to determine the total force on the material. To calculate the force, the potential energy was divided by the total time of the impulse of the magnetic field. In addition, the average velocity of the cylinder was determined by dividing displacement by time.

The potential energy was calculated using

\[ W = mgh \]  \hspace{1cm} [14]

where \( W \) is potential energy (J), \( m \) is mass of the core (kg), \( g \) is acceleration due to gravity (m/s\(^2\)), and \( h \) is the maximum height displacement (m). Potential energy was then divided by time to solve for power, such that

\[ P = \frac{W}{t} \]  \hspace{1cm} [15]

where \( P \) is power (W), \( W \) is potential energy (J), and \( t \) is total time of displacement (s). A second power equation was then used where
\[ P = F \times V \] \hspace{1cm} [16]

In Equation 16, F is the Force imparted by the magnetic field, and V is the average velocity of the core moving through the windings (m/s). By combining Equations 15 and 16, the force imparted on the core can be solved for with

\[ F = \frac{mgh}{tV} \] \hspace{1cm} [17]

To find the spring constant, the mass of the water in the sphere cap was solved for by multiplying the volume of the sphere cap by the density of water using

\[ m_{water} = V_{cap} \times \rho \] \hspace{1cm} [18]

The spring constant was solved for experimentally by finding the natural frequency in air (to eliminate damping from the water) and solving for “k” using

\[ \omega = \sqrt{\frac{k}{m}} \] \hspace{1cm} [19]

Rearranging yields

\[ k = \omega^2 \times m \] \hspace{1cm} [20]

where k is the spring constant, \( \omega \) is the natural frequency in radians/second, and m is the mass.
3.3 Electrical Design

The strength of the electromagnetic field produced by a coil is dependent on the current flowing through the wire. Using Ohm’s law [21], it is apparent that minimizing resistance and maximizing voltage will lead to the highest possible current flow. Ohm’s law states that

\[ I = \frac{V}{R} \]  

where \( I \) is the current, \( V \) is the voltage and \( R \) is the resistance in the circuit. Based on the pulsing nature of the system, there does not need to be a constant, sustained voltage source. For this reason, capacitors are used to discharge into the coil. Figure 19 depicts a schematic for the circuit used to send current through the solenoid coils. A voltage source charges the capacitors which, in turn, open the circuit when filled. When the switch is closed, the capacitors discharge through the coil instantaneously. In a perfect circuit, this method has the benefit of a sustained, although lower, voltage through the coil because the capacitors and voltage source are discharging in parallel through the wire. Another benefit of using capacitors is that they are not limited in their power output. Unlike a battery or a power supply, capacitors can instantaneously discharge all the stored energy, which allows for a higher current in the system.
For this thesis, a capacitance value of 60000 µF was chosen. A 30V, 2A power supply was utilized to drive the system, although the target voltage was 27 V for potential future use with 9V batteries. Since the power supply was limited to a 3 A output, the capacitors were crucial in increasing the current as high as possible instantaneously in order to create a strong magnetic pulse. Figure 20 shows the two capacitors used in the circuit.
The coil contains approximately 450 turns of 17 AWG wire evenly distributed over a 5.5 cm long axle. The total resistance of this wire is 1.1 ohms and the inner diameter of the spindle is 2.66 cm.

In order to accurately pulse the circuit, an Arduino Uno was used to send a square wave at specific frequencies. The code can be found in Appendix A. The frequency was chosen based on the charge and discharge time of the capacitors (The circuit was closed for 250 ms to discharge the capacitors and opened for 500 ms to charge the capacitors). This is further explained in Section 4.1. A signal was sent to a mechanical relay (shown in Figure 21), which acted as the switch in the circuit described above.
The relay shown in Figure 21 is rated for 240 VDC and 120 VAC at 30 A. The mechanical relay was chosen to add overall robustness to the system. A solid-state relay can switch faster, but they are more expensive. Another added benefit of the solid-state relay is the clicking noise that is made every time the internal switch is closed. The noise allowed for easy verification that the triggering setup was working as intended.

An additional benefit of this specific relay is that it has four channels. Thus, the overall switching frequency can be increased to four times that of a single channel, assuming each relay is offset in their triggering. The method of artificially increasing the pulsing frequency is not necessary in this project but could have potential utility in future studies.
3.4 Final Manufacturing Methods

The materials chosen for the final prototype of the water pumping device are Ecoflex 30 for the diaphragm and Sylgard 184 mixed with iron oxide microparticles for the solenoid core.

3.4.1 Diaphragm

The most reliable way to get a smooth, thin, even diaphragm was to pour the EcoFlex 30 on a flat piece of aluminum foil, and let gravity spread it out as it cured. Each diaphragm cured to about 1.5 mm consistently. The only variable was the diameter of the sample, which could be cut to a workable size. This method was found to be simpler than draw coating, and the thickness of 1.5 mm proved to be acceptable for the diaphragm. Figure 22 shows the EcoFlex curing on a piece of aluminum foil.

