

Robotic Electrical Control Testing Universal Module

Senior Design Report submitted to the
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College of Engineering and Applied Science
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requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

Wesley Engle, Evan Sotzing, Ryan Sullivan

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Thesis Advisor:

Dr. Janet Jiaxiang Dong

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Problem Statement

We were looking to create a robot capable of testing live electrical cabinets by extending a probe to connect internal components so that maintenance crews do not have to risk their lives and equip a full arc flash protection suit as stated by NFPA 70E Article 130 safety regulations. Such a robot would ideally be capable of resizing to fit different dimensional electrical boxes while retaining identical functionality. Two separate connectors would be attached at any one time, allowing for the testing of current, voltage, and continuity throughout the cabinet.

Research

Background of the Problem

In industrial settings, breakdowns and repairs are an incredibly common occurrence. Sometimes motors seize up, sensors fail, or one of a thousand electrical components goes bad. Our design project aims to alleviate the stress of locating component problems while providing comfort and safety to workers. Currently, large electrical cabinets are set up in factories to hold all the electrical components to prevent any workers from harming, or being harmed by them. When contractors have to fix something in these cabinets, they must wear up to a category 4 arc flash protection suit that can cost upwards of several thousand dollars [1]. While this may not seem like a large issue in the short-term, it's extremely difficult to test components while the cabinet is off, and if a live cabinet has to be tested a dozen times throughout the day, a contractor has to put on and take off the suit for a test that may only last a couple of seconds. Since humans are not allowed to reach into live electrical cabinets without thorough safety preparation, our goal was to design a robot that can latch to the door of a cabinet and insert probes to the electrical components to provide safety for the operators and save time on testing.

State of the Art

Wesley Engle:

Current state of the art technology is lacking in solving this problem as contractors are required to use hand-held multimeters to test electrical cabinets. For our initial conceptual ideas, most individual parts already exist but combining them will present the biggest challenge. My initial role for this project was to find an xy method of travel that can be implemented into a robot for the most effective movement. For the first x and y movement across the face of the cabinet, CoreXY [2] movement seemed the most promising as it presents fewer motor setup with just as much flexibility as a 4 motor system, although heavier on the coding aspect to properly implement. With the use of two slides set to the left and right of the frame, full movement was

technically possible. In addition, if roller chains are used to connect all the components then this setup can be placed on any cabinet and then resized to fit exactly what's needed.

In a simpler method of travel, linear actuators have been used for a long time in order to achieve easy travel in a single axis. With two linear actuators perpendicular to each other, travel across the entirety of the face of the cabinet can be achieved. While these actuators are easy to program and implement from a design perspective, they're fairly costly and must be very close fitting to the cabinet's size, otherwise they'll begin to encroach on space required for other components. On top of this, they take up more space in the z direction than other methods.

Finally is the linear rail system where rubber tires are attached to motors that grant controlled travel along a uniform surface. With two rails attached perpendicular to each other, similar to the linear actuator method mentioned above, xy travel can be achieved. With this method, the linear rail system is restricted by being unable to resize to different cabinets. The linear rail system is also significantly cheaper when compared to exceptionally lengthy linear actuators and roller chains.

Evan Sotzing:

Originally, my role was to determine how to incorporate the voltmeter into the robot design, but since the customer has decided to use a standard voltmeter setup my component of the project has changed. Now my component for this project was to create a wireless display and controller to analyze the data collected from the voltmeter, control/move the XY assembly, and display a camera input. To make the most ergonomic device the customer can use there are a few options. For a wireless display we wanted to have a free range of movement of approximately 30 ft from the device inside the cabinet.

One setup for this wireless control system consists of a plate with a magnetized back to attach to the front of the cabinet door. This will give the operator a "hands-free" device that they will not need to carry or hold during the servicing. With the controls attached by a magnet to the door the operator can move the device to wherever it is most convenient to use and operate. This setup is great for keeping the operators out of the cabinet, having easy mobility for setup and use of the controls. The materials needed for this device would be minimal as it needs to case the internals of the controls and be light enough to pick up and move on the cabinet. For a fully mobile device the controller can be set up on a stand that can move with the operator.

This setup offers a system that the operator will not need to carry and will hold any tools that may be needed for the servicing of the electrical cabinet. This setup can be made to be adjustable depending on the height of the operator or fixed if requested by the customer. With the use of wheels this design can be very mobile on the shop floor while keeping the operator away from the servicing of the electrical cabinet. From a design standpoint, this set-up would be the costliest as it includes the wheel and the material for the stand to hold the controls system.

Finally, is a device that is to be worn by the operator performing the servicing on the electrical cabinet. This device would be worn using some sort of strapping method to attach to the operator based on size and build. With the device being off the cabinet and easily controlled by the operator this is a great setup to provide safety to the operator. This set-up will be roughly the same as the magnetized system due to the use of a similar build for the controls.

Ryan Sullivan:

As one of the main controlling points in this robot, the robotic arms will be pivotal to the robot's success. The robotic arms should be relatively small, lightweight, sturdy, extendable, easily maneuverable, and for this application, resistant to electricity. Based on the research done, there are not really any robotic arms in existence that fit the description of what we need for this project. The closest example found during research were these manipulator arms made by Kraft Telerobotics for an electrical utilities repair robot. The robot is designed to allow an operator, who sits in an insulated cab, to remotely repair live electrical distribution lines. With the integration of two Kraft force feedback manipulator arms, the Iberdrola robotic system "ROBTET" is designed to complete remote maintenance and repair work on distribution networks up to 49kV. [3] There are some similar problems that the robotic arms built by Kraft addresses. Some of the pros of this current technology are that it is remotely operated, fully insulated, and designed to work on live electrical wiring, and it seems very sturdy. These are all aspects that we can draw inspiration from for our designs. Some of the cons of Kraft's robotic arms are that they are a bit oversized for our application and seem a bit bulky. They also have a much different mounting configuration than what we will need. Their arms are mounted to a large cab, whereas ours will need to be mounted to a much smaller, more mobile frame. There wasn't much information published about the details of their design, but it can be assumed that their control systems will be much different than ours as well.

The second product I researched when looking for other solutions to our robot arm problem isn't really a product at all. It is a telescoping robot arm that a student did for a robotics competition in 2019. There isn't much information available on it, but the design and controls are very similar to what was initially imagined for this robot. It is a telescoping design, which is pretty much required due to our space constraints. The major difference between the researched robotic arm and the robotic arm we will design is the end tooling. On the researched arm, there is a grabbing tool, whereas ours will be an electrical testing probe. There isn't much need for the robot to bend in any other direction, it will just need to move inwards and outwards. The other features of the researched robot that are similar to what we are trying to achieve are its simple motion, lightweight, compact, small mounting area, and easy control. Some of the cons of this design are that it's a bit too big for our application, it doesn't have the right end of arm tooling, and it has extra joints (including a rotational joint) that isn't needed for our design. [4]

The last point of research for the robotic arms was the MERA robot system developed by MIT research engineer Seiichi Teshigawara. [5] MERA stands for the Mobile Extendable Robot Arm and has a number of different possible applications including the maintenance and inspection fields. It consists of two different scissoring extendable arms, so it can reach in tight spaces. The pros from this design are that it has a creative extendable arm system that can be applied to our problem. It also can be used in the same field as our robot will be deployed in, but to solve a different problem. The cons of this solution are that it is much too big, bulky, and complex for our requirements. Its conceptual design could be used for inspiration for our design, so it is worth taking into account and researching more.

Applicable Standards

All standards that will have to be adhered to are listed in the OSHA issued NFPA 70E: Standards for Electrical Safety in the Workplace. This document is focused upon the safety of human workers, and will be useful for assembly and disassembly of the robot. [1]

End User

Our end users will be the maintenance staff that will attach and control the robot, the engineers that can use the readings to create design changes as necessary, and the plant owners as this tool will provide a safe avenue for testing leads without the worry of harming personnel.

Summary of Research

Wesley Engle

Currently, no product exists to perform the tasks outlined above, though individual products can be combined to solve this problem. With the correct usage of xy travel in my part of the design, I have achieved an xy travel system that can fit compactly into tight spaces and is capable of adapting for any size cabinet while following all OSHA standards. While multiple different methods of travel currently exist, CoreXY holds the most promise in my eyes for an easy to adjust and compact travel method given a significant amount of prototyping, while linear actuation provides the most straightforward method of travel

Evan Sotzing:

With the ability to incorporate a control system that works wirelessly to keep the operators servicing the electrical cabinets, It's possible to keep the operators away from any possible arc flash. This device will help workers stay safe while following all of the OSHA standards. While there are many ways to incorporate these controls, a handheld system seems best.

Ryan Sullivan:

The first step to addressing the problem of the robotic arms will be to identify the main functions the robot needs to perform. We decided that the arms will need to extend and retract, while supporting a wrist/hand assembly that will be in charge of grabbing/moving the electrical probes from location to location. This means the arms will need to have enough structural support to hold out the entire wrist assembly at full length. Along with the other requirements such as being lightweight, maneuverable, and ensuring we stay within the safety measures, [1] we have a fairly strict set of criteria. Making sure the design for the arms meets all the criteria is important to achieving our goals and ensuring a good product for our end users. If the robot's arms are too clunky or stiff, they will be more difficult to control for the operators. First, more research and ideation will need to be done to collaborate successfully with the wrist assembly and the mounting box, as well as how the arms will extend and retract. Once we know how much weight the arms will need to support, we can begin adjusting our 3D models and selecting materials to ensure proper structural support. Our first 3D models drew lots of inspiration from the research done on Kraft's electrical utilities robotic arm, [3] and the competition robot design. [4] This gave us a good starting point and first direction as we continued through the design phase.

Quality Function Deployment

The questionnaire sent to our funding company, Industrial Technology Solutions, came back with the following information as our desired features:

Customer Features

- Must be able to be fully enclosed in the cabinet
- Must be easy to set up
- Must be remote controlled
- Easy to transport
- Check continuity, voltage, and current
- Provide adequate safety to operators
- Test up to 600V
- Be battery operated

Engineering Characteristics

- Lightweight (<25 lbs)
- Properly grounded
- Code compliant
- Bluetooth controlled (range of >15m)
- Camera System Control
- Extendable Probe (1' \geq extension)
- Compact (fits standard size of electrical cabinets)
- Interchangeable Battery (>2 hour run time)

Despite our best efforts to accommodate the features and characteristics, we were unable to complete our prototype with an interchangeable battery and instead opted to use a hard-wired method through the seal around an enclosure. In addition, we exchanged the use of a bluetooth control system for a plug-in controller.

Product Objectives

From our House of Quality our relative weights are:

Lightweight (<25 lbs) : 9.6

Properly grounded : 12.7

Code compliant : 15.5

Bluetooth controlled (range of >15m) : 14.3

Camera System Control : 14.3

Extendable Probe ($1' \geq$ extension) : 9.9

Compact (fits standard size of electrical cabinets) : 14.6

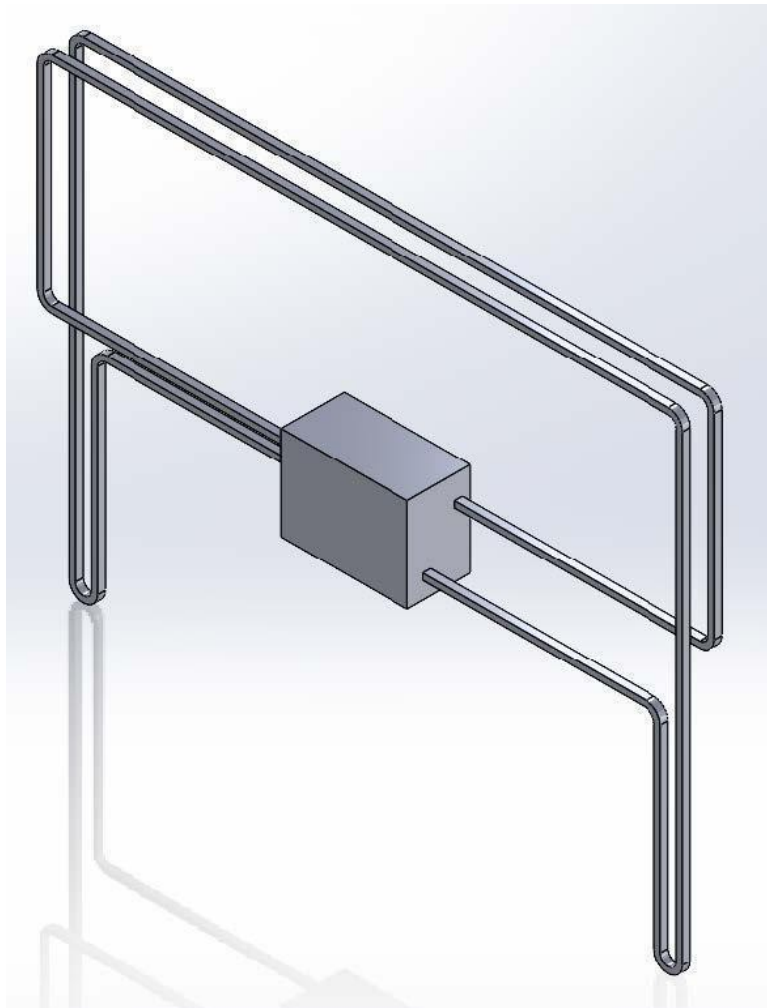
Interchangeable Battery (>2 hour run time) : 9.0

Concepts Drawings

Wesley Engle

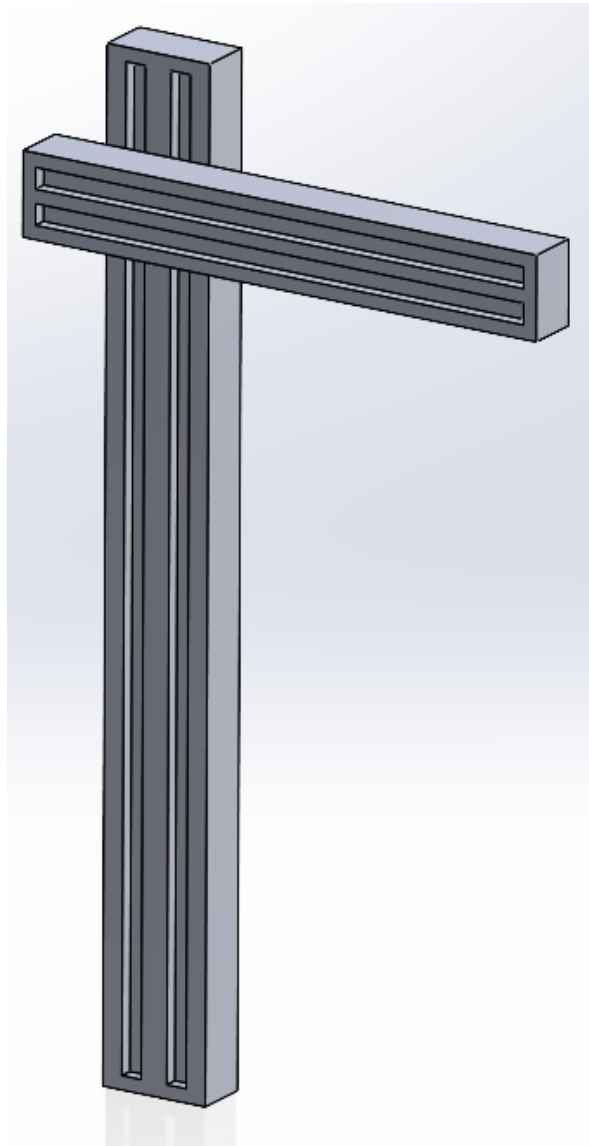
Concept 1: CoreXY

CoreXY[2] travel is a type of two motor control where complete x and y axis travel is possible. Given the limited space and the capacity for less components required, this method seemed most promising to me. Using roller chains, different heights and widths of cabinets can easily be adapted to and custom fit on-site. With the proper use of sprockets and guides, a tight configuration could have been achieved for minimal space being taken up.



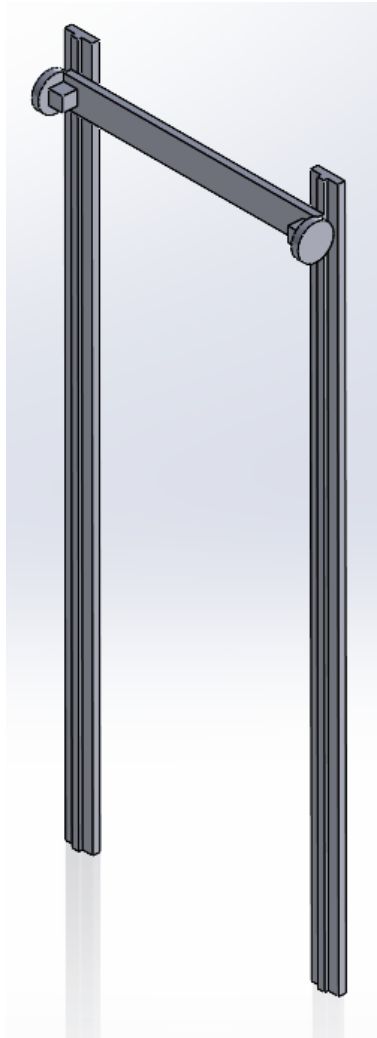
Concept 2: Linear Actuation

Linear actuator travel was the easiest method for xy travel, especially in terms of coding because its positioning can be much more easily calculated and adjusted for. This does leave much to be desired in terms of fitting it to other cabinets as there's very little that can be done for other cabinet sizes besides completely remaking or ordering linear actuators for specific cabinet sizes.



Concept 3: Magnetic Rail System

As opposed to the above concepts, this localized xy travel method was focused on being magnetically locked to the door of the cabinet and working within a pre-arranged work envelope as designed by my team. This configuration, while being relatively simple to design, does not allow access to the entirety of the cabinet and is reliant upon the pre-designed configuration to hopefully reach all the pieces that it needs to.

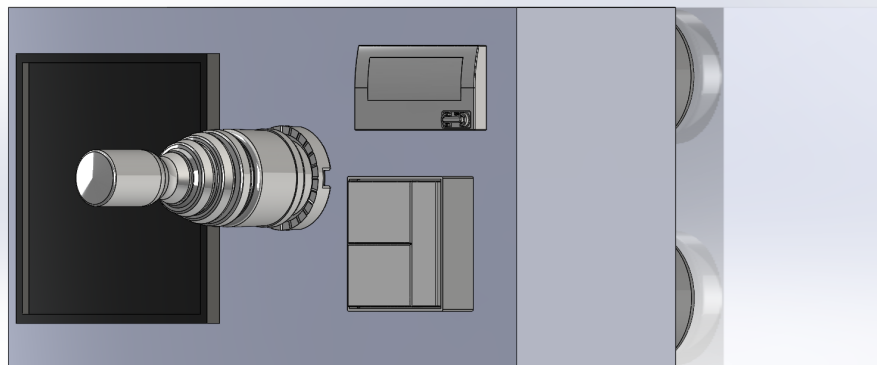


	Stability	Compactness	Adjustability	Weight	Ease of Installation	Total
Weight	0.15	0.15	0.3	0.25	0.15	1
CoreXY	2	4	5	3	2	3.45
Linear Actuation	5	1	3	2	4	2.9
Magnetic Rail	3	2	3	2	4	2.75

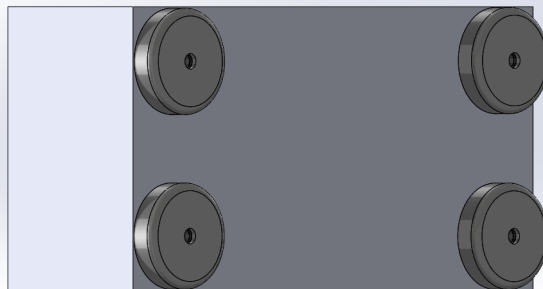
Evan Sotzing:

Concept 1: Magnetized Control Panel

This style of control design allows for the operator to place the device anywhere on a ferrous material to operate the robot inside the electrical cabinet. By using the magnets and having a lightweight design the controls could be moved easily and placed in various locations in the shop. This provides a hands-free controls system for the operators to use. This set-up uses minimal space to operate the machine.



