# Smart CNC

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Bachelor of Science

In Mechanical Engineering Technology

by

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# ABSTRACT

Currently tabletop computer numerically controlled (CNC) mills do not use feedback information to find a proper feed rate. Table top CNC mills operate having to be told by the user what feed rate it should operate. The user is directed to find either use charts or equations to estimate a feed rate. The problem with estimation is if the material is not uniform then the estimated value is only correct some of the time. Since materials have impurities or a range of tolerances, one feed rate may not work for the entire workpiece. Industrial CNC mills operate in a similar fashion as table top CNC mills. However, the industrial CNC mills have the ability to use an additional module to use feedback information to adjust its feed rate during a cut (1). Even with the availability of this module, industrial CNC mills still use constant user input feed rates a majority of the time and rarely use feedback information. The goal of the Smart CNC project is to design, build, and test a tabletop CNC mill that uses the force being applied to the tool bit as feedback information to continuously determine a proper feed rate throw-out a cut. Ideally the feedback will improve the tool life and quality of cut. Also an important feature of the Smart CNC is its enclosed cabinet design to improve the safety of table top CNC mills.

Upon completion of testing, the Smart CNC was shown to achieve its goals. The constant feed rate testing shown that the tool was taking on excessive force which reduces its life. By changing the feed rate based on the feedback force, the tool was able to prolong its life by seeing forces at or below the target force for a majority of the test. The quality of the cut was also increased by limiting the deflection of the tool bit. Constant feed rate testing showed a 50% increase in slot size while the variable feed rate test showed only a 15% increase in slot size. These tests confirm that a feedback system can be used to improve tabletop CNC mills. The overall safety was also increased by adding a safety shield around the entire CNC and by adding switches to the door to prevent the mill from operating while the door is open. These results prove that the Smart CNC project is a viable option for tabletop CNC mills.

# PROBLEM DEFINITION AND RESEARCH

## *BACKGROUND*

Currently CNC mills operate using a constant feed rate that only changes if the operator updates the feed rate. The issue with using a constant feed rate is that the feed rate is calculated based on average results for the material. By selecting the feed rate based on these results we are forced to assume that the material is uniform throughout the workpiece. Unfortunately, in the real world the materials have imperfections that would most likely be better suited for a different feed rate. For example, wood has knots that are denser than the surrounding wood. To mill through these knots the operator would have to write in the G-code to change the feed rate to accommodate the knot. In a mass production situation, rewriting G-code for every knot would be very time consuming and inefficient. A similar issue occurs when there is a soft spot in the material. The system could operate at a faster feed rate which would decrease the operation time; however the operator would have to input the feed rate for that section. This issue is less noticeable in metals, however even metals have variation between each work piece. In order to optimize the operation time and the cut quality the feed rate should be unique to each work piece.

There are many benefits to selecting the proper feed rate. Tool wear can happen at a much quicker rate if the proper feed rate is not selected, which results in low quality cuts over time. Using the example from above, when the tool hits a knot in a piece of wood, it reduces the life of that tool. Another issue is potential damage to the CNC as a result of not selecting the correct feed rate. If the mill were to start cutting a more dense section of material, the router or other components may become over exerted and cause damage to the CNC. In order to reduce the wear and tear on the CNC the proper feed rate needs to be updated throughout the cut. As previously stated, the current option to update the feed rate is to make the changes to the G-code. In order to minimize the tool wear and potential damage to the CNC, the feed rate should be continuously updated.

## *PRODUCT DEFINITION*

My objective is to design a self-modulating CNC mill. The CNC will continuously determine the force required to cut the material in order to modify and optimize the selected feed rate. I will be using the force exerted on the tool, through the material to automatically adjust the feed rate for optimization. I plan to place pressure sensors against the material (wood) that I am milling. My CNC will only be used to mill wood since wood has visual defects (knots) that I will be able to use to verify if the feed rate should increase or decrease. Once the force is determined, the CNC will follow a PID control in order to determine and adjust the feed rate. Through testing, I will also determine the coefficients to optimize the PID control. I anticipate the cost to build the mill will be less than $600. By optimizing the feed rate I will improve the quality of the cut, decrease the operating time, and to limit the wear and tear on the mill. My design will be a guide for modifying some current tabletop CNCs and/or a proof of concept for larger CNC machines.

## *RESEARCH, TECHNOLOGY AND EXISTING PRODUCTS*

Through my research I have not found many references to automatically adjusting feed rates. I have found a reference to an add-on feature for commercial CNCs that can adjust its feed rate depending on the force being applied to the spindle (1). Since this add-on feature is only for commercial products, table top CNCs have yet to be fully optimized. My CNC will can be a proof of concept to prove that small CNC mills can have the automatic feed rate feature at an affordable price or it could be its own product that come standard with the automatic feed rate feature. A similar idea has been proposed to update the feed rate of CNC lathes (2). My CNC will not have the functionality of the lathe and will use different sensors and algorithms to calculate the updated feed rate. The patent uses fiber optics and magnetic sensors which will not be used in my project. I plan to use force sensors in order to save on costs and to simplify the number of sensors being used. Currently feed rates are used based on an average of that material. If the operator uses the maximum feed rate for that material, they risk the tool hitting an uncharacteristic part of the material and breaking the tool. My CNC will continuously update the feed rate while cutting the material in order to prevent tool breakage and improve the cut.

## *CUSTOMER PROFILE*

This product is intended for individuals that enjoy woodworking or "do it yourself" (DIY) projects. The customer should have some knowledge of operating a CNC or other computer controlled devices. The target age of the customer is over 30 years old. Around the age of 30 is when customers purchase houses and begin working on home improvement projects. This is also around the time when the customer is able to spend more of their income on non-essential items. Since woodworkers are all over the world, there is no specific geographical location for this product.

## *CUSTOMER NEEDS*

1. Safety.
2. Decrease in tool wear
3. Decrease in tool breakage

4. Small in size
5. Easy to use

### *PRODUCT ENGINEERING FEATURES*

1. Shut off switch (Y/N)
2. Safety Shield (Y/N)
3. Tool Wear Time (min)
4. Maximum Force Cut Off Switch (Y/N)
5. Product footprint (ft$^2$)
6. Number of steps to complete milling process (steps)

See the House of Quality (Figure 2) in Appendix A.

### *PRODUCT OBJECTIVES*

1. Safety “cage” to prevent the operator from having any body parts in the cutting area. A shutdown switch, enclosed electronics to prevent electrical shock.
2. By selecting the proper feed rate the tool life should improve and reduce the number of tool breaks
3. The overall size must fit on a typical workbench
4. Have quick connects to allow the CNC be easily moved. Simple to operate software

## DESIGN

Each design was split into three sections: CNC, Cabinet, and Software. Each of these sections was then split into subsections. The CNC section was split into designing for the motion and hardware for the milling operation. The cabinet was designed for safety and managing the circuity and wiring needed to control the CNC. The design of the software included software-hardware communication and the user machine interface (UI).

## CNC DESIGN

The CNC was designed to include 3 axis of operation. The X, Y, and Z axis were all designed to give the user the most workable surface area, accurate measurements, and minimal deflections of the linear guides. The X-axis will be two parallel liner rods that will hold the Y and Z axis. This design will be used for all of the concept designs.

### *CONCEPT DESIGN (Y-Z AXIS)*

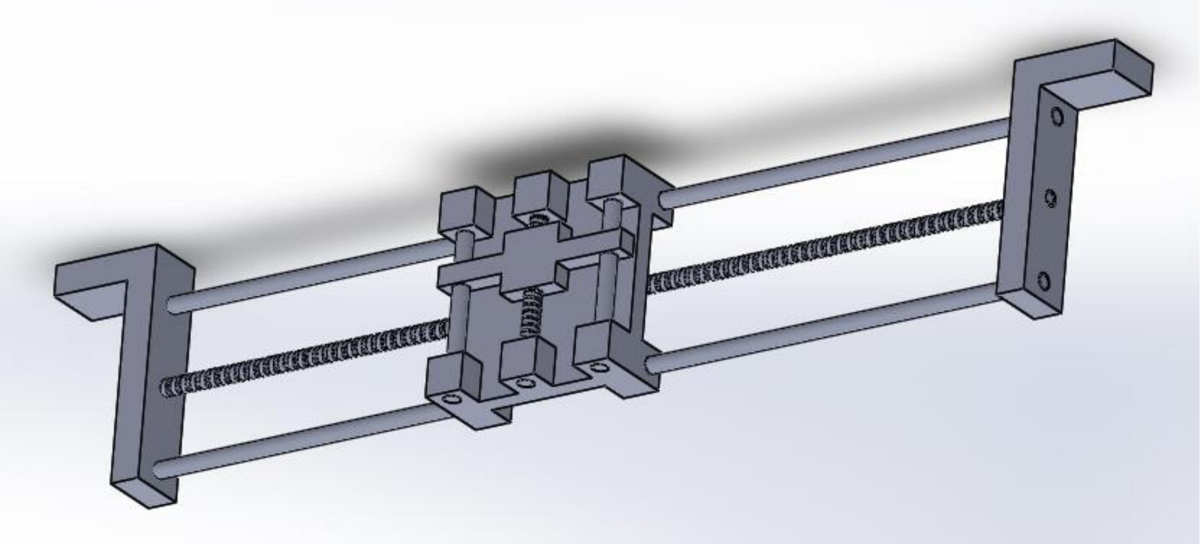


Figure 1: Potential Design For The Y And Z Axis.

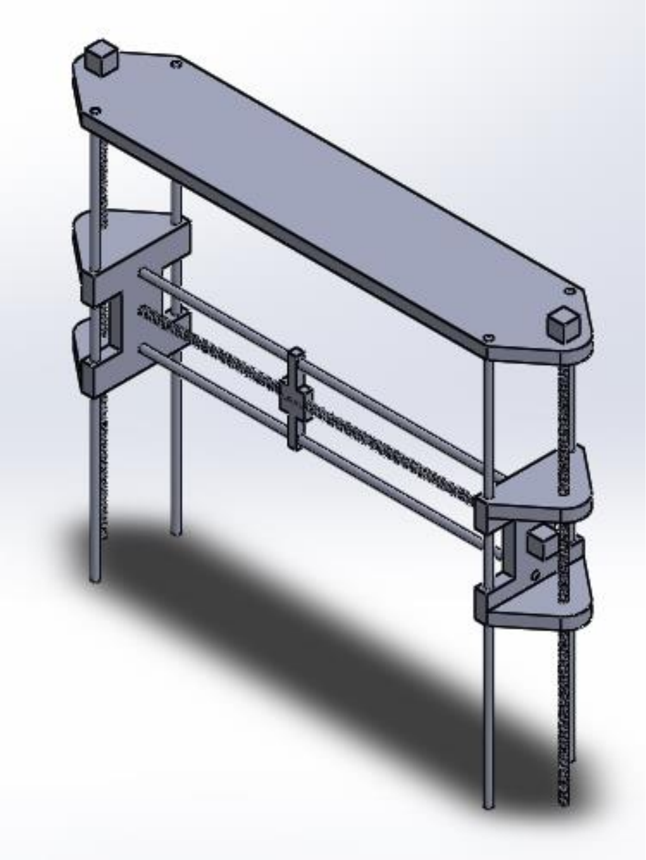


Figure 2: Potential Design For The Y And Z Axis

In comparison, concept number two had a much larger weight which would require larger linear rods for the X-axis. Concept one would require one less stepper motor than concept two. However, concept two has a larger Z-axis range than the Z-axis in concept one. Concept two would require supports to prevent the large Z-axis from becoming top heavy and swaying. However, both concepts would perform the same operations and use the same software. There are several key differences between these two concepts.

In order to determine the best concept, Table 1 was used. The criteria used for determine the optimal design was: resistant to debris, low cost, durable, and large milling area. Each of these criteria was given weights and both concepts were given a rating. The resulting values were used to select the best design.

| Y-Z Axis Concepts | | | | | |
|---|---|---|---|---|---|
| | | Concept 1 X-axis on top | | Concept 2 X-axis on bottom | |
| Criteria | Importance Weight (%) | Rating | Weighted Rating | Rating | Weighted Rating |
| Resistant to Debris | 0.2 | 4 | 0.8 | 1 | 0.2 |
| Low cost | 0.3 | 3 | 0.9 | 2 | 0.6 |
| Durable | 0.3 | 3 | 0.9 | 1 | 0.3 |
| Large milling area | 0.2 | 2 | 0.4 | 3 | 0.6 |
| | 1 | | 3 | | 1.7 |

Table 1: Comparison between the axis concepts

By using Table one, concept one was selected as the best option. The larger linear rods and extra stepper motor would cause the price of parts to greatly increase. The size of concept two would require a large cabinet or would require not having a cabinet at all. This would increase the price to build a cabinet or it would require more safety features. The large Z-axis could cause a top heavy device which can result in uneven and inaccurate cuts. Due to these factors the first concept will be used to design the CNC and cabinet.

### *X-Axis Design*

The X-axis is made up of two separate sections. The X-axis operates by a lead screw “pushing” on the force sensors which allows the axis to slide on the linear rails. This reduces the load of the Y and Z axis that will be applied to the linear rails. The beam deflection was calculated to determine if an 8mm steel linear rail would work for this application.

$$Deflection = \frac{WI^3}{48EI}$$

Equation 1: Beam Deflection At Central Load Point

By assuming a safety factor of 3 to minimize the deflection and a loading of only one linear rail, the results of equation 1 showed a deflection of .2mm. Since the X-axis design uses two linear rails, the maximum deflection would be approximately .1mm. Since this is such a small deflection under worst case scenario conditions, an 8mm rode will be used for all axes. Complete calculations can be found in Appendix D.

