Automated Indexing and Tool Cleaning for Tapping Torque Test Device

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ABSTRACT

Professor Gordon Krauss is interested in testing various lubricants for metal work. To do this a tapping torque tester is utilized. The test results can possibly be extended to other metal forming operations and be used to heighten production rates. We have been asked to automate this process by modifying the machine so that a software program can perform the testing with minimal operator involvement and adequate accuracy and repeatability. The machine must also have the ability to clean the tap after each hole is threaded and a mount for convenient supercritical CO_2 application.

EXECUTIVE SUMMARY

Professor Krauss has asked us to automate a tap machine fixture table used for testing lubricants while also including a cleaning station and a mount for supercritical CO_2 application. Currently the operator must manually align each hole with the tap by sight and using a feeler gauge, which is both time consuming and inaccurate. The tap must also be manually cleaned after each hole is threaded so that different lubricants don't contaminate the next hole tested. Automating the machine will free the operator's time and ensure that undesired conditions can be reduced or eliminated. The most important customer requirements are precise hole alignment, automatic control of the table, and an automatic cleaning station. The most important engineering specifications are positional accuracy, resolution, and cost. The alpha design has been completed on February 18. To automate the table stepper motors are utilized on each axis, the control program for table movement still has to be written. Precise hole alignment will be accomplished through the use of Belleville washers to remove backlash. The cleaning station consists of a solvent bath, air knife, and brush to remove shavings and lubricant after each tapping. Bent thick walled piping with a threaded connector and a nozzle on the ends will be used to deliver supercritical CO_2 to the predrilled tap holes.

The final design has been completed and some changes have been made to the alpha design. These changes include: the computer itself can now be used as the controller with the Mach 3 software; a tin can will be used in the cleaning station instead of a self-manufactured solvent bath; an air knife will not be used in the final design due to its high cost and difficult installation; The CO_2 delivery system has been revamped to simply be a mount for the existing hose and nozzle; other changes also include the orientation and configuration of the mount motor, cleaning station, and supercritical CO_2. An engineering design parameter analysis is provided to describe the approach that was used to determine the specific parameters.

The prototype has been finished with some changes to the design, including a modification to the backlash removal, the addition of limit switches, and a modified Y-axis handle, among other things. We did not achieve our desired engineering specifications, and we have outlined possible modifications that could improve the overall prototype.

We presented the prototype at the Design Expo on April 15th and will be turning it in to our sponsor on April 27th.

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INTRODUCTION

Background

Professor Krauss' lab group is studying lubricant effectiveness utilizing a tap torque testing machine to tap predrilled holes using either thread forming or thread cutting taps. During testing the torque needed to thread a hole is recorded by a computer program and the results can be analyzed.

"The tapping torque test is the only bench scale metal cutting test available at the time. Torque values are measured as a tap cuts threads into a predrilled hole in a metal specimen, which can be made of various metals." Test runs record average torque values and results "may be expressed either as a simple torque force value or as a percent efficiency, the ratio of the average torque value of a reference fluid to that of a test fluid. The same tap is used on both the reference fluid and the test fluid"[8].

Metalworking fluids can have a significant economic and environmental impact in a manufacturing environment. According to research performed by Andres Clarens (a U of M Student under an EPA STAR Fellowship in 2004), metalworking fluids account for approximately 12% of manufacturing costs and can be hazardous to human health because of additives in the fluids, microorganisms and biocides that can contaminate the fluids. Professor Krauss' group is researching ways to reduce both the cost and environmental impact of metalworking fluids.

Problem Description

Currently, between test runs, the user must manually align the table to the next hole location and clean the tap to avoid cross-contamination of lubricants, which can affect test results. The entire process needs to be automated to minimize, or eliminate, errors caused by human inconsistency.

Professor Krauss also studies the use of supercritical carbon dioxide as a lubricant, both on its own and mixed with an oil based lubricant, and he needs a method of reliably applying this lubricant to the hole surfaces for testing.

Backlash is a major concern and must be eliminated or, at the very least, minimized. There are various approaches to eliminating backlash, so a careful analysis of the methods available is necessary to choose an effective method.

The expected outcome is a fully automated tapping torque testing machine that can run on its own under the following conditions. The user must:

1. Insert the desired tap into the machine
2. Select the appropriate hole pattern type from a list in the operating program on a PC
3. Input the number of holes in the plate to be tapped
4. Choose which holes to be tapped
5. Define the hole sequence to be tapped
6. Select the number of cycles the tap must run through the cleaning station between each test
7. Align the tap to one or more reference points on the plate
8. Start the tapping process

Customer Requirements

The customer's requirements are summarized into nine aspects. Most of the customer requirements are focused on precise hole alignment, reducing the time of testing, and minimizing the cost. Precise hole alignment will result in better data and fewer necessary tests, saving time and cost. For this reason precise hole alignment is the most important customer need and the rankings of other requirements are based on the correlation to precise hole alignment.

- Precise hole alignment: Professor Krauss requires the tap to be aligned with the test hole precisely, to minimize any effect misalignment may have on the data collected.
- Automated table control: Professor Krauss wants the table to be fully automated so that it can line up the tap correctly and run the experiment more efficiently.

•Automated tap cleaning ability: The new system is required to be able to remove chips as well as lubricant residue from the tap so that multiple lubricants can be tested in one cycle, with minimal user interaction.

•Supercritical carbon dioxide lubricant delivery: Professor Krauss also wants the supercritical CO_2 lubricant delivery system configured to spray the lubricant from the underside of the work piece. The option of adjusting nozzle to spray from above the work piece is desirable, but not a requirement.

•Low cost: The new system should cost less than current systems that exist in the market and meet the requirements. Typically the customer wants the budget to be 400 dollars.

•Simple, flexible computer interface: Since testing involves different hole patterns, materials, tap sizes, and user defined hole sequences, a simple, flexible computer interface will be extremely helpful to the users.

•Manual control capability: Manual control of the system must be preserved.

•Minimum modifications: Professor Krauss also wants to keep modifications to the current system minimal, though this is a low priority.

•User manual: A user manual with necessary instruction is required to be provided.

ENGINEERING SPECIFICATIONS

A Quality Function Deployment (QFD) chart (Appendix A) has been developed to interpret the customer requirements into the engineering specifications, Table 1. During this process, we developed the specification by taking our customer's specialized requirements into account as well as referring to some other competitive products' parameters. For example, the engineering specification for positional accuracy is directly correlated to the customer requirement for precise hole alignment. These specifications, with the exception of the cleaning effectiveness, are quantitative and measurable. They are ranked based on the correlation to the customer's needs and the other specifications as well.

Table 1: Ranked Engineering Specifications with Target Values

Engineering Specifications	Tentative Target Value	Units
Positional Accuracy	± 30.0	[μm]
Resolution	0 .6	[μm]
Cost	≤ 400	[Dollar]
Repeatability	± 1.3	[μm]
Cleaning Effectiveness	Qualitative	N/A
Preparation Time	5 - 10	[min]
Range	475 × 190	[mm]
Speed of Motion	1.27-63.5	[cm/s]
Strength	≥ 20	[Mpa]

Target values for positional accuracy, resolution and repeatability are the minimum values to be met, and based on the Microtap Autotable. Because the effectiveness of the cleaning station is, effectively, a qualitative measure, we will be conducting further testing to ensure that the cleaning meets the standards Professor Krauss needs.

BENCHMARKING

To understand how well our product should perform, we researched similar products that are currently on the market. We researched a few CNC machines with automatic tables [3,6] and analyzed an automatic table from Microtap [2], and the automatic table of a countertop CNC machine [3] to use as benchmarks for our system. Neither the Microtap nor the CNC machine have methods for cleaning the tools or have a mount for supercritical CO_2. The Microtap also has a very hefty price tag ($9750.00). We then analyzed our current setup and compared it to the other two products. For full benchmarking see the QFD in Appendix A.

Currently, the use of a stepper motor is thought to be the best way to move the table in both the x and y directions for high torque loads at low to medium speeds (≤3000 RPM). The decision is based on the fact that stepper motors can approach the accuracy of conventional DC motors and also can provide a holding torque, which acts as a lock when the motor is powered but not moving. This would prevent the table from moving when external force is applied to it. The advantages and disadvantages of stepper and servo motors are discussed in the concept generation section of this document.

Benchmarked Products

Several products were researched for the benchmarking process, two representative products analyzed were the Microtap Autotable Figure 1 (p. 13) and the CNC Jr. Mill Figure 2 (p. 13). Table 2 compares each product based on the customer requirements.

Table 2: Comparison of Benchmarked Products Based on Customer Requirements

Customer Requirements	Microtap Autotable	CNC Machine
Precise hole alignment		
• Position accuracy	± 30µm	± 2.5µm per cm
• Repeatability	± 1.3µm	± 12.7µm
• Resolution	± 0.6µm	± 5.1µm
Automatic control of Table	Yes	Yes
Automatic cleaning station	No	No
Supercritical CO_2	No	No
Low cost	$9750	$5423
User manual	Yes	Yes
Minimum modifications	N/A	N/A
Manual control option	Yes	Yes
Torque reading ability	Yes	No

The resolution of the Microtap Autotable (0.6µm) is definitely better than the standard mill (≈0.001 in = 25.4µm) and is our minimum goal for resolution of our system. The resolution of the CNC Jr. Mill is also better than a full size CNC machine, but is ≈8.5 times the desired resolution of the system. Accuracy and resolution, while dependant on the motors themselves, are more variable system to system, as they depend heavily on the mechanical components and characteristics of any given system (lead screws, backlash, friction, environment temperature, etc…). Based on these facts, the accuracy and repeatability of the system we design will be determined by characterization of our system. Ideally, repeatability would be 0 µm and the accuracy will be equal to the system resolution, but, as a general rule, accuracy is greater than or equal to repeatability, and three standard deviations of repeatability is greater than or equal to resolution.

Neither the Microtap Autotable nor the CNC Jr. Mill have a cleaning station, and we have not been able to find a solution to fit our needs available on the current market, so we will have to design and build a completely new system. We have also been unable to find a standard delivery system for the supercritical CO_2 necessitating a custom solution for lubricant delivery as well.

Figure 1: Microtap Autotable

Figure 2: CNC Jr. Mill

CONCEPT GENERATION

According to our customer requirements, the main functions of the automated table have been identified as follows: (1) automate table movement, (2) clean tap, (3) deliver supercritical CO_2, (4) remove backlash, (5) align holes accurately, (6) drive the table, (7) user interface flexibility. A morphological method is employed, along with literature research, to develop various concepts for each function as shown Table 3 (p.13-14).

Table 3: Morphological Chart

Functions	Mechanical	Electronic	Pneumatic	Chemical
Automate the Table Movement & Align Holes Accurately	Stepper motor	Electromagnets	Pressure system	
	Servo motor			
	Linear motor	Programs		
	Transmission	Open loop or closed loop control		
Remove Backlash	Spring & extrusion	Closed loop control	Constant pressure chamber	
	Belleville washer			
	Thrust bearing & spring			
	Ball screw			

Clean Tap	Brush		Compressed air	Acetone solvent
Deliver Supercritical CO_2	Throttle, nozzle	Program		
User Interface Flexibility		Open loop or closed loop Program GUI		

Function 1: Automate the Table & Align Holes Accurately
To drive the table, the power system should have an electronic motor and corresponding transmission. There are several specifications, the motor should provide enough torque or force to drive the load, and it should have a large enough holding torque to prevent the table from moving when the test is running. The movement of the table needs to meet the specified accuracy, precision and resolution. The following section will present three possible design concepts for the power system, describing each of the concepts.

Concept 1: Stepper Motor

Figure 3: Stepper Motor

A stepper motor is a brushless, synchronous electric motor which rotates in discrete steps as commanded, rather than rotating continuously. A stepper motor can hold a load stationary when not rotating but powered. The stepper motor doesn’t need a feedback mechanism if the size of the motor is appropriately chosen so that the load doesn’t exceed the holding torque. However, the resolution of the motor is usually limited by the step size of the motor.

Concept 2: Servo Motor

Figure 4: Servo Motor

A servo motor will be used to provide essential torque to move the table. An integral feedback device such as an encoder is attached to the motor shaft to provide the motor's actual position and velocity. Thus the controller can compares the feedback signal to its programmed motion profile to alter its input signal. The servo motor has no holding torque.

Concept 3: Linear Motor

Figure 5: Linear Motor

Instead of producing a torque, a linear motor is an electric motor that produces a linear force along its length using electromagnets that pulse at different iterations. A linear motor requires guide blocks to constrain its motion and to support a load. This would force us to heavily modify the existing table in order to utilize these motors. Moreover, a feedback controller is necessary to provide accurate motion. Like the servo motor, the linear motor has no holding torque.

Function 2: Backlash Removal

The backlash is caused by the clearance between the lead screws and the driving threads. To eliminate the backlash, the concept should be able to reduce the clearance between the mating components by forcing the faces of the threads of each component against each other. An ideal backlash removal system will be compact and easy to install without increasing the friction in the lead screws. The following section will present the design concepts for the backlash removal, giving a description of each concept.

Concept 1: Spring and Extrusion

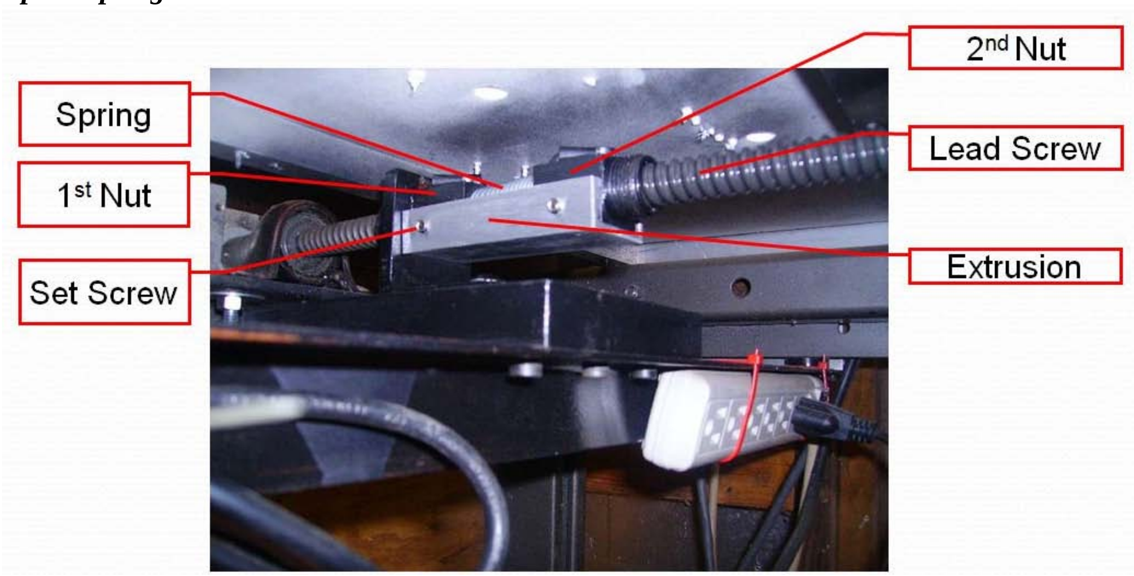


Figure 6: Spring and Extrusion Mechanism

This anti-backlash mechanism includes a spring, extrusion and two nuts. One nut is attached to the driving threads of the table; the other is attached only to the lead screw. The extrusion is used to prevent the rotation of the nuts with each other. A spring is mounted between the two nuts pushing the threads of the driving nut against the threads of the lead screw removing the clearance between the threads, thus the backlash is removed. This concept will introduce additional friction.

Concept 2: Belleville Washer

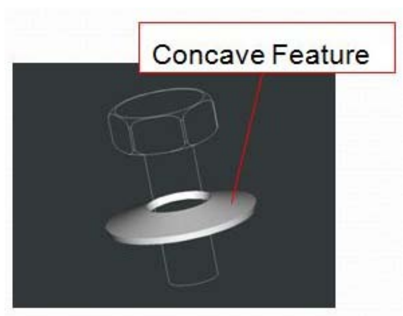


Figure 7: Belleville Washer

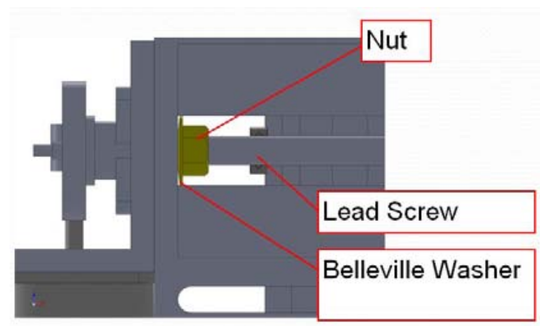


Figure 8: Belleville Washer Mechanism

A Belleville washer and a nut will be mounted to the lead screw. The Belleville washer has concave feature that when compress acts like a spring. The nut tightens the Belleville washer against the table housing, pushing the threads between the lead screw and drive nut together. This mechanics will be applied in both direction of the lead screw to ensure the backlash will be removed. This concept introduces additional friction.