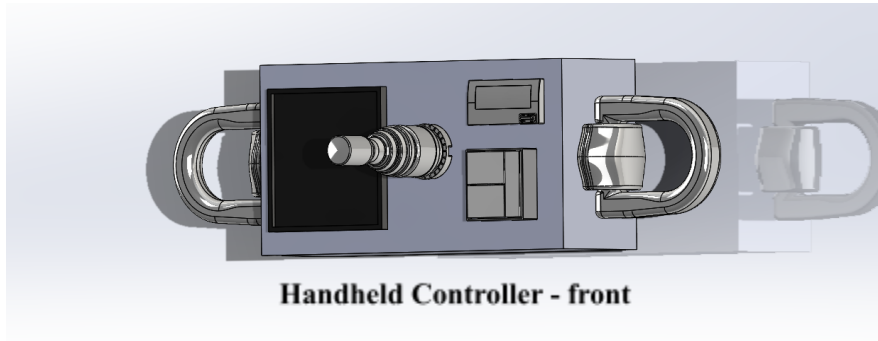
Magnetized Control Panel – front



Magnetized Control Panel - back

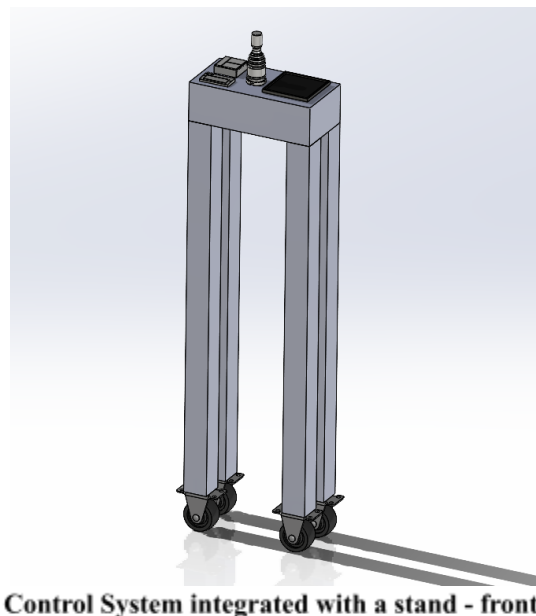
Concept 2: Handheld Controller

This handheld application was designed to be used with straps to attach to the operator. This gives the operator full mobility to move wherever within the bounds of the wireless capabilities. By taking the device off the machine and making it handheld creates a lightweight application that protects the operator from any possible arc flash or electrocution.



Concept 3: Control System integrated with a stand

As opposed to the above concepts, this design allows for mobility of the control system, and it is not necessary to hold/pick up the system. Trays and toolboxes can be integrated to help the operator with moving necessary tools to the workplace. This gives the system full-mobility and keeps the operator away from the cabinet.

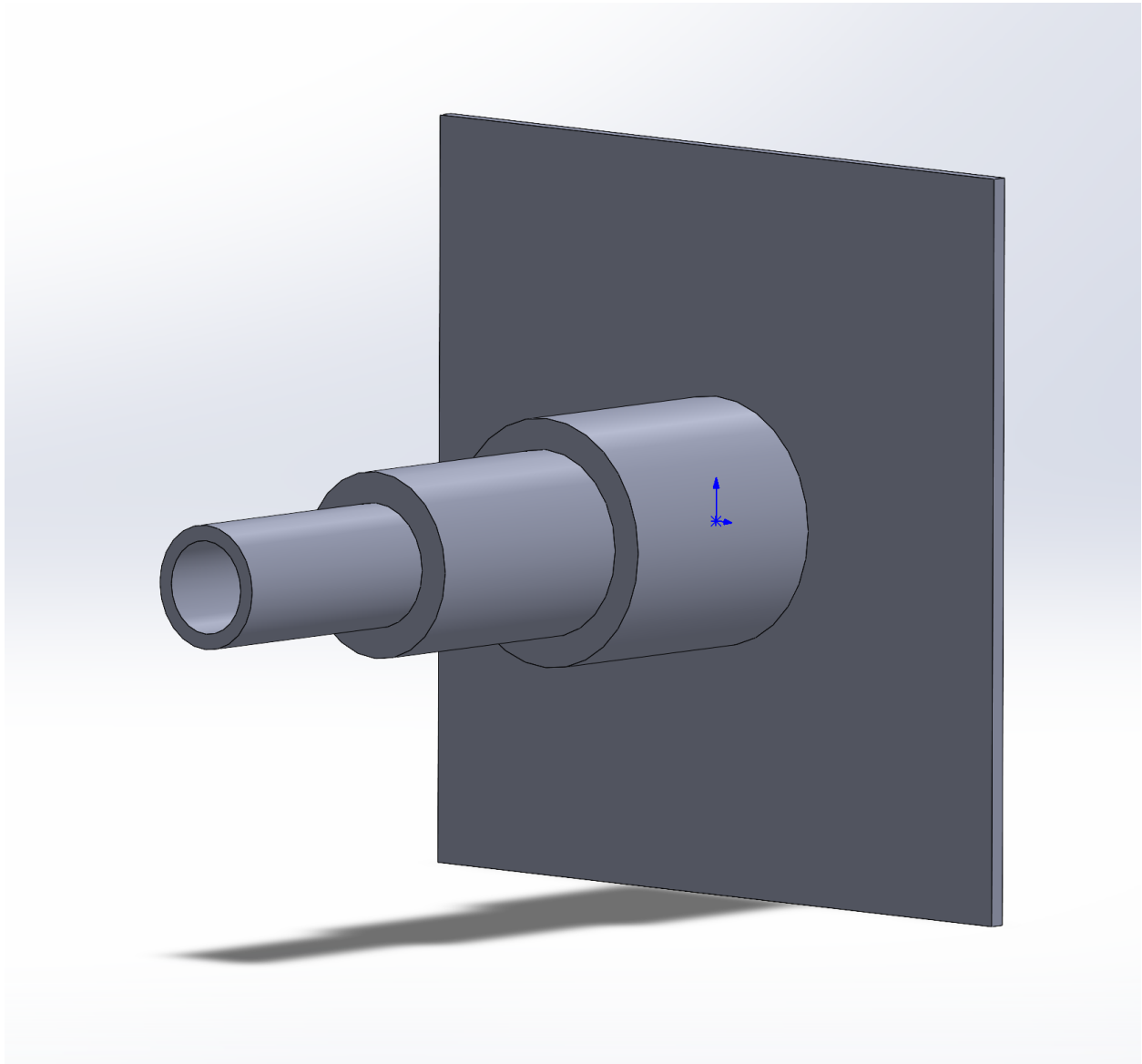


	Stability	Compactness	Mobile	Weight	Ease of Use	Total
Weight	0.15	0.15	0.3	0.25	0.15	1
Magnetic Control Panel	4	5	2	5	4	3.8
Handheld Control Panel	2	4	5	5	4	4.25
Standing Control Panel	3	1	4	2	3	2.75

Ryan Sullivan:

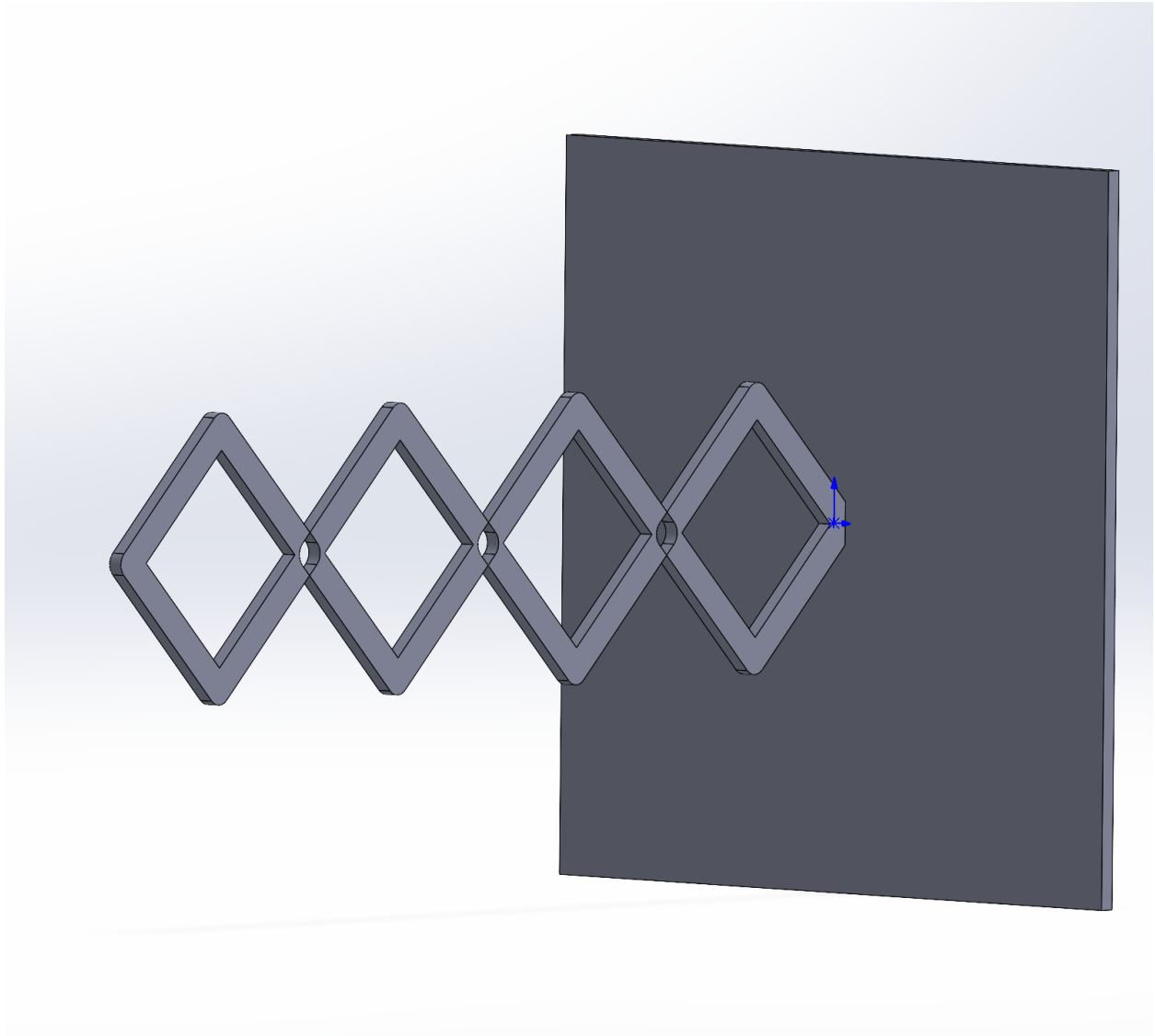
Concept 1 – telescoping cylindrical robotic arm

This design consists of three hollow cylinders that can move in and out of each other and can collapse down to a size that will be more manageable to move. The arm will be mounted on some sort of plate that will be incorporated with the XY travel system. This concept will allow the linear travel required as well as being compact.



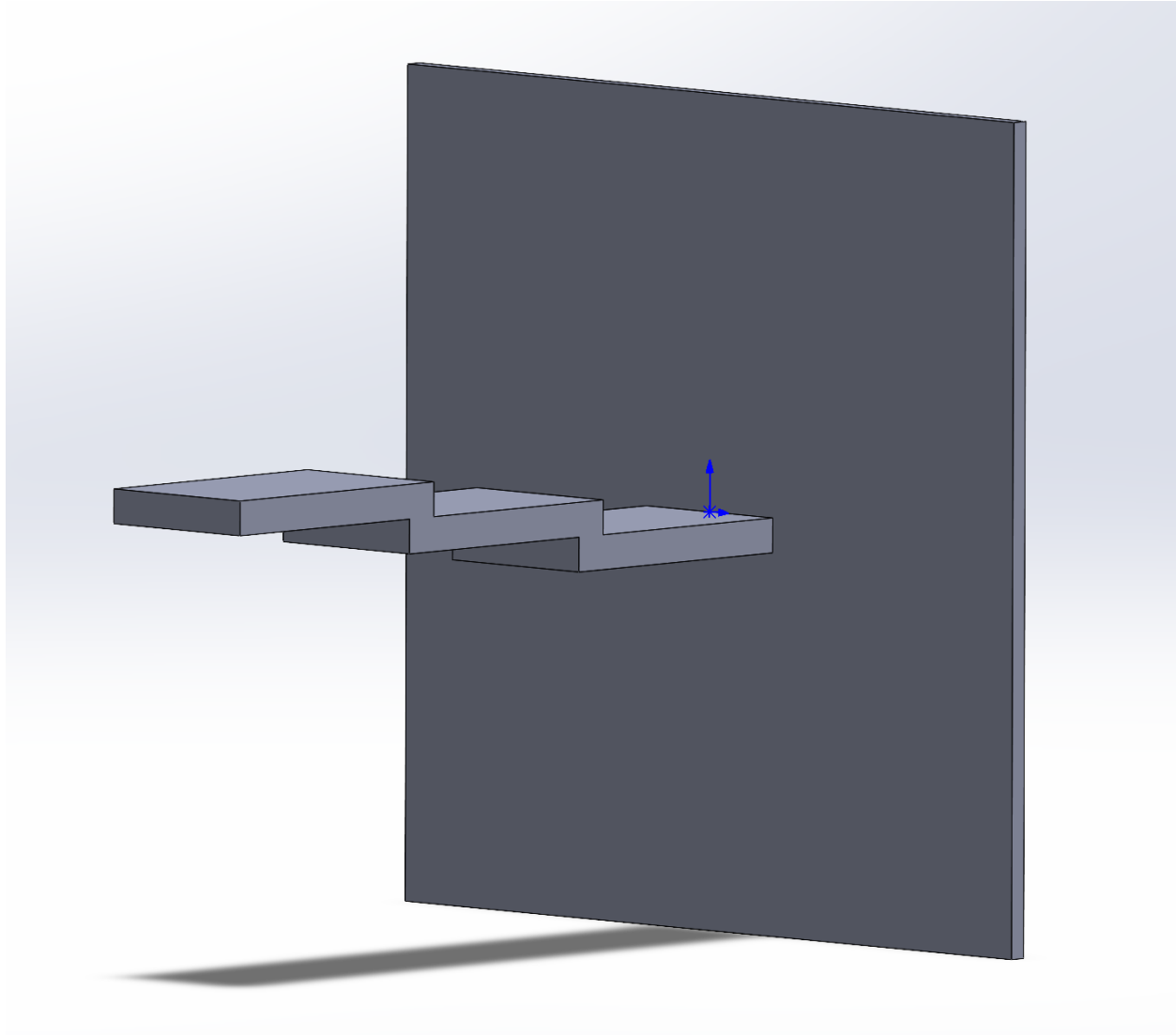
Concept 2 – scissoring extendable arm

This design concept features a standard linkage system that will allow the arm to extend in and out linearly. It is lightweight, simply controlled, and most importantly, compact.



Concept 3 – extendable block system

This concept consists of 3 identical blocks that will stack up on one another vertically. They can be deployed via tracks on the bottom and top with some sort of rack and pinion gearing system. It is simply controlled, compact, and will be sturdy enough to provide accurate probe usage.



Robot Arm Weighted Matrix	Stability	Compactness	Ease of Control	Weight	Accuracy	Total
Weight	0.15	0.25	0.2	0.25	0.15	1.00
Cylindrical Telescoping Arm	5	3	1	3	5	3.00
Scissoring Arm	2	5	5	4	3	4.00
Extendable Block Arm	4	3	2	3	4	3.00

Project Management

Project Budget Limit

\$2,000 initial funds

Key Milestones

Senior Design II: October 11, 2022

Presentation I: November 28th - December 2

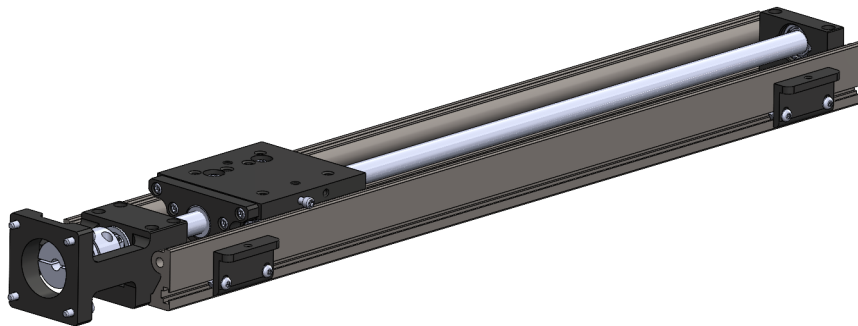
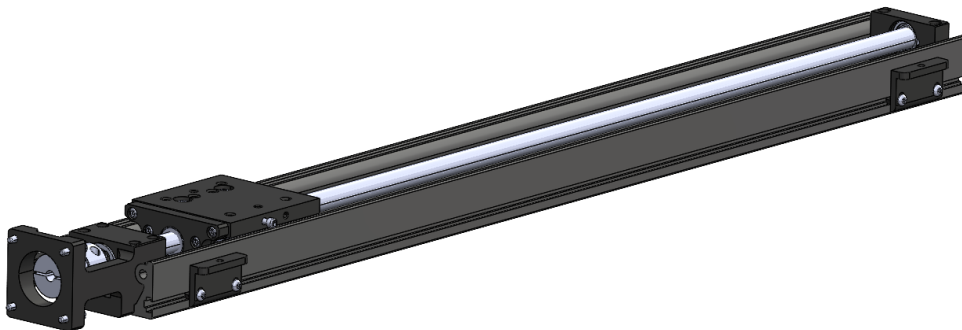
Senior Design III: January 9, 2023

Tech Expo: April 6, 2023

Component Selection

Linear Actuators -

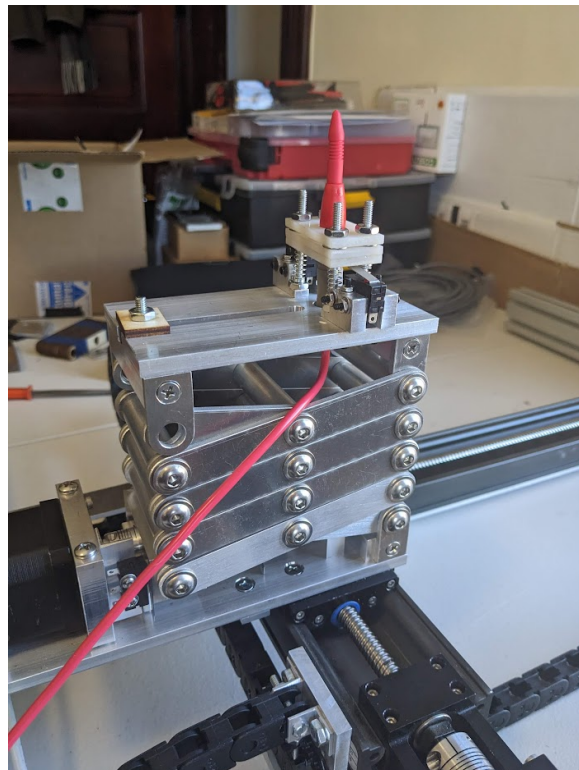
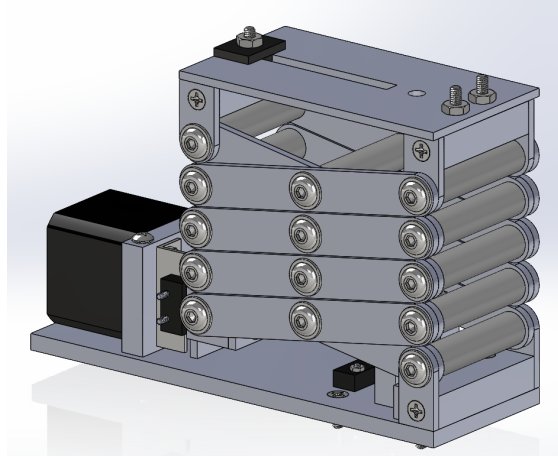
The two linear actuators chosen for this robot are the LAVL2-60T18LP5 (pictured first) and the LAVL2-60T12LP2 (pictured second). These two actuators are part of the same series and are both run by NEMA 17 stepper motors but have variations in their specifications while remaining highly precise and reliable. The T18LP5 has 18" of travel distance, weighs roughly 3.5 lbs, and has a pitch on the lead screw of 0.5". The T12LP2 has 12" of travel distance, weighs roughly 2.8 lbs, and has a pitch on the lead screw of 0.2". This gives the vertical actuator faster travel and the horizontal actuator more precision. Both actuators have nearly identical hole layouts and base design features.



