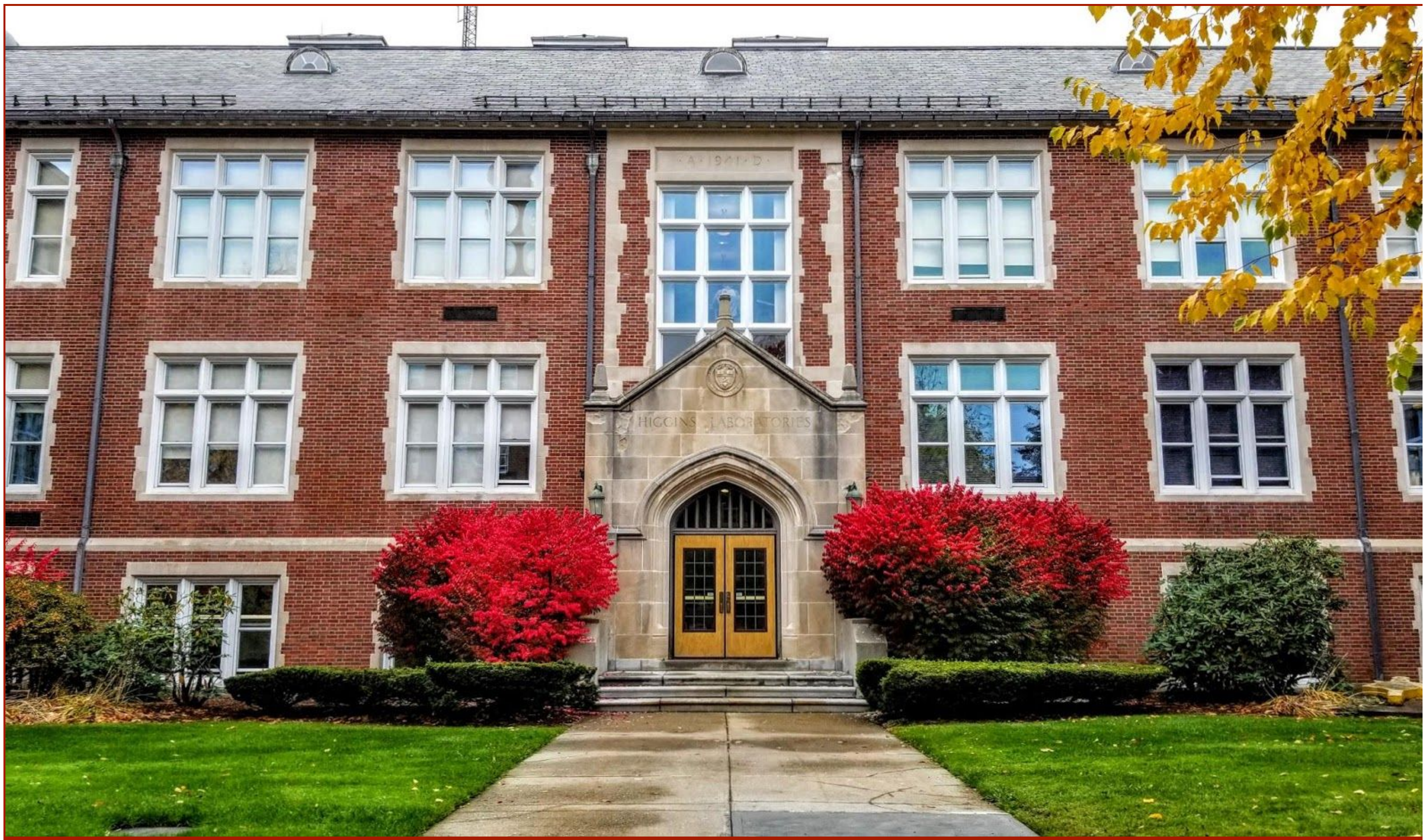

WPI

3D Printed Magnets for use in an Artificial Muscle Actuator

A Major Qualifying Project
submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
Degree of Bachelor of Science

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Abstract

The purpose of this project was to iterate and modify a student-built 3D printer with the goal of manufacturing a radially oriented magnet for use in a novel biomimetic magnetic actuator. The actuator is intended to simulate a sarcomere and to allow for unpowered stability, a low environmental impact, and easy interface with computers and programming. An artificial muscle with an actuator stimulated by a magnet would be favorable over a pneumatic actuating muscle because the bulky air tubes currently used in these muscles could be replaced with smaller, more lightweight batteries and microcontrollers. The ability to 3D print NdFeB magnets will allow for the creation of novel shapes and fields for ultimate design freedom.

Acknowledgements

We would like to thank Professor Stabile for his support and guidance throughout the course of this project. We would also like to thank Professor Gaudette for contributing his ideas and knowledge to our artificial muscle actuator design. In addition, we would like to thank Mathew Bisson and Ian Anderson for their help manufacturing the custom solenoid nozzle in Washburn Shops. Finally, we would like to thank the 2020 *Low Profile Home Speaker* MQP team for the magnetic filament and the 2019 *3D Printing using PA12/NdFeB Filament* MQP team for starting this project.

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Introduction

Additive manufacturing is a production process that builds objects sequentially. The most common example of additive manufacturing is 3D printing, which builds objects layer by layer. With the recent addition of the Foisie Innovation Studio Makerspace on WPI's campus, 3D printing has become increasingly popular among the student body. WPI's 2019 3D Printing Using a PA12/NdFeB Filament MQP focused on the design and creation of a modified conventional 3D printer with a goal of printing magnetic parts using a PA12 nylon and NdFeB composite filament. Ultimately, the printer was capable of printing simple designs with stock polylactic acid (PLA) filament. While both the stock PA12 and custom PA12/NdFeB filaments could be extruded from the printer's nozzle, they could not be printed.

This paper is a continuation of the 2019 project's legacy, as revisions are made to the team's design based on the recommendations given, combined with added knowledge and additional research, with the goal of demonstrating these hypotheses:

Hypothesis 1: Using 3D printing as a magnet manufacturing technique will allow for the creation of novel shapes, which can then produce novel fields, I.E. radially oriented magnets.
Hypothesis 2: With the use of magnets, the new actuator will have more fine control and ability to be programmed than artificial muscles using SMPS. In addition, because it is not reliant on air, the bulk and weight of air tubes necessary for pneumatic actuating muscles can be replaced by smaller, more lightweight batteries and microcontrollers.

The first step in the process of this project was repairing and modifying a custom 3D printer built by Worcester Polytechnic Institute (WPI) students during a 2019 major qualifying project (MQP). The next important step was manufacturing a custom extruder nozzle with the ability to utilize a prototyped solenoid and iron filament. The iron filament was produced by a team working on a parallel project, a Low Profile Home Speaker MQP. A rotating print bed was designed to allow for strong print layers and minimized extruder movement for the creation of a radially oriented magnetic cylinder for use in the artificial muscle actuator. Simultaneously, a self-locking actuator design intended for magnetic stimulation was realized and prototyped. Iterating and modifying the custom 3D printer and manufacturing a radially oriented magnet for use in the biomimicry of an artificial muscle is a step in the right direction for continued research on a better quality of living for individuals in need of muscle replacement.

Background

Home User Printers

Home 3D printers emerged in 2004 with the foundation of the RepRap movement, which seeked to create machines that were capable of building themselves. This movement latched onto 3D printing, as its low cost additive technology would allow for greater flexibility in terms of what could be manufactured. The first RepRap 3D printer, named Darwin, was released in May of 2007, and its sourcing and manufacturing was completed largely by the consumer [1]. The first commercial 3D printing kit, released by Makerbot in 2009, made it possible for consumers to build a Cupcake CNC 3D printer [2]. In the following years, 3D printing became more widespread and grew into a larger marketplace.

FDM printers use plastic filament and deposit a line of plastic that traces out a cross section of the part with a percentage of infill. There are a number of ways to drive an FDM 3D printer, with the most popular being delta, Core X-Y, and cartesian. Delta printers utilize a round print bed and have three arms that work in unison to move the print head. Cartesian printers have one motor connected to each axis, each moving independently to position the print head. Core X-Y printers use one motor to control the Z axis, and two motors to move the print head in the X and Y direction [3]. Regardless of the type of 3D printer, all printers contain the same basic parts. All FDM printers have three motors that move a heating element, which heats plastic into a molten state, relative to a large print area. They also have an additional motor, which drives plastic through the heated element. All FDM 3D printers contain a driving board, a power supply, and rails that allow the motors to move the heating element to its desired locations.

Previous Work: 3D Printing using PA12/NdFeB Filament

An MQP team from 2019 worked on a project called *3D Printing using PA12/NdFeB Filament* with Professor Stabile. The team's main objectives were to build a custom 3D printer with the ability to print magnetic components, to create a filament with magnetic properties, and to print parts with that filament using the 3D printer [4]. Building a custom 3D printer rather than purchasing one was a lofty objective, but it was ideal because it gave the team full control over the design of each aspect of the printer. This was necessary to achieve the end goal of printing magnetic components because there are elements of a generic printer that must be modified to make it possible to print filaments with magnetic properties.