![EcoFlex Diaphragm](image)

*Figure 22: EcoFlex Diaphragm*
3.4.2 Magnetoactive Core

The magnetic core was made of Sylgard 184 and iron oxide microparticles (0.3 \( \mu \text{m in diameter} \) [13]). The process for creation was as follows:

- Combine Sylgard 184 parts A and B in a cup at a 1:10 ratio by weight.
- Add iron oxide particles to the Sylgard 184 at a 1:1 ratio by weight.
- Stir the mixture for five minutes, or until there are no clumps of particles.
- Place the mixture in a vacuum chamber until there are no bubbles leaving the mixture. The stirring time will vary depending on the dimensions of the container. NOTE: The mixture will expand significantly in the chamber.
- Evenly pour the mixture into a mold for the necessary dimensions of the core. The mold used in this project measured 2.2 cm in height and 2.08 cm in diameter. The mold was made from aluminum foil wrapped around a cylindrical bar of the same size.
- Place the filled mold in the vacuum chamber again until no bubbles are present.
- Bake the mold at 100°C for 45 minutes (or any other temperature/time combination specified on the Sylgard 184 spec sheet).
- Cool the cured core, then remove the core from the mold using a razor to cleanly cut one end of the cylinder. Cutting the cylinder should lead to a flat and even surface.

3.4.3 Bonding of Core and Diaphragm

Connecting the magnetoactive cylinder to the diaphragm proved to be a challenge. The first method tried was a corona-wand plasma treatment to attach the bottom of the cylinder and the section of the diaphragm that was to be attached. After treatment, the two samples were pushed together in order to bond the surfaces. This method was not reliable, as it was unpredictable.
whether the bond would be substantial enough to hold. One issue may have been the slight
difference in materials, with one being EcoFlex 30 (the diaphragm) and the other being Sylgard
184 (the core). The root cause of this unpredictable failure was not further investigated and could
be something for future work.

A much more reliable method for bonding the two components was simply to place the core
in the curing EcoFlex and allow it to bond. The connection was still relatively fragile but was
reliable enough to withstand the separation from the aluminum foil and to undergo testing.
Figure 23 shows an image of the core sitting on the diaphragm as it was curing.

![Figure 23: Core placed in EcoFlex](image)
3.5 Initial Testing

Figure 24 shows an early prototype of the device created solely for an initial visualization of the diaphragm pulsing. In this prototype, the coil was placed inside a large glass beaker and the diaphragm was secured on top of the beaker. When tested with the 27 V pulsing circuit, the displacement of the diaphragm varied between 2 and 2.5cm. It is important to note that gravity played a part in this test, with the weight of the magnetic core adding to the downward force causing deflection.

![Figure 24: Dry prototype](image)

The same apparatus described above was then placed underwater in order to better mimic final testing conditions. Figure 25 depicts the deflection of the diaphragm, with the red line indicating the center mark of the core. The total deflection obtained during this test was 0.5 cm. It should be noted that in this preliminary test there were no inlet and outlet valves, so there was a pressure increase in the chamber that caused a decrease in the deflection of the diaphragm.
Figure 26 shows the displacement of the elastomer core in the coil. In this test, both the coil and the cylinder were placed underwater and individual pulses were sent through the circuit to test the efficacy of the magnetic field on the core. The total displacement achieved was 1.75 cm.

3.6 Pump Enclosure Design and Prototyping

The final enclosure for the pump was made primarily of PVC tubing. PVC is a readily available material and is relatively easy to work with. In future iterations, a potential goal may be to create the enclosure out of a soft material, such as silicone.
Figure 27: Top view of enclosure. All measurements are in millimeters.

Figure 28: Side view of enclosure, all units are in millimeters.
Figure 27 and Figure 28 show a diagram of the layout of the final prototype of the enclosure, with all units in millimeters.

In the original design, there were to be two valves – one inlet and one outlet. In the final design of the enclosure, it was decided that there would be only one inlet valve and the outlet would be an open orifice. The open orifice was chosen because of the analysis method in the sections above and because it removed the added resistance that a valve would introduce. Figures 29, 30, and 31 show the different components of the housing.

![Enclosure lid (outlet orifice)](image)

*Figure 29: Enclosure lid (outlet orifice)*

The enclosure lid (depicted in Figure 29) is a 10 cm PVC cap with a 0.75 cm hole drilled in the top to act as the outlet orifice.
Figure 30: Enclosure body with inlet valve attached (on right) and orifice (on left)

Figure 31: Enclosure with diaphragm attached (Black circle is solenoid core inside enclosure.)
The inlet valve is a small aquarium check valve (PS+; Livonia, MI). In addition, there is an inlet orifice for additional flow. The open orifice greatly improved the performance of the pumping mechanism. The aquarium check valve was chosen because of its ability to handle very low flow rates, as well as its overall robustness. The aquarium valve, shown in Figure 32, is a simple one-way valve that requires no external actuation other than fluid movement.

Figure 32: Left: Closed check valve; Right: Open Check Valve

3.7 Experimental Results

In order to test the efficacy of the device, two different methods were used. The first was to measure the maximum displacement of the diaphragm during each of twenty pulses, and the second was to measure the efficacy of the water pumping enclosure by measuring the total water displaced after certain time intervals.

3.7.1 Diaphragm Displacement

The measurements for diaphragm displacement were done visually. The pulses were recorded at 240 frames per second using an iPhone 8. The maximum displacement of a pulse was
measured in relation to a ruler in the frame. These values are depicted in tabular and graphical forms in Sections 4.2 and 4.3.