Concept 3: Thrust Bearing and Spring

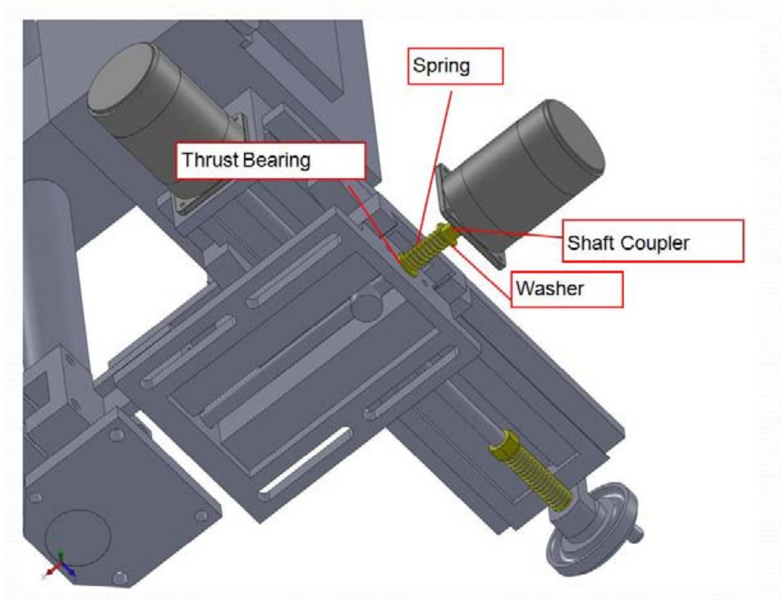


Figure 9: Thrust Bearing and Spring Mechanism

In this concept the backlash is removed from the Y-axis by attaching a spring between the table housing and shaft collar. A thrust bearing is placed between the spring and table housing to reduce the friction. To remove the backlash in the X direction a spring is paced between a nut on the lead screw and the X-axis screw flange, and a thrust bearing is placed between the spring and flange. A nut is used to compress the spring against the flange. The force of the spring then removes the clearance between the threads of the lead screw and driving nut. The use of thrust bearings reduces the friction that would be experienced if the spring was in direct contact with the flange.

Concept 4: Ball Screw

Figure 10: Ball Screw Mechanism

The current lead screws used in system will be replaced with appropriate sized ball screws. Ball screws use ball bearings positioned between two housing that fit in the threads of the lead screw. The fitting of the ball bearing in the threads removes the clearance between the flange and screw, and because the balls rotate they do not wear down compared to standard ACME threads. The original connecting part of the table will be redesigned to fit the ball screws.

Function 3: Cleaning Station

We created four different concepts for a cleaning station. When designing the cleaning station, certain attributes such as cleaning effectiveness, compactness, and the ability to remove and clean the cleaning station itself all had to be considered. The cleaning effectiveness is paramount so that chips or lubricant from the previously tapped hole don't contaminate future tests. Secondly, the station needs to be compact so that it does not physically interfere with any other moving parts or with the supercritical CO_2 delivery system. In order for the cleaning station to have a relatively long life and maintain its cleaning ability, it needs to have the capability to be removed for cleaning. The concepts are as follows:

Concept 1: Air Knife and Drain

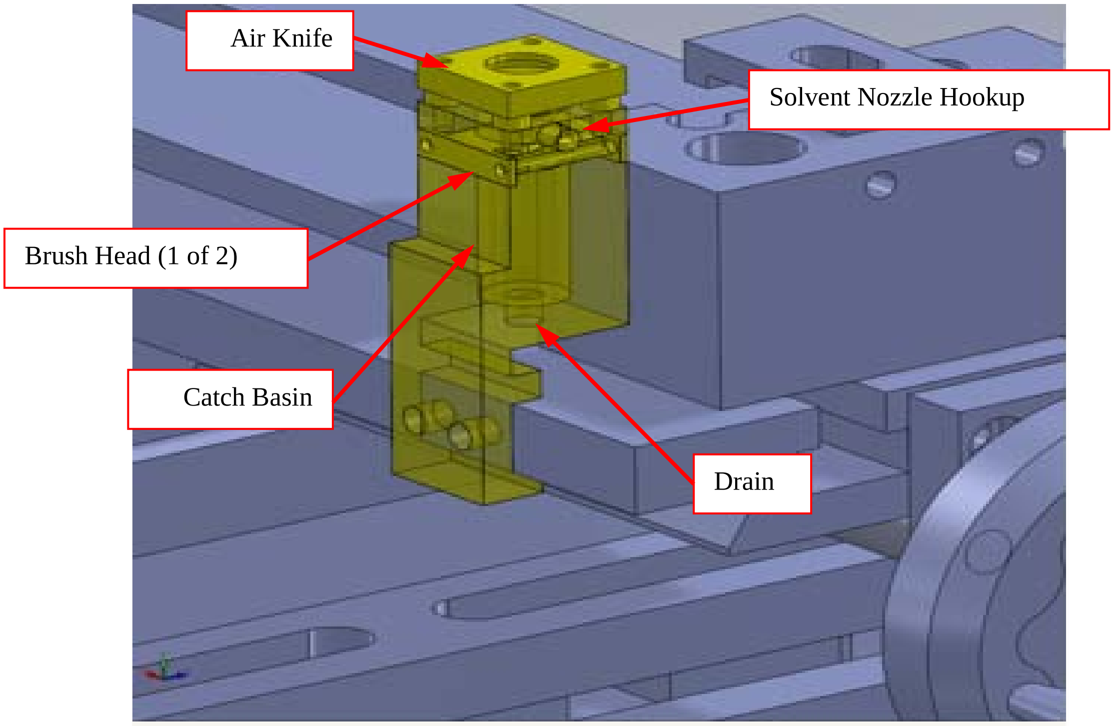


Figure 11: Concept 1 for the cleaning station is fixed to the table and utilizes an air knife, brushes, sprayed solvent, and a drain for waste.

Concept 1, shown in Figure 11, consists of a catch basin, a drain in the bottom of the basin, two brushes inside the basin, and an air knife above the basin. In this design, the tap would be blown off by the air knife, which blows down so all debris are contained in the catch basin. As the tap enters the basin, it will rub against the brushes, removing debris. At the same time, a solvent would be sprayed against the tap to aid in the removal of residue and debris. All the waste from the process would then drain out of the basin through the drain located on the bottom of the basin. The procedure of cleaning of the tap for this design would be: (1) tap enters basin through the air knife, (2) as tap gets deeper into the basin, the solvent is sprayed onto it and the brushes remove debris.

Concept 2: X-axis independent

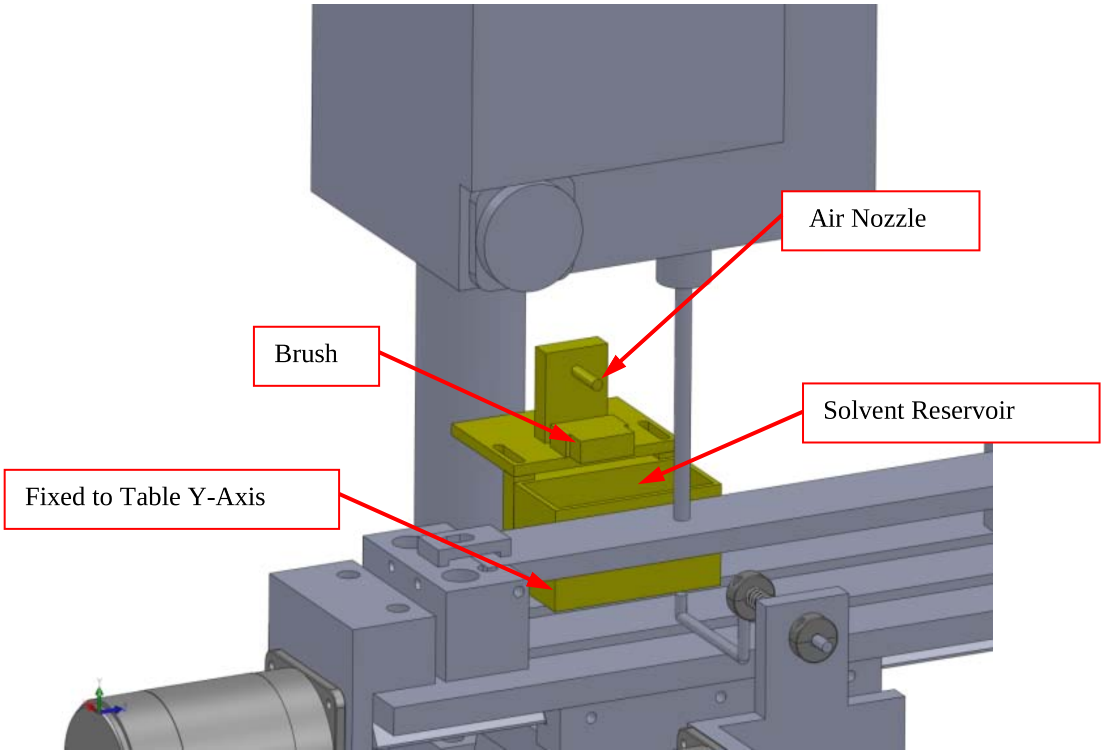


Figure 12: Concept 2 for the cleaning station is fixed only to the Y-Axis and utilizes and air nozzle, a brush and a solvent reservoir

Concept 2, shown in Figure 12, consists of a reservoir for a solvent, a horizontal brush located above the solvent reservoir, and an air nozzle for compressed air located above the brush. This design is unique in that it is fixed to the table only along the y-axis. This allows the station slide above the table when the x-axis is moved and keeps the station in line with the tap. Since the table moves a much larger distance in the x-direction than in the y-direction, the distance the tap must travel to get to the cleaning station is greatly reduced (the table must move only a few centimeters in the y-direction). The procedure of cleaning of the tap for this design would be: (1) tap is brushed off, (2) tap enters solvent, (3) tap is brushed off again, (4) the tap is blown dry and any remaining debris is removed with compressed air.

Concept 3: Horizontal Brush and Reservoir

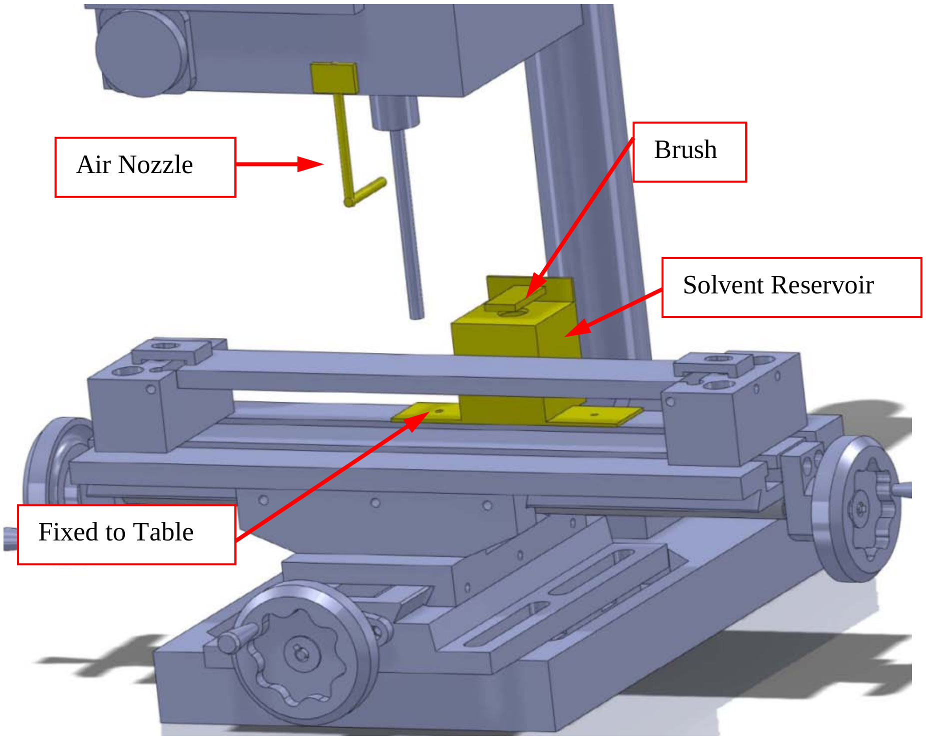


Figure 13: Concept 3 for the cleaning station is fixed to the table and utilizes an air nozzle, a brush and a solvent reservoir

Concept 3, shown in **Error! Reference source not found.**, consists of an air nozzle for compressed air mounted to the front panel of the machine, a solvent reservoir, and a horizontal brush located above the solvent reservoir. The cleaning station reservoir would be fixed to the table and centered along the x-axis. Because of this, the table would have to move on both axes for the tap to reach the station. The procedure for cleaning the tap for this design would be: (1) tap is brushed off, (2) tap enters solvent, (3) tap is brushed off again, (4) the tap is blown dry and any remaining debris is removed with compressed air.

Concept 4: Vertical Brush and Reservoir

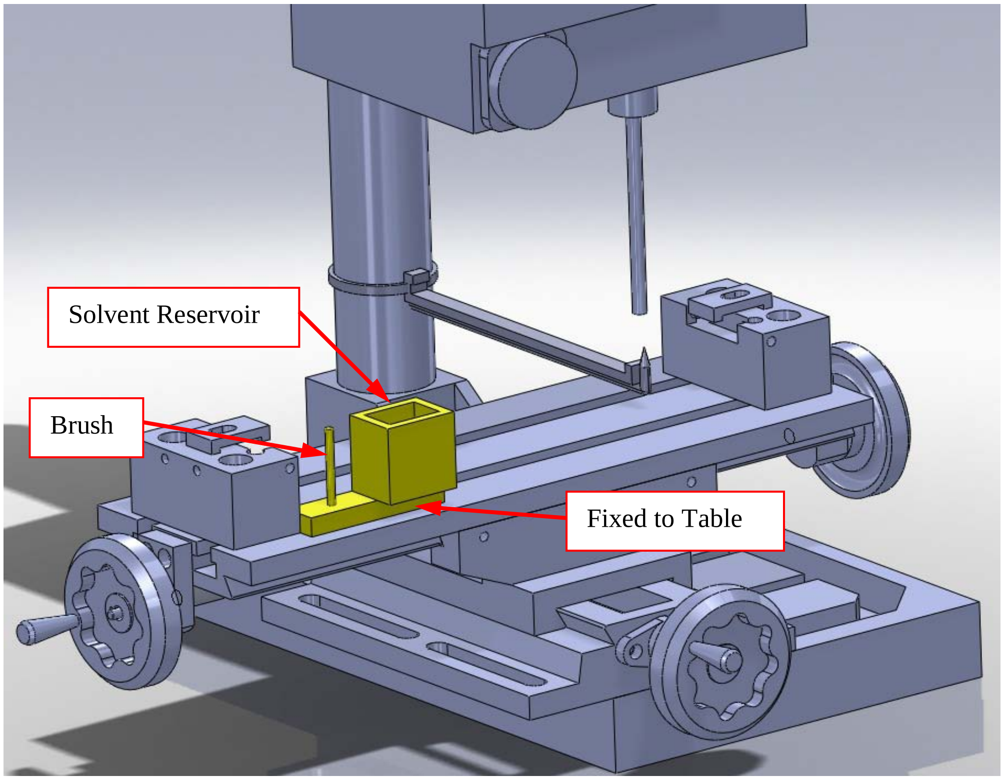


Figure 14: Concept 4 for the cleaning station is fixed to the table and utilizes a vertical brush and a solvent reservoir

Concept 4, shown in **Error! Reference source not found.**, consists of a solvent reservoir and a vertical brush. The station would be fixed to one end of the table. The procedure for cleaning the tap for this design would be (1) tap enters solvent, (2) tap is brought into contact with brush, (3) tap rotates against the brush.

We created three different concepts for a supercritical CO_2 delivery system. See

Table 10 (p.30) for the Pugh chart comparing each design and Table 9 (p. 29) for an outline of the advantages and disadvantages of each. When formulating concepts for the supercritical CO_2 delivery system, we tried to incorporate different characteristics such as simplicity, compactness, the ability to be removed when not in use, and to ensure that it wouldn't interfere with any other accessory attached to the machine. The reason we took into account interference avoidance with the CO_2 delivery system and not the cleaning station is because the delivery system must be directly underneath the tap and the cleaning station would have to be elevated to clear it. This is not desirable because the machine would then have to move a considerable distance in the Z-direction to use the cleaning station, and from a programming stand point could become bothersome. The ability to switch the application of the supercritical CO_2 from either the top or bottom of the work piece is also desirable.

Function 4: Supercritical CO_2 Delivery

Concept 1: El Springo

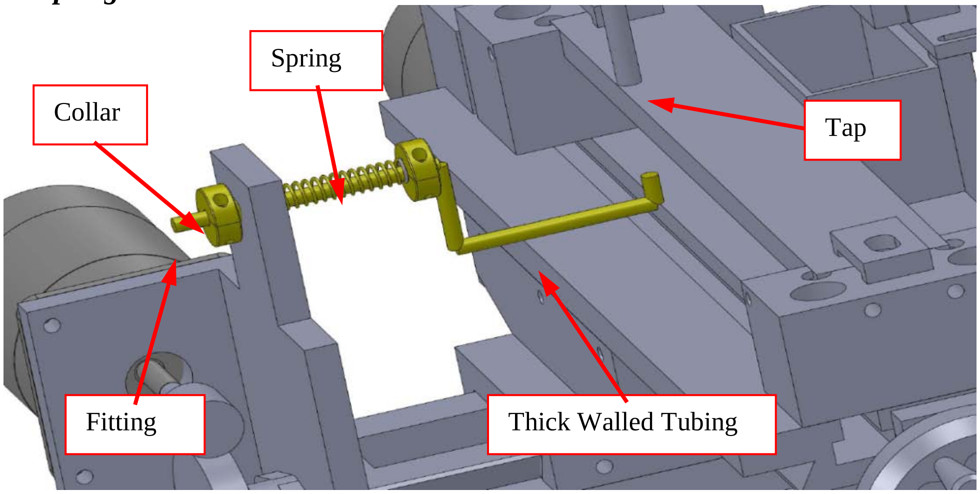


Figure 15: Concept 1 for the delivery system utilizes a spring, thick-walled tubing, two collars and a fitting for CO_2 connection

Concept 1, shown in Figure 15: Concept 1 for the delivery system utilizes a spring, thick-walled tubing, two collars and a fitting for CO2 connection, consists of a mounting bracket, a spring, thick walled tubing, collars, and a fitting for connection with the CO_2 hose. This design allows the nozzle to be flipped, resulting in the application of CO_2 to come from the top or the bottom. The spring is used so that a cleaning station on the opposite end of the table can be installed. Because the CO_2 nozzle is always directly underneath the tap, the spring allows for the nozzle to be pushed away from the by the cleaning station when the tap undergoes cleaning. The collars are used to hold the apparatus in line so that accuracy is maintained.