The 3D Printing using PA12/NdFeB Filament team was successful in building a custom 3d printer with the ability to print stock PLA filament. They also developed a filament made of

NdFeB powder and PA12. They tested varying weight percentages of each component and found the ideal weight ratio to be 20:80 due to its ductility and ferromagnetic properties.

Though the team was successful at building a 3D printer, there were still improvements necessary before the printer would have the ability to print magnetic components. The most pressing issue with the printer was the inconsistency of prints. The team recommended that the hot end be upgraded to one able to print at temperatures exceeding 250 C, the Marlin code be updated, and a more powerful board than the RAMPS 1.4 be utilized. The team also touched on problems with the solenoid and other post-print magnetization issues. The winding procedure they utilized is only capable of producing a solenoid of up to 20 turns, while the recommended number is 50. Theoretically, if the solenoid were winded 50 times around the nozzle, the particles within the filament should be remagnetized, but the printed magnetic components will still need to be exposed to a magnetic field of about 2.5 Teslas to induce magnetization [4].

Printing Magnets

A magnet is a material that produces an external magnetic field, which can attract or repel other magnetic materials, such as iron [5]. To understand their properties more fully, magnetic materials can be observed at an atomic level. An atom's magnetism can be determined by the number of electrons in its outer shell. Elements with half-filled shells have electrons that are unpaired, meaning the polarities of these electrons are oriented in the same direction and do not cancel out, thus producing a magnetic field. However, not all magnetic atoms create magnets. As these polarized magnets form together into molecules, they crystalize in one of two ways. Their atoms can either align their magnetic fields in an alternating fashion, cancelling out their polarity, or they can join forces and align their magnetic fields together to create a stronger magnetic field. The latter alignment is known as ferromagnetic and has the capability of remaining permanently magnetized. [6]

Similar to how ice melts into water, the crystalline structure of a magnet can be disrupted by heat. As with all molecules, a magnet's temperature increase is a representation of an atomic energy increase. This means nicely ordered ferromagnetic fields can be melted into disorder. This melting point is called the Curie Point, and is the temperature at which ferromagnets melt into paramagnets, whose chaotic alignment can be realigned by an adjacent magnetic field. [7]

As the magnetic filament is extruded through the project printer, it reaches its Curie Point, thus becoming paramagnetic. To realign the extruded filament into a ferromagnetic state, a solenoid can be used. A solenoid is an electromagnetic compound with an applied current, which can be used to create a controlled magnetic field. If a solenoid is wrapped in one consistent direction, particle poles will be directed in a consistent manner as a way to achieve proper magnet orientation. [8]

Artificial Muscles

Artificial muscles are devices with the ability to mimic the motion of organic muscles. They are a subset of actuators, which provide motion to mechanisms. They are useful in applications that require soft or flexible components, like soft robotics, or complex motion. Artificial muscles are triggered in three main ways: through electricity, through pressure, or through heat. Electrically activated artificial muscles use special materials, like piezoelectric polymers, which change their shape when exposed to an electric field. Electricity can also power thermally activated polymers when they are coated in a resistive layer. When electricity is applied to the polymer, the resistive layer converts the electricity to heat, which deforms the polymer and allows it to shorten or expand. Pneumatic artificial muscles use tubing and air sacks to provide actuation. Air is forced from the bladder and through the tube, causing it to expand. Thermal artificial muscles are composed of shape memory alloys and polymers with the ability to deform and return to their natural state when exposed to thermal power [9]. These three methods are capable of producing actuators that can respond at the speed of human muscles, but can lift significantly more weight [10].

Though they are impressive innovations, each existing artificial muscle approach has drawbacks. Thermally activated muscles are slow to change shape, exhibit hysteresis, and often require temperatures above what is tolerable in or around the human body [9]. Electrically activated artificial muscles are recent innovations, which have not undergone complete testing and are not commercially viable. In addition, when used with TCPs, they have the same issues as thermally activated muscles. Pneumatic muscles require a large amount of tubing and pumps, and are easily affected by outside variables, such as temperature, that make their performance non-linear[11] . None of the existing varieties of artificial muscles are fail-safe, and can only hold their contraction when they are stimulated. Due to these issues with existing artificial muscle options, the team sought to design a muscle that was fail-safe, non-susceptible to external conditions, able to operate within safe temperatures, and able to interface with computers without requiring a great deal of equipment.

Objective

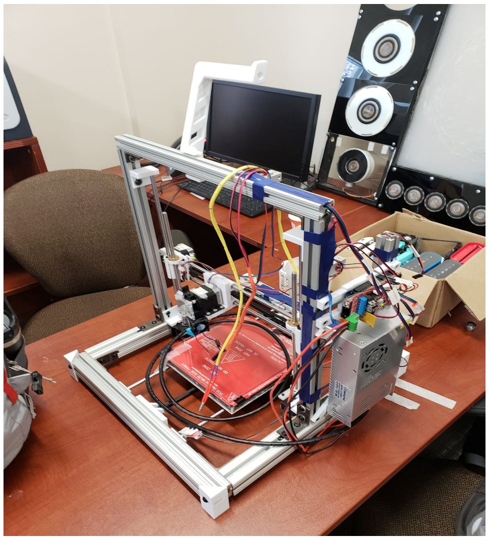
The team’s mission was to 3D print custom magnets to be used in an actuator with the ability to stimulate an artificial muscle. This goal entailed three parts: Enhance the current printer built by last year’s 3D printing team, print a magnet for use in an actuator, and design an actuator that can be utilized to stimulate an artificial muscle.

The first objective was to repair and enhance the custom built printer. When the project began, the printer had both hardware and software issues. It had only been successful in printing very simple shapes of PLA. To achieve the project end goal, it was necessary to replace faulty printer parts, create new parts for printer enhancement, and update the codes that control the printer. The next objective was to 3D print a magnet for utilization in an actuator. To do this, the team first designed and manufactured a custom nozzle with the capability to realign magnetic particles within it, then created a rotating bed for the printer to print a cylinder on. The final objective was to design and prototype an actuator to stimulate an artificial muscle. This design was based on a sarcomere, which is a small part of a muscle that contracts and works with other sarcomeres to allow the muscle as a whole to contract.

Printer

When the project began, the team was given a custom built 3D printer, equipped with an 80/20 aluminum frame, a heat bed, five NEMA 17 motors, an extruder, an arduino board, and various 3D printed parts to hold pieces in place. When the printer was acquired, the wires that connected varying parts of the printer to the power supply were unconstrained and difficult to keep track of, many of the prinet's parts were not ideal for use in printing magnets, and the Marlin code that controlled the printer had errors that did not allow for proper functionality.

The first step in combating these issues was understanding the purpose of each of the printer's wires by organizing and labeling each one because the disorganization interfered with the machine's ability to work properly (Figure 1). The wires were reorganized to make the printer look neater and labelled to make their purposes clear (Figure 2). In the beginning of the term, the printer's hotbed was not working properly because it was not heating up uniformly across the whole bed. This issue was resolved by soldering the temperature wires to the hotbed for a stronger connection for the code to communicate with the printer.



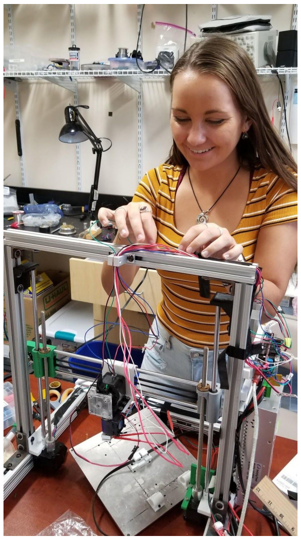
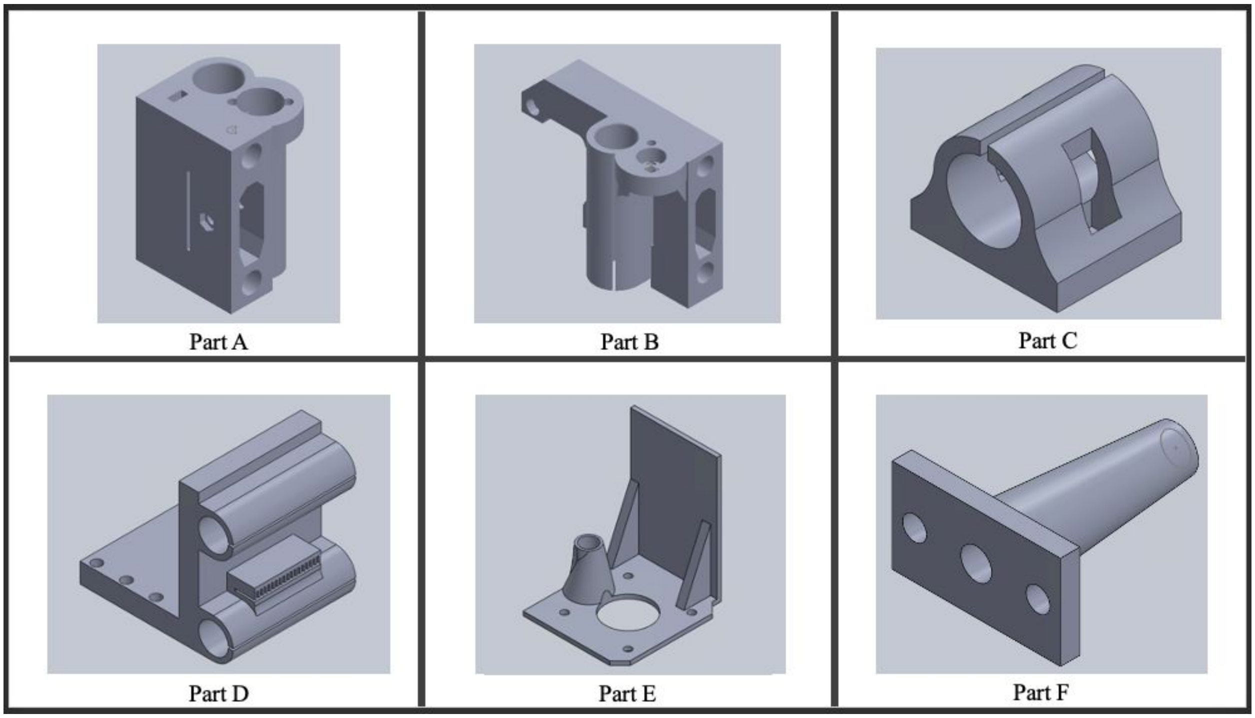


