MULTI-MAGNET ACTUATOR FOR A FERROFLUID BASED SOFT-ROBOT

By

COLE STERCK

(Under the Direction of Mable P. Fok)

ABSTRACT

The soft robotic industry gained popularity due to its “soft” interaction with its environment. Within this field of robotics, there are multiple methods of actuation, with magnetic actuation consisting of one of the growing versions. Electromagnets and permanent magnets consist of the two actuators used within this method. Although having high amounts of control, electromagnets are large in size and consume vast amounts of power, relative to permanent magnets. However, permanent magnets have a constant field which attributes to the lower amount of control. In order to work around these issues, the exploration of multi-magnetic actuation is needed. From placing multiple magnets within certain orientations, a varying magnetic field can be created. The magnetic soft robot will consist of Ferrofluid and silicone due to the flexible and fluidic nature. In this research, multiple orientations of magnets and volumes of magnetic material have been studied.

INDEX WORDS: Soft-Robotics, Magnetic Actuation, Ferrofluid, Permanent Magnet, Electromagnet, Worm, Magnetic Field

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CHAPTER 1

INTRODUCTION

Soft Robotics consists of a new field of research with one of its first autonomous versions being the Octobot [1] in 2016. Soft robotics pertains to the use of soft materials and the combination of unique actuation methods to perform actions that traditional robotics fail to achieve. Utilizing the behavior and motion of human or animalistic traits incorporates soft robotic motion [2]. Some advantages of soft robotics include being lightweight, versatile, and delicate to its environment. Ever since the creation of this new form of robotics, soft robotics rose in use through academia and industry for a multitude of uses.

The idea of soft robotics derives from the delicate interaction between the robot itself and the environment. To achieve this, the robot must be made up of softer materials. Several popular examples of soft materials used include silicone, fabrics, plastic films and gels [3]. Another advantage of utilizing soft materials includes the ability to have free moving joints. As seen in the paper *Mechatronics-Embedded Pneumatic Soft Modular Robot* [4], the range of motion is not limited by a rigid structure and can move around its central axis and face any desired direction, as shown in Figure 1.1.

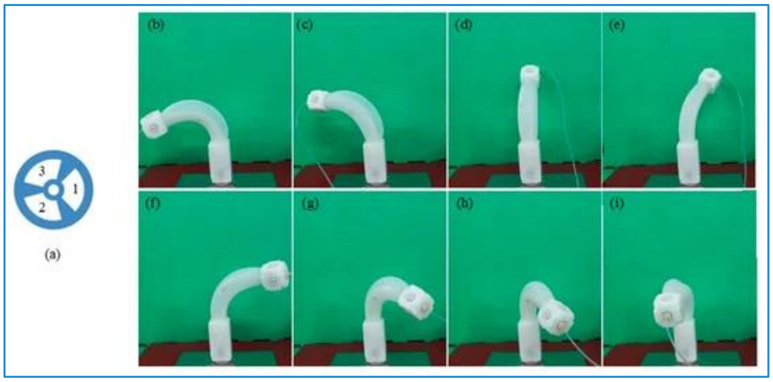

Figure 1.1. Pictures of the Pneumatic soft robot moving around a central axis. [4]

Traditional robotics uses harder, more rigid materials like metals and hard plastics which also inhibits movement. Furthermore, their actuation types follow different locomotion patterns than soft robotics. With a rigid, non-flexible structure, the movement is limited to motor, bearings and hydraulics that move in a singular motion. With soft robotics the multitude of locomotion types can produce movements that differ depending on the internal structures. Most research surrounding soft robotics introduces the ideology of mimicking the motion of biological movements. Several examples include mimicking aquatic creatures, worms and sometimes even bacteria [3].

With the increasing rise of soft robotic actuation, there lies a debate of the most effective form of robotic movement. There are multiple methods of locomotion that soft robotics use such as; pneumatic (vacuum pressure), piezo-driven (ex: dielectric elastomer actuator (DEA)) and magnetic actuation. Pneumatic actuation pertains to the use of either positive or negative fluid pressure to expand or constrict the body to either crawl, hop or grab items. Here the actuation is controlled by a pump with a tube funneling air to the robot. Dielectric Elastomer Actuator (DEA) uses piezo substances reactive to high voltage. When high voltage is applied, through wires, the paste-like material moves. Finally Magnetic actuation consists of utilizing varying magnetic fields to move ferromagnetic materials. This type of actuation allows for a superior amount of control and contains less limitations versus other methods of soft robotic locomotion. Magnetic actuation’s largest advantage is the ability to not be physically tethered. Many forms of soft robotics are limited by tubing or wiring which inhibits the robot's movement and distance.

Pneumatically actuated soft robotics are effective for certain applications but are sometimes limited by the tubing that positively or negatively pressurizes the chambers. In the case of the paper: *A Soft Steerable Continuum Robot That Grows Via Tip Extension* [5], the vacuum pumps air into a series of isolated chambers to turn and extend the length of the soft robot (Figure 1.2).

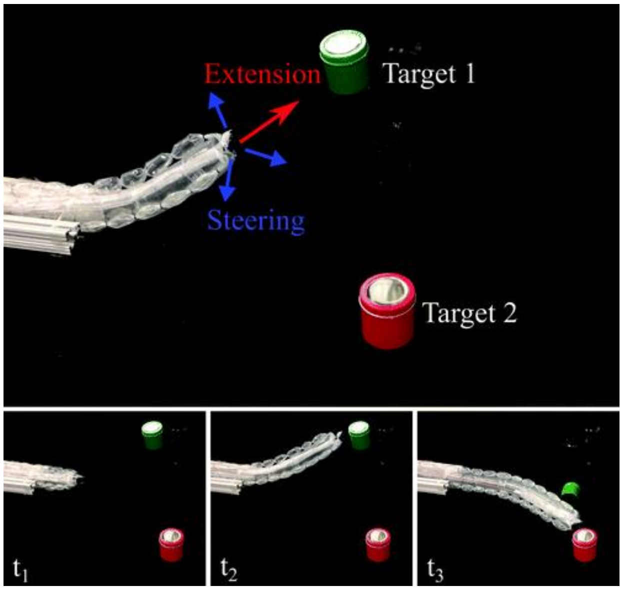

Figure 1.2. Here the steerable tip expansion soft robot is demonstrating directional control towards other targets. [5]

Many degrees of freedom encompass the main argument of the paper and why their pneumatically controlled robot can accomplish that goal. This paper shows the success of a non-magnetic soft robot that can achieve many axis movements. However, there are two major setbacks that were acknowledged. Firstly, while achieving the turning motion, the robot had to extend past its current length. This could pose a problem in certain environments such as tight channels and tubing. The robot also was tethered to a single location. The soft robot's physical base did not move with extension and exploration of testing and so limits the total travel capability. Furthermore, soft robots that are pneumatically actuated can rely on using the environment to help actuate. Within the paper *Worm-Inspired Pipeline Inspection* [6], the researchers built a tunneling worm that travels through a set diameter pipe by expanding its body outwards to grip the tubing. The tube or pipe the soft robotic worm is placed into must be a certain diameter for the robot to travel, as seen in Figure 1.3.

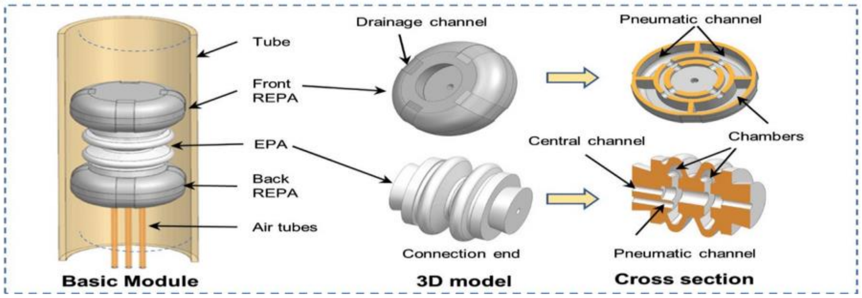

Figure 1.3. The design of the pipeline inspection soft robot. [6]

With this condition, the soft robot is limited to environmental parameters. Although effective at moving, not being able to change the pipe’s diameter hinders the robots’ movement which also physically tethers to the origin point. Pneumatically actuated soft robots can be limited due to the need to change volume to move. Furthermore, the limit is also highlighted by the robot’s physical tethering to its beginning phase.

Within the different types of actuations for soft robotics, the external applied magnetic field provides more control than other forms of soft robots can't achieve. For example, the

Triangular Head-Tail Morphology Soft Robot [7] provides several degrees of freedom (Figure 1.4).

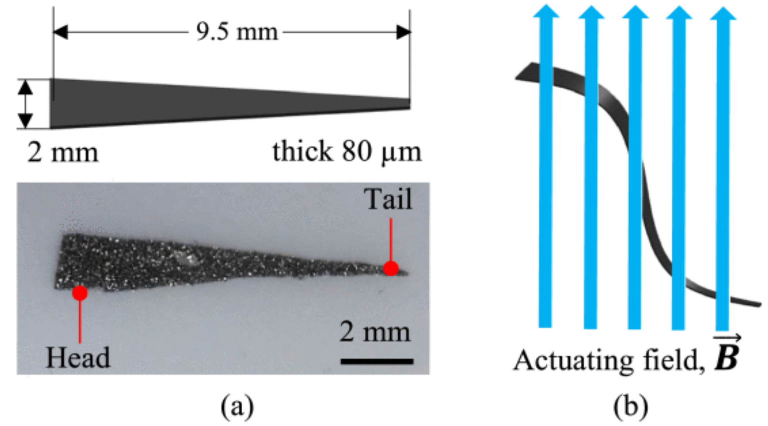

Figure 1.4. The design of the soft robot is laid out with dimensions (a) and the undulation is shown with a concurrent magnetic field (b). [7]

This robot consists of ferromagnetic particles suspended in silicone rubber and is controlled by a series of electromagnets. This robot has a higher degree of freedom and, according to the paper, can change its locomotion strength with different magnetic fields. Within multiple degrees of freedom, the robot can turn, spin, and propel itself in any desired direction due to the multiple electromagnets. Furthermore, this robot was able to turn around on its central axis. The paper discussed that the robot was able to maintain movement in all different sizes of tubing that were reasonable, meaning nothing smaller than the physical range of motion.