Concept 2: Der Stange

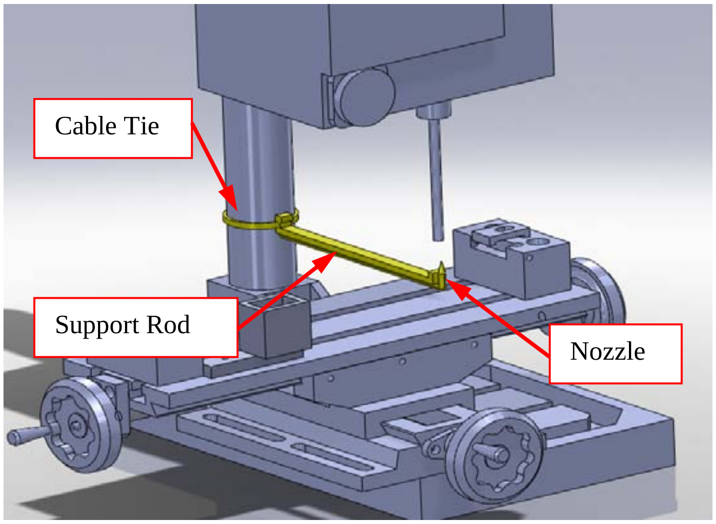


Figure 16: Concept 2 for the delivery system utilizes cable ties, a support rod, and tubing with a nozzle

Concept 2, shown in Figure 16 (p. 23), consists of cable ties, a support rod, and tubing with a nozzle. The support rod is attached to the back post of the machine with cable tie. The tubing is run along the support rod by nylon cable ties and the nozzle is pointed towards the work piece.

Concept 3: Verwirren

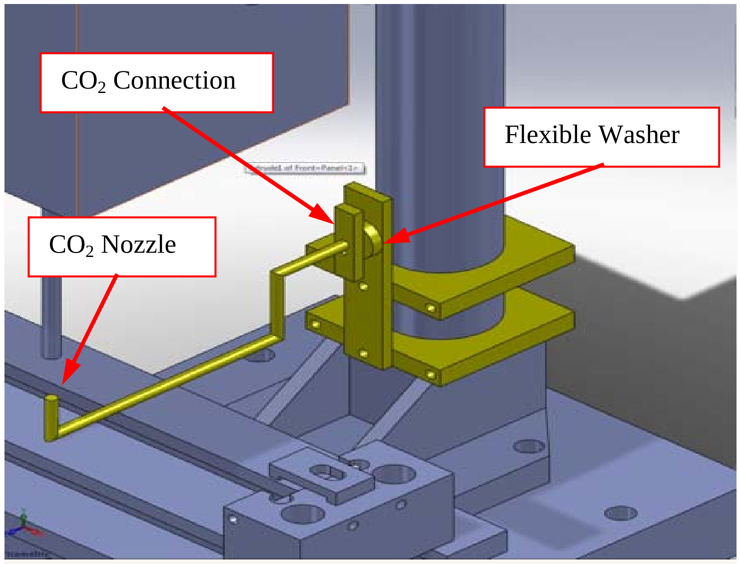


Figure 17: Concept 3 for the delivery system consists of two attachment brackets, a mounting bracket, a flexible washer and thick-walled tubing

Concept 3, shown in Figure 17: Concept 3 for the delivery system consists of two attachment brackets, a mounting bracket, a flexible washer and thick-walled tubing, consists of two attachment brackets, a mounting bracket, a flexible washer, and thick walled tubing. The two attachment brackets connect to the post in the back of the machine, and are then connected to the mounting bracket. The flexible washer is attached to the mounting bracket and the thick walled tubing is attached to the other side of the washer. The CO_2 connection is right next to the washer opposite the mounting bracket. With this alignment, it allows the delivery system to have a joint at the location of the flexible washer without the issue of bending the thick walled tubing. The purpose of this is to allow the mechanism to be pushed out of the way of an object it comes into contact with.

CONCEPT EVALUATION AND SELECTION

Function 1: Automate the Table & Align Holes Accurately

The power system correlates to the engineering specifications of positional accuracy, resolution, cost, and speed of motion. During the concept generation process we recognized these specifications can be decomposed into more detailed criteria to evaluate each concept. These criterions include: does the motor provide enough holding torque? Is a feedback mechanism needed? What is the cost? What precision can the motor achieve? Will it incorporate with the current system well? Our most feasible options are stepper motors, servo motors, and linear motors. Refer to Table 4 (p. 25) for advantages and disadvantages of each, and Table 5 (p. 25) for the Pugh chart displaying how we evaluated them. The following section will discuss the advantages and disadvantages of each concept in more depth.

Stepper motor

Stepper motors provide a certain amount of holding torque, which will help to lock the table when the test is running. The fact that the stepper motor doesn't need a feedback mechanism will help to reduce the cost and make the installation easier. Also it is easy to implement manual control to the table along with stepper motors. Besides, the price for a typical stepper motor is about 200 dollars, which is relatively inexpensive and affordable to our budget. However, due to its internal mechanism, the stepper motor has limited step size. In order to achieve the required resolution, we will use an appropriate controller to incorporate with the stepper motor for micro stepping. The justification of micro stepping will be given in Appendix C. Another drawback is that since a feedback mechanism is not used, the precision will be limited by how well the backlash is removed.

Servo Motor

The precision of a servo motor can be theoretically infinite, but in reality the precision will depend primarily on the resolution of the feedback device used in the closed loop control system. The closed loop control will contribute to reducing the backlash, but on the other hand, the additional sensors, controller, and more complicated program used in the closed loop control will increase the entire cost and labor. For instance, a typical controller that meets our standard would cost more than 300 dollars. Other drawbacks are that the servo motor does not provide any holding torque and the 400 dollar cost is relatively high. The manual control of the table will be feasible after the installation of servo motor.

Linear Motor

The main advantage of the linear motor is that it provides the linear force directly and the resolution and precision is good enough to meet our engineering specifications. However, the linear motor needs to incorporate with a feedback mechanism; it does not provide holding torque and doesn't support manual control; a new connection for the motor and the table will be needed to mount the motor. Last but not least, the 1000 dollar price of a single linear motor is extremely costly.

Table 4: Motor Type Comparison

Motor Type	**Advantages**	**Disadvantages**
Stepper Motor	Provides holding torque No feedback necessary Relatively Inexpensive ($200) few modifications Allows for manual control	Resolution limited by step size Accuracy limited by backlash removal
Servo Motor	High precision Reduces backlash Allows for manual control	Needs feedback control No holding torque Expensive ($400)
Linear Motor	High precision Provides linear force	Needs feedback mechanism No holding torque Needs new connection of motor and table No manual control Heavy modification Expensive ($1000)

Table 5: Motor Type Pugh Chart

Motor Selection	**Stepper Motor**	**Servo Motor**	**Linear Motor**
Cost	1	0	-1
Accuracy	1	1	1
Resolution	0	1	1
Holding Torque	1	-1	-1
Easy to Install	1	0	-1
Manually move	1	1	-1
Total Score	5	2	-2

Function 2: Backlash Removal
The ideal features for backlash removal are effective, compact, inexpensive, and robust and they should introduce less friction and provide enough holding force to ensure the mating components engage tightly. Our concepts include a spring and extrusion, Belleville washers, thrust bearings and spring, and ball screws. Refer to Table 6 (p. 26) for advantages and disadvantages of each, and Table 7 (p. 27) for the Pugh chart displaying how we evaluated them.

Spring and Extrusion
Refer to Figure 6 (p. 16) for a picture of this concept. This design only involves commonly used mechanics, so it won't be costly. The disadvantages of the design are the spring occupies too much space; and it will introduce the internal friction since one lead screw will be engaged to two nuts in opposite direction. Besides, the stiffness of the spring needs to be carefully considered to achieve enough holding force to push the lead screw.

Belleville Washer
Refer to Figure 7 (p. 16) for a picture of this concept. The advantages of the Belleville washer are that they are inexpensive, compact, robust as well as they provide enough holding force. The only drawback is that not only do they increase the internal friction the same way that spring and extrusion does, but the contact surface between the washer and the table will also generate friction.

Thrust Bearing and Spring
Refer to Figure 9 (p. 16) for a picture of this concept. The advantage of this design is that the trust bearing between the spring and the table reduces the contact friction of the two. However, the increase in internal friction due to the engagement between the lead screw and the nuts cannot be avoided. Similar as the spring and extrusion, this design needs to have a carefully chosen spring so that it can provide enough holding force. Also, it is not as compact as the Belleville washer.

Ball Screw
Refer to Figure 10 (p. 18) for a picture of this concept. Due to the nature of its internal structure, the ball screw has higher precision, and less internal friction than a lead screw does. The application of ball screw will reduce the backlash to the level required in our design. The drawback of the ball screw is its expensive cost, and the connection of the screw to the table will need to be rebuilt.

Table 6: Backlash Removal Comparisons

Backlash Removal	**Advantages**	**Disadvantages**
Spring and Extrusion	Inexpensive	Not compact Introduce extra friction Holding force may not be enough
Belleville Washer	Inexpensive Provides holding force Compact Robust	Extra friction introduced
Thrust Bearing and Spring	Introduces little friction	Holding force may not be enough Not compact
Ball Screw	Provides holding force Robust Little internal friction Precise	Needs resign of the internal structure of table Expensive ($300 each screw)

Table 7: Backlash Removal Pugh Chart

Backlash Removal	**Spring & Extrusion**	**Belleville Washer**	**Bearing & Spring**	**Ball Screw**
Cost	0	1	0	-1
Holding Force	0	1	0	1
Compactness	0	1	0	1
Introduction of Friction	0	-1	0	1
Simplicity to Incorporate	-1	1	1	-1
Robustness	0	1	1	1
Total Score	-1	4	2	2

Function 3: Cleaning Station

See Table 11 (p. 32) for the Pugh chart comparing each design and Table 8 (p. 28) for an outline of the advantages and disadvantages of each concept.

Concept 1: Air Knife and Drain

There are many advantages to this design. The first advantage is that it provides very effective cleaning of the tap. The air knife is much more efficient than a standard nozzle removes the necessity of have the tap spin while being blown off. The programming for this is much simpler than if the tap had to spin. Secondly, the design is very compact. This reduces the chance that it will cause interference and creates more options in terms of placement. The location of the brushes is very important in this design. The fact that the brushes and solvent are combined into a single cleaning stage increases the usefulness of the solvent (its purpose to make debris easier to remove). The residue drain is very convenient in keeping the station clean, and reduces the frequency in which the station must be cleaned by the operator.

This design also contains many disadvantages. The first is that the air knife increases the cost. The second is that the solvent must be sprayed in. Because of this, some sort of pump must be used to supply the solvent. In effect the concept would increase the cost, number of parts, and number of modifications. In addition, this design requires there to be three different tubes connections to supply the compressed air to the air knife, the solvent to the basin, and to remove the remains that fall through the drain. This sort of set up can be cumbersome and inconvenient to the operator.

Concept 2: X-axis independent

This design has a few advantages. The first is that the run time of a full test would be reduced since the table travel distance to get the tap to the cleaning station is very short. Another is that the solvent reservoir can be removed which allows for convenient cleaning.

There are, however, many drawbacks to this design. The biggest fault is that the brush is located above the reservoir, which means that the tap would be brushed off before entering solvent. This is a problem because the tap would travel through the brush again on its way out of the solvent, and any debris or residue on the brush would be retransmitted to the tap. The design also does not consist of any sort of "splash shield," so that any debris or residue blown off by the compressed air would be blown all over the work piece. Another issue is that the design is not very simple. There are many slides and components involved, and all of these must be machined and fabricated.

Concept 3: Horizontal Brush and Reservoir

The advantage of this design is that it is relatively simple. It requires no specially fabricated parts or methods, and would be easy to manufacture. It would also blow debris away from the work piece.

This design also has many disadvantages. The biggest fault is that the brush is located above the reservoir, which means that the tap would be brushed off before entering solvent. This is a problem because the tap would travel through the brush again on its way out of the solvent, and any debris or residue on the brush would be retransmitted to the tap. Secondly, because the compressed air is mounted to the front panel of the machine, the hose connected to the nozzle may get in the way of the operator and be a nuisance. In addition the splash would cover the back of the machine since there is no “splash shield.” The station would also be difficult to refill and clean because there is no way to disassemble it and it is located on the back of the table.

Concept 4: Vertical Brush and Reservoir

There are many advantages to this design. To begin with it is very simple. There are only three components, and only two of them would need to be fabricated by us. Because the components are so simple, this design would be very easy to manufacture. This simplicity makes it very cost effective. The vertical brush is also a positive because it can clean the entire tap length at once, and the brush bristles would align with the threads in the tap. Because the station could be mounted to the front of the table, this design would provide convenient refilling of the solvent reservoir.

There are, however, many shortcomings of this design. First, there is no splash shield. When the tap spins against the brush, any debris or residue on it will be propelled all over the work piece and work area. Secondly, there is no compressed air. Not only would this affect the overall cleaning ability of the station, but the tap would resume testing covered in solvent which can affect the test results. Lastly, the run time of the process would be increased as a result of the increased travel distance required, which arises from the placement of the station being at the end of the table.

Table 8: Advantages and Disadvantages of Each Cleaning Station

Cleaning Station	Advantages	Disadvantages
Concept 1: Air Knife and Drain	Compact Effective Residue drain	Higher cost Solvent must be sprayed Many different tubing connections
Concept 2: X-axis independent	Decreased run time	No splash shield Brush above reservoir Many components
Concept 3: Horizontal Brush and Reservoir	Simple Easy to manufacture Minimal splash on work piece	Brush above reservoir Splash blown onto machine Air connection in front Difficult to clean Difficult to refill solvent reservoir
Concept 4: Vertical Brush and Reservoir	Simple Easy to manufacture Vertical brush Cost effective Easy to refill solvent reservoir	No splash shield No compressed air Increased run time

Function 4: Supercritical CO_2 Delivery

Concept 1: El Springo

This design has many advantages including interference avoidance, nozzle can be flipped, and the mechanism can be dismounted. The interference avoidance stems from the use of a spring. This spring allows the nozzle to be pushed out of the way by an installed cleaning station. The nozzle having the capability to be flipped is beneficial because it gives the operator flexibility in where the CO_2 is applied. Having the ability to dismount the delivery system is very convenient since it can be removed from the machine when not in use.

This design also has a few shortfalls in the form of its relative complexity and its susceptibility to fatigue from repeated cycles. The complexity of the concept will slightly increase its cost and increase the manufacturing time. The repeated cycles that the mechanism will undergo may cause it to fail eventually, so it must be designed to ensure that it does not fail in a short period of time.

Concept 2: Der Stange

There are many advantages to this design which include its simplicity, ability to be flipped, and that it can be dismounted. Because of its simplicity this concept would be cost effective and very easy to manufacture. With the ability to be flipped, this design would allow for the CO_2 to be delivered from either the top or the bottom of the work piece. The ability to be dismounted when not in use makes this design very convenient.

This design, however, has no interference avoidance, and it therefore would not be selected for the final concept unless it was modified to include that feature.

Concept 3: Verwirren

The disadvantages of this design include its complexity, the amount of parts, and the dismounting is cumbersome. The complexity is due to the addition of interference avoidance, and this increases the number of parts needed. The manufacturing time would be slightly increased as well as the cost. Because of the robust attachments and the fact that there are two of them, the dismounting is relatively complicated.

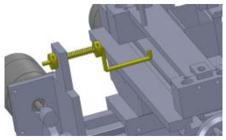
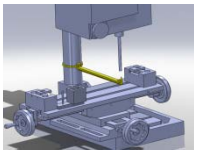
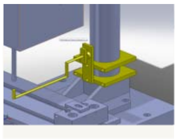
The advantages of this design are that the nozzle can be flipped and the flexible washer gives the attribute of interference avoidance. The nozzle having the capability to be flipped is beneficial because it gives the operator flexibility in where the CO_2 is applied. The interference avoidance comes from the use of the flexible washer.

A listing of the advantages and disadvantages is given in Table 9 (p.29) and the Pugh chart ranking the concepts is shown in Table 10 (p.30).