Figure 1 (left): *3D Printer as left by the 2019 3D Printing Using a PA12/NdFeB Filament MQP*
Figure 2 (right): *Analaide Boissonneault rewiring the printer*

Once the printer's wiring was organized and understood, each of its parts were examined to ensure proper functionality. Through this examination, it was discovered that seven of the printer's components needed to be redesigned to produce ideal prints. The following parts were redesigned in SolidWorks, printed at the Foisie Makerspace, and replaced in the printer: Both X axis braces had improperly sized rod holes, which caused the rods to converge, so the holes were updated to hold the rods parallel to each other (Parts A and B, Figure 3). The connectors that held the print bed on the bearings were loose and breaking, so they were redesigned to hold the bearings tighter and to be easier to screw into the bed (Part C, Figure 3). The extruder support was flimsy, and the diameters of the bearing holes were loose, so this part was redesigned to be stronger and more stable (Part D, Figure 3). The support for one of the vertical rods was broken and the Z switch mount was unable to accommodate a longer nozzle, which made homing impossible, so these parts were combined and adjusted to give the rod enhanced support and allow the switch mount height to be adjustable (Part E, Figure 3). The end stops for the rods that supported the Y Axis were too short, which caused the rods to occasionally come loose, so the rod supports were redesigned to give longer support interfaces between the rods and the printer's frame (Part F, Figure 3). The positions of these parts on the 3D printer can be seen in Figure 4 below. The updated printer assembly can be seen in Figures 5 and 6.



Part A

Part B

Part C

Part D

Part E

Part F

Figure 3: *SolidWorks Models of Redesigned Printer Parts*

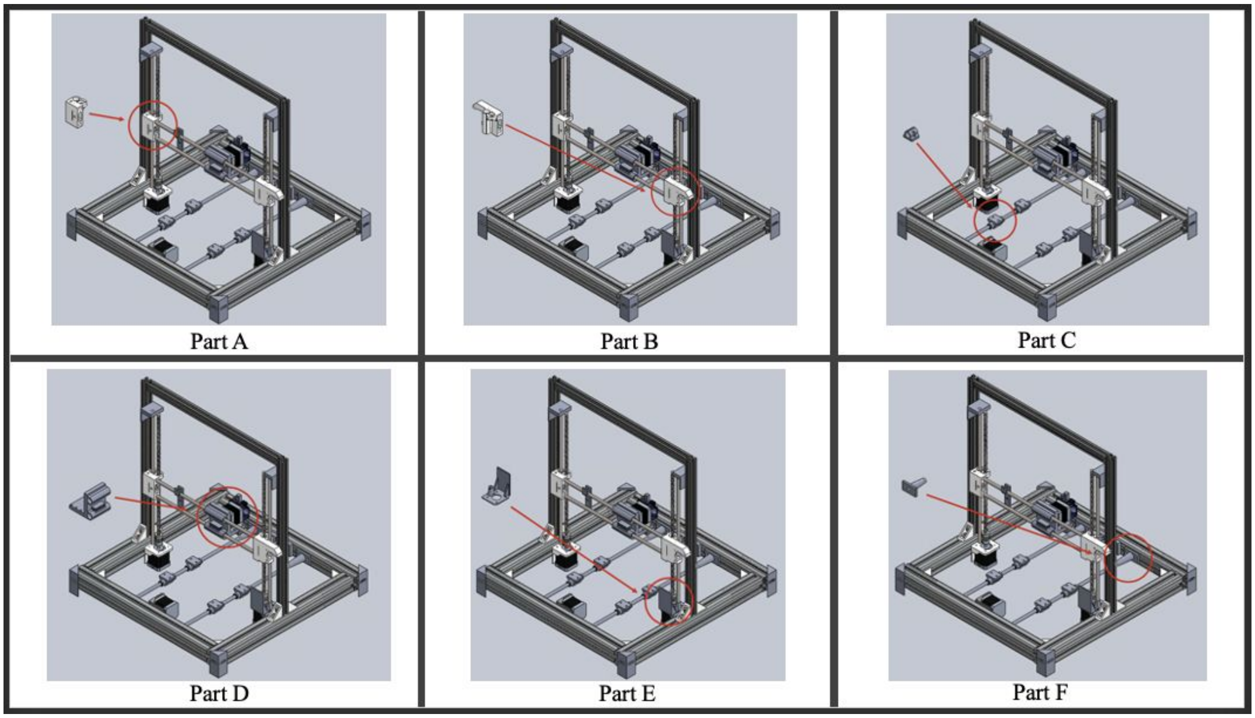

Part A
Part B
Part C
Part D
Part E
Part F

Figure 4: *Redesigned Parts' Positions on Printer*

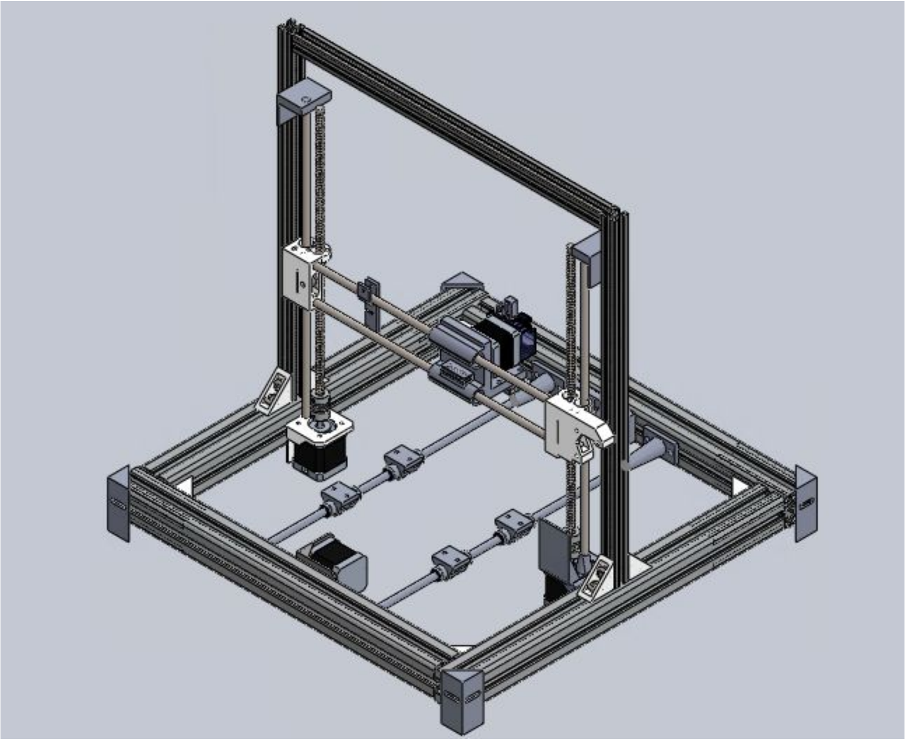
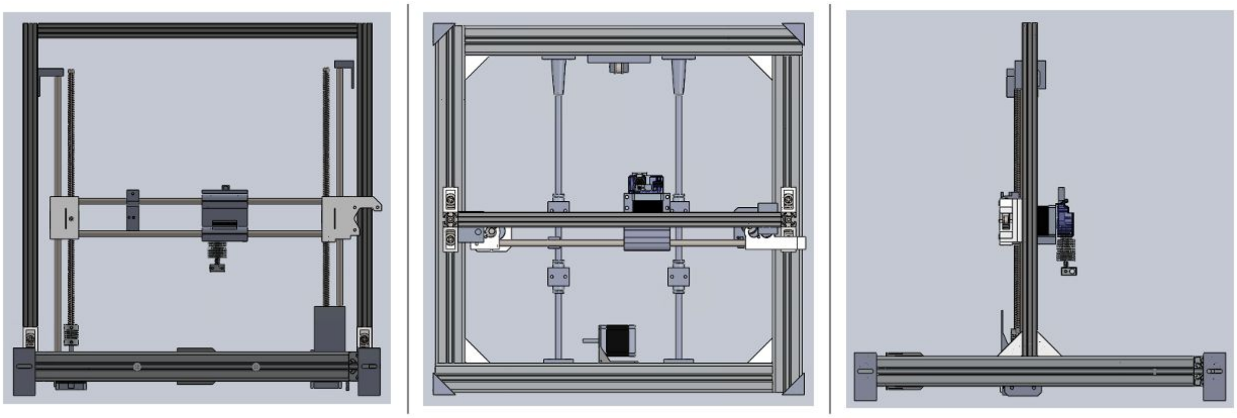


