ME450-F15

Team 16 - Automated Surface Grinder "Slicer"

Final Report

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Sponsored by:

ISLAND CERAMIC GRINDING, INC.

Executive Summary

Mr. Bernn Hitch, President of Island Ceramic Grinding, tasked team 16 to automate a manual Chevalier FSG-618M Surface Grinder so that it can run a simple, repetitive program for slicing ceramic pieces with minimal operator interaction besides the initial setup of the program.

To accomplish this goal, we were given requirements by our sponsor that include automation of the three axes of the surface grinder through one cohesive interface that allows for editing of the program while it is in use and no measurable increase in tolerance of the parts being manufactured for under $5000. Alumina is to be used for all testing, as it will ensure any product that Island Ceramic Grinding currently uses on their grinders will not present any problems for the automation. Engineering specifications were generated according to the requirements such as the tolerance of motion accuracy and precision.

After performing a functional decomposition and brainstorming, several of concepts were generated to meet the requirement of our sponsor and the corresponding engineering specifications. Five Pugh Charts were created for different functionalities that need to be realized, with weighting between one and five for each criterion. The five Pugh Charts decided that the transmission would be timing belts, stepper motors would be used for in-out direction and up-down direction, a DC motor would be used for left-right direction, a sealed keypad would be used for interface; the microcontroller would be a PLC, a Hall Effect sensor would be used to control the motion of the grinder.

Engineering analysis was implemented to determine the required specifications for motors and transmissions. Theoretical modeling and empirical testing were implemented to find out the maximum torque when turning the hand wheels during normal operation. The component selection was narrowed down using the specifications from this analysis, and CAD models of mountings for each axis were generated. A detailed plan for the control system is also described. FMEA and risk analyses were done to discover, evaluate, and minimize potential problems.

Design verification testing was then performed to verify that the individual components performed as expected and would allow the machine to function as intended. Precision of the Y and Z-axes were confirmed to outperform expectations, and the speed of the X-axis was also deemed acceptable. Verification was unable to be performed on the system as a whole due to additional components that were needed and delays in assembling the electrical system.

Table of Contents

Problem Description and Background

For this ME 450 project, the sponsor, Island Ceramic Grinding (ICG) president Bernn Hitch, tasked the team with adding automation to a Chevalier FSG-618M surface grinder [1,2]. In their current manufacturing process, the sponsor uses a similar surface grinder except with limited automation added to perform the specific operation [1]. Manual surface grinders are relatively cheap at around $10,000 for a new machine, but manual input is outdated for this operation since it is not a complicated one. A new CNC machine that could perform it automatically would cost them $40,000 [1]. This gave the economic incentive of at least $30,000 to upgrade a cheaper machine instead of purchasing a CNC model. This economic incentive allowed for the opportunity to sponsor the automation of one of these machines, while still satisfying the previous standard of quality expected from ICG products.

Alumina is the ceramic of primary concern in the design, other ceramics used by ICG will be covered in the design criteria of alumina. Analyzing industry data and writings on the topic, it was found that typical alumina fracture and defect to be most directly related to inadequate force, slow tool head, and depth of cut [3,4,5]. ICG does not have many issues with defects but we have to make sure to maintain their standard of quality. These factors will be explored more with live material testing. The same grinding head used by ICG will be used for testing to provide results as close as possible to the current processes used at ICG [1].

There are already products on the market that can fill the functional capacity that this design will aim to reach. However, most are very expensive and have many more features and functions than the proposed grinder requires. A machine with similar capabilities, but using CNC controls is the Chevalier FSG-H818CNC machine [6]. It can do far more than what is required by ICG, as the operation they perform is repetitive and simple. Our sponsor cites the CNC machine as highly undesirable because it has more set up and is assumed to have longer batch time and deeper operator requirements along with the significant price increase. Replacements of the current unit used by ICG cannot be obtained as they were made custom many years prior [1]. Chevalier also sells an FSG-3A818 automatic surface grinder, which performs all of the functions necessary, but is not distinguished as a CNC unit and is considered fully automated according to the user manual and vendor. This model is a good benchmark to compare the function of this team's prototype to as it is generally what is trying to be created in this project [22]. It should be noted this unit is also very expensive, though a quote was not obtained.

Figure 1. Chevalier FSG-618M surface grinder the team has been tasked with adding automation to. Axes are defined as in this figure, with X being the longitudinal axis of table travel.

Through further research, a machine that had similar changes made to it was found and is able to be used as a better benchmark for the new prototype than machines previously researched. All information presented in the webpage was taken with caution as it cannot be confirmed who the author is and if they were the one to actually perform the automation of the surface grinder. The machine found had one axis automated, the x-axis, which is the longest axis in terms of travel length, using a 3-phase inverter on an inductor motor. A gearbox was connected to the motor and a timing belt was used to connect the motor shaft to the x-axis shaft. A contact switch was used for sensing when to reverse with the manual stops on the machine contacting the switch to tell the motor when to reverse [21].

Checking patents around this area of automated milling and grinding revealed many functionally similar machines, all under expired patents. It is of important note that all these patents are automated grinders and they bear a large degree of similarity. Similar in function to the machine being designed, patent US 5173863 A still uses a standard grinding mill to be converted except with hydraulic actuation, one of the only features being avoided absolutely [7]. The machine will be designed using similar methods of interface and power sourcing. Patent US 4603392 was not as similar to the machine being prototyped, but it did imply much about the control system on a much higher level [8]. The prototype lacks the need for higher order differential controlling but the control method will be used as creative reference. The third patent researched was similar to the others, but required input from an external terminal to receive its controls [9]. This feature was interesting to the control scheme of the future prototype. The basic controls for these patents and the machine being automated could be similar and these patents can serve as excellent creative substance for the grinder design.

User Requirements and Engineering Specifications

The project sponsor, Mr. Hitch, had a list of requirements regarding the automation of the machine. This first is that all tolerances within the machine stay at the current levels or improve when automation is added. The current tolerances are ±0.001” in the y and z axes and ±1” in the x direction. These tolerances are absolutely necessary to maintaining the same level of quality at ICG. This was first addressed when selecting motors and transmissions for each axis, ensuring that each motor possesses the ability to move in small enough increments to allow these tolerances. Then, during the programming phase, the tolerances were accounted for in the size (number of degrees turned by the motor shaft) of the step for each successive pass of the grinding head.

A requirement for testing the machine and any implementation attempted is that alumina is to be used as the sample material. Although ICG uses various ceramics, Mr. Hitch stated that alumina reflects the standard material used and any other ceramic will be captured in its design requirements [1]. ICG grinders can currently run at around 1 foot per second in the cutting direction (X-axis) using alumina. This same or higher feed rate is required to be maintained for an effective design that helps ICG move forward. The grinding head used in this prototype will be the 1A1R 6”x0.017”x1.25” grinding head, P/N: 69014192082, made by Norton Industrial — the same grinding wheel used in current ICG operation, supplied courtesy of Mr. Hitch [1].

Another requirement stated by Mr. Hitch is that the operator be able to edit the program while it is in motion. Due to user or mechanical error, the parts produced can sometimes become out of spec. Currently the whole batch is scrapped and started again, this improvement would allow real time intervention to the program. This will be accomplished by allowing the operator to increment the depth of passes or number of passes on the interface while the program runs without affecting the precision or accuracy of the machine, and is considered a high level priority [1].

Although not explicitly stated by the sponsor, it was decided that motors and key components will need to be covered or protected in some way, possibly through the use of a guard, to prevent debris, coolant or other foreign objects from entering the motor, motor connections, or any electronics. This will increase the life of the motors, as they will stay closer to their factory state for longer. Electronic function will be fully contained to prevent degradation due to the grimy work environment. This specification is of secondary concern, as the machines used by ICG are extremely dirty and open to debris, and have been functioning for an extended period of time. Even the electronics boxes are open on top, while a constant stream of coolant is used.

A requirement not explicitly stated, but that must be taken into consideration is that any motors or electronics that are placed on the machine must be useable with electrical access present in the facility. The machine requires 240 VAC access and this type of plug is currently accessible within the current ICG facility [1].

Another requirement for the programming of the interface was that an interface not using a touch screen is preferred, but would be acceptable if it is the best option for the integration into the machines. The reasoning for this is that the coolant used on the grinding machines is messy and could interfere with a touch screen by accidentally hitting a command or preventing a command from being hit [1].

The last requirement imposed on us by ICG is that the total of any modifications should cost less than $5000. If additional funds are required, approval must be obtained from ICG [1]. This economic concern is of high priority as it is the base incentive for the furthering of any ICG automations.

Concept Generation

Generating numerous design concepts up front allows a large number of possible prototypes to be considered before committing valuable resources. To help increase the choices going into the later designs several methods were used. First off the team performed a functional decomposition in the problem at hand (Appendix A). It defined all areas of operation the machine would have to perform, from designing a control system to modifying hardware, so that concepts proposed would be kept within scope. Brainstorming was used as a primary method of generating concepts; especially since many of the design challenges were well defined through research. The evaluation of knowledge and ideas in a group setting was invaluable. Lastly, design acronyms specified by the course instructor were used to create concept areas and provide creative substance.

Concepts were generated for the areas of transmission, actuation, tray return damping, sensors, microcontrollers, and interface. In these major concept categories not many concepts were wildly different since the function of the prototype is already largely set. One choice that did have a wide range of solutions was the choice of sensor or timing used to switch the table motion from forward to backward or vice versa. The concepts generated range from mechanical switches, to magnetic field sensors, to electrical or mechanical timing only. More than just this category had to be considered as the table will be constantly grinding or decrementing along one or more axis. Not only the switch of direction but also the timing with regard to the other axis movements and the associated damping (or lack thereof) needed to be considered. Encoders were some of the proposed concepts, registering how far the table had traveled over time and using this data to electronically signal when to reverse. Motion sensors were proposed to be placed along the tray in specific, adjustable spots, triggering the direction change when the tray moved far enough. Finally, magnetic field disruption measured by a Hall effect sensor was also proposed. Magnets attracted to the surface of the grinding table could be easily adjusted to disturb a Hall effect trigger at set location on the grinding machine. Electrical, mechanical, both – all options are feasible. Having these choices allows for a more robust choice to be made with regard to the final prototype. Sketches of some of these concepts (including the Hall Effect sensor) can be found below Appendix B (which contains all concepts generated).

Concept Selection

After generating all these concepts, the team then needed an objective way to compare the different ideas. To do this, the criteria that were important for each functional area were determined. These included cost, usability, ease of installation, along with other factors specific to the function, such as service life.

Then, each criterion was assigned a weight 1-5, with 5 being the most desirable properties. Each of the concepts was then ranked in each criterion from -2 to 2, with negative values meaning the concept perform poorly in respect to that criteria and positive values meaning the concept performs well. A sample of the charts used is below in Table 1, and detailed charts can be found in Appendix C. This rank was then multiplied by the weight of the criteria, and the sum for each concept was its total score. The concept with the highest score was the selected concept.

Table 1. The concept selection process used to determine that timing belts would be used as the method of transmission.

Concept		**Belts**	**Gears**	**Chains**
				
Criteria	**Weight**			
Cost	3	0	1	0
Adjustability	4	1	-1	0
Ease of	4	1	-1	0

assemble				
Ease of maintenance	2	1	0	-1
Noise	1	0	0	-1
Service life	4	-1	1	0
Ability to transfer large torque	3	-1	0	1
Sum		**3 (Selected)**	-1	0

Using this method, the best concepts were found to be stepper motors for the y and z-axes, and a DC motor for the x-axis. Stepper motors can meet the requirement of accurate position control in y and z direction by their intrinsic function of stepwise rotation. It requires less effort to develop the control algorithm and parameter tuning when the prototype is developed. It can also produce low speed torque, which is essential for the small movements along y and z-axes. The disadvantages of stepper motors are that they are more expensive than other motors with similar mechanical specifications, and move more slowly. For the x-axis, where constant speed is the most important engineering specification, a normal DC motor was chosen because of its reasonable price, larger speed range and stronger high-speed torque. On the other hand, DC motors require more consideration about control than a stepper motor, and requires AC to DC power conversion to meet power input provided.

Timing belts were chosen as the method of transmission. The most significant advantage of timing belts is the adjustability of the center distance between the original shaft being automated on the machine and the shaft of the motor. This allows more design freedom for the position of the motor. Also, timing belts would not require as much maintenance as chains. Although they are not good at transferring large torque and have a relatively short service life, these two criteria are not as important as the other ones in this situation.

A PLC control system with a sealed keypad input and simple LCD display was found to be the preferred concept. PLC is an industry standard controller that is well suited to working for extended periods of time in industrial environments. Although it is not as cheap as an Arduino controller, it is preferred for this project due to the machine shop environment and other built in features that make PLC more robust. A sealed keypad input with a simple LCD display is preferred mainly due to its durability and user preference.

The preferred design found for changing the x-axis limits was a Hall effect sensor and magnets because of its competitive price and adjustability. It is not as simple as spring, but has more overall benefits for the proposed feedback system, such as velocity interpretation.

In conclusion, the design will include the replacement all three hand wheels. A DC motor will be used for X direction and two stepper motors for the Y and Z direction. Timing belts will be used as transmission. PLC will be used as the controller, with a sealed keypad, LCD display screen and a Hall effect sensor for the x-axis boundaries.

Key Design Drivers and Challenges

The precision output of the motors over time is the end goal for this design, and is one of the largest drivers behind the project. The foremost challenge included within this regime is the mounting of the motors to the machine in a specific location. With the machine being as large as it is, hand tools are the most viable option to make changes to the machine for mounting. This makes precision with the tools more difficult and therefore will require the precision to be focused around the parts manufactured. Further, with factors like belt wear and tolerances, adjustability of motors and mountings is paramount for long-term operation.

Another challenge is determining how to run wires from the X and Y-axis motors to the electronics system because they are mounted on the moving table. The wires must be run with enough slack to not be ripped out of any electronics, while being taut enough to not interfere with the lead screws and the movement of the table. Wire tracks are being investigated and will be implemented once wiring paths have been finalized on the machine.

Difficulty learning a new control system and method of programming is also another challenge. Work has begun to integrate basic parameters and headway is being made toward integrating the various system components. Bringing all these elements into a single control scheme and having the PLC, as the “brain” is the next step.

Fatigue analysis of the selected timing belts presents an additional challenge, as fatigue on the belt must be factored in with fatigue of motors over time. The belt fatigue must be calculated to determine how often the belt needs to be changed to prevent slippage or skipping of the belts, especially with the stepper motors as missed decrements could affect production. More on this information will be included in any assembly manual provided with the prototype.

Concept Description

After concept selection using a Pugh chart and the engineering analysis, a more detailed design plan was generated, shown in Figure 2 below. It can be divided into four subsystems: different drive system designs for three directions (x, y, and z) of table movement and the control system with user interface. Every subsystem will be discussed below in detail. Manufacturing drawings can be found in Appendix F. Manufacturing plans can be found in Appendix H.

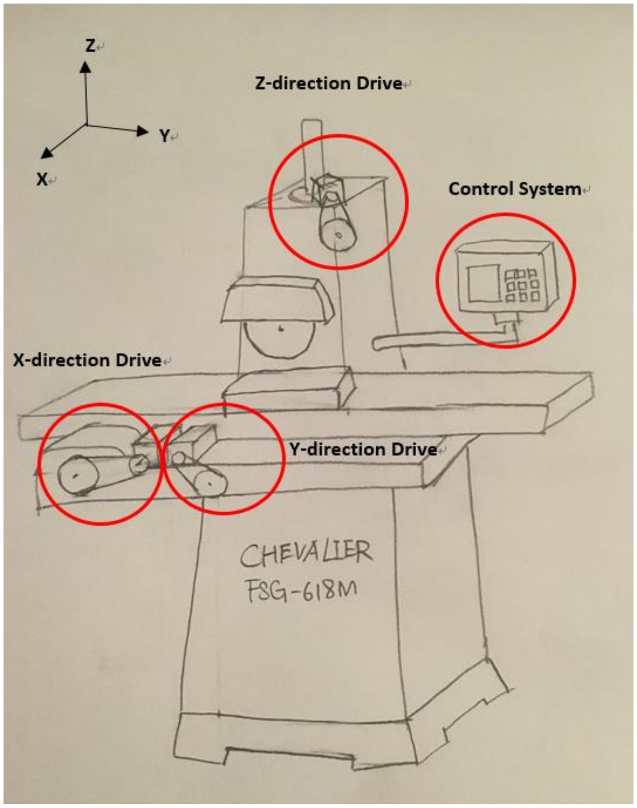

Figure 2. The concept can be divided into four subsystems. X-direction drive, Y-direction drive, Z-direction drive and control system

X Axis DC Motor & Transmission

The following pictures show the design of how to automate the machine in the transverse direction (x-axis). The basic idea is to use a DC motor and transmission type that have the best cumulative result in the Pugh charts. The motor will be mounted to the front half of the table (the magnetic chuck that holds the work piece is at the rear half of the table). One pulley is connected to the original shaft of the machine that controls the movement in this direction, originally controlled by a manual hand wheel. Other pulley is connected to the motor.

The figures below show the major components of the design. After taking the hand wheel of the machine, the machine shaft is measured to be 15 mm. A pulley with a ½ inch diameter hole is bored to match the friction fit of the shaft. For the motor side, the motor will directly connected into the gearbox since consideration has been put to the shaft radius when choosing this combination. A mounting plate and a mounting angle will be used to fasten the motor on the table. The diameter of the output shaft from the gearbox is 6 mm, while the diameter of the pulley hold is ½ inch. A coupler is designed to make the connection.