There are multiple methods of locomotion that soft robotics harness such as; fluid dynamics with vacuums, piezo-reactive materials, and magnetism. However magnetic control is sometimes preferred due to the high amount of control and untethered body. Pneumatically controlled soft robots rely on outward and inward expansion which could inhibit movement along with being tethered to an area from the tubing required for actuation. Piezo-driven actuation like

DEA, has similar issues with wiring limiting the reach of the robot and constricting movement. Magnetic actuated soft robots utilize free movement from maintaining a physical connection with its surroundings.

CHAPTER 2

MAGNETIC ACTUATION IN SOFT ROBOTICS

2.1 Introduction

Magnetic actuation is a very popular choice for soft robotic movement due to its high amount of control and even more so not having a physical tether [8]. However, when dealing with magnetic actuation, there are several negatives that need to be highlighted and improved upon. When choosing how to approach magnetic actuation, two large factors come into play: choosing what type of material to be actuated, and how that material will be actuated.[9] Within my research I found that the use of magnetic liquid called ferrofluid over iron particles could prove to be beneficial as well as using smaller permanent magnets over electromagnets.

2.2 Magnetic Materials

In magnetic soft robotics, the choices of magnetic materials play a crucial role in how to approach the robot's design and structure. There are two main categories of magnetic robotics: those who utilize magnets embedded within soft membrane and those who use magnetically responsive material such as powder or ferrofluid. [10] As seen in the paper *MagWorm: A Biomimetic Magnet Embedded Worm-Like Soft Robot* [11], they utilize differently oriented magnets within the soft robot’s body to create different forms of movement when a magnetic field is introduced. Here the actuator is a permanent magnet placed underneath and it moves around a conveyer belt as seen in Figure 2.1.

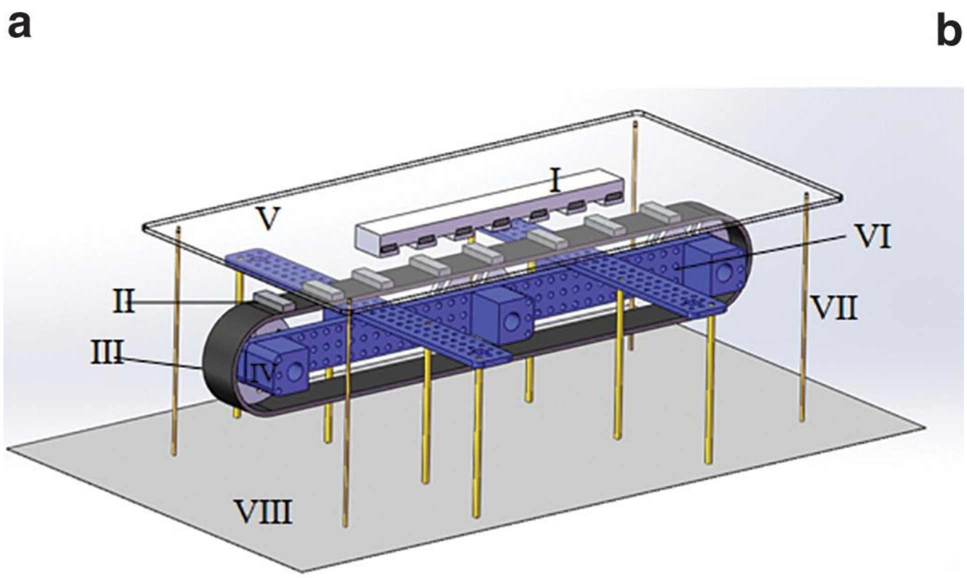

Figure 2.1. The entire system of the MagWorm includes the embedded magnets as well as the conveyer belt. [11]

Depending on the magnet’s location the magnets in the worm will behave differently from the magnetic field produced. The robot can effectively actuate however the motion is very linear and rigid. Meanwhile in *A Bioinspired Multilegged Soft Millirobot that Functions in both Dry and Wet Conditions* [12], a milli-scaled robot with tapered legs actuated by a magnetic field is fabricated. Here they suspend magnetically responsive powered uniformly though out the soft robot to mimic a push and pull motion. Like the previous paper, the robot is actuated with a permanent magnet placed below its environment. However, the difference includes using an oscillatory movement instead of the conveyer belt, as shown in Figure 2.2.

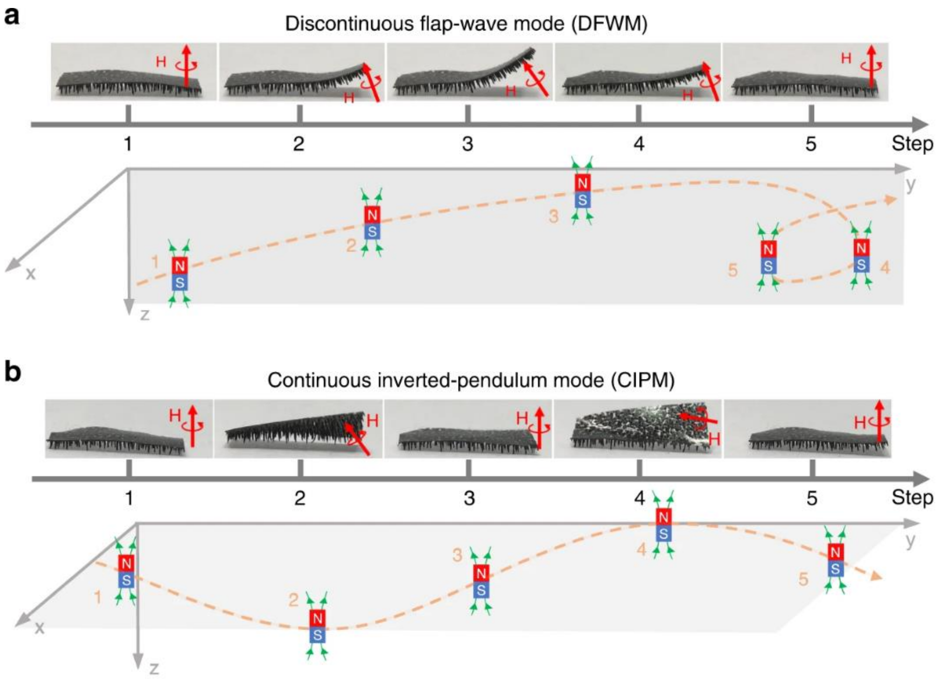

Figure 2.2. The multi-legged soft Millirobot is shown moving with the permanent magnet oscillating below the system. [12]

During this locomotion the robot has specific structures within it to move along a surface from its bodily structure, not so much as the magnetic material suspension. Meanwhile as seen in *Ferrofluid Soft-Robot Bio-Inspired by Amoeba Locomotion* [13], a soft robot is produced using free flowing ferrofluid as the magnetically actuated material. Ferrofluid consists of a black liquid of nanoscopic magnetic particles, roughly the size of 10nm suspended in an oil or water substrate [14]. The soft robot uses the fluid nature of ferrofluid in its design to mimic an amoeba’s movement, called pseudopodia. This phenomenon includes the ability of changing its shape to grip a surface and pull itself forward [15]. A diagram of the soft robot’s movement can be seen in Figure 2.3.

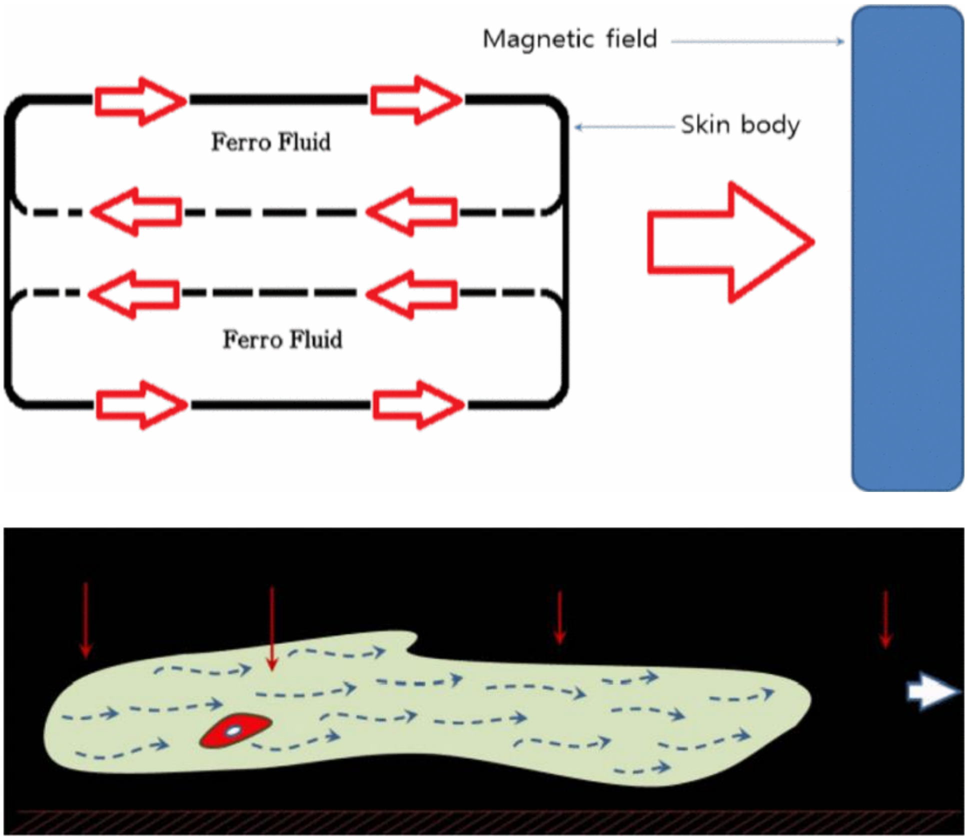

Figure 2.3. The ferrofluid based robot’s theoretical system is shown as well as the phenomena of pseudopodia of an Amoeba. [13]

The ferrofluid acts as the mimicking cytoplasm and works since it is free flowing in a capsule. In order to achieve this motion, powder or embedded magnets cannot be used. From this study, ferrofluid presents a viable option for locomotion due to its free-flowing nature. Embedded magnets are suspended within the polymers in a fixed position which can limit the variety of movement. The powered has a similar issue with being permanently suspended in the silicone substrate and its movement is too rigid. Meanwhile ferrofluid allows the body of the robot to change shape and adapt to its specific movement and I believe it has more capabilities in different locomotion types.