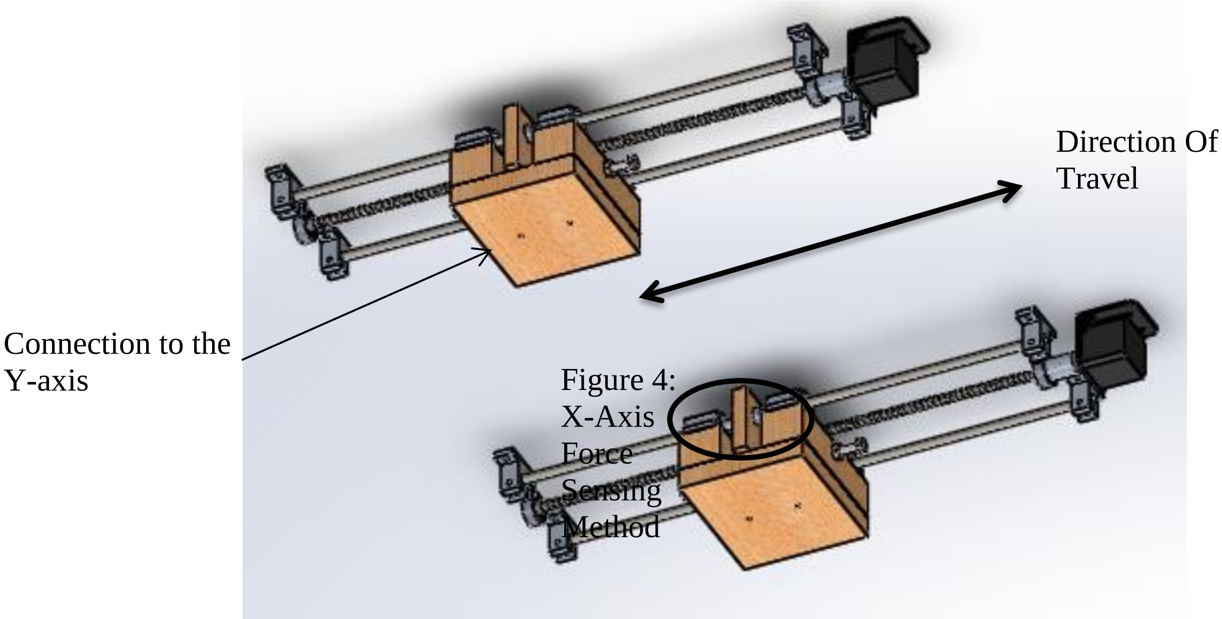


Figure 3: SolidWorks Rendering Of The X-Axis

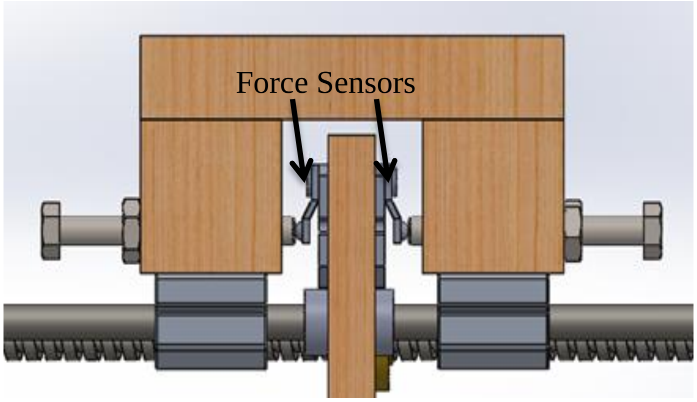


Figure 4: X-Axis Force Sensing Method

The bolts press on the force sensor to as the CNC moves. The bolts act as a way to compensate for tolerances. The threading of the bolts allow for adjustments to be made so that the bolt is resting on the force sensor without applying any unnecessary force. Testing was conducted to verify that the bolts did not add any extra force which would have resulted in false force readings.

### *Y-AXIS DESIGN*

The Y-axis operates similar to the X-axis. It operates using two linear rails that are being "pushed" by a lead screw. The Y-axis connects to both sections of the X-axis and to the Z-axis.

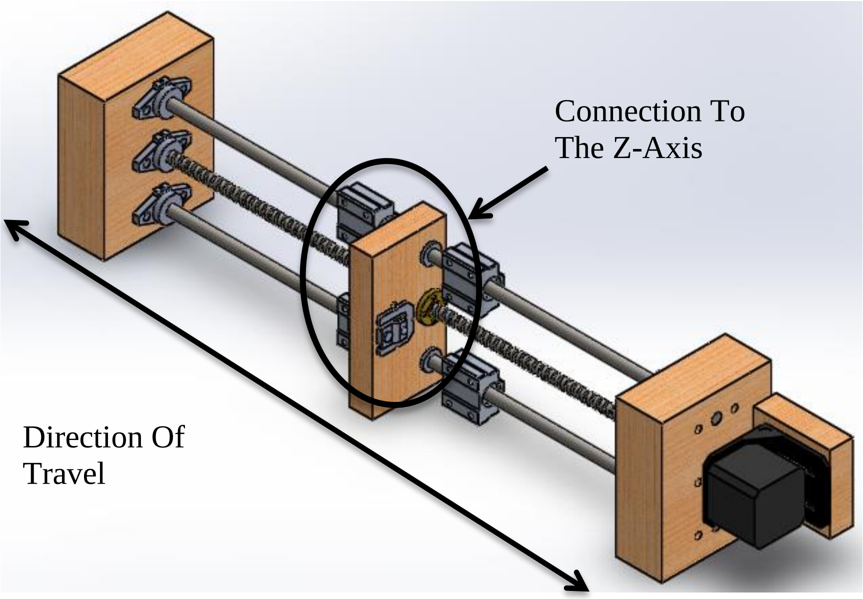


Figure 5: SolidWorks Rendering Of The Y-Axis

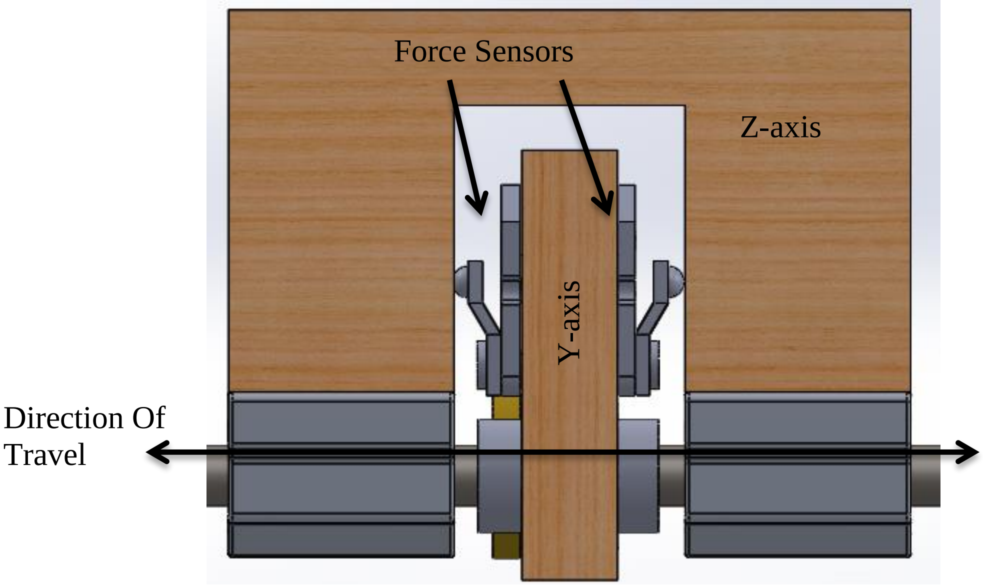


Figure 6: Y-Axis Force Sensing Method

The force sensors on the Y-axis use the same concept as the X-axis. Bolts are used to press on the force sensor. The bolts also remove any error due to tolerance variations. Since the Y-axis will not carry as much weight as the X-axis, it is safe to assume that an 8mm linear rail will work.

### *Z-Axis Design*

The Z-axis is the only axis that does not use force sensors. Since the Z-axis is primarily used for drilling operations, it will not need to have a variable feed rate. The Z-axis will also connect directly to the spindle. Since the Z-axis will only be loaded by the spindle, the 8mm linear rod will once again be adequate.

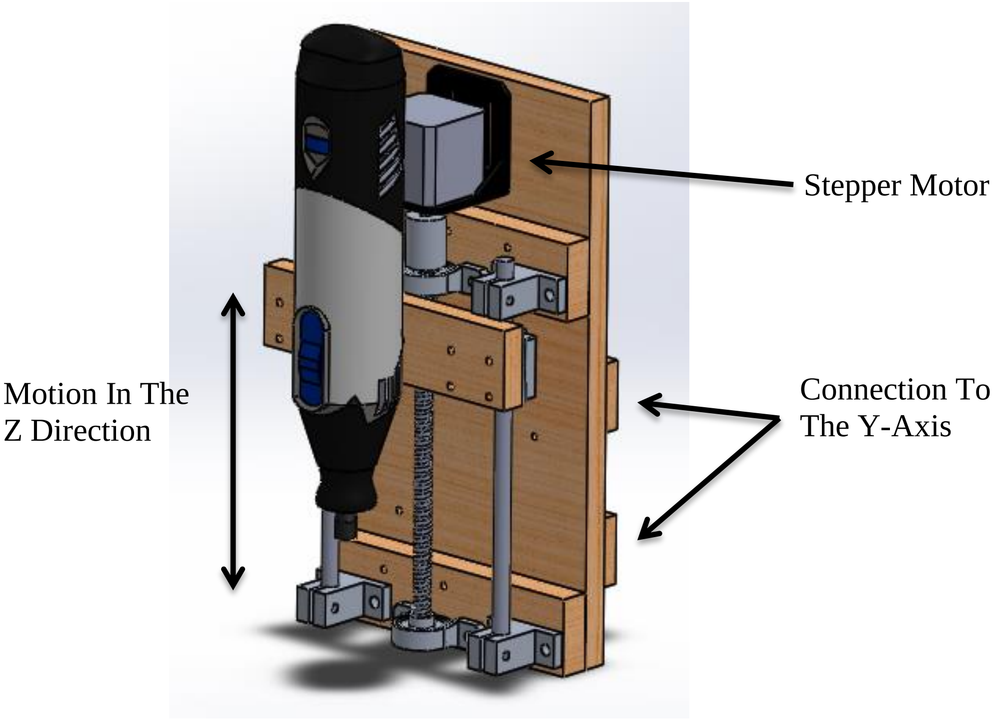


Figure 7: SolidWorks Rendering Of The Z-Axis

### *Full CNC model*

The full CNC model with all of the axis assemblies connected.

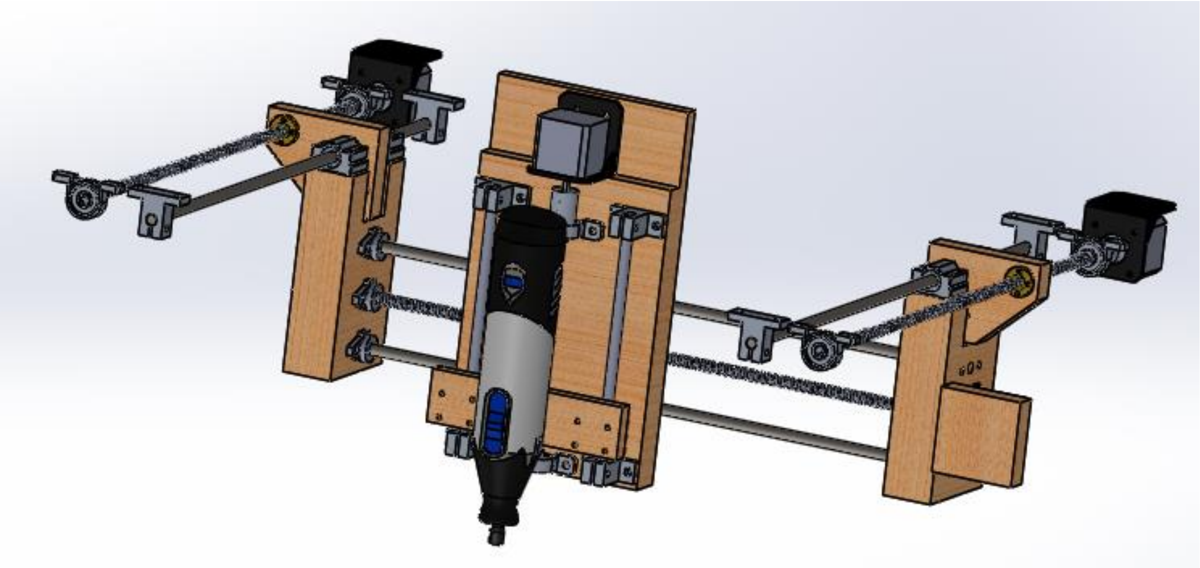


Figure 8: Complete CNC Model

## CABINET DESIGN

The cabinet was designed to safely house the CNC mill along with housing the electrical components needed to operate the mill. The cabinet had two distinct concepts. The first concept was for a cabinet that would have a built in user interface. This concept would require more wiring and software communication which would result in higher expenses. The second concept was very simplistic in relation to the first concept. The second concept would require no additional wiring but would require more information to be displayed on the UI. The final design is a combination of both concepts. Most of the user controls will be displayed on the user interface while still incorporating an emergency shutoff switch. The cabinet will fully enclose the CNC mill with safety switched to shut off the mill when the door is opened. The final design is also space efficient with minimized unusable space. The designed cabinet optimizes the usable space while remaining safe for the user.