Table 9: The Advantages and Disadvantages of CO_2 Delivery Concepts

Supercritical CO_2 Delivery System	**Advantages**	**Disadvantages**
Concept 1: El Springo	Nozzle can be flipped Interference avoidance Can be dismounted	Relatively complex Fatigue from repeated cycles
Concept 2: Der Stange	Simple Nozzle can be flipped Can be dismounted	No interference avoidance
Concept 3: Verwirren	Nozzle can be flipped Interference avoidance	Complex Many components Dismount is cumbersome

Table 10: CO_2 Delivery System Pugh Chart

Supercritical CO_2	Concept 1	Concept 2	Concept 3
			
Cost	1	1	1
Precision	1	1	1
Simplicity	0	1	0
Compactness	0	0	0
Application from top or bottom	1	1	1
Robustness	1	0	1
Interference Avoidance	1	0	0
TOTAL SCORE	5	4	4

ALPHA DESIGN DESCRIPTION

The alpha design shown in Figure 18 was formed by taking the best concept of each of the functions. The functions of the alpha design are discussed in detail in the following section as well as how the design meets the engineering specifications.

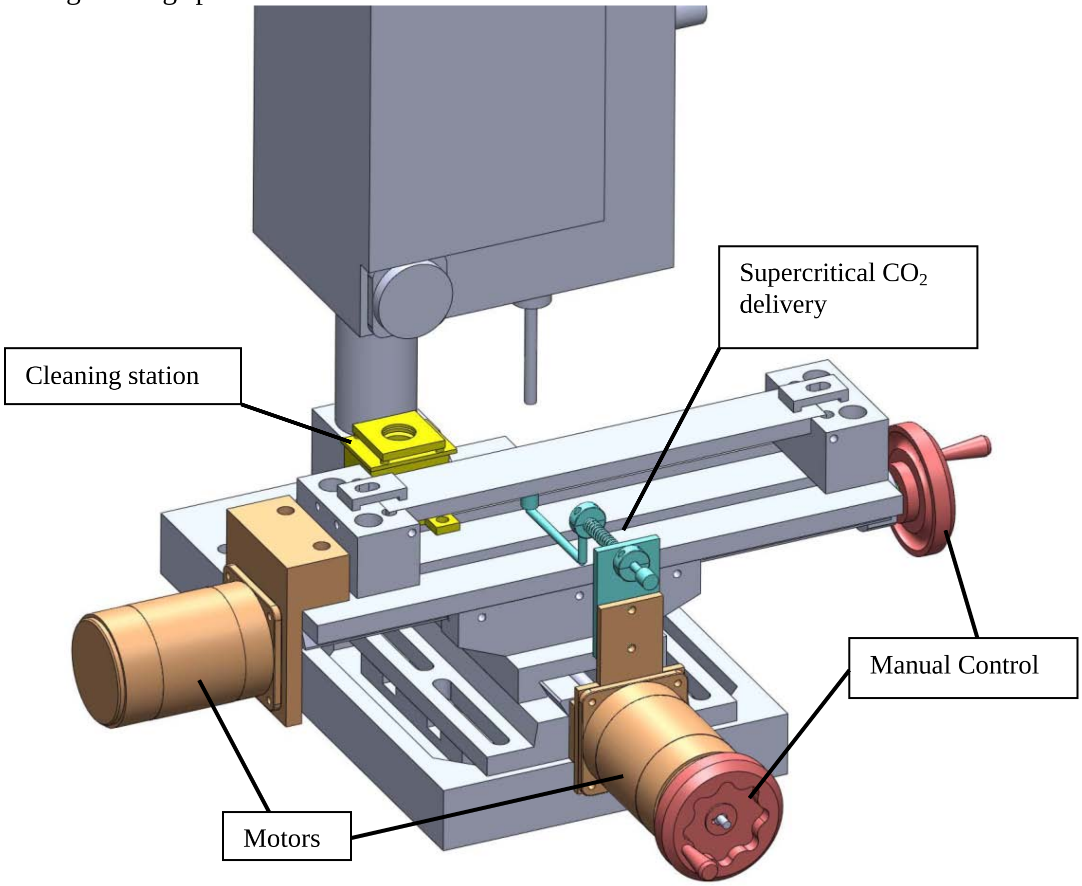


Figure 18: Alpha Design

Motor Selection
The alpha design utilizes stepper motors due to their various advantages over other motors. They provide holding torque which allows them to lock the table in place during testing. Stepper motors are also a cheaper alternative to both servo and linear motors. Steppers can also be operated with no feedback control. The motors are connected directly to the lead screws using shaft couplings to prevent backlash between the motor and lead screw shafts. Stepper motors basic step sized is 1.8 degrees; however, they can be micro stepped.

Cleaning Station
The alpha design of the cleaning station subsystem makes use of the best features of each of the concepts. Figure 19 (p. 31) shows the final design and how the individual pieces fit together.

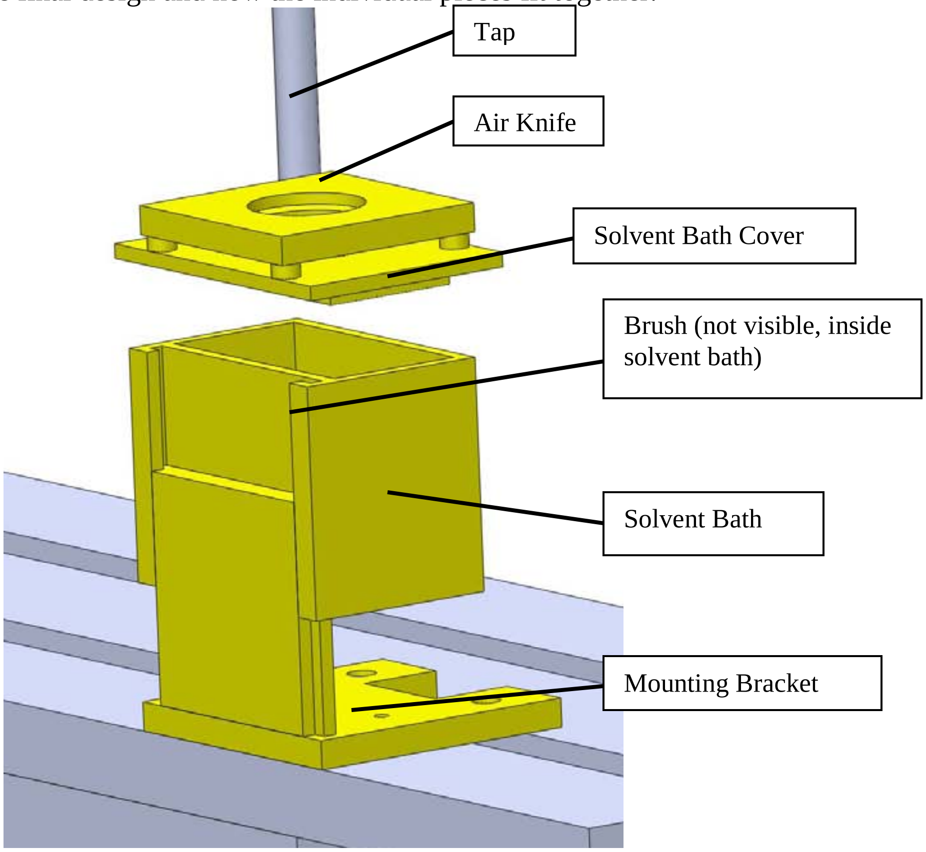
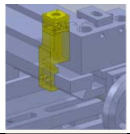
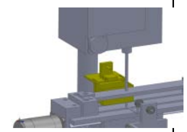
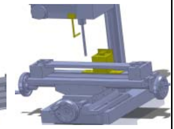
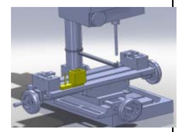
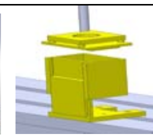


Figure 19: Alpha Design Cleaning Station

The basic design is built on solvent bath. An air knife is used to remove metal shavings from the tap before it enters the solvent bath. The shavings are blown into the bath to prevent them from getting on the test bar. The solvent bath is covered to prevent solvent from splashing unto the test bar during cleaning. The bath is connected to a bracket by flanges on the back so that it can easily be removed and cleaned during testing. The bracket is fastened to the top of the table using T-nuts places in the T-slot. A brush is submerged in the solvent bath to help clean the lubricant off the tap. By keeping the brush submerged it prevents lubricant that is in the brush back on the tap negating the entire cleaning process.
Because the alpha design is a collection of the best features of each concept a Pugh chart was created to analyze the strengths of the alpha design against the concepts. The results are shown in Table 11 (p. 32).

Table 11: Cleaning Station Pugh Chart including Alpha Design

Tap Cleaning					
	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**	**Alpha design**
Cost	-1	1	1	1	0
Simplicity	-1	1	1	1	1
Ease of Cleaning	1	1	0	1	1
Cleaning Effectiveness	1	1	1	1	1
Compactness	1	1	0	1	1
Range of Motion	1	0	1	1	1
Chips Collection	1	-1	-1	-1	1
Anti-Splash	1	-1	1	-1	1
TOTAL SCORE	4	3	4	4	7

The results show that the alpha design does score higher than the concepts and so adding the features of each concept did lead to an improvement in the cleaning station alpha design.

Supercritical CO_2 Delivery

The alpha design of the supercritical CO_2 delivery system is the same as concept 1 above but with an additional feature of being able to be removed when it is not in use. Figure 20 illustrates the final design.

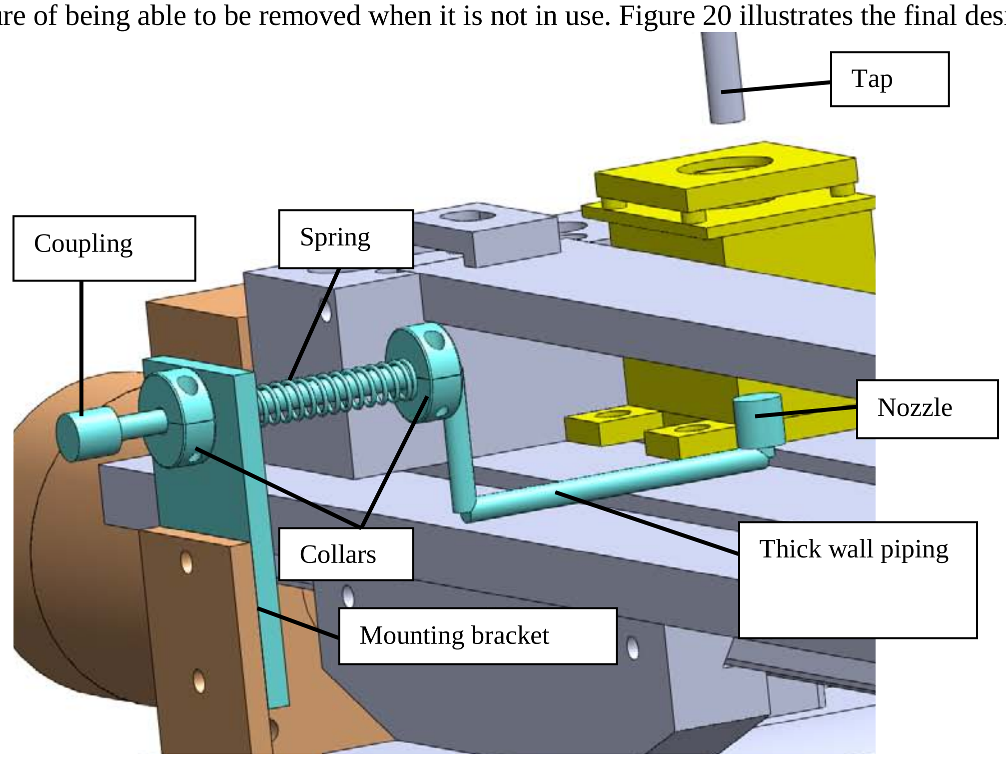


Figure 20: Alpha Design Supercritical CO_2 Delivery System

The system is made of thick walled piping that will be bent to allow the maximum distance between the nozzle and test bar to eliminate the chance of the tap hitting the nozzle during operation. A threaded connector is put on the end of the pipe to allow the current system to connect easily. When the tap is above the cleaning station the pipe is pushed through the mounting bracket when the tap is above a test hole the spring pushes the piping forward to keep the nozzle centered underneath the tap. This design also allows for supercritical application from both above and below the test bar. The pipe can be rotated about the hole in the mounting bracket that is centered with the center of the test bar. For application from the top side the pipe can be left at a slight angle to avoid interference with the tap.

Manual Operation

The alpha design allows for manual control of the table by using a dual shaft stepper motor to drive the Y-axis lead screw.

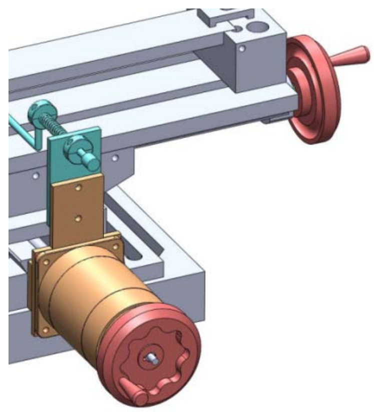


Figure 21: Alpha Design for Manual Operation

The current system's handle can then be modified to fit onto the motor shaft. Manual control of the X-axis is accomplished by leaving one of the handles on the lead screw. Since the current system has two handles for the X-axis one of them can be replaced with a motor and still allow manual control with the other.

Backlash Removal

The alpha design incorporates both thrust bearings and Belleville washers to remove backlash. The design is shown in Figure 22 (p.33).

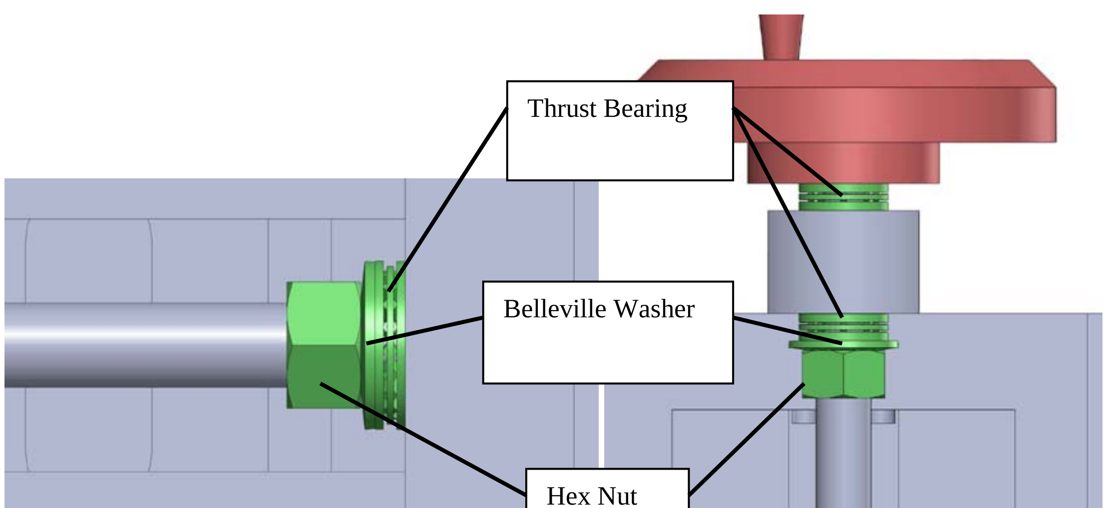


Figure 22: Alpha Design for Backlash Removal

Belleville washers are conical in shape and act like springs when a load is applied to them. Thrust bearing support axial loads and are used in our design to be able to fully tighten the parts of the assembly without dramatically increasing the friction in turn being able to use smaller motors which will reduce cost and space. On the Y axis a thrust bearing is placed around lead screw against the table base. A Belleville washer is then placed against the thrust bearing with a hex nut against the washer. By tightening the nut the screw is forced against the table screw threads to eliminate the backlash. On the X-axis a thrust bearing is placed on both sides of the X-axis screw flange, the Belleville washer and nut are then placed on the inside of the X-axis screw flange.

Control Mechanism
The alpha design will utilize an open loop control mechanism along with limit switches to properly identify the home position. Open loop control is easily implemented with stepper motors. Open loop control of stepper motors provides precise control of the position without the need for expensive sensors.

Customer Requirements and Engineering Specifications
The alpha design meets all of the customer requirements. Precise hole alignment is supported by the use of stepper motors and Belleville washers. Automated control of the table is met by the use of stepper motors. Automatic Tap cleaning is accomplished with the solvent bath, air knife, brush, and stepper motors. Supercritical CO_2 lubricant delivery is accomplished by the use of the piping. The cost is kept to a minimum by the use of thrust bearings and Belleville washers which will reduce the size of the motors and need for sensors. Minimum modifications were accomplished by using the current system and making all the additional features "bolt on". Simple user interface will be accomplished through programming.
The alpha design theoretically meets all the engineering specifications but analysis will have to be done to guarantee the results. The engineering specification for resolution of the alpha design is known. Using the current lead screws which have a pitch of the 10 threads per inch and micro stepping to a ratio of 1/25, the resolution can be decreased to 0.508 microns which is less than the engineering specification of 0.6 microns.

ENGINEERING DESIGN PARAMETER ANALYSIS

Lead Screw Torque
To properly size the stepper motors we had to determine the torque that was necessary to turn the lead screw. This was done by attaching a spring to the handle of both the X-axis and Y-axis table. The spring was then pulled perpendicular to the moment arm and the length of the spring was measured.