2.3 Magnetic Actuators

Regarding the actuator in magnetic soft robotics, the choice between electromagnets and permanent magnets becomes prevalent. Electromagnets provide large amounts of control and versatility due to the oscillating fields produced and the ability to turn off and on. Meanwhile permanent magnets do not consume large amounts of smaller and when relating size. to magnetic field strength, permanent magnets produce a stronger field while maintaining a smaller size. Finding a balance between control and size is a key trait. As seen in the paper: *A Shapeshifting Ferrofluidic Robot* [16], the researchers use large scale electromagnets to move ferrofluid into desired shapes. The robot consists of a collection of droplets with a volume of 5uL when the electromagnet system has the dimensions of 32 x 32 x 35 mm^3. As shown in Figure 2.4, the electromagnet takes up a large amount of space in comparison to the soft robot.

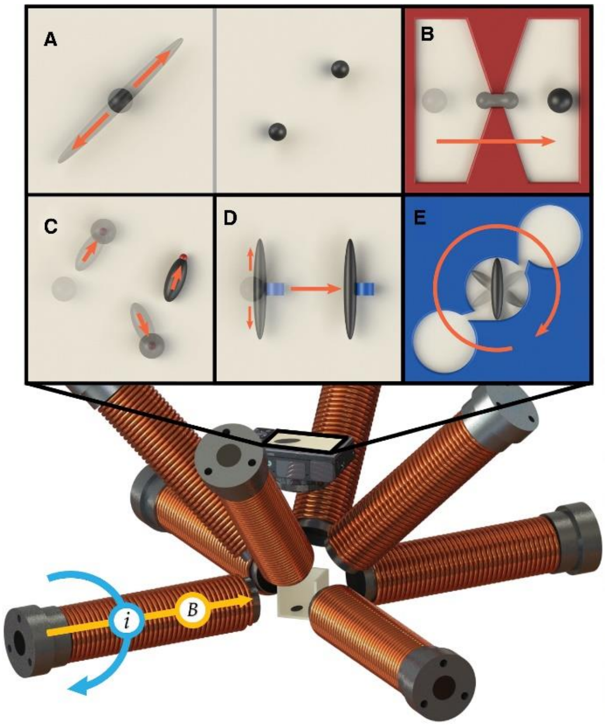

Figure 2.4. The whole electromagnet system and the changing shape of the ferrofluid robot are shown. [16]

Furthermore, the power consumption of the electromagnet is 1200Watts. The paper had high amounts of success with controlling a ferrofluid based soft robot but in order to control a small magnetically actuated soft robot, the electromagnet takes up a majority of the space in the experimental system and consumes a vast amount of power. Meanwhile, within the paper *Miniaturization of Worm-Type Soft Robot Actuated by Magnetic Field* [17] the robots studied are actuated by a permanent magnet. In this paper they test different sized worm robots that undulate differently in a rotating magnetic field, as shown in Figure 2.5.

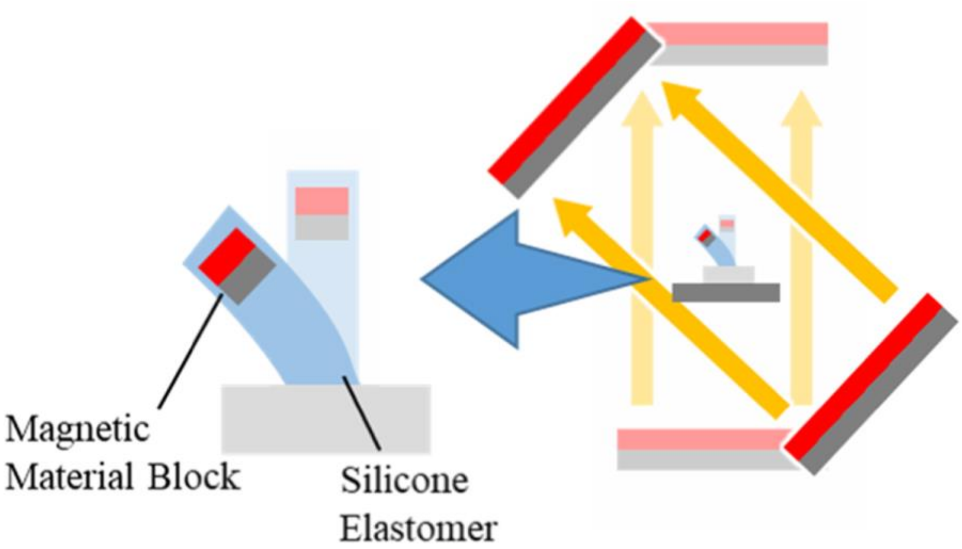

Figure 2.5.A demonstration of the magnetic cantilever with the rotating magnetic field. [17]

The key point of this paper includes a higher amount of control from permanent magnets with the rotating field. They use magnets embedded within the robots to respond to different fields. An issue with this was the bodily materials they used; the research provides ideas on how to implement more control. However, if we implement ferrofluid with the attempted higher control of permanent magnets, more control could be achieved. From this paper and the previous papers that have used permanent magnets, the decision that there might be a possibility in making an electromagnet have similar properties to the electromagnet with control and magnetic field adjusting. In continuation the power consumption of permanent magnets, without motors to move them, remains at zero. The actuator for ferrofluid usually is the electromagnet. However, as seen with other methods the permanent magnet could be feasible for this material.

CHATPER 3

THE DESIGN OF THE SOFT ROBOT

3.1 Introduction

Soft robotics contains unique designs and fabrication methodologies compared to traditional robotics due to its material selection. When using magnetic actuation, the design is broken down into three main components: body material, magnetically responsive material and the magnetic actuator. The material chosen for this robot is silicone due to its flexibility and soft nature. Ferrofluid is a magnetically responsive fluid made of ferromagnetic particles suspended in oil and comprises of the part of the robot that causes movement within a magnetic field. As mentioned above, permanent magnets and electromagnets are the source of the magnetic field. Below contains the design, fabrication and reason behind these choices.

3.2 Robot Design

The general design of the soft robot consists of a soft robotic worm that harnesses magnetic actuation. When looking for specific motion types in soft robotics, the earthworm provided a feasible method to replicate [18]. An earthworm moves by “a slowly travelling wave of thinning and elongation, followed by a wave of thickening of the body” [19]. When the worm is “thinning”, the body contracts certain segments from head to tail and as a result elongates in the desired direction of locomotion. Wave thickening describes the state of thickening the body, where the earthworm compresses each segment of its body to pull the rear. Once the compression is released, thinning and elongation occurs once more, driving the worm forward. [19]. Although simple in design, the earthworm is effective at moving above or below ground due to this motion. Furthermore, this provides a competent method of soft robotic actuation. In comparison, the robot researched was designed to expand outwards toward the magnet due to the external magnetic field and shrink in the “y” direction, as shown in Figure 3.1.

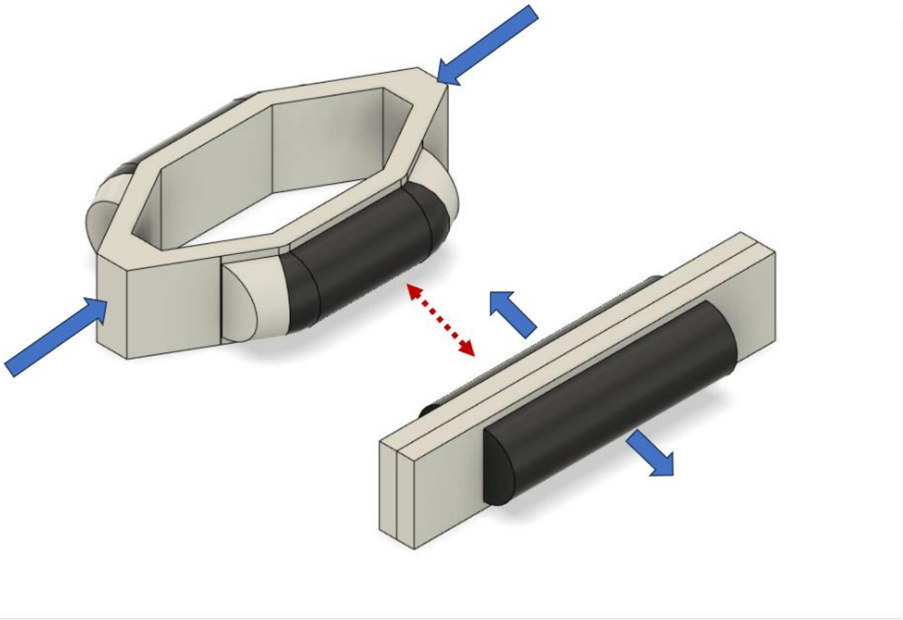

Figure 3.1. The design of the node is demonstrated in Fusion360. When expanded, the nod shrinks in the perpendicular direction to expansion.

When shrinking, the front and rear of the robot collapse inward, creating a change in distance. This repeated change in distance when actuated and then released, causes undulation up and down mimicking an earthworm. The node, which makes up a singular portion of the robot, is made up of two connected tabs of silicone with a pocket of ferrofluid on the outer portion of the node, as shown in Figure 3.1. This pocket acts at the magnetic material that is attracted to the permanent magnets on either side of the system. To maintain the ability of motion, the tabs are not conjoined in the middle but instead are sealed at the tips of the front and back as circled in

Figure 3.2. The unbounded portion is then able to separate to gain the expansion needed for locomotion.