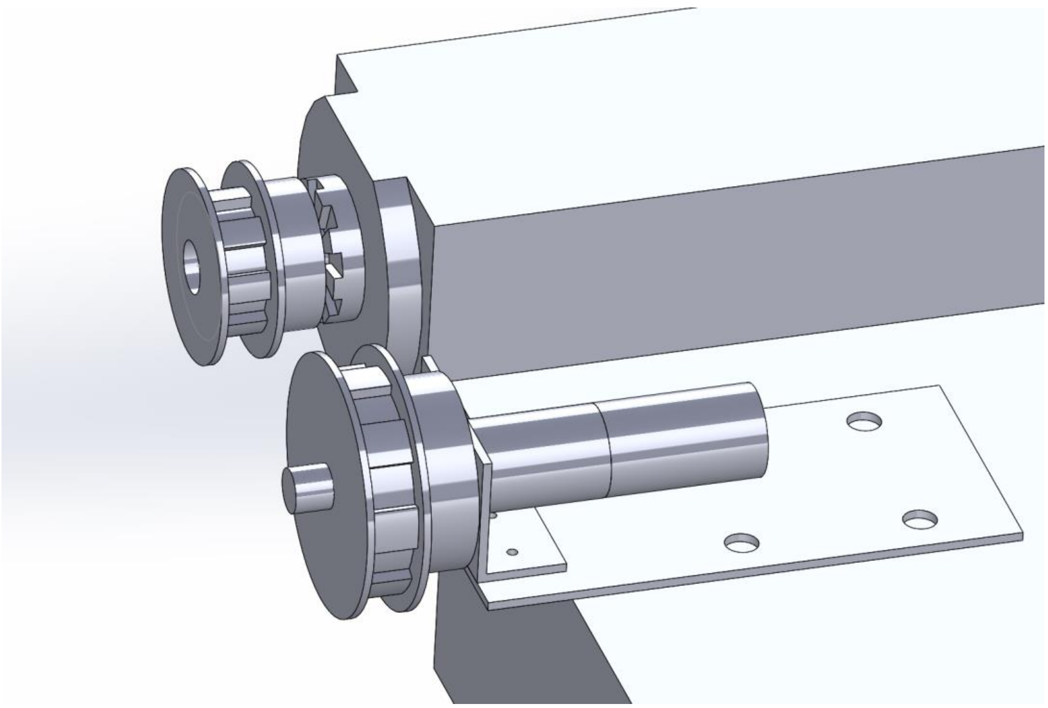

Figure 3. Mounting of X-Axis Motor (without timing belt)

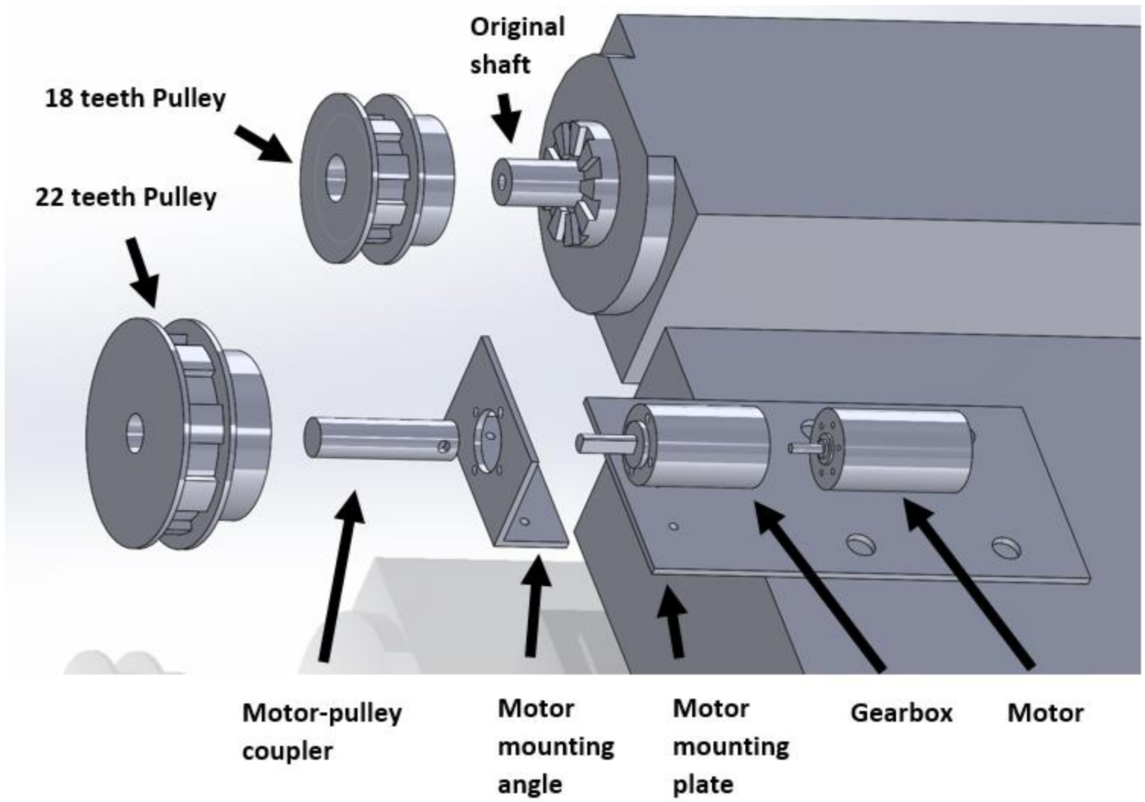

Figure 4. Exploded labeled picture of X-Axis Mounting (without belt)

Y Axis Stepper Motor & Transmission

The overall design of the Y-Axis automation was based around the idea that the purpose of this axis is to decrement to move to the next wafer to be cut. The most effective motor, based upon the concept selection for this axis, is a stepper motor. A stepper motor with 200 steps per revolution was selected. A timing belt and meshing pulleys will be used to connect the stepper motor to the lead screw axis. Timing belts are inexpensive, quiet and reliable for the small movements that will be performed by this motor. A transmission ratio that geared up was required in this case to increase both the torque output and number of steps per revolution transferred to the lead screw. A collar will be manufactured and placed in between the y-axis and the pulley, as the axis is smaller than the inner bore of the pulley. This pulley that is placed on the axis of the machine will be bored to size so the collar can be press fit into it. A mounting plate will be used to extend the axis of the motor farther from the edge of the machine to line up the pulley on the motor with the one on the axis. This design can be seen in Figure 5 and Figure 6.

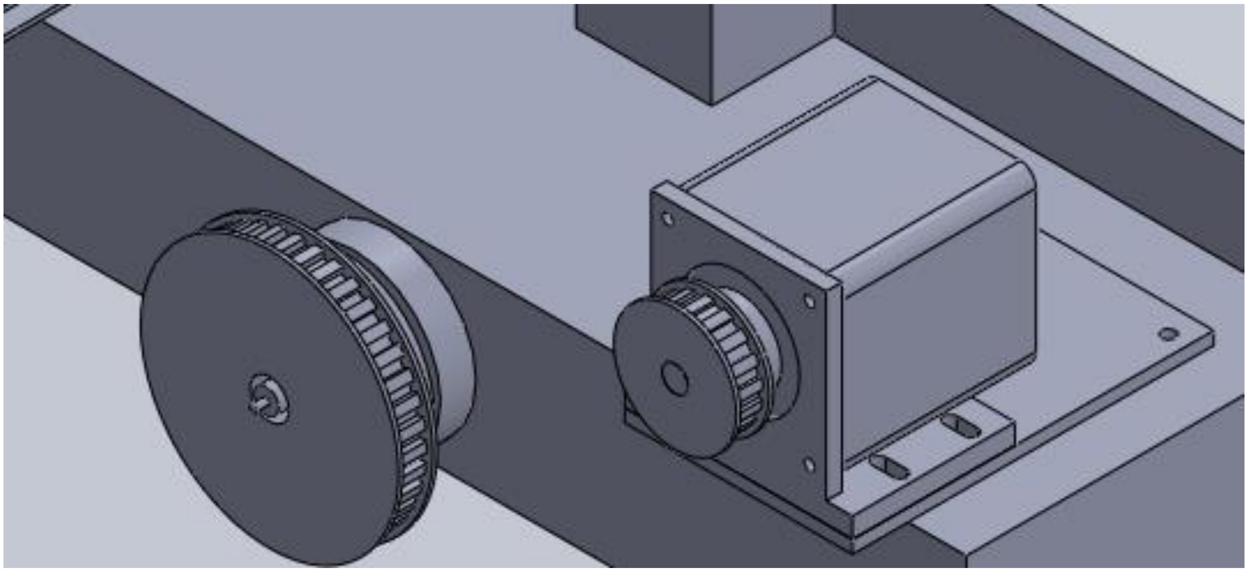

Figure 5. Mounting of Y-Axis Motor (without timing belt)

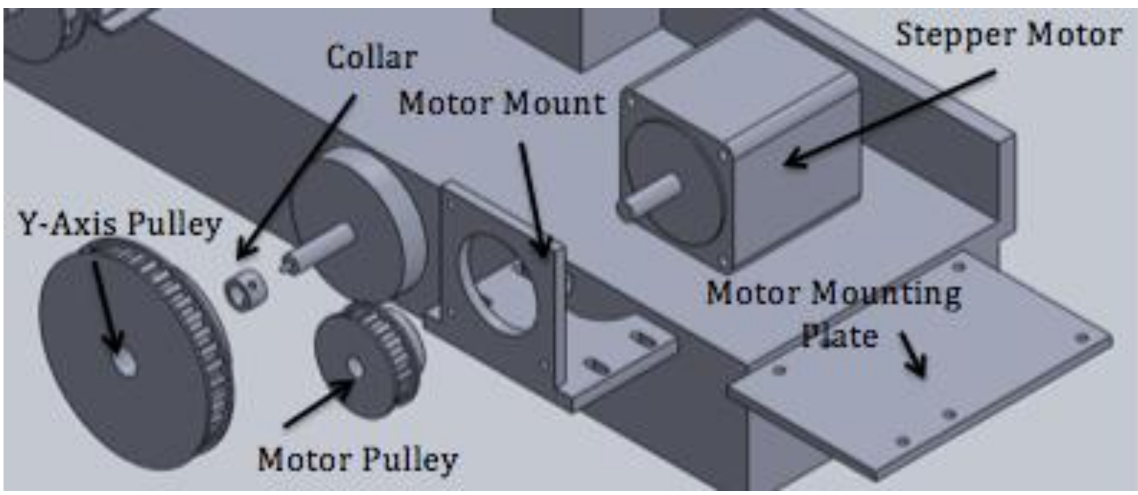

Figure 6. Exploded labeled picture of Y-Axis Mounting (without belt)

Z Axis Stepper Motor & Transmission

The Z-axis is the axis responsible for decrementing the depth of cut used on every pass. ICG usually decrements its depth by .003 inches. With this figure in mind it was decided that the same stepper motor used to satisfy the Y-axis requirement would be suitable for the Z-axis. Again, with 200 steps per revolution and the correct gear ratio very small increments can be made. To keep these movements precise and measureable timing belt was picked as the transmission method. The Z-axis hand wheel can be easily removed. The shaft it was fixed to was slightly too small for the proposed timing cog so a collar will be manufactured and press fit into the desired cog. The motor must be parallel to the input shaft for correct power transmission. Since the Z-axis juts out at 30 degrees to the front face, finding this perfect parallel point is difficult on this machine. The design chosen reflects the analysis put towards having perfectly parallel shafts. An angled plate will be attached to the face of shaft encircling the z-axis and connected with threads already present for securing an axis cover. This design is shown in Figure 7 below. The motor will then be mounted to the top of this plate at a distance suitable for the transmission system. The axis cover was removed to facilitate this process. A support will be mounted between the angle mounting bracket and the machine to reduce any moment felt at the axis face connection. The frictional consideration of this shaft is smaller but it could easily be accounted for with bearings and spacers, though none are planned at this time. The full proposed mounting is shown in Figure 9 below, exploded and with labels. This concept should be entirely feasible for the monetary and time restraints for this project.

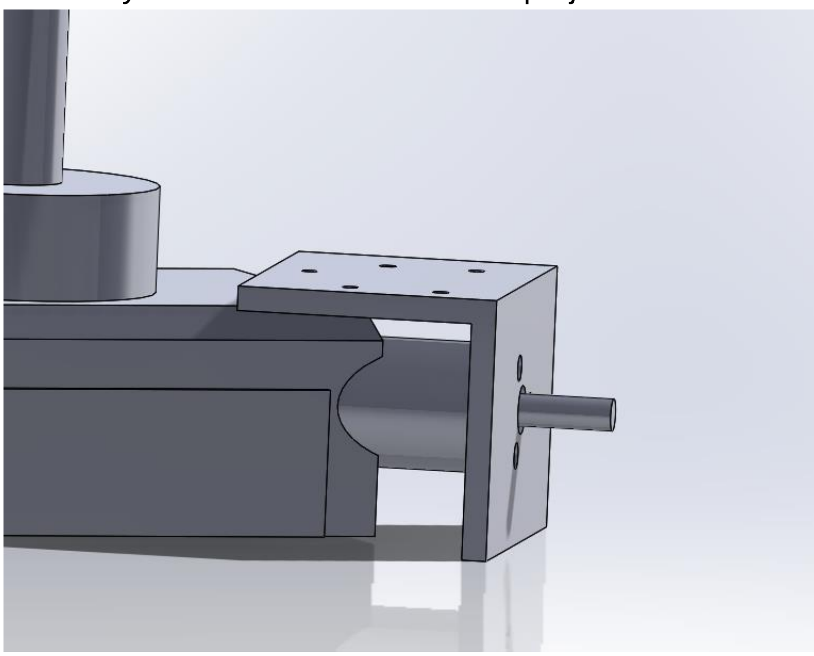

Figure 7. Sole attachment of angled plate to z-axis face.

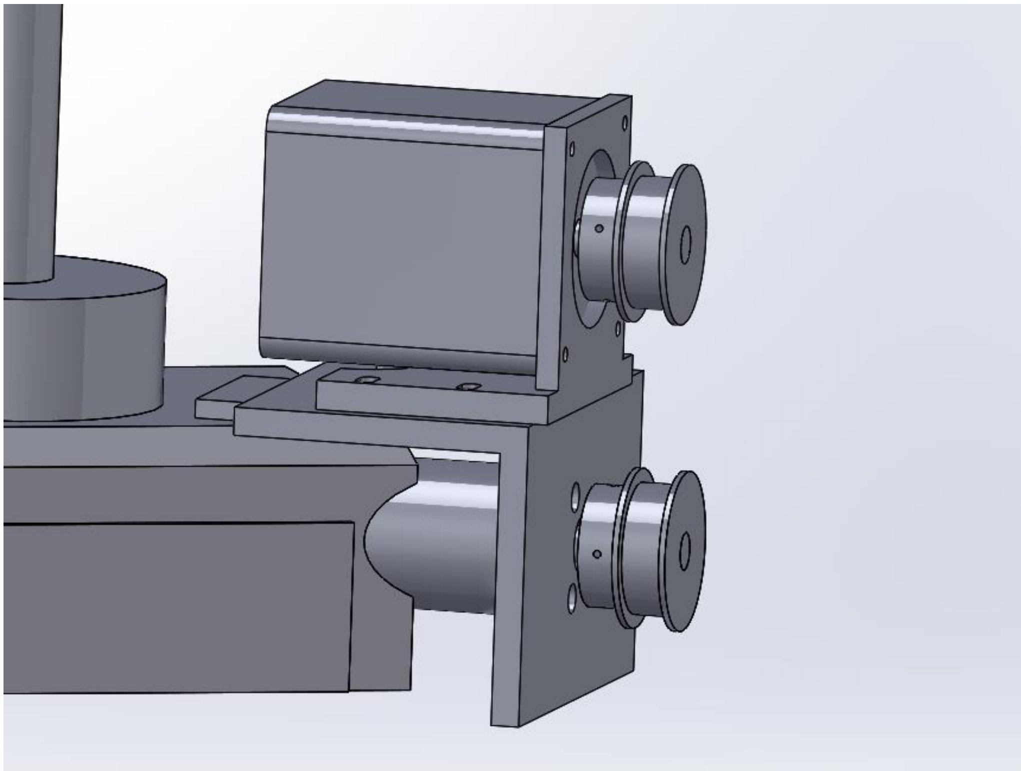

Figure 8. The full motor mounting with cogs included for the eventual timing belt.

