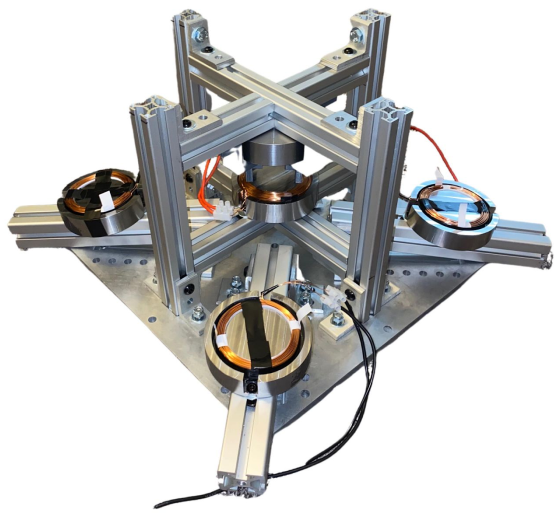
Reconfigurable 3D Magnetic Control System



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Abstract

The Reconfigurable 3D Magnetic Control System was sponsored by the Cai Group at UCSD and will be used to conduct research into improving the efficacy of soft robotics in the future. The rise of small scale soft robots controlled by magnetic fields have seen a spike, especially with applications in the biomedical field. The ability to control a soft robot on the millimeter scale proposes a promising alternative to highly invasive surgical procedures specifically those within arteries and veins. In this report, a Reconfigurable 3D Magnetic Control System design capable of actuating ferromagnetic soft robots is discussed. The functionalities highlighted in this design include reconfigurable electromagnetic actuator (solenoid) pairs, a homogenous magnetic field in any of the X, Y, or Z axes, and the ability to control a soft robot with electrical microcontrollers. Throughout the experiments conducted, there are also significant findings towards manipulating magnetic field lines with iron cores to increase the magnetic flux in desired areas. The report will discuss how the team was able to produce and control a magnetic field density of 80 milliteslas in the z direction and 10 milliteslas in both the x and y directions simultaneously. The electromagnetic actuators were controlled by managing the current provided to each solenoid; the team was able to get within ~0.15 Amps accuracy while controlling the system. The Reconfigurable 3D Magnetic Control System was designed to be open source so that future generations of scientists and engineers can benefit from the team's findings.

Table of Contents

List of Figures

List of Tables

Chapter 1: Project Description
Background:

Magnetic-responsive soft robots can be actuated in any direction solely by manipulating the external magnetic field lines the sample lies within. The chief benefits of such soft robots are found in the biomedical field for use in noninvasive surgical procedures. Small magnetic 'microbots' can efficiently navigate through arteries and veins, unclogging blocked pathways without requiring large actuators within the body. The Zhao Lab at MIT has demonstrated the control of soft microbots through model arteries using nano magnetic technology [8]. One of their primary goals was creating micro magnetic robots that can be controlled with handheld permanent magnets. The dynamic behavior of such robots can be studied and shown to have very precise movements.

The team's sponsor, the CAI Research Group, is interested in studying the behaviour of new nano magnetic responsive materials. Specifically, the research group is trying to find a way to research *automating* magnetic actuation through a control system. In order to do so, they require a system which can produce 3D magnetic field vectors of varying density. In this regard, the goals of the project are different from the Zhao Lab, as the research is focused on creating a closed control system instead of creating new small scale soft robots.

The goal of this project is to design a modular system permitting the sponsor to control the direction and density of magnetic fields within an adjustable working space, optimized for 50 x 50 x 50 mm. To achieve this, 3 electromagnet pairs are operated simultaneously: producing homogeneous field vectors to control the position and movement of the soft robot within the working space. To satisfy the goals of the Cai research group, this chamber will require strong magnetic actuation in all three directions, while allowing the user to adjust the required density to enable repetitive demonstrations of the magnetic chamber. Since the goal of this project is focused on creating a magnetic environment, the maximum field density is one of the most important qualities. The initial goal of the project was to achieve 1 Tesla (T) within the working space. For the resources and timeline allocated to the project, an updated goal was set to achieve 100mT maximum in the vertical (z) direction while 10mT in the x and y directions would be acceptable.

Review of Existing Solutions :

Controlling magnetic soft robots is nothing new: the Zhao Lab at MIT guides soft microbots by physically moving the magnets by hand which shows that microbot positional control can be very precise [8]. The use of permanent neodymium magnets provides strong magnetic fields, however it does not easily lend itself to control as the magnetic field can only be changed by physically moving the magnet: the field produced is non-homogeneous, and high density fields which cannot be turned off can be dangerous in a medical operation. However, these fields sacrifice magnitude and flexibility for high resolution as the working field strength is around 50 mT and the working space is fixed. The benefits of obtaining a reconfigurable 3D magnetic system composed of 6 solenoids is the ability to work up to higher field density (100mT) and variable workspace at lower power and cost. Further, since there are 6 controllable channels of current, the magnitude of each solenoid can be used in relation to provide high resolution as well. Finally the use of solenoid pairs with very large radial cores allow for homogenous field lines within the working space.

Figure 1.1: Zhao lab magnetized wire in 3d blood vessels controlled with neodymium magnets

Another existing solution that allows minimally invasive movement within human bodies has been developed by Monarch for a Bronchoscopy operation [2]. Using rotary pulleys and fluidics systems controlled by a joystick, this robot can travel through lung arteries and major veins, capturing the image inside with a small camera. It is a highly effective and successful endoscopy procedure that is a safer option compared to a surgical biopsy.

Statement of Requirements:

The team's sponsor requested that the team meet the following requirements:

1. Primary
    a. Modularity:
        i. Slots for 3 pairs of removable solenoids to be positioned around a test area of 50x50x50mm
        ii. any iron cores used should be individually removable from solenoid coils
    b. Magnetic Field Homogeneity
        i. Magnetic field produced by each coil pair must be homogeneous within 20x20x20mm space within test area
        ii. Goal of ± 5% axial and radial homogeneity
        iii. ± 10-20% lowest acceptable
    c. Magnetic Field Strength
        i. Magnetic field must be intense within 20x20x20mm space
        ii. Initial goal of 1-1.5T max field density for each coil pair
        iii. Updated goal of maximum 100mT field density in the vertical direction, 10mT density in the horizontal directions
    d. Safety
        i. Coils should operate for 3min at a time without overheating
        ii. Max temperature: touchable without burning hand (130-140ºF)
        iii. No magnetic responsive materials to be used near the electromagnets (iron)
        iv. Ideally 5A or less current in coils, though more may be used if overheating shown not to be an issue.
        v. Structural integrity of frame should secure weights of solenoids +Magnetic force
    e. Space
        i. Entire system lies within 400x400x400mm working space
        ii. Open, accessible, visible test area 50x50x50mm
2. Secondary
    a. Control System
        i. Has an on-off switch for each coil pair
        ii. Ideally have integrated housing for wires
        iii. Wow condition: Arduino controlled, bidirectional field

Deliverables

The team's sponsor requested that the team provide the following deliverables:

1. Primary:
    a. Working space
        i. Modular frame: the sponsor should be able to reconfigure the working space to experiment on different sized samples
    b. Electromagnets
        i. 3 pairs of removable and replaceable electromagnet pairs
        ii. Optimized for field density within the 50x50x50mm working space
        iii. Simulations to predict magnetic field based on electromagnet physics
2. Secondary
    a. Integrated control system, based on current to the electromagnets and wiring

Chapter 2: Description of Final Design Solution

The final design consists of 3D actuation of the magnetic field using three independent electromagnet pairs arranged around the testing area. The pairs magnify the field density in the test area relative to single electromagnets, and increase the homogeneity. The electromagnet pairs were constructed from machined pure iron cores and copper winding solenoids. The iron cores were machined using a CNC Mill to hollow a groove for the windings. The copper windings can be pre-wrapped and inserted into the iron using a custom jig and can use 16-20awg wire depending on the application.

These electromagnet pairs were able to reach a magnetic field density of up to 80 mT with a separation distance of 50mm during the testing phase while the air core solenoids were only capable of reaching a magnetic field density of 10 mT.

Based on the team's sponsor's request, the frame was designed to be reconfigurable. An aluminum base plate consisting of four grooves enables the horizontal mobility of the two pairs of horizontal solenoids (i.e. the solenoids in the x-y plane). In conjunction with the aluminum base plate, T-bars make up the backbone of the project's frame by providing support and stability. In addition to giving the frame its stability, these T-bars also provided a space to mount the iron core solenoids. The sponsor can place the T-bars with solenoids as close as they desire to one another and the working space to optimize the magnetic field density of the magnetic elastomer (i.e. the soft robot) inside the working space.

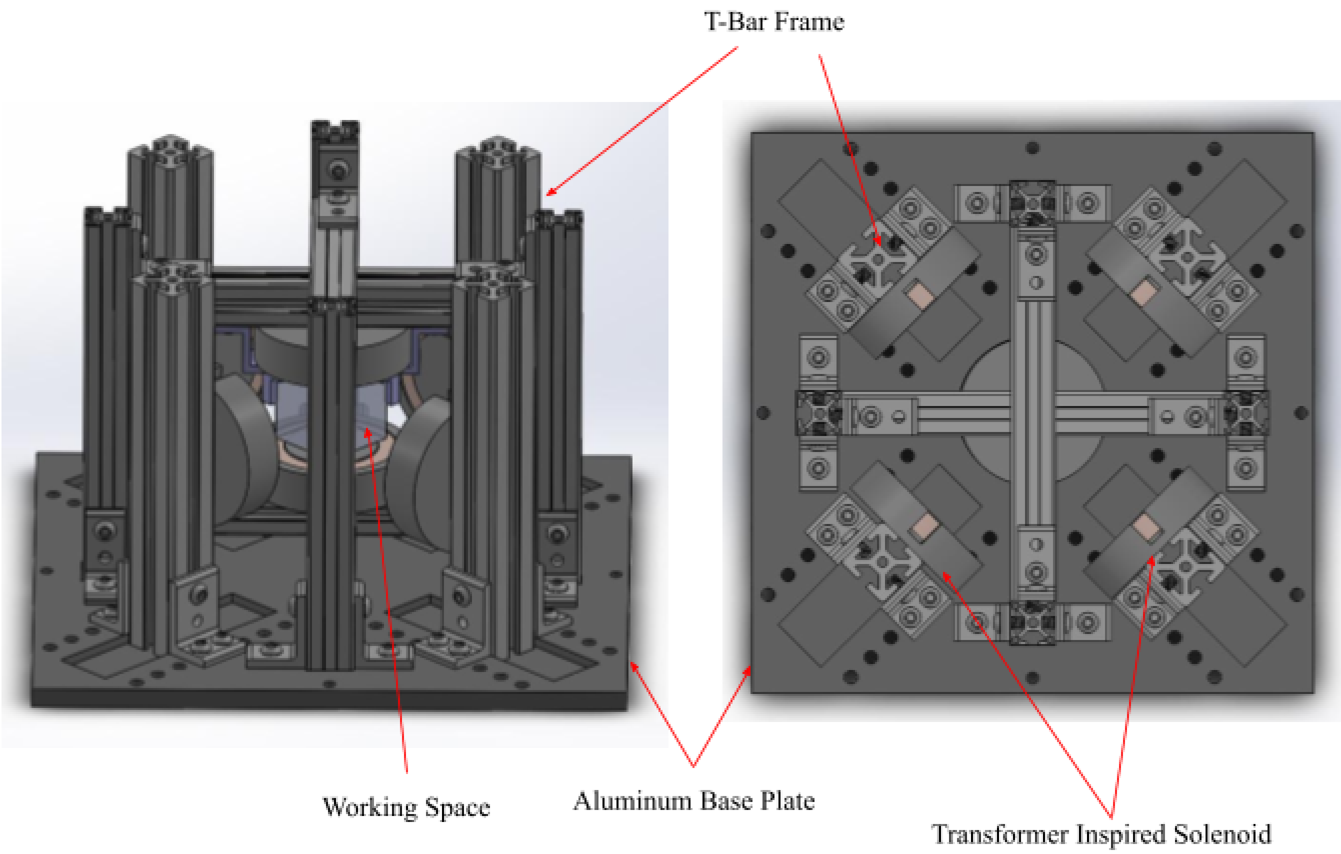


Figure 2.1: Front View of the Frame CAD Design

Figure 2.2: Top View of the Frame CAD Design

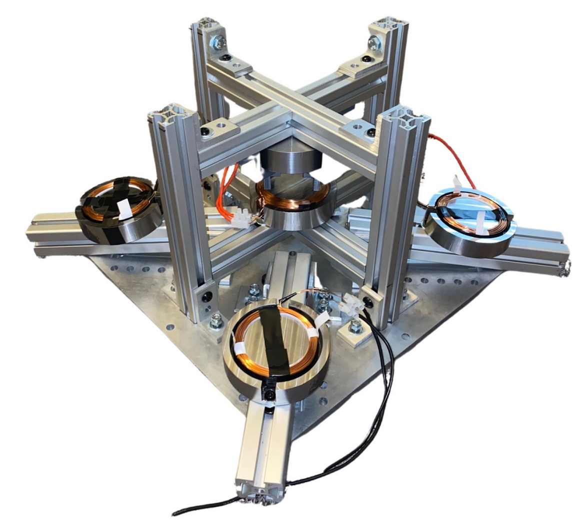


Figure 2.3: Front View of the Frame Design

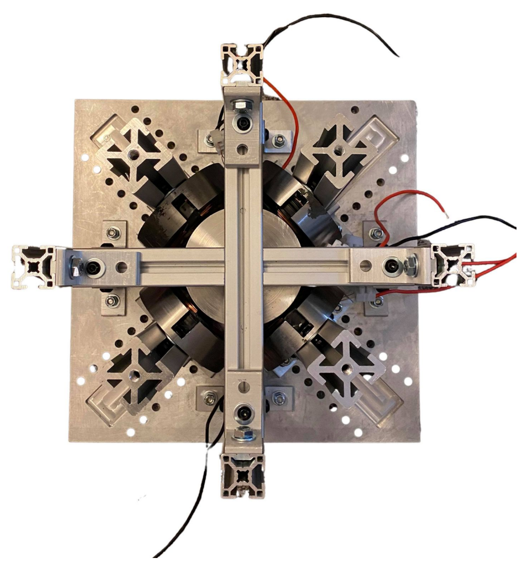


Figure 2.4: Top View of the Frame Design

Another important goal of the project was to develop a controls system and power variable power supply that can be used to accurately control the current powering the system's electromagnets and therefore the magnetic field density. Two controls systems were developed and delivered to the project's sponsor: (1) an Analog Arduino-based potentiometer control system, and (2) a MATLAB-based GUI. Both the MATLAB-based GUI and the Arduino-based potentiometer controller make use of ammeters and feedback loops to ensure that the desired current is provided to each solenoid.

The Analog system utilizes four potentiometers for input from the user: 1 for overall power as a safety feature and 3 to control each bidirectional channel running to X, Y, and Z directions. An LCD screen displays current to the user in real time to help key in on the desired current value. The current is measured, using ammeters, directly from each of the three channels and digitally filtered. An Arduino Mega 2560 and three Cytron 10A motor driver shields were used to limit output from Meanwell single output 12V, 30A and 24V, 15A power supplies. Currently, due to the 10A limit of the motor driver shields, a 9.8A limit is imposed in the arduino script for each channel. The Analog system runs independently from a computer and requires a power outlet and a 5V USB-A source. If the GUI is run, the code for the analog script must be flashed from the Arduino IDE through the USB-A cable in order to run it again.

The other system that was developed is a MATLAB-based GUI. This GUI enables the end user to attain high degrees of precision when working with the 3D magnetic control system. To use the GUI, the user starts by plugging the Arduino Mega 2560 USB cable into their laptop. Next, the user will launch the 3D Magnetic Control System GUI. The GUI will have sliders and switches that enable the user to control how much current is output to each pair of electromagnets and in which direction. There are also dropdown menus that enable the user to update the separation distance of the solenoid pairs in the X and Y directions (the Z direction solenoids are fixed in place). The user can then press the "Update Simulation" button to get an estimate of the magnetic field density vector and magnitude. Once the user is satisfied with the simulation results, they can press the "Send Signal to System" button which will power on the motor drivers and send current through the 10A Cytron motor drivers as specified in the prior steps. While current is being sent through the motor drivers, red LEDs will light up to indicate which pairs of electromagnets are being powered on. When the user is done with the system, they can press the "Power Off" red button to cut power to the motor drivers and turn off the system. Again, no software needs to be flashed to the Arduino Mega 2560 prior to using the MATLAB GUI. However, if the user wants to switch from the MATLAB-based control system to the Arduino-based control system, they will need to flash the Arduino Mega 2560 with the provided Arduino sketch.

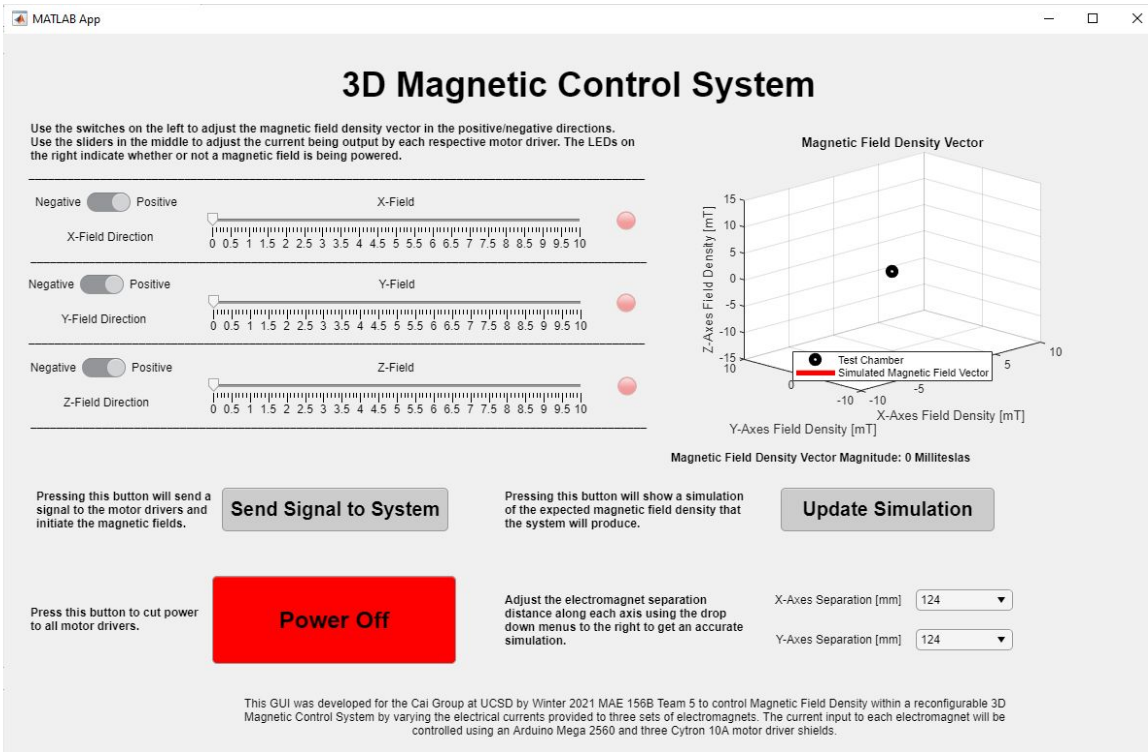


Figure 2.5: MATLAB-Based GUI

Figure 2.6: Analog Control and Power Supply Box

Chapter 3: Design of Key Components

List of Major Components

The device relied on the following major components for its success:

- Solenoid Pairs
- C-Shaped Magnet
- Pre-wrapping Jig
- Base Plate
- Electrical Controls System
- Wire
- Power Supply

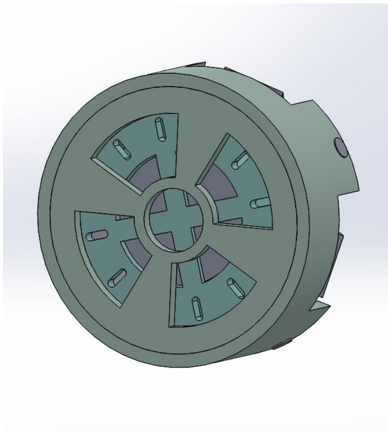
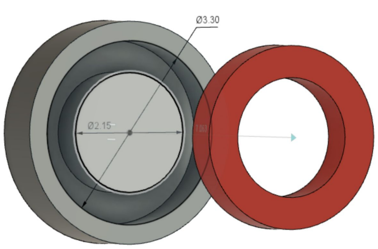
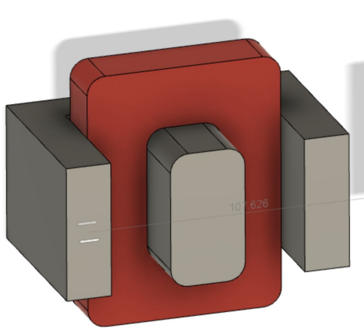
Solenoid Pairs and Iron Core Geometry

Functional Requirement:

- Solenoid pairs must produce at least 10mT in the horizontal direction.
- Solenoid should be secured to its support system to withstand magnetic pulling force

Comparison of Designs Considered:

Table 3.1: Pros and Cons of Solenoid Designs

Design	Pros	Cons
 **Figure 3.1:** Solenoid Design 1	-Sturdy, well manufactured design - Allows wire to be sufficiently thick	-Manufacturing difficulty as tolerances have to be perfectly cut through entire solenoid -Requires welding and creating delicate pieces -Needs 1.5 iron cores to create one
 **Figure 3.2:** Transformer-inspired solenoid	-Uniform, Homogenous design - Easy manufacturing (mill a donut indent to insert wire) - theoretically highest magnification factor	-Radius of uniform field density decreases -Thickness of wire donut is limited to thickness of iron cylinder -Requires pre wrapping
 **Figure 3.3:** Microwave inspired design	-Uses Pre Cut Transformers (2 made) -Can produce 40mT in the middle of working space	-Bulky and heavy -Not homogenous in center (square) -Difficult to attach to metal beams

Justification of the Final Design Choice:

Having a transformer inspired solenoid and standardizing the 6 solenoids increases the manufacturability and the magnetic density due to the return path aiding the magnetic density output. These transformer-inspired solenoids outperformed the other considered solenoid designs in the testing phase and produced larger magnetic field densities.