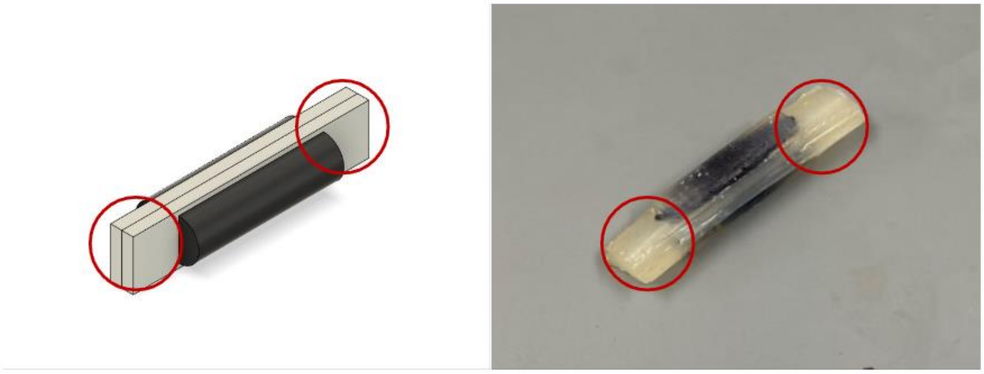

Figure 3.2 The simulated and real image node's connect parts are circled in red.

The black material consists of an oil based ferrofluid, specifically APG 1100 made by FerroTec. APG 1100 Ferrofluid has the saturation magnetization of the ferrofluid is 11mT while having the density of 0.94g/cc, which is important for calculating the exact volume located in the different prototypes used for testing (see Table 3.1). This material was chosen due to its low required magnetic actuation value and longer shelf life, water based ferrofluid tends to dry up faster when interacting with silicone. Furthermore, the reason a magnetic fluid was chosen lies with the nature of its flexibility. Other forms of magnetically actuated robots, as shown earlier, can use iron particles as magnetic material; however, the robots have a more rigid body structure. Using the fluidic nature of ferrofluid, the soft robot can move more freely than powdered or particle based soft robots. When placed in a magnetic field, ferrofluid moves in the direction of the strongest field. As described before, ferrofluid is placed on the outer portions of the two different tabs of the node, however a large concern involves eliminating the issue of the wrong tab being moved by the wrong magnet. Each tab has its designated magnetic actuator to pull the ferrofluid and thus cannot be attracted by the opposite magnetic field. To counteract this, a thicker tab of silicone is placed as a buffer on the inside of each tab. The silicone slab is shown in Figure 3.3. Acting as an insulator the piece of silicone divides the two tabs, isolating the field for the corresponding ferrofluid. However, this only works at certain distances due to the silicone inability to fully shield magnetic fields. This tab needs to counter the initial state of the actuation, once the tabs begin to separate, the increasing distance between them helps isolate the ferrofluid towards the correct actuator.

A singular node isn’t enough to cause movement, however a string of nodes actuating together and then released separately can. However, to achieve this, the singular node is studied, and the multi-node is theorized. The full theoretical body of the worm works by actuating and de-actuating the nodes in a certain order to propel the robot forward.

3.3 Fabrication of Soft Robot

As discussed previously, the main body of the soft robot is made up of silicone, a soft rubber-like material widely used in soft robotics. Smooth On Eco-Flex 30 was the type of silicone used for the body due to its elastic nature. This type of silicone could be moved by the fluid enough to actuate while not ripping due to the external pressure of the magnets. Other types of silicone were either too rigid or fragile for the desired outcome.

Silicone must be molded to get the desired shape of the body. The mold of the tab portion of the singular node is shown below in Figure 3.3. The mold’s design was created using Fusion 360 then 3D printed into two separate parts, the top and bottom portion of the tab. A partial cylindrical shape with a linear decline from the center of the pocket outwards is seen as the top or outside portion of the body. The flat piece in the figure, with a thickness of 0.05mm is the barrier mentioned above that also seals in the ferrofluid. In order to fabricate the node, two of the tabs shown below need to be cured. Silicone is poured into the mold after Vaseline is applied to the print to avoid tearing when removing the soft silicone.

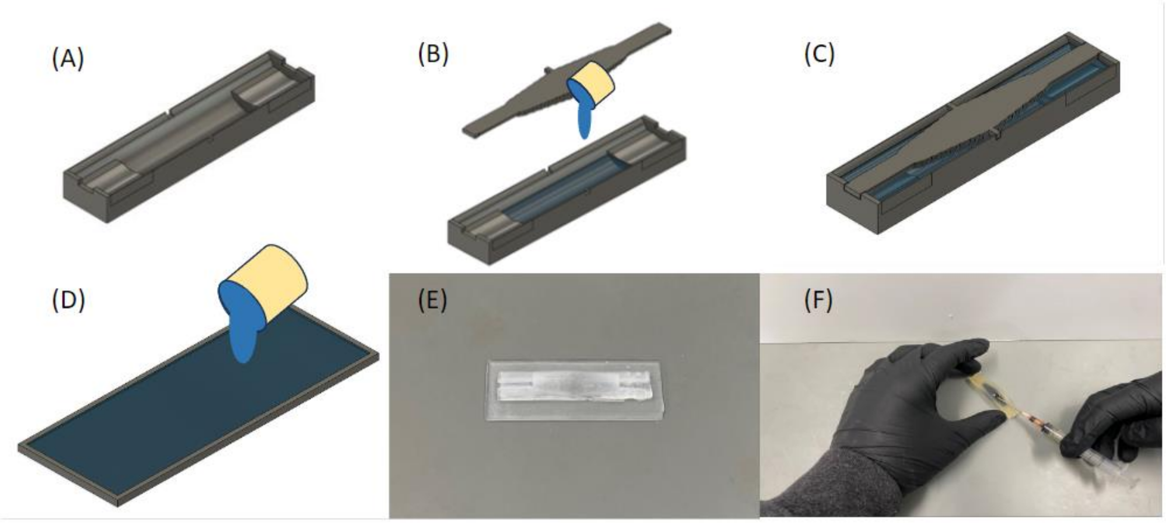

Figure 3.3. Here is the fabrication method for a singular side of the node. The mold of the top portion a). Silicone is poured into the mold then the insert to get the tab shape is placed b), c). The insulating tab is also made, it consists of a flat sheet of silicone d). The two molds are removed and fused together using silicone e). Once cured the ferrofluid is added f).

After roughly 4-6 hours of total curing, both portions of the tab are conjoined using the same type of silicone to create a liquid tight seal to eliminate leaking from the ferrofluid. Once the seal is set, a small puncture is created on the top of the flat part of the tab with a syringe rated for oil fluids. Once the desired volume of ferrofluid is reached, another layer of silicone is brushed on the flat part of the tab to re-seal the punctured hole. The process is duplicated to create two tabs for one node. After curing, two tabs have been created and are joined together at the ends as shown in Figure 3.2. Silicone is also used to conjoin the two tabs since it acts as an effective gluing agent and is flexible. A small piece of paper provides a divider in the middle of the node so that the middle section does not become joined. The length of the paper matches the same length for every version made. After the two have been joined the node is ready for testing. The versions below in Table 3.1 demonstrate the different nodes tested and the volume of ferrofluid within each tab. The different versions were tested and compared within the results section.

Version:	**A**	**B**	**C**	**D**
Volume:	0.2234mL	0.3298mL	0.4468mL	0.5426mL

Table 3.1. The different versions and the volumes

3.4 Magnetic Actuator Design

When it comes to magnetic actuation for soft robotics, the typical method of control includes two options: electromagnets and permanent magnets. Electromagnets utilize induction to generate magnetic fields. When one wraps a metal core, usually iron, with copper wiring and powers the system with high amounts of current, a magnetic field is generated within the core. This system is referred to as a solenoid and it is shown below in Figure 3.4.

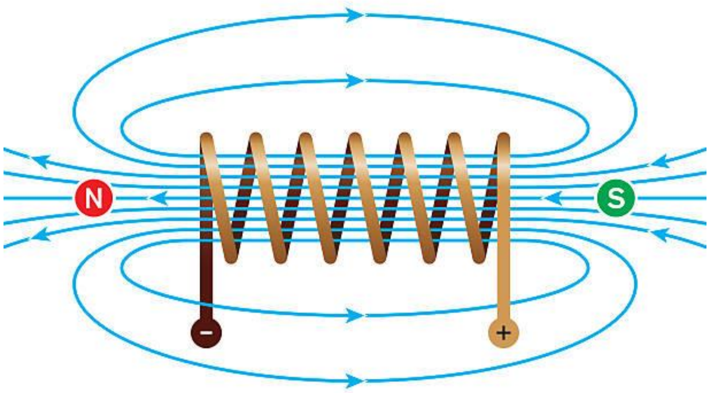

Figure 3.4. An image of a solenoid and its magnetic field. [20]

North and South poles are created at the ends of the core with a strong magnetic field flowing between them. Furthermore, an electromagnet can turn off and or change the produced field. However, a common issue with electromagnets is the magnetic field from the solenoid dissipates quickly and in order to create a strong external field, a high amount of power and large size is needed. As a result, a permanent magnet is used since it produces a strong magnetic field. Although the magnetic field dissipates similarly, the field produced starts off at a higher strength without the required power or large size. As mentioned before, an issue of the permanent magnet is the inability to turn off the field. To overcome this issue, a permanent magnet system to actuate the soft robot was researched. The general idea includes placing two magnetic systems on either side of the robot while using a combination of immobile bar magnets and sliding rod magnets. As seen in Figure 3.5, the orientation of the magnets includes two, three, or four bar-shaped magnets, depending on the testing.

Figure 3.5. The different orientations of the rod and bar magnets are shown.