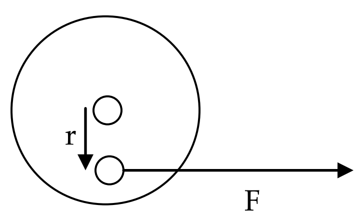


Figure 23: Setup used to determine lead screw torque

To calibrate the spring constant a weight was hung from the end of the spring and the spring length was measured. The following values shown in Table 12 were collected.

Table 12: Measurements used to determine lead screw torque

Measurement	Value
Calibration mass (kg)	.99
Calibration length (in)	19.25
Moment arm (in)	1.375
X-axis maximum deflection (in)	7.0
Y-axis maximum deflection (in)	3.0
Initial spring length (in)	14.0

By changing the units the spring constant was found by dividing the weight of the calibration mass by the deflection in the spring shown in Equation 1.

$$k = \frac{W}{x} \qquad \text{Eq. 1}$$

W= The weight of the calibration mass
x=the change in the spring length

The maximum force necessary to move the handle was then found by multiplying the spring deflection for each of the axis by the spring constant. From this Equation 2 was used to find the maximum toque by converting units it was found the maximum torque required to rotate the lead screws of each axis as 64 oz.-in. or 0.45 N-m. The results are summarized in Table 13.

$$T = F * r \qquad \text{Eq. 2}$$

F= the force due to the spring
r= the moment arm of the force

Table 13: Lead screw torque analysis results

Results	Value
Spring Constant (N/in)	1.848
Max torque (oz-in)	64.0
Max torque (N-m)	.45

Table Position Resolution

The resolution in the table positioning system was analyzed using the relationships of the step size, number of microsteps, and the pitch of the lead screw. The pitch of the lead screw is 10 threads per inch which means that for every revolution of the lead screw the table will be moved 0.1 inches or 2.54 mm. The driver that is being implemented has a micro-step of 1/16 which means that there are 16 micro-steps per motor step. The motor has a step size of 1.8° which results in 200 steps per revolution. These characteristics of the system, along with dimensional analysis results in a resolution of 0.79 μm were done. Equation 3 summarizes the analysis of the table position resolution.

$$\left(\frac{1\ rev}{200\ steps}\right)\left(\frac{1\ step}{16\ micro\ step}\right)\left(\frac{2.54\ mm}{1\ rev}\right) = 0.79\ \frac{\mu m}{microstep} \qquad \text{Eq. 3}$$

Table Movement Speed

The table positioning speed is a function of the motor drive speed and the position resolution. The motor torque-speed graph, shown in Figure 24 (pg. 34), shows that at a torque of 0.45 N-m the motor runs at a speed of 7,250 pulses/sec.

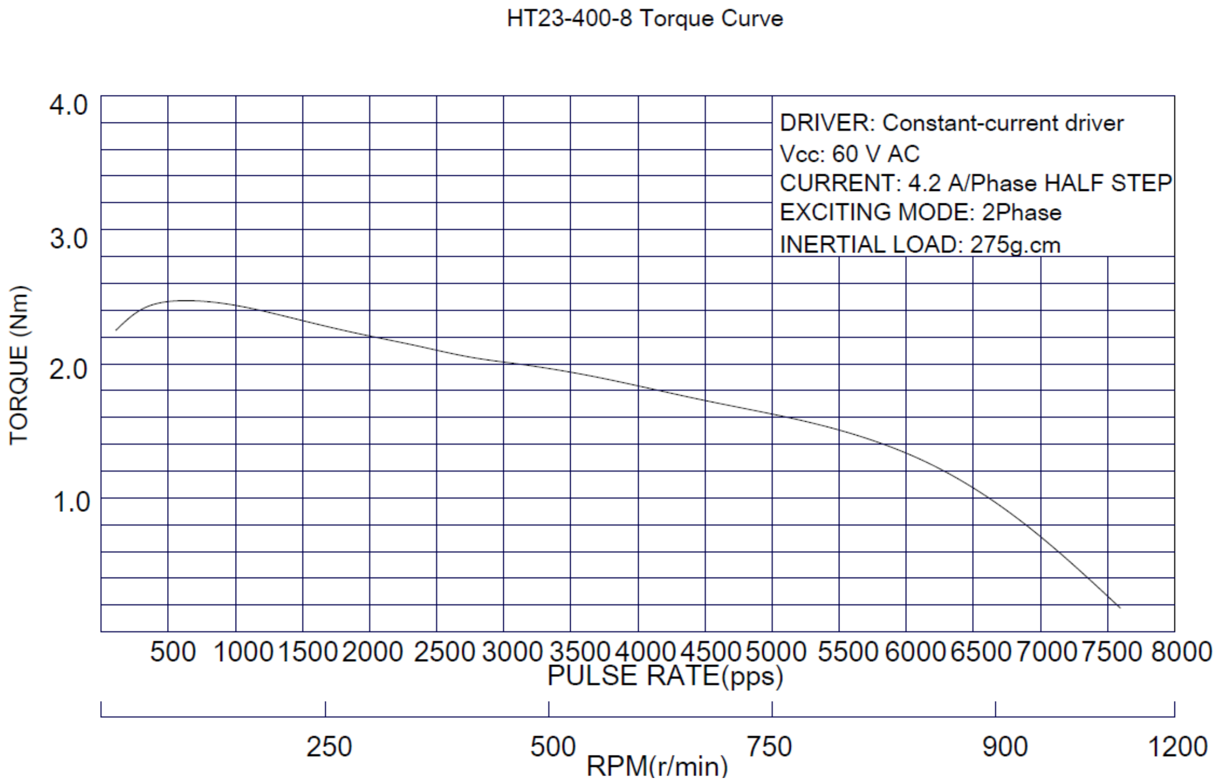


Figure 24: Torque-speed curve of the implemented motor

The resolution of the table positioning system is 0.79 μm/microstep. The theoretical maximum table speed is found by multiplying the motor speed by the resolution, which results in 5.73 mm/s (13.54 inches/min.). Equation 4 summarizes the table speed analysis.

$$\left(\frac{.79\ \mu m}{1\ microstep}\right)\left(\frac{7250\ micosteps}{sec}\right) = 5.73\frac{mm}{s} = 13.54\frac{inches}{min} \qquad \text{Eq. 4}$$

Motor Mount Stress

A Von Mises stress analysis was done on the motor mounts to determine the maximum stress that they would experience during operation. Different stresses had to be analyzed such as the bending stress of the motor hanging from the motor mount, the tensile stress of the motors weight of the mount, as well as the shear stress due to the torque produced by the motor. Equations 5, 6, and 7 give the formula for finding these stresses.

$$\sigma_B = \frac{-M * y}{I} \qquad \text{Eq. 5}$$

$$\sigma_T = \frac{W}{A} \qquad \text{Eq. 6}$$

$$\tau = \frac{T * r}{J} \qquad \text{Eq. 7}$$

M = Moment
y = Distance from the zero stress line
I = Moment of inertia
W = Weight of the motor
A = Cross sectional area of the plate

T = Torque
r = Distance from the center of the motor
J = Angular moment of inertia.

Equation 8 gives the moment of inertia for a rectangular cross section.

$$I = \frac{b * h^3}{12} \quad \text{Eq. 8}$$

b= width of plate
h=thickness of plate

Equation 9 gives the angular moment of inertia.

$$J = \frac{\pi}{2}\left(r_o^4 - r_i^4\right) \quad \text{Eq. 9}$$

r_i=the inner radius
r_o=the outer radius

The model used to analyze the stress is a simple point load equal to the weight of the motor rigidly attached to the motor mount a distance of half the motor length. Figure 25 illustrates this model.

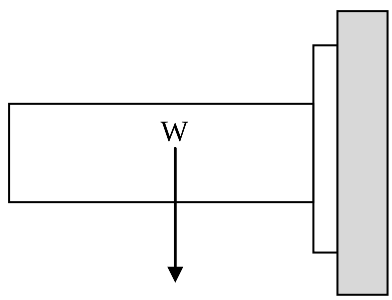


Figure 25: Illustration of the model used to analyze the stress in the motor mounts

The Von Mises stress represents the maximum stress by combining all the stresses. Equation 10 gives the formula for finding the Von Mises stress.

$$\sigma_{vm} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad \text{Eq. 10}$$

Mohr's Circle is utilized to determine the principal stresses where the principal stresses are given by Equations 11 and 12.

$$\sigma_1 = \frac{1}{2}\left(\sigma_x + \sigma_y\right) + \sqrt{\left[\frac{1}{2}\left(\sigma_x - \sigma_y\right)\right]^2 + \tau_{xy}^2} \quad \text{Eq. 11}$$

$$\sigma_2 = \frac{1}{2}\left(\sigma_x + \sigma_y\right) - \sqrt{\left[\frac{1}{2}\left(\sigma_x - \sigma_y\right)\right]^2 + \tau_{xy}^2} \quad \text{Eq. 12}$$

Table 14(pg. 36) gives the values used to calculate the Von Mises stress for both the X and Y axis motor mounts.

Table 14: Motor mount stress analysis

parameter	X-axis	Y-axis	unit
M	1.0976	1.0976	Nm
y	$4.7625*10^{-3}$	4.7625*10-3	m
b	0.1016	0.0699	m
h	$9.525*10^{-3}$	9.525*10-3	m
I	$7.32*10^{-9}$	5.0301*10-9	m^4
W	19.6	19.6	N
A	$9.6774*10^{-4}$	6.6532*10-4	m^2
ro	$33.33*10^{-3}$	33.33*10-3	m
ri	$19.05*10^{-3}$	19.05*10-3	m
J	$1.7316*10^{-6}$	1.7316*10-6	m^4
T	2.8	2.8	Nm
σ_x	0.7344	1.0687	Mpa
T_{xy}	0.0539	.0539	Mpa
σ_1	0.7383	1.0714	Mpa
σ_2	-0.0039	-.0027	Mpa
σ_{vm}	0.7403	1.0728	Mpa

The yield strength of the aluminum plates that are being used is 250 Mpa.
Since 0.7403 Mpa < 1.0728 Mpa << 250 Mpa, the conclusion can be made that neither the X-axis nor Y-axis motor mounts will fail by yielding.

Material and Manufacturing Process Selection

We have used wrought aluminum 6061 T4 for the motor mounts and stainless steel AISI 405 for the acetone dish. With the aid of both the CES EduPack 2009 and SimaPro software, we selected the materials and also analyzed their safety and environmental effects. Simapro did not have aluminum 6061 so we measured the environmental impact of aluminum 6060 instead, which was the closest material to 6061 T4.

We found that .5977 kg of aluminum would be needed for the motor mounts as oppsed to 1.6091 kg of steel. Aluminum has a low raw material impact on the environment, but cast iron has lower air and water emissions. The cast iron also produces less waste. Our results, however, show that over the course of the components lifetime, aluminum actually has a lower environmental impact. Refer to Appendix C for the full material analysis.

When analyzing the conditions of manufacturing our project, we estimate that around 100 units would be made. After selecting the materials to be used for the motor mounts and the acetone dish, we determined what the best ways for producing 100 units of each would be.

The motor mounts, made of aluminum 6061 T4, would be machined by a CNC mill. The capital costs for this process would be relatively low, which is a major consideration since so few parts are being made. The acetone dish, though, would be created by sand casting. Similar to CNC milling, the capital costs are low and the sand casting process is ideal for low production volume. It would probably be, however, more cost effective to purchase a dish from an outside vendor as was done for this prototype. Refer to Appendix C for the full analysis.

FINAL DESIGN DESCRIPTION

The final design shown in Figure 26(pg. 37) was formed by refining the alpha design and addressing the shortcomings. The functions of the final design are discussed in detail in the following section as well as how the design meets the engineering specifications. Refer to Appendix G for engineering drawings of fabricated components and Appendix F for a bill of materials.

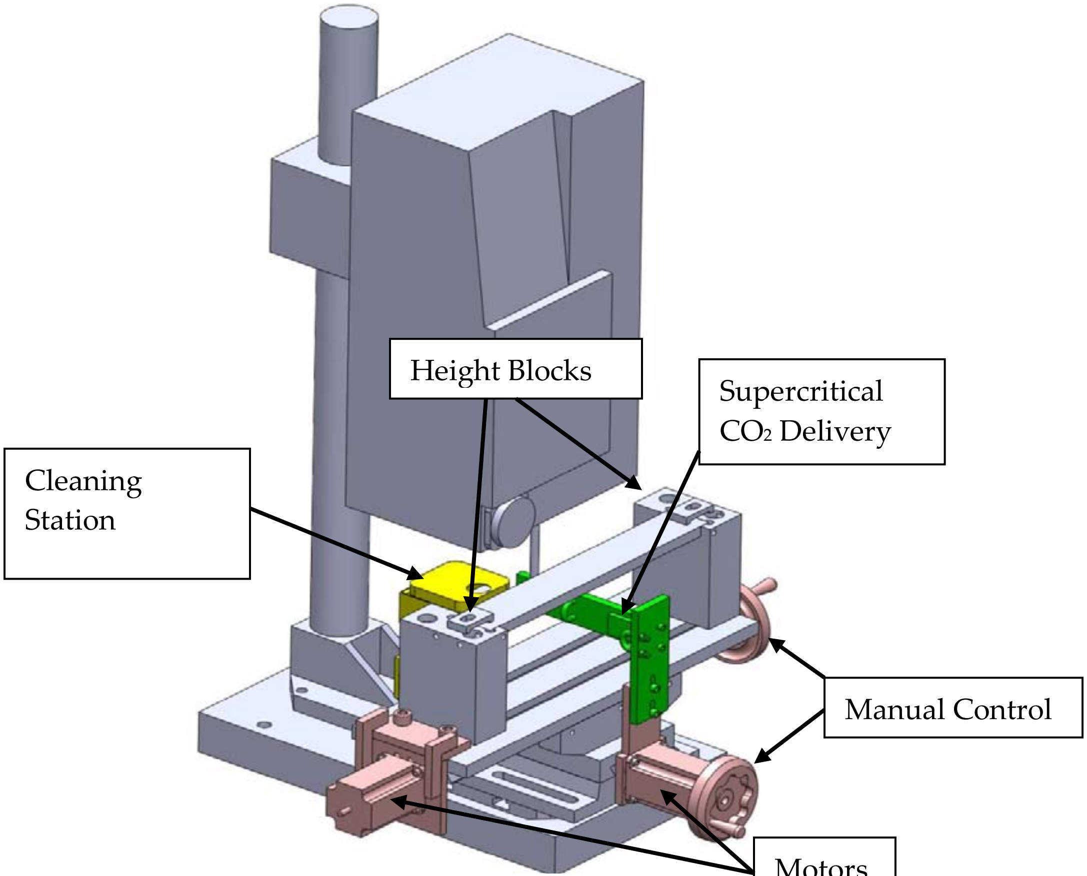


Figure 26: Final design

Height Blocks

The height blocks raise the work piece 3 inches and also moves it forward about a half inch. This change was instituted because after further consideration, we decided that it wasn't ideal for the supercritical CO_2 to pass through multiple valves and pipes with different diameters, however minute those changes may be. We decided to create an assembly that simply mounts the hose and nozzle that originates from the CO_2 pressure chamber. To enact this change, we needed more space under the work piece. While were modifying this aspect, we decided it would help to also move the work piece forward to allow more room for the cleaning station also.

Cleaning Station

Changes from Alpha design: A few changes have been instituted related to the cleaning station. We had to mount it higher because the work piece is now higher, so instead of mounting it to the table it will now be mounted to the height block. We also will now use a purchased tin can as the reservoir; this saves us money not only on material but also on manufacturing. We got rid of the air knife because it was expensive and too large to be easily installed.

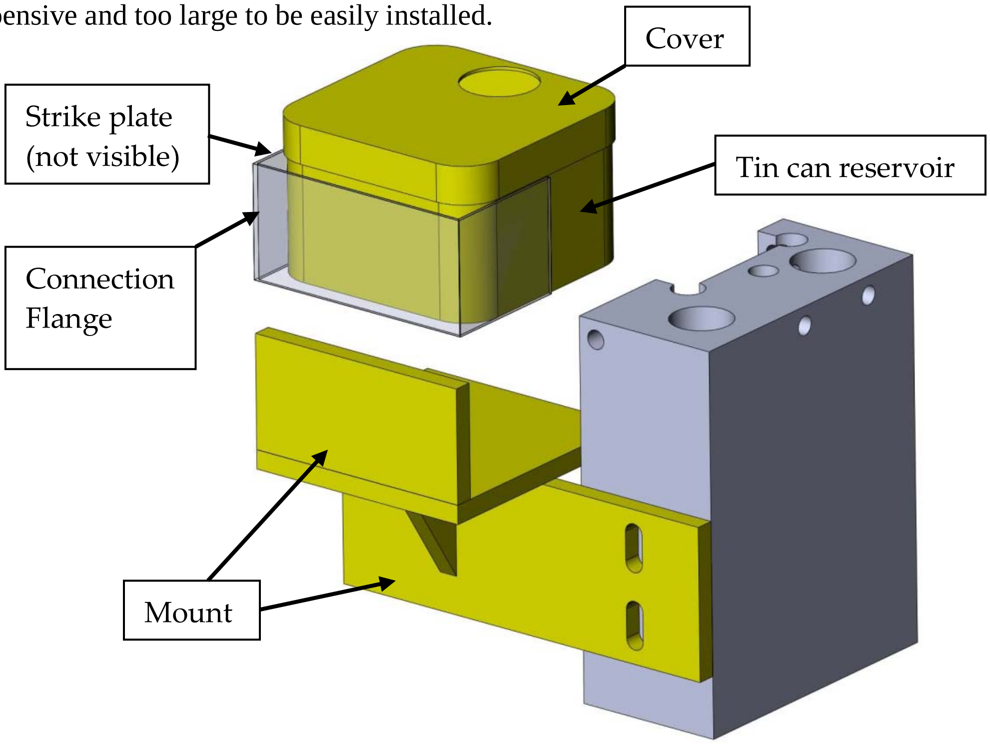


Figure 27: Final design - cleaning station

Description: The new cleaning station design maintains the ability to be easily removed and cleaned. The connection flange simply slides over a bracket on the mount. It has a cover to minimize evaporation, fumes, and splash from the acetone. A brass wire brush is installed inside of the reservoir to ensure that all contamination on the tap has been removed. In replacement of the air knife, we also have the option of using flexible nozzles to blow off the tap with compressed air. No mount was needed for these since they are magnetized and can be attached anywhere on the machine. We also added a strike plate to add strength where the newly designed CO_2 delivery system will continuously come into contact with it.