Robot Arm -

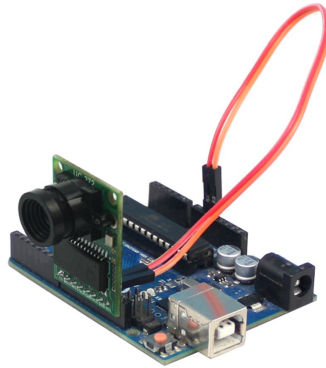
The original components for the robotic arm were chosen from a kit via an online supplier called MakeBlock. The kit features different size linkages and screws for the assembly of any part you desire. We were planning to make the scissoring robot arm from instructions provided by MakeBlock using the kit. The scissoring arm would be actuated by a small servo motor.

The actual robotic arm we used was custom designed to fit the size of the linear actuator and reach the 12" travel size. The material to create most custom pieces in this project was 6061 aluminum, with the probe holder being created from nylon.

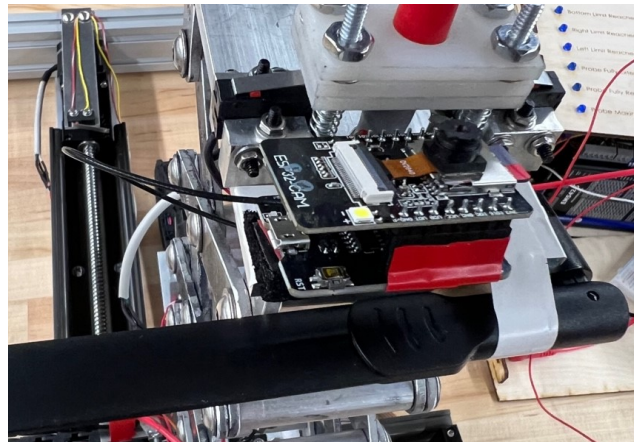
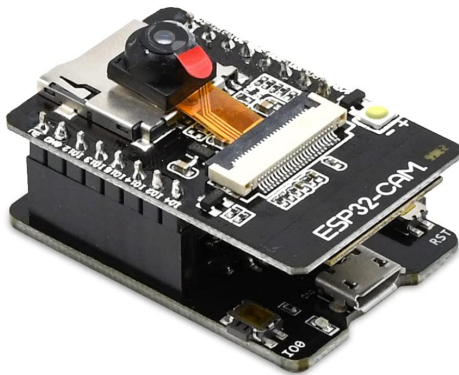


Camera Module -

The original camera module was designed to use an Arduino Uno Rev3 which would control an Arducam Mini Module to capture live video (pictured below). The original design was chosen because of the Arduino's low price, ease of use, and high compatibility with the rest of the project. Arduino products are very common in the industry, so using them for this project made sense. The controller and the rest of the robot were being developed on an Arduino Due board, so there was a strong motivation to keep the camera module Arduino-based. Therefore, many hours of research and development were spent to develop a working live camera feed running off of the Arduino Rev3 board.



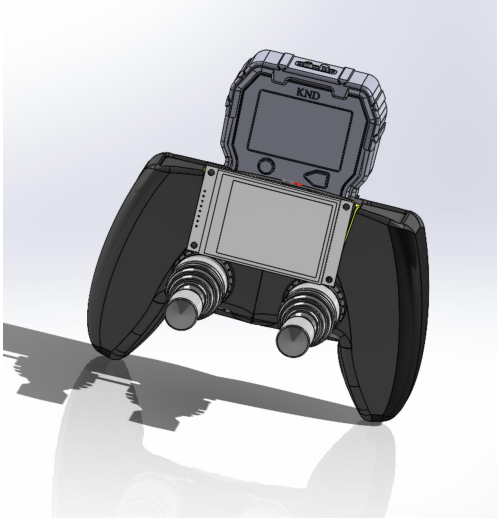
After a few design iterations, the final camera module chosen was the ESP32-CAM microcontroller made by Espressif (pictured below). The ESP32 board was selected for its small size, powerful microcontroller, video quality, and wireless capabilities. The ESP32-CAM module purchased came with a 2.4 GHz antenna and a USB programming adapter. The board comes pre-programmed, but modifications were made, including adding a 16 GB SD card from SanDisk, to improve performance. It uses the antenna provided to transmit live video to a nearby device (either a cellphone or a computer) that is connected to its Wi-Fi access point.



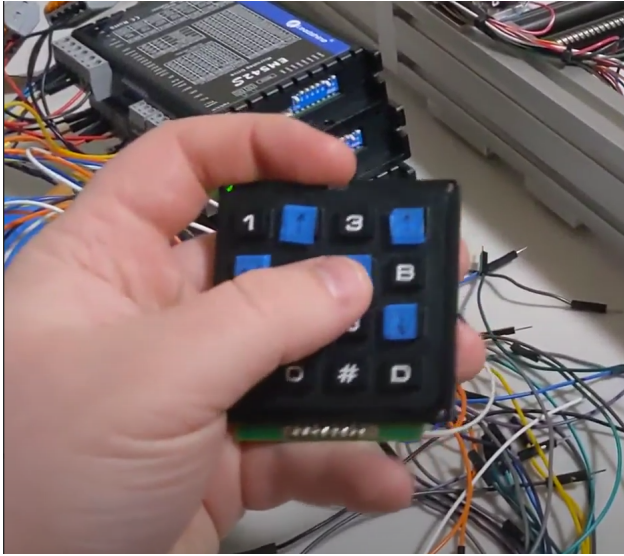
Controller -

The original controller was composed of a bluetooth of a Arduino Nano 33 BLE, a Digikey capacitive LCD screen, two McMaster-Carr analog joy-stick actuators, and the Fluke 233 Remote Display Multimeter. The use of these components was common so it made sense to the development of the device.

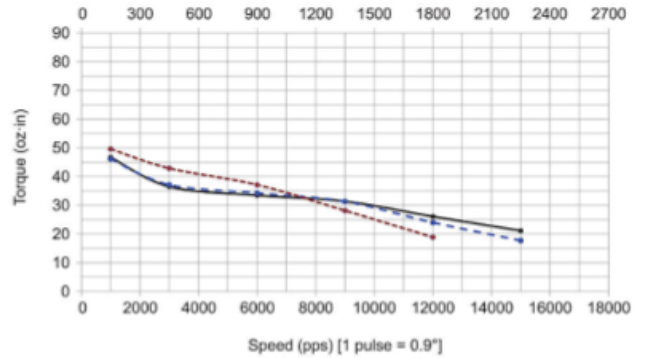
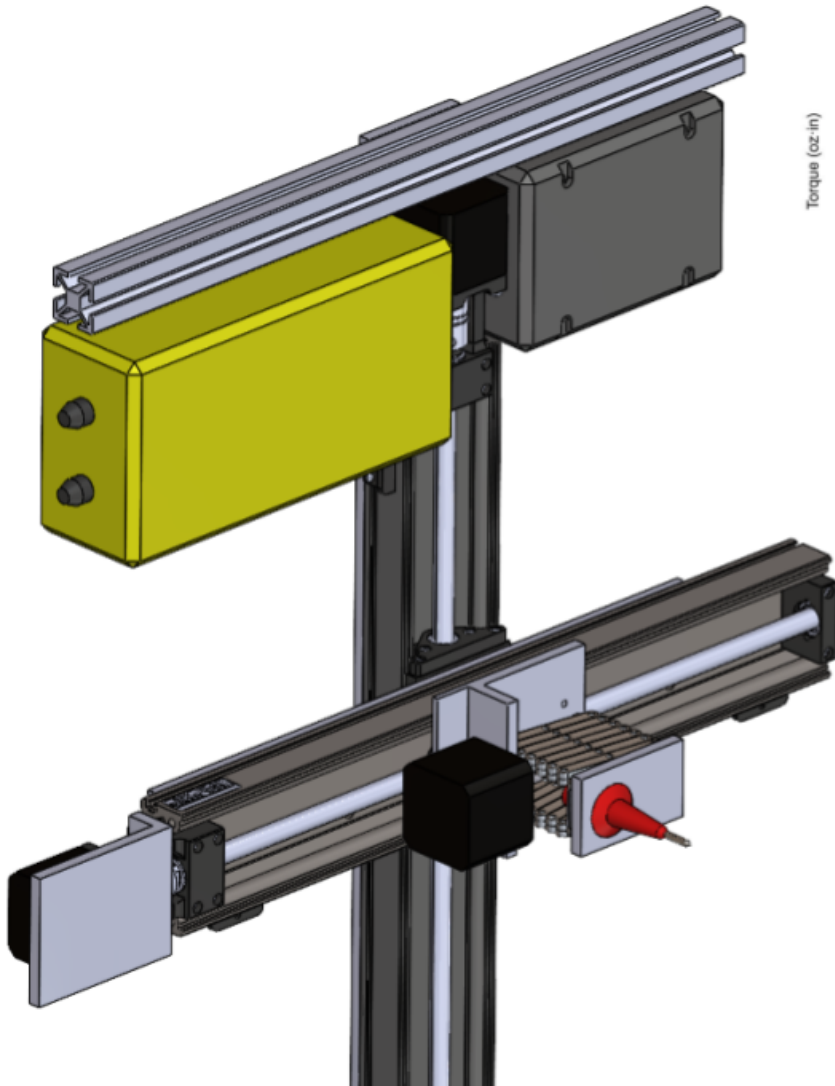
After some design alterations, a Playstation 4 DualShock controller was to be used and modified to hold the multimeter as the original design intended. This controller was assumed to be modded and used in conjunction with the arduino. This design had the capability of connecting through the pc to a smaller led setup but ran into major complications when being implemented to the main device.



Due to these complications with the code for the playstation controller, the final design ended up being a 16 Key Matrix Keypad. The device ran off of the Arduino Due to complete the movements the robot needed.



Calculations



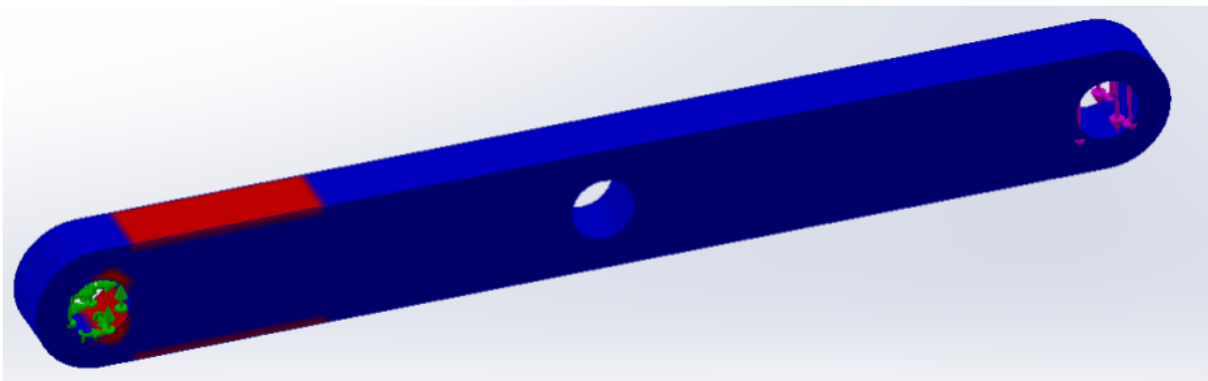
At 1000 pulses per second and at 24V, the motor has an estimated 47 oz.in of torque. At a pulse of 0.9° , this means that the motor completes 2.5 rotations per second. With the 0.5" pitch of the LAVL2-60T18LP5, travel speed is 1.25" per second of 0.104' per second.

Assuming a weight of 6 lbs on the actuator:
 $F = (6 \text{ lbs} + (6\text{lbs}/32.2 \text{ ft/s})(0.104 \text{ ft/s})) = 6.019 \text{ lbs}$ when moving upwards.

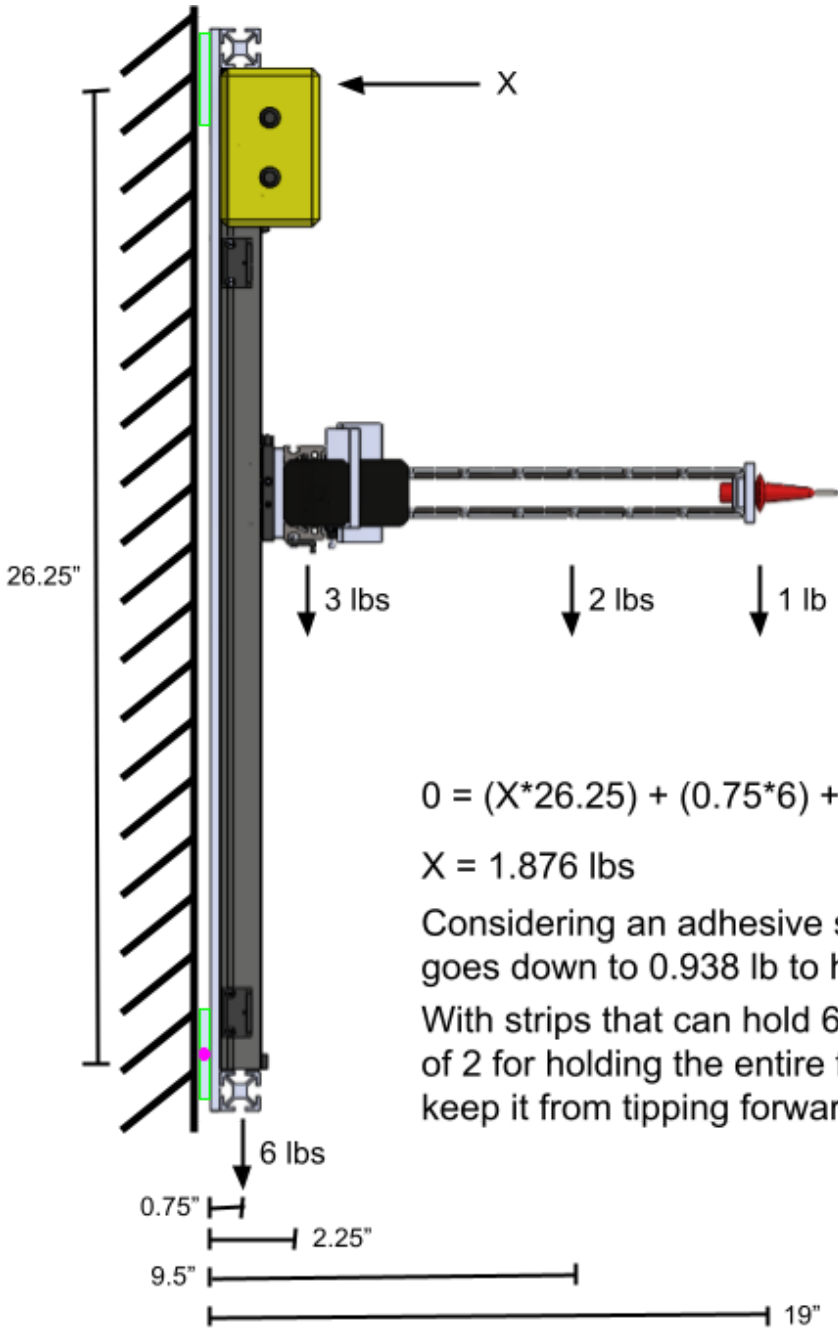
Required Torque = $(\text{Force} * \text{pitch}) / (2 * \pi * (95\% \text{ efficiency}))$

$(6.019 \text{ lbs} * 0.0417 \text{ ft}) / (2 * \pi * 0.95) = 0.042 \text{ lb.f}$

Comparing the minimum torque required and the provided torque, the factor of safety is ~7.5



Given a 15 N force with the most stressed scissor mechanism link, a factor of safety of 2 is appropriate throughout almost all of the link.



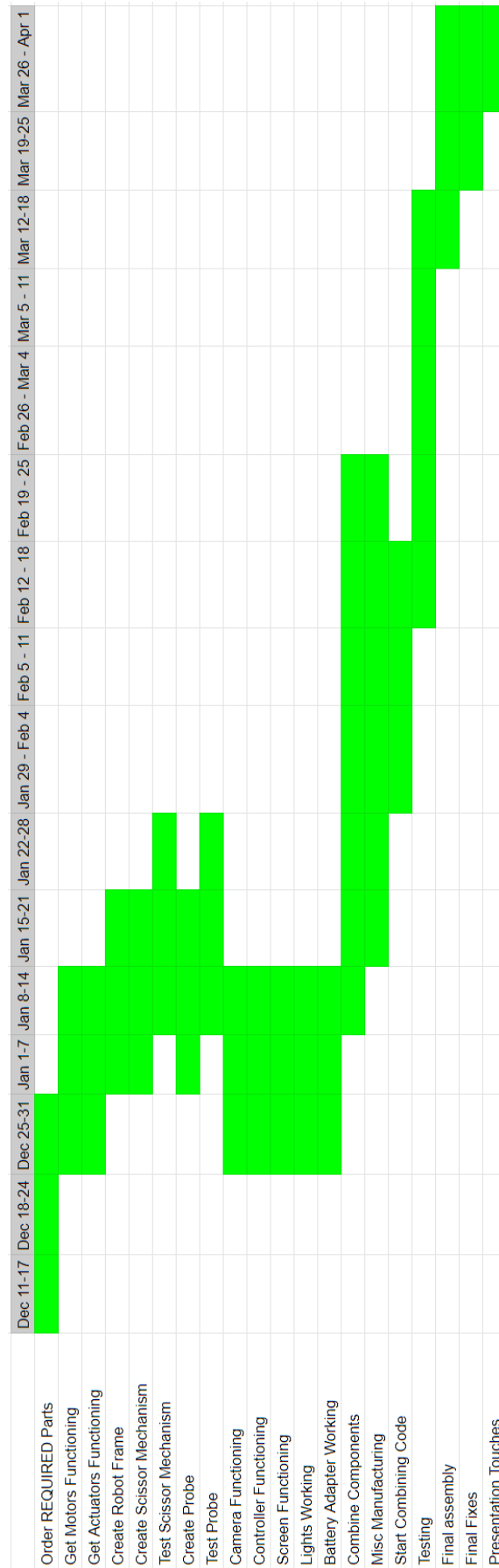
$$0 = (X \cdot 26.25) + (0.75 \cdot 6) + (2.25 \cdot 3) + (9.5 \cdot 2) + (19 \cdot 1)$$

$$X = 1.876 \text{ lbs}$$

Considering an adhesive strip on each corner of the frame, X goes down to 0.938 lb to hold it to the cabinet.