Behind those magnets, the rod-shaped magnet slides in phase or out of phase of the front bar magnets. The secondary sliding magnet “boosts” the magnetic field to actuation strength. When placed at a certain distance from the face of the bar magnet, the node of the soft robot actuates. However, when shifted out of this range the magnetic field isn’t strong enough for actuation; but when the rod slides behind, using the made rail system, the node is pulled towards the magnets and compress perpendicular to the rail.

Permanent magnets vary in strength, shape and size. An important aspect of using multi-magnetic systems includes finding ideal pairing to boost the field. The front portion needs to be strong enough to move the node at a certain distance but weak enough so the rear magnet can have an effect. When it comes to the second magnet, a stronger magnet, relative to the front bar, is needed since it is located farther from the node. Furthermore, it must be stronger than the front to be able to use the boosting effect. The magnets used were made of Neodymium since it is a naturally occurring strong magnetic metal. At the face of a singular bar magnet, the magnetic field is measured at roughly 130.52mT and the rod magnet produces a field of 613.9mT. These values change depending on the distance and location of the magnetometer used. The fields of the magnet also slightly vary with the bar magnet have a clearer pole dictated by the face, while the rod magnet has the poles split down the middle creating a bubble-like field. When making the entire system, multiple bar magnets were tested, attempting to find the ideal magnetic field for the node actuation point.

3.5 Final System Design

Regarding the final testing apparatus, a rendering of the gantry is shown below in Figure 3.6. The final assembly includes two rails made of aluminum due to the metal being non-magnetic. When using magnets, having a high permeability creates issues. Permeability explains how a magnetic field passes through a substance, having high permeability results in the magnetic field easily passing through it and becoming magnetized [21]. The aluminum rails guide the strong Neodymium rods to create the actuating magnetic field. Bar Magnets are held up using 3D printed structures as shown by the black plastic next to the rails. The mounts have a section cut out behind them magnet so the field from the secondary magnet can propagate through the bar without interference from the plastic. A uniform distance was set to 1.5cm from the primary and the secondary magnet. A platform is created to hold the node of the worm when testing. Another black plastic platform, has two different variants; a flat platform and a pegged platform. The flat platform is for optimal actuation but if the nodes tend to sway in either direction of the field too much, the pegged platform is used for locking it into place. As shown within the figures, the magnetic system has two parallel sides in its final assembly. For testing purposes, the systems are set up on a section of plywood to allow adjustments for the rails. At final assembly, the system provided stable and well-regulated movements for accurate testing.

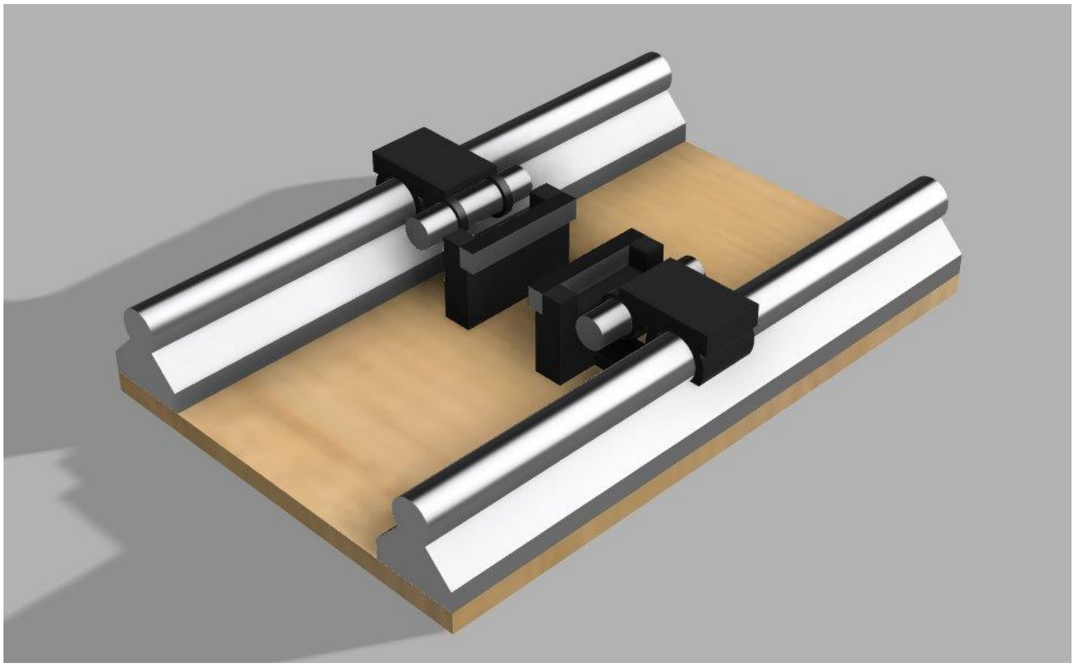

Figure 3.6. A rendered simulation of the gantry in Fusion360.

CHAPTER 4

RESULTS OF TESTING ELECTROMAGNETS, PERMANENT MAGNETS, AND FERROFLUID VOLUME

4.1 Introduction

Overall, my research discusses the relationships of electromagnets, permanent magnets and ferrofluid. The first segment of the results includes the study of electromagnets. Here I explain the shortcomings of electromagnets actuating independently and how I came across the idea of using multiple magnets to actuate magnetic material. The initial combination included an electromagnet with neodymium magnets. However, using both electromagnets and permanent magnets combined are shown to also be a failure below. This led to the completion of multiple permanent magnets only for actuation. Finally, I demonstrate the success of the permanent magnet's boosting characteristic while also testing different volumes within ferrofluid for optimal soft robotic design.

4.2 Electromagnet

When looking at magnetic actuation for the method of movement for the soft robot, the idea of using only electromagnets seemed to be the most effective method. Electromagnets are very popular when actuating ferrofluid due to the high amount of control it gives to the robot. As shown above, permanent magnets ended up being the resulting method of actuation and here is the reason behind that choice.

When measuring the magnetic field strength, I used a magnetometer which produces magnetic flux density values, however for simplicity I will refer to this as strength as these two values are directly related by permeability of free space as shown by the equation below. [21]

$$B = uH$$

At first, the electromagnet seemed to be promising from reading multiple papers and as a result, fabricating one seemed most optimal. Magnetism requires a precise amount of control, and making an electromagnet seemed ideal for fabricating one would give a desired magnetic field strength. The fabrication of the electromagnet became more personalized since the equation seen below allowed for precise dimensions. The equation for the magnetic flux density of an electromagnet is [22]:

$$B = \frac{\mu_o \mu_r I N}{L}$$

$B =$ Magnetic Flux Density (Tesla) $\mu_o \mu_r$ = (4π x 10^-7) * (Relative Permeability) (H/m)

$I =$ Current (Amps) $N =$ Number of Turns $L =$ Length of Electromagnet (m)

Using these equations, an electromagnet was built to fit specific requirements. When testing the self-built electromagnets, a magnetometer was used to measure the poles and hopefully, the reading would match the theoretical values from the equation above. When finding the comparison with the electromagnets tested, the dimensions used from the fabricated electromagnets were used to find the theoretical value. The experimental value resulted from the magnetometer, and after obtaining both values, a percent error calculation was calculated. In total, there were 20 iron core electromagnets built, however, just to demonstrate the large issue of fabrication with electromagnets, the best percentage error was the design chosen. The resulting percentage error was 95.06% error. From this, a conclusion was drawn, human-error within electromagnets causes a large decrease in experimental power and when measuring the field outside of the solenoid the values were extremely weak, at 30.71mT at its strongest but had an average of 26.49mT. The reason for the large disparity came from human error in manufacturing, such as; kinks in the wiring, uneven wrapping and the core was less uniform throughout due to cutting and metal impurities.

After some consideration, buying an electromagnet became viable. The manufacturing process was wasteful and tedious without producing any real results. Companies that specialize in the making of electromagnets produce non-kinked, uniform and reliable electromagnets. When buying electromagnets, three large aspects: size, strength and power consumption must be considered. These three traits correlate to each other, for example, a larger size usually makes the magnet stronger while also consuming more power. The first issue was size, when working with delicate and localized moving systems, a large size can hinder performance. When looking at other papers the electromagnets never moved. In the current set up, the rod magnet would replace the electromagnet, so it would've slid down the aluminum rail as described before. If it is too large, the system breaks. Furthermore, since the systems require a small enough electromagnet, strength is also an issue. From the electromagnet equation, more windings create a stronger field, with a smaller size, the less windings the electromagnet has, resulting in a weaker magnetic field. To somewhat counteract this, more power is needed to flood the electromagnet with current which creates a stronger amount of induction resulting in a stronger field. When trying to reach a high amount of power with a strong field strength and small size, the cost rises out of our budget range. However, to attempt to make the electromagnet system work, two were bought. Two 12-volt electromagnets with diameters of 65mm and 49mm were tested in the hope of possibly actuating the node by itself. During testing the following data was noted:

Electromagnet	0cm	1cm	2cm	3cm
49mm-12Volt	33.06mT	23.67mT	9.800mT	3.900mT
65mm-12Volt	58.82mT	35.05mT	15.66mT	7.720mT

Table 4.1. Two electromagnets were tested at different distances.

The magnetic field was measured at the above distance from 0cm to 3cm with 1cm increasing increments. As demonstrated, the magnetic fields were too weak to actuate the node by itself. From previous testing the field strength required was above the max field strength at the electromagnet poles. This can be shown from the figure below with little to no movement from the node in Figure 4.1. From this, the idea of using multiple magnets was formulated.