Supercritical CO_2 Delivery

Changes from Alpha design: The supercritical CO_2 delivery system was completely revamped. These changes were instituted so that the CO_2 wouldn't need to go through various connections and tubes before being applied to the work piece. We instead created a mount that will hold the hose and nozzle that comes straight from the CO_2 pressure tank.

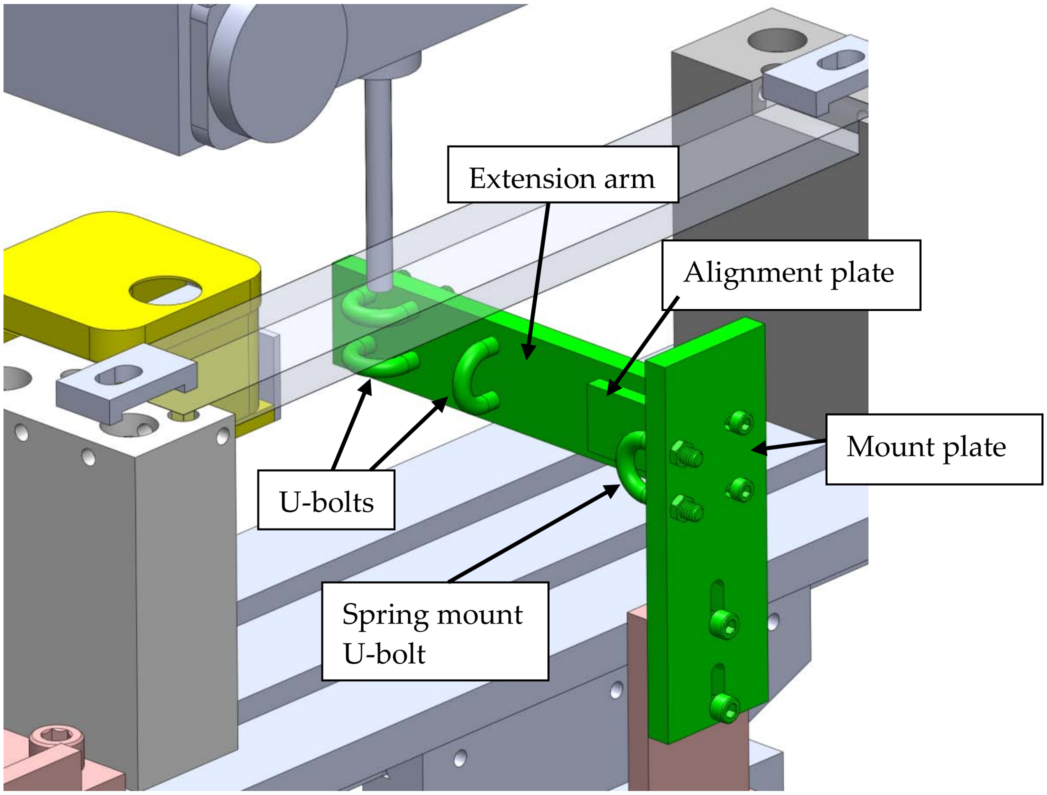


Figure 28: Final design - supercritical CO2 delivery system

Description: The delivery system consists of a spring and hinge connection. The spring pulls the extension arm against an alignment plate when the tap is in use. When the tap goes to the cleaning station, the extension arm will be pushed out of the way. After the tap is done at the cleaning station, the spring will pull the extension arm back into place against the alignment plate. The mounting plate connection holes are actually slot, and this allows for some adjustment as to the location and height of the CO_2 nozzle.

X-Axis Motor Mount

Changes from Alpha design: The x-axis motor mount is no longer made of a single block of material. It now consists of four separate components, which adds to the manufacturing time but it also saves in material costs.

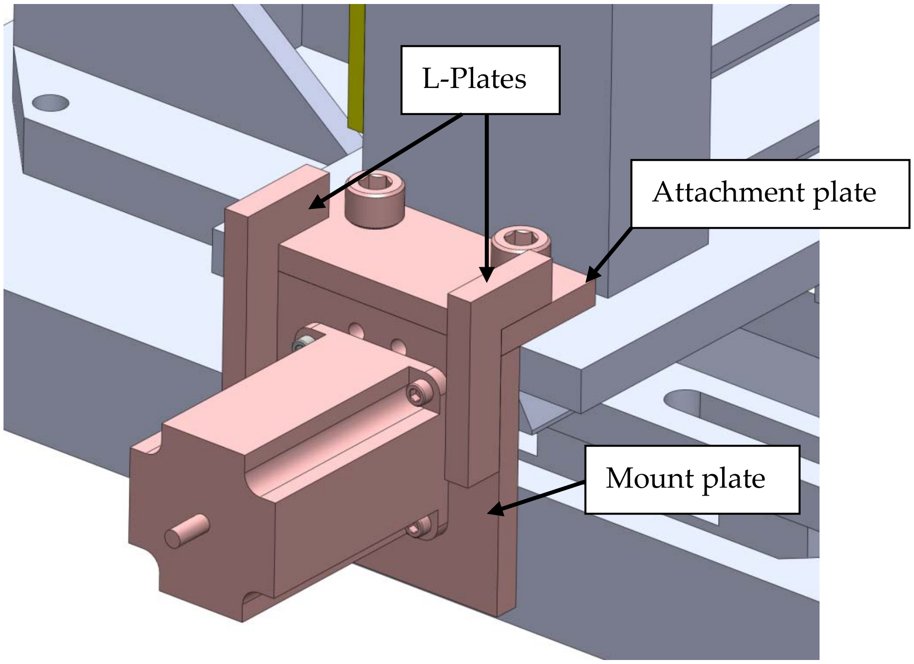


Figure 29: Final design- X-axis motor mount

Description: Similarly to the alpha design, the motor mount will be attached to the table through T-slots. The motor will be attached to a separate plate, and then the two plates will be welded together. To add more stability, two L-shaped brackets will be welded over the joint.

Limit switches

Changes from Alpha design: Limit switches were not originally implemented in the Alpha design. To protect both the motors and the machine itself we decided it would be beneficial to include them on the table.

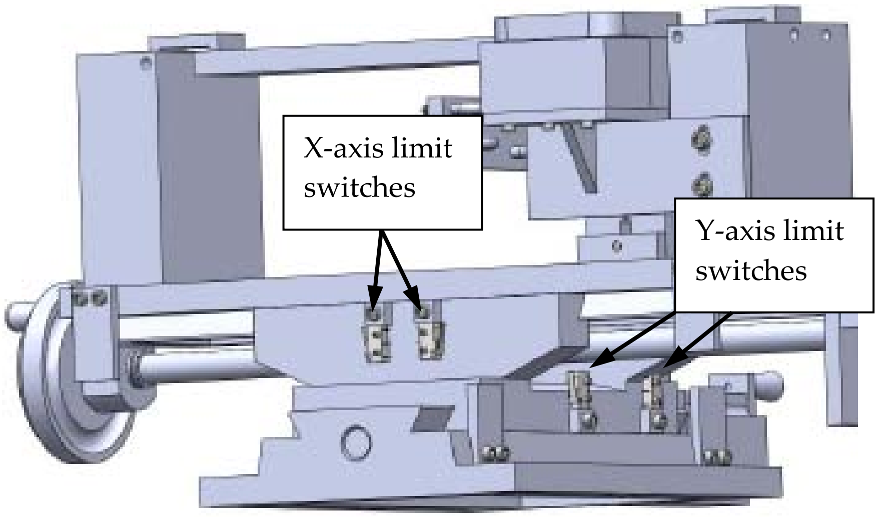


Figure 30: Limit switches on the table

Description: The limit switches are electronic switches that shut down the movement of the motors once the switch is closed. They have been placed so that the table has movement across the entire workpiece.

Manual Operation
Changes from Alpha design: The x-axis mechanism for manual control is has not changed from the alpha design. The y-axis, however, has been modified to simplify the manufacturing.

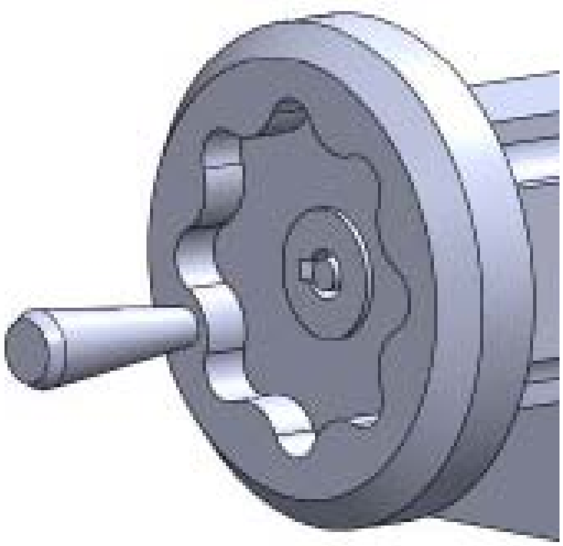


Figure 32: X-Axis handle

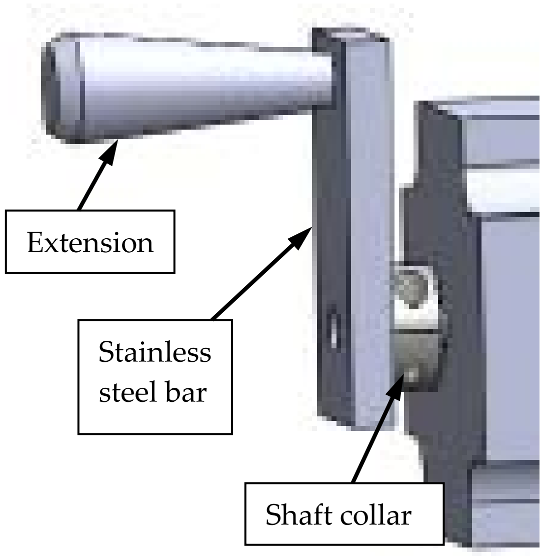


Figure 31: Y-Axis handle

Description: The Y-axis handle is made from a stainless steel flat bar, a shaft collar, and an extension from the original handle. The extension is screwed into the bar. The shaft collar is a two-piece collar, and on of the pieces was welded onto the steel bar. This allows for the collar to be tightened and loosened since only the one half is welded.

Backlash Removal

Changes from Alpha design: Shaft collar is used in place of the ACME nut. For the Y axis a shaft collar is used in place of the ACME nut due to the high cost of the Acme nut.

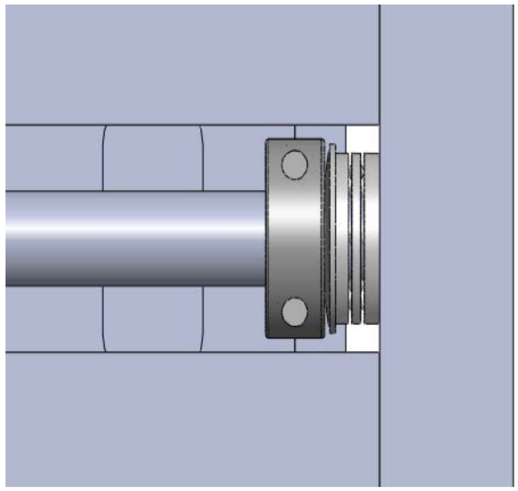


Figure 33: Backlash reduction mechanism

Description: The Belleville washers are sandwiched between the shaft collar and table forcing the two away from each other. This force ensures that the threads of the lead screw are always in contact with the threads of the table, thus minimizing backlash.

FABRICATION PLAN

The purpose of this section is to provide manufacturing and assembly processes involved in the production of the prototype as detailed as possible, so that the readers can understand the implementation of the design and be able to reproduce it. The fabrication plan also notes the changes between the final design and the prototype, and it discusses the corresponding updates of the fabrication plan. Last, a tentative cost analysis for mass manufacturing of the prototype is provided. The fabrication plan is classified into four major categories, including the engineering drawings, manufacturing plan, assembly plan, and cost analysis for mass manufacturing.

Engineering Drawings

This section provides the engineering drawing for each the components that will be fabricated. These drawings are supposed to be used in the corresponding manufacturing process. All the drawings are made using SolidWorks 2009 SP3.0 and are provided in the Appendix G.

Manufacturing Plan

This section discusses the manufacturing plan regarding all the components fabricated. The details of the manufacturing processes, tools used, and the operation condition are provided with careful selection. The manufacturing plan is categorized by the different function that each system serves. These systems include supercritical CO2 delivery, power system, and Cleaning Station.

Supercritical CO_2 delivery

Aluminum components A waterjet cutter was applied to cut the CO_2 plate components from two aluminum plates with sizes of 6’’ × 8’’ × 1/4" and 8’’ × 12’’ × 3/8". The drawing of the configuration of the two plates can be found in Appendix G. Then those components were drilled with appropriate drill bit. The supporting blocks and the T-nuts were cut from a 2’’ thick 6061 aluminum block, and then milled to gain the required surface finishing and other features. Drilling processes were applied to create holes on the above components, after that some of the holes were tapped with the required tap size.

Changes between final design and prototype CO_2 plates 3 and 4 were shortened by ¼’’ and ½’’ by band saw, respectively. The purpose of doing that is to prevent the spring from stretching too much and to avoid interference with the cleaning plates better.

During the above process, the engineering drawings were referenced to determine the cutting profiles, the drill and tap sizes, and location of the holes. The speeds and the feed rate of the milling processes were predetermined by the machinery’s hand book by the equation

$$N = \frac{12 \cdot V}{\pi \cdot D} \qquad \text{Eq. 13}$$

Where N is the spindle speed in revolutions per minute (rpm); V is the cutting speed in feet per minute (fpm) and D is the cutter diameter in inches. The optimum cutting speed is 165 ft/min for 6061 aluminum [1]. By plugging in the diameter values of the different cutter, we determined the optimum cutting speeds in rpm, which is summarized by Table 15.

The spindle speed for drilling was determined by the machine handbook, which was summarized by table 15

Table 15: Recommended operating speeds for drilling of aluminum

Drill Bits Size	Aluminum	Steel	Wood
1/16’’ – 3/16’’	3000	3000	3000

1/4'' – 3/8''	2500	1000	1500
7/16'' – 5/8''	1500	600	750
11/16'' – 1''	1000	300	500

The components fabricated for supercritical CO_2 delivery with corresponding tools information and operation conditions are listed in Table 16.

Table 16: Components fabricated for supercritical CO_2 delivery

		CO_2 plate 1	**CO_2 plate 2**	**CO_2 plate 3**
Material		6061 Al	6061 Al	6061 Al
Qty		1	1	1
1st Mfg Process	Mfg Process	Waterjet cutting	Waterjet cutting	Waterjet cutting
	Tool Info	Waterjet cutter	Waterjet cutter	Waterjet cutter
	Op Condition	Refer to Instruction	Refer to Instruction	Refer to Instruction
2nd Mfg Process	Mfg Process	Tapping	Drilling	Drilling
	Tool Info	3/8-16 tap	0.1875'', 0.15''drill bit	0.1875'' drill
	Op Condition	Back out tap each turn	3000 (rpm)	3000(rpm)
3rd Mfg Process	Mfg Process	N/A	Tapping	Tapping
	Tool Info	N/A	12-32 NEF, 10-24 NC tap	12-32NEF tap
	Op Condition	N/A	Back out tap each turn	Back out tap each turn
		CO2 plate 4	**Support block**	**T-nut**
Material		6061 Al	6061 Al	6061 Al
Qty		1	2	4
1st Mfg Process	Mfg Process	Waterjet cutting	Cutting	Cutting
	Tool Info	Waterjet cutter	Band saw	Band saw
	Op Condition	Refer to Instruction	275 ft/min	275 ft/min
2nd Mfg Process	Mfg Process	Drilling	Milling & Drilling	Drilling
	Tool Info	F drill bit	1'' end mill; 0.201'', 1/4'', 0.21875'',0.375'', 17/32'', 0.8125'' drill bit	17/32'' twist drill bit
	Op Condition	2500 (rpm)	3000, 2500, 1000 (rpm)	1000 (rpm)
3rd Mfg Process	Mfg Process	N/A	Tapping	Tapping
	Tool Info	N/A	5/16-18 NC, 7/16-14 NC tap	5/8-11 NC'' tap
	Op Condition	N/A	Back out tap each turn	Back out tap each turn

Power system

Aluminum components The aluminum components include the aluminum plates used as motor mounts and mechanical stops. A waterjet cutter was applied to cut the aluminum plates from aluminum stock plates with sizes of 6'' × 8'' × 1/4" and 8'' × 12'' × 3/8", and a band saw was used to cut the mechanical stops. Then, all the X plates were welded in the desired manner using tungsten inert gas (TIG) welding. Before welding, the welded part must be cleaned by using acetone and a rag. Then a metal wire brush was used to remove the oxides layer on the surface of the welded part to prevent contamination. The filler material used in the welding was 5356 aluminum as to be compatible with the welded aluminum. After welding, X plates 1 and 2 were drilled and tapped so that it can fasten to the table. The Y plate and mechanical stops were drilled and tapped with appropriate drill bits and taps. Since welding would inevitably lead to a certain amount of deformation to the welded components, the X plates are recommended to be welded before further machining to minimize this kind of negative effect.