### *CONCEPT DESIGN (CABINET)*

The first concept is a complex cabinet. This design includes a location to place a laptop with easy USB connections installed on the top of the cabinet. In addition to the USB, there will also be a power port for the laptop in case of long milling operations. The cabinet will have a single standard power cord that is compatible with all standard outlets. Internally, the cabinet will divert the electricity to the CNC, rotary tool outlet, laptop charging port, and the user control panel. The electrical components will be housed in side cabinet with an access panel in the back of the CNC cabinet. The CNC cabinet will have acrylic walls that provide safety and visibility to the user. On the door, there will be limit switches that will prevent the mill from operating when the door is open. This will prevent the user from coming in contact with the mill while the mill is operating. The mill can also be left alone without the worry of another individual coming into contact with the operating mill. This concept also includes a user panel that would include the ability to manually control the CNC in order to create a user defined zero location. The manual control would be operated by push buttons or a joystick with a course and fine adjustment options. The control panel would also include a LCD screen that would display the estimated milling time, fault codes or other useful information. A key feature for the control panel is the emergency stop button. The emergency stop button will immediately shut the CNC off in case the user see a potential issue and needs to stop the CNC. Figure 9 shows a sketch of the complex cabinet concept. All of the key features are labeled with a brief description of the feature.

Features

1) Standard Wall Plug
2) Large Space For Placing The User’s Laptop.
3) USB Connection With Additional Power For The Laptop
4) Clear Acrylic Walls
5) Outlet That Will Power The Rotary Tool
6) User Control Panel That Includes Manual CNC Control, LCD Display, Emergency Stop Button
7) Shop-Vac Hose Connection For Easy Clean-Up
8) Door Switches To Prevent The Mill From Operating With The Door Open.
9) Electrical Cabinet

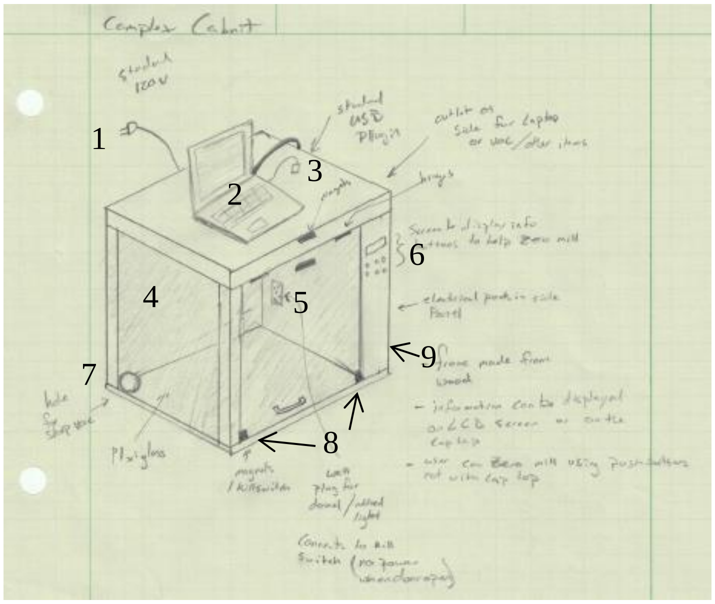
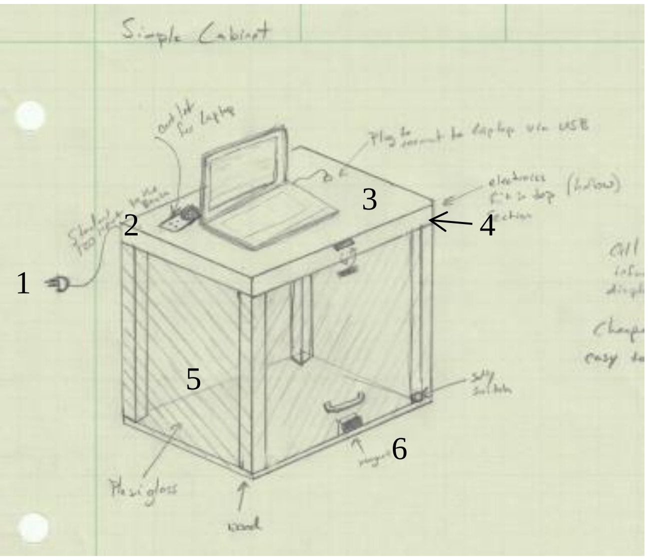


Figure 9: Complex Cabinet Design Including Listed Features

The simple cabinet concept has minimal features. The cabinet has the same space for a loptop to be charged and connected to the CNC by a USB plug as the complex cabinet. The simple cabinet also has the same single standard power cord. The electronics would be stored in an narrow section under where the laptop sits. The electronics would have an access panel in the back of the cabinet in case of maintainance. All four side walls would be made of acrylic so the user would be able to see the mill from all angles. All user controls would be displayed on the UI instead of using a physical control panel. This saves in the cost of hardware but reduces the saftey of the product by not having an emergency shut off switch. Figure 10 shows a sketch of the simplistic cabinet concept. The features are also listed next to the sketch with a breif discription of the feature.



1) Standard Wall Plug
2) USB Connection With Additional Power For The Laptop
3) Large Space For Placing The User's Laptop.
4) Electrical Cabinet
5) Clear Acrylic Walls
6) Door Switches To Prevent The Mill From Operating With The Door Open.

Figure 10: Simplistic Cabinet With Alternative Magnet Locations

Both cabinet concepts were compared using Table 2. Along with these two cabinet designs, the idea of not using a cabinet was also considered. After discussing the criteria with potential customers, the importance weights were created and values were assigned to each cabinet. Over all the complex cabinet was selected as the best option.

| Cabinet Concepts | | | | | | | |
|---|---|---|---|---|---|---|---|
| ▨ | | Complex Cabinet | | Simple Cabinet | | No Cabinet | |
| Criteria | Importance Weight (%) | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating |
| Safety | 0.3 | 4 | 1.2 | 3 | 0.9 | 0 | 0 |
| Low cost | 0.2 | 2 | 0.4 | 3 | 0.6 | 4 | 0.8 |
| Easy Maintenance | 0.2 | 3 | 0.6 | 2 | 0.4 | 3 | 0.6 |
| Appearance | 0.1 | 3 | 0.3 | 2 | 0.2 | 1 | 0.1 |
| User Interface | 0.2 | 3 | 0.6 | 1 | 0.2 | 0 | 0 |
| ▨ | 1 | ▨ | 3.1 | ▨ | 2.3 | ▨ | 1.5 |

Table 2: Cabinet Concept Selection

## *CONCEPT DESIGN (CABINET DOOR)*

Two designs for the cabinet door were created. Design A shows the magnetic door lock and safety switch in the center of the door opening. Concept B shows two magnets on the outer edges of the door. Since concept A would interfere with inserting and taking out the workpiece, concept B was chosen as the door design. This door design will be added to the complex cabinet which was determined to be the ideal choice based on the customer input.

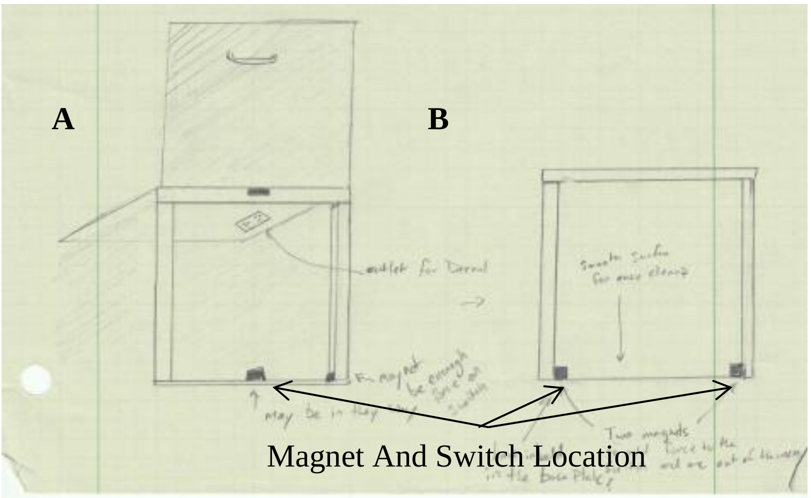


Figure 11: Concepts For The Cabinet Door Magnets And Safety Switches

The final design was a combination of the simple and complex design. The final design will utilize the side electrical cabinet with the master kill switch that is easily accessible. The remaining controls will be incorporated into the software. The door will use magnets to keep the door latched during operation while being out of the way during the loading and unloading if the CNC.

Figure 12: SolidWorks Rendering Of The Final Cabinet Design

# SOFTWARE DESIGN

## *CONCEPT DESIGN (USER INTERFACE)*

The user interface (UI) is the direct connection between the operator and the CNC. The interface needs to be simplistic in design and intuitive. As testing of the CNC is conducted, the UI will continue to be updated to optimize the experience for the user.

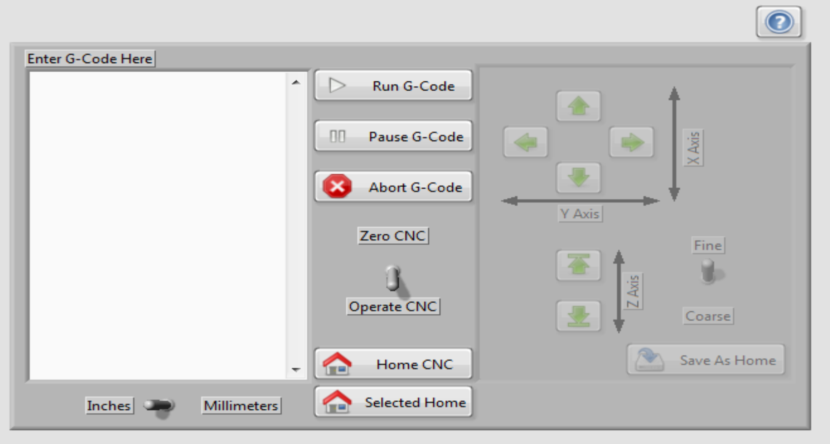


Figure 13: Preliminary Design For The User Interface

# COMPLETE DESIGN

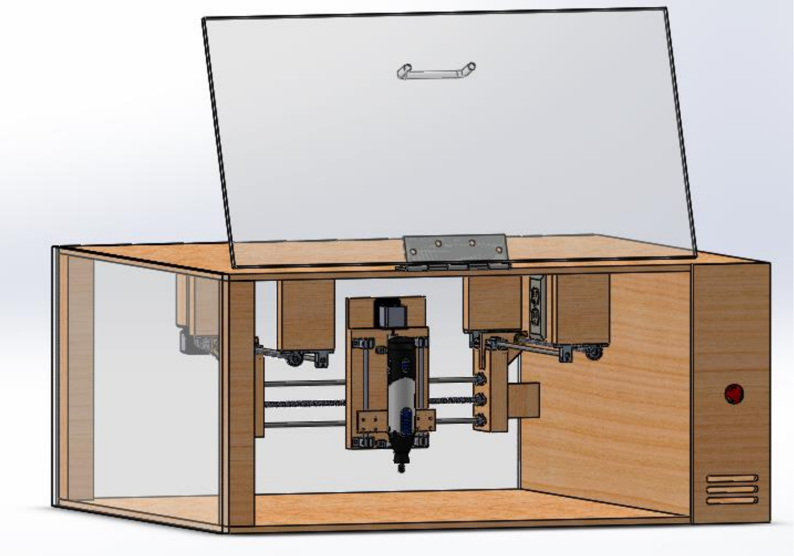


Figure 14: Full CNC Assembly

All SolidWorks drawings can be found in Appendix B

## MANUFACTURING

The manufacturing process was broken down into three sections; mechanical, electrical, and software. The mechanical components include the cabinet and the X-Y-Z axes. The electrical portion includes the force sensors, stepper motors, and the main electrical power that will be supplied to the CNC. The software includes the communication to the Arduino Mega micro-controller, converting voltage from the force sensors, ability to read G-code commands, and the simple to use UI. Each of these sections were then blended together to form the functioning CNC mill.

### *MECHANICAL*

Most of the manufactured components were made using wood. Wood was selected for its light weight, low cost, and ease of machining. Aluminum and steel were also considered but due to the cost of the raw materials and the cost of machining, these materials were ruled out as viable options. Parts for custom 3D printers were used as the remaining mechanical components. The 3D printer parts were selected for their accuracy and low cost.

All manufacturing was completed in a home workshop using commonly found tools. To improve the accuracy of the location of holes, the SolidWorks drawing were printed to full size and taped to the surface of the work piece. By using the actual drawing, this limits the error of using other measuring devices and guarantees the proper distance between holes.

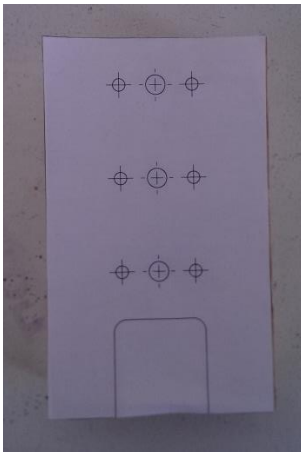


Figure 15: SolidWorks Drawling Printed And Cut To Full Scale

Once the drawling has been taped to the workpiece, a drill press is used to accurately drill the holes. A drill press allows for perfectly perpendicular holes where a hand drill would have caused the hole to be drilled at an improper angle. Wrong angle could cause the axes to bind and potentially damage the stepper motors.

Figure 16: Drill Press Operation

A table saw was used to cut the large panels of the cabinet. The large panels were cut using a 1/8th in saw blade. Smaller components were cut by using a circular saw.

Figure 17: Circular Saw Operation

### *ELECTRICAL*

The electrical components were selected based on their ease of use and their low cost. The Arduino Mega was selected as the micro-controller specifically for its high number of digital input/output (DI/O) pins. Since there are eight safety switches and four stepper motors, the total DI/O needed was 14 which exceed the Arduino Uno's capability. The Arduino Mega also is capable of communicating with Labview software which will be the chosen software. The 5 volt pin on the Arduino Mega was used to supply voltage to the safety switches and to the force sensors since the Arduino Mega is only able to measure up to 5 volts and since minimal current was needed.