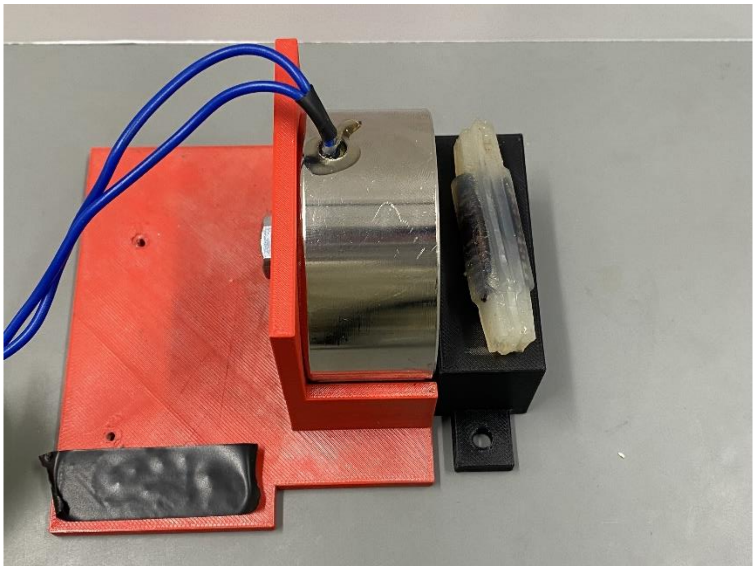

Figure 4.1. The electromagnet, when turned on, had zero effect on node.

4.3 Electromagnet and Permanent Magnet

After minimal to no movement was observed Figure 4.1 two different permanent magnets were placed in front of the electromagnet. When testing the electromagnet with the permanent magnets, two results became clear. Firstly, if the permanent magnet was able to produce a stronger field for the soft robot node to actuate, the electromagnet was too weak. When the node was placed outside of the permanent magnet's range, the electromagnet couldn't increase the strength of the field to the actuation point needed to expand. The test includes the 65mm electromagnet, a single bar magnet, and measuring the magnetic field strength in Tesla. As shown in Table 4.3, the electromagnet increased the field of the singular bar magnet for every given distance starting at 0.5cm to 3.0cm with an increase of 0.5cm. However, as described, the magnet was able to create a stronger field but when testing with the different nodes, only Version D (0.5426mL) showed any movement. The other nodes had little to no actuation, meaning this method was a failure, but also proved that the phenomena of boosting works.

State	**0.5cm**	**1.0cm**	**1.5cm**	**2.0cm**	**2.5cm**	**3.0cm**
off	71.92mT	27.17mT	15.13mT	8.21mT	4.92mT	3.82mT
on	75.83mT	34.54mT	22.80mT	13.98mT	8.92mT	6.30mT

Table 4.3. The result from testing the electromagnet and the bar magnet.

From the failed electromagnet and singular bar system, an additional bar magnet was introduced to attempt to actuate the remainder of the nodes. The second set of testing included the electromagnet and 2 Neodymium bar magnets spaced 1.5cm apart, as described in the design section. For this experiment, the goal included the actuation of the node by increasing the number of bars used which increases the magnetic field strength. From previous testing, the 2 bars alone can actuate the node, so to find out if the system works, the nodes were tested with both the electromagnets off and on. If the system operates correctly, then the difference of the node's actuation limit should be noticeable. As shown in Table 4.4, the difference in distance for each version was either 0.000cm or minimal.

Version	Emag off	Emag on	Diff
A	0.600cm	0.600cm	0.000cm
B	0.850cm	0.875cm	0.025cm
C	0.933cm	0.930cm	0.003cm
D	1.100cm	1.150cm	0.050cm

Table 4.4. The electromagnet was tested with different versions of volume.

The electromagnet provided little to no additional distance of the soft robot's actuation limit. This was due to the electromagnet's inability to create a stronger field than the permanent magnet. Although the permanent magnet was strong enough to actuate the node, the electromagnet provided close to zero help with increased distance and therefore was a failure. In summary, when the electromagnet produced a boosting effect for the permanent magnet; the field created was too weak to actuate the node and when the node was able to be actuated by the permanent magnet, the electromagnet did not boost the magnetic field to the soft robot's actuation point. After discovering the electromagnet was too weak to actuate the soft robot, the final method was studied of using multiple permanent magnets to actuate the soft robot.

4.4 Permanent Magnet Testing

Once choosing an entirely permanent magnet-based actuator, the comparison of different orientations and volumes were studied. The first segment of testing to see if the system works includes the analysis of a single sided actuator, meaning, only one side of the fabricated tab is moved. This testing method can be seen in Figure 3.5. The reason behind this involves finding the optimal location of movement to then mirror the distance found to the other side of the rail. The mirroring allows the soft robotic tabs to be only actuated by its desired and designated side, without interference from the opposing magnets. When testing, two different magnets were used:

neodymium bar-shaped magnets and cylindrical rod-shaped magnets. The orientations observed include: 2 Bar Magnets with no rod magnet; 2 Bar Magnets with 1 rod magnet; 3 Bar Magnets with no rod magnet; 3 Bar Magnets with 1 rod magnet; 4 Bar Magnets with no rod magnet; and 4 Bar Magnets with 1 rod magnet (shown in Figure 4.2. and Table 4.6.). Furthermore, four different volumes were also studied as demonstrated earlier in the Design chapter:

Version:	**A**	**B**	**C**	**D**
Volume:	0.2234mL	0.3298mL	0.4468mL	0.5426mL

Table 4.5. The different versions are displayed with their volumes.

The main study focuses on how the secondary Neodymium rod pushes or "boosts" the magnetic field from the bar magnets from out of actuation zone to the node moving. The testing can be broken up into 6 orientations that are individually tested for multiple values and trends. Orientations vary based on the number of magnets and the neodymium's rod state. Below is a table that describes these various setups.

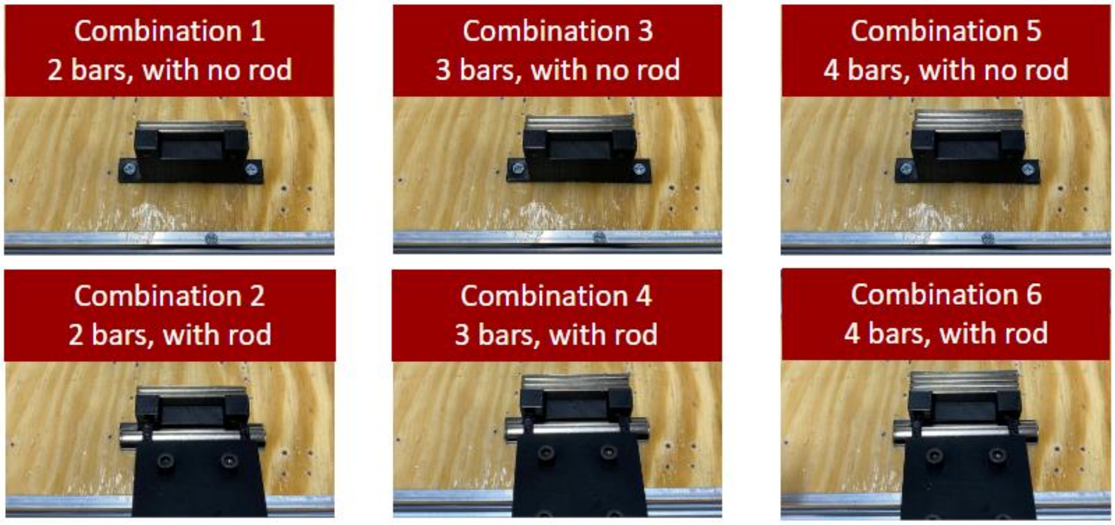

Figure 4.2. The orientations of the tested bar and rod magnets.

Orientation 1	2 Bar Magnets	Rod Magnet Removed
Orientation 2	2 Bar Magnets	Rod Magnet Present
Orientation 3	3 Bar Magnets	Rod Magnet Removed
Orientation 4	3 Bar Magnets	Rod Magnet Present
Orientation 5	4 Bar Magnets	Rod Magnet Removed
Orientation 6	4 Bar Magnets	Rod Magnet Present

Table 4.6. The lists of different orientations regarding magnets.

4.5 Test 1: Single Sided Orientation 1 and 2

At the weakest section of the testing, the isolated two bar magnetic system comprises of the first orientation tested. This system was the lowest magnetic strength magnet setup that actuated all four variants successfully. The distance from the face of the magnet to the tabs’ flat conjoined portion is what was measured. As predicted, the amount of ferrofluid allowed for the soft robotic node to be actuated farther from the base of the magnets. Overall, the trend makes logical sense for orientation 1 and furthermore when the rod was introduced, the distance increased as well. When the secondary rod rolled in behind the primary magnets, the increase of the node’s magnetic actuation limit increased in a similar trend to the first test. However, for Version C the difference was smaller than that of Version B and D, but it was still a positive difference, which follows the general trend. The values of the tests as well as the trends are shown below in Table 4.7. and Figure 4.3.

Version	**Orientation 1**	**Orientation 2**	**Difference**
A (0.2234mL)	0.295cm	0.345cm	0.050cm
B (0.3298mL)	0.545cm	0.562cm	0.017cm
C (0.4468mL)	0.628cm	0.728cm	0.100cm
D (0.5426mL)	0.795cm	0.945cm	0.150cm

Table 4.7. The results from orientation 1 and 2.