3.7.2 Pumping Efficacy

The pumping efficacy of the device was tested by measuring the total amount of water being expelled from the orifice of the enclosure. The device was placed with the orifice sitting 0.5 mm above the surface of a pool of water. A pulsing signal was then sent through the coil, allowing the diaphragm to pulse. The pulsing caused water to be expelled from the orifice and pool on the surface of the device. The pooled water was then vacuumed into a graduated cylinder and measured after a specified period of time. Figure 33 shows the motor used to pump the pooled water into the graduated cylinder.

![Figure 33: Pumping motor used to vacuum pooled water for measurement.](image)

Chapter 4 - Data

In this section, the results from the testing methods described above are presented. The pulsing electrical signal is broken down and testing data from in-air and in-water experiments are shown.

4.1 Pulsing Circuit

Figure 34: Single Example Pulse

Figure 34 shows a single pulse from the pulsing circuit. The two leads were placed on either side of the coil and the measurement shows the signal being sent through the windings. The initial input value was 27 V and this signal shows that the loss through the circuit was minimal. The initial spike was created by the discharging capacitors. The capacitors were almost completely discharged within 250 ms of closing the circuit. After the spike, there was an elbow that leveled off at around 3 V. The leveling off occurred because the capacitors were fully
discharged and the only voltage through the system was coming from the power supply. The power supply is limited to 3 A and, following Ohm’s law, the 1 Ohm of resistance through the coil leads to a limit of 3 V being output from the power supply. After the initial leveling off, there was a sharp cutoff where the voltage dropped to zero. The drop-off occurred when the circuit was opened. An open time of around 500 ms was necessary in between pulses to let the capacitors recharge.

Figure 35 shows an example of sequential pulses. Here, the Arduino was programmed to close the circuit for 250 ms and open it for 500 ms. The same peak described above was seen here in all the pulses, but there was a much steeper drop-off, as opposed to the elbow seen in
Figure 34. The off time was therefore set much shorter in order to increase the frequency of the pulsing.

4.2 In-Air Testing

4.2.1 Measured Displacement

The data below correlates to the maximum displacement of the diaphragm during each pulse. Twenty pulses were recorded, each with the circuit closed for 250 ms and opened for 500 ms, and the maximum displacement values of the solenoid core are reported in Table 3.

The highest displacement was 2.72 cm and the lowest was 2.5 cm, giving a range of 0.22 cm and an average displacement value of 2.62 cm. The standard deviation for the data is 0.06 cm, indicating a very low spread in data values compared to the average.

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>Displacement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
</tr>
<tr>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>2.7</td>
</tr>
<tr>
<td>6</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>2.7</td>
</tr>
<tr>
<td>8</td>
<td>2.7</td>
</tr>
<tr>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>11</td>
<td>2.5</td>
</tr>
<tr>
<td>12</td>
<td>2.6</td>
</tr>
<tr>
<td>13</td>
<td>2.6</td>
</tr>
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<td>14</td>
<td>2.6</td>
</tr>
<tr>
<td>15</td>
<td>2.6</td>
</tr>
<tr>
<td>16</td>
<td>2.7</td>
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<tr>
<td>17</td>
<td>2.6</td>
</tr>
<tr>
<td>18</td>
<td>2.6</td>
</tr>
<tr>
<td>19</td>
<td>2.7</td>
</tr>
<tr>
<td>20</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Figure 33 shows the clustering of the maximum displacement values. Twenty pulses were measured, and the displacements were recorded in the plot below.

![In-Air Maximum Displacement](image)

**Figure 36: In-Air Maximum Displacement Values**

The blue bars on each point are error bars, showing the standard error for each measurement. This error was found to be 0.013. The red horizontal line indicates the average value of 2.62 cm.

![Time lapse of In-Air displacement](image)

**Figure 37: Time lapse of In-Air displacement (Note: all times are in seconds)**

T=0 s  T=0.15 s  T=0.25 s  T=0.45 s  T=0.55 s
Figure 37 shows a representative series of frames from the slow motion video of the in-air diaphragm displacement video with the ruler in place. The maximum displacements were determined visually. In Figure 37, the maximum displacement can be seen at $T = 0.25$ s.
4.3 Underwater Testing

4.3.1 Measured Displacement

Underwater testing results can be seen in Table 4. Table 4 contains the maximum displacement values for each of twenty pulses of the diaphragm. The maximum observed displacement was 0.46 cm and the minimum was 0.38 cm, leading to a range of 0.08 cm. The average value was 0.407 cm and the standard deviation was 0.0213. The low standard deviation indicates the repeatability of the displacement measurements. An explanation for the difference in the points may be the elastomer core rubbing against the inside wall of the cylindrical coil holder. It may rub slightly differently each time leading to a difference in displacement values.