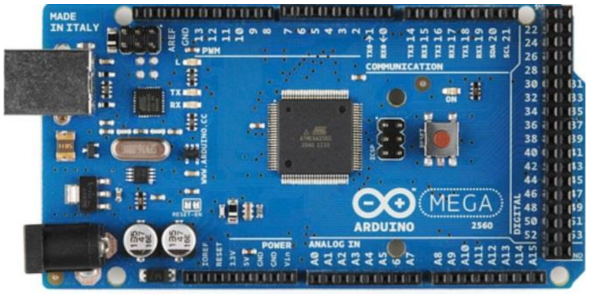


Figure 18: Arduino Mega Micro-Controller

The motion is being controlled by Nema 17 stepper motors paired with the DRV8824 stepper driver chip. The Nema 17 uses 2 amps (A) per phase and has a holding torque of 64oz.-in. The Nema 17 stepper motors are commonly used in 3D printing applications due to their high accuracy and small size. The DRV8824 was selected because it has the ability to control stepper motors with high currents. The DRV8824 is also easy to use by only requiring two wire communications from the Arduino Mega (step and direction).

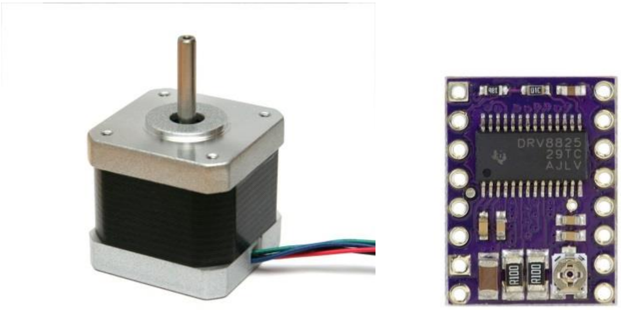


Figure 19: (Left) Nema 17 Stepper Motor. (Right) DRV8824 Stepper Motor Driver

A 12 volt 30A power supply was used to power all of the electrical components inside of the CNC. Calculations show that the minimum current needed in the CNC would be approximately 15A. The safety factor of 2 allows the CNC to operate without the potential of overloading the power supply or causing other electrical damage.

The Pololu force sensors were use because they are easy to use, have a small footprint, and measure up to 22 lbs. Testing of the CNC shown that only in unlikely situations would the force seen at the tool bit exceed 3 lbs. The Pololu force sensors are able to accurately measure the forces between 0 and 3 lbs.

Figure 20: Pololu Force Sensor

The circuits were tested on a bread board to prove that the circuit worked before hardwiring it. The breadboard would allow for easy changed to be made to the circuit without having to re-soldier sections.

Figure 21: Testing Of The Stepper Motor Circuit

Once testing was completed, the circuit was transferred to a soldier board that has the same footprint as the bread board. By having the same footprint, the circuit did not need to be redesigned to fit a different board. The completed circuit was again tested before connecting it to the CNC.

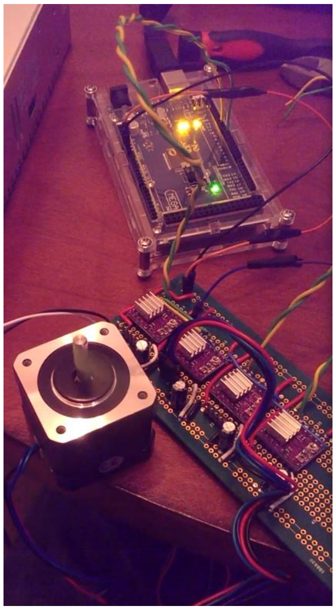


Figure 22: Testing Of Completed Circuit Board

The circuit board, Arduino Mega, and power supply were then mounted in the electrical cabinet of the CNC.  The Electrical cabinet is walled off so that individuals can not touch the electronics during the milling operation.

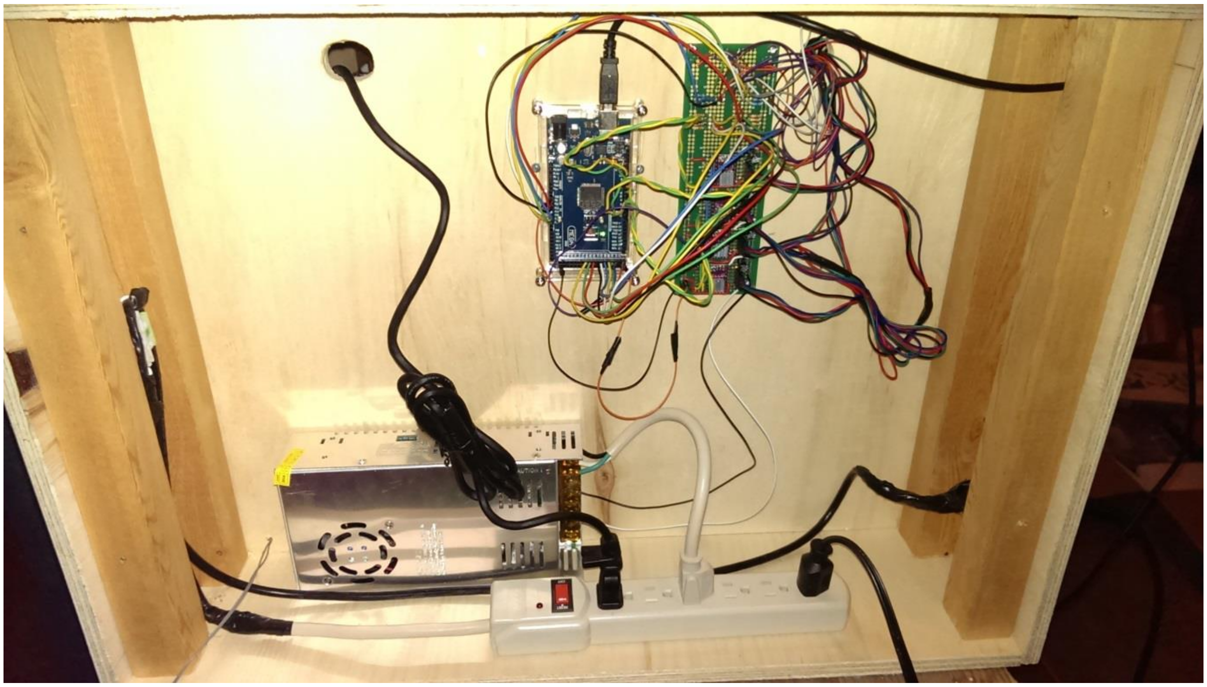


Figure 23: Mounted Electrical Components With Safety Wall Removed

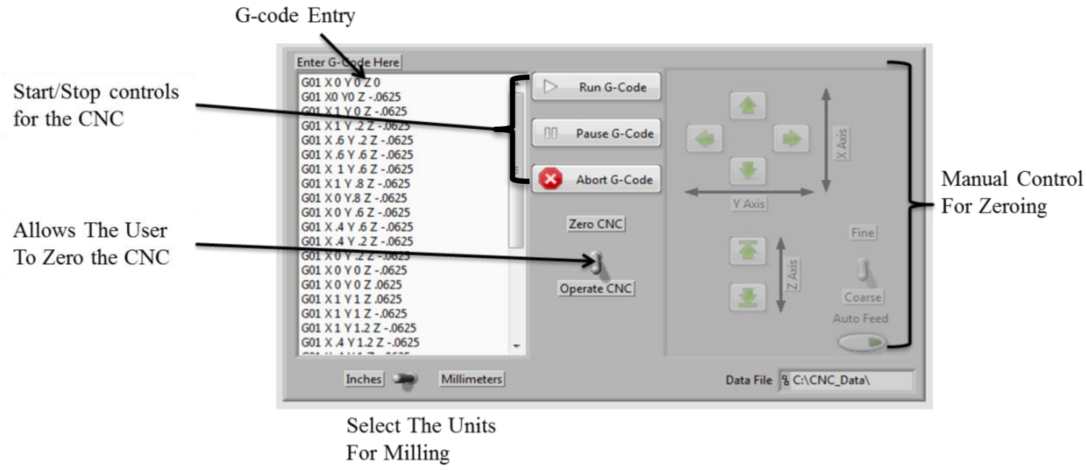
The internal power supply is connected to the master kill switch. When the master kill switch is pressed, all of the electronics in the system will lose power.

Electrical components and wiring diagrams are located in Appendix C.

### *SOFTWARE*

The UI was created using Labview software. Labview is graphical software that uses images for coding instead of the common "C" style of coding. Labview also has the capability of having multiple operations happen at the same time in a single loop. The ability to have multiple operations in a single loop allows for the safety switches to stop the operation of the CNC without having to stop the main loop to check the switches. Labview also has the capability to have multiple loops running at the same time. The multiple loops are ideal for a "sensing loop" and a "recording loop." The sensing loop communicates with the Arduino mega to read the force sensors, determine the new feed rate, and then send the new feed rate to the stepper motors. The recording loop takes the recorded force readings and feed rate values and saves them to a comma separated file (csv). The csv can then be open in Microsoft Excel.

The final design of the UI was very similar to the preliminary design. Some features were removed due to complexities in the coding. All of the features shown are functional. The user has the ability to enter G-code, select the milling units, start the mill, pause the mill, stop the mill, and manually zero the CNC. These features were determined as the most important features to be included in the UI.

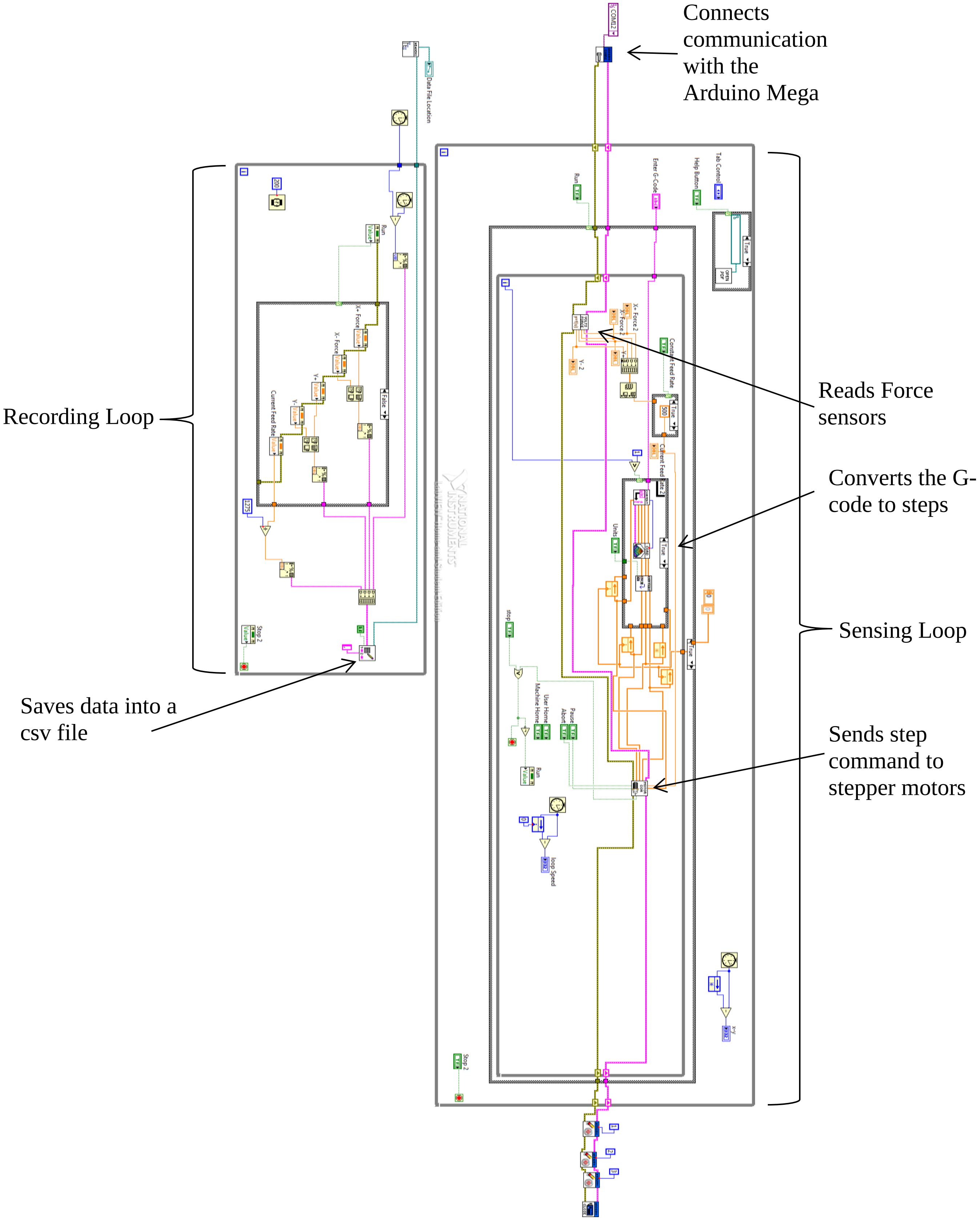


```
G01 X 0 Y 0 Z 0
G01 X0 Y0 Z -.0625
G01 X 1 Y 0 Z -.0625
G01 X 1 Y .2 Z -.0625
G01 X .6 Y .2 Z -.0625
G01 X .6 Y .6 Z -.0625
G01 X 1 Y .6 Z -.0625
G01 X 1 Y .8 Z -.0625
G01 X 0 Y.8 Z -.0625
G01 X 0 Y .6 Z -.0625
G01 X .4 Y .6 Z -.0625
G01 X .4 Y .2 Z -.0625
G01 X 0 Y .2 Z -.0625
G01 X 0 Y 0 Z -.0625
G01 X 0 Y 0 Z .0625
G01 X 1 Y 1 Z .0625
G01 X 1 Y 1 Z -.0625
G01 X 1 Y 1.2 Z -.0625
G01 X .4 Y 1.2 Z -.0625
```

Figure 24: Final User Interface Design

Labview also allows for multiple levels of coding. These different levels allow for large portions of code to be represented by an individual block instead of actual code. Each block also has multiple layers. The blocks allow for easier debugging by simply finding the block that is having the error. These blocks also make the source code easier to read and understand.