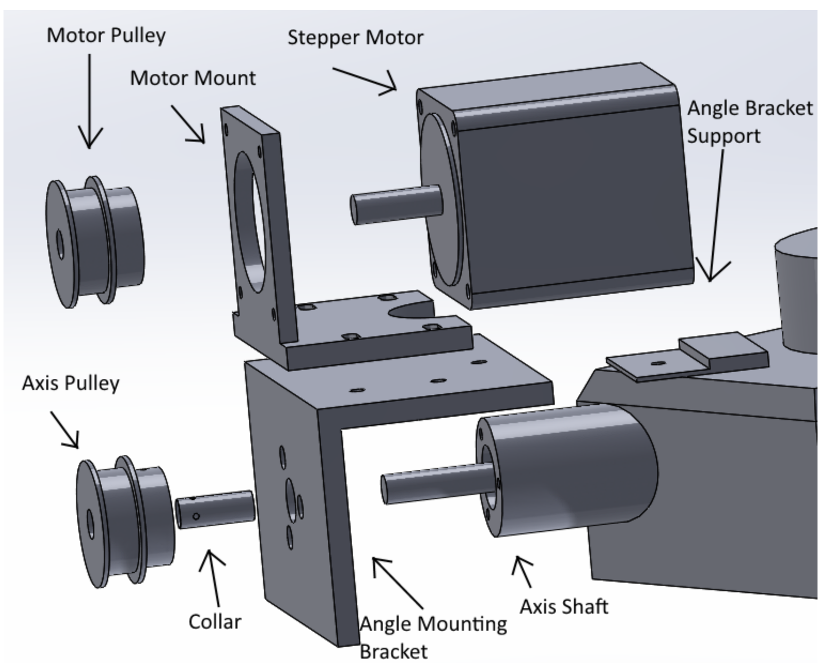

Figure 9. A labeled exploded diagram of all components of the z-axis design.

Control System

The control system is responsible for reading any inputs from the system and outputting signals according to a program, such as reading the user-set parameters and sending power to the motors.

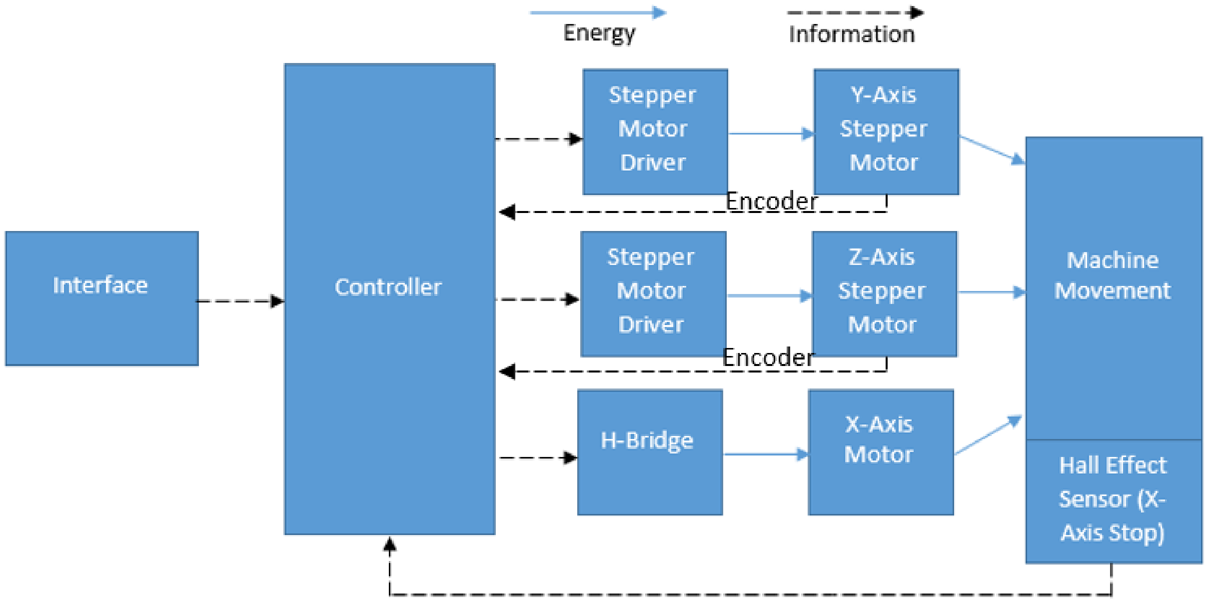

Figure 10. Block diagram of control system using the current design.

As seen in Figure 10 above, closed-loop control will be used for each axis to ensure proper performance. The DC motor is attached with a Hall effect sensor. The maxon motor driver has an integrated PI controller and can be tuned with its software. Taking the desired speed from PLC as an input, the motor driver ("H-Bridge") will implement the feedback control for the DC motor. For the y and z-axes, rotary encoders are included on the stepper motors. The signals from the encoders will be read directly by the PLC, which can then determine whether any steps were missed and can compensate for any such event. Lastly, a hall sensor and user adjustable magnets will be used to set the table travel interval.

The Hall effect sensor is used to indicate the position limit of the X-axis. It is an NPN transistor. When two magnets attached to the moving table reaches the sensor, they will trigger the transistor and send a high voltage signal to the PLC input port.

In addition to the control system, it is also required that there be a way for the operator to input certain program parameters, such as number of slices, before the machine is run. The operator interface integrated with the PLC will allow the operator to perform this task. Using the parameters input to the operator interface, the PLC will then complete the process while the operator interface displays progress and other pertinent information to the user.

Lastly, the connections between the motors, controller, and sensors must be able to be protected over time. Two of the motors and a sensor are mounted on the table and will inevitably have moving wires that must stay connected. The Hall effect sensor planned will also need to be accounted for in a similar way. Wire carriers capable of restraining the motion of the wires will be used to protect the electrical integrity of the prototype in the long term.

Engineering Analysis

General mode of analysis

To narrow down the selection, both empirical testing and theoretical modeling were used to find out the desired specifications for the motor and the transmission.

The requirement for speed and position is already known. The next step would be to find out the maximum torque for each axis that is able to move the machine at any position. The equation for calculating the torque is:

$$\tau = F \times (rsin(\theta)) \quad \text{(Eq. 1)}$$

Where τ is the torque of the axis, $F$is the applied force on the rigid body, $rsin(\theta)$ is the lever arm, perpendicular distance from the center of the axis to the line of action of the force. Figure 11 below shows the relationship among these physical elements.

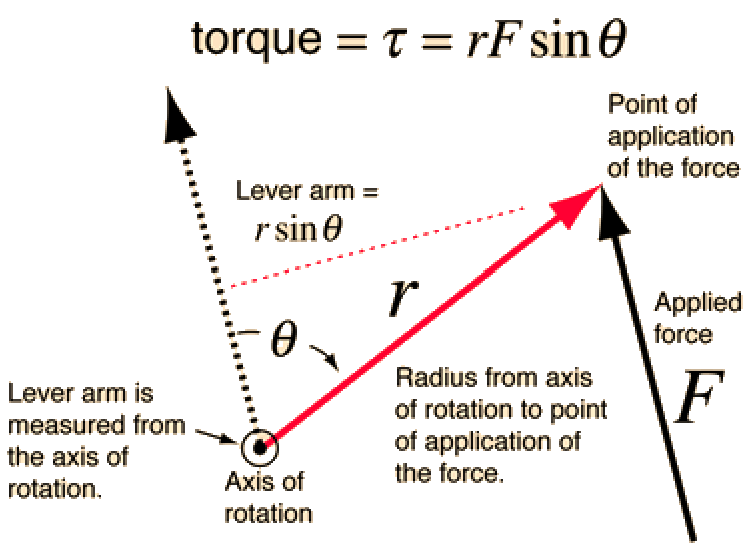

Figure 11. Theoretical Modeling for torque measurement [23]

According to the Eq.1 , in order to get the torque τ, the measure of the actual force and lever arm will be taken for each axis. The experimental setup is shown in Figure 12. The left picture shows that a caliper can be used to accurately estimate the lever arm length, which is the distance between the centers of the hand wheel to the center of the hand wheel handle. The right picture shows the force gauge being connected to the center of the hand wheel handle and pulled orthogonally. During rotation, the force gauge is always tangential to the circle of hand wheel, to make sure the force exerted is always orthogonal to the lever arm.

Only the maximum value of the tangential force was taken during testing. This is because the testing result is for motor selection, and the motor should be able to rotate the shaft under the maximum operating condition. Force for acceleration and deceleration were also taken into account on the x-axis because it is at these times when the motor will output the largest torque. Many data points were taken about the force required to reverse table direction while it was in motion. The average value is used here for the x-axis and will be compensated with a high safety factor. Sponsor data shows that the inertia of the material will be negligible compared to the whole table. The extra force required to overcome the friction of the alumina during actual grinding are considered to be quite low as the cut geometry is miniscule. This friction will be captured in the large safety factor on the motors.

Figure 12. Experimental Setup for Torque Measurement of Z-Axis(Left for lever arm measurement, Right for force measurement)

To find a suitable motor without choosing a transmission, the power was also calculated:

$$P = \tau \times \omega \quad \text{(Eq. 2)}$$

where P is the power, τ is the torque, and ω is the rotational speed.

All the motors under consideration have information about the maximum torques they produce, axial force, and moments they can withstand. This information will be used when determining possible bending or yield of any axis shafts. The moment rating comes in the form of a load per length away from the motor face. Note the motor face exists where the shaft exits the motor enclosure. This rating must be taken into consideration when determining where along a shaft a timing cog can be placed, and is how this choice will be validated.

The length of timing belt (neglecting environment & material of choice) depends on the geometry of the axes one is trying to connect. This comes from many factors, chief of which is transmission ratio for this project. Depending on what cogs are used in the transmission the timing belt required would vary in length. The general formula for computing a timing belt length is shown below for two different timing cogs designated as cog 1 and cog 2:

$$Length_{timing} = 2 * (x) + (1/2) * (C_{cog\ 1} + C_{cog\ 2}) \quad \text{(Eq. 3)}$$

Where Length is the length of the timing belt, x is the distance from like points on the two pulleys, and C is the circumference of the selected cog. Using this equation, the length of belt required for each transmission was determined. It should be noted that the belt does not always sit perfectly at the outside diameter of the cog but the true number used is the specification from the supplier, which accounts for this. This diameter of belt and cog was verified upon receiving the cogs physically.

X Axis DC Motor & Transmission

The requirement for the x-axis is 1 foot per second, which is 2 rotations per second according to the measurement of the travel distance when turning the hand wheel for one rotation. This means 120 rpm is needed for this axis. After testing, it was found that the maximum force during travel is 13.3 N, which occurs at deceleration. The lever arm is 3.125 inch. Using Eq.1, one calculates 1.06 N*m. According to Eq.2, there are around 13.2 watts. Applying a safety factor of 3, a motor of at least 40 watts should be chosen.

According to the stock availability and the specification requirements, the motor chosen is a Maxon EC-max motor with specification of 60 watts maximum continuous power, 12V nominal voltage, nominal speed of 8130 rpm, nominal torque of 64.1 mNm, 197 rpm/V. With a 35V power supply, it achieves a nominal speed of 6895 rpm. A Maxon Planetary Gearhead with 66:1 ratio was chosen to reduce the speed to 104 rpm, while increasing the torque. After the gearbox, it results in a 4.23Nm torque output.

For the transmission, an 18 tooth pulley and a 22 tooth pulley were chosen to result in a 127 rpm output speed at motor’s nominal speed, resulting in 3.46Nm maximum continuous torque output.

Y Axis Stepper Motor & Transmission

To analyze the y-axis and find the appropriate stepper motor, theoretical modeling was used with force and torque analysis of the axis. Using a force gauge, the force to turn the handle attached to the y-axis hand wheel was measured, which was round up to 96 ounces (*F*). Then the distance between the center of the lead screw and the handle of the hand wheel was measured to be 3.9 inches (*d*). Multiplying these two values together (Eq. 1), the torque to move the hand wheel from a stationary position was found to be 374.4 oz-in (τ).

A resolution of at least ±0.001” is required based upon the engineering specifications, which translates to a rotation of 3.6° of the hand wheel. This means that if a transmission ratio of 1:1 is used, the stepper motor would need at least 100 steps per revolution to obtain the needed resolution.

Next, a safety factor of three was chosen to ensure that the torque transferred from the motor to the lead screw would sustain itself as the motor and transmission fatigues inevitably over time. Using this safety factor, a torque output from the motor of at least 1123.2 oz-in was required. A stepper motor with 200 steps per revolution and a holding torque of 880 oz-in was selected. With the holding torque and the required torque including the safety factor, a transmission ratio of at least 1.3 is required. Although only a transmission ratio of 1.3 is required based upon the selections, a pulley with 18 teeth was selected for the motor and a pulley with 36 teeth was selected for the motor, resulting in a transmission ratio of 2. Using the transmission ratio, a safety factor of approximately 4.7 is calculated, higher than the required 3.

To calculate the resolution, the length of travel for one rotation of the hand wheel is divided by the value of the number of steps in the stepper motor multiplied by the transmission ratio. This results in a resolution of ±0.00025”, which is below the required 0.001”.

The current location of the motor mount is variable based upon the timing belt length chosen. There do not appear to be any present problems with the motor mount as the location of the screws that secure the mount will not be within the half inch walls present on the sides of the table. This allows for the use of a locknut and a bolt to be used to secure the mount.

The pulley for this axis is set to be mounted to the end of the shafts of both the machine axis and the motor. The motor is rated for a load of 58 pounds at this distance from the shaft end. The max force needed to turn the wheel is 6lbs. The force of the machine actually performing its grinding motion is relatively low due to the cut dimension being very small. The mass of the pulley is around 0.25 pounds. It is clear to see the shaft is rated for much more radial load than the operation will ever require. The same force that is contained there must be able to be transferred from the purchased motor mount and through our materials. The yield strength of aluminum is high enough to be disregarded in this analysis. The purchased motor mount is metal and has their guarantee that it can withstand the same load the motor does without deformation. The plate stock used for the motor mounting plate was also selected to be thick enough that deformation is not a concern.

A belt with a 24” outer diameter was selected for use on the y-axis using equation 3 and the size of the respective timing cogs, while also factoring in the geometry of the table and the location of supports and parts on the underside of the table. A fatigue analysis will have to be performed to determine the acceptable life of the belt. If the belt is seen to be too long in analysis and is causing backlash, a shorter belt can be purchased as variability in the mounting location in the motor is available with the current design. The table has a large amount of available space on the underside of the table and the location of the supports underneath do not restrict the belt length or mounting location within reasonable values of belt length. The offset location of the motor mount was selected to ensure a taut belt when the motor is in motion, without creating unnecessary forces on the motor and y-axis shafts with over tightening of the belt. The mount has short slots on the base, which allows the motor to be slid a small amount on the table to ensure a taut belt when in use and to allow for easy removal and replacement when necessary. Any changes to the design since DR4 can be seen in Appendix F.

Z Axis Stepper Motor & Transmission

To analyze the z-axis and find the appropriate stepper motor, theoretical modeling was used with force and torque analysis of the axis, as mentioned above. Using a force gauge, the force needed to turn the handle attached to the z-axis hand wheel was measured, which was rounded up to 48 ounces (F). The distance between the center of the lead screw and the handle of the hand wheel was measured to be about 3.16 inches (d). Multiplying these two values together by Eq. 1, the torque to move the hand wheel from a stationary position was found to be 151.68 oz-in (τ).

A resolution of at least ±0.001” is required based upon ICG’s process specifications, which translates to a rotation of 7.2° of the hand wheel, which moves the table 0.05” in one revolution. This means that if a transmission ratio of 1:1 is used, the stepper motor would need at least 50 steps per revolution to obtain the needed resolution.

Next, a safety factor of three was chosen to ensure that the torque transferred from the motor to the lead screw would sustain itself as the motor and transmission fatigues inevitably over time. Using this safety factor, a torque output from the motor of at least 455.04 oz-in was required. Noting that motors are most effective near the middle of their torque-speed curve a stepper motor with a holding torque of 620 oz-in was chosen; the middle of its torque-speed curve fell to around 450 oz-in, indicating a good efficiency at this value. A stepper motor with 200 steps and an included encoder was chosen to guarantee accuracy on the z-axis.

Transmission can be used to alter the rotational speeds and torque from inputs to outputs. It can be defined many different ways, here it will be defined as the ratio of the output pulley teeth to the input pulley teeth. The specifications for the z-axis can be fully defined from the motor side alone so a transmission ratio of 1 was chosen. This is to say the input and output timing cogs are the same diameter and have the same number of teeth (18 teeth).

To calculate the resolution, the length of travel for one rotation of the hand wheel is divided by the value of the number of steps in the stepper motor multiplied by the transmission ratio. This results in a resolution of ±0.00025”, which is below the required 0.001”.

The pulley for this axis is set to be mounted to the end of the shafts of both the machine axis and the motor. The motor is rated for a load of 58 pounds at this distance from the shaft end. The max force needed to turn the wheel is 3lb. The force of the machine actually performing its grinding motion is relatively low due to the cut dimension being very small. The mass of the pulley is around 0.25 pounds. It is clear to see the shaft is rated for much more radial load than the operation will ever require. The same force that is contained there must be able to be transferred from the purchased motor mount and through the other materials. The yield strength of aluminum and steel are both high enough to be disregarded in this analysis. The purchased motor mount is plastic but supplied by the same company that makes the motor and has their guarantee it can take the same load the motor does without deformation. This same force would be transferred through the three screws mounting the angle mounting plate to the axis face, as well as a moment for being a distance away from the belt. A special design implement was introduced to catch any moment introduced to this plane. This piece will be bolted precisely under the back end of the angle mounting bracket and to the top of the machine to provide a rigid support and the angle mount’s back end. It can be seen below in Figure 9, the full exploded diagram.

Many factors had to be accounted for when placing the motor mount on top of the angle mounting bracket. Foremost was ensuring a tight fit in whatever belt selection was made. Using Equation 3 and geometric certainties about the motor axis height as well as clearances for mounting screws, a belt of 15 inches was chosen that could ensure adjustability of the motor mount while not interfering with the function of the actual machine. The motor was placed at a slight offset from directly over the axis shaft to ensure the belt could be tightened or loosened accordingly. The adjustable positions of the motor (via slots in the motor mount) are also such that the elements used to mount the motor will not interfere with any part of the design or machine. All pulleys used with this belt will be attached with a set screws to ensure good connection.