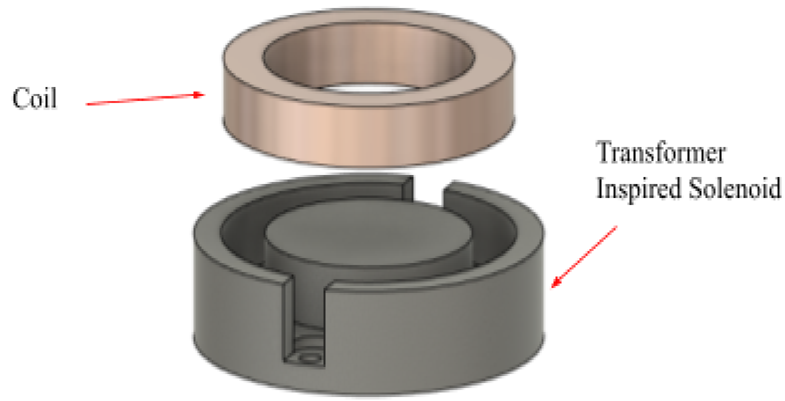


Figure 3.4: Single Solenoid Actuator **Figure 3.5:** Major Components of the Solenoid

Fabrication methods employed:
A CNC Mill was utilized to manufacture the transformer-inspired solenoids after a tooling path was generated in Autodesk Fusion 360.

Transformer Solenoid

Functional Requirement:

The transformer solenoid pairs should be able to output at least 100mT in vertical actuation at 50mm separation distance

Comparison of Designs Considered:

Table 3.2: Pros and Cons of Transformer Solenoid Designs

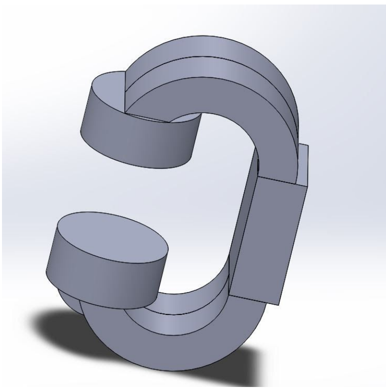
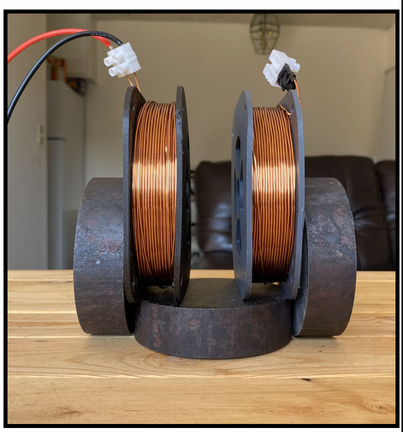
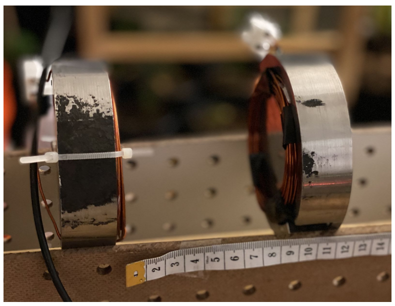
Design	Pros	Cons
 **Figure 3.6:** Welded C-Shaped Magnet	- Satisfies working space parameters(at least 50mm)	- Requires welding of individually machined components - Needs multiple iron cores to create
 **Figure 3.7:** Air Core Solenoids with Iron Core Return Paths	- Prototype model, proof of concept for return paths	- Very simple design - Nothing is optimized nor secured in place

 **Figure 3.8:** C-Shaped Magnet cut from iron core	- Most intense magnetic field - One solid body	- Small working space (0.6in) - Small cross section - Not adjustable
 **Figure 3.9:** Iron-core transformer solenoid designs	- Manufacturability - Easy to set up - Can be adjusted if needed	- Magnetic density dependent on the distance between 2 solenoids

Justification of the Final Design Choice:
Up until week 8 of the Winter 2021 quarter, the design choice for vertical actuation was the welded C-bar electromagnet (Figure 3.6). However, due to material and time constraints, the transformer solenoid was chosen to be the team's final design. The transformer solenoid was easier to manufacture due to it only needing a CNC machine. Meanwhile, the welded C-bar electromagnet required both waterjet cutting and welding. Another reason for the selection of the transformer solenoid was because it outperformed the C-shaped magnet (Figure 3.8) during magnetic field density testing. The C-shaped magnet was much weaker than the simulations had initially predicted which suggested that the iron core purity of the team's cores was not as high as initially believed. Meanwhile, the iron-core transformer solenoids were able to produce a magnetic field density of 80 mT at a 50mm separation distance.

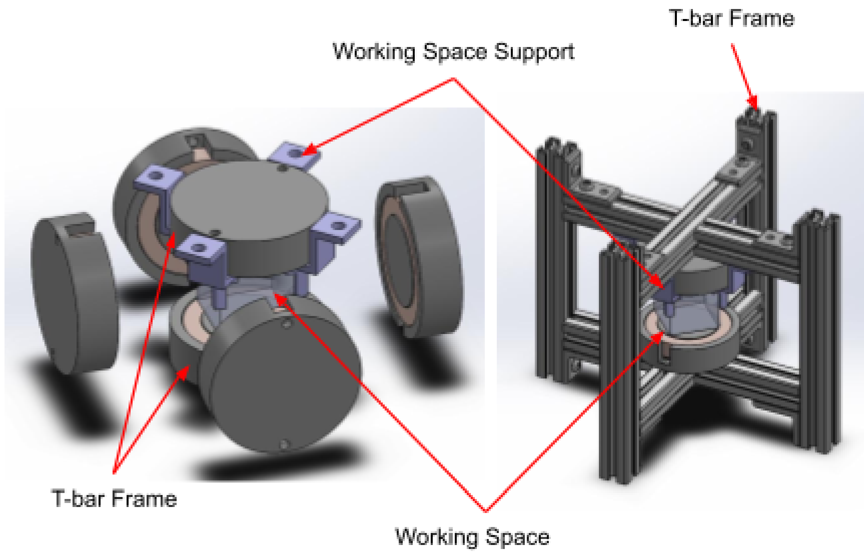


Figure 3.10: Transformer solenoid and the pairs within the frame design

Fabrication methods employed:
A CNC machine was utilized to manufacture the transformer-inspired solenoids after a tooling path was generated in Autodesk Fusion 360.

Coil Wrapping: Pre-wrapping Jig

Functional Requirements:
The wrapping jig must enable the user to maintain tension while wrapping, to wrap tightly within an exact working space (defined by the machined groove in the iron cores) and permit smoothn transfer into the iron core groove.

Final Design:
A 3D printed jig was designed to allow tight hand wrapping of the copper coil before transfering to the iron core. The jig has 3 parts: a base frame (1), a top plate which clamps onto the base while wrapping (2), and a loose inner ring which aids in distributing the force applied to the coil when transfering from the jig to the iron core (3).

Figure 3.11: CAD Exploded View of 3 Piece Coil Wrapping Jig.
Parts are:
1: Top
2: Wire
3: Ring
4: Base

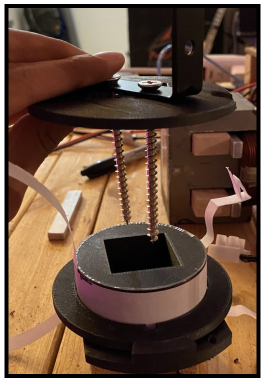


Figure 3.12: Preparation of Coil Wrapping Jig to wrap coils for the solenoids

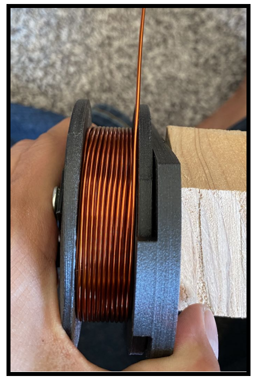


Figure 3.13: Coil Wrapping with the help of Coil Wrapping Jig

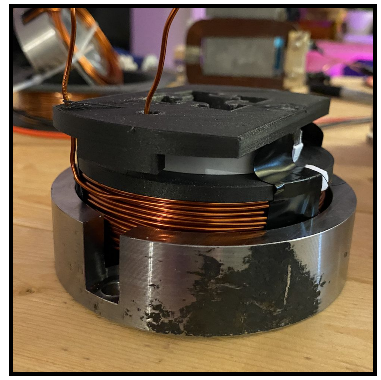


Figure 3.14: Transferring wrapped coil to the solenoid

Fabrication Methods Employed:
The Wrapping jig was 3D printed from carbon filled nylon, with the ring section set to maximum infill.

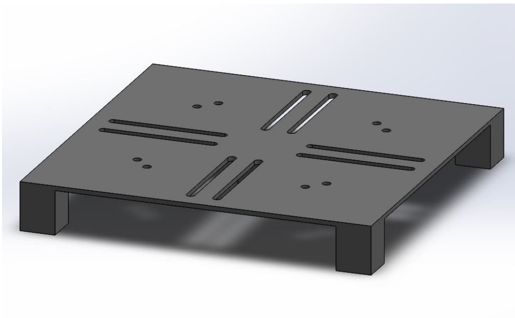
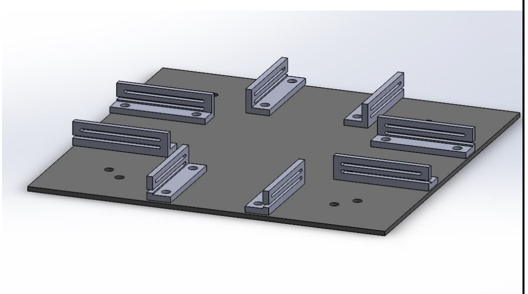
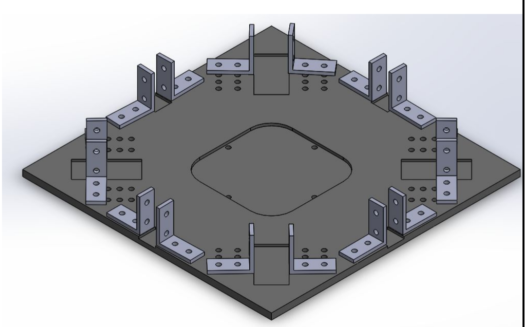
Aluminum Base Plate

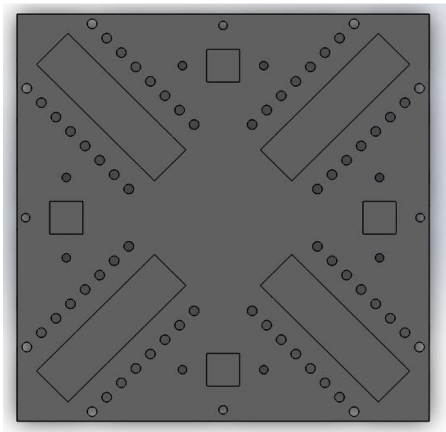
Functional Requirements:

- Grooves for mobility in horizontal directions
- Must be able to secure T-bars to the base plate
- Strong base for structural integrity: must be able to withstand generated magnetic forces

Comparison of Designs Considered:

Table 3.3: Pros and Cons of Base Plate Designs

Design	Pros	Cons
 **Figure 3.15:** Base Plate Iteration 1	- Mobility in X,Y,Z direction - Variable distances between solenoid paires not restricted	- There may be bending on plate - Cannot withstand strong magnetic pulling force - Difficult to set distances with accuracy
 **Figure 3.16:** Base Plate Iteration 2	- Rails for mobility with no restriction of variable distances - No bending stress on the plate	- Rails may not be stable - Cannot withstand strong magnetic pulling force - Difficult to set distances with accuracy
 **Figure 3.17:** Base Plate Iteration 3	- Grooves for Mobility - Set variable distances between two pairs	- Fixed bottom solenoid in vertical motion - Horizontal pairs are restricted in variable distances

 **Figure 3.18:** Base Plate Iteration 4	- Grooves for mobility - Mobility of x,y, and z solenoids	- Difficult, but possible, to move variable distance between the vertical pairs

Justification of the Final Design Choice:
In the end, Base Plate Iteration 4 (Figure 3.18) was selected as the team's final design. Iteration 4 met the functional requirements including good mobility and the ability to withstand magnetic forces generated from the magnetic field density. The final design allows better control of setting electromagnet separation distances while keeping plate easy to manufacture.

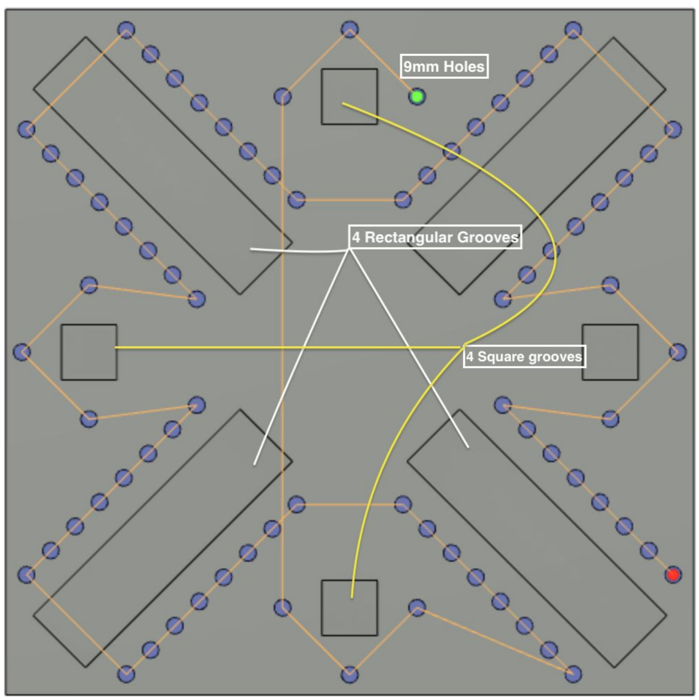


Figure 3.19: Final Base Plate Design

Fabrication methods employed:
A CNC machine was utilized to manufacture the finalized base plate design after a tooling path was generated in Autodesk Fusion 360.

Control System

Functional Requirement: ability to modify three electromagnets to manipulate magnetic field densities in three dimensions.

Comparison of Designs Considered:

Table 3.4: Pros and Cons of Control System Configurations

Design	Pros	Cons
Analog Potentiometer Control System	- Simple to develop - Performs necessary functions reliably - Independent of serial connection - Ability to rapidly change - Ability to read current outputs in amps to each channel	- End user has less control over the system's magnetic field densities - More difficult for the end user to visualize what the magnetic field density vector looks like
MATLAB-Based GUI Control System	- Looks more professional - Gives end user more control over the system - Allows the end user to see a simulation of the magnetic field density (in milliteslas) that they will be producing to get more useful information from their research	- More difficult to develop - Sponsor has stated that the control system was a secondary concern - Need an external computer to control the system - Rapid changing of magnetic field density vector difficult due to system lag between MATLAB and Arduino

Justification of the Final Design Choice: At the sponsor's request, the team decided to provide the sponsor with both control systems. Each design provides the sponsor with unique benefits that they can elect to use depending on the task at hand. If the sponsor wants a rapidly changing magnetic field or uses a configuration the GUI is not calibrated to calculate the field for, the Analog potentiometer control system would be preferable. Further, if the sponsor does not want to use an external computer, the Arduino-based system is self-contained and can be controlled using the potentiometers as an input. On the other hand, if the team's sponsor uses the system as intended and desires to see a simulation of the magnetic field density vectors that they will be producing, the MATLAB GUI is preferable. The main drawbacks to the GUI are that an external computer must be used and the field density can take a few seconds between iterations to update. It is relatively simple to switch between platforms based on the sponsor's needs. To switch from the Arduino potentiometers to the MATLAB GUI, the end user will only need to plug in the Arduino Mega to their computer and open the MATLAB GUI to start control with this method. In order to switch from MATLAB to Arduino, the sponsor will need to use the Arduino IDE to flash the Arduino Mega with the potentiometer control file. From there, the system will be self contained and no further external devices will be necessary.

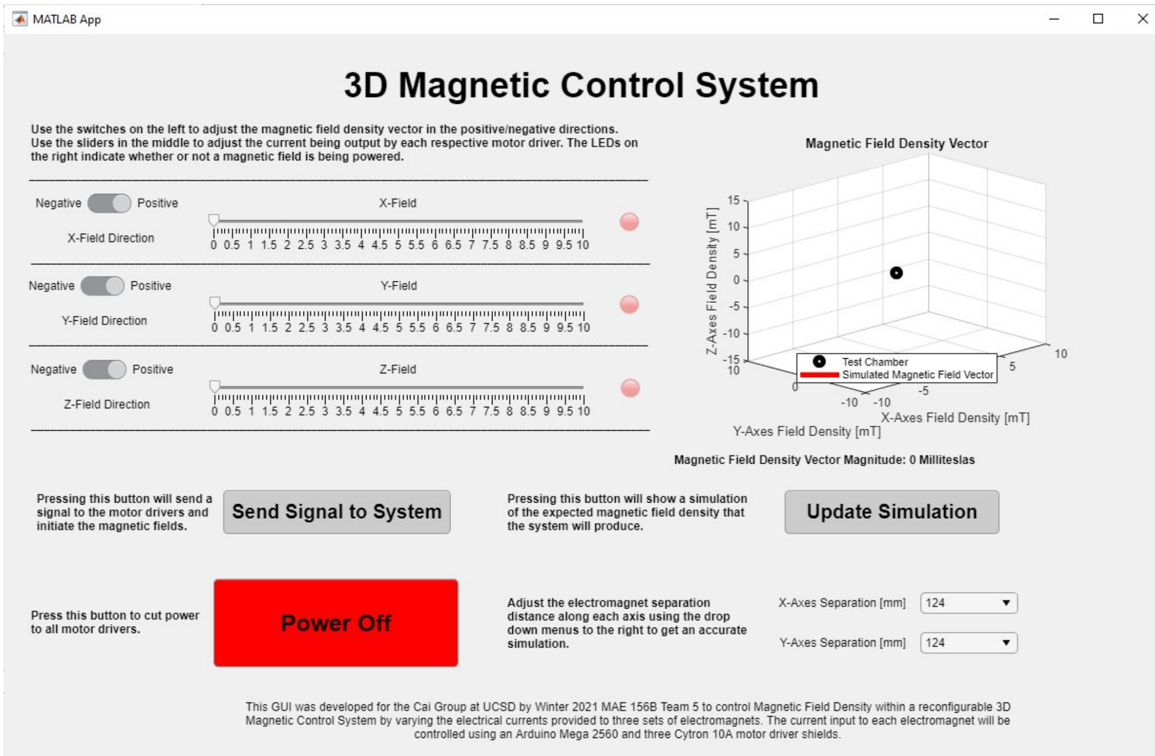


Figure 3.20: MATLAB-Based GUI for 3D Magnetic Control System GUI

Figure 3.21: Analog Control System and Insulated Power Supply

Fabrication methods employed: The primary fabrication methods employed to build the control systems were soldering, breadboard prototyping and programming in the MATLAB/Arduino languages. If the team had access to a larger budget, the breadboard could have been replaced with a printed circuit board to make the design more robust if moved around. The breadboard is not largely an aesthetic issue since the majority of these components are covered by a wooden panel. These control systems both meet and exceed the sponsor's secondary requirements.