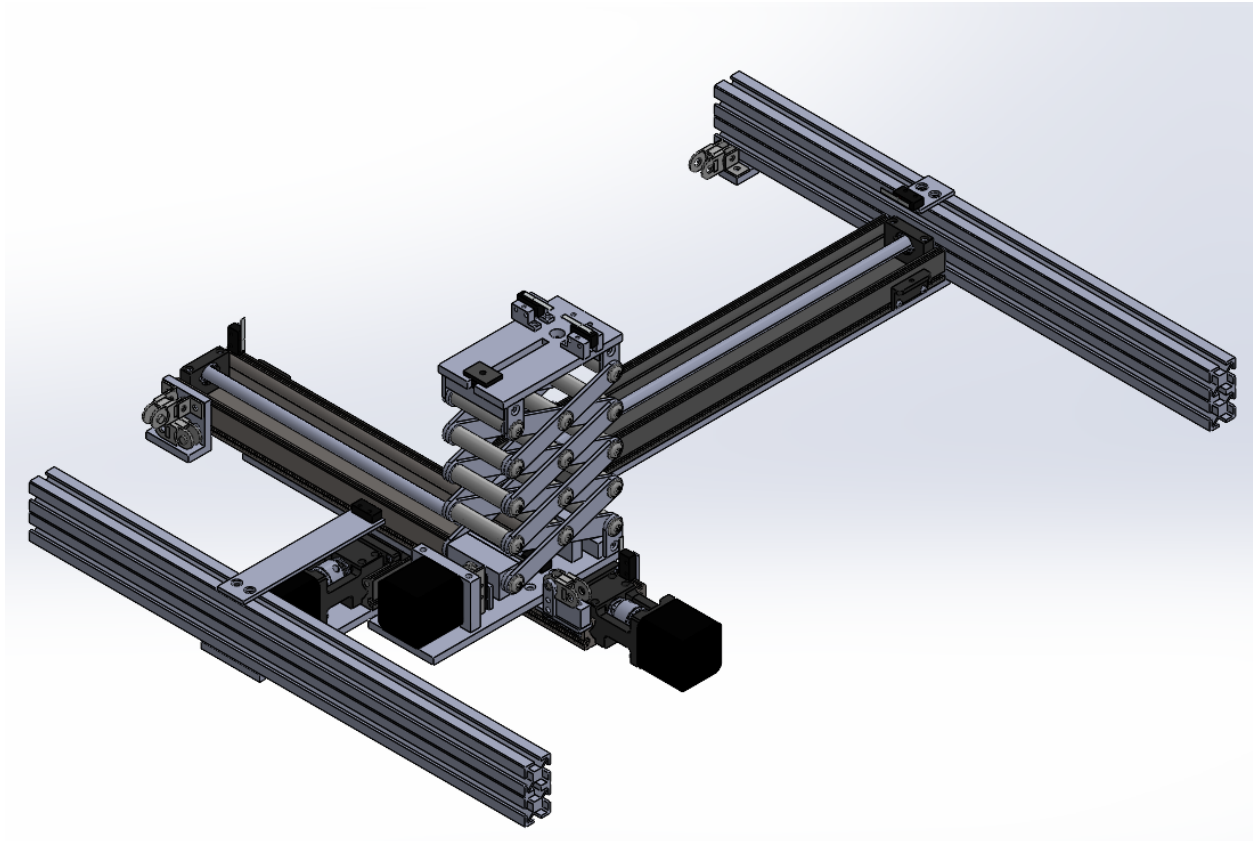
With strips that can hold 6 lbs each, there's a factor of safety of 2 for holding the entire frame, and a factor of safety of 6 to keep it from tipping forward.

Fabrication and Testing Plan



Fabrication and Assembly

The full list of purchased parts and machining drawings are included at the end of this document, with the project broken into smaller parts. Drawings used during production and all ordered parts are included at the end of this document.



Fabrication for this project was achieved on 4 machines, though various redesigns were done at several stages. The use of a CO2 laser cutter allowed for the production of nylon pieces used in the probe holder and several limit switches. The use of a waterjet cutter allowed for a rapid and precise cutting of 1/8" thick aluminum pieces such as the bar linkages, limit switch plates, and various spacers. a CNC lathe was used to produce the lead screw for the scissor mechanism movement but was otherwise unused. A manual mill was the most used piece of equipment in this project, with most parts being created on it. Hardware and specialty pieces were purchased from McMaster-Carr. A complete purchase list will be included at the end of this document.

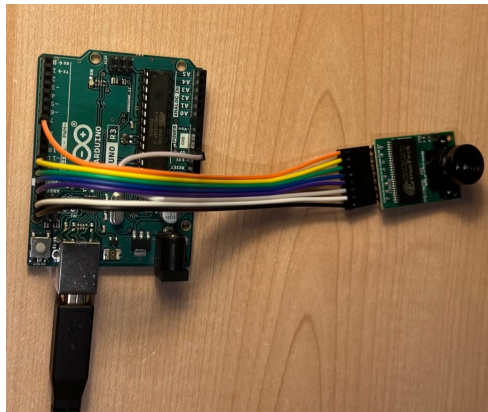
Testing Results and Analysis

X,Y, and Z travel -

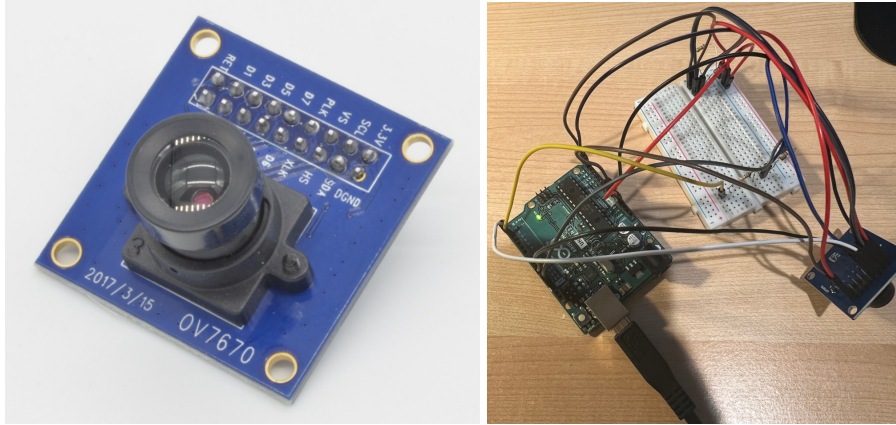
For testing purposes, our intent was to purchase an enclosure at least 36" tall and 24" wide to be capable of fitting our robot, and create a back-plate of electrical components to assure our testing apparatus is complete. Along with the enclosure, we were planning to follow standard health and safety procedures outlined in NFPA 70E despite no power initially going into the enclosure. In the end however, we had significant difficulties not only with the capabilities of the stepper motors, but with the height of the robot. While the depth of the enclosure obtained was initially enough to fit the robot, once the back plate and electrical components were added there was not enough for travel. As previously mentioned, the stepper motor for vertical travel was also insufficient to lift the weight of the scissor mechanism and the horizontal linear actuator, leading to stalling. My guess as to why this is is likely a combination of provided voltage being too low and the weight of the parts being too high.

Camera Module -

The original camera module design using the Arducam Mini Module was set up with the Arduino Uno Rev3 based on the instructions included with the product (pictured below). Connecting all the hardware was simple, the problems began with the software, when trying to view the captured images. Most of the code and instructions were out of date, making the testing way more complicated than it needed to be. After extended research on the Arducam set up and code, it was found that in order to get the camera to work, there would have to be mass amounts of coding done from scratch. Considering the time commitment that would require, we started looking elsewhere for camera options.

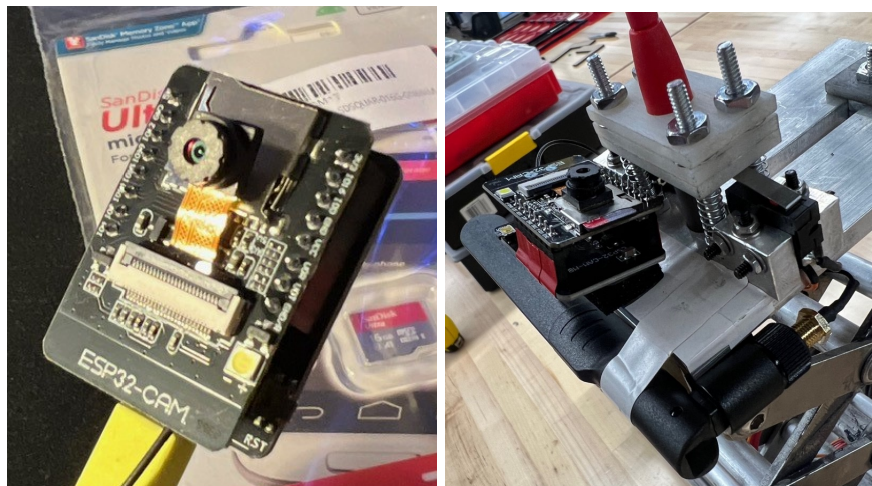


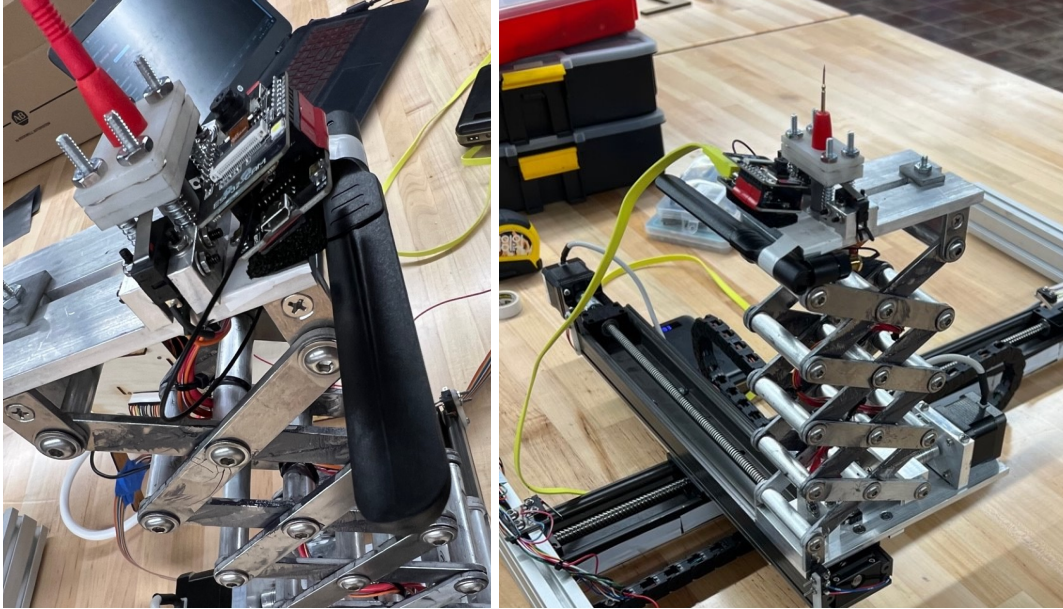
The second iteration of the camera module was found after researching more Arduino-compatible cameras. The second camera chosen was the OV7670 made by BC Robotics (pictured below), which advertises a 640 x 480 resolution at a max frame rate of 30 fps. This camera was easier to get working than the Arducam, as it was more commonly used and had up-to-date references. After some time, live images were finally able to be retrieved from the camera. There were still many problems however, the most troubling issue being the extremely low framerate. After more testing and research on cameras, image processing, and how cameras transmit data, the most likely cause of the low frame rates was hypothesized to be the limited processor size of the Arduino Uno Rev3.



Since the problem was determined to be the Arduino Uno Rev3's inadequate processing power, the Arduino Due was chosen to replace it. The Due has much more processing power with its 32-bit ARM core CPU running at 84 MHz, compared to the Uno Rev3's 8-bit CPU running at 16 MHz. The OV7670 was set up in the same way on the Due, and tested again. Even with the better processor, the Due was not able to improve the frame rate at all. Worse still, the picture quality went down and some of the color sensors were not working. A few more iterations of the camera module were tested, trying different combinations of the two camera sensors with the Arduino Uno and Due, along with different wires and testing hardware to eliminate those from being possible sources of error. Unfortunately, none of the combinations tested were able to achieve a usable form of live video for the project. At this point, time was running out and there needed to be a better solution to the camera problems so final assembly could start.

The final iteration of the camera module used the ESP32-CAM microprocessor made by Espressif (pictured below). Since time was running out, the decision was made to move away from an Arduino-based camera module. The ESP32 is separate from Arduino, as it has its own on-board processor. Luckily, it is still compatible with Arduino IDE, so coding it was still relatively simple. Testing the ESP32 board was very easy as it is very popular among the IoT community, and thus has plenty of updated resources to refer to during troubleshooting. Right away the ESP camera performed far better than any of the camera module iterations previously. After configuring some camera settings, a stable live video feed was achieved with an estimated frame rate of 20-30 fps. After the testing, it was clear that the ESP32-CAM module was the right choice for the project.

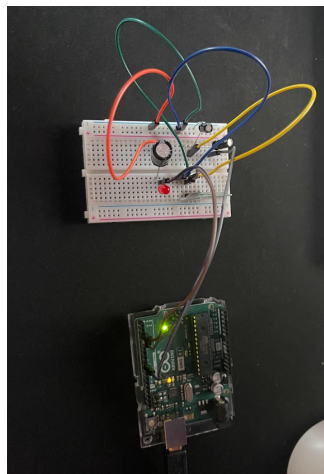




Controller -

The original controller design included an Arduino Nano 33 BLE at the heart and a homemade controller setup for the controls. This controller was used to contact the controller and the Arduino Uno Rev3 together so that the controller could be used wirelessly. This was determined to not have the capabilities needed for the actions needed to control the device. This then moved us to the second iteration.

The second iteration of the controller included the switch to the Arduino Due and the use of a Playstation DualShock 4 controller. This setup was a wire setup controlled through the use of a computer to connect to the Arduino Due. This setup worked on the small led setup to control the Arduino Due using the DualShock 4 controller but had major complications when used in tandem with the main device. The coding issue was found to be a connection issue with the controller to the device and a signal interference. The controller would send a continuous signal to the stepper motors where they worked on pulses. This turned into an issue with the controller and the code itself. The coding issues were not solved leading us to the final iteration of the controller.



The final iteration was a 16 Keys Matrix Keypad. This controller did not have any complications during the movements of the device. After the coding flaws with the DualShock 4 controller were found this controller was used. The working code was uploaded to this controller and the main device was able to be controlled.



Conclusions, Lessons Learned, and Future Work

X and Y travel -

While the design on this portion is technically functional, much is left to be desired when attempting to realistically integrate it into a work environment. Using linear actuators means that the height of the robot is nearly 10" tall while fully compacted, and the large flat space required to mount the device makes attaching it to a cabinet impractical. In addition, stronger motors are required to properly move the heavier weights present. If given more time, an exploration into developing the COREXY system would be the best way to increase the practicality of its use.

Z travel -

Z travel using the scissor mechanism was one of the aspects of the project that I feel went smoothly through nearly the entire process. While ideally, most of the components would be replaced with a hard plastic and a stronger stepper motor would be substituted, not much of this design would be changed. Custom machining a probe for a lower clearance level is within the realm of possibility for improvement, but not necessary to improve functionality.

Camera Module -

Given that the entire original design for the camera had to be thrown out, the camera ended up turning out alright. The final solution ended up meeting almost all of the criteria that was set out for it. The camera was wireless, lightweight, lit up the inside of the cabinet, was easy to use, and most importantly, had a high frame rate that showed a clear live video of the inside of the cabinet so the robot could be manipulated accurately. Although it would have been nice to have the camera controlled by the same Arduino Due that controls the rest of the robot, it would be far more complicated to integrate the two systems. The camera module itself simply demands too much processing resources to be run on an Arduino for this project.

Working on the camera module has been very interesting, and has taught me many lessons along the way. The most impactful of which is the value of thorough research and planning ahead. Looking back, there were many road bumps that could have been completely avoided if more extensive research ahead of time was done. At the time, it seemed like I was doing more than enough research for each of the camera components used in the different iterations of the camera module. But later on during the testing phase for each prototype, I would stumble onto more information that would seriously impact the viability of the prototype, causing me to go back to the drawing board and lose more valuable time. From this, I have learned that it is extremely important to completely research a component's viability before committing to a design. Even if the part may seem like a perfect fit with a few hours of research, it is worth it to spend an extra few hours to prove its usefulness before continuing.

With more time, some future work could be done to improve the camera module even further. The camera works well as is, but could definitely perform better and more consistently. To solve some of these minor issues, we could improve the Wi-Fi connection by upgrading the antenna or adding a third party wireless network for the camera to connect to. This would allow more of the camera's resources to go into camera performance instead of being used to create its own wireless access point, which would increase image quality and frames per second.

Controller -

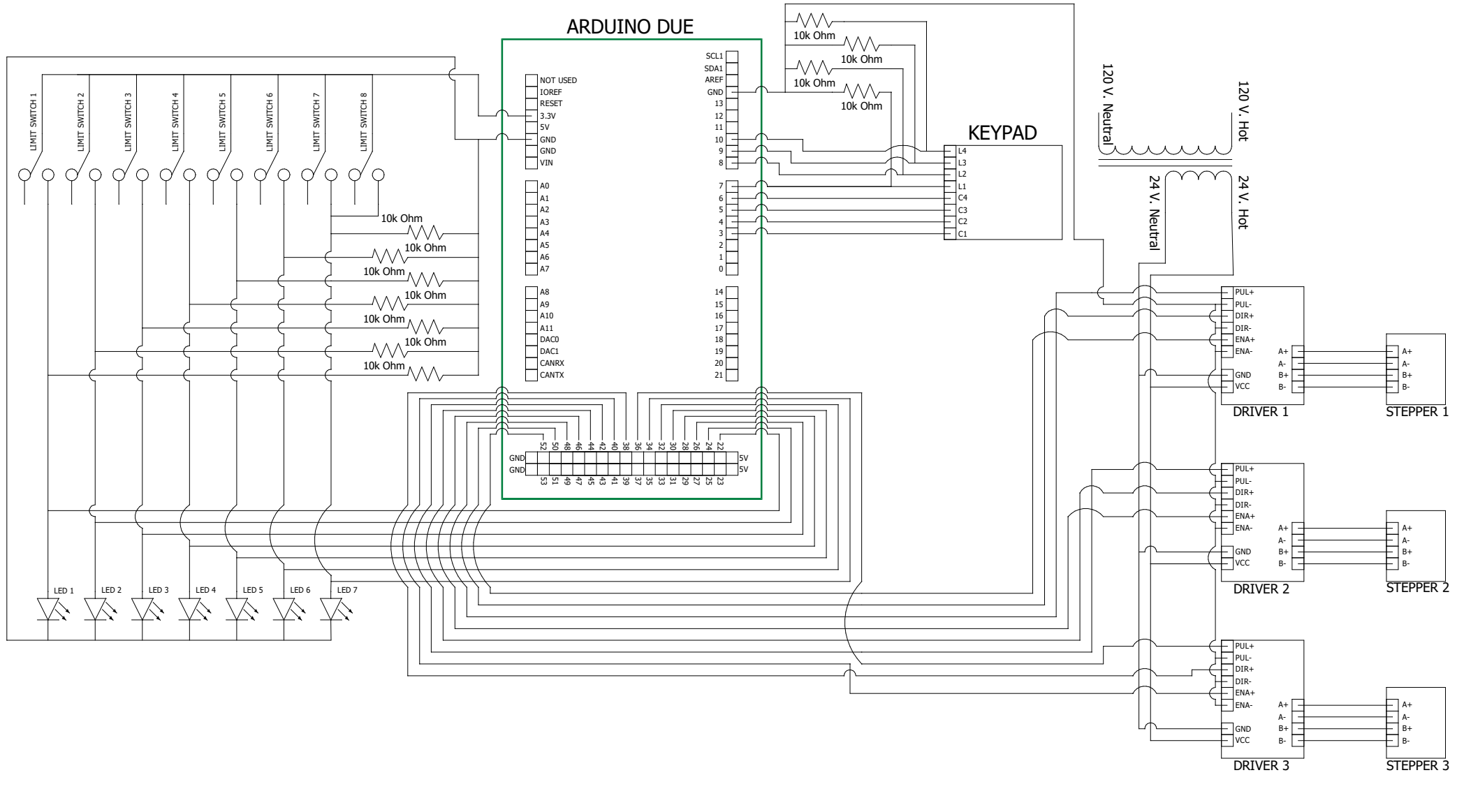
While the design of the controller is functionable, it is not set up in the ideal manner. Using the 16 Key Matrix works to move the robot in the directions chosen by the operator but it does not have an ergonomic design. It also is not set up to connect to the display of the multimeter, the removable piece, so you have to set the multimeter aside to get your readings. It is also not as easy to hold and change the direction of the robot as the game controller could have been.