The last consideration on this axis was that the machine axis was not perfectly set at 0.5 inches in diameter and had to have a separate collar manufactured to ensure a good fit. It is 0.48” on its inside diameter and spans around half of the pulley. The collar is set to be press fit into the pulley, which was adapted to take a larger inside width of 0.75”. This collar will have one set screw thread continued inside of it from the pulley, allowing it to be attached to the axis shaft. This collar is set to be made of aluminum and made in the machine shop.

Ultimately, there are only a few parts that will need to be manufactured. They are the angle mounting bracket, the angle mount support, and the collar for the axis shaft. Engineering drawings that will be used to produce these parts are shown in Appendix E. Changes to these designs after the fourth Design Review will be present in Appendix F, if applicable.

FMEA and Risk Analysis

After generating concepts and evaluating them, a failure modes and effects analysis (FMEA) and a risk analysis were performed on the system. The full FMEA, its scoring system, and the risk analysis can be found in Appendix D.

The most pressing results of the FMEA were in failure modes that would inevitably have to occur with frequent use or with operator errors. Due to the automatic nature of the machine most of the defects expected are from loss of precision with time, so failures involving harm or loss of human life naturally have a high risk priority number (RPN) even if they are very unlikely to occur. Although the chances seem low, the ranking system used for the FMEA (shown in appendix D) had the mounting of the grinding head placed highest. If the geometry or alignment is altered during the process parts would be consistently out of spec with low noticeability. Loss of precision in general (motor, transmission, grinding head, etc.) has noticeable RPN in the FMEA as this will usually produce out of spec parts quickly with low detection. To against this standard change times will be suggested in handing off the prototype. Covers to the active parts of the operation are a large consideration suggested by this FMEA as they would protect against most foreign material, slowing machine degradation and precision loss. Another large implication is that the introduction of a closed feedback control loop would greatly reduce the RPN for most categories as well as make many proposed solutions obsolete. The complexity of the feedback loop is severely hindered by the length and budget provided to this project, and will be added as the time limit deems appropriate.

Using the risk analysis, the most common and severe types of failure were found to be due to foreign materials getting caught in the transmission, grinding wheel, or other moving parts. The risk for this is high without proper guarding, since there are multiple rotating parts with large amounts of energy. The consequences are also severe, damaging the machine or creating safety hazards for the user. This could also lead to severe injury if part of the operator is caught in a moving part. The most effective way to combat this risk is to design guards around the moving parts to protect users and prevent foreign materials from coming in contact with the moving parts. Using properly installed guards, this risk is greatly reduced, and therefore guards around all actuators and transmissions should be present before using the machine.

Design Verification

Due to the fact that there are relatively few engineering specifications for the project, there are four verification tests required to determine if the machine fully meets the user and engineering requirements.

First, the precision control of the y and z axes was tested. For the z-axis, a height gauge was set on the machine table and made rigid contact with a point on the machine that moves with the z-axis. Then, a signal was sent to the motor to move the machine a distance of 0.001 in. along the z-axis and the measured change in height of the height gauge was recorded. This process was repeated 20 times and the difference between the commanded and actual movement distance was be calculated for each data point. The direction of travel was then reversed and 20 additional data points were taken. The difference between commanded and actual distance must be less than 0.0005 in. at each data point for validation to be acceptable. The machine met this requirement, validating the z-axis. The test setup used in precision verification can be seen below in Figure 13.

Figure 13. The height gauge test setup used to verify the y and z axes.

Similarly, in the y-axis, a dial indicator was mounted on a stationary part of the machine, and its measurement point on a part that moves with the y-axis. The same process as above was used to test the y-axis: command the machine to move the y-axis 0.001 in. and record the measured change in the reading of the indicator. This process was then repeated 20 times. The direction of travel was then reversed and 20 additional data points were taken. The benchmark was set to be the difference between commanded and actual distance, which must be less than 0.0005 in. at each data point for validation to be acceptable. The machine met this requirement, validating the y-axis.

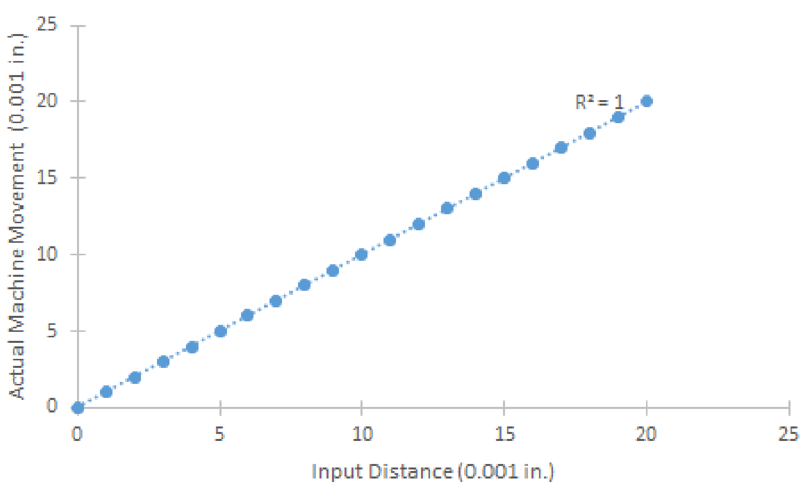

Figure 14. Machine movement was exactly what the commanded movement expected it to be. Hysteresis was not an issue; data was taken 0 to 0.020” to 0.

Measuring cycle time validated speed performance of the x-axis. The motor was set to its highest speed and the machine was then commanded to move between two points 12 inches apart. Video was recorded of this motion 3 times, and using the video, the average time was determined to be 1.2 seconds, for a speed of 0.83 ft/s. While this did not meet the speed engineering requirement, it will be up to the sponsor to determine if it is acceptable.

For future additional verification, the machine will be commanded to undergo 100 cycles of oscillating the table a distance of 12 inches. If the average cycle time is less than 2 seconds (back and forth), we will consider x-axis speed to be validated. This test will also serve to determine the acceleration and thermal performance characteristics of the system.

Once guards have been designed and are in place, the machine will finally be subjected to an ingress protection test. To ensure the motors and transmissions are properly guarded to prevent ingress of foreign materials, the machine will be tested up to IP20 standards. To do so, a finger test will be conducted with the machine unplugged, to see if any areas of potential danger can be accessed. All positions of the table, grinder head, and work piece will be tested to ensure the machine is properly guarded during any operating conditions.

Discussion

Having completed implementation of our design, the efficacy of the chosen design can now be analyzed. One of the strengths of the final design is the precision control of the Y and Z axes. Given a theoretical resolution of 0.00025 inches per step (or 4x the required precision), this allowed for the desired precision and will account a large amount backlash or looseness in the transmission for the future. The torque from the stepper motors also is very strong, ensuring a very low chance of being backdriven or not being able to drive the axis as the machine wears.

The PLC and operator interface is also another strength of the design. Using a PLC makes the system much less likely to encounter problems due to electrical noise and interference, and is also much more durable and suited to an industrial environment. The interface, which is the part of the system that typically fails most often on the current machines ICG has, is also sealed, which should make it last much longer and be more reliable.

There are also many improvements that can be made to our prototype. The X axis was slightly slower than expected, reaching 0.83 ft/s instead of the goal of 1 ft/s. This may be remedied by a larger motor, or perhaps gearing the axis down to increase speed. Torque requirements must still be met if implementing the latter.

There are also some design changes or additions that are required before the machine is ready for full-time operation. First, the wires connecting from the PLC to the X and Y axes motors should be enclosed in a cable carrier to ensure they don't wear over time. The material has already been obtained for implementing such a change, but modifications to the machine and design must be made. Second, the electronics must be mounted and sealed in an enclosure. This was discussed in the design, but has not been implemented. Additionally, guards were also discussed in the design but need to be designed and implemented.

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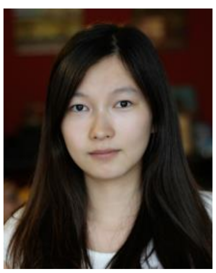

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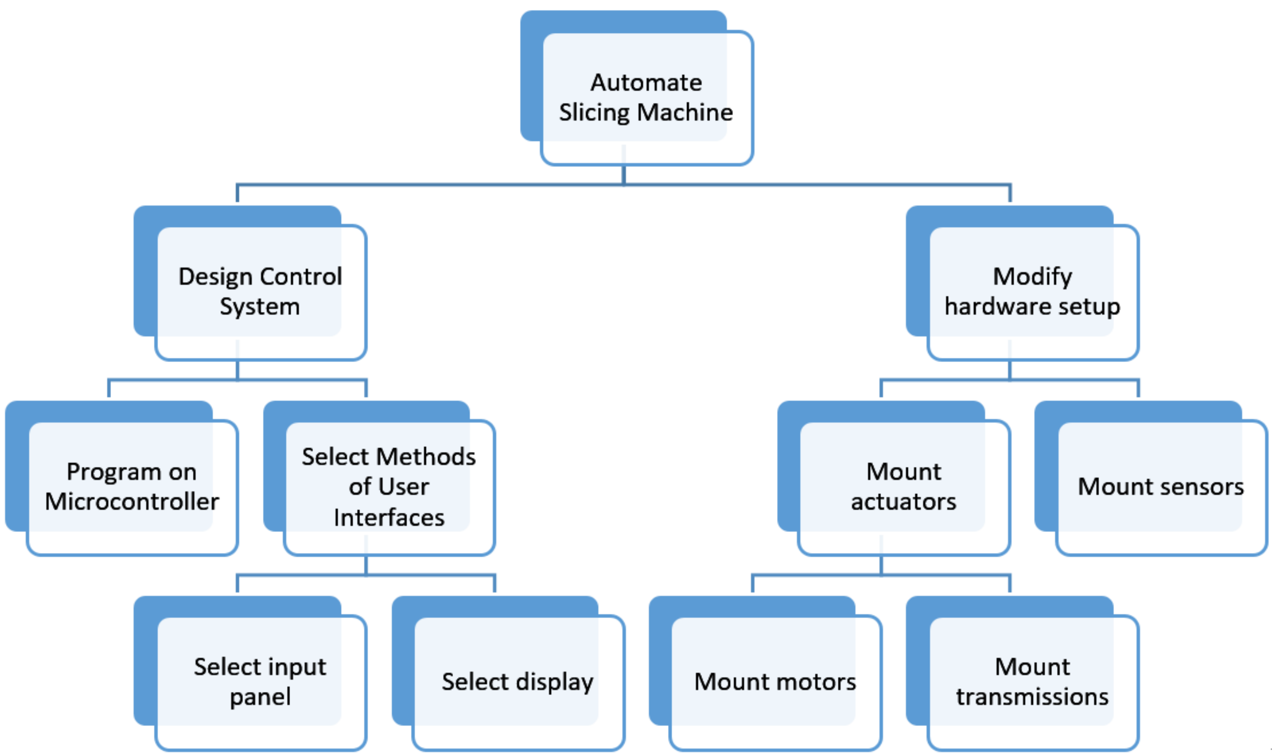
Appendix A: Functional decomposition

From the functional decomposition above, we divide our tasks into two main categories: designing control system and modifying hardware setup. Hardware modification is the basis of this project. Actuators and sensors will be mounted considering the space and shape of the given manual slicing machine. This process contains design and manufacturing work. Under control system, what we need to do is to automate the machine using microcontroller and user interfaces. Connecting circuits and programming will be the focus under this category.

Figure A.1 Functional decomposition of meeting the goal of automate the machine



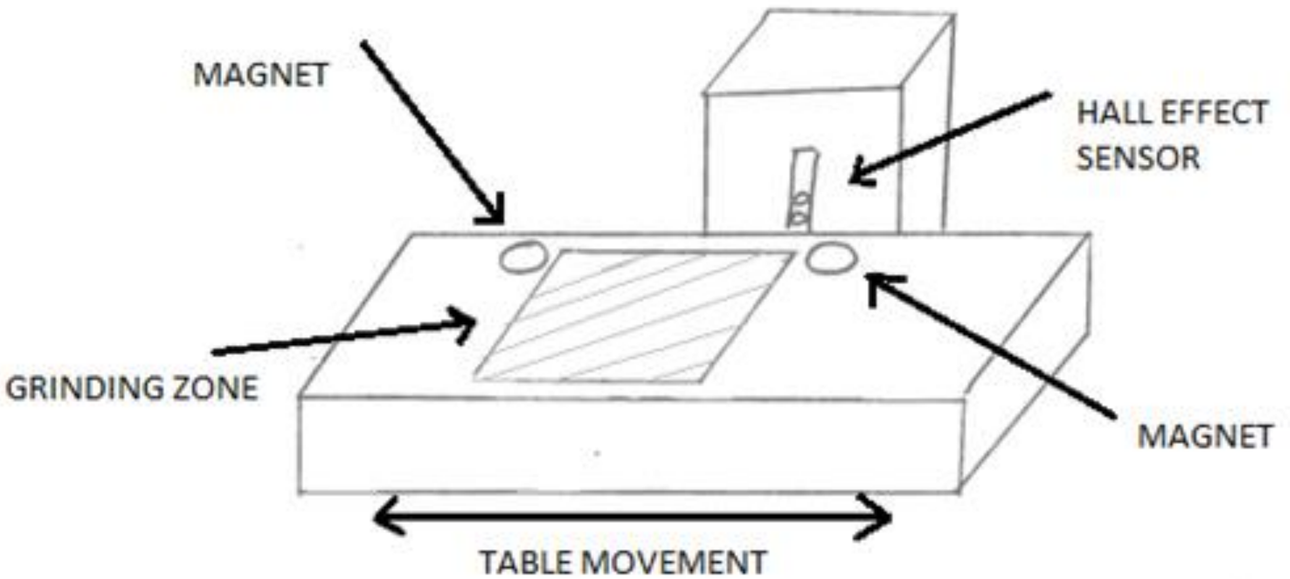
Appendix B: Concepts Generated and Sketches

Table B.1 Concept generation brainstorming result

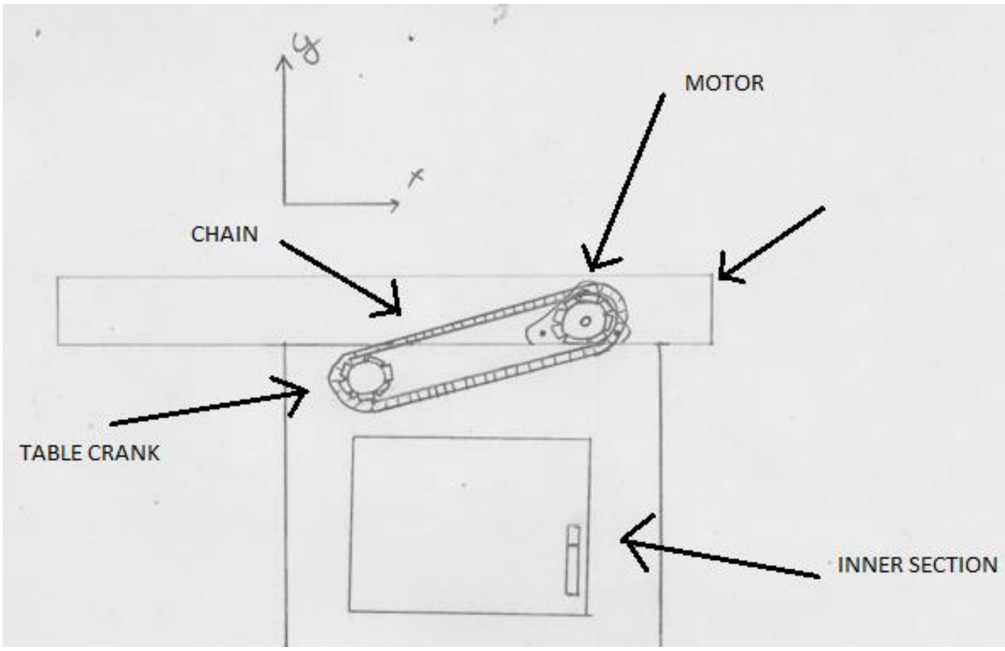
#	Functional Group	Concept	Description	Design Tools Used	Drawing
1	Transmission	Belts	Belts can transfer power from the motors to turn the main cranks. This option is wear intensive but easy to design.	Brainstorming, Functional Decomposition, SCAMPER	No
2	Transmission	Gears	Gears can precisely transfer power from the motors to the main cranks. They will require additional design work for gear mountings.	Brainstorming, Functional Decomposition	Yes
3	Transmission	Chains	Chains will allow for power transfer from the motors to the main cranks. This option has low wear and will require a gear mounting.	Brainstorming, Functional Decomposition, SCAMPER	Yes
4	Transmission	None	The motor shaft would be inside a hole bored into the axis shaft and would use a set screw or pin through the set of shafts.	Brainstorming, Functional Decomposition	No
5	Motor	Stepper Motor	This motor will be able to deliver the necessary power to move our machine. This motor is integrated with technology so it works at repeatable intervals, which will allow us to keep precision high in our manufacturing scheme.	Brainstorming, Functional Decomposition, SCAMPER	No
6	Motor	DC Motor	This motor will be able to deliver the necessary power to move our machine. It will require a convertor to our power scheme but will be powerful.	Brainstorming, Functional Decomposition	No
7	Motor	AC Motor	This motor will be able to deliver the necessary power to move our machine. AC motors often require a gearbox to help tailor them to an application.	Brainstorming, Functional Decomposition	No
8	Return Action	Motor Timing	Programming the motors to return after a certain cut distance will help preserve the machine and increase operational efficiency. This method of return could be easily switched and would not change within a single program run.	Brainstorming, Functional Decomposition	Yes
9	Return Action	New Springs	Having mechanical springs attached to the end beds of the grinding chuck would help preserve the machine action. Further, the cutting motor could be used more liberally. No programming changes required per operation.	Brainstorming, Functional Decomposition, SCAMPER	No
10	Return Action	Included Stoppers	The machine we are working with has adjustable mechanical stoppers along the	Brainstorming, Functional	No