Since the Arduino Mega can only measure voltage and the Pololu sensor only works using resistance, a conversion equation was needed. The Derivation of the equation can be found in Appendix D.



Connects communication with the Arduino Mega

Recording Loop

Reads Force sensors

Converts the G-code to steps

Sensing Loop

Saves data into a csv file

Sends step command to stepper motors

Figure 25: Half Of The Top Level Of Source Code

## RESULTS

The two tests that were conducted were meant to show the improvement that the algorithm has on the deflection of the tool bit and to limit the forces seen by the tool bit. The deflection test was conducted by starting the tool bit off of the edge of a piece of wood. The tool bit would then impact the wood to cause a deflection. The process was completed using a constant feed rate and then using the feedback algorithm.

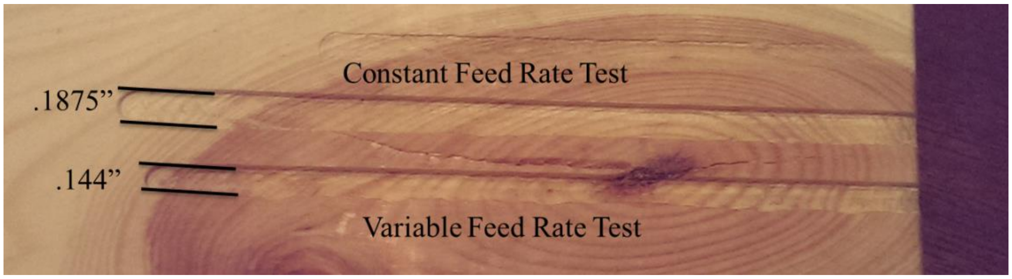


Figure 26: Impact Deflection Test Results

The desired slot size is .125”. The constant feed rate test resulted in a slot the size of .1875” which is 50% larger than desired. The variable feed rate test resulted in a slot size of .144” which is 15% larger than desired.

The force sensing test was conducted by milling similar portions of wood with a constant feed rate and a variable feed rate. The cuts were made at the same depth and with the same spindle speed. Through testing, the average force seen by the tool bit was .4 lbs. The control algorithm was set to try to maintain a constant force of .4 lbs. Any force over .4 lbs. is considered to be a loss of tool life while any force below the .4 lbs. is considered to prolong the life of the tool.

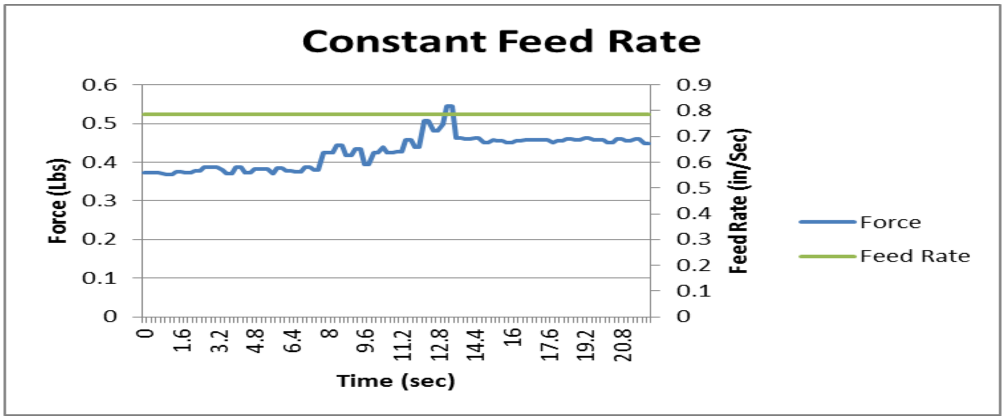


Figure 27: Constant Feed Rate Test Results

The constant feed rate test saw forces greater than the .4 lbs. for over half of the test. These forces will result in a loss of tool life.

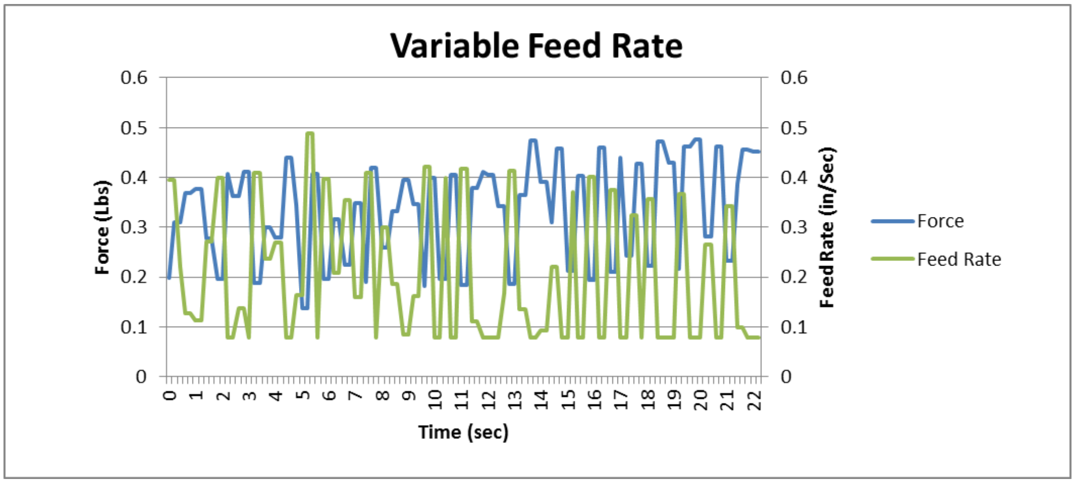


Figure 28: Variable Feed Rate Test Results

The variable feed rate test shows that the control algorithm tries to maintain the force to .4 lbs. The majority of the test shows a force below the ideal .4 lbs. This would result in an increase in tool life. The small portion of the test that the force was above .4 lbs, the feed rate can be seen to be at is minimum value.

## CONCLUSION

The control logic worked as expected. The feed could be seen increasing and decreasing with the force. The constant feed rate tests shown a higher deflection of the tool bit and saw forces higher than the target of 0.4 pounds. The variable feed rate tests show the feed rate adjusting to try to maintain the target force. These tests confirm that a tabletop CNC mill can be improved by adding a feedback system to monitor the tool bit force. The quality of cut could be seen to increase in the deflection test by reducing the error form 50% to 15%.

In order to see more results, more testing of the control algorithm needs to be conducted. As the testing is completed, the algorithm can be improved which will result in an improved cut quality and feedback control. As the algorithm is improved, the quality and reaction of the system is expected to be increased.

## PROJECT MANAGEMENT

### *BUDGET (PROPOSED)*

The proposed budget for the Smart CNC was $600. Upon completion of the construction, the total amount spent was $682. The over budget is due to new force sensors being purchased and the purchasing of a new version of Labview. These two purchases were unforeseen but needed to be made for the project to be completed.

## SCHEDULE (PROPOSED)

Near the end of the project, manufacturing and testing became delayed. Due to shipment issues, redesigns, and purchasing of new materials, the testing was not able to be completed as originally projected. However once all of the materials arrived, the manufacturing as able to be completed and testing was able to conducted. All of the original scheduled testing was able to be completed before the project due date.

| Brandon Bercot<br>Smart CNC<br>TASKS | 8/24/2016 | 8/31/2016 | 9/7/2016 | 9/14/2016 | 9/21/2016 | 9/28/2016 | 10/5/2016 | 10/12/2016 | 10/19/2016 | 10/26/2016 | 11/2/2016 | 11/9/2016 | 11/16/2016 | 11/23/2016 | 11/30/2016 | 12/7/2016 | 12/14/2016 | 12/21/2016 | 12/28/2016 | 1/4/2017 | 1/11/2017 | 1/18/2017 | 1/25/2017 | 2/1/2017 | 2/8/2017 | 2/15/2017 | 2/22/2017 | 3/1/2017 | 3/8/2017 | 3/15/2017 | 3/22/2017 | 3/29/2017 | 4/5/2017 | 4/12/2017 | 4/19/2017 | 4/26/2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Design I** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design Draft | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Revise Draft | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Final Design Report | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design II | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Begin Design Sketches | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Proof of Design Agree (advisor) | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Revise Design/ Consepts | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Concepts/Selection (advisor) | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (Individual Parts) | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (x-Axis Assembly) | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (Dremel Holder) | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (y,z- Axis Assembly) | | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (Cabinet) | | | | | | | | | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | | |
| 3D Model - (Full System) | | | | | | | | | | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | | |
| Model Analysis (FEA) | | | | | | | | | | | | | | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | | |
| Model Analysis (Motion) | | | | | | | | | | | | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | |
| Update Design Report | | | | | | | | 🟩 | | 🟩 | | 🟩 | | 🟩 | | 🟩 | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | |
| Design Presentation | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | |
| Design III | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Manufacture | | | | | | | | | | | | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | | | | | | |
| Test | | | | | | | | | | | | | | | | | | | | | | | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | | | | |
| Tech Expo | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | |
| Project Presentation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | |

🟩 Completed On Time
🟥 Delayed
🟨 Completed After Delay

Figure 29: The Final Schedule For The Smart CNC Project.

## WORKS CITED

1. Find Your Feed Rate On The Fly. *Modern Machine Shop.* [Online] July 15, 1998. [Cited: September 19, 2016.] http://www.mmsonline.com/articles/find-your-feed-rate-on-the-fly.
2. **Travez, Joe V., et al., et al.** *Closed-loop CNC machine system and method. US8136432 B2* United States, March 18, 2011. Grant.

## APPENDIX A

| | | | **Engineering Requirements** (units) | | | | | | | | | | | | | | **Customer Satisfaction Rating** (0.00 - 1.00) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Importance wt.** | Shut Off Switch (Y/N) | Safety Shield (Y/N) | Maximum Force Cut Off (Y/N) | Tool Wear Time (min) | Product Footprint (ft^2) | Steps To Complete Milling Pricess (Steps) | | | | | | | | | | | | |
| | **Customer Requirements** | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | CP | A | B | C |
| 1 | Saftey | 0.15 | 9 | 9 | 9 | | | | | | | | | | | | | | | |
| 2 | Limit Tool Wear | 0.25 | | | 3 | 9 | | | | | | | | | | | | | | |
| 3 | Decrease Tool Breakage | 0.35 | | | 3 | 9 | | | | | | | | | | | | | | |
| 4 | Small In Size | 0.10 | | 1 | | | 9 | | | | | | | | | | | | | |
| 5 | Easy To Use | 0.15 | | | | | 1 | 9 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | | | | | | |
| | Total Importance | 1.00 | | | | | | | | | | | | | | | | | | |
| | Engineering requirement importance | | 1.35 | 1.45 | 3.15 | 5.4 | 1.05 | 1.35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| **Performance** | Current Product | | | | | | | | | | | | | | | | | | | |
| | competitor A | | | | | | | | | | | | | | | | | | | |
| | competitor B | | | | | | | | | | | | | | | | | | | |
| | competitor C | | | | | | | | | | | | | | | | | | | |
| | New Product Targets | | | | | | | | | | | | | | | | | | | |

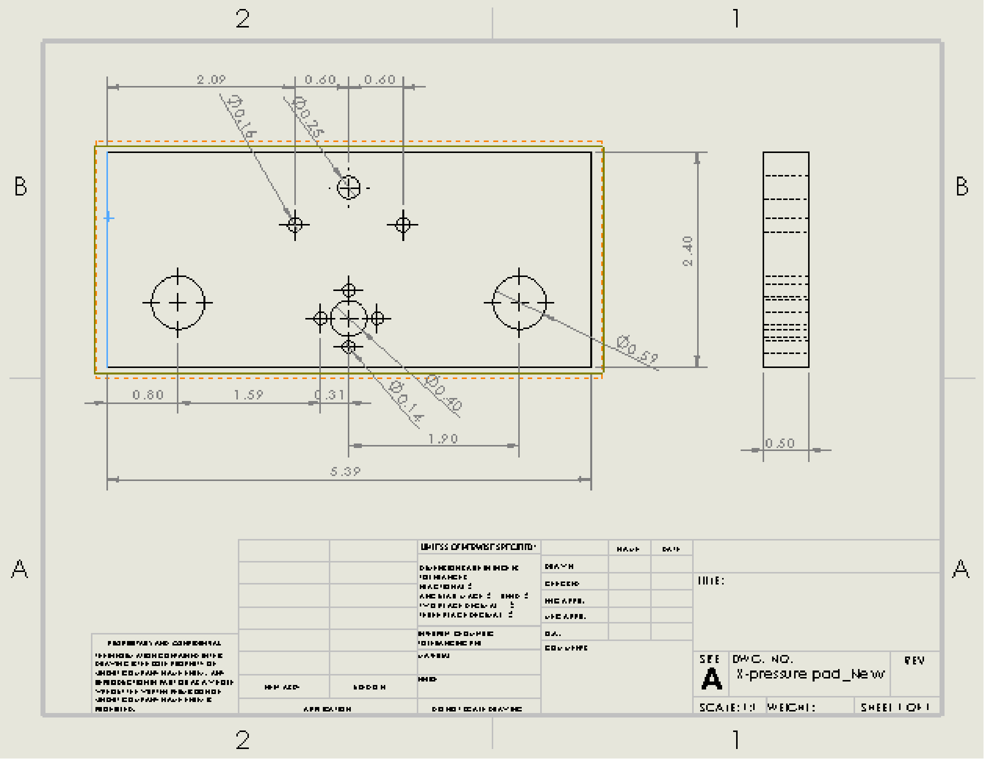
Figure 30: House Of Quality For The Smart CNC Project.