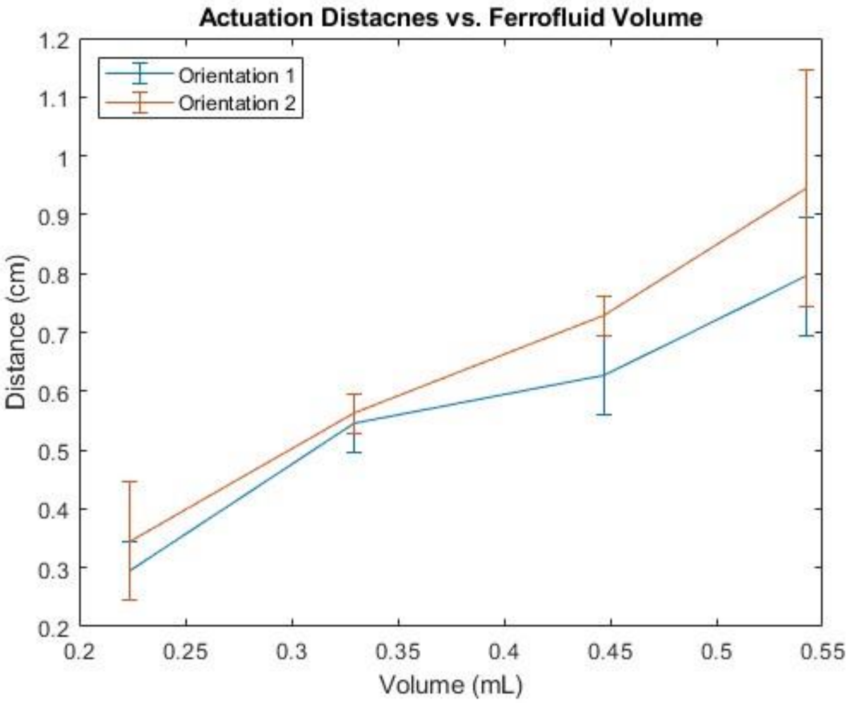

Figure 4.3. Graphical representation with error bars for orientations 1 and 2.

4.6 Test 2: Single Sided Orientation 3 and 4

Regarding the second set of permanent magnet testing, the number of bars in the primary position increased from 2 to 3. With this increase, the hypothesis is that the magnetic field limit's distance would also increase. As shown below in Table 4.8 and Figure 4.4, this was correct. When including another magnet, the distance of actuation is further increased. Furthermore, the secondary rod continues to push the magnetic field outward causing an even more increase of actuation strength. This is caused by the primary magnet having a stronger initial field while the rod magnet maintains a higher ration of field strength than the primary bar magnet. There was some variety from the first tests; the first version, A, saw the most increase from this effect, unlike from the first segment of testing where Version E gained the most from the secondary rod magnet. Furthermore, version C has a dip again from the first segment and then the similar trend increases from C to D and D to E returned.

Version	Orientation 3	Orientation 4	Difference
A (0.2234mL)	0.269cm	0.494cm	0.225cm
B (0.3298mL)	0.694cm	0.744cm	0.050cm
C (0.4468mL)	0.794cm	0.927cm	0.133cm
D (0.5426mL)	0.844cm	1.024cm	0.180cm

Table 4.8. The results from orientation 3 and 4.

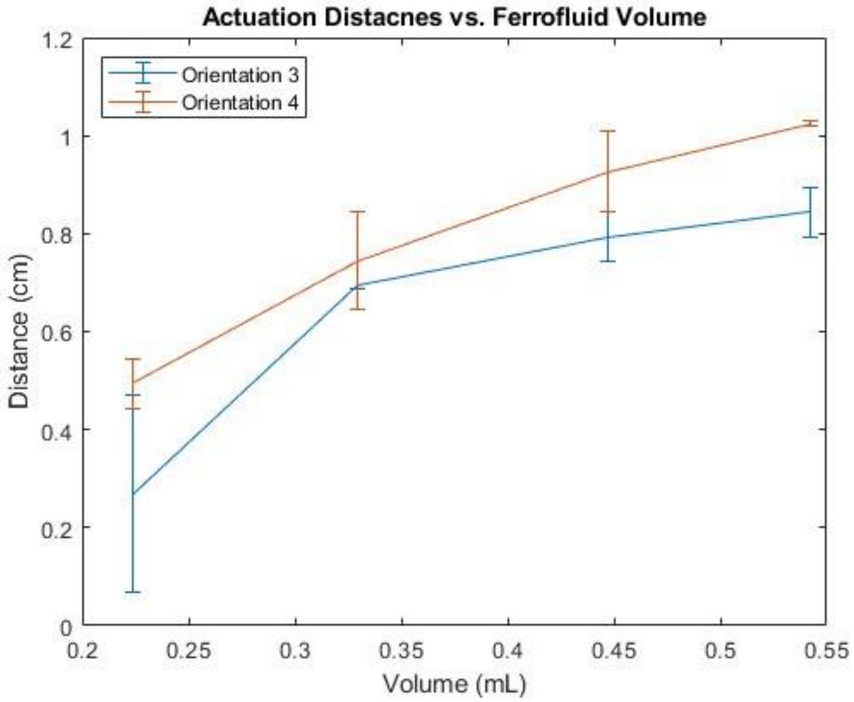

Figure 4.4. Graphical representation with error bars for orientations 3 and 4.

4.7 Test 3: Single Sided Orientation 5 and 6

Within this test, the number of magnets increased to 4 bar magnets. The results were not as I thought they would be. The general trend of this test resulted in Version B having the highest amount of difference between the surface of the 4th magnet and the node. The farthest distance in total from the permanent magnet includes Version D, as expected since this has the most ferrofluid within the tabs. However, it was assumed that this version would have the largest difference just because of the amount of ferrofluid within the tabs. The results are shown in the Table 4.9 below as well as the trend of magnetic actuation distance within Figure 4.5. Version A and C surprisingly has little difference from the primary and secondary phases.

Version	**Orientation 5**	**Orientation 6**	**Difference**
A (0.2234mL)	0.291cm	0.307cm	0.016
B (0.3298mL)	0.691cm	0.808cm	0.117
C (0.4468mL)	0.858cm	0.941cm	0.083
D (0.5426mL)	0.941cm	0.948cm	0.007cm

Table 4.9. The results from orientation 5 and 6.

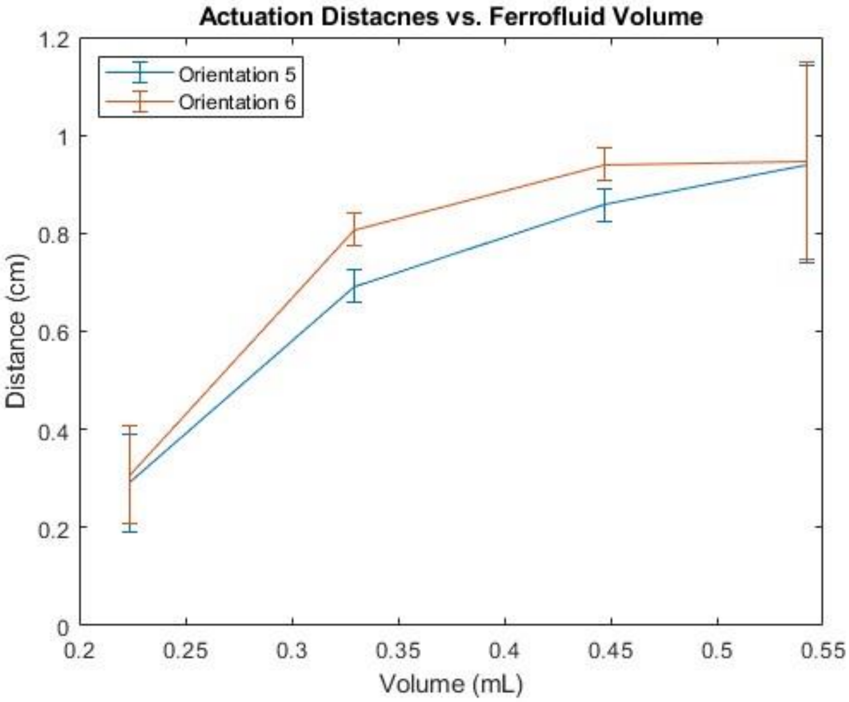

Figure 4.5. Graphical representation with error bars for orientations 5 and 6.

4.8 Test 4: Single Sided Tesla Value: Orientation 3 and 4

When comparing electromagnets and permanent magnets in terms of field strength, the increase of the tesla value can be measured. Using the 3 bar magnet orientations with rod and no rod, one can see that there is a general increase of magnetic field strength when the secondary magnet is introduced. As shown below in Table 4.10 and Figure 4.6, the rod magnet when slid into place increases the tesla value even when reaching extremely weak fields at 3.5cm and above. At the face of the magnet the field increases the most with a 19.50mT boost, as expected since the magnetometer is closer to the rod, however from 0.5cm to 2.5cm there seems to be a more consistent trend. The average magnetic flux density for these distances includes: 10.844mT. From this, one can see a successful increase of roughly 11mT can separate an actuated and non-actuated zone.

State	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
NR	271.2	116.2	59.66	37.47	21.74	14.89	9.91	7.39	5.64	4.66	3.37
WR	290.7	126.9	70.58	48.88	32.84	24.98	18.57	13.67	10.48	8.53	7.09
Diff	19.5	10.7	10.92	11.41	11.1	10.09	8.66	6.28	4.84	3.87	3.72

Table 4.10. The results of the magnetic flux density of orientation 3 and 4.

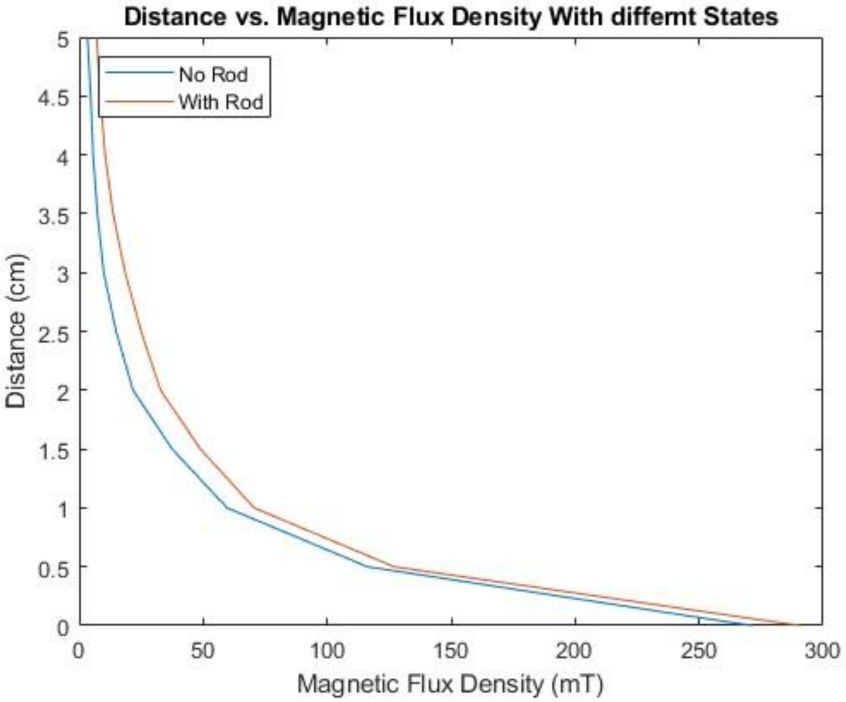

Figure 4.6. Magnetic field of the different states between orientation 3 and 4.