Lead screw In order to fit the motor mount, the lead screw was cut by a band saw and then was turned by a lathe to get the desired diameter.

Table base In order to fit the Y motor mount, the table base used for the Y axis lead screw was drilled using a drill press to create 4 screw holes. Then those holes were tapped with the appropriate taps.

Y handle In order to fit the Y motor mount, a new handle was made out of stainless steel. The handle was first cut from a stainless steel bar and then drilled and tapped to create screw holes. Then the handle was welded to a two piece shaft collar in order to allow connection to the motor shaft. The welding was conducted using the TIG welding technique. Before welding, the welded part must be cleaned by using acetone and a rag. Then a metal wire brush was used to remove the oxides layer on the surface of the welded part to prevent contamination.

Changes between final design and prototype In order to prevent accidental damage caused by moving the table too far, we designed and manufactured four mechanical stops which were attached the table base. Correspondingly, four electrical triggers were attached at the table base. Once the mechanical stop hits the trigger, the trigger will send electrical signals to the computer and the system will be stopped immediately. Another change is a new Y handle was made since the original y handle could not be mounted to the shaft of the Y motor.

During the above process, the corresponding engineering drawings were referenced to determine the cutting profile, the size of the drill bits and the taps, and the location of the holes. The speeds for cutting and drilling were predetermined by the machinery's hand book and Eq. 13, Pg. 46. The components fabricated for the power system, corresponding tools information, and operation conditions are listed in Table 17.

Table 17: Components fabricated for power system

		X plate 3	**X plate 1**	**X plate 2**
Material		6061 Al	6061 Al	6061 Al
Qty		2	1	1
1st Mfg Process	Mfg Process	Waterjet cutting	Waterjet cutting	Waterjet cutting
	Tool Info	Waterjet cutter	Waterjet cutter	Waterjet cutter
	Op Condition	Refer to Instruction	Refer to Instruction	Refer to Instruction
2nd Mfg Process	Mfg Process	TIG welding	TIG welding	TIG welding
	Tool Info	TIG equipment & Filler rod of 5356 Al	TIG equipment & Filler rod of 5356 Al	TIG equipment & Filler rod of 5356 Al
	Op Condition	Surface pre-cleaned	Surface pre-cleaned	Surface pre-cleaned
3rd Mfg	Mfg Process	N/A	Drilling	Drilling

Process	Tool Info	N/A	0.25'',0.187'' drill bit	0.5'' drill bit
	Op Condition	N/A	3000 (rpm)	1500(rpm)
4th Mfg Process	Mfg Process	N/A	Tapping	Tapping
	Tool Info	N/A	5/16-18, 12-32 NEF tap	9/16-18 NF tap
	Op Condition	N/A	Back out tap each turn	Back out tap each turn
		Y plate 1	**Y table base**	**Mech stop 1**
Material		6061 Al	Steel	6061 Al
Qty		1	2	2
1st Mfg Process	Mfg Process	Waterjet cutting	Drilling	Cutting
	Tool Info	Waterjet cutter	# 7 drill bit	Band saw
	Op Condition	Refer to Instruction	3000 (rpm)	275 ft/min
2nd Mfg Process	Mfg Process	Drilling	Tapping	Drilling
	Tool Info	3/16'', #7, #2 drill bit	¼ - 20 tap	0.5'' drill bit
	Op Condition	3000 (rpm)	Back out tap each turn	1500 (rpm)
3rd Mfg Process	Mfg Process	Tapping	N/A	Tapping
	Tool Info	12-24, ¼ -20, ¼ - 28 tap	N/A	9/16-18 NF tap
	Op Condition	Back out tap each turn	N/A	Back out tap each turn
		Mech stop 2	**Mech stop 3**	**Lead screw**
Material		6061 Al	6061 Al	Stainless steel
Qty		2	2	1
1st Mfg Process	Mfg Process	Cutting	Cutting	Curring
	Tool Info	Band saw	Band saw	Band saw
	Op Condition	275 ft/min	275 ft/min	75 ft/min
2nd Mfg Process	Mfg Process	Drilling	Drilling	Lathing
	Tool Info	# 13 drill bit	# 13 drill bit	Facing tool
	Op Condition	3000 (rpm)	3000 (rpm)	1146 (rpm)
3rd Mfg Process	Mfg Process	Tapping	Tapping	N/A
	Tool Info	12-32 NEF	12-32 NEF	N/A
	Op Condition	Back out tap each turn	Back out tap each turn	N/A
		Y handle		
Material		Stainless steel		
Qty		1		
1st Mfg Process	Mfg Process	Cutting		
	Tool Info	Band saw		
	Op Condition	75 ft/min		
2nd Mfg Process	Mfg Process	Drilling / Tapping		
	Tool Info	¼'' drill bit / 5/16-18 NC		
	Op Condition	3000 (rpm)		
3rd Mfg	Mfg Process	Welding		

Process	Tool Info	TIG welding equipment		
	Op Condition	Surface pre-cleaned		

Cleaning station

Aluminum components The aluminum components used for the cleaning station were cut by a waterjet cutter and a band saw from two stock aluminum plates with sizes of 6’’ × 8’’ × 1/4" and 8’’ × 12’’ × 3/8". Before welding, the welded part must be cleaned by using acetone and a rag. Then a metal wire brush was used to remove the oxides layer on the surface of the welded part to prevent contamination. The filler material used in the welding was 5356 aluminum as to be compatible with the welded aluminum. Then each component was drilled and tapped respectively.

Tin can cover In order to allow the tap to dip into the acetone stored in the reservoir, a 1’’ diameter hole was cut out in the tin can cover by using a knife. The engineering drawing will be utilized to determine the position and the size of the hole.

Tin can flange and Brush flange The tin can flange and the brush flange were made from a tin can simial to the one which served as the acetone reservoir. The tin cans were cut by the band saw to obtain the desired flange shape, and then the flanges were attached to the reservoir by soldering. The brush flange was drilled to create two screw holes before soldering.

Brush A brass wire brush was cut by a band saw for a certain length to fit the cleaning system. After cutting, the part with brass wire was drilled and tapped to create screw holes so that it could be fastened with the brush flange.

Changes between final design and prototype The only change that has been made for cleaning station is that the strike plate wasn’t used due to its incompatibility with the table’s movement.

During the above manufacturing processes, the corresponding engineering draws were utilized to determine the machining profile, drilling and tapping sizes as well as the soldering location. The cutting speeds were predetermined by the machinery’s hand book and Eq. 13, Pg.46. The components fabricated for cleaning station with corresponding tools information and operation conditions are summarized in Table 18.

Table 18: Components fabricated for cleaning system

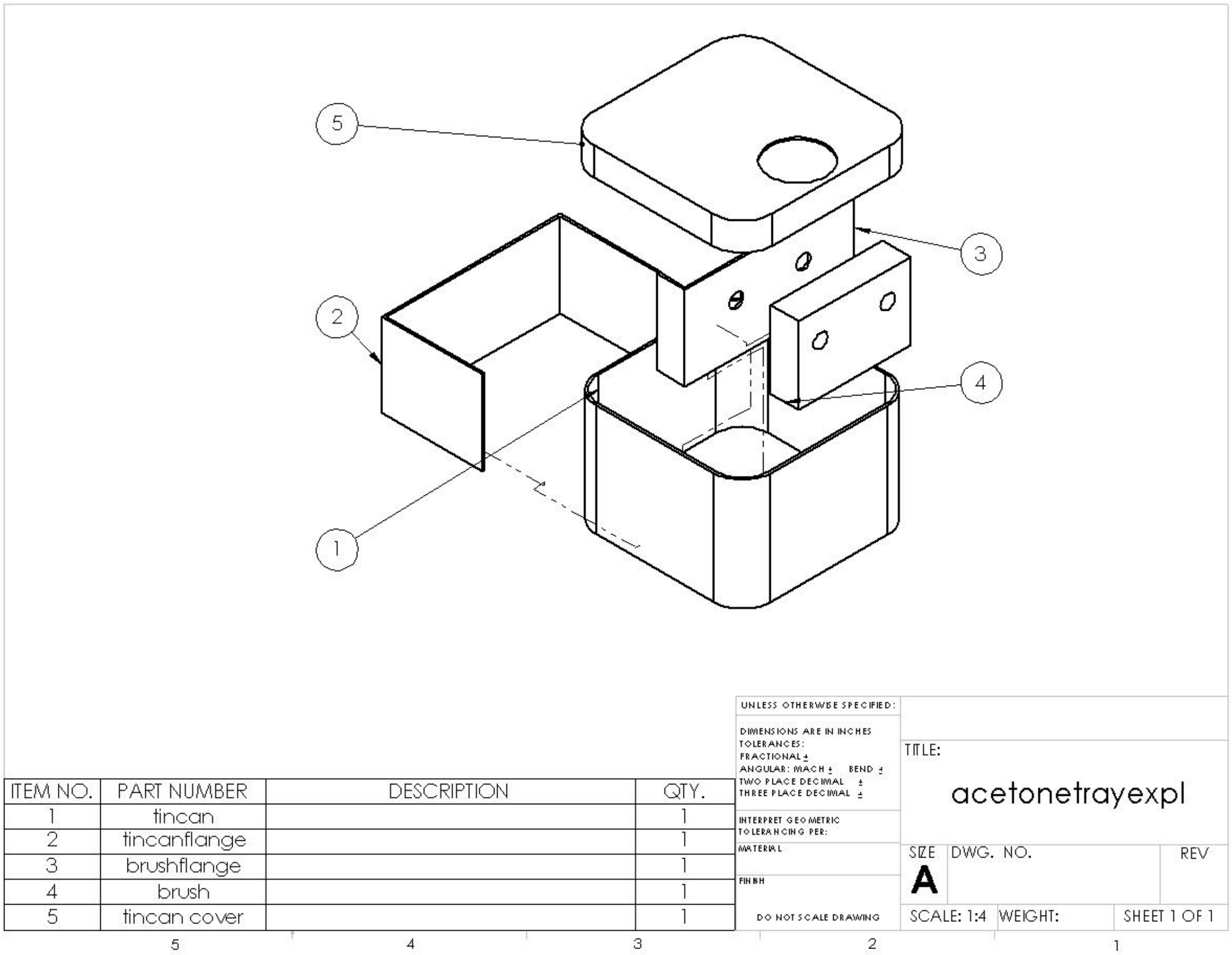
		Cleaning plate 1	**Cleaning plate 2**	**Cleaning plate 3**
Material		6061 Al	6061 Al	6061 Al
Qty		1	1	1
1st Mfg Process	Mfg Process	Waterjet cutting	Waterjet cutting	Waterjet cutting
	Tool Info	Waterjet cutter	Waterjet cutter	Waterjet cutter
	Op Condition	Refer to Instruction	Refer to Instruction	Refer to Instruction
2nd Mfg Process	Mfg Process	Milling	Drilling / Tapping	TIG welding
	Tool Info	No. 5 end mill	# 16, #35drill bit / 12-24 NC, 6-32 NC tap	TIG equipment & Filler rod of 5356 Al
	Op Condition	2500 (rpm)	3000 (rpm)	Surface pre-cleaned
3rd Mfg Process	Mfg Process	TIG welding	TIG welding	N/A
	Tool Info	TIG equipment & Filler	TIG equipment & Filler	N/A

		rod of 5356 Al	rod of 5356 Al	
	Op Condition	Surface pre-cleaned	Surface pre-cleaned	N/A
		CS+Back+BRKT	**Tin can cover**	**Tin can flange**
Material		6061 Al	Tin alloy	Tin alloy
Qty		1	1	1
1st Mfg Process	Mfg Process	Cutting	Cutting	Cutting
	Tool Info	Band saw	Knife	Band saw
	Op Condition	275 ft/min	N/A	150 ft/min
2nd Mfg Process	Mfg Process	Drilling	N/A	Soldering
	Tool Info	#29 drill bit	N/A	Soldering equipment, solder alloy
	Op Condition	3000 (rpm)	N/A	Solder the flange and tin can together
3rd Mfg Process	Mfg Process	Tapping	N/A	N/A
	Tool Info	8-32 NC	N/A	N/A
	Op Condition	Back out tap each turn	N/A	N/A
		Brush	**Brush flange**	**Strike Plate**
Material		Wood, brass wire	Tin alloy	6061 Al
Qty		1	1	1
1st Mfg Process	Mfg Process	Cutting	Cutting	Waterjet cutting
	Tool Info	Band saw	Band saw	Waterjet cutter
	Op Condition	150 ft/min	150 ft/min	Refer to Instruction
2nd Mfg Process	Mfg Process	Drilling	Tapping	Drilling
	Tool Info	17/64'' drill bit	5/16-18 NC	# 29 drill bit
	Op Condition	1500 (rpm)	Back out tap each turn	3000 (rpm)
3rd Mfg Process	Mfg Process	Tapping	Soldering	Tapping
	Tool Info	5/16-18 NC	Soldering equipment, solder alloy	8-32 NC tap
	Op Condition	Back out tap each turn	Solder the flange and tin can together	Back out tap each turn

Assembly Plan

This section describes how all of the fabricated and modified components will be assembled together to form the final product. Corresponding engineering drawing for the configuration is provided.

Acetone reservoir



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	tincan		1
2	tincanflange		1
3	brushflange		1
4	brush		1
5	tincan cover		1

Figure 34: Assembly drawing of the acetone dish

<u>Description:</u> The main component of the acetone reservoir is the tin can (No. 1). A brush flange (3) was soldered to the inside of the tin can in order to hold the brush (4) in place. The brush was attached to the brush flange by two screws. The cover (5) of the tin can was placed on top of the reservoir in order to minimize evaporation of the acetone and also contain any splashing while the tap is being cleaned. Another flange (2) was attached to the outside of the tin can by soldering. This flange would allow the reservoir to be easily removed from the cleaning station mount.