Table 4: In-Water Maximum Displacement Values

<table>
<thead>
<tr>
<th>Pulse #</th>
<th>Displacement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>0.4</td>
</tr>
<tr>
<td>12</td>
<td>0.4</td>
</tr>
<tr>
<td>13</td>
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</tr>
<tr>
<td>14</td>
<td>0.4</td>
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<td>15</td>
<td>0.4</td>
</tr>
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<td>16</td>
<td>0.4</td>
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<tr>
<td>17</td>
<td>0.4</td>
</tr>
<tr>
<td>18</td>
<td>0.4</td>
</tr>
<tr>
<td>19</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Figure 38 below shows the spread of maximum displacement values for 20 pulses of the diaphragm. The range of the data set is 0.08 cm, indicating a tight spread of data points. The bars on the top and bottom of each point show the error in each measurement. The error is 0.005 cm, which suggests that consistent displacement measurements are obtained with each pulse of the circuit. The red line shows the average displacement value and further proves the consistency of the displacements due to the tight grouping around the average.
Figure 39 illustrates the data collected for each of three different tests. The orange points indicate the total volume of water pumped in 120 seconds (2 minutes). The blue points show the total volume of water pumped in 60 seconds (1 minute), and the yellow points show the total volume of water pumped after 100 displacements of the diaphragm. The green, blue, and purple horizontal lines show the average values for the 120 second, 100 pulse, and 60 second trials, respectively.

The first notable difference is the change in pumping rate between the 1 and 2 minute trials. The average total volume pumped for the 1 minute trial was 250 ml, whereas the volume pumped during the 2 minute trial was 460 ml. This was not a linear pattern and was likely due to the slight change in the water level of the water bath as water was removed. Another notable statistic is the range in each set of data. The volume range in the 1 minute trials was 28 ml and the range for the 2 minute trials was 25 ml. This range is relatively small compared to the total amount of water pumped and validates the repeatability of the pumping efficacy for set periods of time. Table 5 shows statistics for the trials, with the most notable statistic being the standard deviation. The values are very low compared to the averages, indicating a consistent pumping rate for each trial.

<table>
<thead>
<tr>
<th></th>
<th>60 Second (ml)</th>
<th>120 Second (ml)</th>
<th>100 Pulses (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation</td>
<td>8.71</td>
<td>5.49</td>
<td>4.53</td>
</tr>
<tr>
<td>Range</td>
<td>28.00</td>
<td>25.00</td>
<td>18.00</td>
</tr>
<tr>
<td>Average</td>
<td>252.80</td>
<td>460.05</td>
<td>301.00</td>
</tr>
<tr>
<td>Error</td>
<td>1.95</td>
<td>1.23</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Figure 39: Pumping Data

Figure 40: Time Until 500 ml Pumped
Figure 40 is a graph of the time taken for the device to pump to 500 ml. The blue lines above and below each point are error bars, with the error being 0.46 seconds. The standard deviation of the data is 2.04 seconds, deviating from the mean of 131.8 seconds, indicated by the orange line, only slightly. The small standard deviation indicates a consistent pumping method, as the total time remains very similar throughout twenty trials.

Figure 41 shows the nonlinearity of the volume being pumped over time. Each point is an average measurement value of the tests discussed above. When connected, the slope of the connecting line changes, indicating a change in the pumping rate over different time intervals.
Figure 42 below shows an image of the expulsion of water in action. Underneath are small timestamps indicating when each step occurred.

Figure 42: Frames from slow motion video of in-water pumping test (Note: all times are in seconds)

T=0 s       T=0.2 s       T=0.3 s       T=0.55 s       T=0.6 s

Note how the water exits the orifice as a cylindrical slug and turns into a mushroom shape, like the vortices mentioned in section 2.1.5 by Thomas et al. [9]
Chapter 5 - Discussion

The goals of this thesis were to:

- Develop an elastomer solenoid core.
- Create a diaphragm capable of pulsing when subject to an external force.
- Eliminate the need for high voltages and pneumatics.
- Implement the core and diaphragm in a soft actuation device capable of pumping 500 ml/min of water.

Overall, the work performed in this thesis was a success. The elastomer solenoid core was effective in actuation via a magnetic field. The diaphragm was created using Ecoflex 30 and was also effective in using it to pulse and create pressure differences inside an enclosure. The maximum voltage used was 27 volts, which is well below threshold to be considered high voltage. Lastly, the pump was capable of pumping 250 ml of water in a minute. The original goal was 500 ml/min, meaning the pump fell short by 250 ml, but overall the development of the prototype was a success. The following sections go into further detail on these topics.

5.1.1 Develop an elastomer solenoid core

The cornerstone of this work was the development and implementation of an elastomer core capable of propagating a magnetic field. The development of the core was successful. Utilizing Sylgard 184 as the elastomer material with which to mix iron oxide particles turned out to be a much better choice than Ecoflex 30 for the reasons stated previously. Initial tests of adding windings to the outside of the core and applying a voltage caused the silicone to become a soft electromagnet.
5.1.2 Develop a diaphragm capable of deformation to create pressure fluctuations

The development of the diaphragm was a success. The use of Ecoflex 30 instead of Sylgard 184 proved to be a good choice due to the high elasticity of the Ecoflex compared to the Sylgard. Using gravity as a method of evening out the membrane also proved to be a success over using a draw coater because of the simplicity and repeatability.

5.1.3 Eliminate the need for high voltage and pneumatics

The two big fallbacks for the current popular soft actuators are the need for high voltages and pneumatic tubes/compressors. Eliminating the need for pneumatic tubing to inflate artificial muscles was a success. The device is self-contained, requiring only an applied voltage.