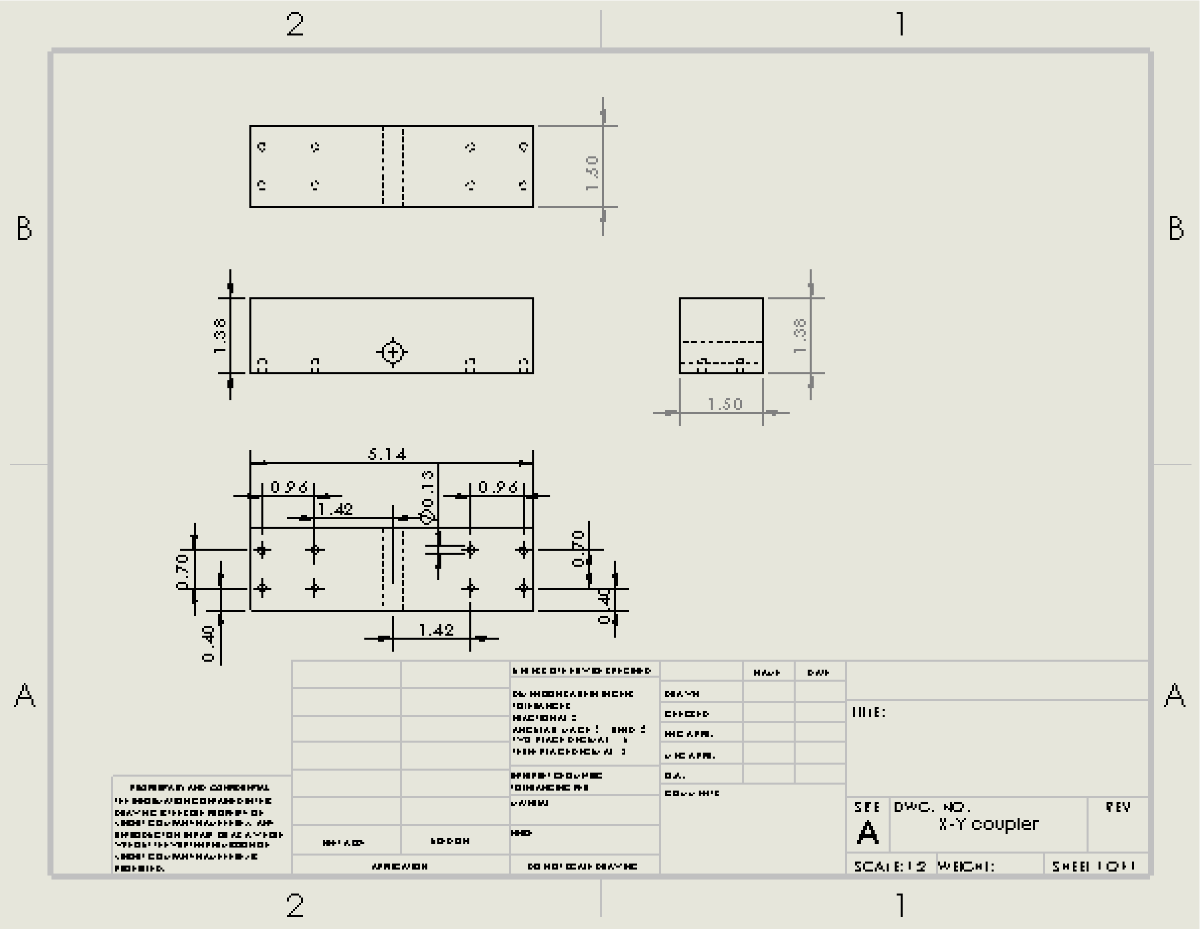
| Part Name | Quantity | Price | Extended Price |
|---|---|---|---|
| 12v 30A Power Supply | 1 | $19.98 | $19.98 |
| 200mm Lead Screw Set | 2 | $13.57 | $27.14 |
| 500mm Lead Screw Set | 1 | $17.50 | $17.50 |
| 500mm Lead Screw Set | 2 | $16.99 | $33.98 |
| 600mm Linear Rod | 1 | $55.64 | $55.64 |
| 8mm Linear Rod Support (10 Pack) | 1 | $15.99 | $15.99 |
| 8mm Linear Rod Support (2 Pack) | 2 | $4.46 | $8.92 |
| 8mm Nut Block (2 Pack) | 1 | $12.98 | $12.98 |
| Arduino Mega | 1 | $13.15 | $13.15 |
| Breadboard (3 Pack) | 1 | $7.84 | $7.84 |
| Drag Chain | 1 | $10.14 | $10.14 |
| Flanged Linear Rod Support (2 Pack) | 2 | $6.50 | $13.00 |
| Flanged Pillow Block (2 Pack) | 1 | $7.96 | $7.96 |
| Limit Switch (10 Pack) | 1 | $4.64 | $4.64 |
| Linear Bearings (6 Pack) | 1 | $7.99 | $7.99 |
| LM358 Op-Amp (10 Pack) | 1 | $5.69 | $5.69 |
| Nema 17 (5 Pack) | 1 | $62.00 | $62.00 |
| Slide Bearing (4 Pack) | 1 | $9.98 | $9.98 |
| Slide Bearing (4 Pack) | 2 | $6.80 | $13.60 |
| Stepper Moter Coupler (2 Pack) | 1 | $5.97 | $5.97 |
| Stepper Motor Driver (5 Pack) | 1 | $13.99 | $13.99 |
| Stepper Motor Mount (5 Pack) | 1 | $17.79 | $17.79 |
| Weight Sensors (4 Pack) | 2 | $8.99 | $17.98 |
| Lumber | 6 | $0.80 | $4.80 |
| Screws | 1 | $38.88 | $38.88 |
| USB Cable Mount | 1 | $5.91 | $5.91 |
| Emergency Stop Button | 1 | $6.63 | $6.63 |
| Wires | 1 | $15.99 | $15.99 |
| Force Sensors | 6 | $14.99 | $89.94 |
| 4'X2' plywood | 3 | $10.00 | $30.00 |
| 1.5'X2' acrylic | 1 | $21.00 | $21.00 |
| Large acrylic | 1 | $40.00 | $40.00 |
| Labview Software | 1 | $25.00 | $25.00 |
|  |  | Total: | $682.00 |
|  |  | Remaining: | -$82.00 |

Table 3: Budget For The Smart CNC

# APPENDIX B

Drawings:

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1.38
1.50
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0.70
0.40
0.40
1.42
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REV
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SHEET 1 OF 1
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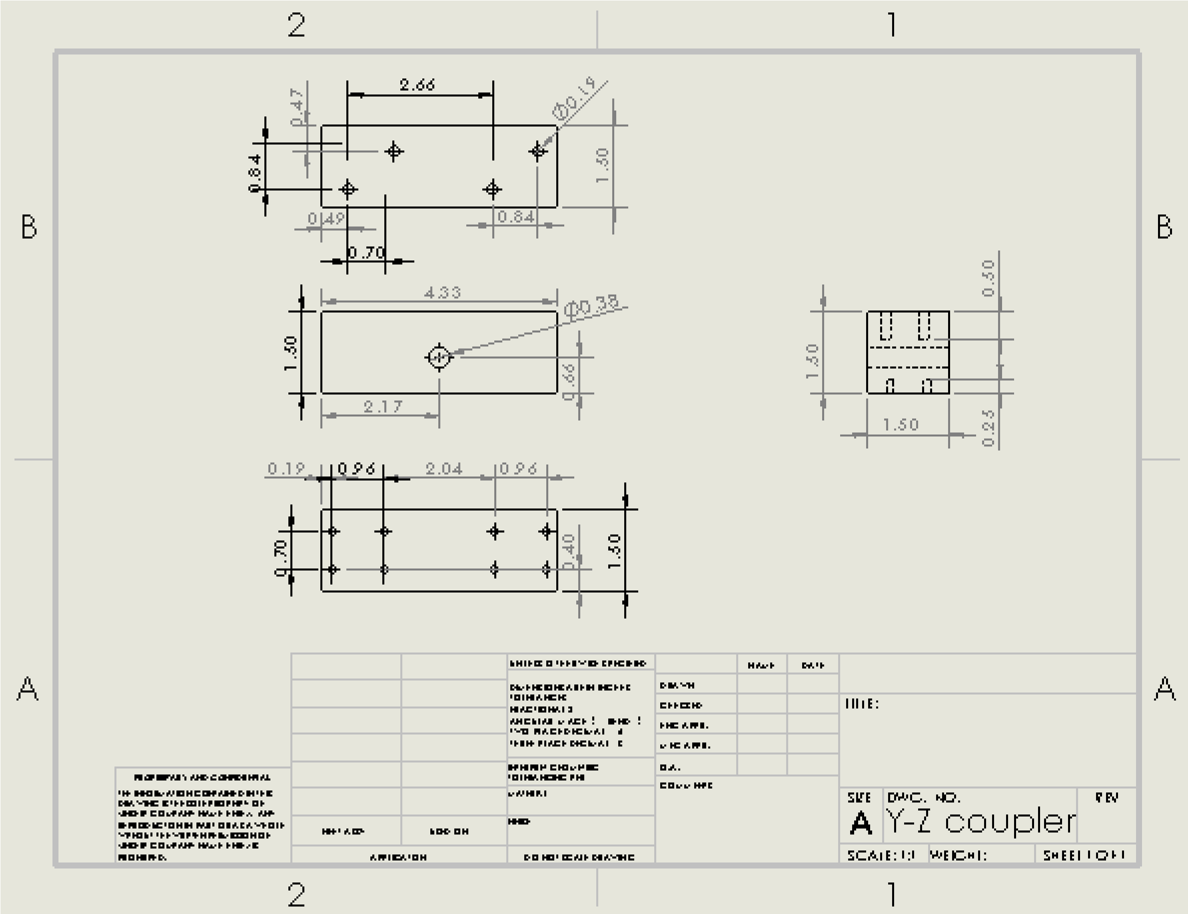
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1.50
0.66
2.17
0.50
1.50
1.50
0.25
0.19
0.96
2.04
0.96
0.70
0.40
1.50
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
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REV
A
Y-Z coupler
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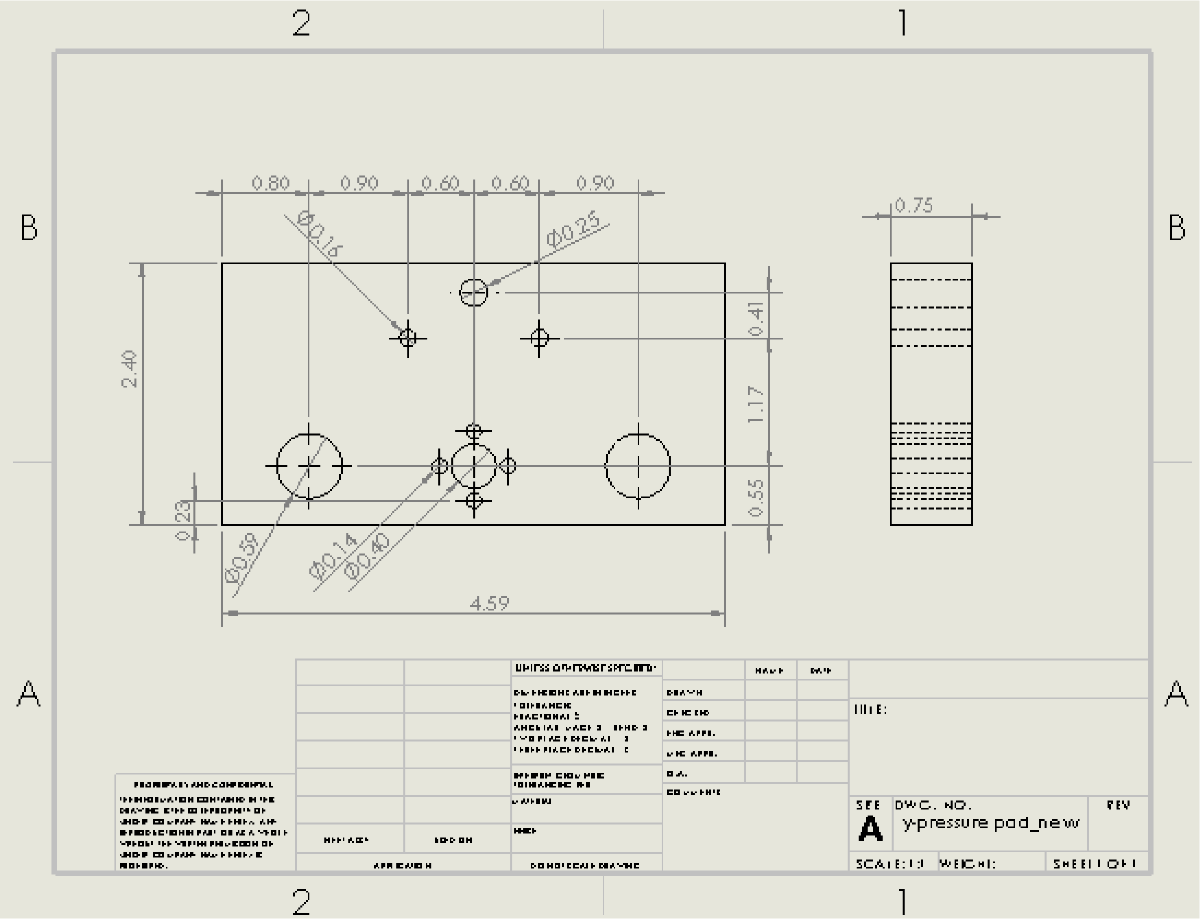
WEIGHT:
SHEET 1 OF 1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Ø0.25
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1.17
0.55
0.23
Ø0.59
Ø0.14
Ø0.40
4.59
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
y-pressure pad_new
REV
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WEIGHT:
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APPLICATION
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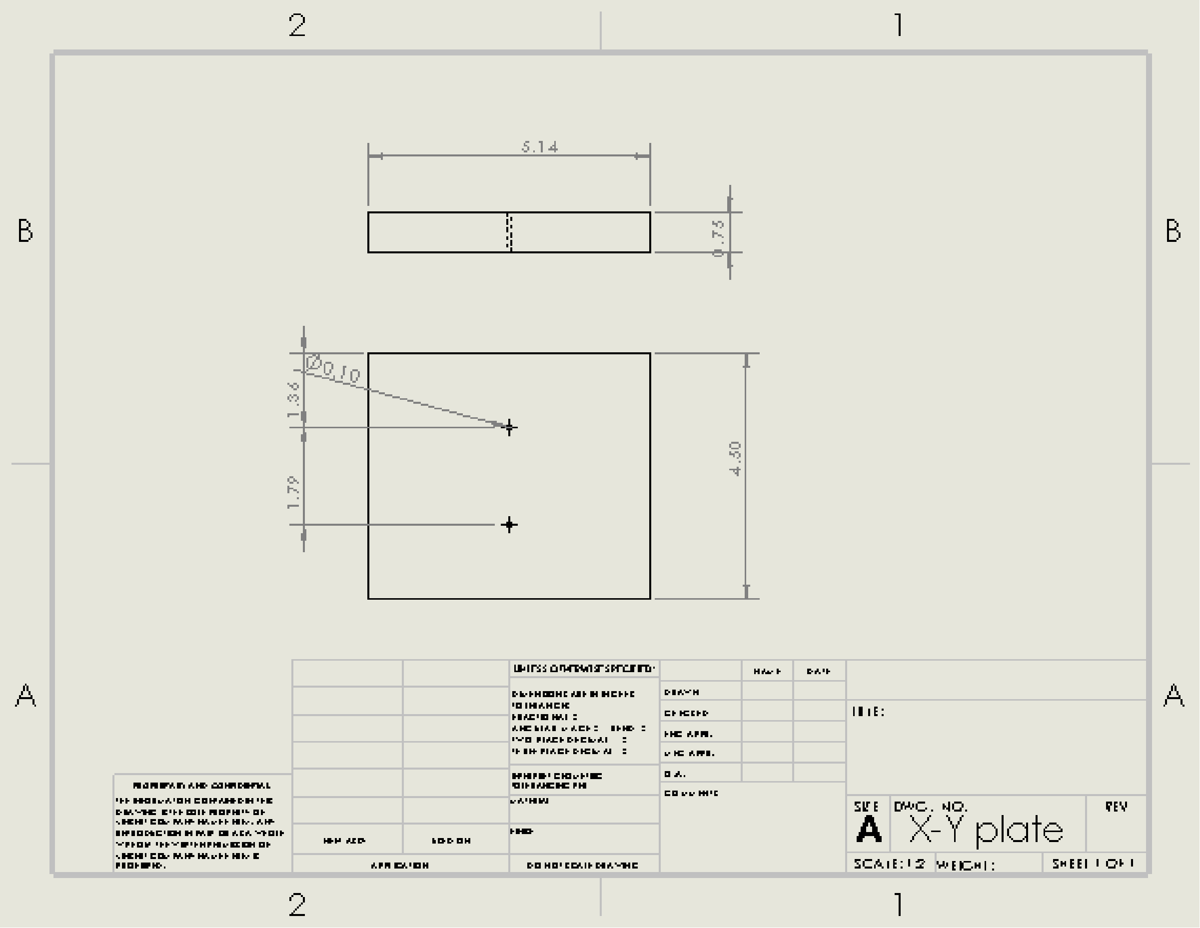
PROPRIETARY AND CONFIDENTIAL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4.50
UNLESS OTHERWISE SPECIFIED:
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DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS
TITLE:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
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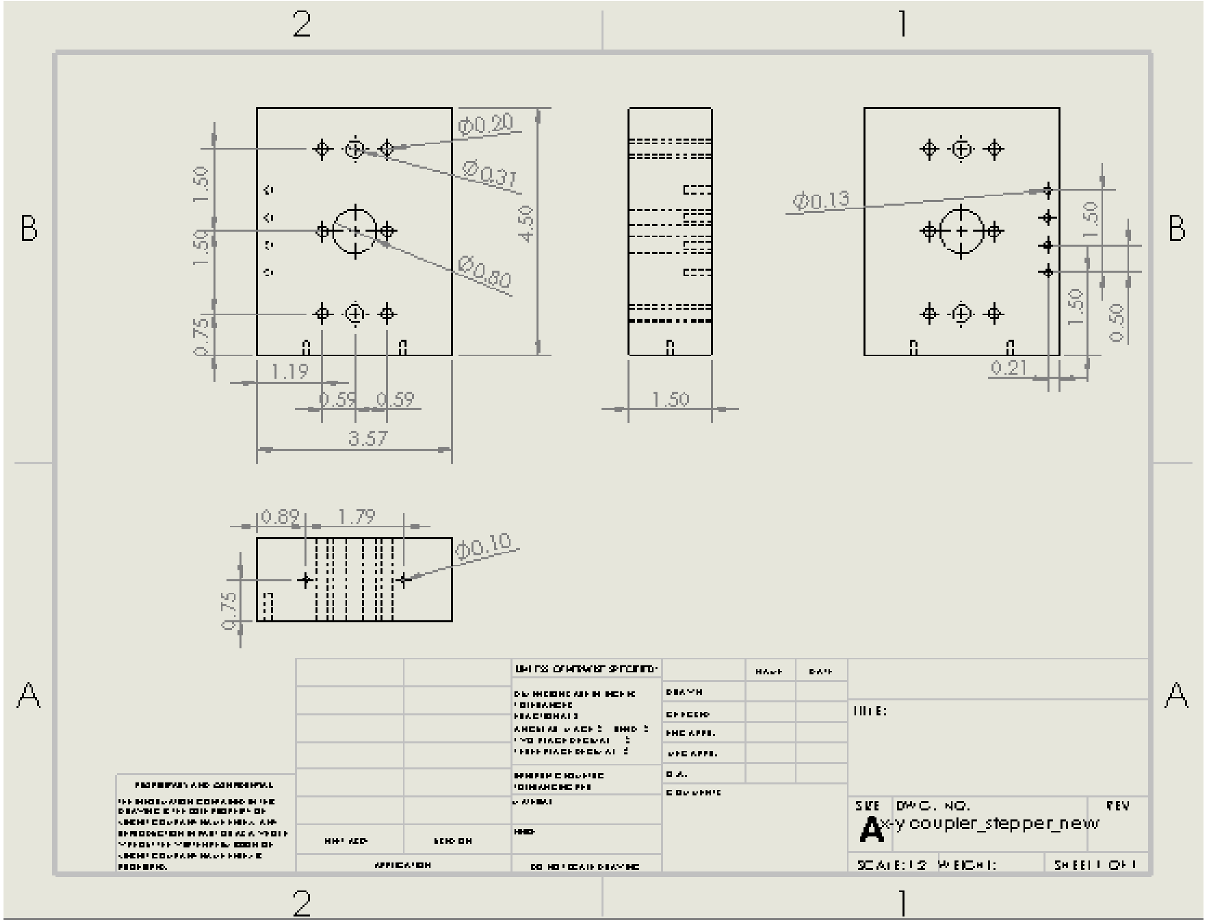
X-Y plate
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1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Ø0.31
Ø0.80
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0.59
3.57
1.50
Ø0.13
1.50
1.50
0.50
0.21
0.89
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Ø0.10
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x-y coupler_stepper_new
REV
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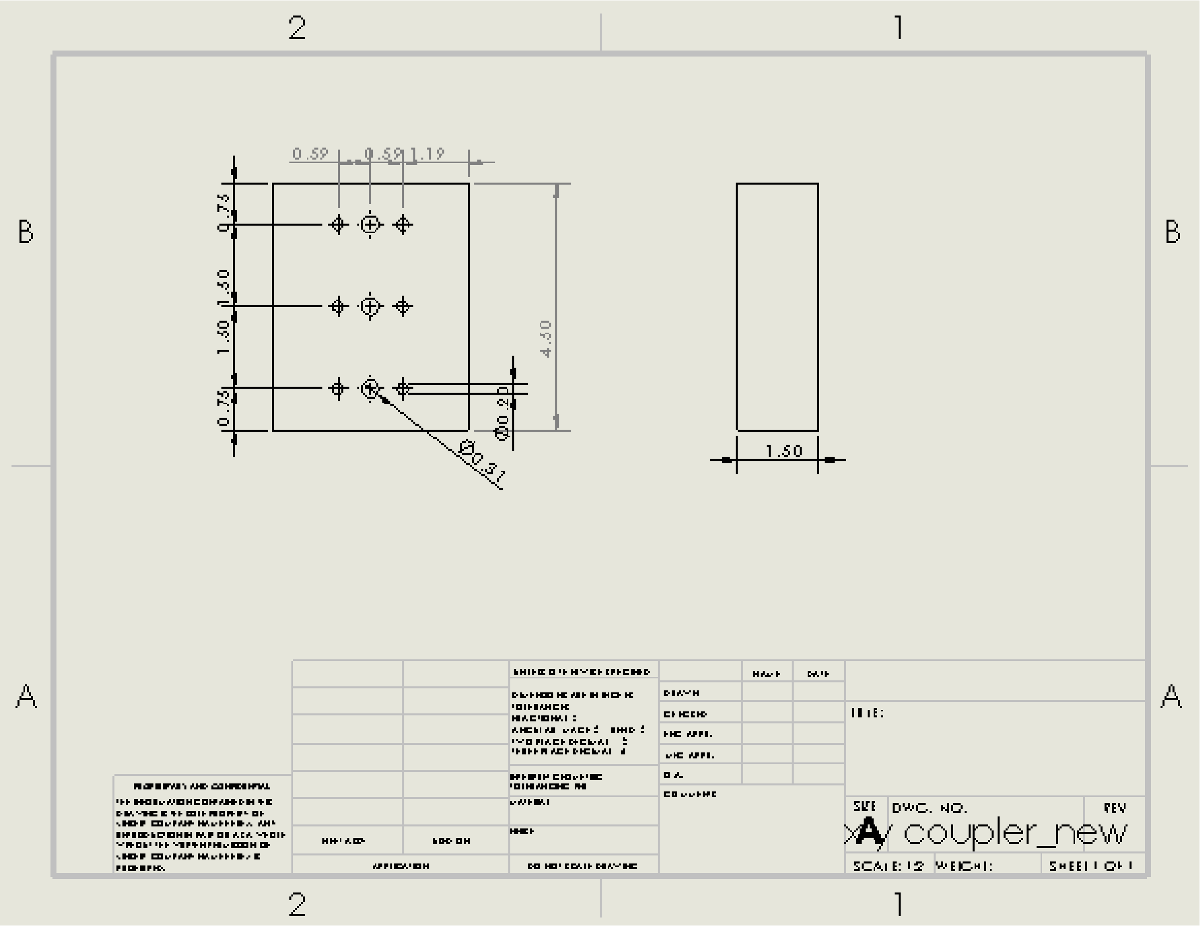
SHEET 1 OF 1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Ø0.31
1.50
UNLESS OTHERWISE SPECIFIED
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS
TITLE:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
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REV
A
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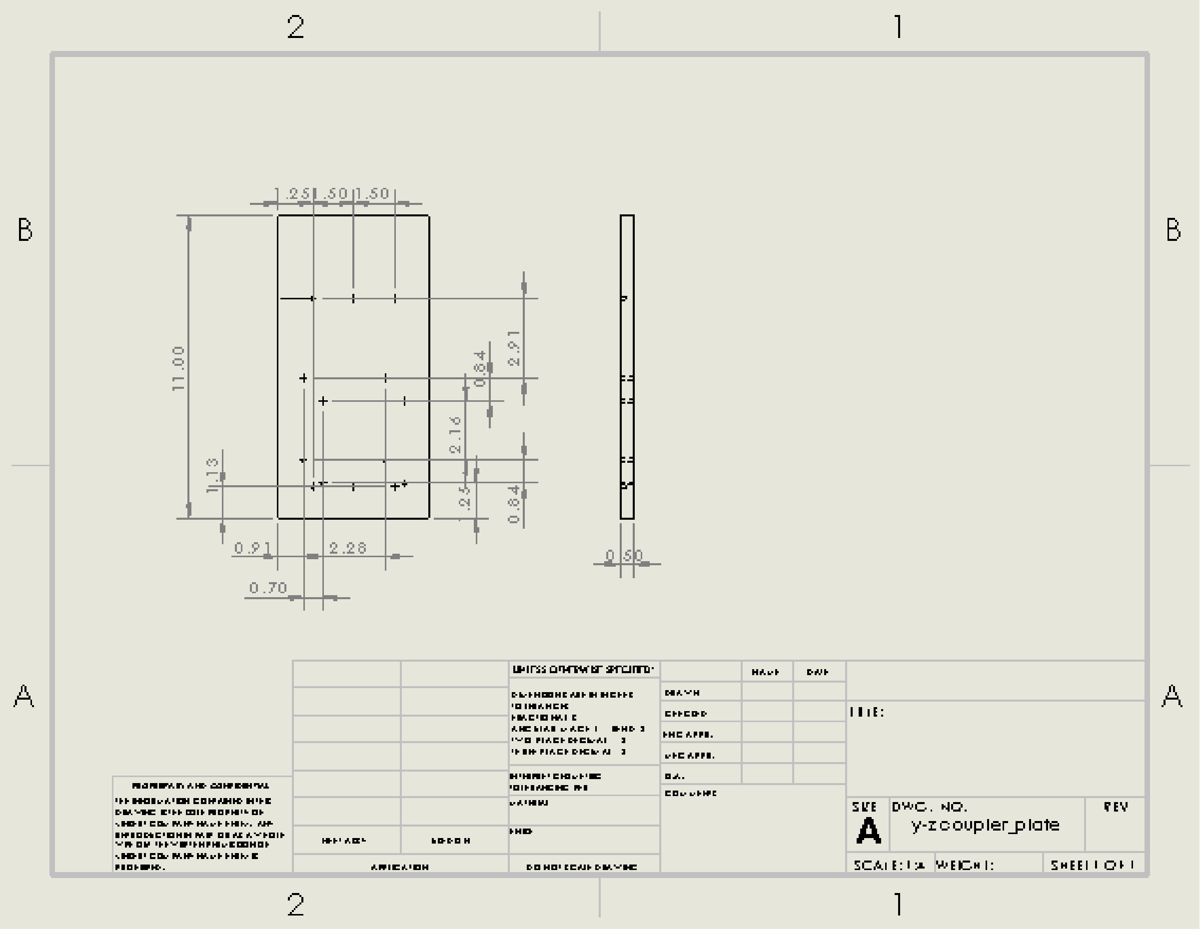
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1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2.91
0.84
2.16
1.13
.25
0.84
0.91
2.28
0.70
0.50
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
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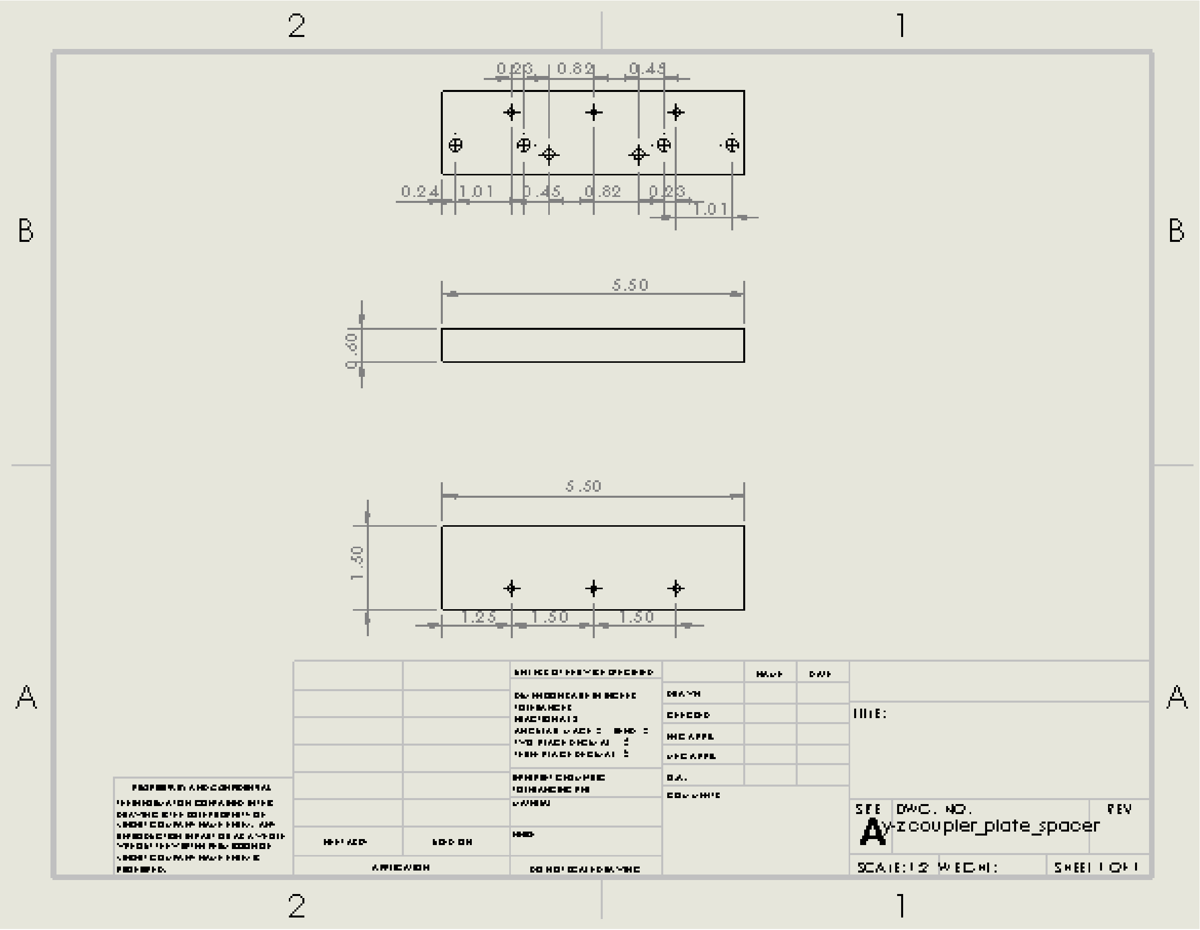
DWG. NO.
y-zcoupler_plate
REV
SCALE:1:
WEIGHT:
SHEET 1 OF 1