Wiring

Functional Requirements: The wiring used in the system needs to be capable of carrying large electrical currents with minimal internal resistance. In addition, the wire must also be flexible enough to wrap tightly around electromagnet designs in order to reduce issues associated with loose packing factors.

Comparison of Designs Considered:

Table 3.5: Pros and Cons of Wiring Types Considered

Design	Pros	Cons
16 AWG Copper Magnet Wire	- 13.2 Ohms/1000 meters	- Less flexible than thinner 20 AWG wire which can lead to a lower packing factor
20 AWG Copper Magnet Wire	- More flexible than the 16 AWG wire which can lead to a higher packing factor	- 33.2 Ohms/1000 meters - Resistance was larger than expected based on online values

Justification of the Final Design Choice: 20 awg wire was chosen due to its greater potential with further power supply and cooling upgrades. Physical tests show that a 48V would be more than sufficient to generate 100mT in the vertical direction. It should be noted that higher current motor drivers, and an integrated cooling system would be required to realize this potential.

Fabrication Methods Employed: The magnetic wiring was purchased from Amazon. After the wire was received, the team designed and 3D printed a wire wrapping jig. This jig was used to hand wrap the solenoid tightly to achieve a higher packing factor which in turn led to a higher magnetic field density.

Power Supply

Functional Requirements: The device's power supply must be capable of powering three pairs of electromagnets simultaneously.

Comparison of Designs Considered:

Table 3.6: Pros and Cons of Power Supplies Considered

Design	Pros	Cons
12V, 29A Power Supply	- Capable of meeting sponsor's base requirements	- Lower voltage may lead to lower overall current output - Current output larger than originally requested by sponsor
24V, 15A Power Supply	- Capable of meeting sponsor's base requirements - Higher voltage which can lead to higher overall current output	- Potentially lower current output per channel. - Current output significantly larger than originally requested by sponsor

Justification of the Final Design Choice: The team decided to utilize both power supplies to maximize the magnetic field density that was output by the system. The coil pair in the Z-direction will be attached to the 24V, 15A Power Supply which will maximize this direction's magnetic field density. The 12V, 29A Power Supply, will be hooked up to the X and Y direction coils to allow each coil pair to maximize the current and voltage (i.e. limited to 10 Amps because of 10 Amp motor drivers) that it can output. It should be noted that the resistance of the Z direction pair is 4.5ohms, while the resistance in the X and Y directions is 3 ohms. This means that if wired correctly, the system cannot exceed 10A on channel minimizing risk of overloading the motor drivers.

Fabrication Methods Employed: The team purchased the power supplies from Amazon. An AC power was cut and screwed in parallel to each power supply's live, neutral, and ground terminals. The DC terminals were then screwed to each motor driver, the Z channel connected to the 24V supply while the X and Y were connected to the 12V.

Chapter 4: Prototype Performance

Theoretical Predictions

The team ran numerous MATLAB simulations to determine the efficacy of the electromagnets within the Reconfigurable 3D Magnetic Control System. These simulations were run by utilizing the following equation [9]:

$$B(z) = \frac{1}{2} \cdot \mu_0 \cdot N \cdot I \cdot R^2 \cdot \left\{ [R^2 + (z + \frac{R}{2})^2]^{-\frac{3}{2}} + [R^2 + (z - \frac{R}{2})^2]^{-\frac{3}{2}} \right\}$$

This equation represents the following Helmholtz coil configuration:

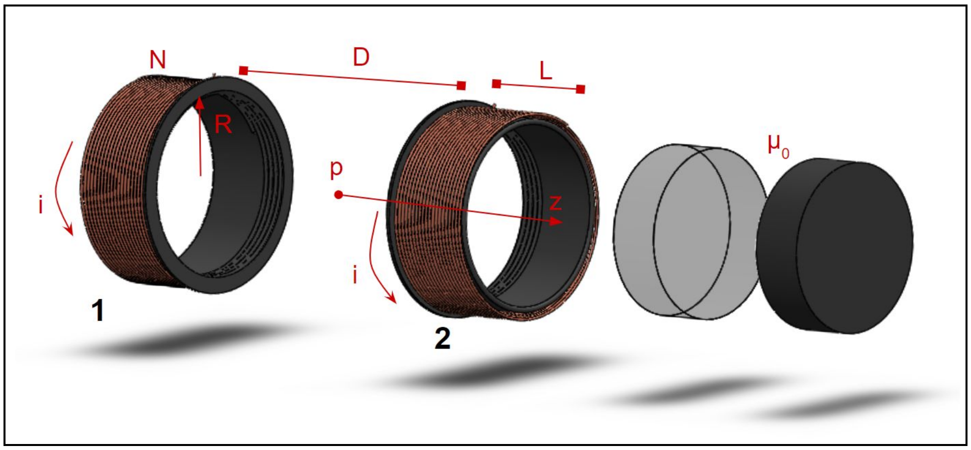


Figure 4.1: Anatomy of a Helmholtz coil

In the setup displayed in Figure 4.1 above, B represents the magnetic field density (in Teslas), z represents the distance from the center of the Helmholtz coils which is denoted by p. D is the separation distance (in meters) between the two solenoids and R is the radius (in meters) of each solenoid (D=R in a perfect Helmholtz coil but this equation can also be used when $D \neq R$). L is the length of each solenoid (in meters). N is the number of coil turns on each solenoid and i is the number of amps being supplied to the Helmholtz coils. Lastly, μ_0 is the magnetic permeability of the core material (measured in $\frac{H}{m}$). [9]

Further, a literature review of work published by Jorge Enrique García-Farieta [6] revealed that the magnetic field density should be axially homogenous in the region between the two solenoids of a Helmholtz coil. This was important to the team's sponsor who desired a magnetic field density axial homogeneity of ± 5%. This is illustrated in Figure 4.2 below:

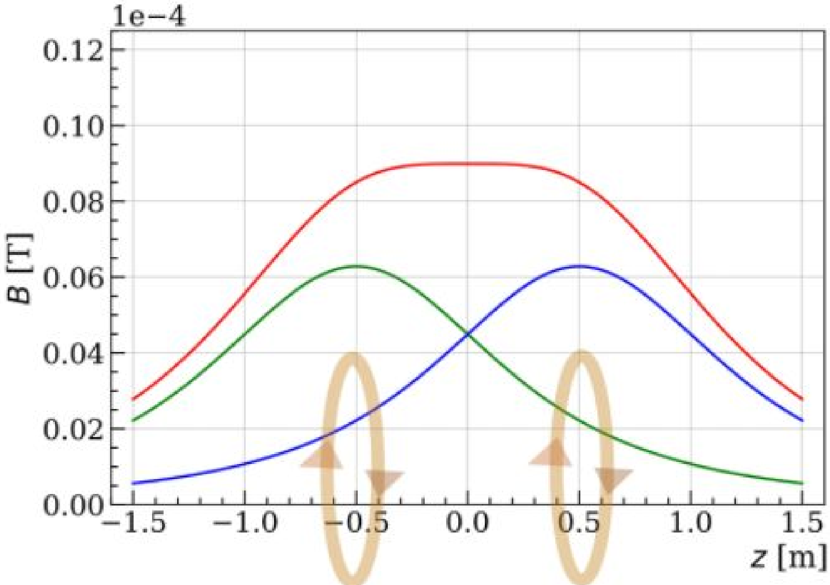


Figure 4.2: Magnetic field density between two solenoids [6]

Test Conditions

MATLAB Simulations

MATLAB simulations were performed by inputting the equations introduced in the Chapter 4: Theoretical Predictions section to MATLAB and varying system parameters to determine expected system performance. These MATLAB simulations focused on optimizing expected magnetic field density.

Magnetic Field Homogeneity Test

One test that the team conducted had the goal of determining the homogeneity of the magnetic field density that the system was producing. This test was conducted by moving a compass between two solenoids and seeing how it behaved. If the compass's arrow pointed the same way at all points between the two solenoids, then the team could conclude the magnetic field density was radially homogeneous. If the compass's arrow fluctuated as it was moved between the two solenoids, then the team could conclude that the magnetic field density produced by the two solenoids was not radially homogeneous. The team also ran MATLAB simulations which illustrated the device's axial homogeneity by sampling the magnetic field density at various points between the two solenoids. The similarity of these magnetic field densities determined how axially homogenous the two solenoids were.

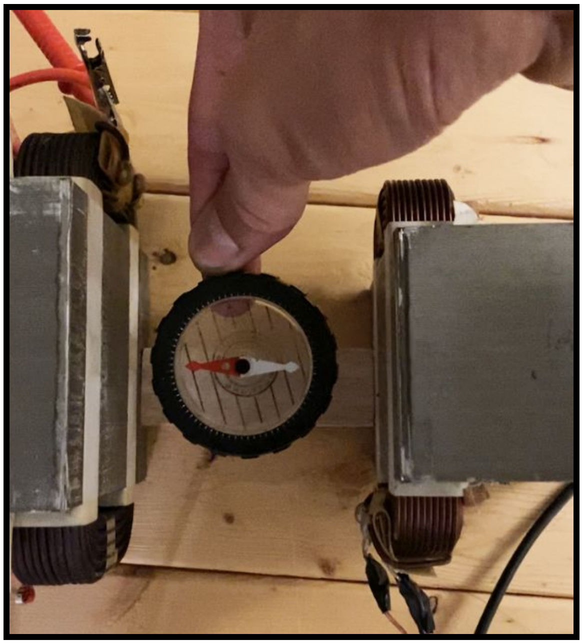


Figure 4.3: Compass between two solenoids to test radial homogeneity.

Magnetic Field Density Test

This test was conducted using a Tesla Meter to determine the magnetic field density that the team's system was capable of producing. The team kept careful note of factors that were relevant to the magnetic field density such as: (1) how much current was run through the system, (2) the radius of the solenoid, (3) separation distance between the two solenoids, and (4) the number of coil turns of wire that was being used.

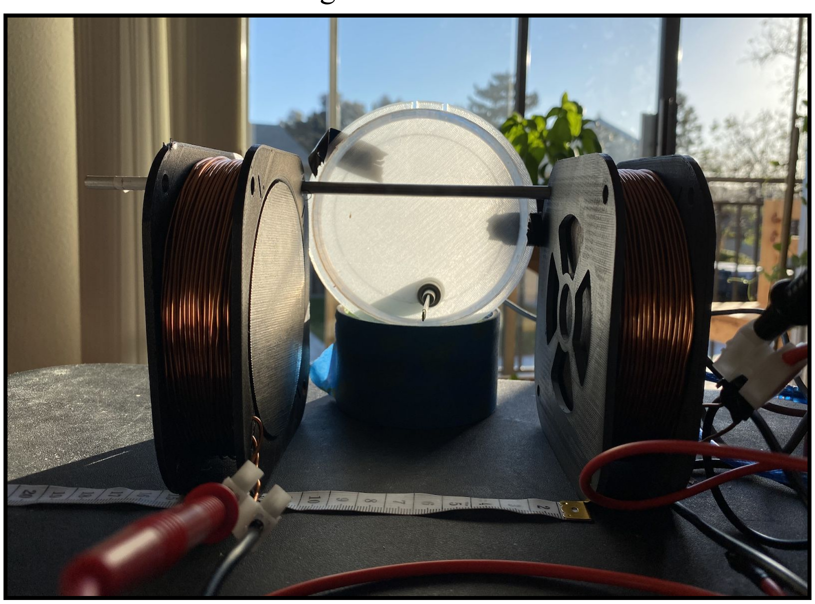


Figure 4.4: Magnetic field density test using a teslameter and two solenoids

Results

MATLAB Simulation Results

Based on the aforementioned Helmholtz coil equation, the team was able to predict that the magnetic field density should increase as the current running through the wiring is increased and as the number of wire wrappings on a solenoid is increased. The Helmholtz coil theory predicted that the ideal separation distance between two solenoids was equal to the radius of the two solenoids that made up the system. Furthermore, the Helmholtz coil theory predicted that the addition of iron cores to each solenoid would drastically increase the magnetic field density within the system since iron cores have a larger magnetic permeability (μ_0) than air does. These predictions are illustrated in Figure 4.2 below:

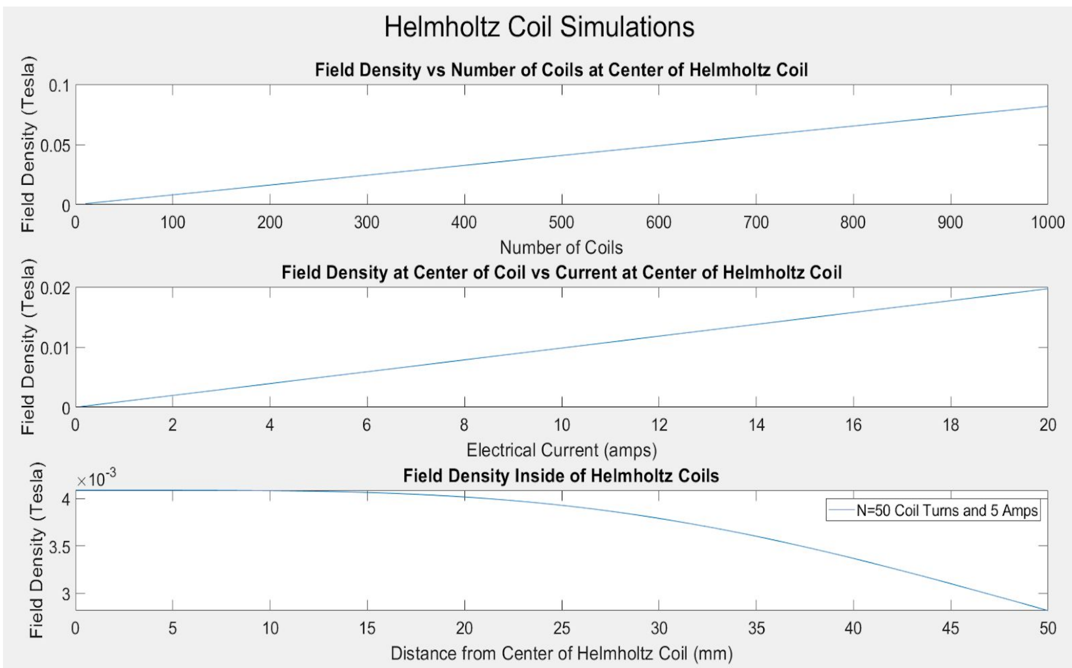


Figure 4.5: MATLAB results showing magnetic field density as different parameters are varied. The top subplot varies the number of coils, the middle subplot varies current provided to the solenoids, and the bottom subplot varies axial distance from the center of the solenoid.

The team's Helmholtz coil simulation predicted that a magnetic field density of 4.09 millitesla would be produced when each air solenoid had fifty coil turns and was supplied with five amps of current. In order to reach 1 Tesla, the Helmholtz coil simulations predicted that either (1) 50 coil turns and 410 A current or (2) 12,250 coil turns and 5 A current; neither of which would be physically feasible for the team's physical design. The 410 amps of supplied current was unfeasible because of heating concerns (i.e. as more current is supplied through a wire, the temperature increases). The 12,250 coil turns option was unfeasible because of sizing concerns within the system. Based on the Helmholtz coil equation and simulations, the team predicted that using iron core solenoids in lieu of air core solenoids would make it possible to achieve a magnetic field density greater than 1 Tesla since the magnetic permeability of iron is much greater than that of air (i.e. $\mu_{0,air} = 1.26 \bullet 10^{-6} \frac{H}{m}$ while $\mu_{0,iron} = 6.3 \bullet 10^{-3} \frac{H}{m}$) [10] Using iron's magnetic permeability led the team's simulation to predict that a magnetic field density of 20.49 Teslas would be attainable with 50 coil turns and 5 amps of current supplied to the system. The team's magnetic field density tests (discussed later in the results section) with a Tesla meter showed that this was not the case.

Before machining the iron cores, the team conducted optimization simulations to determine the ideal solenoid radius and number of coil turns. The solenoid radius parameters were varied between 20 mm and 100 mm while the number of coil turns was varied between 0 and 150 coil turns. This optimization simulation accounted for added resistance within the solenoids from increased number of coil turns and revealed that an optimized magnetic field density would occur at a solenoid radius of approximately 49 mm and 150 coil turns. The team used these results while designing its final solenoid design iteration.

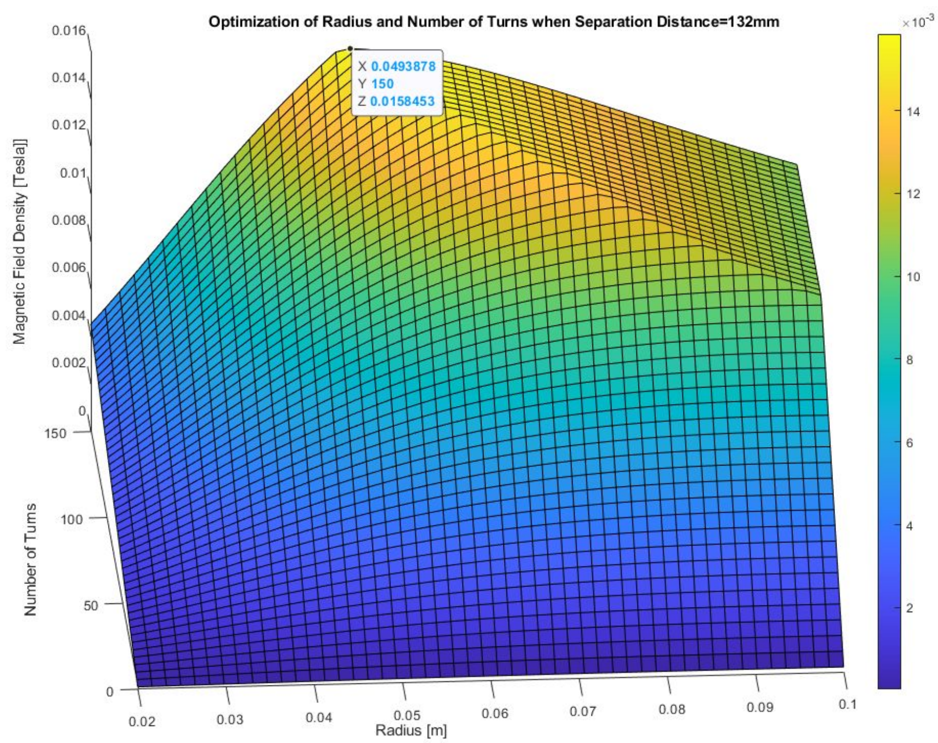


Figure 4.6: MATLAB optimization results obtained by varying: (1) solenoid radius between 20 mm and 100 mm, and (2) number of turns between 0 and 150.

Magnetic Field Homogeneity Test Results

This test revealed that the magnetic field between two solenoids was indeed largely homogenous as the theory had predicted. This was revealed by the fact that the compass's north arrow faced the same direction at every point between two solenoids. This showed that the solenoid pairs were radially homogeneous. MATLAB simulations that sampled multiple points between two solenoids affirmed the theoretical predictions that when separation distance was less than solenoid radius, the magnetic field density would be axially homogeneous. When the separation distance was much greater than the solenoid radius, axial homogeneity decreased significantly but was still within an acceptable range within the working space. These results are displayed in Figure 4.7 below.