The elimination of high voltage was also a success. This device is being driven with 27 V; a value attainable with typical benchtop power supplies. Additionally, the American National Standard for Electric Power Systems and Equipment defines low voltage as anything below 600V [14]. The device that was developed uses 4.5% of the voltage needed to be classified as high voltage and is considered low voltage by a large margin. This is advantageous over electroactive polymers (EAP) which require kilovolts to function properly.

5.1.4 Develop a device capable of pumping 500ml/min of water

The original goal for this device was to pump 500ml/min of water. In final testing, the device fell short, being able to pump an average of 250ml/min. Although this was the case, it does prove the viability of the use for an elastomer as a solenoid core for a soft robotic actuator. Additionally, this goal was secondary to the implementation of the magnetic solenoid core.

The original calculation for the 500 ml came from the formula for a sphere cap, denoted in Equation 13 above. This original equation called for a perfectly round deformation of the
diaphragm to lead to 700 ml/min of water pumped. This number was reduced to 500 ml/min to account for an imperfect system where the diaphragm would not be completely round. From experimentation, the observed deformation of the diaphragm was different entirely. Figure 43 is a cross section of the diaphragm shape. The solenoid pulled upward, creating internal pressure in the enclosure. The pressure caused the outer edges of the diaphragm to push downwards. The downward movements on the outer edges of the diaphragm were not accounted for in the initial calculations. Three things were done to attempt to alleviate the movements: increase tension on the diaphragm, add a stiff brace on the outer edge of the diaphragm to prevent movement in the wrong direction, and increase the thickness of the diaphragm. None of the methods increased the amount of water pumped out of the device.

![Deformed Diaphragm](image)

_Figure 43: Deformed Diaphragm; Red arrows denote downward pressure from enclosure, blue arrow denotes upward force from magnetic field._

Another theory for why the calculated volume is incorrect is that the water being pumped is only the water sitting in the cylinder surrounded by the coil. When the core is pulled through the coils, it pushes the water out in a cylindrical slug. This slug is independent of the total volume of the sphere cap and may explain the differences in the data.
5.1.4.1 Pump Comparisons

Below is a table of small pumps for comparison to the pump developed in this research.

<table>
<thead>
<tr>
<th>Name</th>
<th>Pumping Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decdeal Ultra-quiet Mini Brushless Water Pump</td>
<td>4.66L/min</td>
</tr>
<tr>
<td>Homasy Submersible Water Pump</td>
<td>5L/min</td>
</tr>
<tr>
<td>VicTsing Submersible Water Pump</td>
<td>5L/min</td>
</tr>
<tr>
<td>GC Series External Gear Pump</td>
<td>.4L/min</td>
</tr>
<tr>
<td>GJ Series External Gear Pump</td>
<td>.158L/min</td>
</tr>
</tbody>
</table>

*Table 6: Table of Comparable Pumps [15] [16] [17] [18] [19]*

The top three pumps in Table 6 are typical fish tank water pumps for circulating water through filtration systems or simply creating a current in the water. All three of these have higher pumping rates than the pump created in this research. They are of similar size and weight to the soft actuator developed. The bottom two pumps are also of similar size to the pulsing diaphragm pump developed above, but with much lower flow rates. These pumps are meant to take up less space and to be fitted to specific heads in specialty scenarios. Their flow rates are much lower and are much closer to that of the pump developed in this research.

In its current form, the pump developed in this research may be applied to specialty applications but would require further research and development in order to make it comparable to current commercial pumps, such as those mentioned above. However, all of the pumps above are rigid, thus, the progress made is substantial for the field of soft robotics and validates the notion that further research should be done in this area.
Chapter 6 - Societal Context

Soft robotics is an emerging field with many applications from biomedical to underwater research. The issue with many of the current soft actuation methods is that there is a lot of added equipment such as air compressors and tubes that take away from the true soft nature of the devices. Metal components add weight and take up a lot of space. The goal of my research was to integrate the functionality of metal solenoid-based devices with the development of an elastomer solenoid. This proof of concept may lead the way to things like elastomer motors in everyday devices. These motors would be extremely easy to replicate, be lighter, cheaper, and more versatile than their metal counterparts.

The pulsing action to be mimicked here could also help to further the understanding of the softest organisms on earth such as jellyfish, octopus, and squid. From this, the technology could expand to underwater exploration. A hull made from silicone would withstand bumping into a hard rock wall much better than a metal hull, because of the inherent elastic properties.

A third application of this technology could be to reduce it down to a much smaller scale and implement it into micro-size applications. This opens the way for new types of pumps in medical devices and propulsion methods for micro-robots.
Chapter 7 – Future Work

7.1 Magnetoactive Diaphragm

Jayaneththi et al. [3] previously developed magnetoactive diaphragms. As described in the preliminary research section of this paper, the incorporation of this technology was investigated, but there was difficulty in efficiently including a magnetic diaphragm into final pumping device. For the purposes of the research, the diaphragm needed to be as elastic as possible and from experimentation, the inclusion of particles was a detriment to this necessity.