The controller setup that the device has is fully functional but lacks the ergonomic design of the game controller that was expected to be completed. With the issues that arose while coding the game controller and changing the design the use of that controller was not attainable before the engineering expo. With more time and less problems then the ergonomic controller design that was planned for could have been achieved. All in all, the controller that is in use is fully functional for the use of the device.

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LAVL2-60T18LP5	1	\$1,435.00	\$1,435.00	18" 0.5" pitch linear actuator	https://www.automationdirect.com/adc/shopping/catalog/power_transmission_(mechanical)/linear_motion_slides_and_actuators/lead_screw_driven_linear_actuators/lavl2-60t18lp5
LAVL2-60T12LP2	1	\$1,185.00	\$1,185.00	12" 0.2" pitch linear actuator	https://www.automationdirect.com/adc/shopping/catalog/power_transmission_(mechanical)/linear_motion_slides_and_actuators/lead_screw_driven_linear_actuators/lavl2-60t12lp2
STP-MTR-17040	3	\$22.50	\$67.50	NEMA 17 61 oz-in stepper motor	https://www.automationdirect.com/adc/shopping/catalog/motion_control/stepper_systems/single_shaft_stepper_motors/stp-mtr-17040
EM542S	3	\$50.00	\$150.00	Stepper Drive	https://www.automationdirect.com/adc/shopping/catalog/motion_control/stepper_systems/stepper_drives/em542s
Arduino UNO Rev 3	1	\$27.60	\$27.60	Arduino Control Board	https://store-usa.arduino.cc/products/arduino-uno-rev3
Arduino Due	1	\$42.00	\$42.00	Arduino Control Board	https://store.arduino.cc/products/arduino-due
Micro USB cable	1	\$16.00	\$16.00	20 ft Micro USB cable	https://www.amazon.com/dp/B07ZGCT7QB?ref=ppx_yo2ov_dt_b_product_details&th=1
Flat Ribbon Cable	1	\$11.00	\$11.00	5M 20cnt ribbon cable	https://www.amazon.com/dp/B01NC2L2WB?ref=ppx_yo2ov_dt_b_product_details&th=1
10 kOhm resistors	1	\$6.81	\$6.81	100 kOhm resistors	https://www.amazon.com/your-orders/orders?_encoding=UTF8&startIndex=10&ref=ppx_yo2ov_dt_b_pagination_1_2
4x4 Keypad	1	\$9.00	\$9.00	16 keys arduino keypad	https://www.amazon.com/dp/B07B4DR5SH?psc=1&ref=ppx_yo2ov_dt_b_product_details
Limit Switches	1	\$7.66	\$7.66	10cnt micro limit switches	https://www.amazon.com/dp/B07P25F2DL?ref=ppx_yo2ov_dt_b_product_details&th=1
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93330A672	16	\$2.96	\$47.36	Female Threaded Round Standoffs	https://www.mcmaster.com/93330A672/
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6389K352	40	\$0.80	\$32.00	Dry-Running Sleeve Bearing	https://www.mcmaster.com/6389K352/
91772A524	1	\$10.72	\$10.72	1 7/8" X 8-32 Pan Head Screw	https://www.mcmaster.com/91772A524/
91292A027	1	\$7.63	\$7.63	14 mm, M3 X 0.5 mm Thread Socket Head	https://www.mcmaster.com/91292A027/
88805K684	1	\$7.75	\$7.75	90 Deg Angle, 1/16" Thk, 1/2" X 1/2" X 4"	https://www.mcmaster.com/88805K684/
94815A007	5	\$3.19	\$15.95	1/2"-16 Hex Nut	https://www.mcmaster.com/94815A007/
98935A803	1	\$4.47	\$4.47	1/4"-16 Lead Screw, 3' long	https://www.mcmaster.com/98935A803/
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Line diagram

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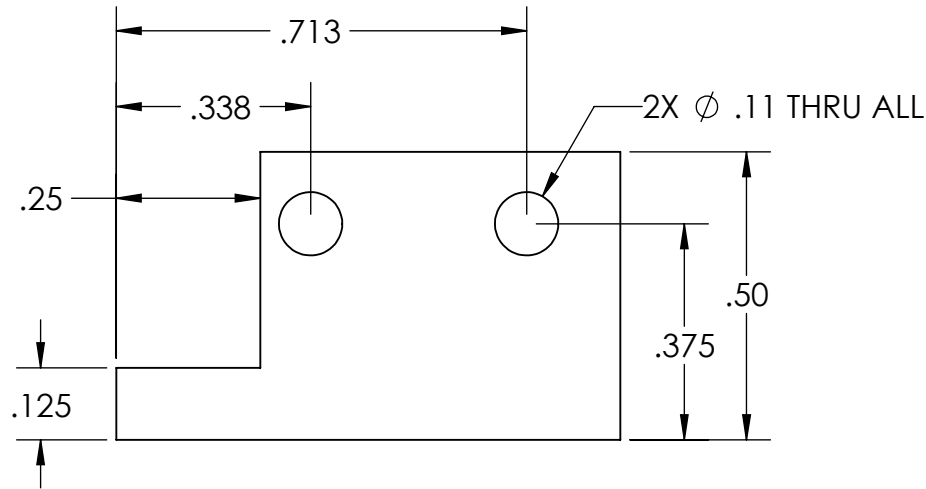
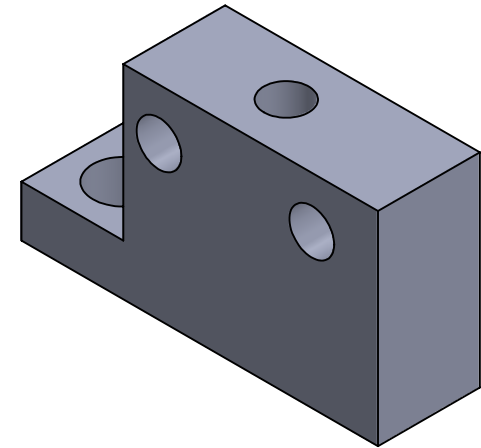
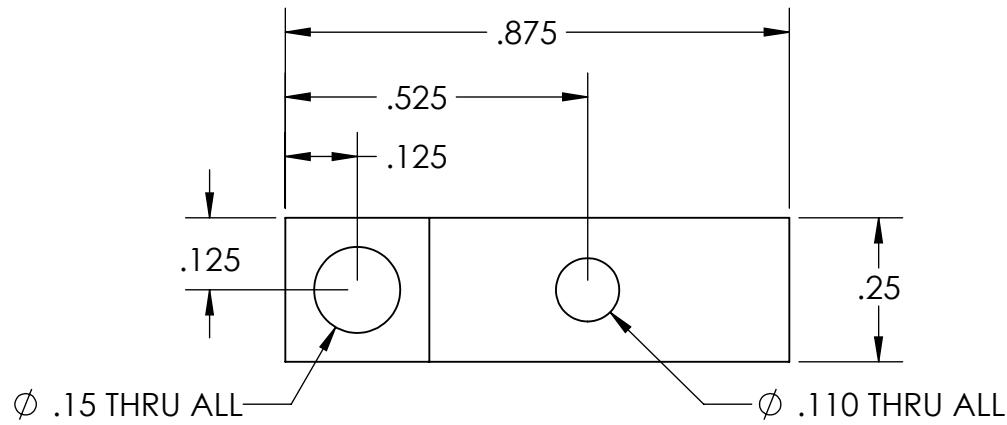
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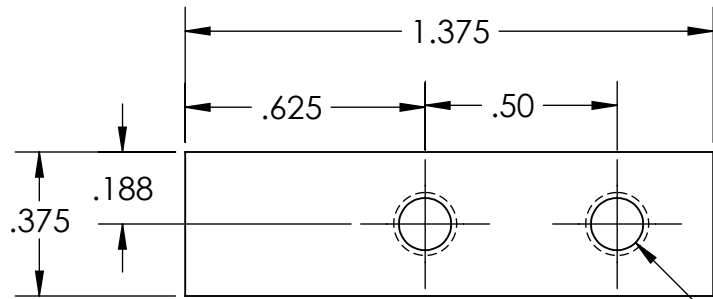
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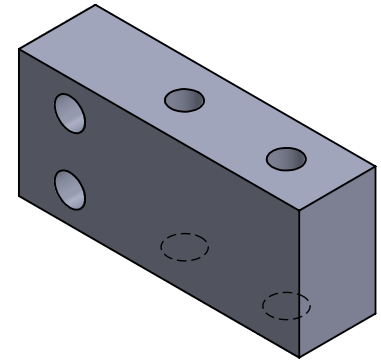
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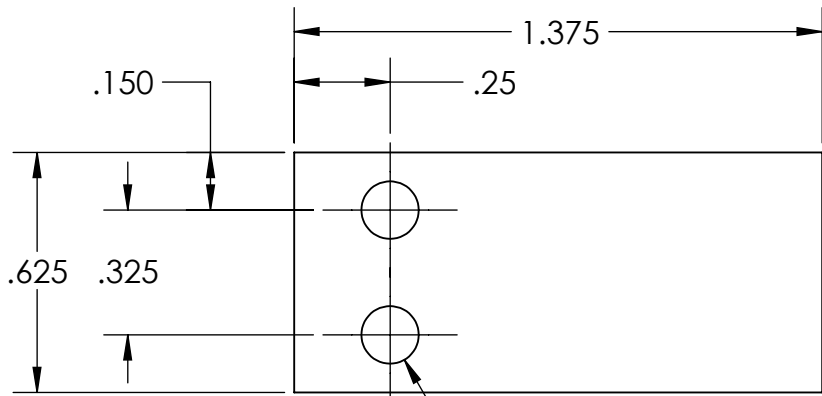
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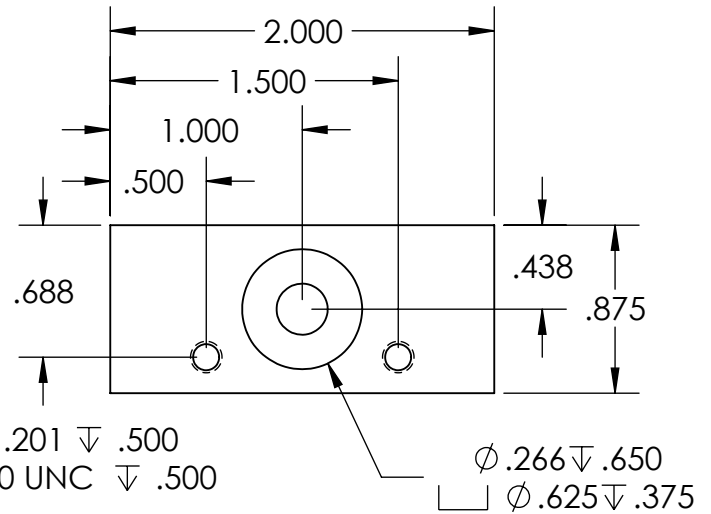
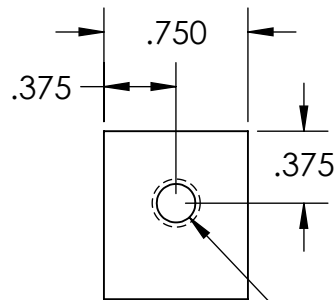
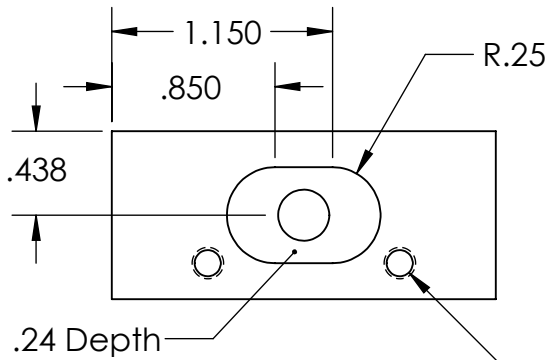
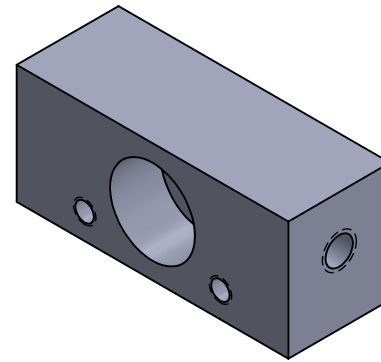
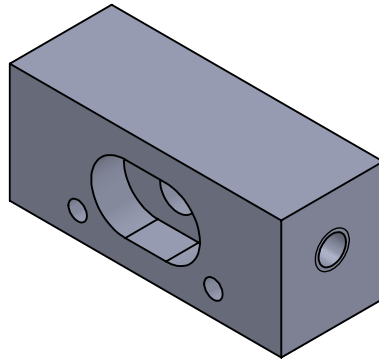
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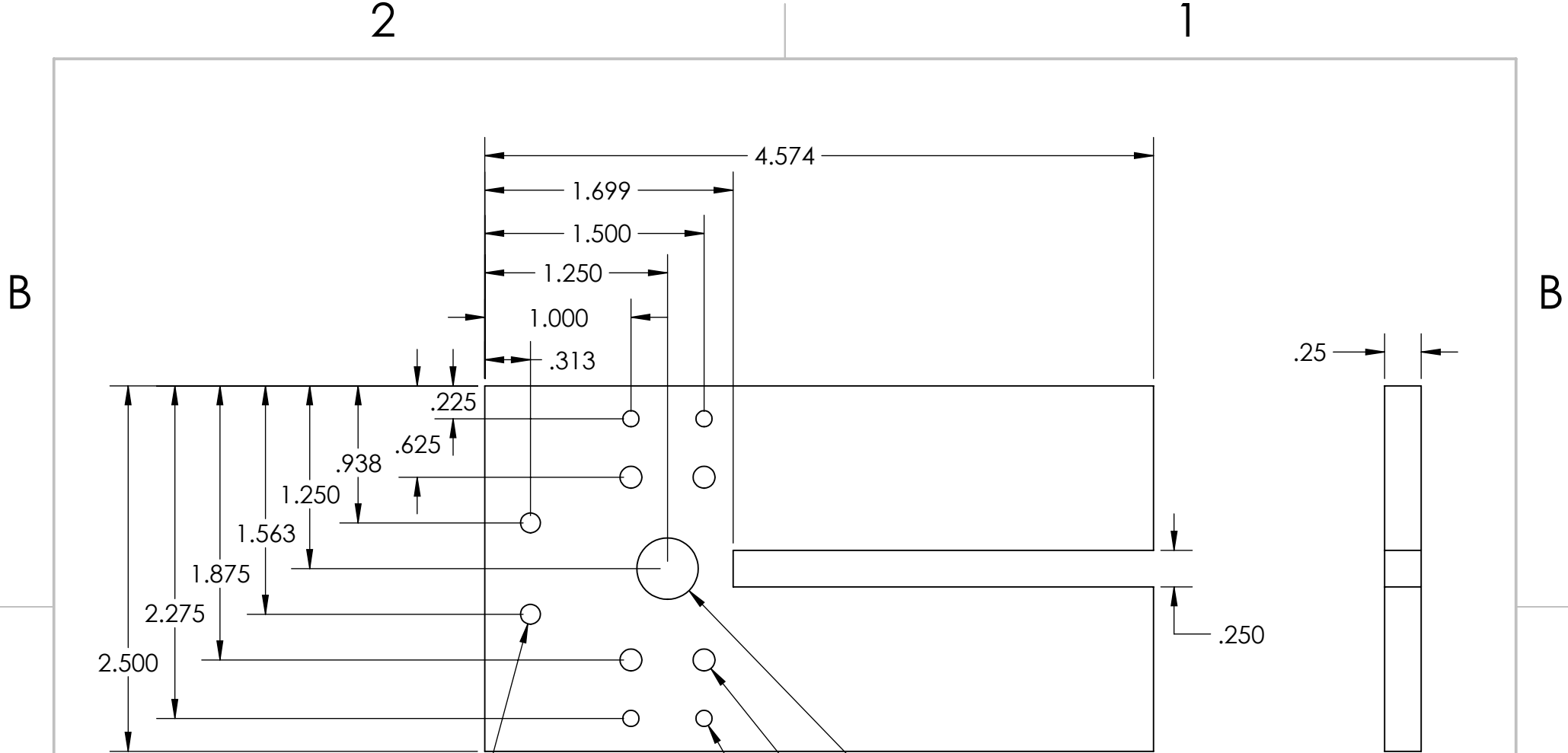
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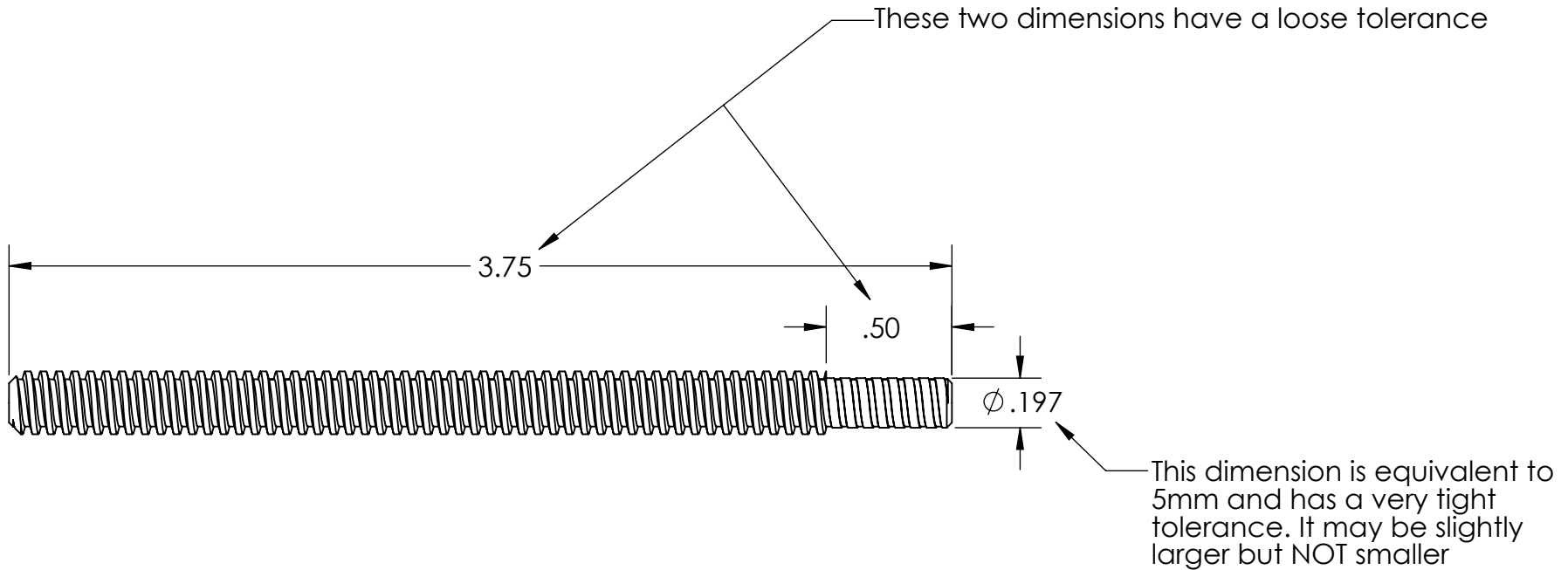
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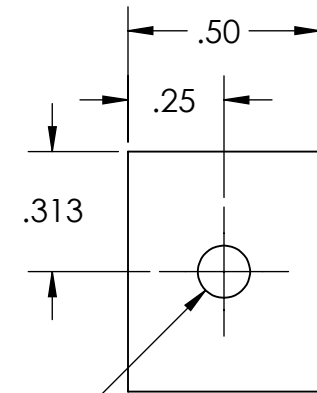
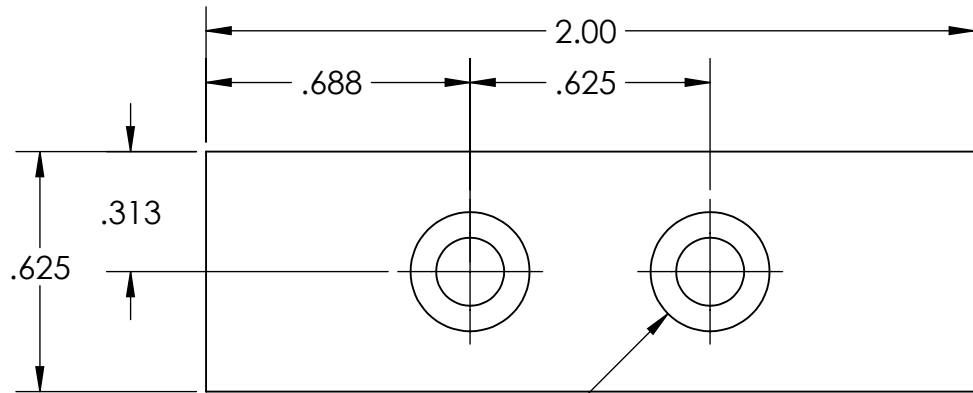
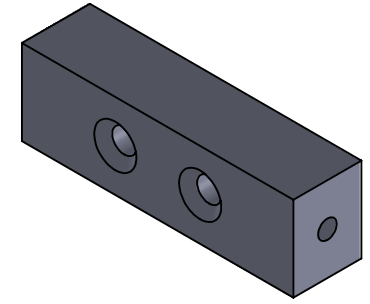
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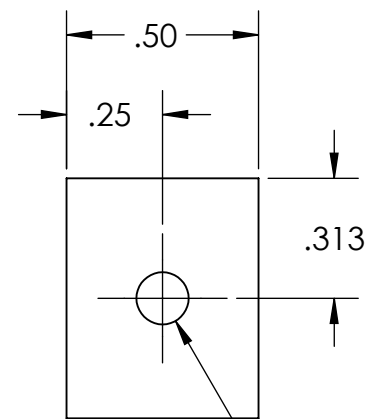
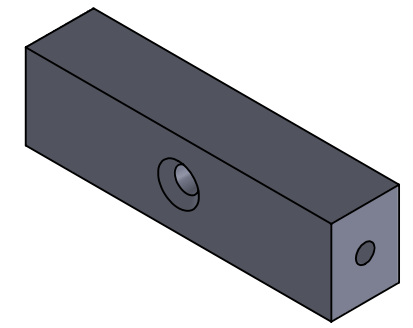
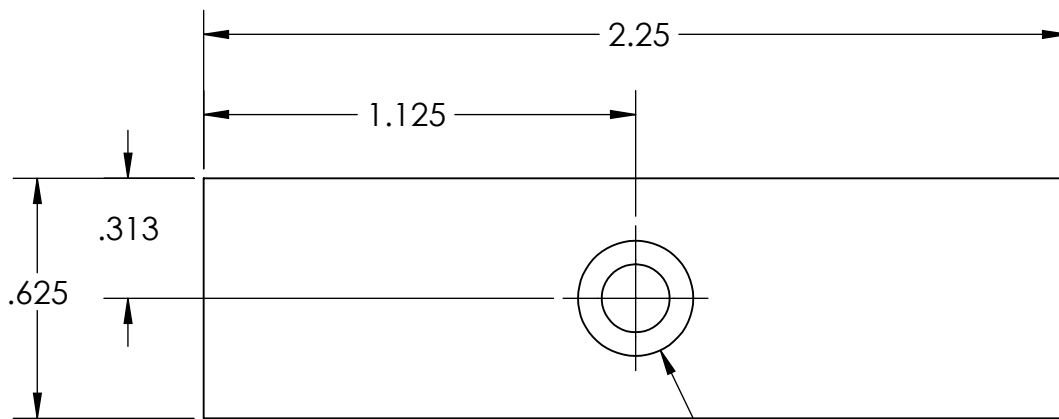
TITLE:
Tap Attachment

SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 2:1	WEIGHT:	SHEET 6 OF 24

2

1

B



ϕ .18 THRU ALL
 ϕ .30 X 90°, FAR SIDE

ϕ .14 ∇ .50
 8-32 UNC ∇ .33

QTY: 1

A

A

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		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL \pm	ENG APPR.		
		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Tap Attachment

2

SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 2:1	WEIGHT:	SHEET 7 OF 24

2

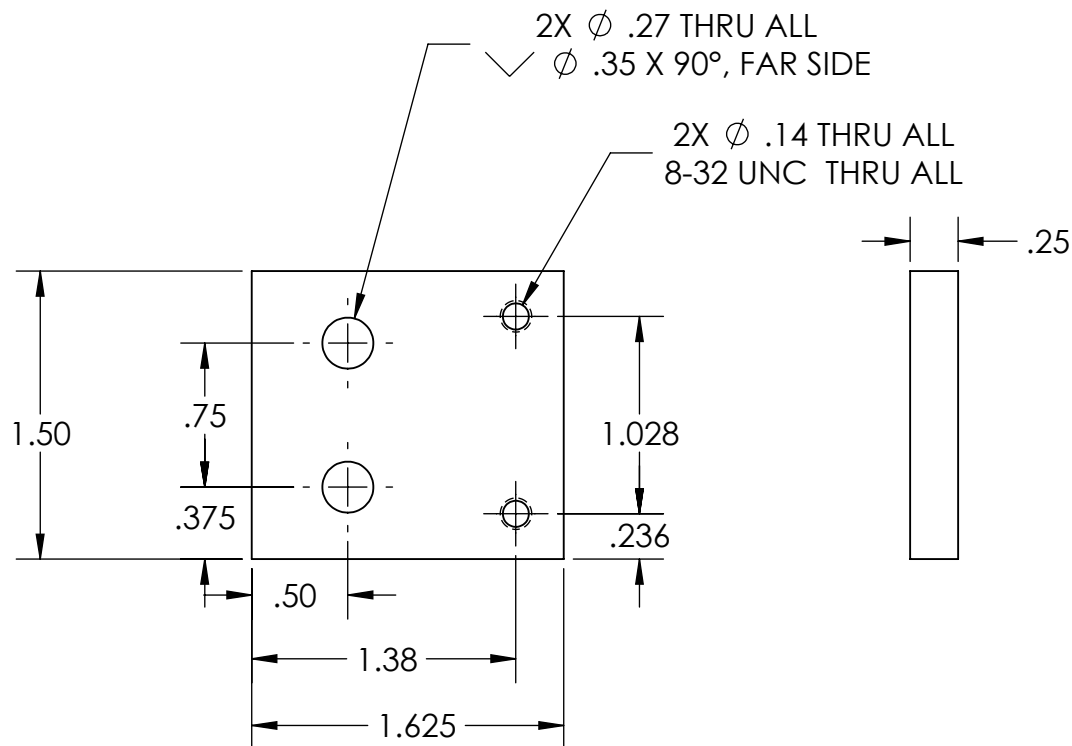
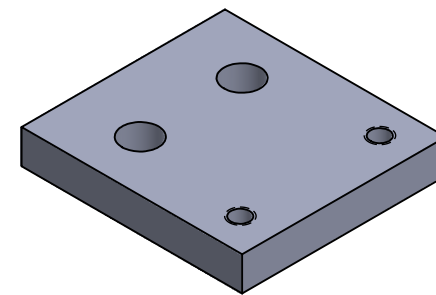
1

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QTY: 1

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		TOLERANCES:	CHECKED		
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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Cable Plate		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 1:1	WEIGHT:	SHEET 8 OF 24

2

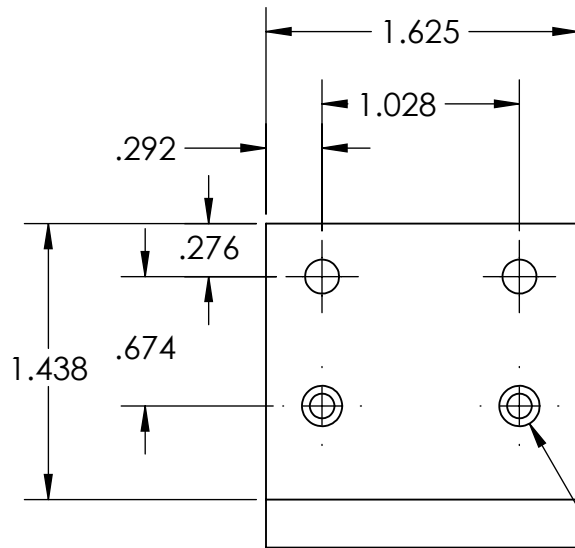
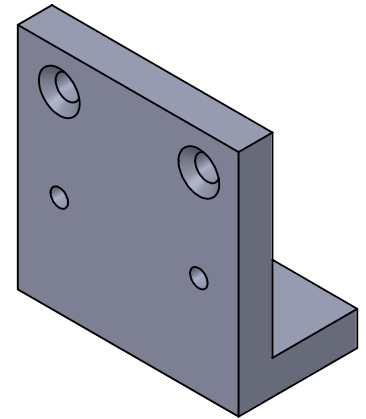
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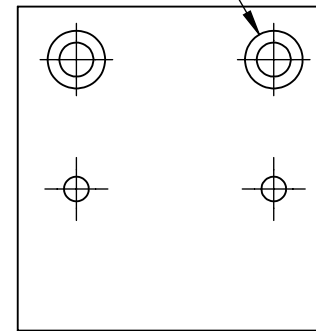
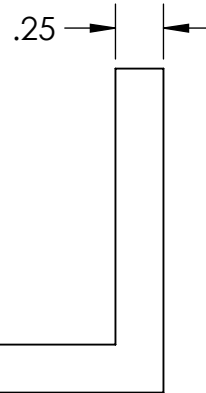
1

B

B



2X ϕ 0 THRU ALL
 \checkmark ϕ .30 X 90°, FAR SIDE



2X ϕ .129 THRU ALL
 \sqsubset ϕ .21 ∇ .13

QTY: 1

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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Cable Plate 2		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 1:1	WEIGHT:	SHEET 9 OF 24

2

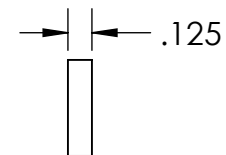
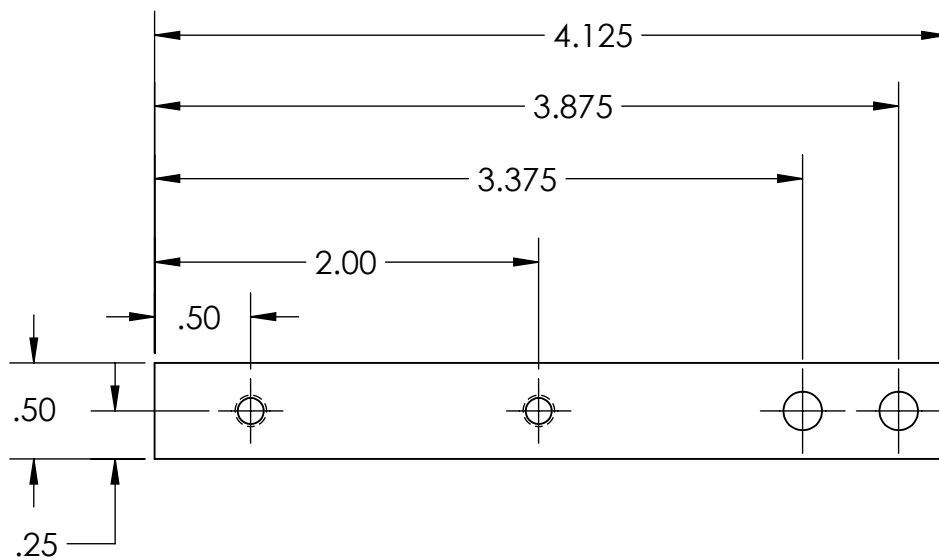
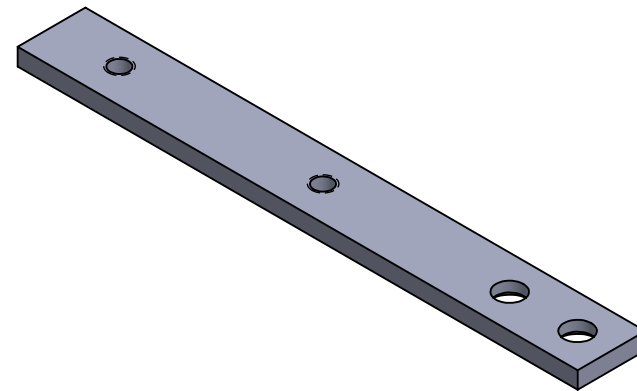
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QTY: 1

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		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Cable Plate 3

SIZE DWG. NO. REV
A Final Drawings

SCALE: 1:1 WEIGHT: SHEET 10 OF 24

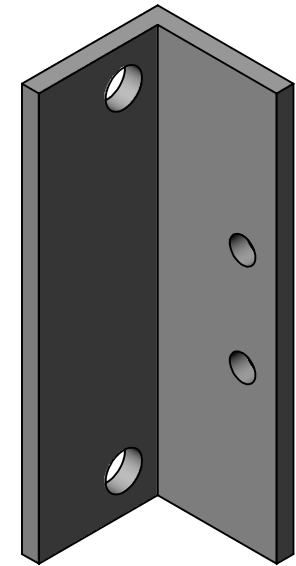
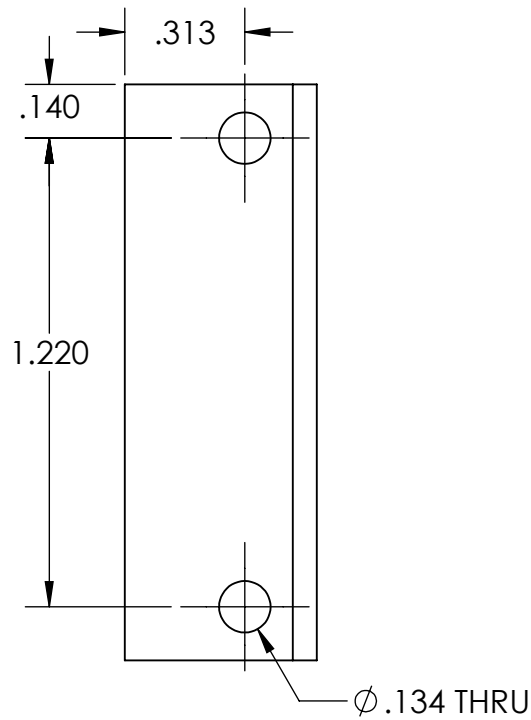
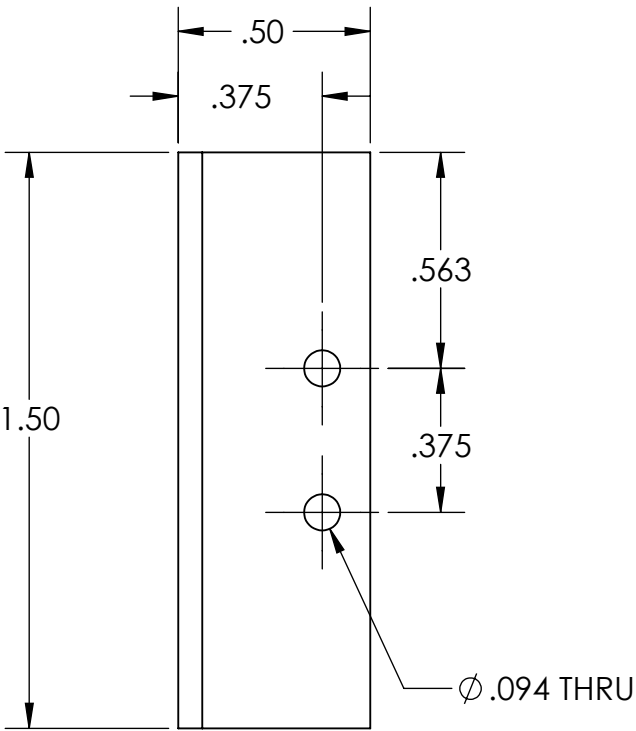
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QTY: 1

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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

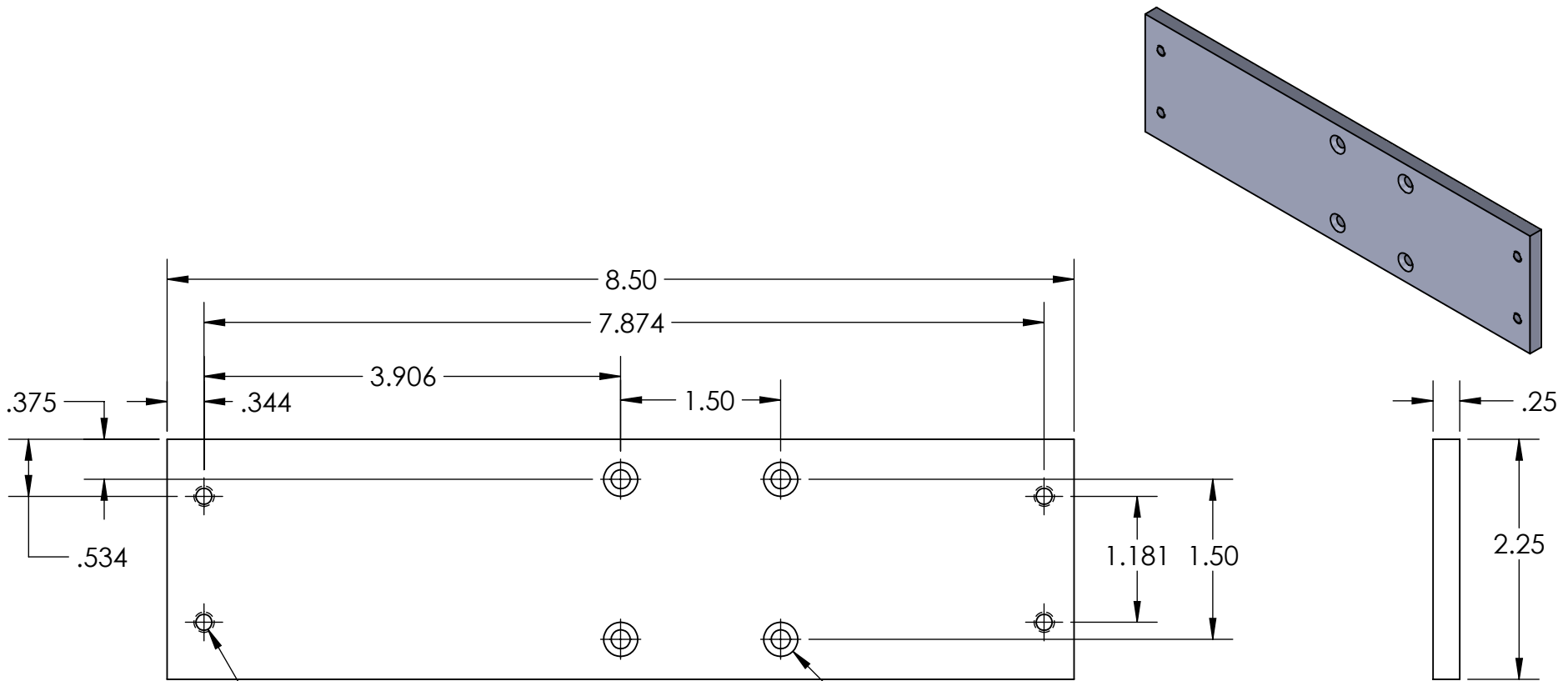
TITLE: Limit Angle		
SIZE A	DWG. NO. Final Drawings	REV
SCALE: 2:1	WEIGHT:	SHEET 11 OF 24