2
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A
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0.82
0.45
0.24
1.01
0.45
0.82
0.23
1.01
5.50
0.60
5.50
1.50
1.25
1.50
1.50
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
y-z coupler_plate_spacer
REV
SCALE: 1:2
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SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL

## APPENDIX C

Electrical Components and wiring diagrams:

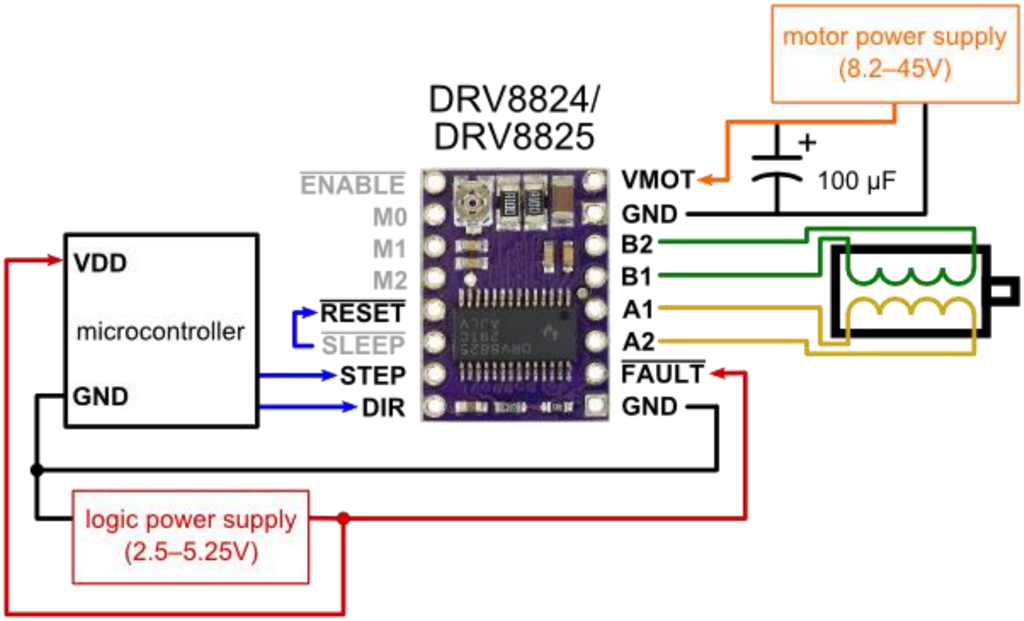


Figure 31: DRV8824 Stepper Motor Driver Circuit

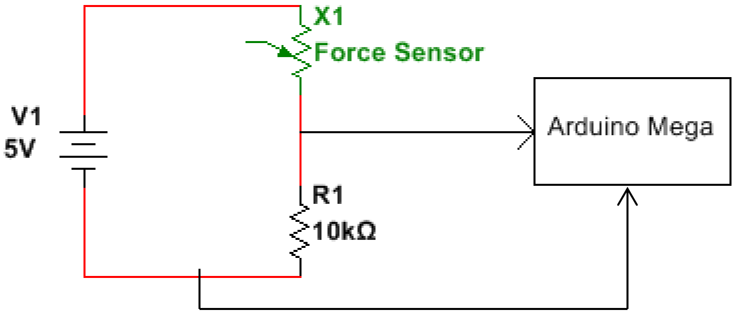
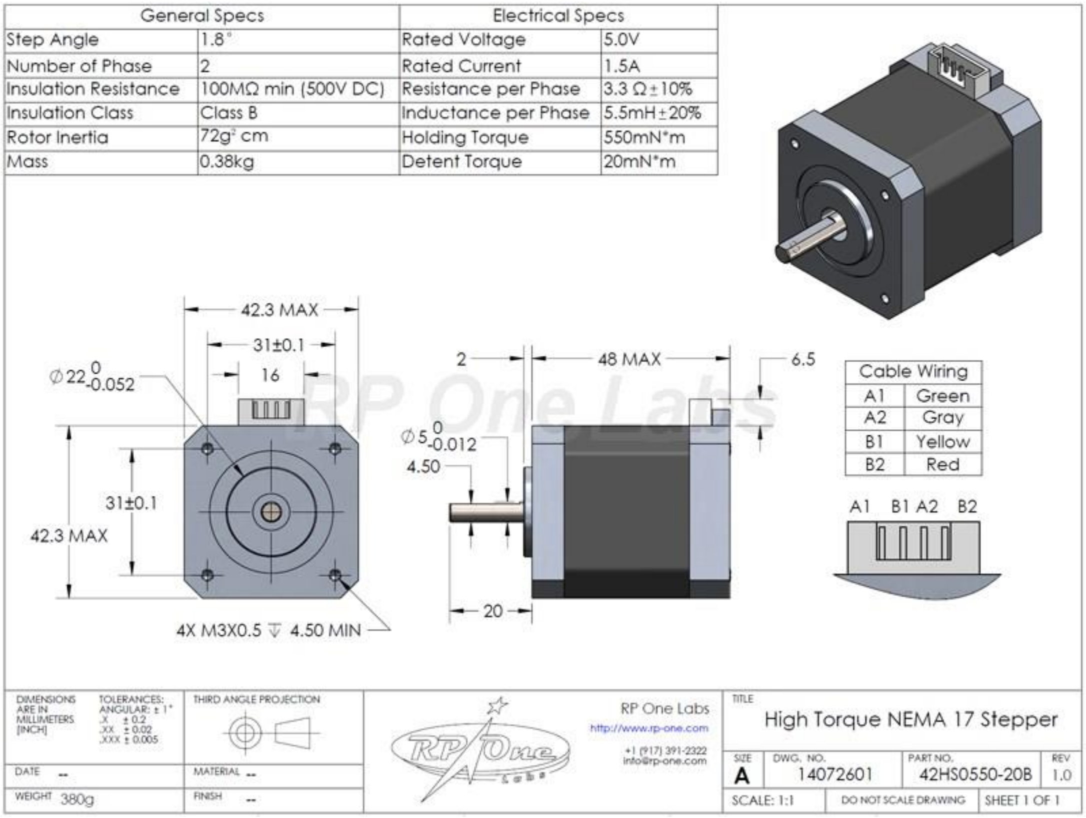


Figure 32: Force Sensor Circuit



| General Specs | | Electrical Specs | |
|---|---|---|---|
| Step Angle | 1.8° | Rated Voltage | 5.0V |
| Number of Phase | 2 | Rated Current | 1.5A |
| Insulation Resistance | 100MΩ min (500V DC) | Resistance per Phase | 3.3 Ω±10% |
| Insulation Class | Class B | Inductance per Phase | 5.5mH±20% |
| Rotor Inertia | 72g² cm | Holding Torque | 550mN*m |
| Mass | 0.38kg | Detent Torque | 20mN*m |

| Cable Wiring | |
|---|---|
| A1 | Green |
| A2 | Gray |
| B1 | Yellow |
| B2 | Red |

Figure 33: Nema 17 Stepper Motor

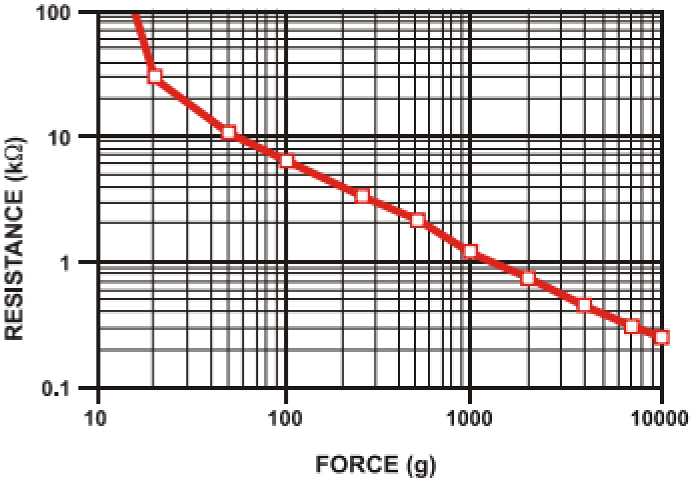


Figure 34: Pololu Force Sensor Resistance Curve

## APPENDIX D

Calculation for beam deflection:

$$Deflection = \frac{WI^3}{48EI}$$
$$W = 4.5\ Kg$$
$$L = .45\ meter$$
$$I = 2.0096e^{-10}\ meter^4$$
$$E = 207\ GPa$$
$$Deflection = \frac{4.5 *. 45^3}{48 * 20x10^9 * 2.0096e^{-10}}$$

Force Sensor Calculation:

The force sensor acts as a potentiometer with a variable resistance. In order to determine the actual resistance, the force sensor was wired as shown in Figure 32: Force Sensor Circuit.

$$R_1 = 10{,}000\Omega$$
$$V_1 = 5\ Volts$$
$$I = \frac{V_1}{R_1 + X_1}$$
$$V_{drop} = V_1 - V_{measured}$$
$$I = \frac{V_{drop}}{X_1}$$
$$\therefore \frac{V_1}{R_1 + X_1} = \frac{V_{drop}}{X_1} = \frac{V_1 - V_{measured}}{X_1}$$

Solving For $X_1$

$$X_1 = \frac{R_1 * (V_1 - V_{measured})}{V_{measured}} = \frac{10{,}000\Omega * (5\ Volts - V_{measured})}{V_{measured}}$$

$X_1$ is the resistance of the force sensor.