With this being said, extensive research was not performed in this work on the topic of a magnetic elastomer diaphragm. This topic does not have substantial understanding, and further developing the relationship between different elastic materials and the inclusion of magnetic particles for the purposes of a pulsing diaphragm is something that could benefit from more in-depth research.

7.2 Inlet Valve

The current valve on the enclosure is meant for a low flow aquarium pump. The low flow rating is the reason it was chosen, but it certainly has flaws. With the pulsing nature of the enclosure, the valve cannot keep up perfectly. It creates a lot of resistance for water to get into the enclosure. Further research on an extremely low flow inlet valve is something that, while seemingly niche, can have further potential use with this project and any other with a similar rapid pulse and low flow rate fluid movement.
7.3 Soft Enclosure

The initial plan for this project was to have the entire enclosure be made of a soft elastomer material like Ecoflex 30 or Sylgard 184. The PVC was chosen in order to keep the focus on the crux of the project, the magnetoactive elastomer core. Developing a completely soft enclosure is something that would further this research and further prove the viability of the technology in the soft robotics field. This could go even further with bringing the scale of the device down for potential use in the medical field or in everyday uses.

7.4 Liquid Metal Windings

Lazarus and Meyer [7] discussed the use of a ferrofluid solenoid core. This was the focus of the paper, but the authors also discussed the use of liquid metal as the wire for a solenoid. A liquid metal encased in a silicone mold of the proper geometry can act as a wire and, if the mold is created to make windings like in a solenoid, a completely soft electromagnet can be made. This concept is something that could greatly increase the viability of the research performed for this thesis and would allow for a completely soft actuation mechanism.

This would also open new potential avenues with the liquid metal windings. With further development, these windings could connect to multiple actuators and the same metal could be recycled to other solenoids, thus saving weight and materials.
7.5 Diaphragm Tension and Spring Constant

A big difficulty for this project was finding a reliable way to create even tension across the diaphragm. As mentioned above, the tension on the diaphragm affects the spring constant of the material. Finding an easily replicated method of evenly stretching the film is something that would increase the accuracy of the device and could be incorporated into other areas of research, such as magnetoactive diaphragms.

7.6 System Model Accuracy

The work done by Thomas et al. [9] in defining the system characteristics is something that can be further utilized for this project, and even turned into a project in itself. An accurate system model for this device would cut down on the time needed for testing different parameters. This model could give optimal dimensions and material properties for this technology to work as well as possible.

There are two theories laid out in the section above that offer differing thoughts on how the diaphragm deforms and how the water is being pumped. Both theories would benefit from future research and could have potential use in other applications. Sections 7.6.2 and 7.6.3 detail preliminary system model simulations. Section 7.6.1 shows the simplified mathematical model of the system.

7.6.1 System Model Equation

The flexible pulsing diaphragm can be simplified to a mass, spring and damper system. The general equation is

\[ m\ddot{x} + c\dot{x} + kx = u \]  \[22\]

where m is mass, c is the damping constant, and k is the spring constant.
The state space form for the system is shown below in Equations 15 and 16. MATLAB was used to simulate the system with an input of \(u\), the magnetic field. The simulations are shown in sections 7.6.1 and 7.6.2 below.

\[
\begin{bmatrix}
\dot{x}_1(t) \\
\dot{x}_2(t)
\end{bmatrix} = \begin{bmatrix}
0 & 1 \\
-\frac{c}{m} & -\frac{k}{m}
\end{bmatrix} \begin{bmatrix}
x_1(t) \\
x_2(t)
\end{bmatrix} + \begin{bmatrix}
1
\end{bmatrix} u(t) \tag{23}
\]

\[
y(t) = \begin{bmatrix}
1 & 0
\end{bmatrix} \begin{bmatrix}
x_1(t) \\
x_2(t)
\end{bmatrix} \tag{24}
\]
7.6.2 In-Air Simulation

Figure 34 is a MATLAB plot of the in-air simulation of the diaphragm displacement. In the sections above, the system was simplified down to a mass, spring, and damper system. From here the system was put into state space form where a specific input was entered. The blue plot corresponds to the diaphragm displacement and the left axis. The orange plot signifies the input signal and relates to the right axis.

![In-Air Membrane Displacement Simulation](image)

*Figure 44: In-Air Displacement MATLAB Simulation*

In order to run this simulation, a few values were needed: c; the damping constant, and k; the spring constant. The spring constant was found experimentally by stretching the diaphragm and measuring the force imparted due to displacement. This constant was found to be variable.
depending on the tension in the diaphragm and is something that could benefit from future research. The spring constant was determined to be 116 N/m. From here, the damping constant could be estimated. This value was found to be 2.5. Although it is not applicable to this thesis because of the slow pulsing frequency ultimately used, the resonant frequency was calculated using Equation 12 and found to be 32.15 rad/sec, or 5.12 Hz.

The simulated value puts the total vertical displacement of the diaphragm at around 4 cm. This deviates from the total displacement of the in-air test by about 1.4 cm. This may be due to the imperfect spring estimation of the silicone diaphragm. It is possible that this circular film has a nonlinear spring constant that changes at different tensions.