2

1

B

B



4X Ø .15 THRU ALL
10-24 UNC THRU ALL

4X Ø .18 THRU ALL
Ø .32 X 90°, NEAR SIDE

QTY: 1

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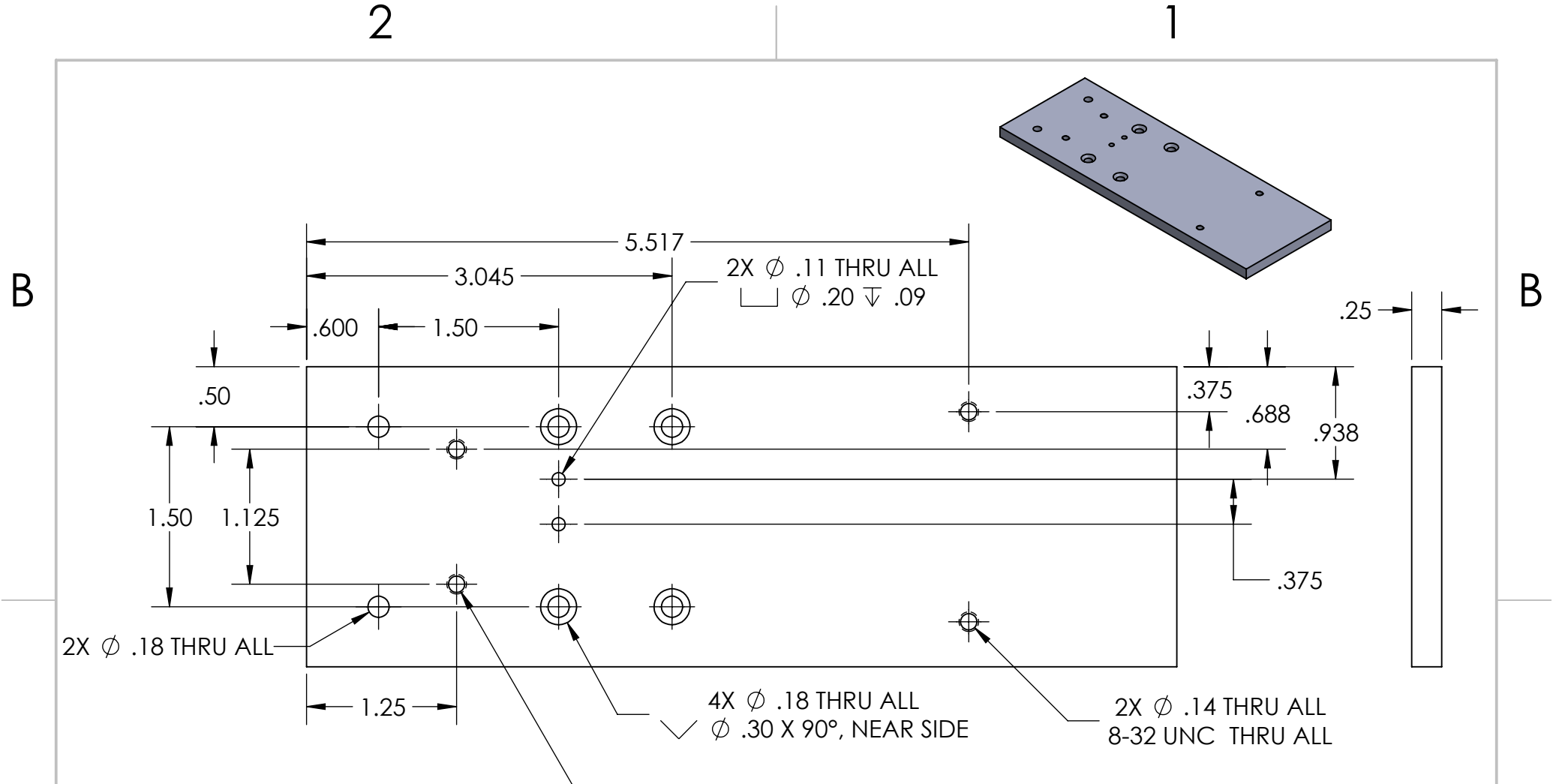
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		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
		INTERPRET GEOMETRIC TOLERANCING PER:	CHECKED		
		MATERIAL	ENG APPR.		
		FINISH	MFG APPR.		
NEXT ASSY	USED ON		Q.A.		
APPLICATION		DO NOT SCALE DRAWING	COMMENTS:		

TITLE: Actuator Bar		
SIZE A	DWG. NO. Final Drawings	REV
SCALE: 1:2	WEIGHT:	SHEET 12 OF 24

2

1



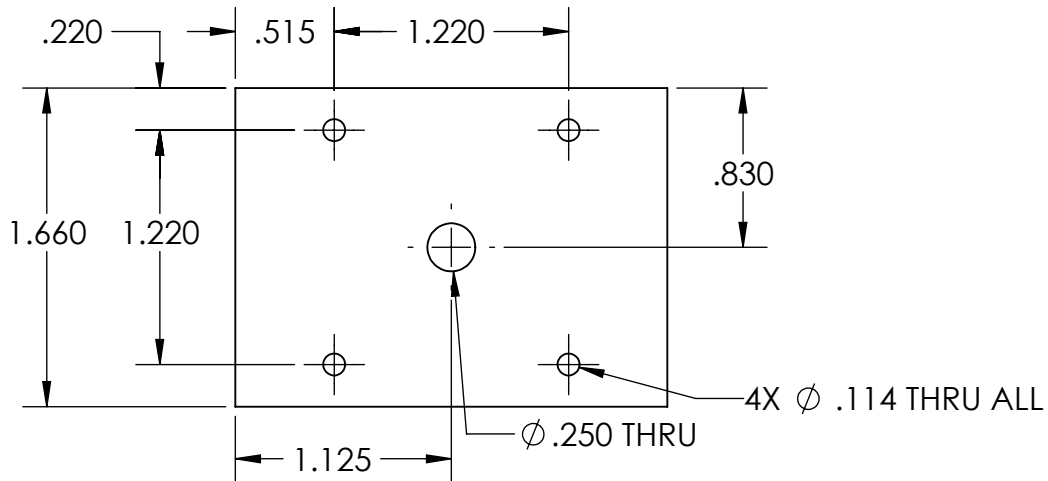
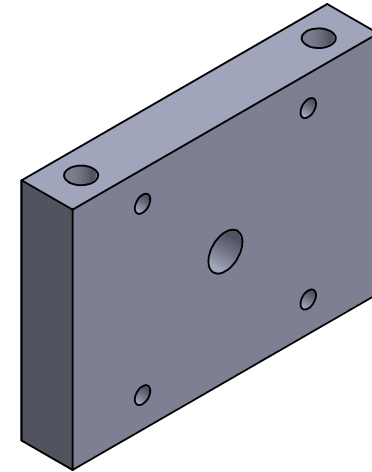
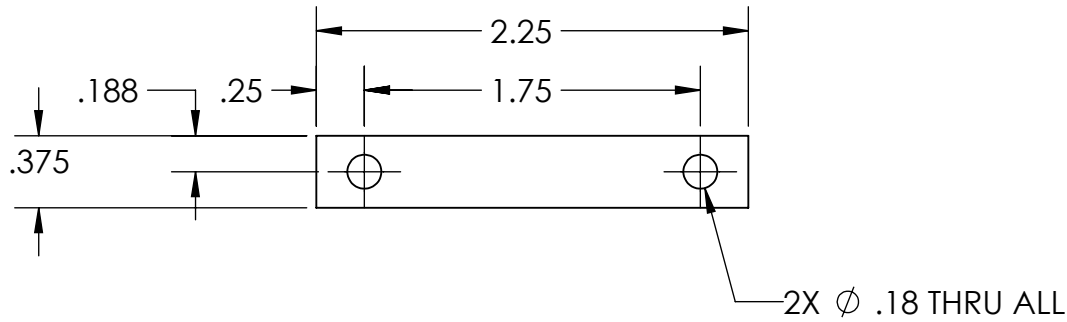
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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE: Base		
SIZE A	DWG. NO. Final Drawings	REV
SCALE: 1:2	WEIGHT:	SHEET 13 OF 24

2

1



QTY: 1

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		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Stepper Support

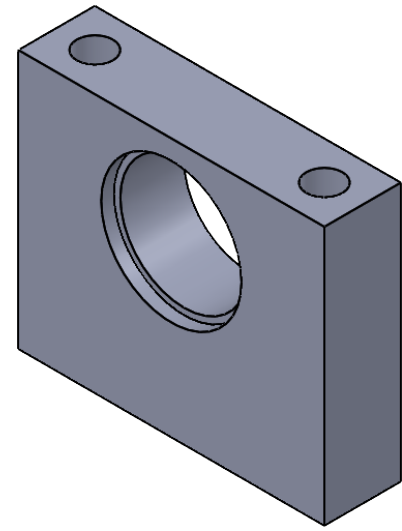
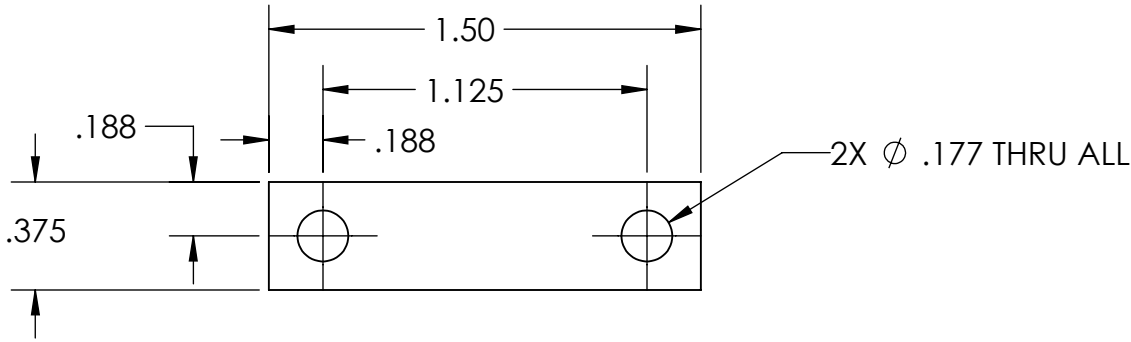
SIZE	DWG. NO.	REV
A	Final Drawings	

SCALE: 1:1	WEIGHT:	SHEET 14 OF 24
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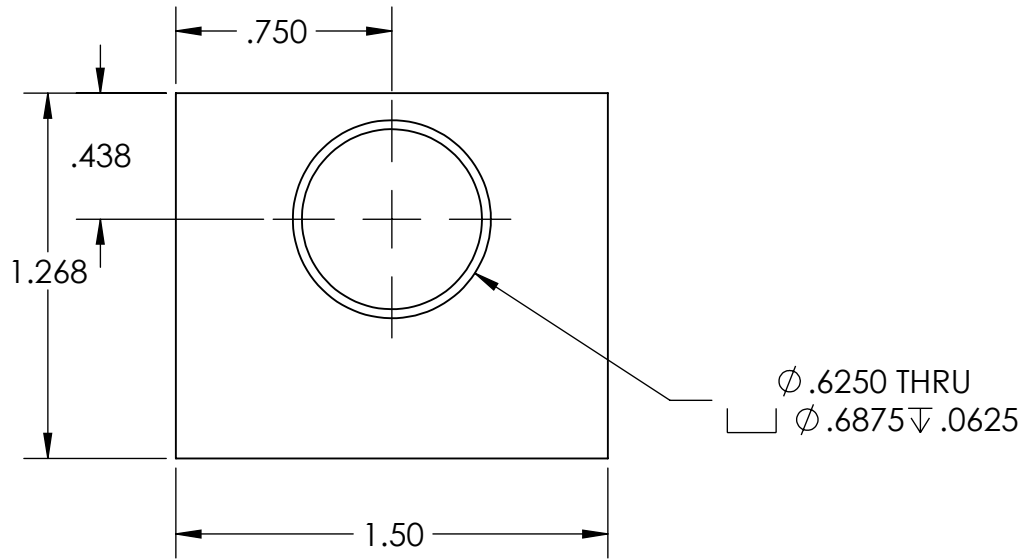
2

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QTY: 1

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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Support Block

SIZE DWG. NO. REV
A Final Drawings

SCALE: 1:1 WEIGHT: SHEET 15 OF 24

2

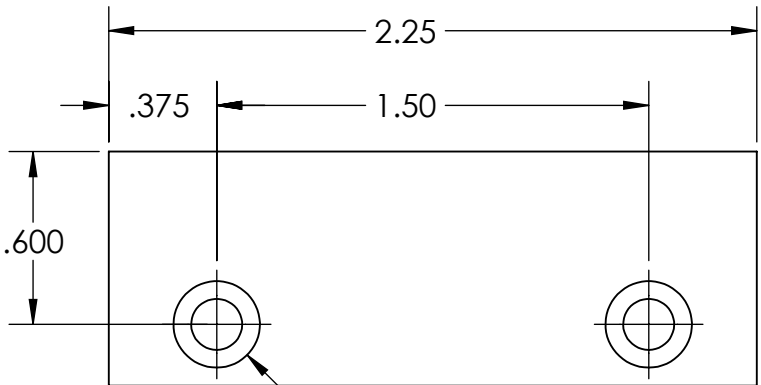
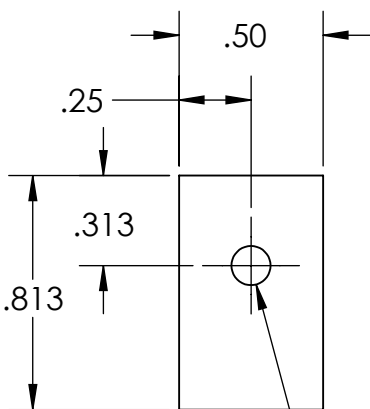
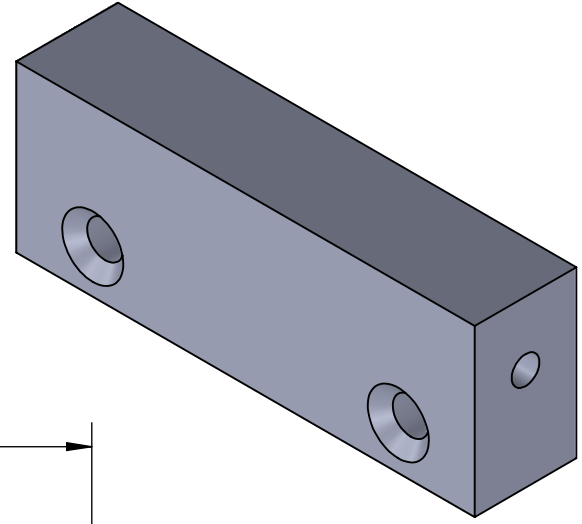
1

2

1

B

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2X ϕ .14 ∇ .50
8-32 UNC ∇ .50

2X ϕ .18 THRU ALL
 ϕ .30 X 90°, NEAR SIDE

QTY: 1

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		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Pivot Support		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 1:1	WEIGHT:	SHEET 16 OF 24

2

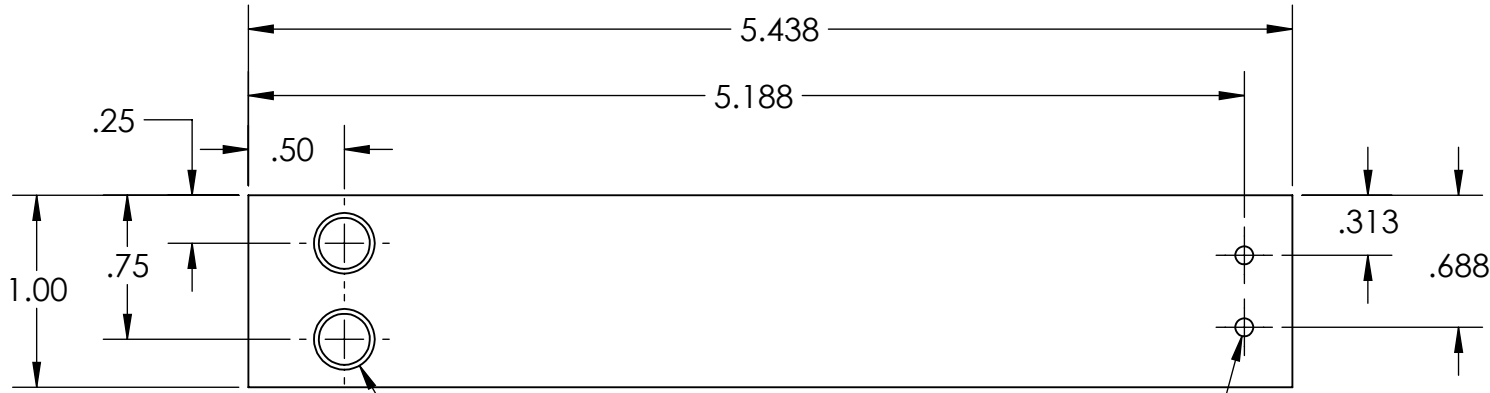
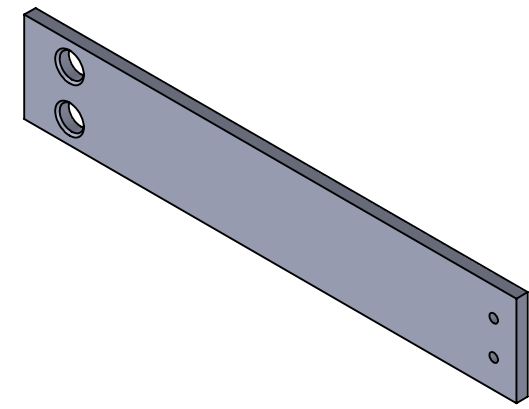
1

2

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B

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2X ϕ .27 THRU ALL
 ϕ .32 X 90°, NEAR SIDE

2X ϕ .09 THRU

QTY: 1

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		TOLERANCES:	CHECKED		
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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Top Limit Switch Plate

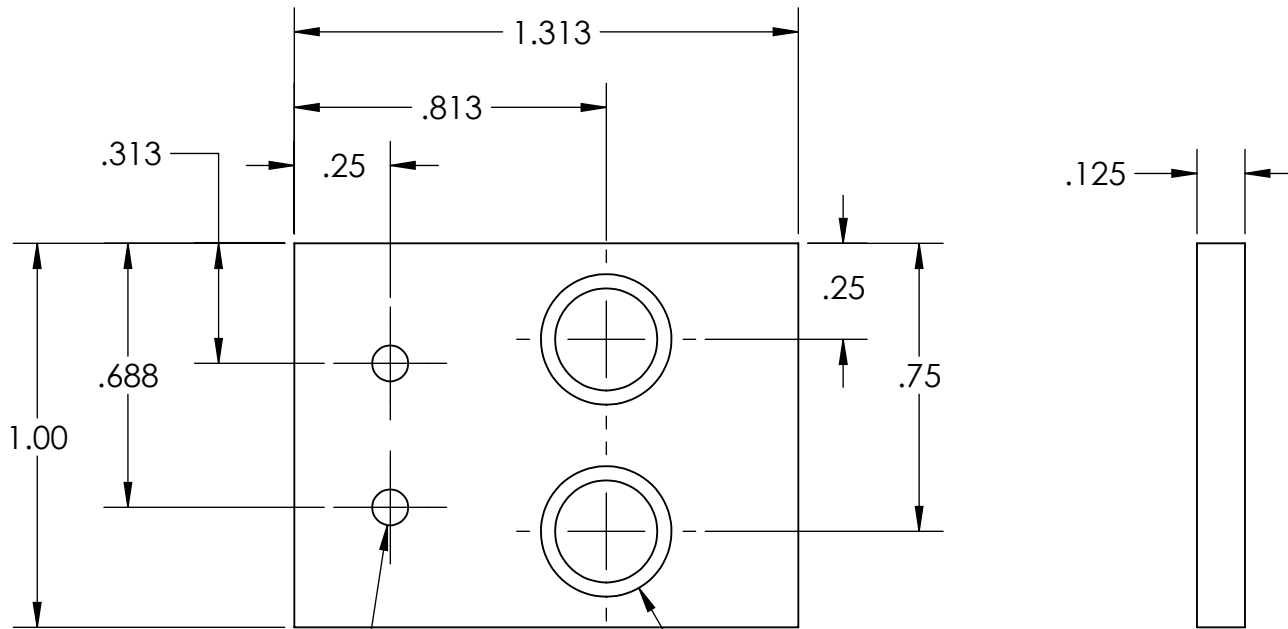
SIZE DWG. NO. REV
A Final Drawings

SCALE: 1:2 WEIGHT: SHEET 17 OF 24

2

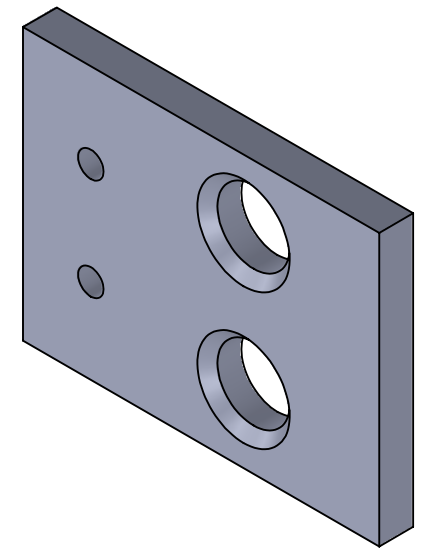
1

B

2X ϕ .09 THRU2X ϕ .27 THRU ALL
 ϕ .34 X 90°, NEAR SIDE

QTY: 1

B



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		INTERPRET GEOMETRIC TOLERANCING PER:	CHECKED	
		MATERIAL	ENG APPR.	
		FINISH	MFG APPR.	
NEXT ASSY	USED ON		Q.A.	
APPLICATION	DO NOT SCALE DRAWING		COMMENTS:	