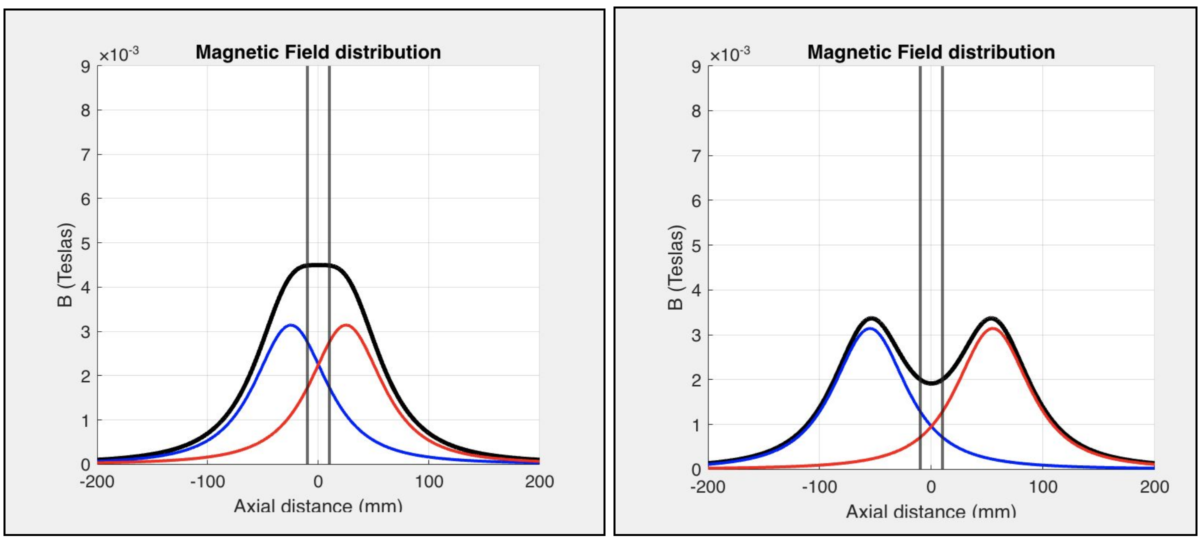


Figure 4.7: Magnetic field density between two solenoids in a Helmholtz coil setup. The image on the left shows that the magnetic field density is very homogeneous when the separation distance is less than or equal to the radii of the solenoids. The image on the right shows that the homogeneity of the magnetic field density decreases when the separation distance is greater than the radii of the solenoids. In both cases, the solenoid radius is 50 mm. On the left, the separation distance is 50 mm while the separation distance is 110 mm for the simulation on the right.

Magnetic Field Density Test Results

This test revealed that the magnetic field density did in fact increase as the number of coil turns and current within a system was increased. For the air core Helmholtz coils, the MATLAB simulation matched the experimental results that were conducted very closely. However, for the iron core solenoids, the experimental results did not match the theoretical results. Instead of seeing the 500 times larger simulated increase in magnetic field density, the iron cores only contributed a 1.9 times magnification of magnetic field density when compared to the air core solenoids. These results can be seen in Figure 4.8 below. While not as high as was initially hoped, the team did elect to still make use of this magnetic field density boost by creating some transformer-inspired solenoid out of the iron cores. With the transformer-inspired solenoid cores, the team was able to produce a magnetic field density of 80 mT as measured by the team's Tesla meter.

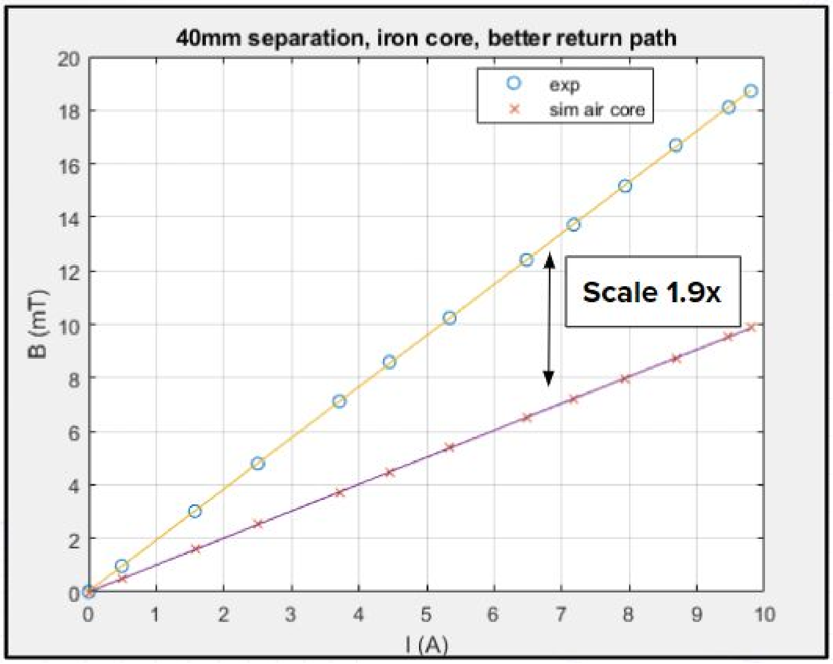


Figure 4.8: Comparison of Simulated Air Core Solenoid Performance to Experimental Values from iron core solenoids

Comparison of Results to Initial Performance Requirements

The team's initial goal was to achieve a magnetic field density of 1 tesla in all three directions. However the team's testing (see figure 4.X) and industry research showed early on that this would be unobtainable given the team's resources and time constraints. Industry research showed the devices that were capable of producing a magnetic field density of 1 Tesla in a single direction at the separation distance asked (50mm) had a price range of $50,000 and were only capable of producing a field of that strength in a single direction; not all three. [1] Further, this industry-available product also included a water-cooling system to deal with overheating issues experienced when dealing with high currents. The team's sponsor agreed that a more realistic goal would be 100mT at 50mm and 10mT at 124mm.

In the end, the team was able to achieve a maximum magnetic field density of 80 millitesla in the Z direction at 50mm while the other two solenoid core pairs were only able to reach 15 milliteslas at 124mm and using the 24V supply. Using 3 channels simultaneously, and therefore the 12V supply, the X and Y channels can achieve only 7mT at 124mm.

While the magnetic field density results were not as ideal as initially hoped, the team's magnetic field homogeneity tests provided favorable results. The team's sponsor had requested that the team's device produce a magnetic field density that had ± 5% axial and radial homogeneities. The experimental results with the compass showed that the team's device produced a vertical magnetic field density that was very homogeneous (± 5%) and horizontal field densities that were reasonably homogeneous (± 10%). This high degree of homogeneity was in line with what the available Helmholtz coil theory [6] had initially predicted for the 50mm separation, and the additional inhomogeneity at the longer separation distance is accounted for by the deviation from the ideal helmholtz configuration.

Chapter 5: Design Recommendations and Conclusions

Design Recommendations for the Future

The chief components of the system so far described include: the electromagnetic actuators, the control system (and power supply units), and the reconfigurable frame. The electromagnets were optimized for high power in order to accommodate future upgrades to the power supply system. The 20awg coils used are removable and can be replaced by 18-22awg for either lower voltage requirement (18awg) or even higher potential field density (22awg) however for maximum field density it is recommended to keep the 20awg windings and improve the power supply and control system. Additional electromagnet cooling systems, such as fans or even application of liquid nitrogen will be necessary to safely reach 100mT in any situation and will both increase efficiency and maximum field density attainable without compromising safety as a water based cooling system might. Other considerations for future electromagnet design include the use of 16awg, no iron core, large diameter coils for large design spaces. The electromagnets used in the project currently are optimized for the 50mm space and become ineffective past 150mm separation distance. Larger diameter coils will permit 10-20mT fields in each direction at the greater separation distance if more power is used. If no core is used, larger diameter wire (lower gauge) is desirable due to lower resistance and higher current carrying capability allowing for many windings (>150 turns) and low chance of overheating.

The system potential will be most drastically increased with an increased DC power source. a 48V, 30A power supply such as the SE-1500-48 Meanwell system would be sufficient to power all three directions. Improved Motor Drivers, such as the 25A, 58V Cytron model (PN00218-CYT13) will permit handling of the higher power without burning out. The arduino control system will not be altered in any other way. If desired, the LCD screen and potentiometer inputs can be soldered rather than connected with jumper wires, although this will prevent easy disassembly for repairs.

Finally, the frame as constructed provides a robust and replicable means of reconfiguring the working space of the system. However the process is still laborious, and the vertical adjustment is very limited. Longer T-beams will permit greater flexibility in the vertical separation, while easier reconfigurability (while maintaining rigidity) is a challenge worthy of a new project.

Safety Considerations

The Reconfigurable 3D Magnetic Control System presented the team with many safety concerns. These safety concerns primarily revolved around the large currents and voltages that were being employed for this project's purposes, and the crushing strength of the magnets employed. As little as 50 milliamps can be deadly for humans [3]. The Reconfigurable 3D Magnetic Control System draws power from grid outlets and includes live wires operating at 110V AC capable of outputting 15A. As such, minimizing the risks associated with this device was a top priority. To combat this, the team always wired the system while shut off and used a surge protector while testing (i.e. since it has a breaker, kill switch, and was grounded). Once constructed, an insulated wood box was designed and treated to contain all live wire connections to minimize risk of stray contact.

Another safety concern that arose revolved around potential overheating in the device's coils. Essentially, as high currents are fed through wires, the wires heat up due to ohmic resistance within the wires. At high enough power, these wires can burn skin, release fumes by burning plastic, or in the worst case breakdown the insulation of the wire and start a fire. To combat this, testing was undertaken with an IR thermal gun to determine safe power levels and the team made sure to have a fire extinguisher on hand in case any thermal related disasters occurred. Another concern was whether the device would produce a strong enough magnetic field to tear itself apart and crush the users limbs. The team minimized this risk by running magnetic force simulations in MATLAB and Finite Element Analysis (FEA) in SolidWorks to ensure that the device was safe. Once constructed, safety testing was conducted to ensure robustness. One final safety consideration was to make sure that the device did not fall off where it was placed and land on someone's foot. In response to this, the team recommends placing the system on a sturdy surface away from any edges.

Applicable Standards

There are a number of standards that engineers must take into account when designing new devices to ensure the safety of users as well as the efficacy of the device. These standards are also applicable to the Reconfigurable 3D Magnetic Control system. As could be expected when working with electromagnetic devices with relatively large voltages, the need for safety standards are of paramount importance. For example, this device will need to take into account electrical safety (i.e. this device will utilize relatively large voltages and currents that could harm the user if not careful), temperature (i.e. the solenoid coils will heat up as current is run through them), and noise exposure limits (the device produces a buzzing sound while in operation). The Occupational Safety and Health Administration (OSHA) [3] warns about the dangers present while dealing with electricity and ways to mitigate these potential dangers. OSHA summarizes many of the potential dangers associated with working with electricity in the following table:

Table 5.1: Table outlining the risks associated with electrical currents from OSHA [3]

Effects of Electric Current in the Human Body

Current	Reaction
Below 1 milliampere	Generally not perceptible
1 milliampere	Faint tingle
5 milliamperes	Slight shock felt; not painful but disturbing. Average individual can let go. Strong involuntary reactions can lead to other injuries.
6–25 milliamperes (women)	Painful shock, loss of muscular control*
9–30 milliamperes (men)	The freezing current or "let-go" range.* Individual cannot let go, but can be thrown away from the circuit if extensor muscles are stimulated.
50–150 milliamperes	Extreme pain, respiratory arrest, severe muscular contractions. Death is possible.
1,000–4,300 milliamperes	Rhythmic pumping action of the heart ceases. Muscular contraction and nerve damage occur; death likely.
10,000 milliamperes	Cardiac arrest, severe burns; death probable

* If the extensor muscles are excited by the shock, the person may be thrown away from the power source.

Since the Reconfigurable 3D Magnetic Control system deals with electrical currents in the range of 5-15 A (5,000-15,000 mA), electrical safety needs to be a top priority. It should be noted that under safe laboratory conditions, the voltage range of the active system (12V-24V

DC) cannot induce more than 1mA through the body of a dry user due to the resistance of human skin. However in the worst case scenario (if the user has wet hands, damaged skin), currents up to 20-40mA may be able to travel across the body at these voltages. Furthermore, the power supply terminals connect directly to wall outlet power (120V AC) which can easily kill. OSHA recommends covering exposed electrical wires with an insulator to prevent unintended electrical discharge. Further, OSHA recommends grounding the device in order to further reduce the chance of serious injury due to electrical shock. OSHA notes that while grounding a device helps reduce risk it does not completely get rid of the potential for risk. Next, OSHA recommends implementing circuit protection devices (e.g. fuses, circuit breakers, ground-fault circuit interrupters, and Arc-fault devices) which reduce or cut off flow of current when irregularities (i.e. ground fault, overload, short circuit) are detected. Further, if any maintenance work is done on the device, the circuitry should be discharged first. As a last measure of protection for users and workers alike, wearing rubber gloves are recommended if there is any reason to manipulate the system while powered.

ASTM C1055 [4] is a standard that regulates temperature limits of devices that have surfaces exposed to users. The primary point on the system that needs to be monitored for temperature concerns are the solenoid coils since they heat up when a high current is run through them. For this device's purposes, a maximum temperature of 60℃ (140℉) on exposed surfaces is allowable since contact between a person and a surface at this temperature for up five seconds would not contribute to irreversible damage.

As for noise control, The National Institute for Occupational Safety and Health (NIOSH) [7] provides guidelines that establish a maximum daily exposure limit to loud noises. When operating, the system produces a low humming noise. As such, the team needed to be sure that the noise levels were within the acceptable limits set by NIOSH. These limits are expressed in the following table:

Table 5.2: Max allowable noise exposure in a 24 hour period. Table taken from NIOSH [7]

Time to reach 100% noise dose	Exposure level per NIOSH REL
8 hours	85 dB(A)
4 hours	88 dB(A)
2 hours	91 dB(A)
60 minutes	94 dB(A)
30 minutes	97 dB(A)
15 minutes	100 dB(A)

The use of electromagnets also poses the risk of unintentionally attracting nearby magnetic objects. Although it is intuitive that any workspace must be kept clean and free of obstructions, it is especially important that all experiments using the magnetic chamber are done in a suitable environment free from attractive metals. Metal jewelry such as rings, necklaces, earrings should be removed, and tools such as screwdrivers, hammers, brackets should be put away. Before the magnetic field is turned on, it is imperative that the working space within the chamber be inspected for loose screws, small strips of metal caught in the T-beam slots. Furthermore, all screws securing the electromagnets should be double checked to be tightened.

When designing Reconfigurable 3D Magnetic Control systems, standard tolerancing and standard units must be followed to avoid catastrophic failures that can be a result of a measurement error. American Society of Mechanical Engineers (ASME) standardizes the geometric dimensioning and tolerancing commonly referred to as GD&T (ASME Y14.5 [5]). This encourages better communication of the design between multiple team members, teams, and even different organizations when working on complex projects. The Society of Automobile Engineers (SAE) Technical Standards Board established standards for using International Systems of Units (SI) in both engineering information and application (TSB003_199905 [11]). Standardizing into a single unit system helps avoid critical measurement error and the need for assumption when working with different organizations. Due to the current Coronavirus situation, standardizing measurements is critical to avoid manufacturing errors as the team members do not have access to the fabrication of the team's project. All CAD models are transferred with the same SI units, and all 2D drawings of tolerances reflect the same.

Impact on Society

The purpose of this project was to create a 3D magnetic control system that can use magnetic fields to manipulate soft robotics for research purposes. Soft robotics have shown promising results in the medical field for use as prosthetic limbs and in decreasing the invasiveness of surgical procedures. In each of these applications, the ability to manipulate the soft robot is crucial. Soft robots can be controlled using a variety of methods such as: (1) magnetic fields, (2) thermal, (3) electric fields, and (4) pressure differences. As mentioned before, this project focused on creating a system that will utilize magnetic fields for the control of soft robots. This project was sponsored by the Cai Group at UCSD and will allow the researchers to enhance their research efforts in soft robotics.

This project has the ability to impact society in a number of ways. From a public health standpoint, the ability to conduct advanced research into the field of soft robotics can potentially improve the lives of those living with missing limbs through the introduction of advanced prosthetics. Alternatively, it can also aid those needing internal surgeries that can be difficult to conduct using contemporary technology. As opposed to highly invasive procedures such as basic surgery or Chemotherapy treatments, a magnetic field has no effect on the human body since there are negligible amounts of ferromagnetic material (iron) present. Thus, there holds large promise that this advantage in using magnetic fields for procedures will show up in biomedical applications in the form of MRIs, soft robot surgeries, etc. On the socio-political side of this, this device may increase the technological gap further between those living in wealthier environments when compared to those living in poorer environments as soft robotics technology will likely be expensive when they are first introduced. However, from an economic standpoint, this project has the potential to help lower the cost of soft robotics by continuing to make soft robotics more mainstream. As more research is conducted into soft robots, more uses will be found for the technology which will contribute to more soft robots being produced. Due to the principle of economies of scale, the price of soft robots will be driven down as more soft robotic systems are created. Looking at this device from a technological standpoint, this project has the ability to enable research that can greatly improve the efficacy of robotic manipulation. This can take a variety of forms. Examples include more lifelike robotic systems, new manufacturing techniques, and less-invasive surgical techniques.

Professional Responsibility

The main purpose of this project is to aid the Cai Group at UCSD in their research in soft robotics. When taken a step further, this project may help medical fields with testing soft robots for their specific purposes. Professionals need to be responsible for meeting health and safety criteria outlined by government entities that will ensure the safety of patients.

Professionals need to be environmentally conscious when mass producing soft robotics and need to consider the effects of populating the concept of soft robotics within the medical industry. Professionals should consider the tradeoffs between potentially negative environmental and potentially positive public health impacts as soft robots pertain to medical purposes. Any new technological advances introduced to the medical field have to undergo a series of ethical and safety questions that need to be addressed before that technology can be implemented. For example, if a new surgical method has been developed that utilizes soft robots, initial testing can be heavily controversial. In regard to the Reconfigurable 3D Magnetic Control System itself, it is a professional responsibility to ensure that this device does not compromise the safety of its users. To address this professional responsibility, an emergency kill switch will be implemented to allow the end user to abruptly turn off the device should anything go wrong with the device while it is operating. Furthermore, a fuse will be included to address the danger of working with electricity. As necessary, safety features should be updated periodically to ensure up-to-date functionality of these safety features.

As was explained in the impact on society section, this device may contribute to a larger technology gap in regards to soft robotics between wealthier societies and poorer societies. As engineers, it is a professional responsibility to make this technology in a way that it does not permanently enable this technological divide (i.e. economies of scale was discussed as a method to decrease the cost of soft robotics in the long run). This device will address this professional responsibility by aiding research that will make soft robotics more mainstream and thus more accessible to all.

Lessons Learned

The team learned many lessons throughout the duration of this project. Possibly the most important lesson that the team learned was the importance of teamwork on projects such as this. This project presented the team with many unique challenges including: (1) a unique engineering challenge, (2) a constrained budget, (3) a relatively short timeline, and (4) a limited ability to meet in person because of the COVID-19 pandemic. Each of these challenges associated with the team's project were mitigated because of the team's teamwork and organization. Early on in the project's timeline, the team realized the importance of doing research into electromagnets to learn about the strongest magnets that the team would be able to produce. While this initial research push focused heavily on academic research, it would have also been helpful to conduct more market research earlier into the technology that was currently available on the market. This market research revealed that in order to attain a magnetic field density of 1 Tesla in just 1 direction (i.e. the team was originally supposed to attain a 1 Tesla Magnetic Field Density in all three directions) would cost in the range of $50,000 [1]. After discovering this, the team was able to refine its objectives in order to set more attainable targets that could be achieved within the team's budget and time constraints. The team realized that a magnetic field density of 100 mT in one direction and 10 mT would actually be achievable based on the aforementioned concerns and presented these findings to the team's sponsor. Upon seeing these findings, the sponsor approved the team's proposed project scope change. Apart from the technical challenges experienced throughout this project, there were also the challenges of constrained budgets and timelines which are present in most engineering projects. The team overcame the budget constraint challenges by researching multiple components for the project and selecting the component with the best value. For time constraints, the team started by creating a Gantt chart which highlighted major milestones that the team would need to meet in order to complete the project in the allotted time frame. These major milestones were then delegated to the project's members to ensure that all team members were contributing a fair amount. While there were some minor deviations from the proposed timeline, the Gantt chart did help to keep the team accountable and allowed them to finish the project on time. One added challenge that is not often encountered was the presence of the ongoing COVID-19 pandemic which severely limited opportunities for in person collaboration. The team learned to overcome this challenge by collaborating virtually over Zoom meetings and by observing all safety recommendations (i.e. regular COVID testing, wearing masks, and socially distancing) while in person. The team was also able to split tasks up by having remote team members focus more on designing the system in SolidWorks and Autodesk Fusion 360, writing software to control the system, or creating prototypes that could be remade by the team's in person contingent. Meanwhile, the members who were located in San Diego were able to focus more on constructing the actual frame and testing the device's performance. These lessons can be applied to future projects after the pandemic ends by reminding team members of the importance of splitting up tasks so that future projects are finished as quickly and efficiently as possible.