4.9 Test 5: Double Sided Expansion

Since this research includes nodular expansion for the actuation, this test compares the different versions in their “optimal” actuator to find the best node. Each of the orientations had a corresponding version that had the most difference in distance, this will be the defining factor of optimization. The following consists of the optimal pairings: the 2 Bar magnet system, Version D at a distance of 0.945cm; the 3 Bar magnet system, Version A at a distance of 0.494cm; the 4 Bar magnet system, Version B at a distance of 0.808cm; Version C was not optimal in any of the orientations. Below in Table 4.11 are the resulted changes in total length to demonstrate the expansion. As shown, Version D has a change of length of 3.65cm when using the 2-bar magnet system. This is the largest change in the node since the other could not fit nor expanded as much. Version A had 0.26cm distance change with the 3-bar magnet orientation. As mentioned before, Version C was not tested. Version B had an actuation issue that surrounded the 4 magnets not being set up in the testing system. The actuating distance of 0.808cm which helped formula the distance between the holders and when attempting to place the 4 bar system together the magnets had too strong of a repelling force that the system broke. As a result, the optimal paring ended up being Version D, the most amount of ferrofluid, with the 2 Bar system, the weakest permanent magnet orientation.

Version	**Default Length**	**Expanded**	**Change**	**Orientation**
A	57.14mm	56.88	0.260cm	3 Bar Magnets
B	56.24mm	x	x	4 Bar Magnets
C	x	x	x	x
D	57.54mm	53.89mm	3.650cm	2 Bar Magnets

Table 4.11. The node’s expanded length with optimized orientations.

4.10 Discussion

As one can see from the results, tables and graphs above, the multi-magnet system researched is conclusively better than the fabricated or purchased electromagnets. Furthermore, for multiple orientations the primary and secondary permanent magnets continually boost the magnetic field as hypothesized and desired. The magnetic flux density from secondary rod neodymium magnets allowed for the theorized worm-like robot to actuate farther from a singular set of magnets as shown by the 2, 3, and 4 bar primary magnets. In terms of the soft robot, for each change in volume the amount of actuation distance increases as shown by Version D (0.5426mL). When comparing the most optimal orientations for the singular sides, each version, except for Version C had a corresponding pairing, however it was Version D that had the most expansion from the least number of magnets. When testing, it was theorized that a stronger magnetic field would cause a larger amount of expansion, but as seen this is not entirely the case. Version D, the most amount of ferrofluid, worked best with the least number of magnets with the 2 Neodymium bars. This could be due to the fact that adding additional bar magnets, in close proximity, causes magnetic interference when put into the double-sided system due to the stronger field. Regarding the other nodes, there was little to no expansion when put into the other orientations. Overall, the permanent magnet system could be viable when actuating magnetic soft robots with specific dimensions.

CHAPTER 5

CONCLUSION AND FUTURE

5.1 Conclusion

Magnetic actuation within soft robotics has many desired reasons for use. In industry and research, the applications include biomedical and agricultural uses due to certain advantages. These advantages include high amounts of control, free moving robots and sometimes low power if permanent magnets are used. In recent years this method of actuation has grown, and it continues to evolve. Two improvements/changes consist of the material affected and the actuator that produces the magnetic field. The materials consist of embedded magnets, magnetic powder or ferrofluid, with the actuator including electromagnets or permanent magnets. Within my research the soft robot was made of ferrofluid and actuated by a multi-magnet system.

Ferrofluid was the chosen material for actuation due to its free moving nature. Embedded magnets cannot be moved once set into the soft robot which can limit the orientation and versatility. Magnetic powder also has its limitation due its rigid nature. The powder, when mixed in a substrate for the robot creates a stiffer body which in certain applications hurts the capabilities. Meanwhile ferrofluid has the most possible movement for the material in a magnetic soft robot since it is a liquid. Most of the time it is used with a lighter, thin film but within this research it was placed within silicone. The silicone and ferrofluid can mimic the earthworm due to the stretchy nature of the silicone and high fluidic nature for the ferrofluid.

When discussing the soft robotic actuators available, the electromagnet is the more popular choice for ferrofluid, however a permanent magnet system was researched. The electromagnet itself can adjust or turn off its field but in order to achieve the same field strength large amounts of power and size are needed. As demonstrated from previous research, the electromagnet consists of a proportionally larger size actuator to move a smaller robot. Within this thesis, we have successfully seen permanent magnets adjust the magnetic field flux density and in result change the strength by using multiple magnets. Multiple orientations were tested to find the results of boosting, which was demonstrated by multiple permanent magnets. Specifically, using a stronger secondary magnet behind the primary magnet increased the field strength. However, within the applied setup, electromagnets failed to achieve similar results. This concluded that the magnet field can be increased to the desired field using multiple permanent magnets. Furthermore, the permanent magnet system was also tested with a nodular portion of a future soft robot and as discussed before, the more ferrofluid within the node and the 2 Bar magnet with a secondary rod consists of the most optimal system. In the end a ferrofluid soft robot could be actuated with high control using multiple permanent magnets.

5.2 Future Investigation

This research will have future exploration in the forms of more testing and final soft robotic designing. There are countless combinations and systems to test to find the more optimal form of actuation when not limited by time or budget. Furthermore, the final goal for this project revolves around making a subterranean worm mimicking robot that deploys nutrients. In this section I will briefly discuss these future investigations.

When it comes to the system of the actuator, there are several examples of future testing for optimizing and gathering information. These include testing different types of neodymium magnets, different numbers of magnets, and differing orientations in the actuator itself. The magnets tested consisted of neodymium bar and cylindrical magnets. Magnets come in many different shapes, sizes and materials. Finding more powerful magnets with the same size or slightly large would help the distance of actuation. The priority would be making the rear magnet stronger but ideally the entire system with a similar ratio of boosting would be beneficial. When the better magnets are acquired, the same tests would be performed but also some additional ones would help the research. I'd try finding more combinations to harness for different volumes of ferrofluid. These combinations include measuring more magnetic flux densities and increasing the number of sides for the actuator. I'd study double and triple the number of sides to achieve the end goal actuator. Furthermore, would varying the side actuators orientations be feasible for steering or locomotion. For example, having two bar magnets on one side and three on the other and then possibly design a system that changes the amount of bar magnets in an orientation for a desired movement.

Another aspect of research I'd explore would be finalizing the robot's design. The initial goal of this research included fabricating a navigational and nutrient sensing magnetically actuated sub-terranean worm. The future prototype is seen below in Figure 5.1. The prototype consists of 3 nodes aligned in a row and is simulated in Fusion360. In theory, actuating every node then releasing in a particular order would move the robot forward. Releasing the nodes from front then moving to the rear would move the prototype but also anchor the robot to prevent it from moving backwards. More designs would need to be explored regarding the head, body and tail. Fiber Optics would also be incorporated to allow sensing since they are not affected by magnetic fields unlike electrical sensors. Furthermore, the fiber would be flexible enough to follow the bending nature of the robot.

As robotics has shown in the past the first parts of fabricating a successful prototype include studying how to achieve locomotion. Within soft robotics, the actuator is an important aspect, more than traditional robotics, so finding a new and more effective system is crucial.

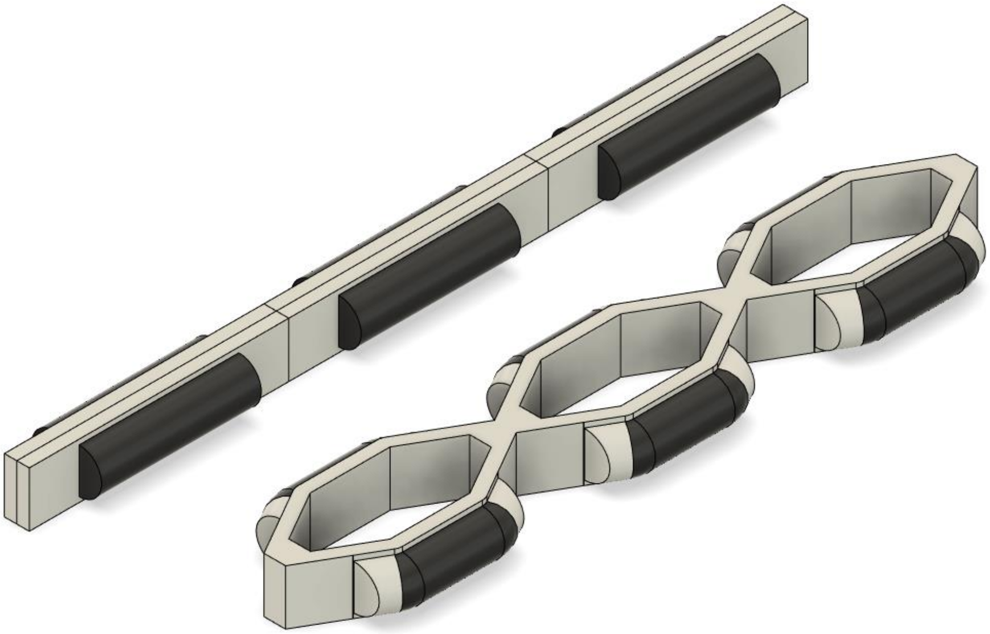

Figure 5.1. The simulated future soft robotic worm non-actuated and then expanded (actuated).

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