![Image](image_url)

*Figure 45: Spring Constant of Varying thickness SU-8 [20]*

Figure 45, from Grégoire et al. [20], shows the nonlinear relationship between the thickness of SU-8, a similar crosslinked polymer, and the spring constant. Figure 42 is included to demonstrate the point stated above; as the sample of Ecoflex is stretched, the thickness varies. The variations in thickness have the potential to change the overall spring constant of the
material. The combination of constant stretching and relaxing could lead to potential plastic deformation, which would permanently change the physics of the system.

7.6.3 In-Water Simulation

In the underwater simulation, the two variables that change are the damping constant and the equivalent mass of the system. The spring constant stays the same, as the material does not change.

![Figure 46: Underwater Simulation](image)

The largest difference in this system is that the total displacement of the diaphragm is significantly lower than that of the in-air simulation. The simulation places the maximum displacement at 0.65 cm, varying significantly from the actual displacement value of approximately 0.2 cm.
Chapter 8 - Acknowledgements

I thank my parents for your never-ending support in everything I do, my sister for keeping me grounded and your genuine aspiration to make the world a better place, and my friends that continuously push me to be better. Thank you, Dr. Lamkin-Kennard for the use of your lab, your academic guidance, and your support of my research. I would also like to thank the members of my thesis committee: Dr. Ghoneim, Dr. Kempski, and Dr. Kolodziej, for your time, interest in my work, and for your support over the past year.
Appendices

Appendix A: Arduino code for pulsing circuit

    /*
     * Blink
     *
     * Turns an LED on for one second, then off for one second, repeatedly.
     *
     * Most Arduinos have an on-board LED you can control. On the UNO, MEGA and ZERO
     * it is attached to digital pin 13, on MKR1000 on pin 6. LED_BUILTIN is set to
     * the correct LED pin independent of which board is used.
     * If you want to know what pin the on-board LED is connected to on your Arduino
     * model, check the Technical Specs of your board at:
     * https://www.arduino.cc/en/Main/Products
     *
     * modified 8 May 2014
     * by Scott Fitzgerald
     * modified 2 Sep 2016
     * by Arturo Guadalupi
     * modified 8 Sep 2016
     * by Colby Newman
     *
     * This example code is in the public domain.
     *
     * http://www.arduino.cc/en/Tutorial/Blink
     */
// the setup function runs once when you press reset or power the board
void setup() {

    // initialize digital pin LED_BUILTIN as an output.
    pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {

digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
delay(80);                      // wait for a second
digitalWrite(LED_BUILTIN, LOW);  // turn the LED off by making the voltage LOW
delay(170);                     // wait for a second
}
Appendix B: MATLAB Code

In-Air System Model:

% Code by Eric Damm
% 2019

clear;
clc;
close all

ai=.25*pi*.01^2; % inlet orifice area
ao=ai; % outlet orifice area
ad=.25*pi*.1^2; % diaphragm area
k=116;
R1=2;
R2=2;

m=.06;
% q=1/R(dp); % flow rate

M=.011;
G=9.81;
H=.0367;
T=.07;
V1=H/T;
F=(M*G*H)/(T*V1)

% k=770^2*m;
k=116;
data1;
U=nV;
t=0:.001:length(U)*.001-.001;
t=t';
%p=kx/ad; % pressure in vessel

C=((k/(ad*ad))*(1/R1-1/R2))/m;
c=2.5;

A=[0 1;-k/m -c/m];
B=[1/m;0];
C=[1 0;0 0];
D=[0;0];
sys=ss(A,B,C,D);
[z,y]=lsim(sys,U,t,[0,0]);

xx=length(y);

plot(t(1:xx),z(1:xx))
ylabel('Displacement (m)')
hold on
yyaxis right
plot(t(1:xx),n1)
legend('Membrane Displacement (m)', 'Input signal (V)', 'fontsize',14)
title('In-Air Membrane Displacement Simulation', 'fontsize',16)
xlabel('Time (s)', 'fontsize',16)
ylabel('Input Signal (V)', 'fontsize',16)
grid on
%Code by Eric Damm
%2019

clear;
clc;
close all

ai=.25*pi*.01^2; %inlet orifice area
ao=ai; %outlet orifice area
ad=.25*pi*.1^2; %diaphragm area
k=1.16;
R1=2;
R2=2;

m=1.3;
%q=1/R(dp); %flow rate

M=.011;
G=9.81;
H=.0367;
T=.07;
V1=H/T;
F=(M*G*H)/(T*V1)

%k=770^2*m;
k=116;
data1;
U=nV;
t=0:.001:length(U)*.001-.001;
t=t';
%p=kx/ad; %pressure in vessel
c=((k/(ad*ad))*(1/R1-1/R2))/m;
c=14;

A=[0 1;-k/m -c/m];
B=[1/m;0];
C=[1 0;0 0];
D=[0;0];
sys=ss(A,B,C,D);
[z,y]=lsim(sys,U,t,[0,0]);
xx=length(y);
READINGs;
plot(t(1:xx),z(1:xx))
hold on
xlabel('Trial Number','fontsize',16)
ylabel('Volume/ml','fontsize',16)
title('Pumping Data','fontsize',16)
legend('Volume/60s','Volume/120s','Volume/100 pulses','Average 60s','Average 120s','Average 100 pulses','fontsize',14)