Conclusions

The Reconfigurable 3D Magnetic Control System provides a versatile platform that is capable of accurately and precisely controlling three dimensional magnetic field densities applied to a working space at the center of the device. The system's frame is both durable and reconfigurable which enables the device to withstand the magnetic forces that it produces while also allowing the end user to change the spacing of the system's solenoids. End users will have two options to control the system: (1) an Arduino-based potentiometer input method which will allow the user to rapidly alter the magnetic field density that is supplied to the system, and (2) a MATLAB-based GUI input method which enables the user to see a simulation of the magnetic field density provided to the device's working space. While commercially available systems [1] capable of producing 1 Tesla in a single direction cost $50,000, the team's Reconfigurable 3D Magnetic Control System cost $615.47 and was capable of producing a magnetic field density of 80 milliteslas in the z-direction and 10 milliteslas in the x and y directions. In other words, the team was able to produce eight percent of the magnetic field density for a little more than one percent of the commercial cost. The Reconfigurable 3D Magnetic Control System was made to be open source so that future generations of scientists and engineers can benefit from this technology.

Acknowledgements

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[10] “Permeability: Electromagnetism and Formation of Magnetic Fields.” Engineering ToolBox, Engineering ToolBox, www.engineeringtoolbox.com/permeability-d_1923.html.

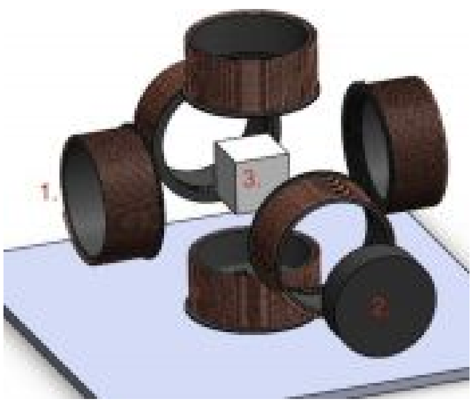
[11] TSB003: Rules for SAE Use of SI (Metric) Units - SAE International, www.sae.org/standards/content/tsb003_199905/.

Appendix A: Individual Component Reports

A.1: Solenoid/electromagnet Core material:

Functional Requirement:
Quantity and Size: 6 solid cylinders 4'' Diameter by 1''.

In combination with the solenoid coils, the core should increase the magnetic field strength to be 1 tesla across working space between two solenoids. There will be three pairs of solenoids oriented in x y z direction. The working space is a 2x2x2cm box in the center of all 6 solenoids [see figure below]. Ideally, in all three directions, the solenoid + core component will achieve 1 tesla magnetic field in the working space.



1. Solenoid wire wrapping
2. Core component
3. Working Space

Figure A.1.1: basic schematic of core components

This further implies

1. Core Material's magnetic permeability is orders of magnitude high
    a. Relative permeability amplifies the magnetic field
2. Magnetic retention is low
    a. Switching off current will result back to 0 magnetic field- ideal case
    b. Low coercive force
3. Magnetic saturation is above 1 Tesla
    a. Core material maximum magnetic field possible under electric field

Materials such as iron, nickel, cobalt have magnetic domains that align with magnetic fields thereby amplifying the magnetic field. In the presence of a magnetic field, these domains take energy to align. Switching off the magnetic field, the magnetic domains will still be somewhat aligned (retentivity) and there is a necessary magnetic field in the opposing direction to set the magnetic retentivity to 0 (coercive force). Since control of the magnitude of magnetic field is crucial, a material with low *coercive force* is desired as it implies the magnetic field to have a quick response to changes in the current of solenoids. Further, it is important to keep in mind relative magnetic permeability is the amplification of the magnetic field compared to the

permeability of air (a relative permeability of 1000 would indicate the material is 1000 times more permeable than air).
Team 5: Individual component analysis Everbrook Zhou A15207422

Popular core selections for electromagnets have been generally classified as “ferromagnets”. There are two general classifications of ferromagnets: soft vs hard. This component analysis paper will analyze the two ferromagnets classes and pick several materials from the better class and get a quote on those materials.

Table A.1.1: Hard Ferromagnets [1]:

Hard Magnetic Materials	Coercivity (Am^{-1})	Retentivity (T)	$BH_{max}(Jm^{-1})$
Alnico 5 (Alcomax) (51% Fe, 24% Co,14% Ni, 8% Al, 3% Cu)	44,000	1,25	36,000
Anico 2 (55% Fe, 12% Co, 17% Ni, 10% Al, 6% Cu)	44,800	0,7	13,600
Chrome Steel (98% Fe, 0.9% Cr, 0.6% C, 0.4 % Mn)	4,000	1,0	1,600
Oxide (57% Fe, 28% O, 15% Co)	72,000	0,2	4,800

Although the retentivity of these materials are high, the coercive force and retentivity is also very high. These magnets will achieve the 1 Tesla rating, but once current is shut off, they will stay with high magnetic strength. These essentially are permanent magnets that are “boosted” by the team’s solenoid coils. Although these magnets will definitely achieve 1 tesla field rating, they will not allow us to change the magnetic field to control the 3D space the way that the team wants. Thus, the materials that the team are looking for are in *soft* ferromagnets.

Table A.1.2: Soft Ferromagnets [2]

Material	Relative Permeability - μ / μ_0-	Coercive Force (mT)	Saturation point (T)	Average Cost per 1 lb	Additional Sources
Iron, 99.8% pure	5000	0.01	1.6	**$10-50**	http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/magprop.html#c2
Iron, 99.95% pure	**200,000**	**0.05**	1.3	$50-120	http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/magprop.html#c2
Ferro Cobalt:	18,000	0.13	**2.3-2.45**	$60-100	https://www.engineeringtoolbox.com/permeability-d_1923.html
Ferro Nickel 99.98%	3,000	0.07-.27	0.6170	$25-50	https://apps.dtic.mil/dtic/tr/fulltext/u2/a381960.pdf

From this table, the best choice is Iron 99.95% pure as iron has the highest relative permeability with low coercive force. As a second choice, Ferro cobalt has the best saturation point with decent permeability. However, performance entails higher cost, and getting more pure iron is much more expensive. Further, upon researching and reaching out to vendors, most locations don't sell pure alloys but compounds of each, such as iron and nickel or iron and cobalt mixture.

Table A.1.3: From Specialized Vendors

Material	Properties	Pros	Cons
Ferro Cobalt: *VACOFLUX x1*	Permeability: 18,000 Coercive Force: .063mT Saturation Point: 2.2T **Quote:** 77$/lb [Alibaba]*	-Very high saturation point -Strong permeability even at low magnetic fields	-High cost -noticeable coercive force
Iron and Nickel Alloy: *Fe55/Ni45*	Max Permeability: 40,000 Coercive Force: .012mT Saturation Point: 1.6T **Quote:** 1inx 10in rod - 275$ [Goodfellow]	-one of Best permeability -achieves desired saturation point	- highest cost material -vendor does not supply desired size requirements
Ferro iron: *Iron 99.95%*	Max Permeability: 200,000 Coercive Force: .05mT Saturation Point: 1.3T **Quote:** 250$ for 6 cylinders**	-Highest permeability -achieves desired saturation force	-permeability rating is inaccurate for low magnetic fields <.1T

* the original company for vacoflux did not respond to email inquiry.
** investor has already purchased this and supplied this quote

Conclusion:

The best materials to purchase is pure iron at 99.95% as it accomplishes all of the functional requirements in theory. However, it is important to keep in mind that the solenoids can only produce magnetic fields of up to 30mT. The core material permeability ratings are generally ratings under a comparable magnetic field (greater than 100mT) thus the true relative permeability, called initial permeability, of iron core will be around 4000-6000. As for now, soft

pure iron is the safest and best bet since the core material has the best theoretical magnetic properties and also it has already been purchased by the team's sponsor. Once testing has started and if the desired 1 Tesla field has not been achieved, Vacoflux will be considered next.
Team 5: Individual component analysis Everbrook Zhou A15207422

Sources and Vendors:

[1] Hard Magnetic Materials
https://www.electrical4u.com/hard-magnetic-materials/

[2] Nickel and its Alloys
U.S. department of Commerce,
National Bureau of Standards
https://apps.dtic.mil/dtic/tr/fulltext/u2/a381960.pdf

Vacoflux Catalog: https://vacuumschmelze.com/9-to-30-Cobalt-Iron

Goodfellow Catalog:
http://www.goodfellow.com/catalogue/GFCat4I.php?ewd_token=g1kkITQwjWbi8anBMh7WyV8sCDzwpG&n=o93kadXUJOp8VuXuWONC8gTerXxBsK&ewd_urlNo=GFCat411&Catite=FE187930&CatSearNum=5

A.2: Frame Material

Base Frame Material is one of the critical components that needs to be able to support Helmholtz coils in three different directions: X, Y, and Z. Frame allows the solenoid to move in their respective directions to modify workspace for experiments. The primary project goal is to generate a magnetic field of 1 Tesla in 3 different directions with the help of iron core which may weigh up to 3kg. The core provided by the sponsor weighs approximately 1.75kg, but the frame should be able to handle 3kg iron core without significant bending. With the different number of turns of the coil on the solenoid, the solenoid can get very heavy, so the base frame material should be able to support the weight of different components.

Functional requirements for this component:

- Size Dimension of 400mm X 400mm (approximately 15.75in X 15.75in)
    - Thickness of the material is subject to change depending on the budget and functionality
- MRI Compatible material
    - Helmholtz coil needs to be able to generate a magnetic field of 1 Tesla, so MRI compatible material is necessary to prevent the material from being affected by the magnetic field.
- High resistance to heat
    - Resistance to heat is necessary to avoid deformation of the material
- Resistance to deflection
    - Mass of solenoid with a core material and variable number of coil

Core Material： 3kg (1.75kg actual)

Mass of each solenoid=5kg

$$F = m \cdot g = (6 \cdot 5kg) \cdot 9.8\frac{m}{s^2} \approx 300\ N$$

F=350N

- Should be able to withstand 350N as a precaution

MRI Compatible Metal:

- Titanium
- Aluminum
- Brass
- Copper
- Bronze
- Aluminum Bronze Alloy

3D Plastic Materials

- Acrylonitrile Butadiene Styrene (ABS)
- Polylactic Acid (PLA)
- Carbon Fiber

Table A.2.1: Properties and Cost of MRI Compatible metals found on McMaster-Carr. For easier comparison, cost of the same sized (24” X 24” X 0.016”) material has been used. [1][2][5]

Material Type	Young’s Modulus (GPa)	Density (g*cm^-3)	Melting Point (°C)	COST($)	Part Number
Aluminum	69	2.70	660.32	27.51	89015K123
Brass	100	8.73	900-940	35.72	8956K72

Table A.2.2: Properties of 3D printing materials [3][5]

Material Type	Young’s Modulus (GPa)	Density (g*cm^-3)	Melting Point (°C)	COST($)	Part Number
Acrylonitrile butadiene styree (ABS)	1.4-3.1	1.53	190	Available on campus 32.81(1.75 mm dia. spool)	1317N531
Polylactic acid (PLA)	3.5	1.3	130	Available on campus 32.81(1.75mm dia. spool)	1317N24

The individual component analysis will focus on Aluminum and Brass for MRI compatible metal and ABS and PLA as 3D Plastic Materials. Table A.2.1 and Table A.2.2 shows the properties and the costs of various MRI compatible materials including the 3D materials that the team will use for different components within the frame. One of the top reasons for choosing these materials is budget and availability of these materials. Aluminum and brass are widely available and cheap compared to the different MRI compatible materials. ABS and PLA can be easily accessed when needed as the material is available on campus.

Table A.2.3: Pros and Cons of the Materials Considered [1][2][3][4]

Material Type	Pros	Cons
Aluminum [1]	• Use as grounding material • Does not tarnish • Long lifespan • Lightweight • Cheap	• Weaker compared to other MRI compatible metals • Lower melting point
Brass [2][3]	• Higher melting point • Corrosive Resistance • Easily Machined	• Can Tarnish • Expensive • Require regular maintenance
ABS [4]	• Durable • Strong • Slightly flexible • Heat Resistant • Easily Machined	• Prone to cracking if cooled too quickly • Only have 100 hours for 3D printing (may need for different components)
PLA [4]	• Widely available • Bio-degradable material • Environmental-friendly • More detail	• Less heat resistant • Less sturdy • Lower melting point

Aluminum:
Aluminum is one of the cheaper MRI compatible materials that are widely available and used throughout industry. Aluminum is a lightweight material that offers longer lifespan. However, Aluminum has low Young's Modulus and modulus that should be considered when running simulations to see what fits the best.

Table A.2.4: Cost and Part Number from McMaster-Carr of Multipurpose 6061 Aluminum sheets 24" X 24" with varying thickness (Yield Strength = 35,000 psi) [5]

Thickness of Aluminum 6061 Plate (measured in inches)	Cost ($)	Part Number
0.016"	27.62	89015K123
0.05"	42.65	89015K44
0.1"	83.14	89015K966
0.19"	112.76	89015K33

Table A.2.5: Cost and Part Number from McMaster-Carr of Anodized Multipurpose 6061 Aluminum Sheets 24" X 24" with varying thickness (Yield Strength = 35,000psi) [5]

Thickness of Aluminum 6061 Plate (measured in inches)	Cost ($)	Part Number
1/4"	291.67	7255K4
3/8"	295.08	7255K5
1/2"	354.84	7255K6

On McMaster-Carr, the maximum thickness for multipurpose 6061 aluminum plate is 0.19" (Table A.2.5). After 0.19" the next cheapest available is anodized multipurpose 6061 aluminum sheets, increasing the cost of aluminum plate to more than 2 times (Table A.2.5). Depending on the magnitude of deflection allowed for the team's project, the price may or may not jump.

Brass:
Brass is another MRI compatible material that has higher Young's Modulus and melting point that adds to durability of the material and suitability to support the frame material. However, the material is more expensive than Aluminum.

Table A.2.6: Cost and Part Number of Ultra-Formable 260 Brass Sheet of 24" X 24" (Yield Strength = 52,000psi) [5]

Thickness of 260 Brass Sheets (measured in inches)	Cost ($)	Part Number
1/4"	393.07	8956K85

Ultra-Formable 260 Brass is one of the cheapest brass sheets that is available at McMaster-Carr. The table shows ¼" thick brass is more expensive than ¼" thick anodized aluminum sheets.

ABS:
Since some of the team's components will be 3D printed, it can help the project look much nicer and uniformed. ABS can either be bought as a sheet from McMaster-Carr or 3D printed using the school's 3D printer. It is a very cheap option, but it is not ideal to carry heavy loads due to low Young's Modulus and low melting point. However, it can be great for making holders to hold different components together for the frame.

PLA:
If the environment is one of the concerns, it would be good to choose PLA as it is biodegradable material. PLA offers very nice detail compared to ABS. However, this material has lower melting than ABS, so it may not be ideal for using as one of the frame components due to the potential for the temperature to increase while running the experiments.

Conclusion:
Aluminum may be the best choice of the material due to being cheap, having wider choices with the same amount of budget, and longer lifespan without maintenance. The team decided to use CNC for the majority of the project and aluminum is highly machinable. Since the team has access to 3D printing, ABS will most likely aid with the whole frame design to combine different components together. Both ABS and Aluminum will be used for the frame with Aluminum being the most common material used for the project.

References:

[1] *Advantages of Aluminum*, Thyssenkrupp
https://www.thyssenkrupp-materials.co.uk/advantages-of-aluminium.html

[2] *Advantages of Brass*, Extreme Metal Works
https://www.exmetalworks.com/brass.htm

[3] *ABS vs PLA Filament*, 3devo
https://3devo.com/blog/abs-vs-pla-filament-whats-the-difference/

[4] *Bronze & Brass Reference Guide*, Gunderlin
http://www.gunderlin.com/prodserv/materials/bronze.htm

[5] McMaster-Carr Catalogue, Keywords: Aluminum, Brass, PLA, ABS

A.3: Circuits Components and Controller

Functional Requirements:

Minimum requirements:

- circuitry must handle 5A current
- pairs must be able to be turned 'on' and 'off'
- Because of induction in solenoids, large voltage spikes should be handled

Best case:

- Current (voltage) should be independently controllable over a range with reversible polarity for each coil pair
- Control with feedback to achieve specific current

Options:

1. **(Cheapest) Protoboard Circuit with single voltage power supply and simple connection leads to reverse polarity**

   This system would consist of a simple circuit dedicated to providing 5A to each coil connected to power. Field direction for each coil can be switched while the system is off by reversing power leads.

   Main components:

   - >20A DC power supply (or 3x 5A DC power supplies)
   - Prototyping board
   - Resistors (depending on voltage of power supply)
   - Diodes
   - Jumper cables

Figure A.3.1: Power supply

Pros:

- Achieves minimum requirements
- Simple construction and easy to repair

Cons:

- No flexibility in testing

2. Analog variable output control

This system would build on option 1 by adding a switch to reverse coil polarity while system is on as well as additional circuitry for variable output (potentiometer controlled variable output). An ammeter can be added inline to display and/or record exact current across each coil pair

Additional components over option 1

- 3x polarity reversing rocker switch
- 3x variable speed regulator
- 3x ammeters

Figure A.3.2: Ammeter Rocker switch

Pros:

- Achieves minimum requirements
- Simple construction
- Straightforward UI, experimentation

Cons:

- More expensive than option 1
- Requires an operator to change output
- Does not record amperage

3. (Most complex) Digital control

This system would add digital control using an arduino, relays, and some form of power control. Power control options include PWM using transistors or digipot. If using a digipot, Digital ammeters can be added inline to display and/or record current through coils. Control theory can be applied on the output current in order to follow desired outputs.

Pros:
- Significant increase in experimental flexibility, including implementation of time varying functions

Cons:
- Increased experimental complexity (need to program the output)
- Increased Cost
- Significant increase in design complexity
- More places for circuit fail

Summary:

Table A.3.1: This table shows selection criteria for the viable candidates proposed for the controller.

	Option 1	**Option 2**	**Option 3**
Pros	Cheap	Easy operation Straightforward design	Most control
Cons	Restrictive	Less control than 3	Most complex/ expensive
Cost	~$50	~$100-130	~$100-160

Conclusion

Considering a restrictive budget of $500, Option 1 will be initially implemented. If funds and time permit, Options 2 and/or 3 will be discussed with the sponsor and implemented accordingly.

References:

[1] *Design and Analysis of Multilayer Solenoid Coil for Faraday Modulator***,** Wang, Jia et al.