			track that already can constrain the bed. They are flimsy and would need to be adjusted for different sized pieces. Possible retrofitting to the forces required during manufacturing are possible with this option.	Decomposition	
11	Sensor	Sensor Trigger	A motion sensor could be placed at the proposed end of the cutting bed. Crossing it would trigger the motor to reverse directions. It would have to be reconfigured for different sized pieces.	Brainstorming, Functional Decomposition, SCAMPER	No
12	Sensor	Hall Effect Sensor	Magnetic sensor that can switch when introduced to a magnetic field. Adjustable magnets could set this sensor off to change table direction mid use.	Brainstorming, Functional Decomposition, SCAMPER	No
13	Sensor	Encoder	An standard encoder. Will detect how far the motor has gone and be programmed to switch after a set distance. Prone to error in constant use.	Brainstorming, Functional Decomposition	No
14	Sensor	Linear Encoder	An encoder in linear style, Will detect how far the motor has gone and be programmed to switch after a set distance. Prone to error in constant use.	Brainstorming, Functional Decomposition	No
15	Sensor	Toggle Switch	A physical switch that would be triggered by the hard stops, currently in place on the chuck, and would reverse the motor direction. The stops would need to be moved based upon the size of the piece of material.	Brainstorming, Functional Decomposition	No
16	Microcontroller	Arduino	Arduino is a common microcontroller for small scale mechatronic systems. It is cheap, easy to learn and has many extensive modules available.	Brainstorming, Functional Decomposition	No
17	Microcontroller	PLC	An industry standard microcontroller. Compatible with CNC machines, medium user skill.	Brainstorming, Functional Decomposition	No
18	Microcontroller	FPGA	Another industry microcontroller	Brainstorming, Functional Decomposition	No
19	Interface	Toggle Buttons	Toggle buttons have the most common settings for the machines decrements. Choices would be discreet so the machine would be less adaptable but have less chance of operator error.	Brainstorming, Functional Decomposition	No
20	Interface	Touch-screen	Any logical display could be easily configured on a corresponding touch pad for an operator. It could also be customized further in the future if ever need be. Easy to make mistakes though and environment is a concern.	Brainstorming, Functional Decomposition	No
21	Interface	Button Display	An LCD display with manual button controls. High degree of variability in	Brainstorming, Functional	No

			entering choices and programming variability with use.	Decomposition	
22	Interface	Operator's Terminal	A remote station capable of controlling the work cycle of any machine. A single skilled technician could remotely program any of the networked grinders.	Brainstorming, Functional Decomposition, SCAMPER	No



Sketch 1. In this design the direction of the motor moving the grinding table back and forth will be controlled by a Hall Effect sensor. Magnets attached to the grinding table will trigger this sensor and switch the action of the motor. The location of the magnets can help to reduce cycle time.



Sketch 2. This is a basic design for the chain transmission of power from the motor to the table crank. The motor will be mounted on the table for easy operation.

Appendix C: Concept Selection Charts

Weighting and scoring of different parts of the design are given below. Discussion about the criteria and the chosen design can be found under "Concept Selection" section.

Table C.1 Pugh chart of rates the best transmission to be timing belts

Concept		**Belts**	**Gears**	**Chains**
				
Criteria	**Weight**			
Cost	3	0	1	0
Adjustability	4	1	-1	0
Ease of assemble	4	1	-1	0
Ease of maintenance	2	1	0	-1
Noise	1	0	0	-1
Service life	4	-1	1	0
Ability to transfer large torque	3	-1	0	1
Sum		**3 (Selected)**	-1	0

Reference: ME350 lecture notes

Table C.2 Pugh chart rates the best design to be DC motor for X direction and stepper motor for Y and Z direction

Concept			**Stepper**	**Normal DC**	**AC Motor**

			Motor	Motor	
	For X direction	For Y and Z direction			
Criteria	**Weight**	**Weight**			
Cost	4	4	-1	1	0
Position control	1	5	2	0	0
Speed control	5	1	1	0	0
Ease of drive design	3	3	1	1	-1
Ease of Maintenance	2	2	-1	0	1
Max operation speed	5	0	-1	1	1
Low speed torque	1	3	1	0	0
High speed torque	5	0	0	1	-1
Power Efficiency	1	1	-1	0	1
Sum for X direction			-4	**18 (Selected)**	-1
Sum for Y and Z direction			**10 (Selected)**	7	0

Reference:
http://www.slideshare.net/fikakhamis/advantages-and-disadvatages-of-acdc-motor
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Table C.3 Pugh chart rates the most suitable microprocessor to be Arduino/PLC

Concept		**Arduino**	**PLC**	**FPGA**
Criteria	**Weight**			
Cost	1	2	0	0
Size	2	1	0	0
Ability of processing	1	0	2	2
Industrial applicability	1	0	2	1

Ease of programming	2	1	1	0
Sum		**6 (Selected)**	**6 (Selected)**	3

Table C.4 Pugh chart rates the most suitable interface to be a sealed keypad with a LCD screen.

Concept		**Keypad w/ Screen**	**Membrane Keypad w/ Screen**	**Touchscreen**
Criteria	**Weight**			
Cost	4	0	0	-1
Size	3	0	0	0
Ease of integration to control system	2	0	0	-1
Durability	5	0	1	-1
Ease of installation	2	0	0	0
Sum		0	**5 (Selected)**	-11

Table C.5 Pugh chart rates the most suitable sensor for X-Axis to be hall effect sensor

Concept		**Hall Effect Sensor**	**Limit Switches**	**Springs**
Criteria	**Weight**			
Cost	4	1	1	1
Size	1	1	1	0
Ease of integration to control system	3	1	1	2
Durability	5	1	1	1
Ease of	2	1	1	0

installation				
Limits can be easily adjusted	4	2	1	0
Sum		**23 (Selected)**	19	15

Appendix D. FMEA and Risk Analysis

FMEA Scoring

Score	Severity	Occurrence	Detection
10	User is injured or killed. Plant is damaged or put in danger	Failure all but guaranteed	Absolutely no way to detect failure before release to customer
7	Device breaks or must be stopped for maintenance. This includes producing many out of specification wafers	repeated but unpredictable failure	Highly likely customer will find this issue (~70%)
5	Operator intervention required, but operation can continue. This includes producing up to a whole batch of ruined alumina wafers	Occasional failure (quarterly)	Moderate chance of customer finding this defect (~50%)
3	Machine remains operable, run time intervention required, up to 5 rows (row =8-10 alumina rods) of wafers defective	yearly failure	Low chance of customer finding this issue (~30%)
1	Minor difficulty with no intervention required. This includes producing one out of spec part	Very low probability of occurrence	Almost certain chance of finding this issue before project close

FMEA

Component/ Function	**Potential Failure Mode**	**Failure Effects**	**SEV**	**Potential Causes or Mechanisms**	**OCUR**	**Current Controls**	**DET-ECT**	**RPN**	**Actions Taken**
Machine Inertia									

The machine must be able to stay stable and upright during automatic operation. Its inertia during use is what would cause any failure to the machines static base.	Strong table movement along x axis	Machine tips slightly and falls back into place, damaging components. Repeatable.	7	Machine physics	1	Included floor bolts	1	7	None
		Machine falls over along x axis	10	Machine physics	1	Included floor bolts	1	10	None
	Earthquake (California based company)	Machine tips slightly and falls back into place, damaging components. Repeatable.	7	Machine physics, the earth	1	Included floor bolts	1	7	None
		Machine falls over in some direction	10	Machine physics, the earth	1	Included floor bolts	1	10	None
Hall Effect Sensor									
A magnetic toggle switch used to tell the machine when to reverse its x axis cutting motion	Sensor looses power or contact	X axis switching is no longer automatic in one direction	7	Sensor fatigue, sensor mounting fatigue, table magnet dislodged/out of place	1	Sensors required for table movement	5	35	Closed loop feedback
	false positive	X axis switches before full cut	7	Sensor fatigue, sensor mounting fatigue, table magnet dislodged/out of place	1	Sensors required for table movement	5	35	Closed loop feedback
	unregistered table movement	X axis skips one cycle of depth cutting, requiring a cut of double depth on the next pulse	1	Sensor fatigue, sensor mounting fatigue, table magnet dislodged/out of place	1	Sensors required for table movement	5	5	Closed loop feedback
		X axis does not return, machine stalls	7	Sensor fatigue, sensor mounting fatigue, table magnet dislodged/out of place	1	Sensors required for table movement	5	35	Closed loop feedback
Grinding Head									
The grinding wheel used to slice through the sections of alumina. Stationary, while the table moves under it	Mounting loosens	Grinding wheel jiggles, losing precision	7	Fatigue, vibrations	1	Machine grinder mounting already evaluated at industry standards	3	21	None
		grinding wheel dismounts	10	Fatigue, vibrations, screw failure	1	Machine grinder mounting	1	10	None

						already evaluated at industry standards			
	Foreign matter is introduced	Grinding wheel geometry damaged	5	Operator, alumina defect, plant conditions	5	None	10	250	Grinder guard
		Grinding action broken	7	Operator, alumina defect, plant conditions	1	None	10	70	Grinder guard
	Wear decreases the size of wheel	Less precise z axis depth cuts are made	5	Wheel properties, fatigue	10	Grinding heads scheduled for regular replaceme nt based on ICG standards	3	150	Statistical analysis of grinding head wear for proper replaceme nt times
Interface									
The panel by which operators will input the machine program. Able to be used while the machine runs	Operator leans over active machine to use panel	Operator killed or mutilated	10	Panel inconveniently located, operator error	1	panel easily reached from side, away from grinding wheel	10	100	Extra warning signs and memo to ICG
	Button input is poorly connected	key doesn't work and operator notices	7	wiring fatigue, machine vibration, keypad fatigue	1	Extensive testing, high durability keyboard	3	21	extensive testing
		key doesn't work and operator still runs program	7	wiring fatigue, machine vibration, keypad fatigue	1	Extensive testing, high durability keyboard	1	7	extensive testing
		Manual stop defective	10	wiring fatigue, machine vibration, keypad fatigue	1	Extensive testing, high durability keyboard	1	10	extensive testing
Wiring									
Method by which electrical signals are sent to motor controllers and ultimately how the machine will send all input and output.	Short circuit	One or more operations is denied signal	10	Wires not properly protected, foreign materials introduced, fatigue	3	Wiring procedure, protected wires, hard soldering connection s	1	30	Extra insulated wire
		Machine stops functioning	10	Wires not properly protected, foreign materials introduced, fatigue	3	Wiring procedure, protected wires, hard soldering connection	1	30	Extra insulated wire

						s			
	overheating	Fire	10	Wires not properly protected, foreign materials introduced, fatigue, too much power or demand	1	Wiring procedure, protected wires	3	30	Extra insulated wire
Stepper Motor									
Provides precise, small increments to the y and z axes of the machine according to the controller	Incrementer breaks and performs out of spec	Machine produces out of spec parts	7	motor fatigue, dust build up	1	Dust shield	10	70	Extra consideration in motor life, precision, and wear. Closed loop feedback control
	Motor actuation fails	Machine no longer works along the y or z axes	7	Motor fatigue, dust build up	1	Dust shield	10	70	Extra consideration in motor life, precision, and wear. Closed loop feedback control
	Motor mount fails partially	Slack in transmission allows for slippage/movement. machine still functions	5	Screw wear, Vibrations work mount loose	3	Precision of design and manufacturing.	7	105	Extra consideration in motor life, precision, and wear. Closed loop feedback control. Precision mounting and bolts
		Slack in transmission allows for transmission to disengage, machine still functions	7	Screw wear, Vibrations work mount loose	1	Precision of design and manufacturing.	5	35	Extra consideration in motor life, precision, and wear. Closed loop feedback control. Precision mounting and bolts
	Does not receive pulse	Y axis does not step when it should, the same wafer section	1	Motor fatigue	1	None	10	10	Closed loop feedback

		is redone (not a defect)							control
		Z axis does not step when it should, the full depth of cut is not achieved	3	Motor fatigue	1	None	10	30	Closed loop feedback control
DC Motor									
Provides simple, reciprocating motion in the x axis according to the controller	Motor actuation fails	Machine no longer works along the x axis	7	Motor fatigue, dust build up	1	Precision of design and manufacturing. Dust shield	7	49	Closed loop feedback. Motor dust shields
	Motor travels shorter than its setting	Incomplete cuts are performed	7	Motor fatigue, transmission fatigue, dust build up	1	Programming and testing	3	21	Motor dust shields. Closed loop feedback
	Motor travels farther than its setting	Grinding head travels farther than expected	1	Motor fatigue, transmission fatigue, dust build up, electrical error	1	Programming and testing	3	3	Motor dust shields. Closed loop feedback
	Motor mount fails partially	Slack in transmission allows for slippage/movement. machine still functions	5	Screw wear, Vibrations work mount loose, tolerance of fit	3	Precision of design and manufacturing	7	105	Extra consideration in motor life, precision, and wear. Closed loop feedback control. Precision mounting and bolts
		Slack in transmission allows for transmission to disengage, machine still functions	7	Screw wear, Vibrations work mount loose, tolerance of fit	1	Precision of design and manufacturing	5	35	Extra consideration in motor life, precision, and wear. Closed loop feedback control. Precision mounting and bolts
Timing Belt and Cog									
The selected transmission and control gauge for the stepper motors. The belt has teeth that mesh consistently	Belt loosens with time	Belt dislodges from cog teeth, doesn't work along this axis	7	Belt fatigue, dust build up, speed of operation, tolerance of fit	1	Precision of design and manufacturing, dust shield	10	70	Closed loop feedback control. Extra considerati

with the cog teeth in order to maintain precision.									on to precision, mounting, and tolerances. Locked cover to block all but applicable personnel
		Belt slips on cog teeth, staying mounted, losing precision	5	Belt fatigue, dust build up, speed of operation, tolerance of fit	3	Precision of design and manufacturing, dust shield	7	105	Extra consideration to precision, mounting, and tolerances. Locked cover to block all but applicable personnel
Pulley									
The selected transmission method for the x axis dc motor. No timing is required.	Pulley loosens with time	Pulley dislodges, no longer transmits power	7	Fatigue, dust build up, speed used, tolerance	1	Precision of design and manufacturing, dust shield	10	70	Closed loop feedback control. Extra consideration to precision, mounting, and tolerances. Locked cover to block all but applicable personnel
		Pulley loosens allowing for slippage	3	Fatigue, dust build up, speed used, tolerance	3	Precision of design and manufacturing, dust shield	7	63	Extra consideration to precision, mounting, and tolerances. Locked cover to block all but applicable personnel

Risk Analysis

Hazard	Hazardous Situation	Likelihood	Impact	Technical Performance	Schedule	Cost	Action to minimize hazard
Cut	User could be cut by sharp edges.	Low	Medium	None	Sets back the production schedule due to treatment of the cut.	Operator injury, possible workman's comp.	Ensure there are no sharp edges or exposed components.
Object caught in transmission	The transmission and shafts can catch cloth or skin within their timing belts or around the axis.	Medium	High	Machine must be stopped to have material removed from transmission.	Sets back the production of the ceramics as machine may need to be restarted or repaired.	New transmission may need to be ordered as belt could have stretched with object present or with injury.	Protect motors and transmissions with guards to avoid debris being able to enter the path of the transmission.
Transmission Failure	Transmission could break, causing damage to the machine or injury	Low	High	Transmission must be replaced		New transmission	Calculations for transmission lifetime and regular maintenance minimize danger
Electrical Shock	When repairing or using the device, the customer could be shocked by exposed connections or at the power sources.	Low	High	The machine will malfunction if electrical shock occurs within the machine and may cause machine to shut off of act erratically.	Machine will need to be restarted. Motor and plug may need to be replaced depending upon the damage.	Cost of lost product during that time and can increase to cost of new electrical components of the machine.	Insulate all connections, use fuses, and keep liquids out of operating area.
Overheat	The motor on the back of the machine can overheat if too much stress is applied to it.	Medium	Medium	The machine will need to cool down, but if it is bad enough, it could cause failure and the motor could need replaced.	Ranges from the time it takes the motor to cool down to the amount of time to order and replace the motor present.	Could be the cost of lost product as time is waiting for cooldown or additionally the cost of a new motor.	
Object caught in wheel	The grinding wheel spins at approximately 3450 RPM and can grab material and spin it around its spindle in a very small period of time.	Low	High	The machine may continue, can cause severe problems to the functioning if it burns out the motor or dislocates the grinding wheel in any way	May cause large delay if the spindle is affected. Machine may need to be repaired or replaced.	Cost could be minimal to an entirely new machine.	Guard is already in place on the machine, but it cannot be completely sealed as the wheel must be exposed to slice the material.
Missing safety screw leaves wheel exposed	Machine cannot be run until a new safety screw is acquired as there is unnecessary risk in doing this.	High	High	Machine cannot be run safely without the machine	All grinding must be stopped until new screw arrives.	Slip til the new screw arrives, < 1 month	Order a new safety screw.
Tipping	If the machine is not set flat on the ground and secured using the supplied bolts, it may be unsafe for use with in any	Low	High	Machine cannot perform any functions until it is brought upright, leveled and the grinding wheel and table	Time spent releveling or replacing machine loses time spent in production.	Can be the price of a new machine if the damage from the tipping is severe enough.	Ensure machine is on a stable base and there is no contact between the machine and other objects as well as being

	situation.			are balanced and leveled respectively.			secured.
Table contact / sliding	The table can contact surround objects as it has a large range of travel when in use in the longitudinal direction.	Medium	Low				Ensure the machine is sitting on a flat base or is leveled safely and ensure that no objects are within the tables range of motion.
Airborne material	The material is mounted onto a magnetic chuck, which is engaged using a lever and can be removed if the grinding forces are too strong or if not correctly engaged.	Low	High	Machine can restart once new material is secured to the magnetic chuck, unless magnetic chuck needs replaced if magnets are weak.	Loss of product that is being cut plus more delays if a new magnetic chuck must be ordered and installed.	Cost of replacement of magnetic chuck, if that is issue or cost of damage to employees or machinery hit by object	Operator training to ensure material is properly mounted.
Electrical Noise	Electrical noise or interference could cause undesired operation.	Low	Medium	Diagnose and add additional shielding to electrical system.	Sets back production schedule as machine is down for repair.	Operator injury and/or machine damage.	Shielded cables, etc.