%Air
figure(3)
AVGair=mean(readings(:,4));
xair=[1:1:20];
yair=readings(:,4);
plot(xair,yair,'*',[1:1:20],AVGair*ones(size([1:1:20])),'r'
,[1:1:20],(AVGair-.01)*ones(size([1:1:20])),'--
r',[1:1:20],(AVGair+.01)*ones(size([1:1:20])),'--r')
%errair=.013*ones(size([1:1:20]));
%errorbar(xair,yair,errair,'*')
hold on
%plot(AVGair*ones(size([1:1:20])), 'r');
grid on
xlabel('Pulse Number', 'fontsize', 16)
ylabel('Displacement (cm)', 'fontsize', 16)
title('In-Air Maximum Displacement', 'fontsize', 16)
legend('Maximum Displacement Values', 'Average Value', 'Uncertainty (.01 cm)', 'fontsize', 14)

%Water
figure(4)
AVGwater=mean(readings(:,5));
xwater=[1:1:20];
ywater=readings(:,5);
plot([1:1:20],readings(:,5), '*', [1:1:20], AVGwater*ones(size([1:1:20])), 'r')
errwater=.005*ones(size([1:1:20]));
errorbar(xwater, ywater, errwater, '*')
hold on
plot(xwater, ywater, '*', xwater, AVGwater*ones(size([1:1:20])), 'r', xwater, (AVGwater+.01)*ones(size([1:1:20])), '--r', xwater, (AVGwater-.01)*ones(size([1:1:20])), '--r');
grid on
xlabel('Pulse Number', 'fontsize', 16)
ylabel('Displacement (cm)', 'fontsize', 16)
title('In-Water Maximum Displacement', 'fontsize', 16)
legend('Maximum Displacement Values', 'Average Value', 'Uncertainty (.01 cm)', 'fontsize', 14)

figure(5)
hold on
x500=[1:1:20];
y500=readings(:,6);
%err500=.46*ones(size([1:1:20]));
%errorbar(x500, y500, err500, '*')
plot(x500, y500, '*', x500, mean(readings(:,6))*ones(size([1:1:20])), 'r', x500, (mean(readings(:,6))+.46)*ones(size([1:1:20])), '--r', x500, (mean(readings(:,6))-.46)*ones(size([1:1:20])), '--r');
grid on
title('Time Until 500 ml Pumped','fontsize',16)
xlabel('Test Number','fontsize',16)
ylabel('Time (s)','fontsize',16)
legend('Time Until 500 ml','Average Time Until 500 ml','Uncertainty (.46 seconds)','fontsize',14)

xxx=[0,60,75,120];
yyy=[0,mean(readings(:,1)),mean(readings(:,3)),mean(readings(:,2))];
figure(6)
hold on
grid on
plot([0,60,75,120],[0,mean(readings(:,1)),mean(readings(:,3)),mean(readings(:,2))],0,0,'r*',60,mean(readings(:,1)),'r*',75,mean(readings(:,3)),'r*',120,mean(readings(:,2)),'r*')
title('Average Volume','fontsize',16)
xlabel('Time','fontsize',16)
ylabel('Volume (ml)','fontsize',16)
Simulation Data

%Code by Eric Damm
%2019

F;
V = F/25;

n1 = [];
for n = [25.1:-.1:1];
    n = n-.1;
    n1 = [n1; n];
end

for n = [0:.1:49.9];
    n = 0;
    n1 = [n1; n];
end

nV = [n1]*V;
nV = [nV; nV; nV; nV; nV];
n1 = [nV]/V;
%Code by Eric Damm
%2019

clear;
clc;
close all

%sphere cap
%V=((pi*h^2)/3)*(3*r-h)

%original calculations
h1=.005;
r1=.1;
V1=((pi*h1^2)/3)*(3*r1-h1)*1000;
f1=1.5;
T1=60*f1;
V1=V1*T1

%Final calcs
V2=.250;
f2=.75;
T2=60*f2;
V2=V2/T2

%r2=.1;
%V2=((pi*h2^2)/3)*(3*r2-h2)*1000;
%h2=.005;
V3=(V1/T1)
n=sqrt(119/((V3+.11)))
%n=n/(pi/2)
Data Readings

%Data Collected by Eric Damm
%2019

%1min
%2min
%V/100 pulses
%DisplacementAir
%DisplacementWater
%time to 500ml

readings=[
250 460 300 2.6 0.4 132
248 455 290 2.6 0.4 135
245 465 295 2.6 0.4 131
260 460 298 2.6 0.4 130
265 460 300 2.7 0.4 132
263 470 300 2.6 0.4 132
240 468 305 2.7 0.4 134
243 465 303 2.7 0.4 130
243 460 303 2.5 0.4 135
248 453 305 2.5 0.5 129
250 460 298 2.5 0.4 133
248 463 298 2.6 0.4 129
248 445 303 2.6 0.4 132
263 460 303 2.6 0.4 132
268 455 295 2.6 0.4 136
263 463 303 2.7 0.4 129
263 458 308 2.6 0.4 130
245 458 305 2.6 0.4 132
250 460 308 2.7 0.4 131
253 463 300 2.6 0.4 132
];
References