[2] TE connectivity database, Keywords: Polarity Reversing Switch, wire connector

[3] *Power Management*, *Electronic Design,* Bob Zollo. https://www.electronicdesign.com/power-management/article/21795484/turn-positive-voltages-negative-with-relays

[4] https://www.instructables.com/Arduino-Tutorial-Handling-High-Power-Devices/

[5] Reprogrammable shape morphing of magnetic soft machines Yunus Alapan, Alp C. Karacakol, Seyda N. Guzelhan, Irem Isik and Metin Sitti

Part links

Option 1

- Prototyping boards
  - https://www.amazon.com/gp/product/B07Y3PVDMZ/ref=crt_ewc_title_dp_2?ie=U TF8&psc=1&smid=A2UIWYS7E6PLOL
- Power Supply
  - https://www.amazon.com/MENZO-Universal-Regulated-Switching-Computer/dp/B06VWV5YCH/ref=sr_1_6?dchild=1&gclid=CjwKCAiAlNf-BRB_EiwA2osbxVde1q4RIuSkb5KEZsrnCJ-ysza9_np2jUrC67iqL9Mcl0qjS3xmgxoCSzIQAvD_BwE&hvadid=409936255617&hvdev=c&hvlocphy=9061191&hvnetw=g&hvqmt=e&hvrand=7564369348780050325&hvtargid=kwd-340036944898&hydadcr=19109_11276355&keywords=20a+dc+power+supply&qid=1607922487&sr=8-6&tag=googhydr -20
- Flyback diodes
  - https://www.amazon.com/gp/product/B07XDJGDQP/ref=crt_ewc_title_dp_1?ie= UTF8&psc=1&smid=A2RFXKS6GNXFWP

Option 2

- Polarity reversing rocker switch
  - https://www.amazon.com/IndusTec-Polarity-Reversing-Rocker-Maintained/dp/B07W72XJQH/ref=sr_1_3?dchild=1&gclid=CjwKCAiAlNf-BRB_EiwA2osbxUoIzhN2gGOKxf7B-2fuJzpJeaizenlbOBgEkWxxs_umSUyCSwbERRoCDDcQAvD_BwE&hvadid=177563992227&hvdev=c&hvlocphy=9061191&hvnetw=g&hvqmt=e&hvrand=4779993787293515620&hvtargid=kwd-36538069385&hydadcr=5765_9590506&keywords=reverse+polarity+rocker+switch&qid=1607921468&sr=8-3&tag=go oghydr-20

- Variable speed regulator
  - https://www.amazon.com/DZS-Elec-Controller-Variable-Regulator/dp/B0779QXY SR/ref=asc_df_B0779QXYSR/?tag=hyprod-20&linkCode=df0&hvadid=22660149 2573&hvpos=&hvnetw=g&hvrand=3298947223822236383&hvpone=&hvptwo=& hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9061191&hvtargid=pla-3913 10304926&psc=1
- Ammeters
  - https://www.amazon.com/Eiechip0-28-Digital-display-Volt-Meter/dp/B079L33VG2 /ref=asc_df_B079L33VG2/?tag=hyprod-20&linkCode=df0&hvadid=24202204435 8&hvpos=&hvnetw=g&hvrand=3712577068981345774&hvpone=&hvptwo=&hvq mt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9061191&hvtargid=pla-4889543 67515&psc=1

A.4: Simulation Software

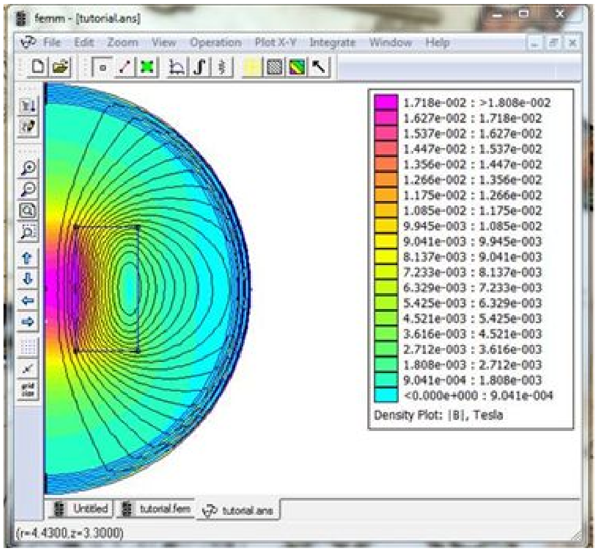
The goal of this project is to create a 3D magnetic control system using Helmholtz coils and iron cores that can be used in the sponsor's lab to support their research in soft robotics. The sponsor, Darren Dong, requested that the team produce at least 1 Tesla magnetic flux density. Due to the fact that this project has a short timeline and limited resources, an important aspect of the project is to use software to model magnetism in the project so that the team can save time and resources as they continue on with this project. This will enable the team to save time prototyping since it is quicker to update/alter a model than it is to build multiple versions of a prototype.

At a minimum, the simulation software needs to meet the following functional requirements:

1. Able to accurately simulate magnetic flux density
2. Ability to vary the following parameters:
    a. Number of coils on the Helmholtz Coil
    b. Wire gauge
    c. Electrical current
    d. Core type
3. Identifying areas of highly concentrated stress on the team's frame stemming from the magnetic fields.

With these functional requirements in mind, a number of simulation applications came to mind. In regards to the frame modeling requirements, SolidWorks is capable of modeling stress concentrations using a 3D model and the expected loads that will be applied. In addition, SolidWorks is free for students which makes it easily accessible for the team's needs. As such, this component analysis will mainly be focused on modeling magnetic flux density and the ability to vary the aforementioned parameters. MATLAB was one potential solution that was suggested by the team's sponsor. Almost any system can be modeled in MATLAB if the correct equations are employed. Further, students have access to this tool for free. In addition to MATLAB, this report will analyze potential alternative software packages that can more easily and accurately model magnetic flux density. With these design considerations in mind, an online search engine was used to identify the following potential solutions (Note: relevant links are embedded in the underlined blue text):

1) Finite Element Method Magnetics



Key Features: Finite element method magnetics is free and offers a high degree of customization. The user is able to vary solenoid parameters such as number of coils, wire type and gauge, and electrical current. The model is then capable of computing the magnetic flux density along the axis of the solenoid. Fortunately, there is also a tutorial which makes the software more user friendly. The main con with this software is that the results are only in 2D instead of in 3D. (The figure to the left shows the results of a solenoid simulation)

Figure A.4.1: Finite Element Method Magnetics

2) COMSOL Multiphysics

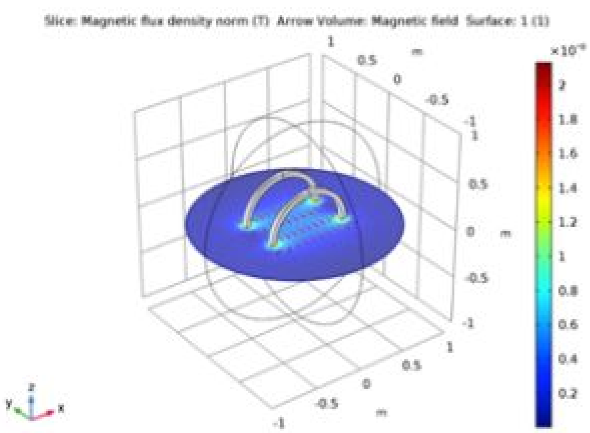


Figure A.4.2: COMSOL Multiphysics

Key Features: COMSOL Multiphysics is a software package that enables you to simulate a variety of physical models including helmholtz coils and permanent magnets in 3 dimensions. The end user is able to customize simulation parameters such as number of coil turns, current, permeability, and a variety of other parameters. Similar to the Finite element method magnetics program, there are a number of available tutorials to make the software more user friendly. Another pro was customer service. It was extremely easy to get a quote by calling them at 310-441-4800. Deborah Cruz emailed the team a quote $998 for one year or $1995 for a perpetual license for the base version of Comsol Multiphysics. (The above figure shows the results of a helmholtz coil simulation.)

3) [MATLAB]

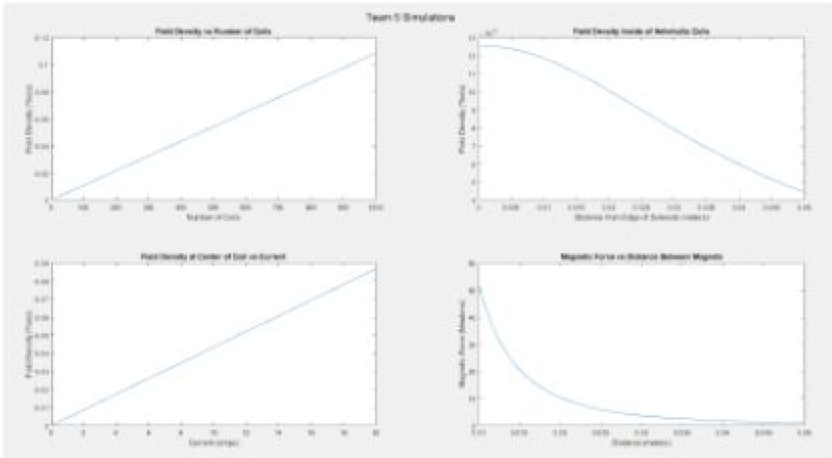


Figure A.4.3: MATLAB Simulation Preview

Key Features: MATLAB is widely used in academic institutions because of its versatility. The plots to the left were produced by modeling equations for field density (in Teslas) and magnetic force. One of the main downsides to MATLAB is that the simulation results may not look as visually appealing to the end user as other forms of simulation are. Another potential drawback is that the produced system is only as accurate as the equations which are used to model the system.

4) [MagNet]

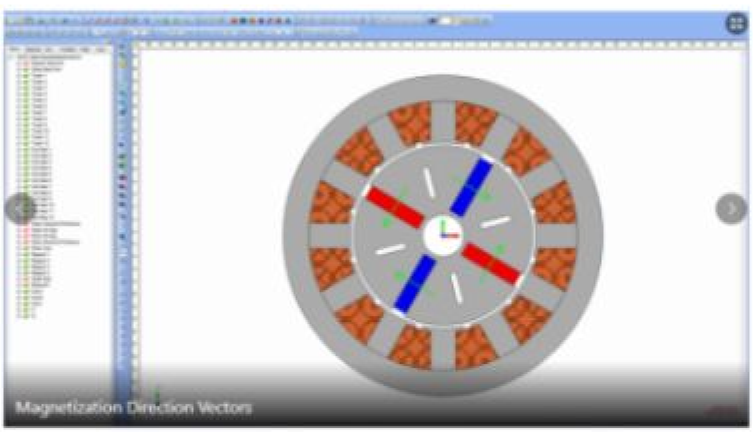


Figure A.4.4: MagNet Simulation Preview

Key Features: MagNet is a simulation software from Mentor, A Siemens Business. It is highly customizable and can be used for modeling a myriad of electromagnetic and electromechanical devices including solenoids and permanent magnets. The figure to the left shows the MagNet simulation software in action. The team reached out to Mentor using the company's website's chat function. Unfortunately, quotes are not available to undergraduate students (i.e. graduate students and up can get quotes) and an industry email is required otherwise. However, the Mentor representative, Roth Chan, provided information on a 14 day free trial program that was available that could allow the team enough time to meet their short term modeling requirements. Roth Chan did note that users can not export models from the cloud-based trial which is another con of this software package.

The above information for each of these aforementioned software packages has been compiled into Table A.4.1 below which outlines the pros, cons, and price of each software package:

Table A.4.1: This table shows selection criteria for the viable candidates proposed for the simulation software.

Component	Pros	Cons	Price
Finite Element Method Magnetics	Free, Able to adjust solenoid parameters, Able to simulate magnetic flux density, Tutorials available	Only simulates in two dimensions	Free
COMSOL Multiphysics	Highly customizable, Models Helmholtz coils and permanent magnets in three dimensions, Many tutorials available, User friendly	Price (Can ignore this since there is a free student version)	$998 for one year license; Free Student Version
MATLAB	Free for students, Lots of experience using, Can simulate almost any equation, Able to vary listed parameters, Able to simulate magnetic flux and force	Simulations may be inaccurate, Have to code simulation which may lead to inaccuracies, Produced simulation may be more difficult for the end user to understand and analyze	Free for Students
MagNet	Ability to model solenoids and permanent magnets, User friendly, Tutorials available, 14 day free trial	Quote unavailable, Inability to export models from the free trial	Quote Unavailable

Conclusion

Comparing these pros and cons to the functional requirements, the best choice for the simulation software would be COMSOL Multiphysics. It is capable of modeling helmholtz coils and permanent magnets while remaining user friendly by having many tutorials available. In addition, there is a free student version that the team can utilize that won't use any of the team's budget which makes this software package budget-friendly. Once a desirable magnetic flux density is achieved in the simulations using COMSOL Multiphysics, these design considerations (i.e. weight and forces stemming from magnetism) can be modeled in SolidWorks to identify potential strengths and weaknesses in the team's frame design.

Summary:

Databases Used - Google

Keywords - Magnetism, Simulation, Solenoids, Helmholtz Coil, Permanent Magnet, Magnetic Flux Density

Email - Roth Chan, Mentor, a Siemens Business, roth_chan@mentor.cm

Deborah (Debbie) Cruz, COMSOL Inc., Deborah.Cruz@comsol.com

Phone Calls - Deborah (Debbie) Cruz, COMSOL Inc., (310)-441-4800

A.5: Engineering Drawings

3D MAGNETIC CONTROL SYSTEM DRAWING

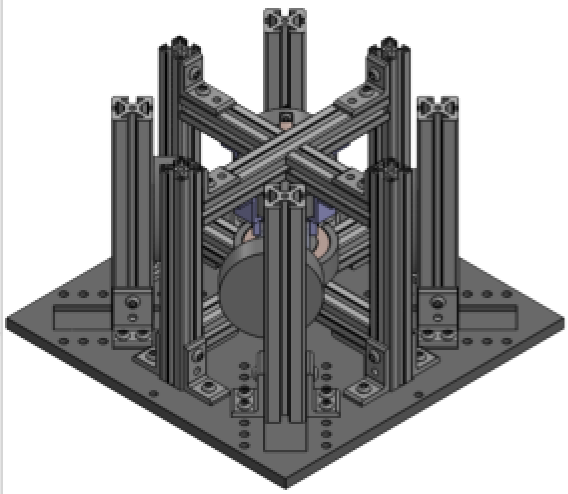


TABLE OF CONTENTS	
PAGE	CONTENT
1	TABLE OF CONTENTS
2	OVERALL DESIGN (BILL OF MATERIALS)
3	LIST OF SCREWS AND FASTENERS
4	DESIGN ASSEMBLY
5	BASE PLATE
6	SOLENOID
7	40MM TBAR FOR DESIGN ASSEMBLY
8	TOP/BOTTOM SUBASSEMBLY
9	30MM TBAR FOR TOP/BOTTOM ASSEMBLY
10	WORKSPACE SUPPORT
11	1.5IN BRACKET
12	1IN BRACKET
13	COIL WRAPPER
14	COIL WRAPPING JIG BASE
15	COIL WRAPPING JIG RING
16	COIL WRAPPING JIG TOP
17	DESIGN ASSEMBLY EXPLODED VIEW
18	TOP/BOTTOM SOLENOID EXPLODED VIEW
19	COIL WRAPPING JIG EXPLODED VIEW

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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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DRAWN	JAE HYEOG LEE	3/4/2021
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MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: TABLE OF CONTENT
SIZE A | DWG. NO. TOC1 | REV
SCALE: 1:8 | WEIGHT: | SHEET 1 OF 19

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2 1

B B

BILL OF MATERIALS

ITEM NO.	PART NAME	QTY.	DESCRIPTION
1	BASE PLATE	1	15IN X 15IN X 15IN
2	TOP AND BOTTOM SOLENOID SUBASSEMBLY		INCLUDES 3,4,7,8,9,10,11
3	SOLENOID	6	
4	COIL	6	
5	40MM T-SLOTTED FRAME 10IN	4	10IN
6	1.5IN CORNER BRACKET	8	1.5IN
7	1IN CORNER BRACKET	8	1IN
8	30MM T-SLOTTED FRAME 10IN	6	10IN
9	30MM T-SLOTTED FRAME 4.5IN	4	4.6IN
10	WORKSPACE	2	50MM X 50MM X 50MM
11	WORKSPACE SUPPORT	1	CAN BE 3D PRINTED FOR VARIOUS HEIGHTS
12	SOLENOID COIL WRAPPING JIG	1	USED TO WRAP COILS; INCLUDES BASE,RING,TOP

A A

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DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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	NAME	DATE
DRAWN	TEAM 5	3/4/21
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ENG APPR.		
MFG APPR.		
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COMMENTS:
REFER TO BOM EXCEL FOR DETAILS

TITLE:
OVERALL DESIGN BILL OF MATERIALS

SIZE A DWG. NO. DES1 REV

SCALE: 1:8 WEIGHT: SHEET 2 OF 19

NEXT ASSY USED ON
APPLICATION

2 1

2 1

B B

LIST OF SCREWS AND FASTENERS

PART NAME	QTY.	DESCRIPTION
M6 SCREW	16	WORKSPACE AND SOLENOIDS
M6 FASTENER	16	WORKSPACE AND SOLENOID
M8 SCREWS	64	CORNER BRACKETS AND SOLENOIDS (REQUIRE 60) 4 EXTRA M8 SCREWS FOR ADDITIONAL SOLENOID SUPPORT
M8 FASTENER	64	CORNER BRACKETS AND SOLENOIDS

A A

	NAME	DATE
DRAWN	JAE HYEOG LEE	3/12/2021
CHECKED	TANNER HANSON	3/12/2021
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
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APPLICATION

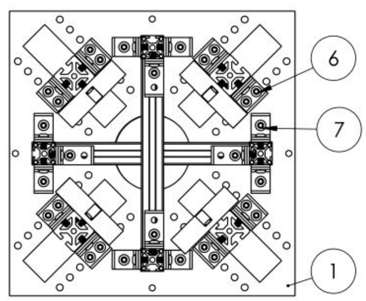
COMMENTS:
REFER TO BOM EXCEL FOR DETAILS

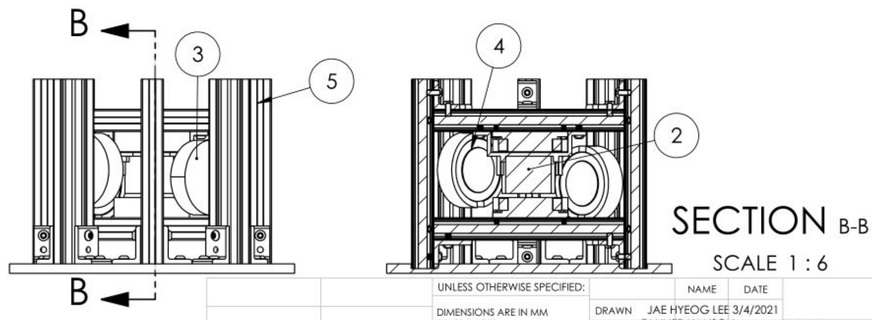
TITLE:
LIST OF SCREWS AND FASTENERS

SIZE A | DWG. NO. DES2 | REV
SCALE: 1:8 | WEIGHT: | SHEET 3 OF 19

2 1

ITEM NO.	PART NAME	QTY.	DESCRIPTION
1	BASE PLATE	1	15IN X 15IN X 0.5IN
2	TOP AND BOTTOM SOLENOID SUBASSEMBLY	1	INCLUDES 3,4,7,8,9,10,11
3	SOLENOID	4	
4	COIL	4	
5	40MM T-SLOTTED FRAME 10IN	4	
6	1.5 INCORNER BRACKET	8	USED FOR 40MM T-FRAMING RAILS
7	1IN CORNER BRACKET	11	USED FOR 30MM T-FRAMING RAILS





UNLESS OTHERWISE SPECIFIED:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
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INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

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COMMENTS:

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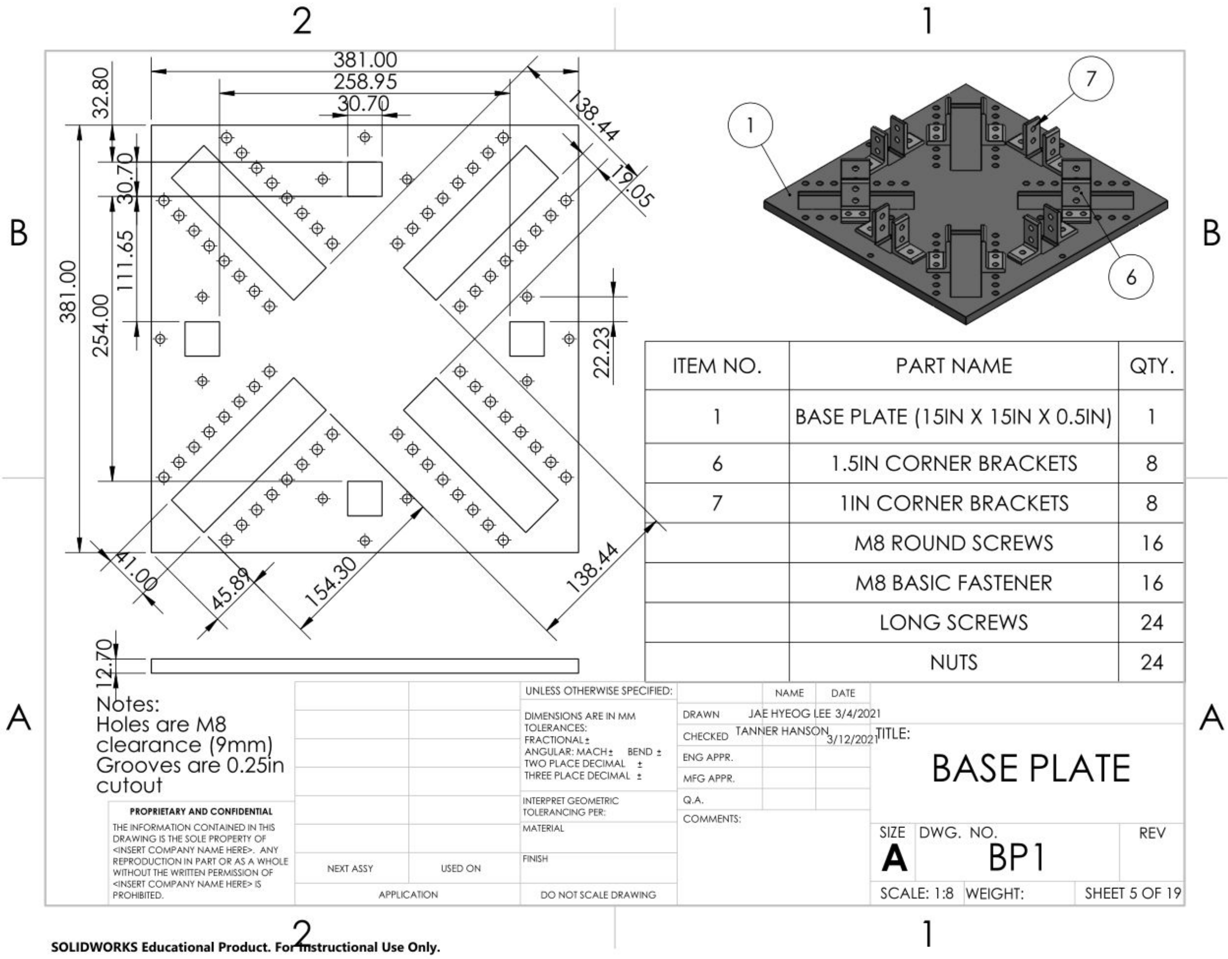
TITLE:

DESIGN ASSEMBLY

SIZE A | DWG. NO. DAS1 | REV

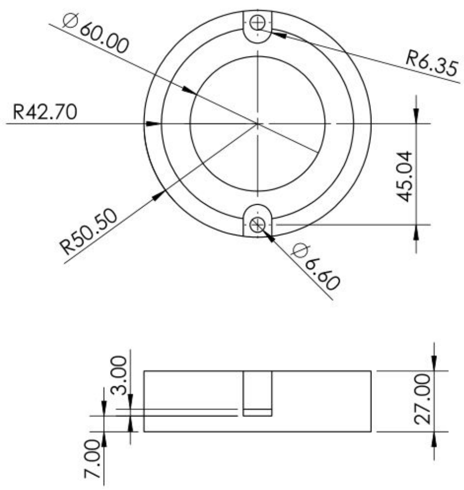
SCALE: 1:8 | WEIGHT: | SHEET 4 OF 19

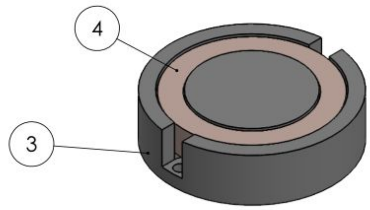


ITEM NO.	PART NAME	QTY.
1	BASE PLATE (15IN X 15IN X 0.5IN)	1
6	1.5IN CORNER BRACKETS	8
7	1IN CORNER BRACKETS	8
	M8 ROUND SCREWS	16
	M8 BASIC FASTENER	16
	LONG SCREWS	24
	NUTS	24

2 | 1

B





NOTE: BILL OF MATERIAL FOR SOLENOID
REFERS TO TOTAL NUMBER OF MATERIALS

ITEM NO.	PART NAME	QTY.
3	SOLENOID	6
4	COIL	6
	M6 SCREWS	12
	M6 FASTENER	12
	M8 SCREW (OPTIONAL)	4
	M8 FASTENER (OPTIONAL)	4

A

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TWO PLACE DECIMAL ±
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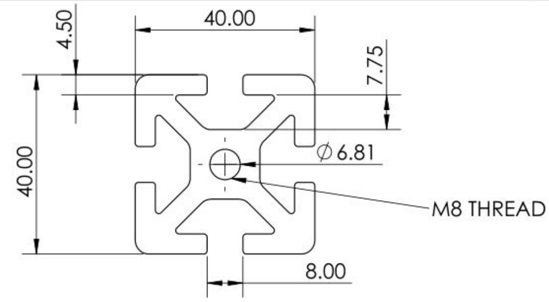
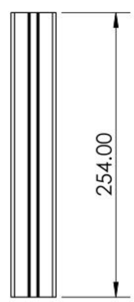
Q.A.		
COMMENTS:		

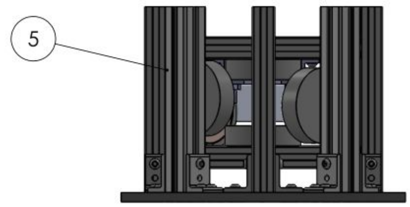
TITLE:
SOLENOID

SIZE A | DWG. NO. SOL1 | REV
SCALE: 1:8 | WEIGHT: | SHEET 6 OF 19

2 | 1







NOTE:
40MM T-SLOTTED FRAMING RAILS TO HOLD SOLENOIDS

ITEM NO.	PART NAME	QTY.
5	40MM T-SLOTTED FRAMING RAILS	4
	M8 SCREWS	4

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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
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MFG APPR.		
Q.A.		

COMMENTS:
MCMASTER-CARR PART (5537T507)

TITLE:
40MM T-SLOTTED FRAMING RAILS

SIZE A | DWG. NO. TB40-10 | REV

SCALE: 1:8 | WEIGHT: | SHEET 7 OF 19

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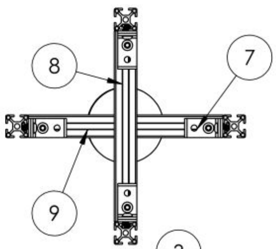
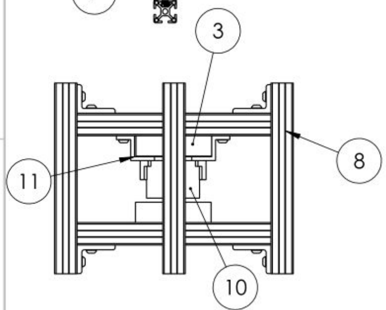
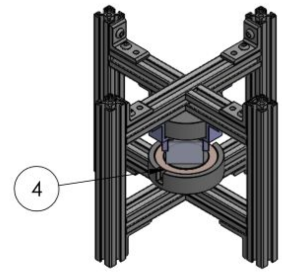
2 1

B B







ITEM NO.	PART NAME	QTY	DESCRIPTION
3	SOLENOID	2	SOLENOID AND WIRE
4	COIL	2	
7	CORNER BRACKET	8	1IN
8	30MM T-SLOTTED FRAME 10IN	6	10IN
9	30MM T-SLOTTED FRAME 4.5IN	4	4.5IN
10	WORKSPACE	1	50MM X 50MM X 50MM
11	WORKSPACE SUPPORT	1	PLA; 3D PRINTED

A A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH

	NAME	DATE
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CHECKED	TANNER HANSON	3/12/2021
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

TOP / BOTTOM SUBASSEMBLY

SIZE A DWG. NO. TBS1 REV

SCALE: 1:1 WEIGHT: SHEET 8 OF 19

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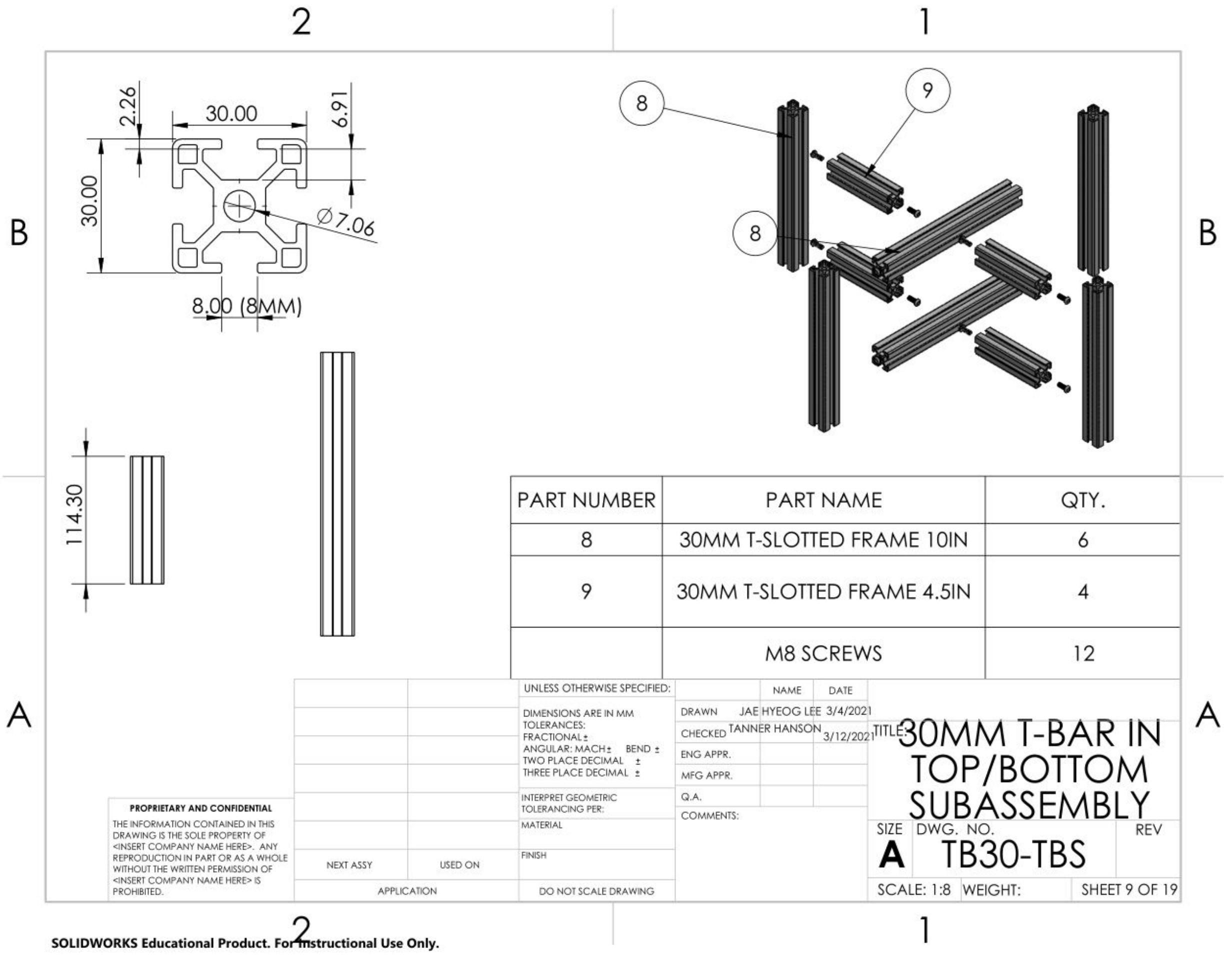
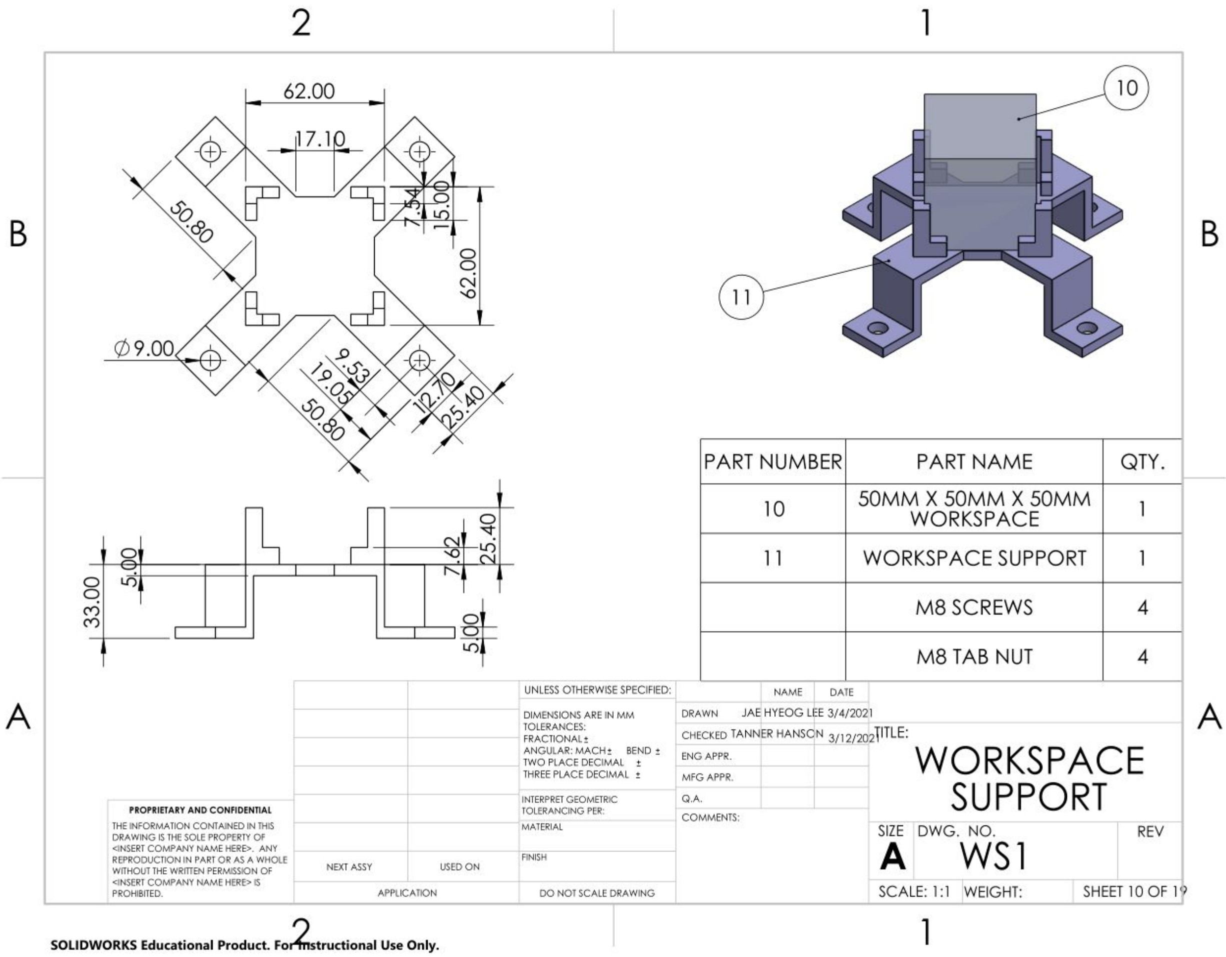
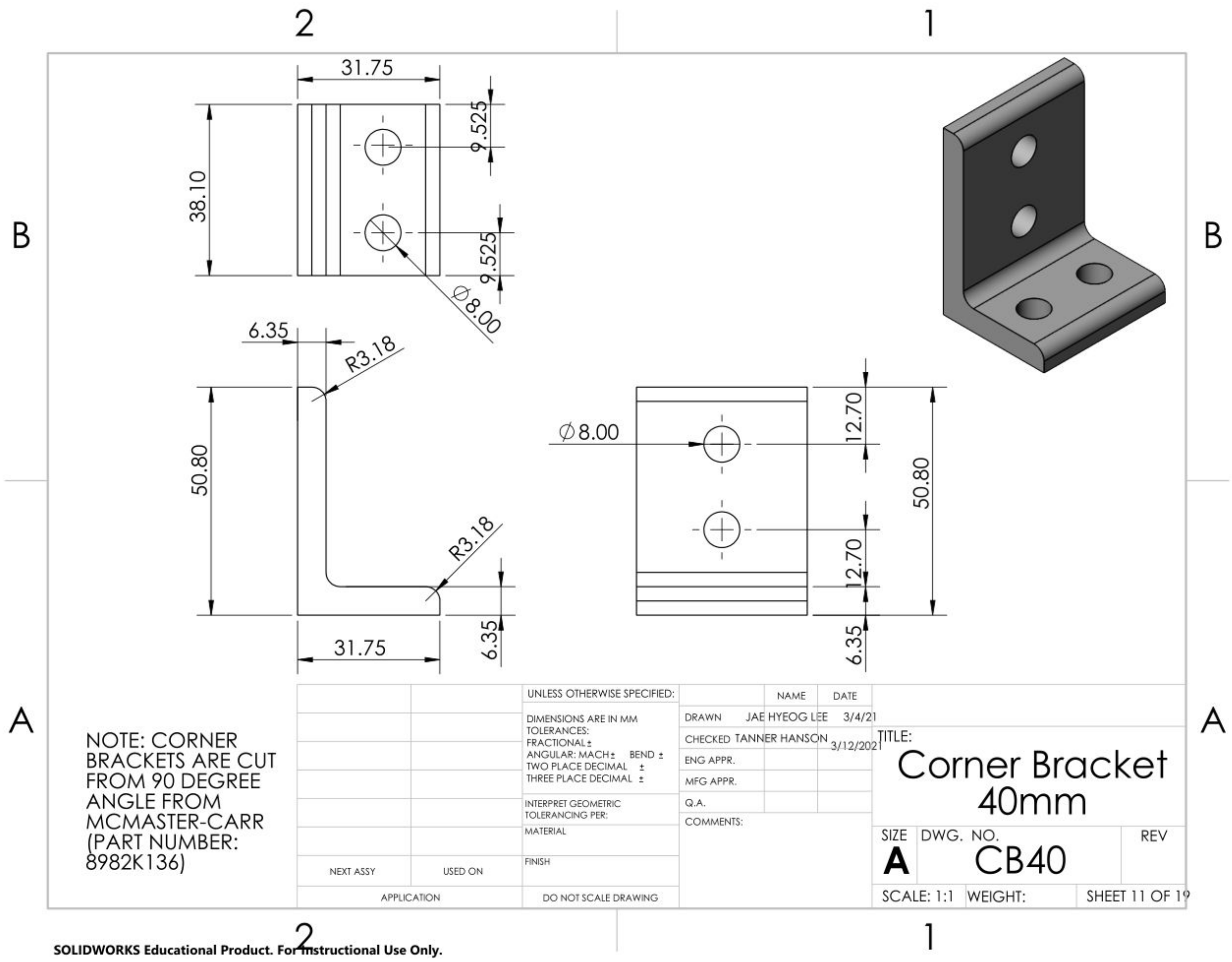


PART NUMBER	PART NAME	QTY.
8	30MM T-SLOTTED FRAME 10IN	6
9	30MM T-SLOTTED FRAME 4.5IN	4
	M8 SCREWS	12



PART NUMBER	PART NAME	QTY.
10	50MM X 50MM X 50MM WORKSPACE	1
11	WORKSPACE SUPPORT	1
	M8 SCREWS	4
	M8 TAB NUT	4



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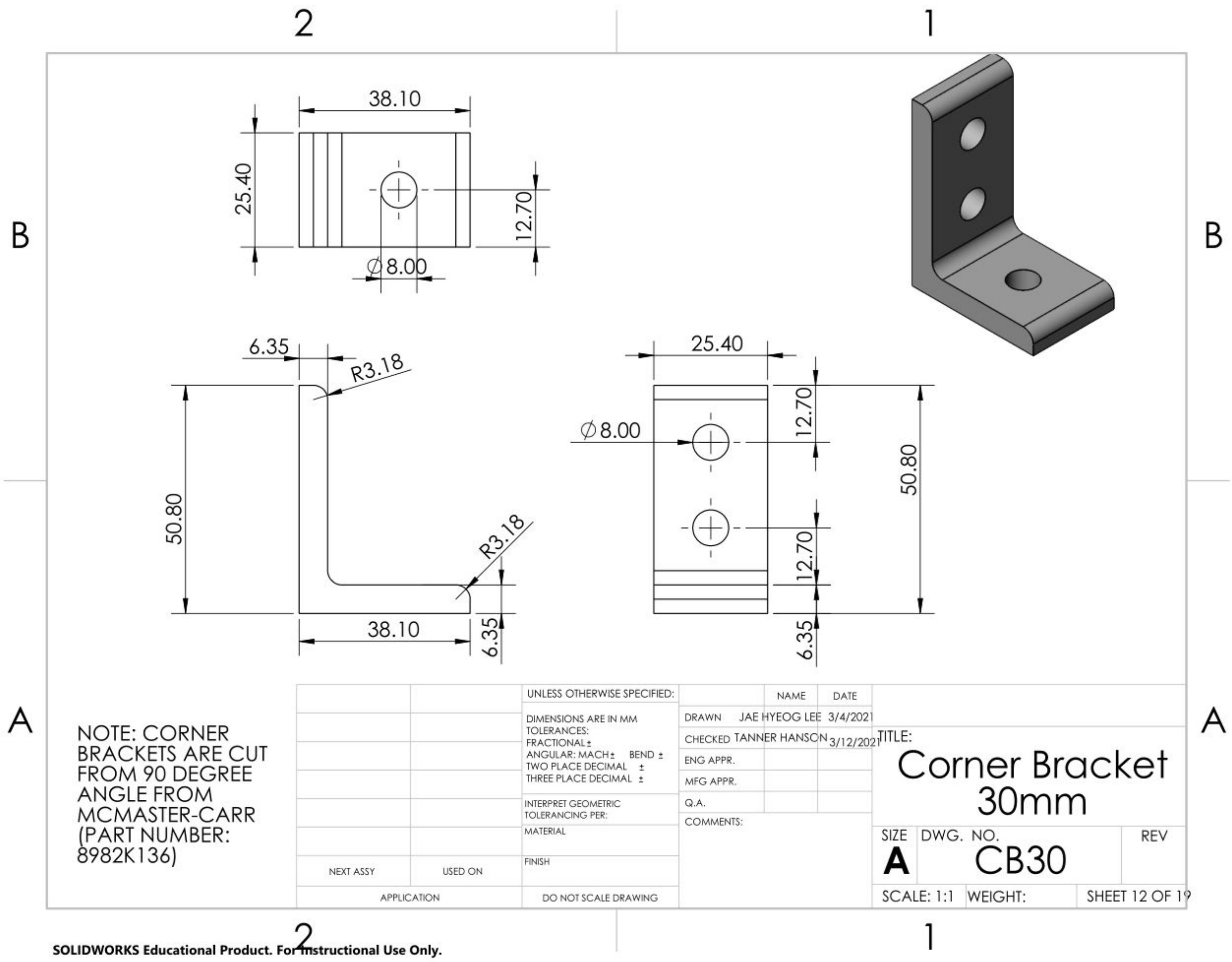
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25.40
12.70
⌀8.00
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R3.18
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R3.18
38.10
6.35
25.40
⌀8.00
12.70
50.80
12.70
6.35
NOTE: CORNER BRACKETS ARE CUT FROM 90 DEGREE ANGLE FROM MCMASTER-CARR (PART NUMBER: 8982K136)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
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DO NOT SCALE DRAWING
NAME
DATE
DRAWN JAE HYEOG LEE 3/4/2021
CHECKED TANNER HANSON 3/12/2021
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Corner Bracket 30mm
SIZE A
DWG. NO. CB30
REV
SCALE: 1:1
WEIGHT:
SHEET 12 OF 19
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2 1