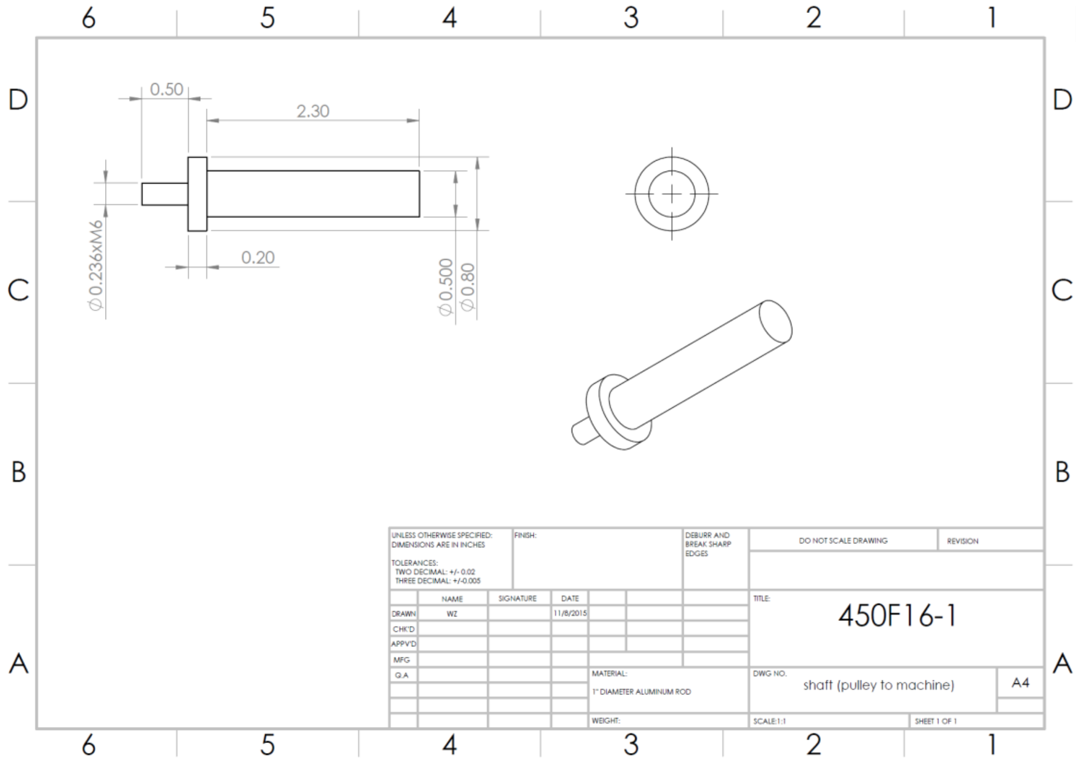
Appendix E. Bill of Materials

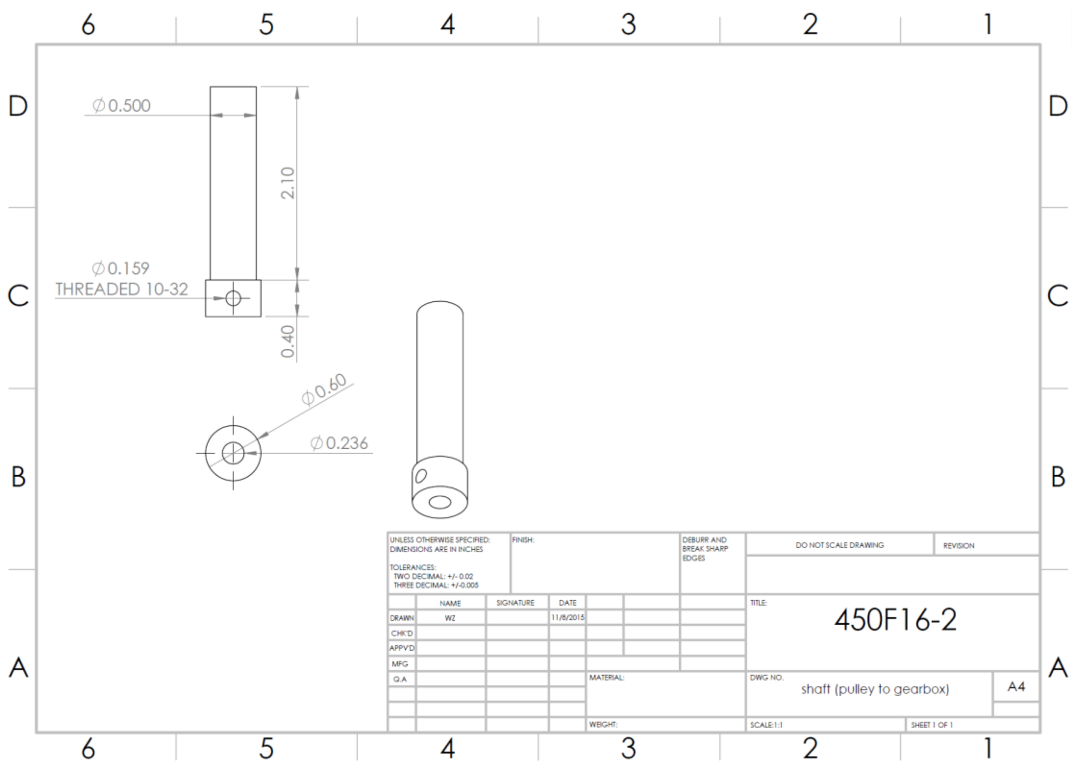
Category	Description	Price (USD)	Quantity	Part Number	Supplier
Motor	EC-max 30 Ø30 mm, brushless, 60 Watt, with Hall sensors	405.90	1	272765	Maxon Motor
Gearbox	Planetary Gearhead GP 32 C Ø32 mm, 1.0 - 6.0 Nm, integrated in motor	/	1	414533	Maxon Motor
Driver	ESCON 36/3 EC, 4-Q Servo controller for EC motors, 2.7/9 A, 10 - 36 VDC	199.5	1	414533	Maxon Motor
Motor	PK Series Stepper Motor	205	2	PK299-01AA	Oriental Motor
Motor	Mounting Bracket	19	2	PAL4P-2	Oriental Motor
Driver	Microstep Driver	184	2	CMD2120P	Oriental Motor
Encoder Cable	2ft. Encoder Cable	5	2	LCR04060A	Oriental
Controller	SCX11 Universal Stepper Motor Controller	296.65	2	SCX11	Oriental Motor
Pulley	Corrosion Resistant L Timing Belt Pulley, Fits 1/2" Belt Width, 4.52" OD, 36 Teeth	71.38	1	1304N19	McMaster-Carr
Pulley	Corrosion Resistant L Timing Belt Pulley, Fits 1/2" Belt Width, 2.375" OD, 18 Teeth	21.07	4	1304N11	McMaster-Carr
Pulley	Corrosion Resistant L Timing Belt Pulley, Fits 1/2" Belt Width, 2.875" OD, 22 Teeth	21.07	1	1304N11	McMaster-Carr
Mount Plate	Z-axis mounting plate from 1/2" aluminum stock with four mounting holes (more holes to come with motor mounting).	28.80	1	6061-T6 Aluminum	Machine Shop
Axle	Customs axle extensions for motors	0.00	2	Aluminum 5/8" Diameter Round Stock	Machine Shop

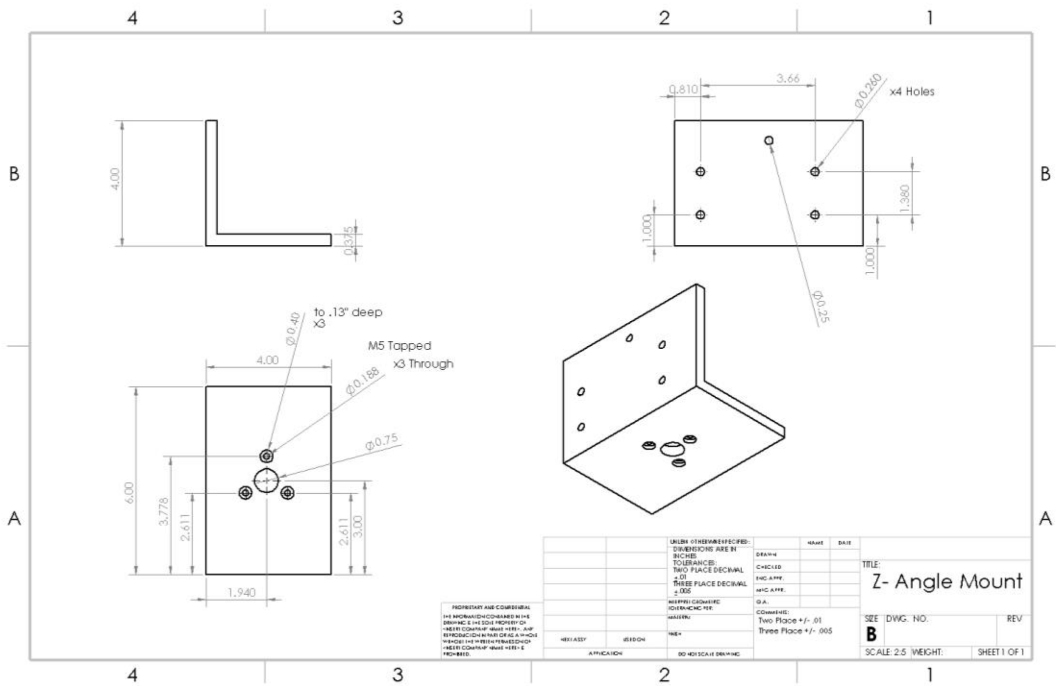
Aluminum rod	Corrosion-Resistant Easy-to-Machine 6020 Aluminum, 1", 1ft	24.28	1	9038K34	McMaster-Carr
Power Supply	TDK LAMBDA power supply 201W 36V 5.6A	86.41		967-LS200-36/L	Mouser
Timing Belt	Trapezoidal Tooth Urethane Timing Belt, 3/8" Pitch, 173L Trade Size, 17.3" Long, 1/2" Wide	9.72	1	1679K237	McMaster-Carr
Timing Belt	Trapezoidal Tooth Urethane Timing Belt, 3/8" Pitch, Trade Size 150L, 15" Outer Circle, 1/2" Wide	11.9	1	1679K261	McMaster-Carr
Belt	Trapezoidal Tooth Urethane Timing Belt, 3/8" Pitch, 240L Trade Size, 24" Long, 1/2" Wide	11.62	1	1679K244	McMaster-Carr
PLC	Vision 130™ is a palm-sized PLC with a built-in Operator Panel	399	1	V130-33-TR34	Behco

Appendix F. Initial Manufacturing Drawings

Changes are in Appendix G.