Figure 5: *Isometric View of 3D Printer SolidWorks Assembly*



Front View

Top View

Side View

Figure 6: *Varying Views of 3D Printer SolidWorks Assembly*

Switches

The team adjusted the placement of the Y and Z axis switches. The Y axis switch was moved from the print bed axil to the y axis motor. The previous placement of the switch utilized a mount which was prone to rotate in such a way that the print bed would miss contact with the switch, causing crashes duringY homing. Mounting the Y axis switch to the Y axis motor made the switch more stable and less likely to shift out of place. Since remounting the switch, there have been no observable problems with the Y homing of the print bed.

The Z axis switch was moved for a number of reasons. Previously, the Z axis switch was placed too low, causing the nozzle to routinely collide with the print bed during homing. It was decided that not only should the Z axis mount be redesigned to allow for an adjustable switch height, but that the switch should be moved to the opposite side of the printer. The team came to this decision when the Z axis support staff disconnected from its broken mount on the side where the Z axis motor is mounted. In designing a new switch mount, the team could simultaneously provide a replacement mount for the Z axis support staff.

Software

In addition to its hardware issues, the printer had software issues that prevented it from working properly. Initially, the code that controlled the printer was buggy and crashed Pronterface when it was plugged in. After consulting with the previous year's team, it was discovered that the most recent version of Marlin that was installed on the printer was no longer available. This led the team to reprogram the code from scratch. The config.h file in Marlin 1.8 was updated with the correct thermistor information, the PID control for bed and nozzle heating was autotuned, the end stops were set up with ensured functionality, and axis step per unit values for the X, Y, and Z value were corrected. Toward the end of the year, the team found that the extrusion step per unit value was set to about ¼ of what it should have been, causing a great deal of under extrusion and preventing proper printing. To set the axis step per unit values, the prusa calculator was used to determine the X, Y, and Z axis step per mm. Once the code was compiled, it was flashed to the printer and was successful in connecting and printing. A table containing each change in the code compared to the original can be found in Appendix C. In addition, to future proof this process the team has created a version of Marlin 2.0 (the latest release at the time of writing) with the edits made and included it in the files for next year's MQP.

Printing a Magnet

Filament

To practice printing with filaments other than PLA, the team cooperated with the Low Profile Home Speaker team mentioned above, to print a custom filament they produced. This team utilized a Filastruder to create an iron filament made of PLA and iron, with 15 wt. % iron. The filament had a diameter of 1.75 mm. When the team first gained access to the filament, a traditional nozzle with an extrusion diameter of 0.5 mm was being used. Due to this small diameter, the extruder was constantly getting clogged with pieces of iron, making it impossible to print parts using this filament through this nozzle. In addition, the nozzles would wear out and lose functionality. These issues were solved with the manufacturing of a nozzle custom designed to print metallic and magnetic parts. This nozzle would have a larger end diameter, and be easy to manufacture to combat wear caused by the abrasive metallic particles.

Nozzle

To reach the goal of 3D printing a magnet, the team had to reconsider the traditional nozzle design being used in the printer's extruder. The extrusion diameter was insufficient, which continually caused nozzle clogs, and heat from extrusion denatures magnetic particles into anti-ferromagnetic formations, causing them to lose their magnetic fields. To address the nozzle clogs, an enlarged extrusion diameter is necessary, and to counter the heating dilemma, the magnetic field must be reoriented before the extruded material cools. This can be accomplished with the use of a solenoid. A solenoid is a cylindrically wound coil that conducts an electric current, which creates a magnetic field.[12] To create a solenoid for use in printing magnets, a coil must be wrapped around the printer nozzle 50 times and given current to create a magnetic field powerful enough to realign the magnetic particles so that the magnet can return to a ferromagnetic state when magnetized [4]. With this knowledge, the team decided to design and manufacture a custom nozzle with a gap large enough for solenoid utilization and a diameter large enough to extrude large particles (Figure 7).

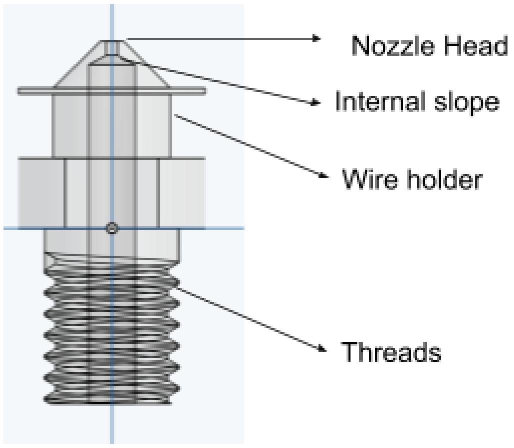


Figure 7: *Diagram Displaying Added Features of the Newly Designed Solenoid Print Nozzle*

Once the preliminary design for the nozzle was sketched up in computer-aided design (CAD) software, it was translated into Esprit computer-aided manufacturing (CAM) software to be manufactured using the lathes in Washburn Shops. The team originally planned to manufacture a stainless steel nozzle with a 60˚ smooth internal wall, and an angled head to allow for greater print complexity. However, steel induces a magnetic field, which could interfere with the prints. For this reason, the team decided to machine the part out of brass, which is weaker in terms of wear, but is magnetically inert. This decision was made because once a nozzle is CAMed, it is simple to machine a new one if it wears out.

After creating a CAM file for the nozzle, it became clear that the ideal design was not possible to manufacture. Creating a smooth internal diameter that scaled from 2mm to 0.5 mm was outside of the abilities of the shop, and would result in sharp step downs that could cause clogging and difficulty in cleaning. Through guidance from student workers and faculty in Washburn Shops, the team was able to CAM a feasible nozzle head, internal drill holes that transition between 2mm and 1 mm, and a thread for the nozzle to screw into the extruder. Once the nozzle was CAMed, the part was ready to be manufactured. After sourcing and purchasing brass stock and custom drill bits to produce the correctly sized internal and nozzle holes, the part was machined.

A problem the team ran into during the manufacturing process was that Washburn Shops is primarily student run and used for education, so the machines used for manufacturing were often crashed and were not completely accurate. This is not a substantial issue for large parts, but it introduces issues to the accuracy of small parts. For the nozzle to work, the hole the filament goes through must be centered, which was not the case for the first three manufactured parts. It was found that the lathes themselves were not centered, so they had to be calibrated to allow the drill to be centered in respect to the stock. Once calibration was complete, the resulting nozzles were centered and could print with no difficulty. The final product (Figure 8) has an extrusion diameter of 1mm and includes a ring that acts as a barrier to hold the solenoid in place.

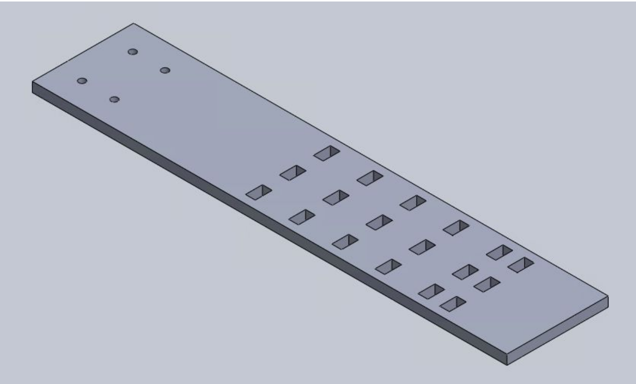
Figure 8: *Manufactured Product of the Solenoid Print Nozzle*

Rotating Bed Mount

Design

Since a cylinder will function as the external shell for the magnetized muscle, the team sought out to print a strong and accurate cylinder. A rotating bed was designed and built to give the printer the ability to print an ideal cylinder with enhanced strength and accuracy. A rotating print bed allows for layers to be printed at an angle, which can increase the strength of the cylinder in both tension and compression, as well as the shear strength. The utilization of a rotating bed also allows for greater accuracy, as it allows the printer to use gravity to ensure a continuous cylindrical shape, rather than printing vertically and fighting gravity [13]. This also allows for the creation of novel shapes that would be impossible on a cartesian printer due to large overhangs [14]. In addition, the rotating bed causes the direction of the filament, and therefore the particles to be consistent and radially oriented, allowing for the production of radially oriented magnets. Utilizing this rotating bed will also be easier on the printer than printing a vertical cylinder, as it allows it to move in only one direction (along the X axis), rather than all three.