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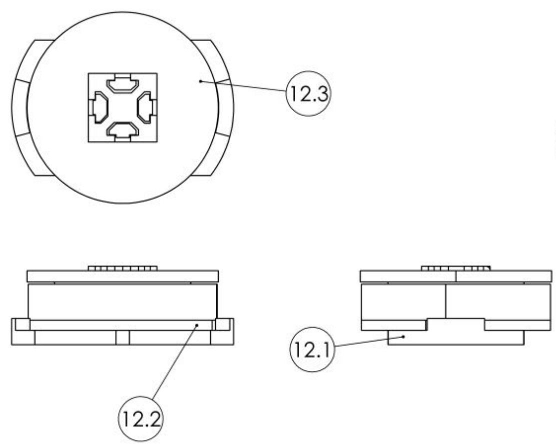

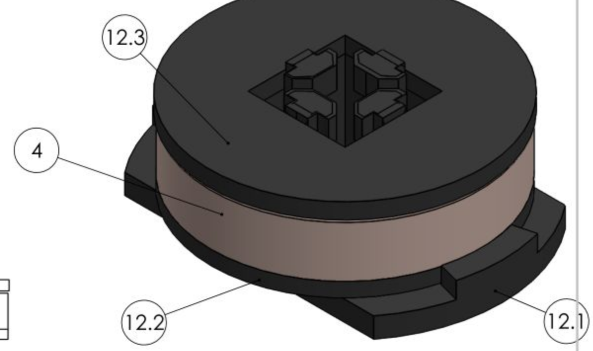

General Table		
ITEM NUMBER	PART NUMBER	QTY
12.1	COIL WRAPPER BASE	1
12.2	COIL WRAPPER RING	1
12.3	COIL WRAPPER TOP	1
4	COIL	1

A A

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DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

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MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
SOLENOID COIL WRAPPER

SIZE A | DWG. NO. CW1 | REV

SCALE: 1:2 | WEIGHT: | SHEET 13 OF 19

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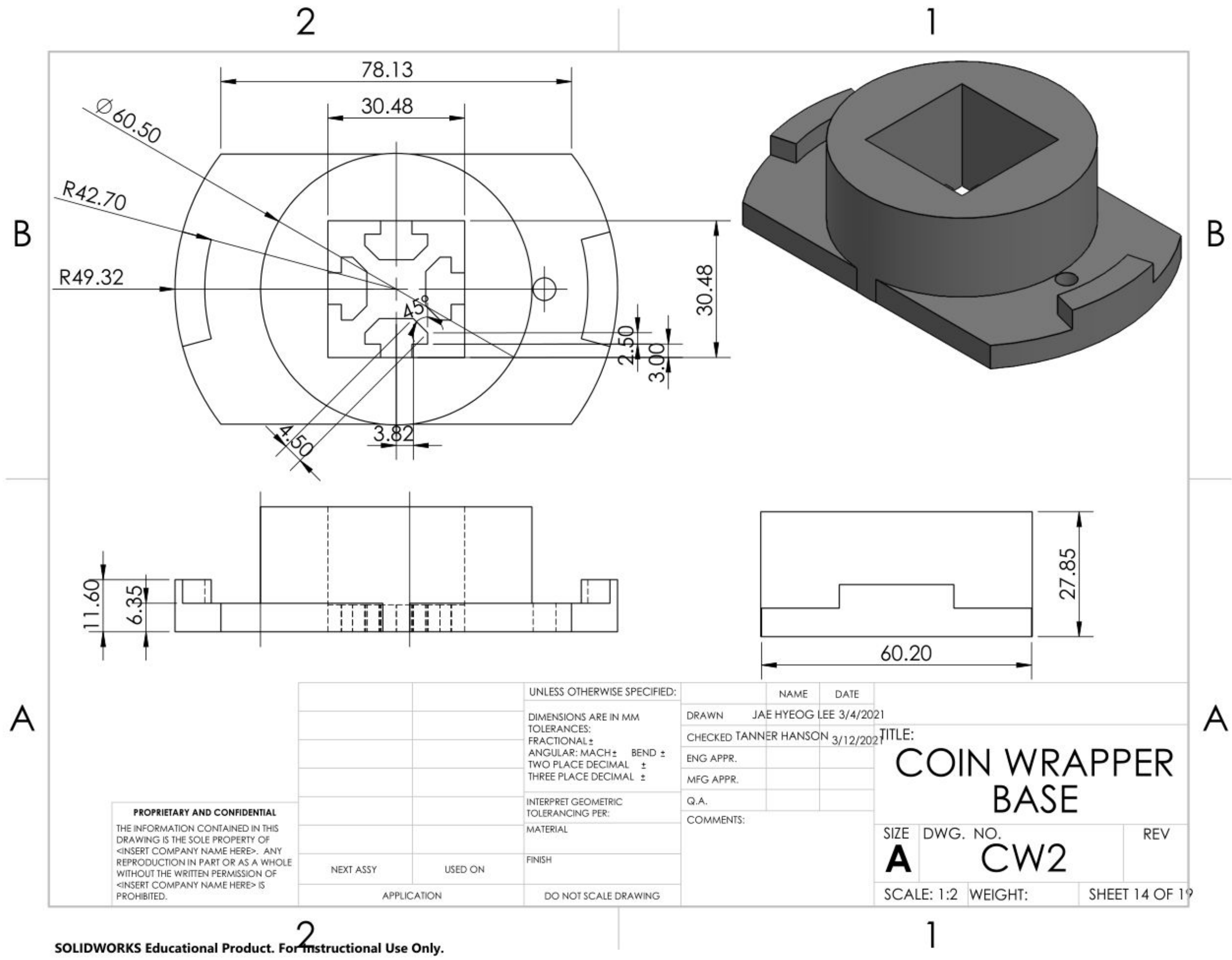

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∅60.50
R42.70
R49.32
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2.50
3.00
4.50
3.82
11.60
6.35
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60.20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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TOLERANCING PER:
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DATE
DRAWN JAE HYEOG LEE 3/4/2021
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
COIN WRAPPER BASE
SIZE A
DWG. NO. CW2
REV
SCALE: 1:2
WEIGHT:
SHEET 14 OF 19
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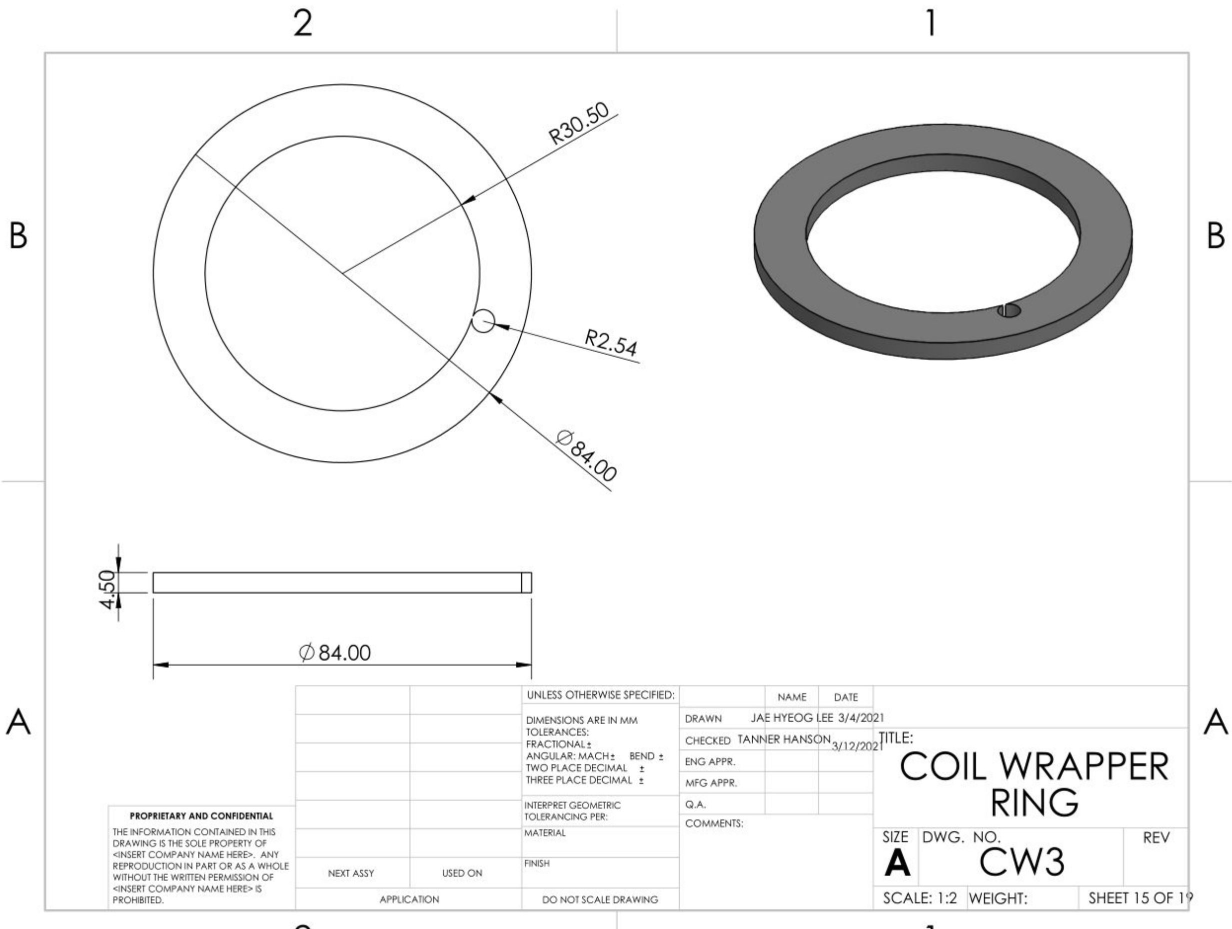

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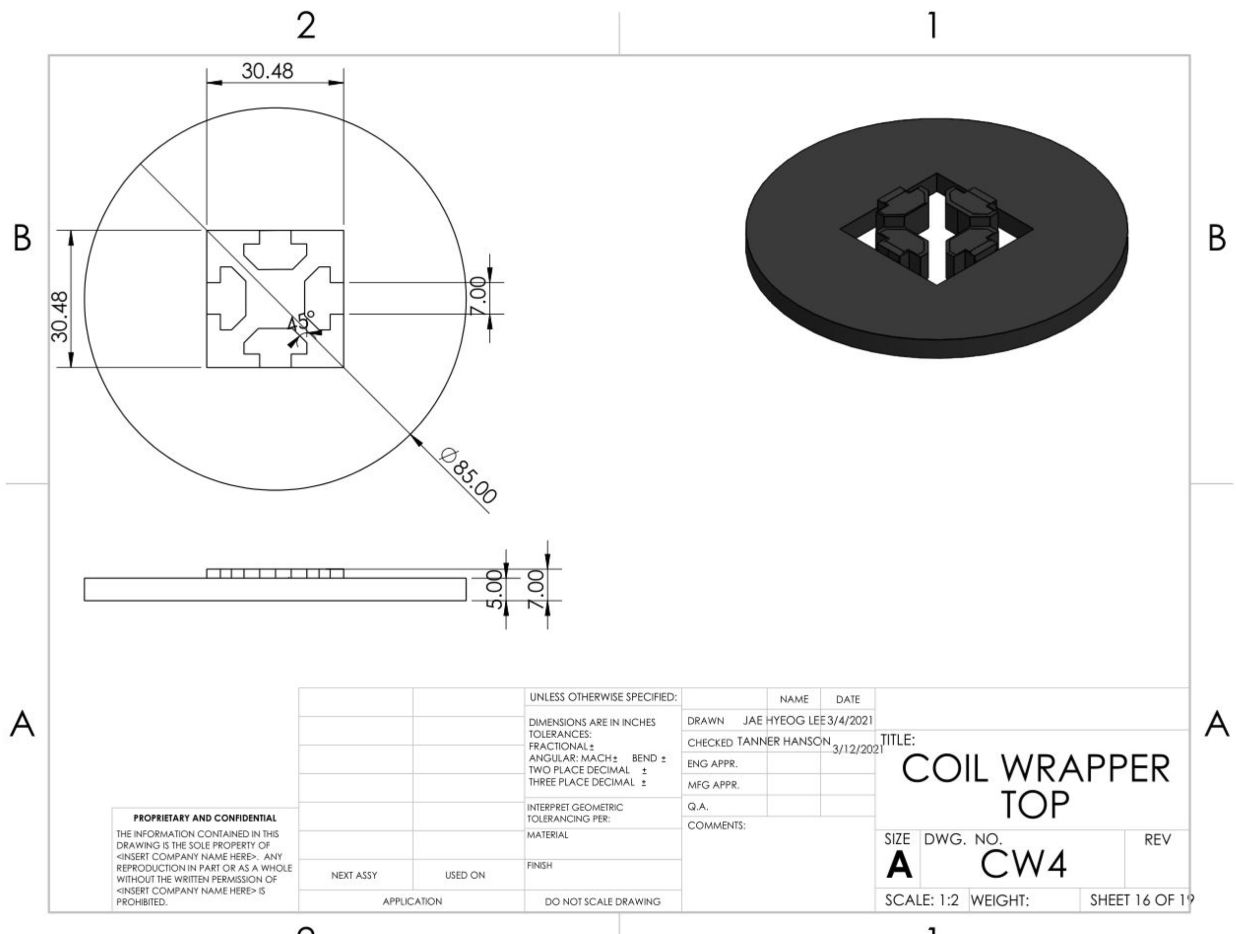

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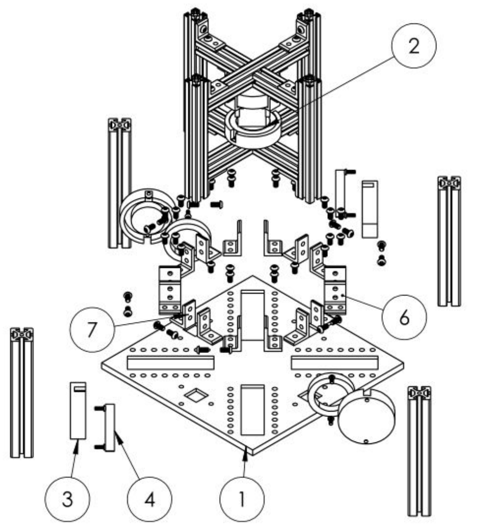

ITEM NO.	PART NAME	QTY.	DESCRIPTION
1	BASE PLATE	1	15IN X 15IN X 0.5IN
2	TOP AND BOTTOM SOLENOID ASSEMBLY	1	TOP AND BOTTOM SOLENOID ASSEMBLY
3	TRANSFORMER SOLENOID	4	
4	COIL	4	
5	40MM T-SLOTTED FRAME 10IN	4	
6	1.5 INCORNER BRACKET	8	USED FOR 40MM T-FRAMING RAILS
7	1IN CORNER BRACKET	11	USED FOR 30MM T-FRAMING RAILS
	M8 SCREWS	40	USED FOR CONER BRACKETS
	M6 SCREWS	8	USED FOR SOLENOIDS

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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

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MFG APPR.		
Q.A.		

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TITLE:
3D MAGNETIC CONTROL SYSTEM EXPLODE VIEW

SIZE A DWG. NO. DAS2 REV

SCALE: 1:16 WEIGHT: SHEET 17 OF 19

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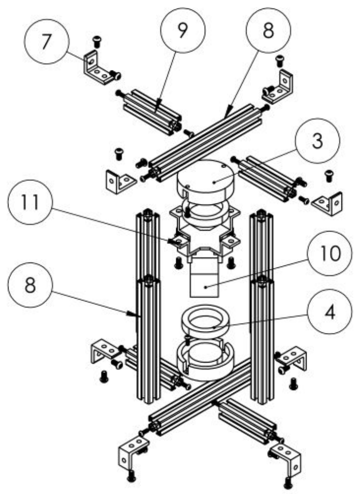
B B



ITEM NO.	PART NAME	QTY	DESCRIPTION
3	SOLENOID	2	SOLENOID AND WIRE
4	COIL	2	
7	CORNER BRACKET	8	1IN
8	30MM T-SLOTTED FRAME 10IN	6	10IN
9	30MM T-SLOTTED FRAME 4.5IN	4	4.5IN
10	WORKSPACE	1	50MM X 50MM X 50MM
11	WORKSPACE SUPPORT	1	PLA; 3D PRINTED
	M6 SCREWS	16	WORKSPACE SUPPORT
	M6 FASTENER	16	WORKSPACE SUPPORT
	M8 SCREW	20	CORNER BRACKETS / SOLENOIDS
	M8 FASTENER	20	CORNER BRACKETS / SOLENOIDS

A A

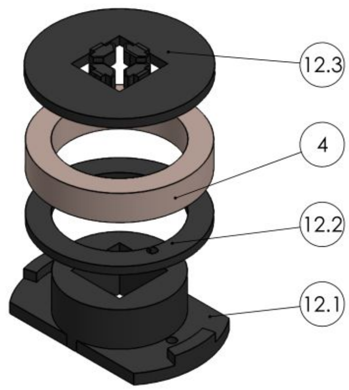
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY | USED ON
APPLICATION | DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JAE HYEOG LEE	3/12/2021
CHECKED	TANNER HANSON	3/12/2021
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:
TOP BOTTOM SUBASSEMBLY EXPLODE VIEW

SIZE A | DWG. NO. TBS2 | REV
SCALE: 1:12 | WEIGHT: | SHEET 18 OF 19

2 1



ITEM NUMBER	PART NUMBER	QTY
12.1	COIL WRAPPER BASE	1
12.2	COIL WRAPPER RING	1
12.3	COIL WRAPPER TOP	1
4	COIL	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JAE HYEOG LEE	3/12/2021
CHECKED	TANNER HANSON	3/12/2021
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY | USED ON
APPLICATION

TITLE:
COIL WRAPPING JIG
EXPLODE VIEW

SIZE A | DWG. NO. CW5 | REV

SCALE: 1:8 | WEIGHT: | SHEET 19 OF 19

A.6: Team 5 GitHub

The team's GitHub contains all of the team's relevant software and CAD files and can be accessed at this link: https://github.com/MAE-156B-3D-Magnetic-Control-System.