TITLE:

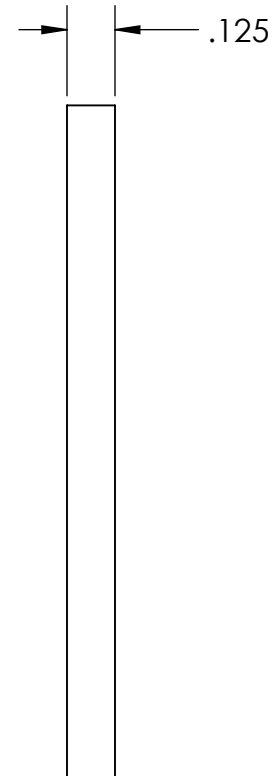
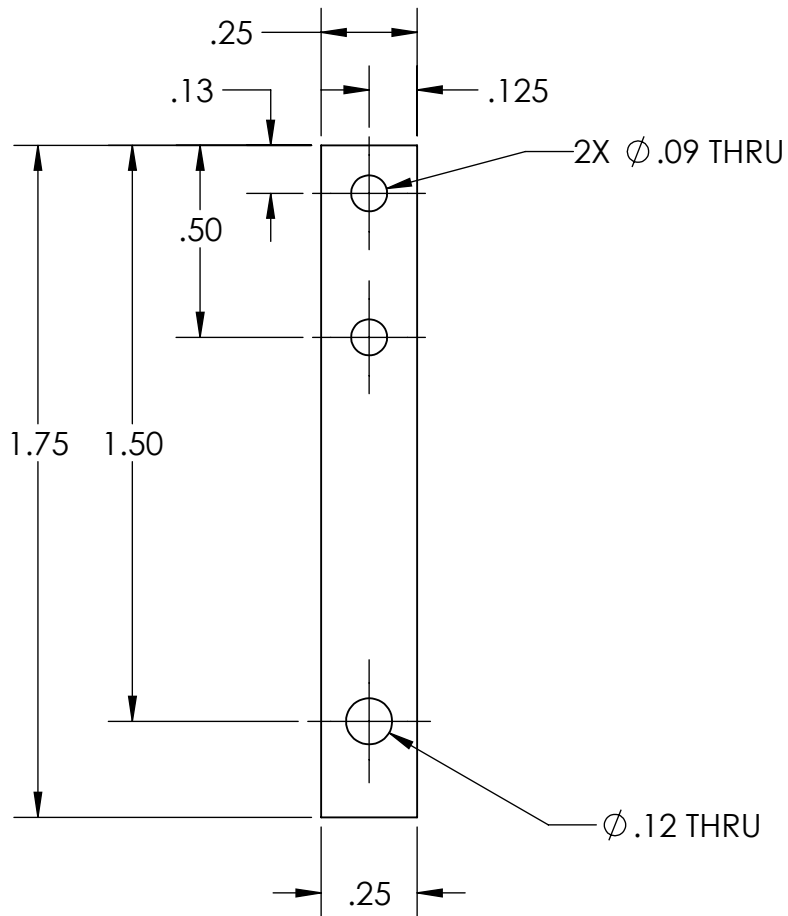
Bottom Limit
Switch Plate

SIZE A	DWG. NO. Final Drawings	REV
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SCALE: 2:1	WEIGHT:	SHEET 18 OF 24
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B



B

QTY: 2

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		TOLERANCES:	CHECKED	
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		ANGULAR: MACH ± BEND ±	MFG APPR.	
		TWO PLACE DECIMAL ±	Q.A.	
		THREE PLACE DECIMAL ±	COMMENTS:	
		INTERPRET GEOMETRIC TOLERANCING PER:		
		MATERIAL		
NEXT ASSY	USED ON	FINISH		
APPLICATION		DO NOT SCALE DRAWING		

TITLE:

Limit Switch Plate

SIZE

A

DWG. NO.

Final Drawings

REV

SCALE: 2:1

WEIGHT:

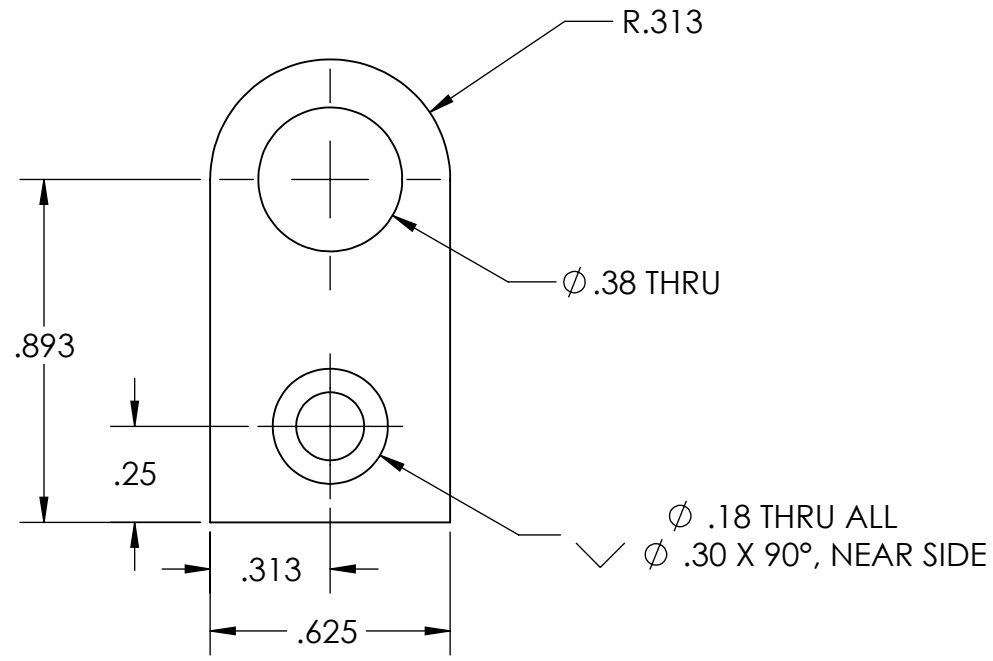
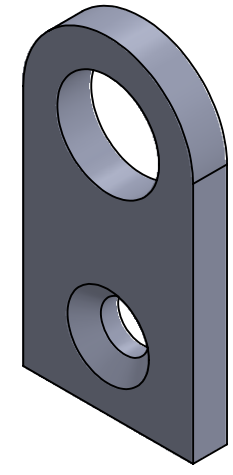
SHEET 19 OF 24

2

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QTY: 6

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		TOLERANCES:	CHECKED		
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		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Pivot		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 2:1	WEIGHT:	SHEET 20 OF 24

2

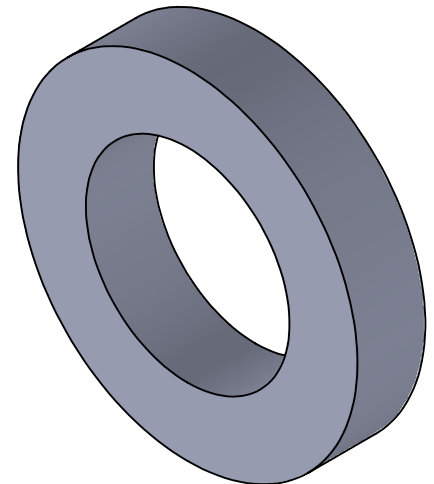
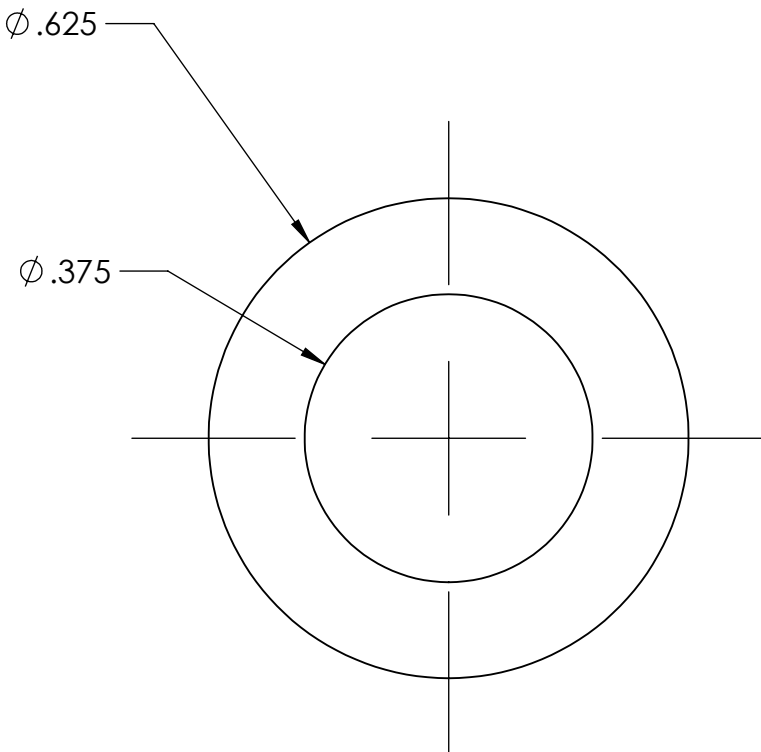
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QTY: 2

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		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL \pm	ENG APPR.		
		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Ring		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 4:1	WEIGHT:	SHEET 21 OF 24

2

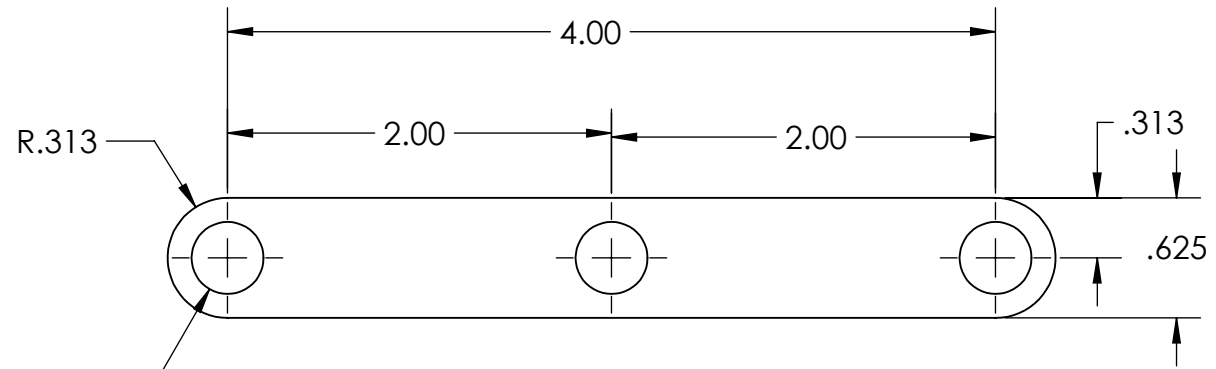
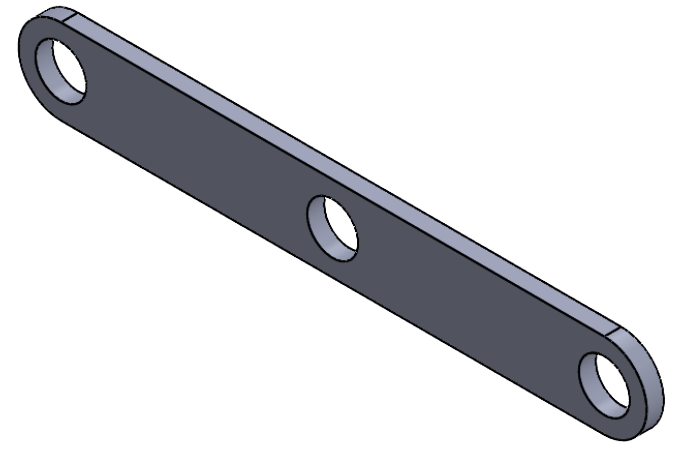
1

2

1

B

B



3X Ø .375 THRU

QTY: 16

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		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL ±	ENG APPR.		
		ANGULAR: MACH ± BEND ±	MFG APPR.		
		TWO PLACE DECIMAL ±	Q.A.		
		THREE PLACE DECIMAL ±	COMMENTS:		
		INTERPRET GEOMETRIC			
		TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:		
Bar		
SIZE	DWG. NO.	REV
A	Final Drawings	
SCALE: 1:1	WEIGHT:	SHEET 22 OF 24

2

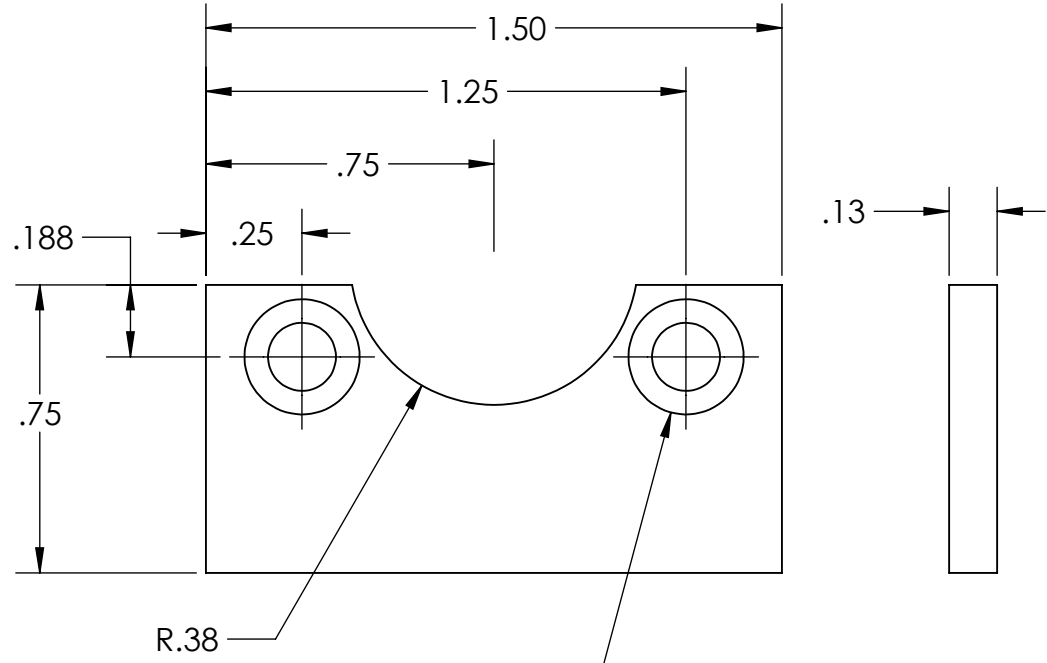
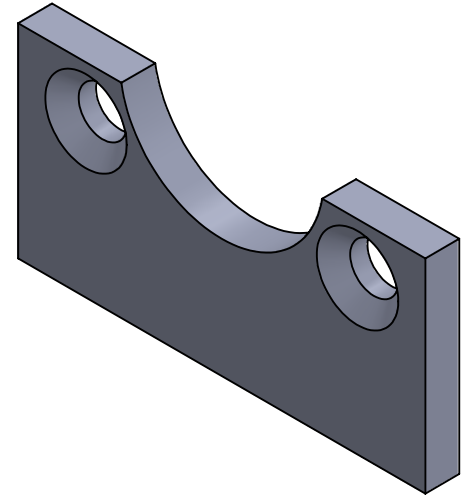
1

2

1

B

B



2X ϕ .18 THRU ALL
 \surd ϕ .30 X 90°, NEAR SIDE

QTY: 1

A

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		DIMENSIONS ARE IN INCHES	DRAWN		
		TOLERANCES:	CHECKED		
		FRACTIONAL \pm	ENG APPR.		
		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE:
Switch Plate

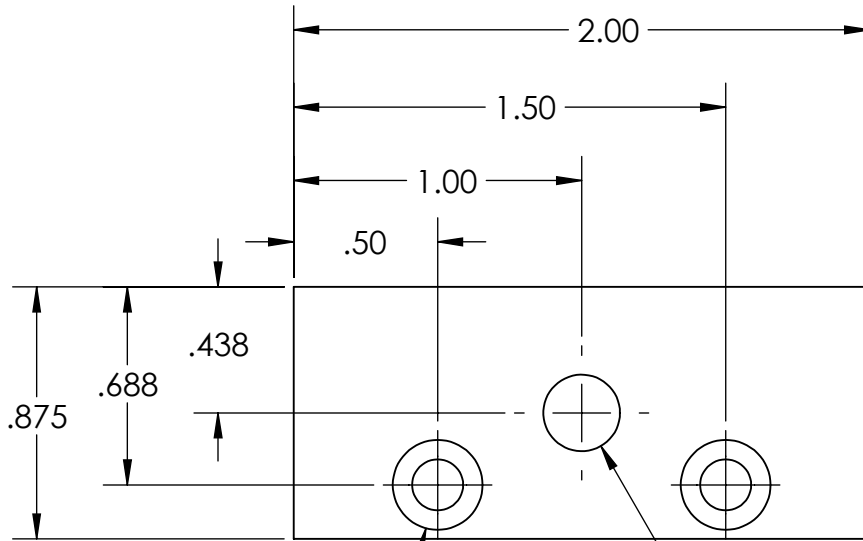
SIZE DWG. NO. REV
A Final Drawings

SCALE: 2:1 WEIGHT: SHEET 23 OF 24

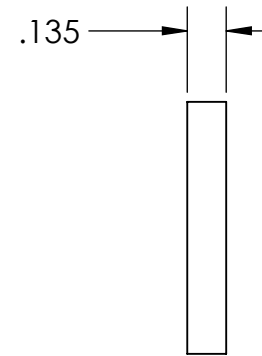
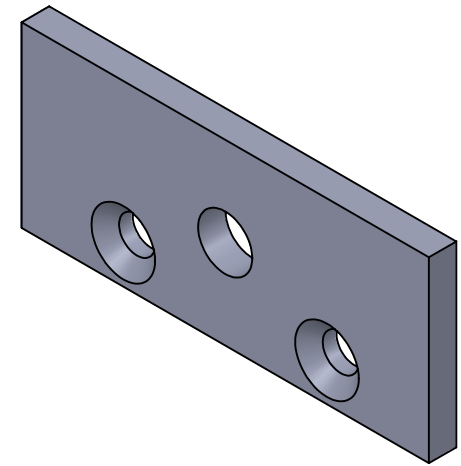
2

1

B



2X ϕ .18 THRU ALL
 ✓ ϕ .31 X 90°, NEAR SIDE
 ϕ .27 THRU ALL



B

QTY: 1

A

A

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		TOLERANCES:	CHECKED		
		FRACTIONAL \pm	ENG APPR.		
		ANGULAR: MACH \pm BEND \pm	MFG APPR.		
		TWO PLACE DECIMAL \pm	Q.A.		
		THREE PLACE DECIMAL \pm	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

TITLE: Nut Cover		
SIZE A	DWG. NO. Final Drawings	REV
SCALE: 1:1	WEIGHT:	SHEET 24 OF 24

2

1