The team researched previous methods of creating rotating print beds, and found one based out of London. Based on that paper, the team was able to generate G code, which would create a continuous cylinder on a rotating bed. To build the bed, two pieces of acrylic were laser cut: One designed to work as a bed mount and one to work as a rod support. Holes were cut in the mount at various lengths to allow for a more customizable print bed size (Figure 9). The support was designed to be placed in any of these holes, depending on what length cylinder was being printed (Figure 10). A stepper motor was then screwed into the mount, with the ability to be coupled to a rod that would go through the acrylic support (Figure 11). This system was designed to be removable so that the printer could print cylinders on the rotating bed, but would still have the ability to function normally, depending on what print was being achieved.



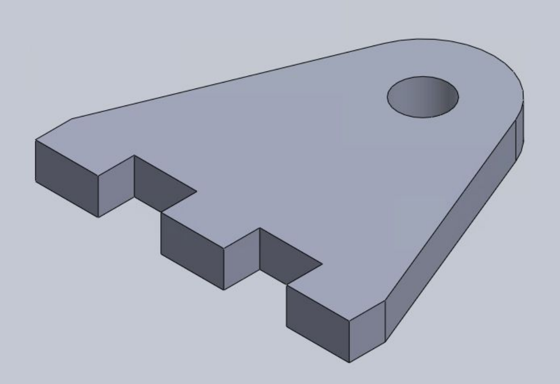


Figure 9 (left): *SolidWorks Model of the Rotating Bed Mount*
Figure 10 (right): *SolidWorks Model of the Rotating Bed Rod Support*

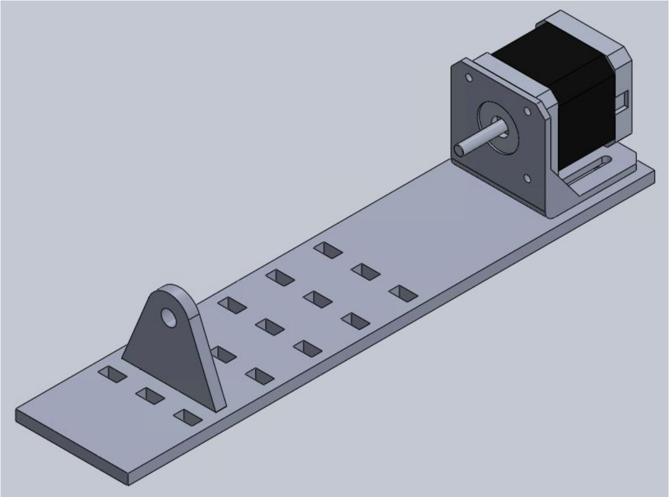
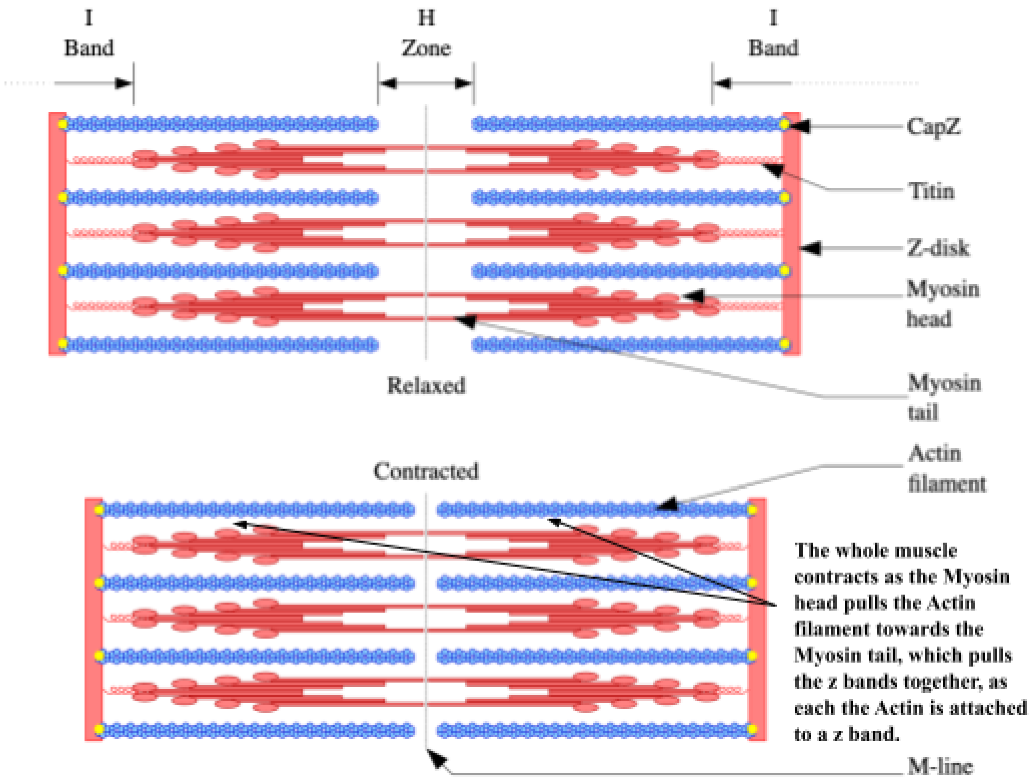


Figure 11: *SolidWorks Assembly of the Rotating Bed Excluding the Print Rod*

Actuator

An actuator is a part of a system that provides movement to or through a mechanism. A linear actuator is capable of moving in a straight line. In the human body, muscles act as linear actuators, with individual cells moving along a line and causing overall contraction that can be used for a variety of movements. Muscles are composed of many fibrils, which are composed of sarcomeres. The sarcomere, which is shown in Figure 12, consists of 3 main sections components: a thick myosin filament (represented in red), a thin actin filament (represented in blue), and Z bands (represented in pink). The thick filaments attach to the Z bands using a protein called Titan (represented by pink spring), which is elastic. When a muscle contracts, the heads of the myosin filament bond with specific areas of the actin filament and exert force on them. This force draws the Actin filament towards the H zone, which also pulls the Z bands together. The formation of these bonds does not require energy, but releasing myosin to allow for further contraction does require energy in the form of ATP. This creates a linear motion where the amount of movement is a function of the spacing of the actin bonding points, which allows for a controlled and fail safe mechanism for linear actuation.



The whole muscle contracts as the Myosin head pulls the Actin filament towards the Myosin tail, which pulls the z bands together, as each the Actin is attached to a z band.

Figure 12: *Diagram Demonstrating the Contraction of a Sarcomere*

Design 1

When creating the initial artificial muscle design, the team decided to use biomimicry to allow for future iterations of the device to be used inside the body. A novel locking mechanism was developed to prevent an actuated coil from relapsing to its previous position (Figure 13). For proof of this concept, a ratcheting system was designed and prototyped as seen in Figure 14.

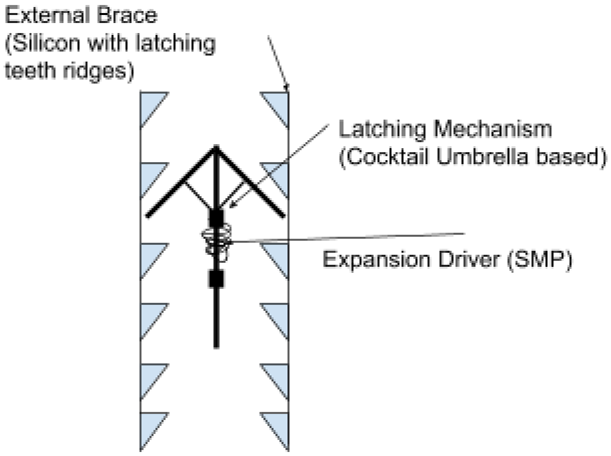


Figure 13: *Diagram Demonstrating the First Iteration of the Ratcheting System Design*

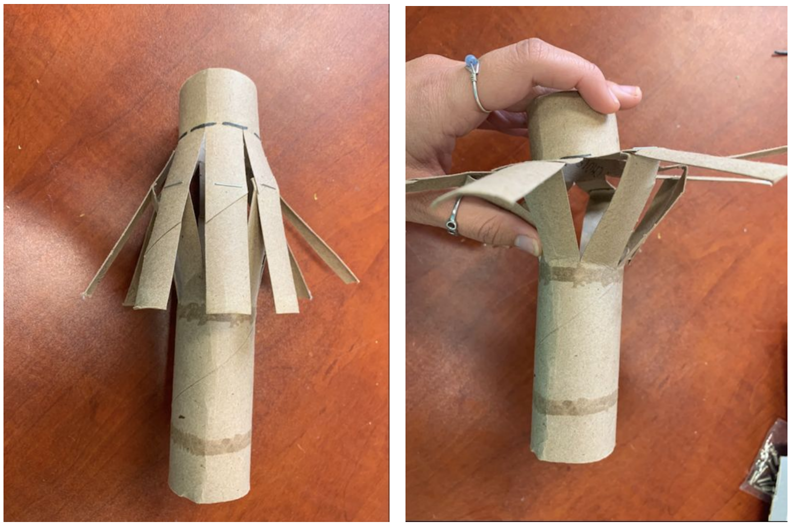


Figure 14: *Cardboard Constructed Prototype of Ratcheting System*

As depicted in the initial blueprint above, the ratcheting system in the first iteration of the design consisted of an umbrella-like latching mechanism that could collapse in on itself with a downward force exerted on it, which would align the stretcher and the wings in a vertical orientation. The interior of the external brace had teeth used to catch the latching mechanism when the umbrella was open. The shape memory polymer (SMP) spring acted as an expansion driver that pushed the latching mechanism wings outward, however was capable of triggering the collapse of the latching mechanism previously described.