4.00
0.375
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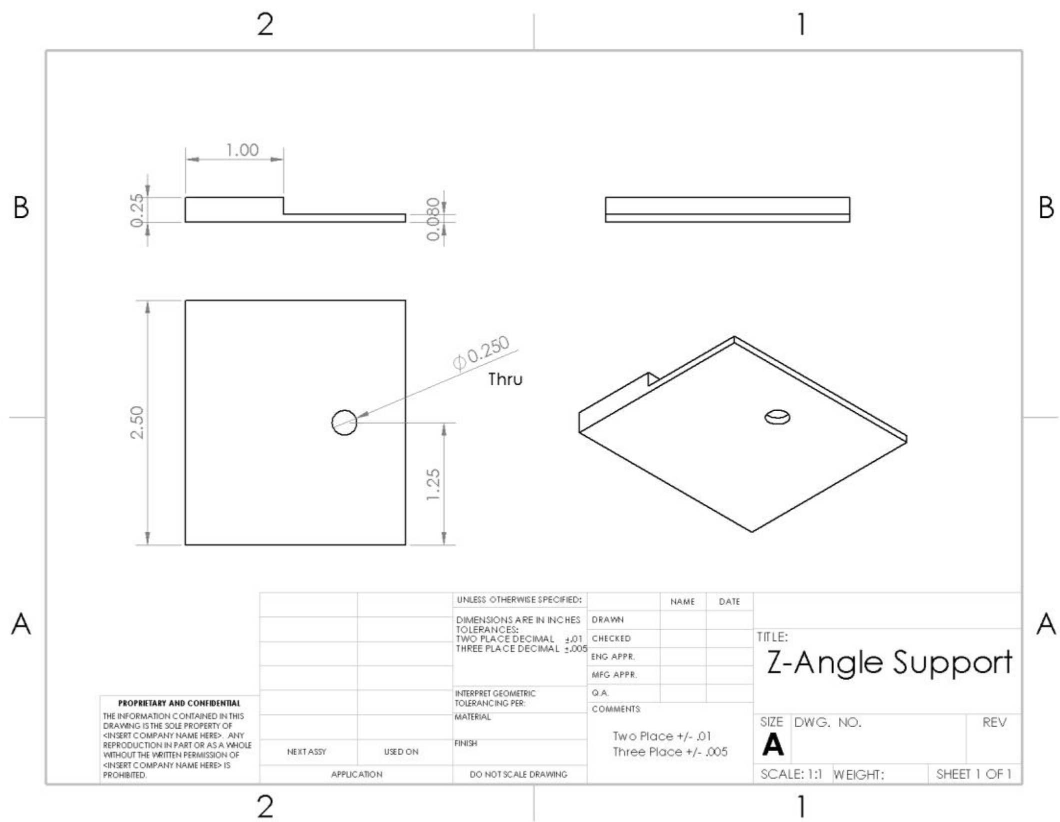
x4 Holes
1.000
1.380
1.000
Ø0.25
to .13" deep
x3
Ø0.40
M5 Tapped
x3 Through
4.00
Ø0.188
Ø0.75
6.00
3.778
2.611
2.611
3.00
1.940
Z- Angle Mount
Two Place +/- .01
Three Place +/- .005
SCALE: 2:5
SHEET 1 OF 1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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
TITLE:
Z-Angle Support
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Three Place +/- .005
SIZE A
DWG. NO.
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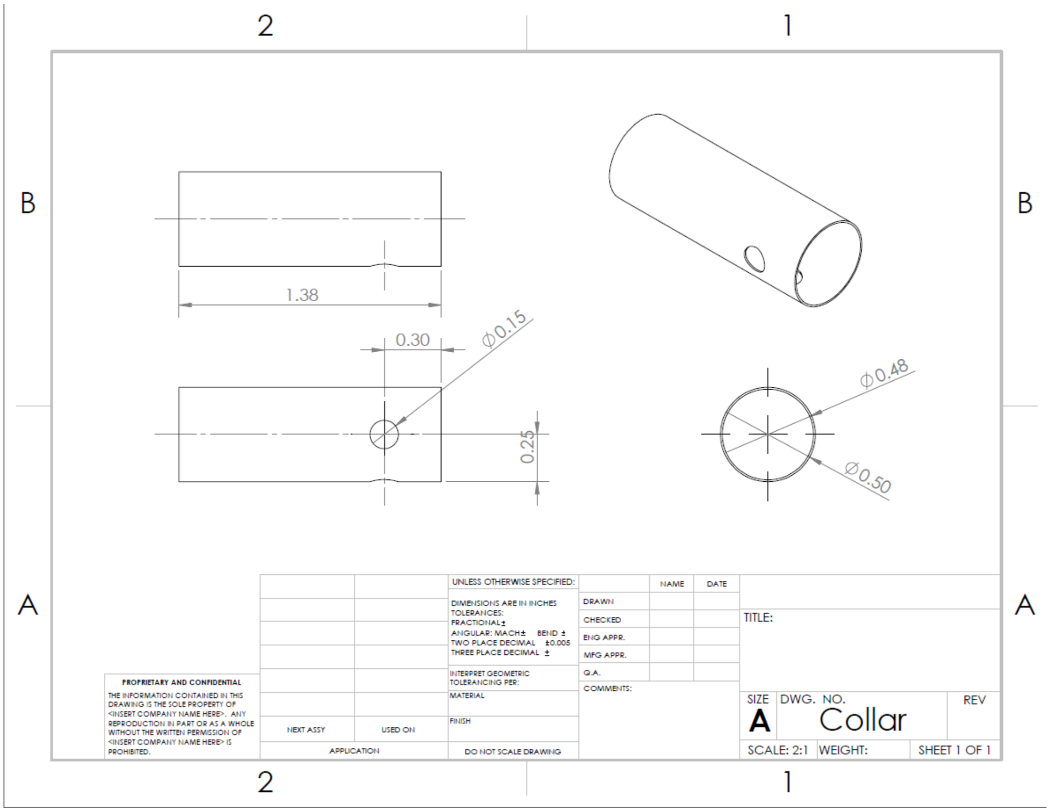
SHEET 1 OF 1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INTERPRET GEOMETRIC TOLERANCING PER:
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SIZE
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Collar
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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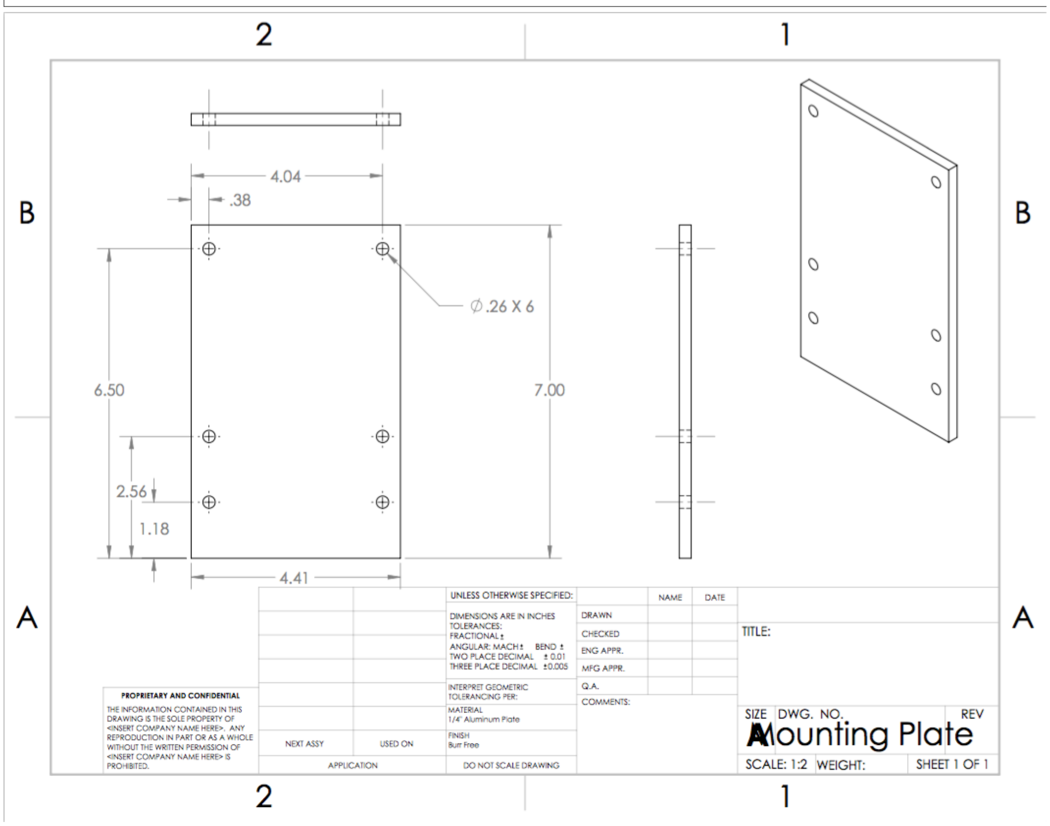
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UNLESS OTHERWISE SPECIFIED:
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1/4" Aluminum Plate
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A
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Mounting Plate
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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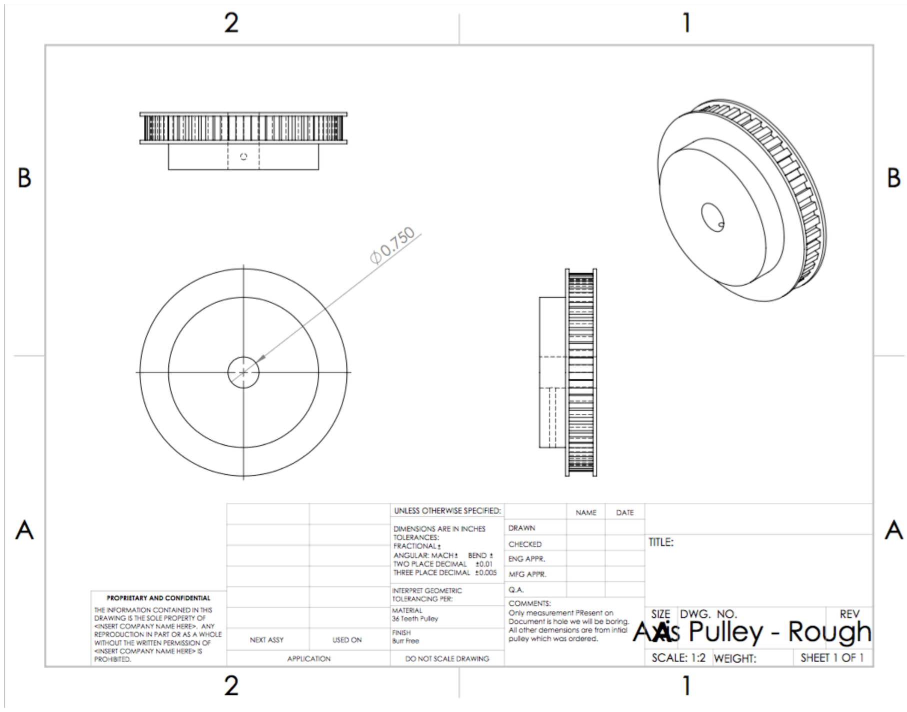
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
36 Teeth Pulley
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Burr Free
DO NOT SCALE DRAWING
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USED ON
APPLICATION
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Only measurement PResent on Document is hole we will be boring. All other demensions are from intial pulley which was ordered.
TITLE:
SIZE
DWG. NO.
REV
A
Axis Pulley - Rough
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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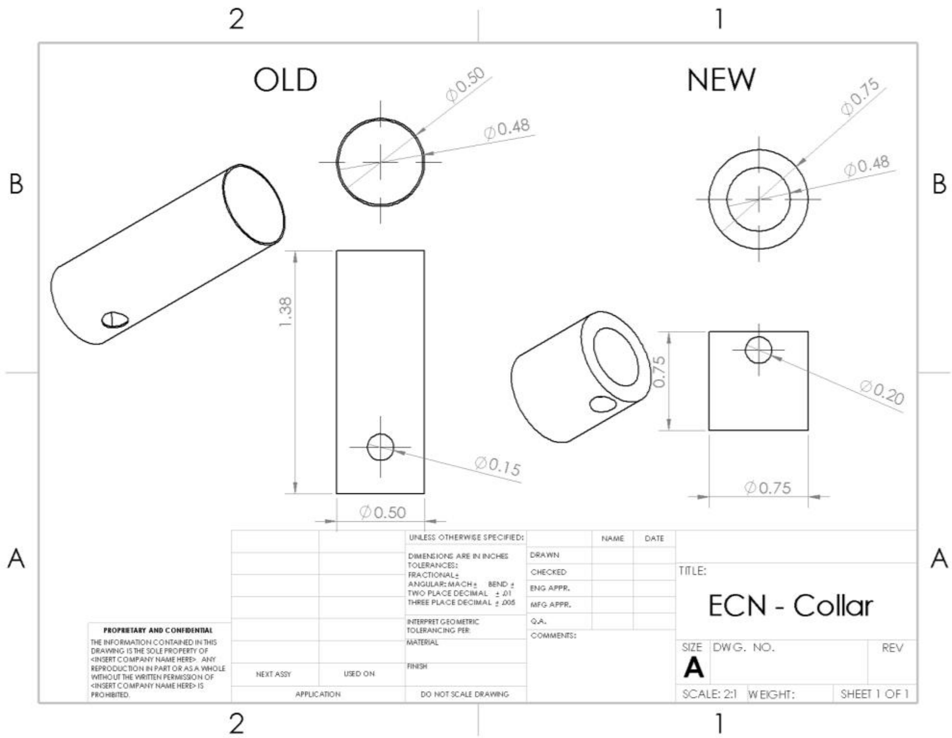
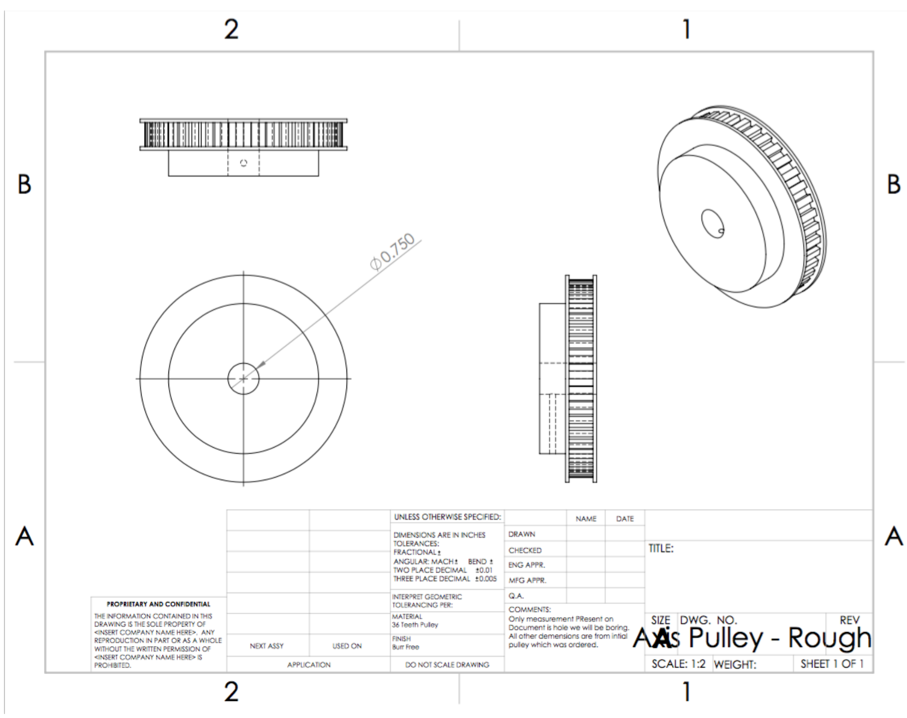
Appendix G. Engineering Change Notices

G.1. Collar and Axis Pulley (Y and Z Axes)



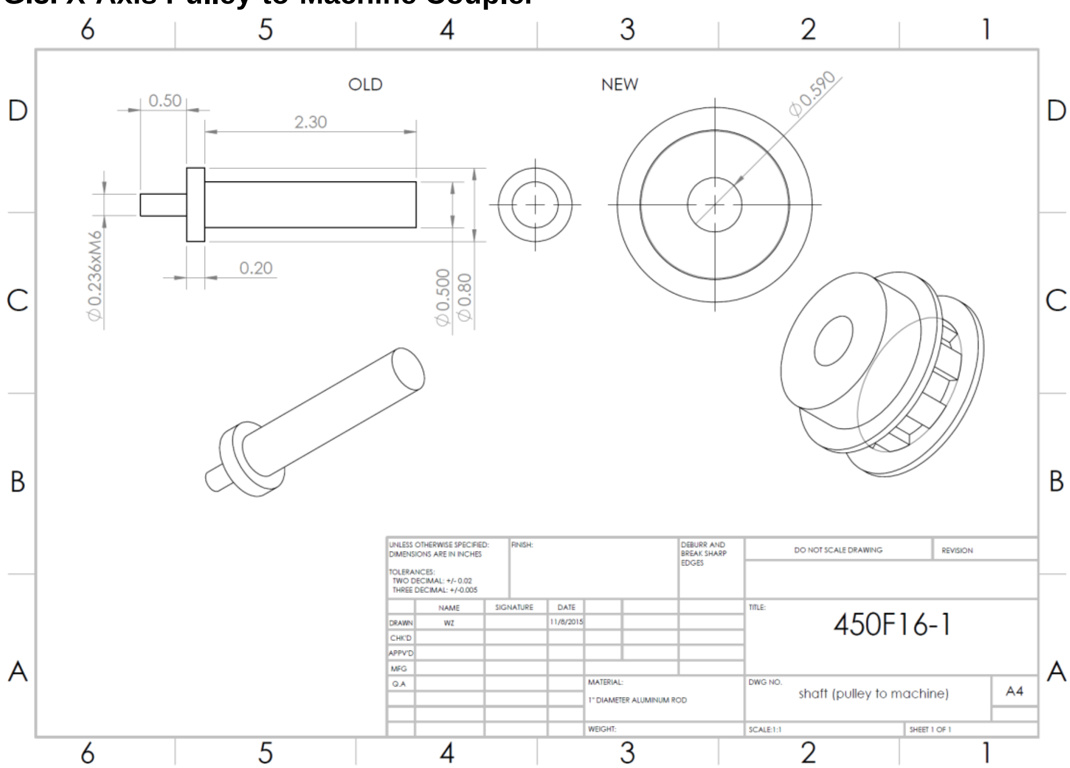


The collar shown above is meant to bridge the gap between the pulley and the axis shaft for the Y and Z axes. Its outer dimension was 0.5" (the inner dimension of the pulley hole) and its inner dimension was 0.48" (the outer dimension of the axis shaft). The proposed collar would have been very difficult to manufacture and was advised against by machine shop employees so a design change was made. The team agreed unanimously to alter the geometry of not only the collar but also the pulley it would sit in. The pulley hole and outer dimension of the collar were widened to 0.75" while the inner dimension remained the same. The collar was then press fit into the pulley permanently before further manufacturing. Further, the set screw hole which merely had to be included before was widened to flush with the pulley hole (a 0.2" diameter hole) and threaded due to its increased length. Only one set screw was planned to be used due to the press fit. The collar did not need to be the full length and was advised against by machine shop employees. Mr. Hitch had already allowed for rolling design changes in the efforts of completing this project.

G.2. Angle Mount Support

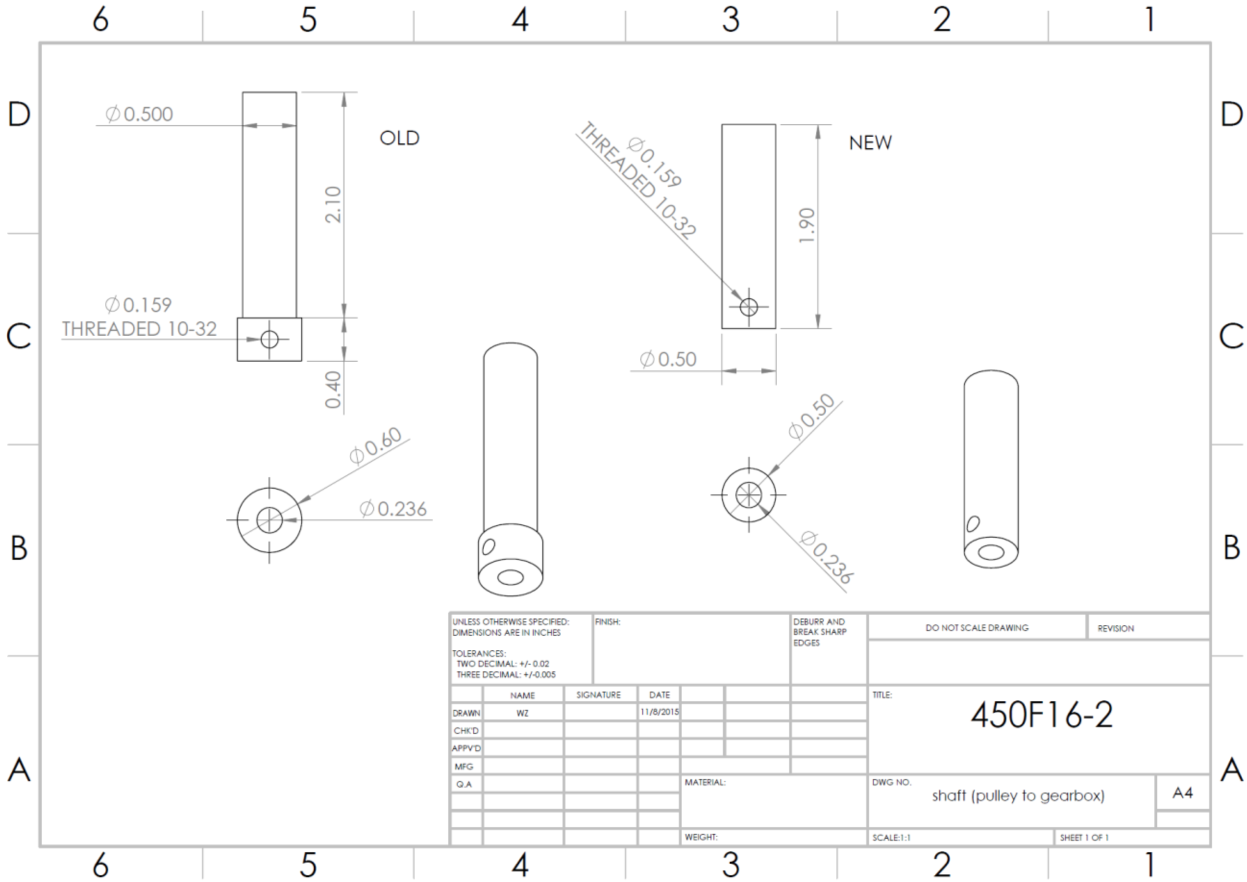
This component can be seen in the manufacturing drawings appendix. It was already planned on the manufacturing plan to check this part's geometry during manufacturing with the actual space it was meant to support. This plan can be found in the "Updated Manufacturing Plans" section. During this process it was found the piece fit the gap before the full width had been shaved off. This was expected, and planned for, but it should still be noted the part has a width of 0.18" instead of 0.08". Nothing else from the drawing was different.