Design 2

The second iteration (Figures 15 and 16) of the actuator design attempted to simplify the required hinge mechanics by replacing the umbrella with a buckle, inspired by a backpack's quick side release buckle. The external brace of the second design had latching ridges, similar to those present in the initial design, but the ridges were modified to be embedded in the wall of the brace and provide a shaft for the closing of the buckle. A helical design was used to allow the buckle to transfer to an open tube for quick release of the muscle and the ability to return to an initial state.

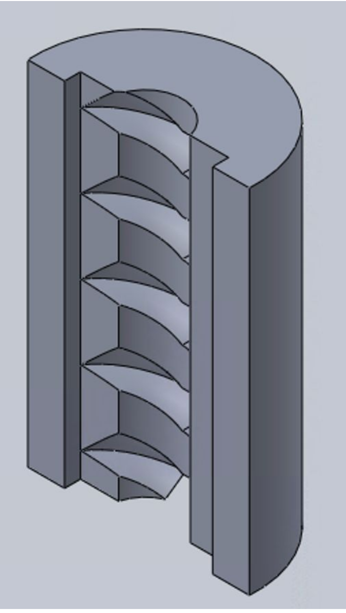


Figure 15: *Second iteration of Ratcheting System Design Helix*

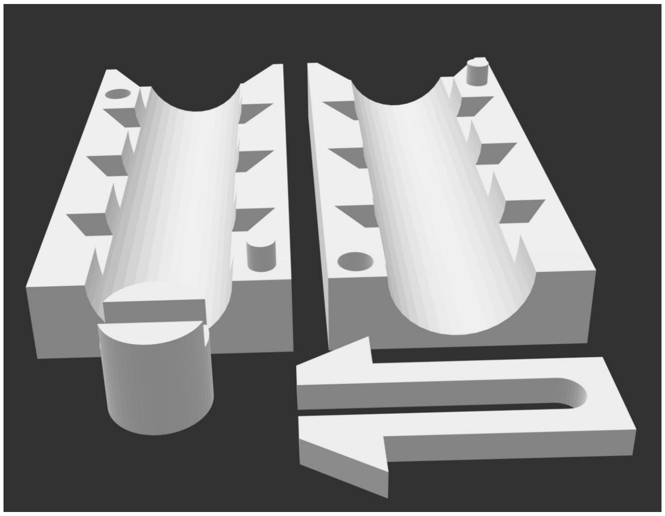
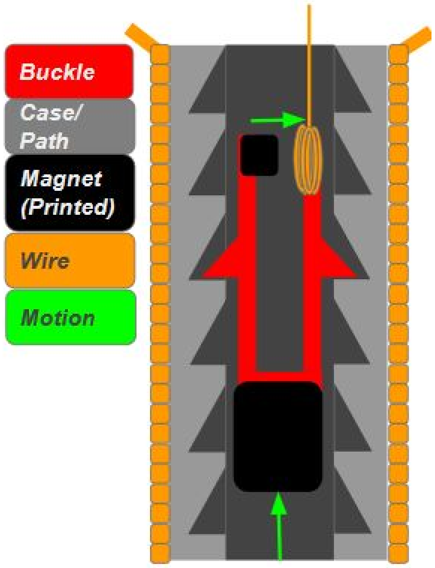


Figure 16: *Second iteration of Ratcheting System Design Simplified*

Design 3

The third design iteration (Figure 17) used the same brace as the second iteration, but the walls were given indentations to allow the buckle to interface and lock in place. Also, instead of utilizing a helical tube to release the buckle, a secondary magnetic latch was designed to protrude from the top of the buckle and allow for the clips to come together, no longer interfacing with the walls of the brace. The buckle was also simplified in this design iteration. The SMP was removed for simplicity and a magnet was placed at the bottom of the buckle to allow for upward and downward movement of the buckle (Figure 18).



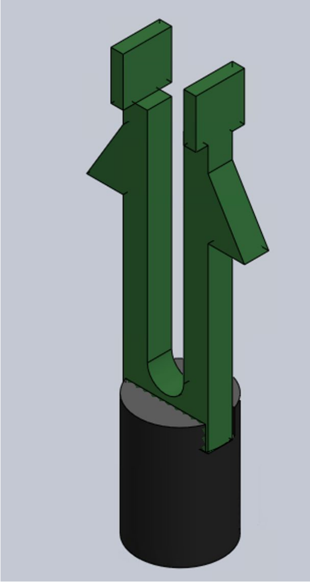


Figure 17: *Diagram Depicting the Third Iteration of the Ratcheting System Design*

Figure 18: *Isometric View of Buckle and Magnet*

Testing

The team planned on completing testing during the final term of the school year, but due to difficulties brought on by COVID-19, some parts of testing were cut short. Luckily, Professor Stabile, the team's advisor, was able to bring the printer to his home and conduct tests with the team through Zoom video calls. However, there were still some tests that were incomplete.

Throughout the building and troubleshooting process, the team regularly ran test prints to determine the functionality of varying print factors and to assess overall print quality in an effort to enhance the printer's functionality. Many of these tests focussed on determining the ideal settings on Slic3r G-code for the 3D printer.

The first print tests converted a CAD stator (Figure 19) into several variations of G-Code using Slic3r. In the first print, the team used the Slic3r default settings (shown in Table 1) for a 1.75 mm diameter PLA filament. The resulting print, shown in Figure 20**,** had a thin extrusion output, resulting in a stringy effect. There were issues with filament adhesion, causing many gaps and poor structural integrity. The team used this trial as a foundation of what worked, and what needed to be changed. From observations made during the first attempt, the team did some preliminary research on how to improve print variables. The next print used an increased extrusion multiplier, with a modified first layer thickness. The results showed massive improvement, as the second print was stronger and better defined. The team continued to make small modifications, however, did not find much improvement after the second iteration of the stator. The third print had over melted the layers and the fourth was stringy and had poor adhesion.

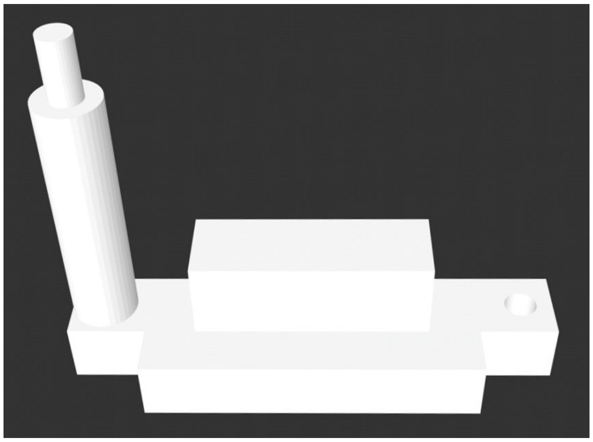


Figure 19: *Stator Design Modeled in SolidWorks*

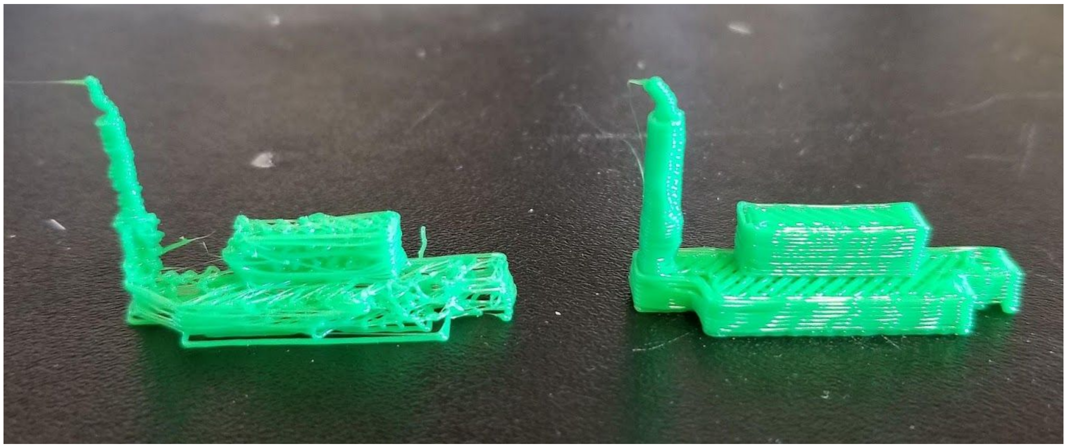


Figure 20: *Printing Trial One (left) and Trial Two (right) of the Stator Design*

Table 1: *Slic3r Variables for the Stator Trial Prints*

			DEFAULT	**TRIAL 1**	**TRIAL 2**	**TRIAL 3**
Layers and Perimeters	Layer Height					
		Layer Height	0.3mm	0.3mm	0.3mm	0.3mm
		First Layer Height	0.35mm	**0.7mm**	0.7mm	0.35mm
Infill	Infill					
		Fill Density	20%	20%	20%	20%
		Fill Pattern	Honeycomb	Honeycomb	Honeycomb	Honeycomb

		Top/Bottom Fill Pattern	Rectilinear	Rectilinear	Rectilinear	Rectilinear
Speed	Speed for print moves					
		Perimeters:	60 mm/s	60 mm/s	**50 mm/s**	**40 mm/s**
		Infill	80 mm/s	80 mm/s	**70 mm/s**	**60 mm/s**
		Solid Infill	20 mm/s	20 mm/s	20 mm/s	20 mm/s
	Autospeed (advanced)					
		Max Print Speed	80 mm/s	80 mm/s	80 mm/s	80 mm/s
		Max Volumetric Speed	0 cumm/s	0 cumm/s	0 cumm/s	0 cumm/s
Filament	Filament					
		Extrusion Multiplier	1	3	3	2
	Temperature (C)					
		Extruder	185	185	185	185
		Bed	50	50	50	50

As the team continued to improve upon the 3D Printer, further testing was documented using an early version of the buckle featured in the actuator design. Five trial runs were completed and documented to determine the ideal settings necessary to print a strong, accurate buckle. These trial parts were then compared with a part printed using an Ultimaker 2 in the Foisie Makerspace. A comparison photo is shown in Figure 21, with the part printed at the Makerspace shown all the way to the left, and the various trial parts shown subsequently from the second part on the left to the right. Of note is the nozzle diameter and layer height for each of these prints was much greater, which caused the lack of clear finish. A comparison of printer settings for each trial can be found in Table 2.

Figure 21: *Compared Results of Various Print Settings Used for the Actuator Buckle*

Table 2: *Slic3r Variables for the Actuator Buckle Trial Prints*

			TRIAL 1	**TRIAL 2**	**TRIAL 3**	**TRIAL 4**	**TRIAL 5**
Layers and Perimeters	Layer Height						
		Layer Height	0.37mm	0.30mm	0.30mm	0.37mm	0.40mm
		First Layer Height	0.45mm	0.35mm	0.40mm	0.40mm	0.45mm
Infill	Infill						

		Fill Density	20%	40%	40%	20%	20%
		Fill Pattern	Hilbert Curve	Hilbert Curve	Hilbert Curve	Hilbert Curve	Hilbert Curve
		Top/Bottom Fill Pattern	Hilbert Curve	Hilbert Curve	Hilbert Curve	Hilbert Curve	Hilbert Curve
Speed	Speed for print moves						
		Perimeters:	60 mm/s	60 mm/s	50 mm/s	50 mm/s	50 mm/s
		Infill	80 mm/s	80 mm/s	80 mm/s	80 mm/s	80 mm/s
		Solid Infill	20 mm/s	20 mm/s	20 mm/s	20 mm/s	20 mm/s
	Autospeed (advanced)						
		Max Print Speed	80 mm/s	80 mm/s	80 mm/s	80 mm/s	80 mm/s
		Max Volumetric Speed	0 cumm/s	0 cumm/s	0 cumm/s	0 cumm/s	0 cumm/s
Filament	Filament						
		Extrusion Multiplier	3	3	3	4	4
	Temperature (C)						
		Extruder	185	185	185	185	185
		Bed	50	50	50	50	50

Reiteration

While these tests were useful, they did not give the team reliable information about correct G code settings due to an issue with under extrusion. The team initially suspected this was a hardware issue, as the extruder routinely clogged and misbehaved, but it was discovered that the steps per unit for the extrusion in the software was off by a factor of 4. This was corrected during the last weeks of C term, but the team was unable to perform further testing on print settings after this discovery due to the shortened school year.

D Term Testing

Test printing on a rotating bed and printing with a live solenoid were completed in D term through Zoom video calls with Professor Stabile. Unfortunately, the original rotating bed was left at WPI, so an improvised rotating bed was built using a motor with a rod connected via a coupler. Once the rod was set up, a custom MATLAB program wrote G code to allow for the printer to print on the rotating bed. The G code was based on the work of a team that completed a similar task in London, but was modified to accommodate the custom printer. First, the G code set the nozzle's position of the Z-axis shown in Figure 22 to be 0, so it did not have to level itself and potentially crash on the rod. Next, the G code adjusted the steps per unit in the Y direction to allow the printer to accurately print on the rod, which used a different correction factor than the flat bed. Finally, the G code homed the X direction and printed. To determine how much filament print, the G code took in the filament diameter, desired print length, and rod size and outputted a G code that would print a cylinder of those dimensions. One issue the team initially ran into was print bed adhesion, but using a glue stick on the rod allowed the PLA to adhere to the rotating bed.

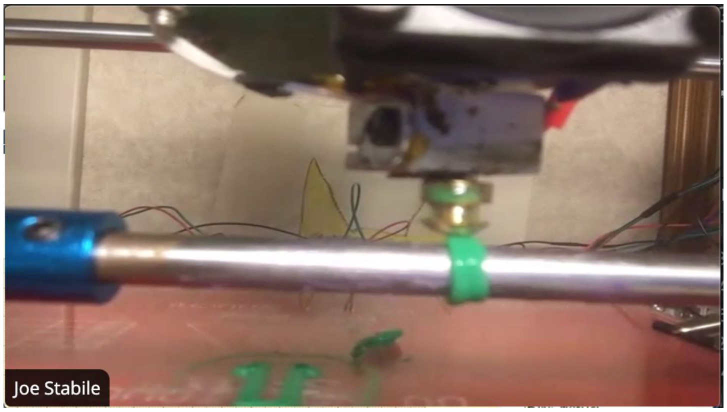


Figure 22: *Screenshot of Print on Rotating Bed*

After testing the rotating bed, the team tested the solenoid. Professor Stabile set up the solenoid and powered it with a 9 volt battery. He was only able to wrap the solenoid about 20 times around the nozzle, which was less than initially planned. The team then used metallic filament acquired from the Low Profile Home Speaker team to print on the rotating bed. The metallic elements changed the heat requirements of the filament and caused it to not print at first. After the temperature of the nozzle was adjusted to 230 degrees Celsius, the filament began to print properly and a cylindrical layer of magnetically loaded PLA was deposited on the metal cylinder. Given that the coil was energized it is assumed the particles in the PLA were oriented when they were deposited, however due to testing constraints this was not able to be confirmed. In future prints the particles will be magnetized using a pulse charge, but this equipment was not available at Professor Stabile's home. In addition to orienting the part this print also proved that the nozzle had the ability to print using the metallic filament and gave another example of a successful print using the rotating bed (Figure 23).

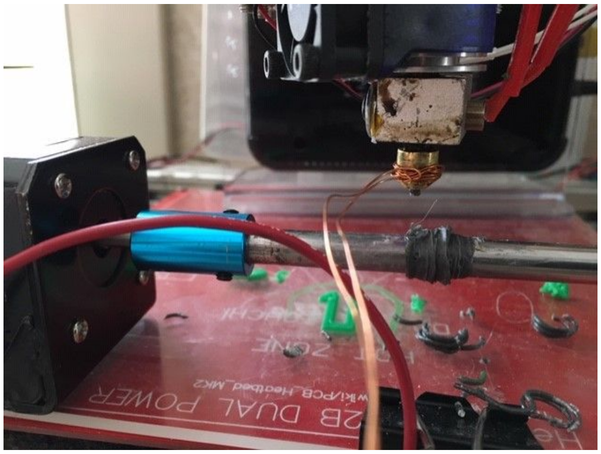


Figure 23: *Photo of Complete Print Using the Solenoid and Iron Filament*

Conclusion

This project was constructed to 3D Printed Magnets for use in an Artificial Muscle Actuator by investigating 2 hypotheses:

> **Hypothesis 1:** Using 3D printing as a magnet manufacturing technique will allow for the creation of novel shapes, which can then produce novel fields, I.E. radially oriented magnets.
>
> **Hypothesis 2:** With the use of magnets, the new actuator will have more fine control and ability to be programmed than artificial muscles using SMPS. In addition, because it is not reliant on air, the bulk and weight of air tubes necessary for pneumatic actuating muscles can be replaced by smaller, more lightweight batteries and microcontrollers.