G.3. X-Axis Pulley-to-Machine Coupler



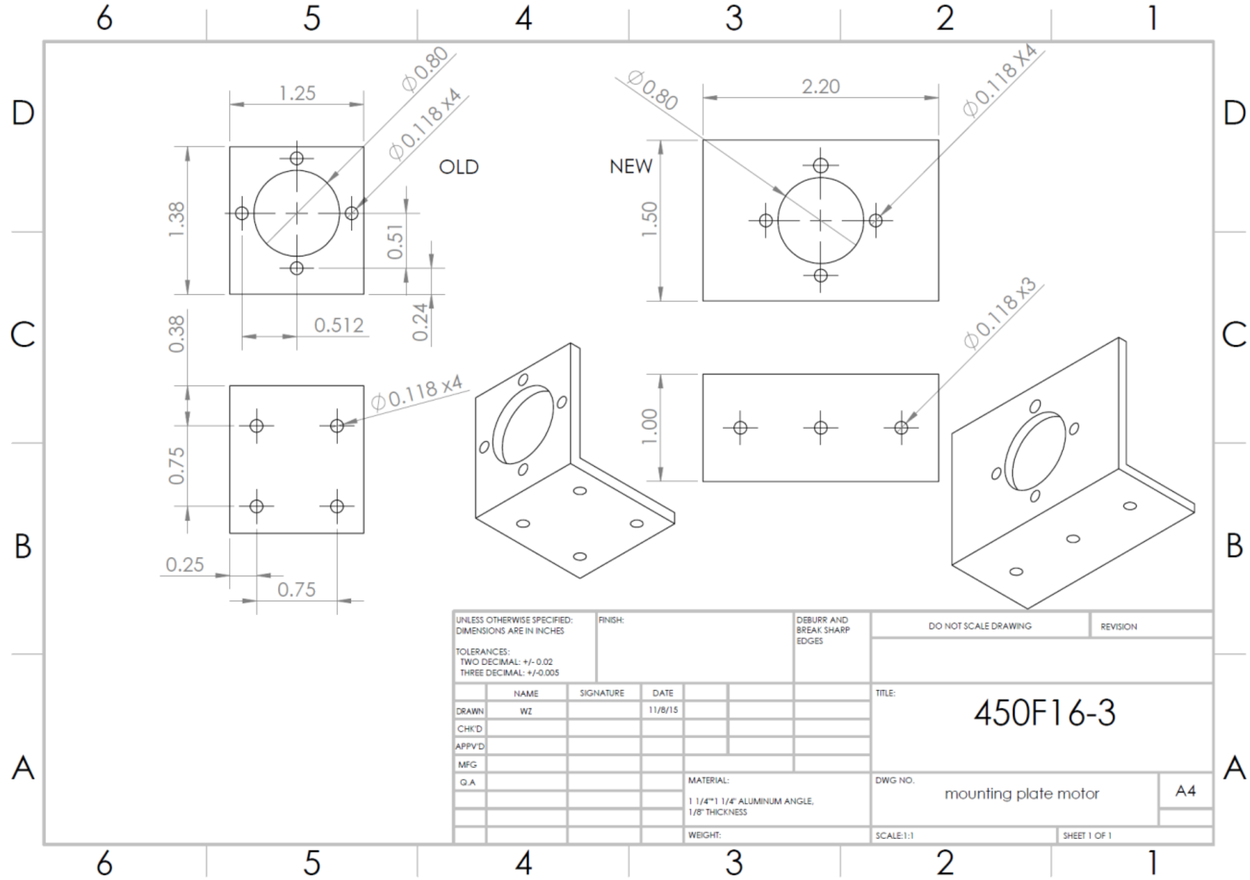
This part is removed because the pulley is bored and directly connected to the machine. This simplifies our design and makes the center of gravity of the gearbox and the motor farther from the edge of the table.

G.4. X-Axis Pulley-to-Motor Coupler



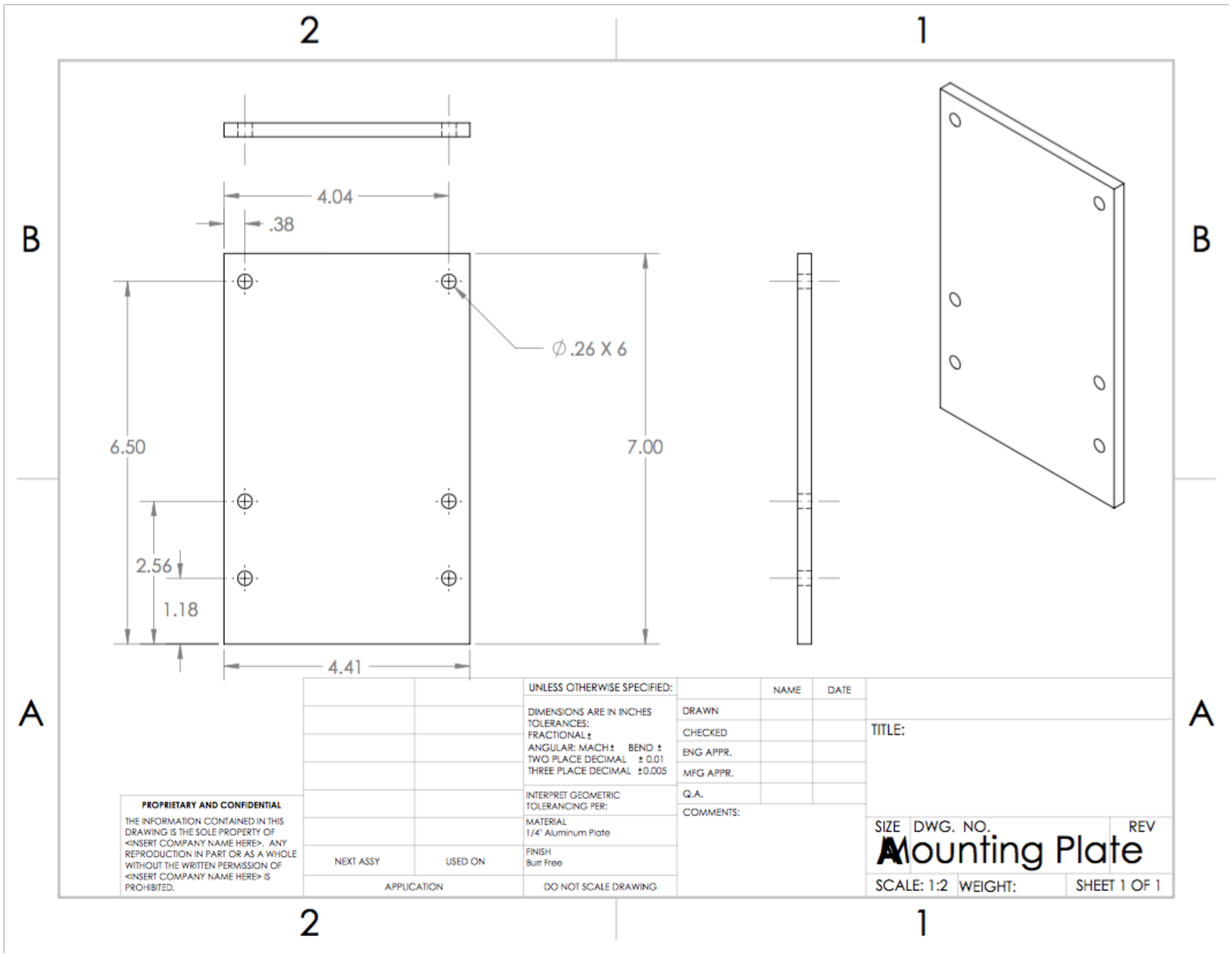
Due to the change described in F.3., both pulleys are closer to the machine. So the edge of the original design is eliminated to make the pulley fit closer to the motor.

G.5. X-Axis Motor Mounting Angle



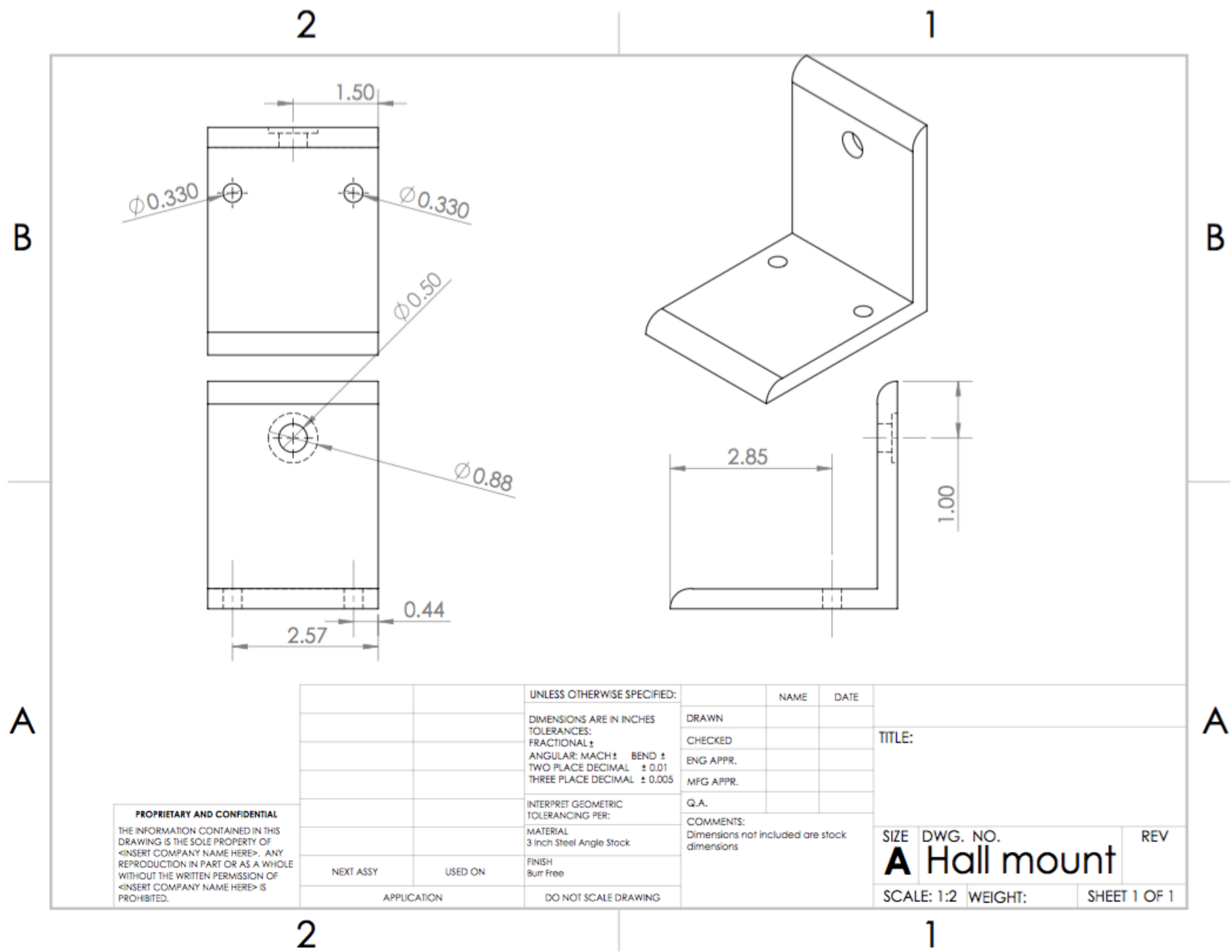
The mounting angle is changed because of the availability of the aluminum angle stock in the machine shop. It performs the same purpose and mates in the same ways.

G.6. Y-axis Motor Mounting Plate



The design for mounting the motor mount of the Y-axis stepper motor to the table was to not use any type of extension and place the mount purchased from Oriental Motors directly to the table. The orientation of the pulley being switched to have the set screws on the inside versus the outside of the table created a need for a mounting plate to extend the axis of the motor to a distance where the pulleys on the motor and Y-axis were aligned. The plate shown above is attached to the table at 4 points and is also attached to the motor mount from Oriental Motors at 4 points, 2 of these points contacting both the table and the motor mount simultaneously.

G.7. Hall Sensor Mount



The Hall Effect Mount was not implemented prior to DR4 due to not having the part yet. Once it was received a mount was designed to hold the sensor next to the table.

Appendix H. Manufacturing Plans

The most efficient way to produce the custom parts needed for this project is through the provided mechanical engineering machine shop. Contracting and ordering pail in comparison to the price incentive and speed of making the parts in person. Aluminum is usually provided by the machine shop and is assumed to be free of charge, a major incentive. Further, design errors can be seen whilst machining and tolerances become a matter of personal pride. This team will machine as many of its parts as possible, going to precision vendors only when needed.

Corresponding drawings are in Appendix F and Appendix G.

Part Number: 450F16-1 Part Name: X-axis Pulley Raw Material Stock: 22 teeth aluminum pulley				Revision Date: 11/20/2015	
Step #	Process Description	Machine	Fixtures	Tool(s)	Speed (RPM)
1	Hold the pulley on the lathe	Lathe	Tool Post		800
2	Bore the hole to 0.59 inch diameter	Lathe	Tool Post	Boring tool	800
3	De-burr part			Deburring tool	

Part Number: 450F16-2 Part Name: Shaft (pulley to gearbox) Raw Material Stock: Aluminum 1" Diameter Round Stock				Revision Date: 11/20/2015	
Step #	Process Description	Machine	Fixtures	Tool(s)	Speed (RPM)
1	Measure and cut round stock to around 2.5"	Band Saw	Vise		
2	Break edges with file			File	
3	Machine part to length	Lathe	Tool Post	turning/facing tool; 6" scale	1000
4	Lathe the surface to .5" diameter	Lathe	Tool Post	turning/facing tool; 6" scale	1000

5	Drill a .236" hole for .4"	Lathe	Tool Post	Drill chunk Size B drill bit	1000
6	De-burr part	Lathe	Tool Post	File	150
7	Take piece to mill	Mill	Vise; Parallels		
8	Drill the side hole shown in drawing	Mill	Vise; Parallels	Drill chuck #39 drill bit	1000
9	Tap the hole with M3 tap		Vise	M3 Tapping tool	

Part Number: 450F16-3 Part Name: Motor mounting plate for X axis Raw Material Stock: 6061 Aluminum Angle, 1 1/4" x 1 1/4" x 1/8"				Revision Date: 11/20/2015	
Step #	Process Description	Machine	Fixtures	Tool(s)	Speed (RPM)
1	Measure and cut the length to 1.25"	Band Saw	Vise		
2	Break edges with file			File	
3	Place part in vise and find the datums	Mill	Vise Parallels	Edge finder Drill chuck	500
4	Center-drill 5 holes in one side	Mill	Vise Parallels	Drill chuck Center drill	800
5	Drill 4 small holes through as the drawing shows	Mill	Vise Parallels	Drill chuck #31 drill bit	1200
6	Flip the part, center-drill other holes	Mill	Vise Parallels	Drill chuck Center drill	800
7	Drill 3 small holes through as the drawing shows	Mill	Vise Parallels	Drill chuck #31 drill bit	1200
8	Mill the largest hole to size	Mill	Vise Parallels	1/2" End mill	800
9	Break edges with file			File	

Part Number: 450F16-z-2				Revision Date: 11/18/2015	
Part Name: Support for Angle Mounting Bracket					
Raw Material Stock: 6061 Aluminum, .25" Stock					
Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*

1	Cut off a piece of around 3 by 2 inches	Band Saw	Vise		
2	Break edges with file			File	
3	Place part in vise and square edges.	Mill	Vise, Parallels, Bracing plate for Damping	3/4" Collet, 3/4" 2 Fluted end mill	840
4	Mill 0.02" passes until correct width and length dimensions are achieved	Mill	Vise, Parallels, Bracing plate for Damping	3/4" Collet, 3/4" 2 Fluted end mill	840
5	Find datum lines.	Mill	Vise, Parallels, Bracing plate for Damping	Edge finder Drill chuck	1000
6	Center drill the .25" hole	Mill	Vise, Parallels, Bracing plate for Damping	Drill chuck Center drill	800
7	Drill the hole	Mill	Vise, Parallels, Bracing plate for Damping	Drill chuck, 1/4" drill bit	1200
8	Readjust the part in the vise to perform a facing cut along the longest side of the piece.	Mill	Vise, Parallels, Bracing plate for Damping		
9	Find the datums on this edge	Mill	Vise, Parallels, Bracing plate for Damping	Edge finder Drill chuck	1000
10	Face this edge in 3 passes of .05" and a final pass of .02" depth	Mill	Vise, Parallels, Bracing plate for Damping	3/4" Collet, 3/4" 2 Fluted end mill	840
11	Remove part and check fit on				

	machine. Continue manufacturing as needed by above process.				
12	Break edges with a file			File	
13	Measure dimensions with calipers and remachine if it does not meet desired width.			Calipers	