To complete this project, the team began by making repairs and modifications to a custom 3D printer built during a preliminary project. These modifications included both minor and major hardware and software updates. One major hardware update was the replacement of a traditional 3D printer nozzle with a custom nozzle that included a built-in solenoid, designed and manufactured to print magnets. Next was the creation of a rotating print bed intended to print strong cylindrical structures. While changes and additions to the printer were being made, a self-locking linear actuator designed to be powered by magnetic stimulation was designed and prototyped.

Due to the sudden outbreak of COVID 19, the project was put on hold and the team was unable to complete sufficient testing to find evidence to support these hypotheses. However, the team’s research and prototypes will be crucial groundwork for the future.

Complications

The team ran into many obstacles over the course of the project. The challenges associated with getting the printer to work properly were underestimated and fixing its issues took a greater amount of time than expected, leaving insufficient time to focus on the end goals of printing magnetic parts and utilizing them in a muscle actuator. Throughout the year, increasing numbers of parts were found to be incorrectly designed or broken, causing the need for redesign and reprinting. Oftentimes, the team would have to start from scratch in designing these parts in SolidWorks because the resource drive that was obtained from the team that built the printer was incomplete and was missing up-to-date files for many of the parts. In addition to this, once a part is sent to the Foisie Makerspace it is difficult to tell how long it will take for it to be printed, so there were times the printer sat unused for days, waiting for replacement parts. There were also many bugs in the software used to control the printer, which often led to improper functionality.

The team was unable to test its end devices as expected due to COVID-19. The original plan was to fix the printer and build prototypes during the first three terms of the academic year, then complete testing and tweaks during the final term. Unfortunately, this testing period was cut short when the team was unable to attend campus for D term. Luckily, Professor Stabile was very helpful and understanding in all of this, but he is only one man with other groups to advise and classes to teach, so there was only so much time that could be dedicated to testing and reiterations.

Future Work

The team has three recommended focuses for future work on this project: Enhancement of the rotating bed, testing and reiterations of the solenoid, and the creation of a physical prototype of the actuator with the custom magnets.

It is recommended that future teams working on this project create G code with the ability to print each line at an angle; this will utilize the true potential of the rotating bed. While the current set-up produces enhanced rotationally oriented magnets, a stronger cylinder would be produced if each layer were printed at an alternating 45˚ angle. Additionally, work could be done to allow for the mounting of varying cylinders to allow for the printer to print on top of round objects, which could then be removed.

A future team could also focus on testing the hypothesis that the presence of a solenoid during extrusion will reorient particles that have crossed their Curie temperature and lost their magnetism to cause stronger magnets to form post print. The team that worked on this project in 2019 predicted that a solenoid wrapped around a nozzle 50 times would make this possible; the printer now has a nozzle with a large enough gap for a solenoid to be wrapped around it 50 times, but there was insufficient time to test the theory with the hardware.

Once the solenoid is tested and reiterations are made to allow for the printing of magnetic parts, a physical prototype of the actuator with custom shaped magnets can be used to test the actuator's functionality. If this is completed, future work will include developing ways to pair the actuator design with the magnet to simulate contraction and expansion of a sarcomere. This contraction will be made possible by holding the internal buckle in a fixed position and allowing the casings to move towards or away from each other. Additional experiments can be conducted to determine the optimal number of notches in the actuator's wall.

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Appendices

Appendix A: Matlab code and G code for rotating bed printing

Matlab code:

```
%% Layer 1
%Set initial conditions, Import dimensions

w=1; %Filament width
d=8.1; %Diameter of bed
p=d*pi; %Perimeter of bed
p0=p; %Actual perimeter
ml=12; %Length of magnet
RpL=ml/w; %Number of rotations to print total length
x0=10; %x start point from end plate
x=x0; %initialize x (Axial)
y=0; %initialize y (Rotational)
z=0; %initialize z (vertical)
e=0; %extrusion coordinate
i=1; %initialize counter
filename = ['rotating-gcode-' date];
file = [filename '.gcode'];
FID = fopen(file,'w');

% Send initital Comands to printer
fprintf(FID,'G92 Z0 E0 ; sets the current position as reference point for extrusion and z axis \n');
fprintf(FID,'G28 X0; zeros x  \n');
fprintf(FID,'M104 S240 ; Sets temp to 240 degrees\n');
fprintf(FID,'M109 S240 ; Sets temp to 240 degrees \n');
fprintf(FID,'G90 ; use absolute coordinates \n');
fprintf(FID,'G21 ; Set units to millimeters \n');
fprintf(FID,'M92 Y127.3; Sets steps per millimeter for y xis for a 8mm bar \n');
fprintf(FID,'M82 ; Use absolute distances for extrusion\n');

% Start the printing instructions
fprintf(FID,'G1 F500 \n'); %sets feedrate
L=0 ;
while i<=RpL
    script=strcat('G1 X',num2str(x),' Y',num2str(y),' Z',num2str(z),' E',num2str(e),'\n');
    fprintf(FID,script);
    x=x+w; %Updates x coordinate
    y=y+p0; %Updates rotational coordinate
    i=i+1; %updates counter
    e=e+p0; %updates extrusion value
end
```

G code:

```
G92 Z0 E0 ; sets the current position as reference point for extrusion and z axis
G28 X0; zeros x
M104 S240 ; Sets temp to 240 degrees
M109 S240 ; Sets temp to 240 degrees
G90 ; use absolute coordinates
G21 ; Set units to millimeters
M92 Y127.3; Sets steps per millimeter for y xis for a 8mm bar
M82 ; Use absolute distances for extrusion
```

```
G1 F500
G1 X10 Y0 Z0 E0
G1 X11 Y25.4469 Z0 E25.4469
G1 X12 Y50.8938 Z0 E50.8938
G1 X13 Y76.3407 Z0 E76.3407
G1 X14 Y101.7876 Z0 E101.7876
G1 X15 Y127.2345 Z0 E127.2345
G1 X16 Y152.6814 Z0 E152.6814
G1 X17 Y178.1283 Z0 E178.1283
G1 X18 Y203.5752 Z0 E203.5752
G1 X19 Y229.0221 Z0 E229.0221
G1 X20 Y254.469 Z0 E254.469
G1 X21 Y279.9159 Z0 E279.9159
```

Appendix B: Videos of Rotating Printing and Nozzle Manufacture

Video simulation of custom nozzle manufacture using a lathe:
https://www.youtube.com/watch?v=4iGC8XUnBy4

Video of rotating print:
https://www.youtube.com/watch?v=05b51nMTauo

Appendix C: Table of Marlin Edits

General area	Original	Updated
Filament size	#define DEFAULT_NOMINAL_FILAMENT_DIA 3.0	#define DEFAULT_NOMINAL_FILAMENT_DIA 1.78
Bed thermistor	#define TEMP_SENSOR_BED 0	#define TEMP_SENSOR_BED 1
End stop inverting	#define X_MIN_ENDSTOP_INVERTING false // Set to true to invert the logic of the endstop. #define Y_MIN_ENDSTOP_INVERTING false // Set to true to invert the logic of the endstop. #define Z_MIN_ENDSTOP_INVERTING false // Set to true to invert the logic of the endstop. #define X_MAX_ENDSTOP_INVERTING false // Set to true to invert the logic of the endstop. #define Y_MAX_ENDSTOP_INVERTING false	#define X_MIN_ENDSTOP_INVERTING true // Set to true to invert the logic of the endstop. #define Y_MIN_ENDSTOP_INVERTING true // Set to true to invert the logic of the endstop. #define Z_MIN_ENDSTOP_INVERTING true // Set to true to invert the logic of the endstop. #define X_MAX_ENDSTOP_INVERTING true // Set to true to invert the logic of the endstop. #define Y_MAX_ENDSTOP_INVERTING true
Steps per unit	#define DEFAULT_AXIS_STEPS_PER_UNIT { 80, 80, 4000, 500 }	#define DEFAULT_AXIS_STEPS_PER_UNIT { 100, 100, 400, 405.75 } This is based on current hardware. If hardware changes this would also need to change

Max Feed Rate	#define DEFAULT_MAX_FEEDRATE { 300, 300, 5, 25 }	#define DEFAULT_MAX_FEEDRATE { 200, 200, 2, 20 }
Extruder Jerk	#define DEFAULT_EJERK 5.0	#define DEFAULT_EJERK 2.0
Invert x and y stepper	#define INVERT_X_DIR false #define INVERT_Y_DIR true	#define INVERT_X_DIR true #define INVERT_Y_DIR false
Bed Size	#define X_BED_SIZE 200 #define Y_BED_SIZE 200 #define Z_MAX_POS 200	#define X_BED_SIZE 60 #define Y_BED_SIZE 60 #define Z_MAX_POS 100
PID Bed Heating	#define DEFAULT_bedKp 10.00 #define DEFAULT_bedKi .023 #define DEFAULT_bedKd 305.4	Send "M303 E-1 C8 S90" in pronterface to get values, and reflash with correct values after. We had the correct values in our default, so we left them the same.

Follow this tutorial for step by step instructions:
https://www.youtube.com/watch?v=0pt_b2ZizQM
Use notepad++ and the compare function to update:
Notepad++:https://notepad-plus-plus.org/
Compare plugin:https://github.com/pnedev/compare-plugin/releases