Cleaning station mount

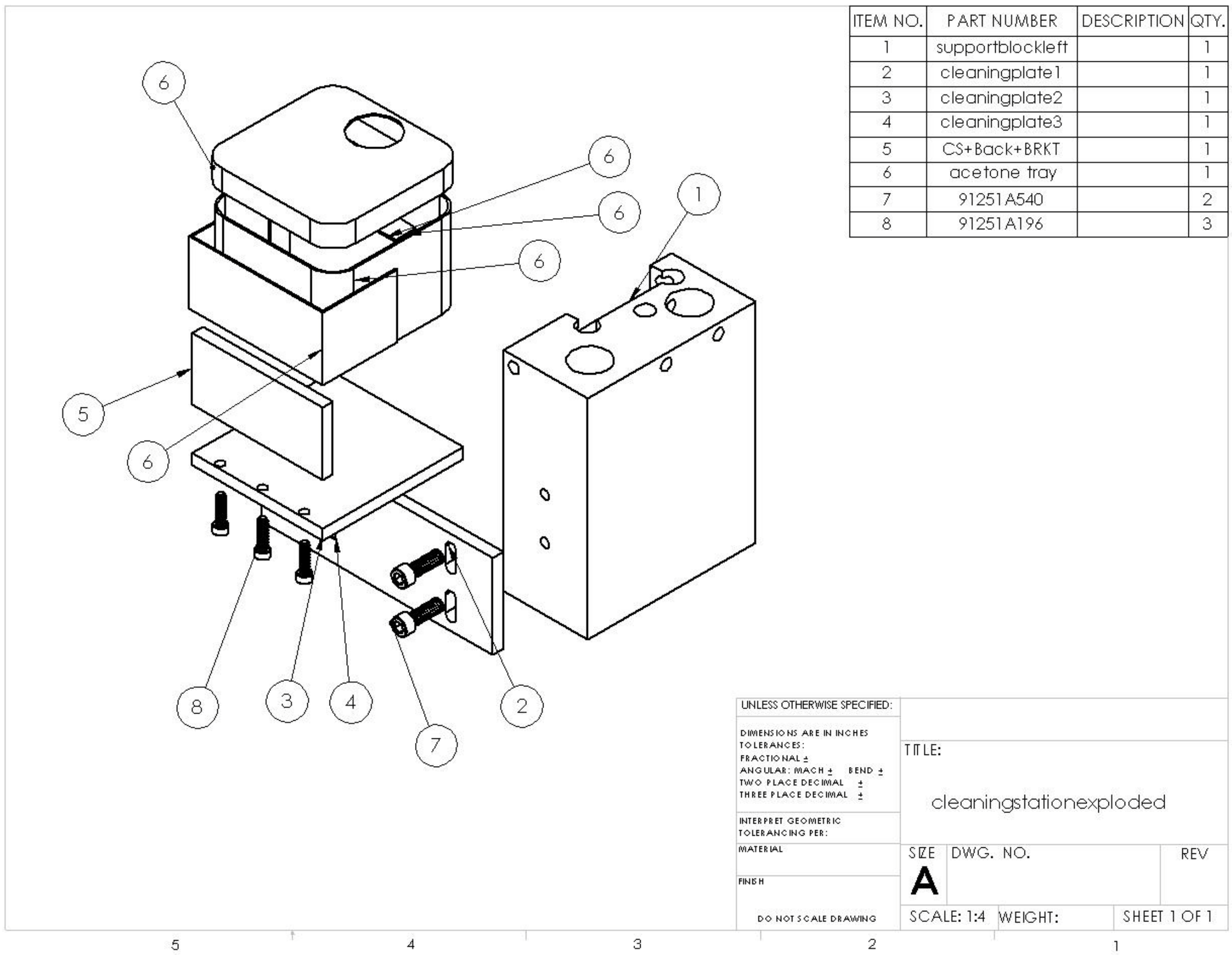
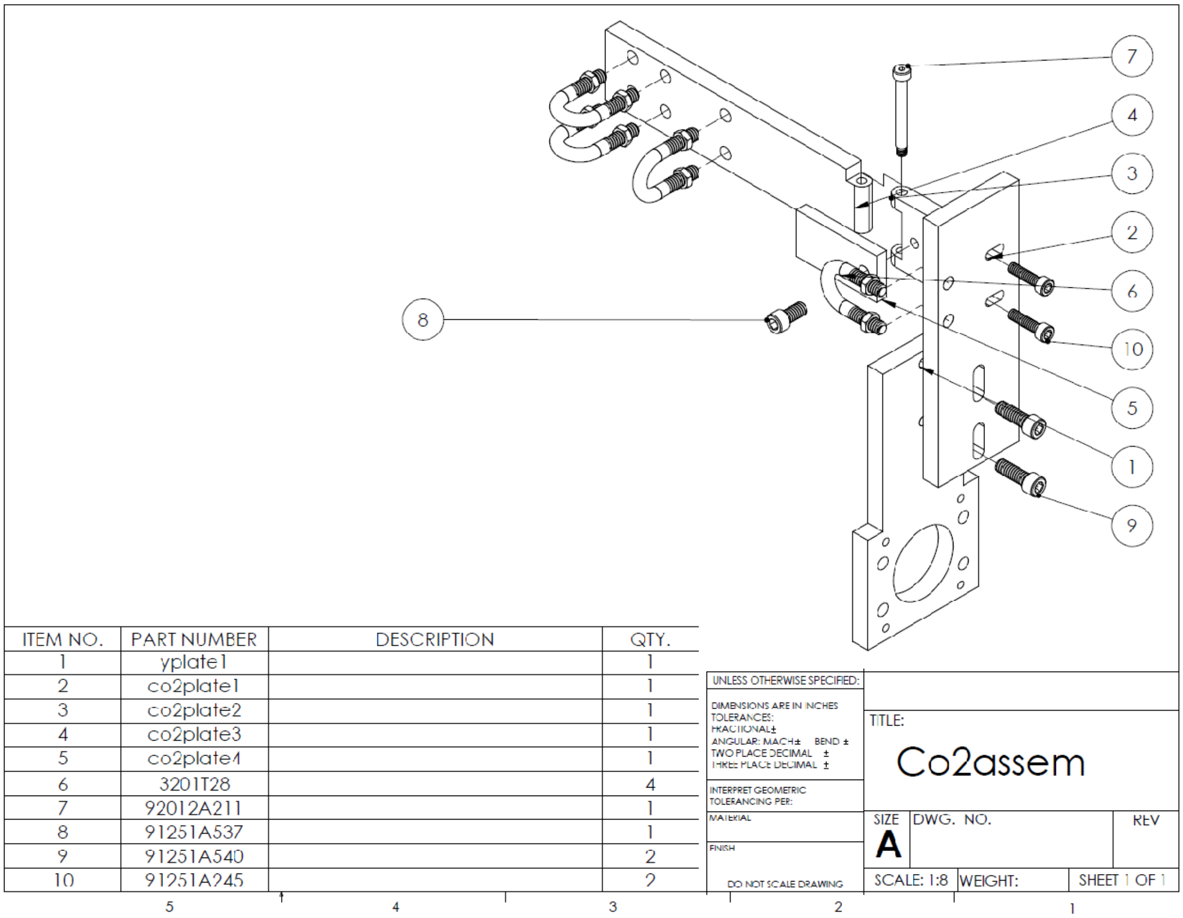


Figure 35: Assembly drawing of the cleaning station

Description: The cleaning station mount was attached to the table through the support block (1). A cleaning plate 1 (2) was screwed into the side of the support block by two screws (7). Another plate (3) was attached to plate 1 (2) by TIG welding. The cleaning plate (4), which cannot be seen in the above picture, was also welded to cleaning plates 1 and 2 to add rigidity. A back bracket (5) was screwed into plate 2 by three screws (8). This back bracket provided a means for the acetone reservoir (6) to be easily mounted and removed from the assembly.

Changes between final design and prototype: The strike plate was taken off to prevent the interference of the cleaning station and supercritical CO_2 delivery.

Supercritical CO_2 delivery system



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	yplate1		1
2	co2plate1		1
3	co2plate2		1
4	co2plate3		1
5	co2plate4		1
6	3201T28		4
7	92012A211		1
8	91251A537		1
9	91251A540		2
10	91251A245		2

Figure 36: Assembly drawing of the supercritical CO_2 delivery system

Description: The CO_2 delivery system attached to the table through the same mounting plate (1) as the y-axis motor does. Another plate (2) screwed into the mounting plate through slots that allow for the adjustment of placement for the system. The extension plate (4) was attached to plate 2 through a hinged connection (7, 3). U-bolts (6) were attached to the extension plate to provide a way for the CO_2 hose to be mounted to the system. Another u-bolt was attached to plate 2 to provide a mounting place for a spring. This spring in combination with the hinge would pull the extension plate against the alignment plate (5) when the tap is in use. When the tap engages the cleaning station, the system would be pushed to the side. When the tap left the cleaning station, the system would be realigned by the spring.

X-Axis motor mount

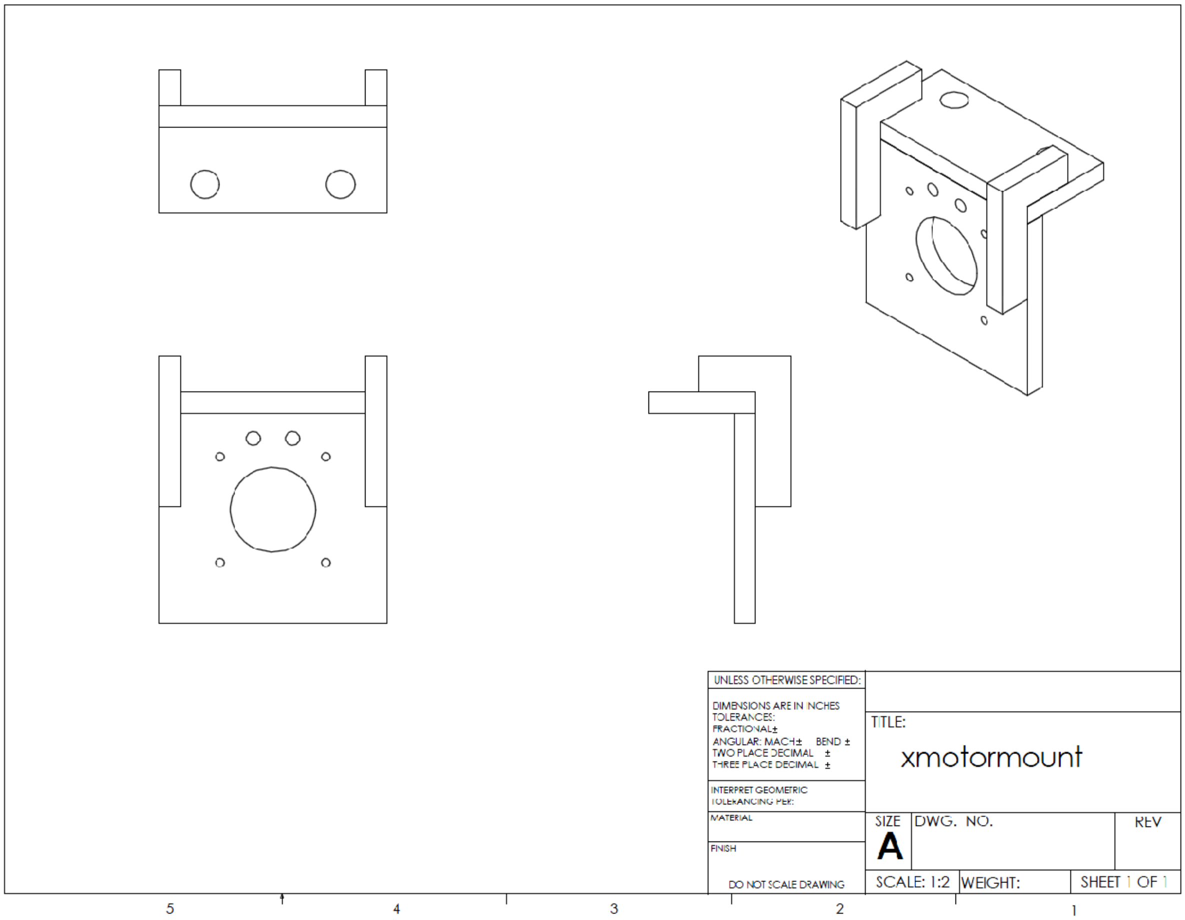


Figure 37: Assembly drawing of the X-axis motor mount

Description: The x-axis motor mount consists of 4 components. The motor itself was attached to the large plate through the use of screws. Another plate was needed attach the mount to the table. This was done by taking advantage of the T-nuts that are on the table. To attach these two plates, two L-plates were welded onto the joint to add strength and rigidity.

X-Axis

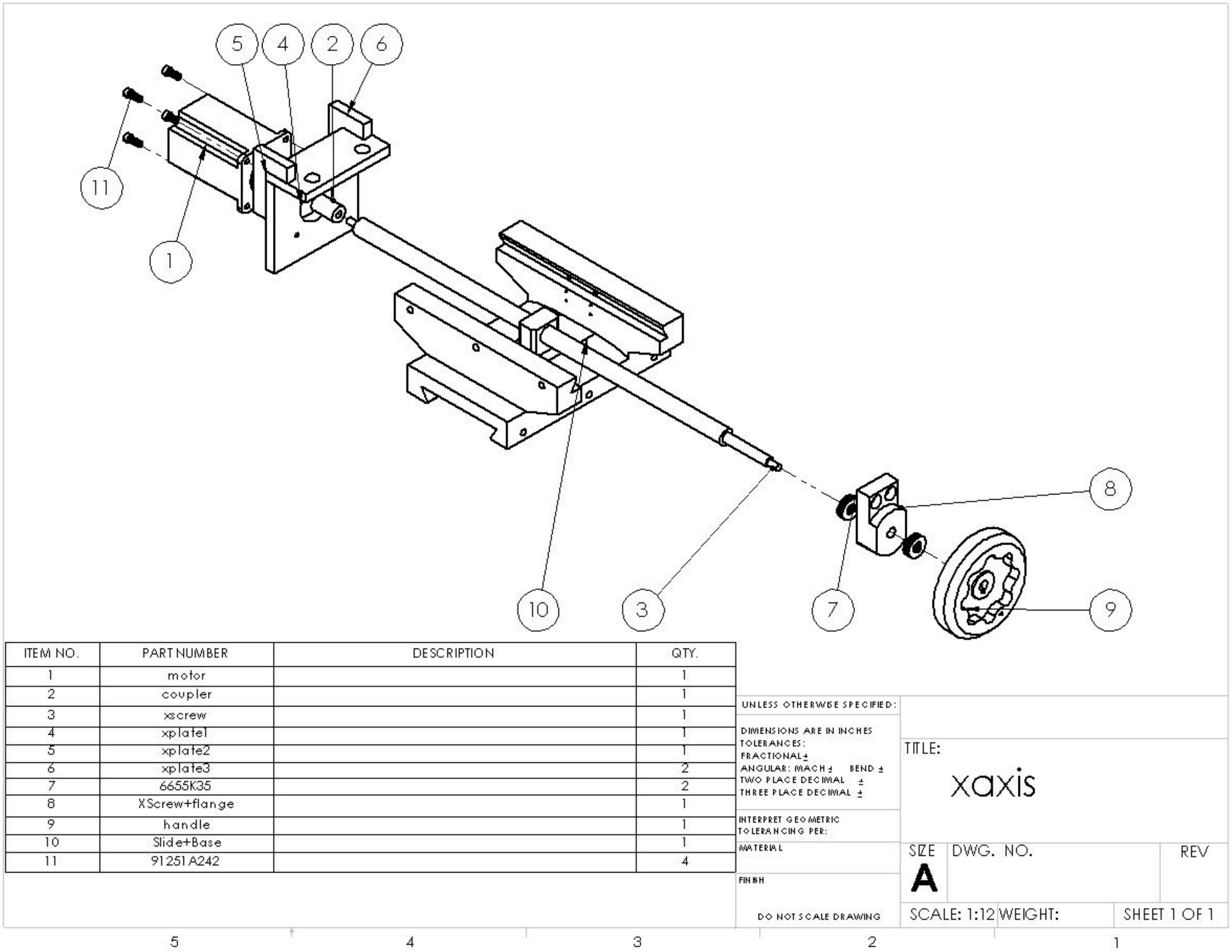
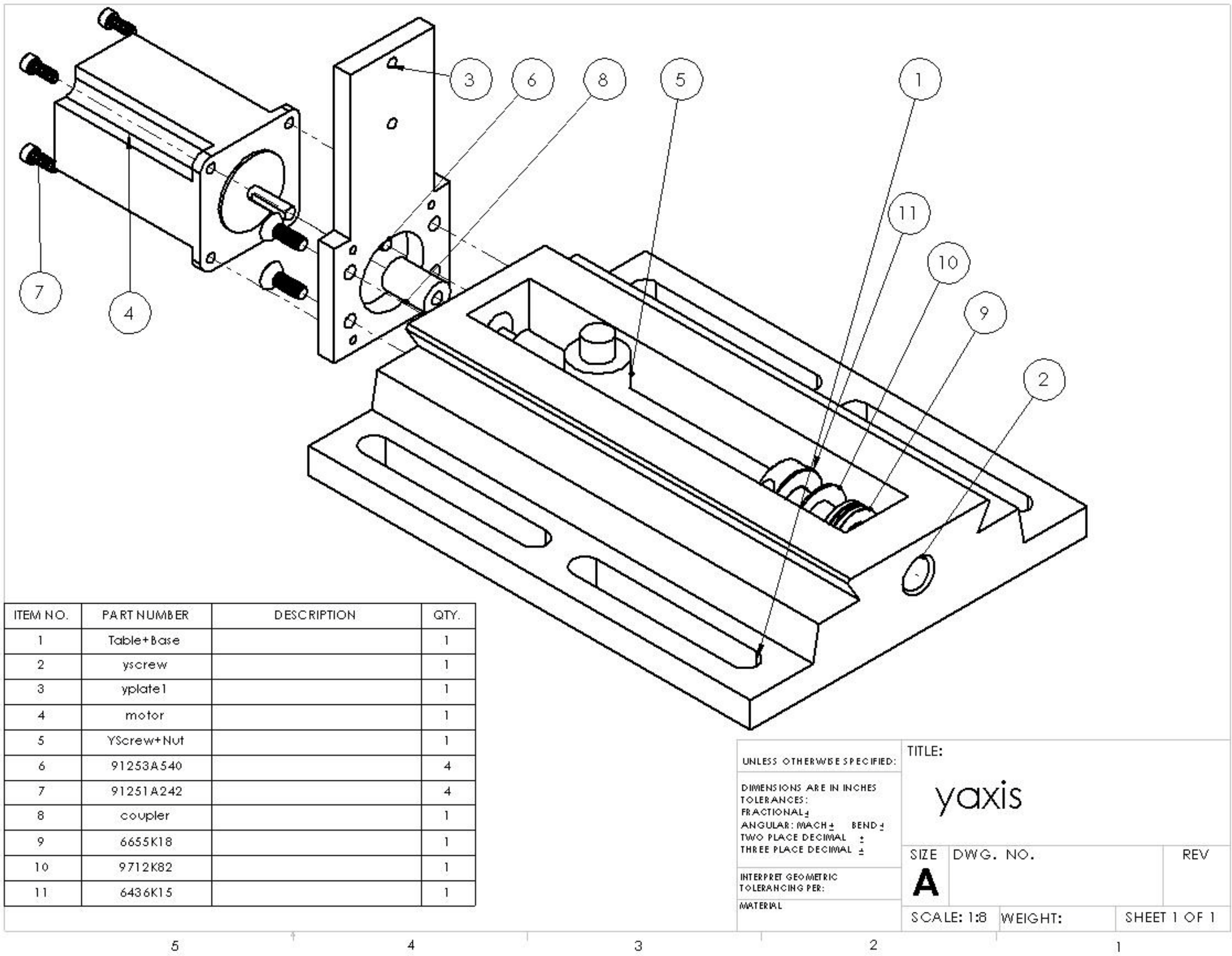


Figure 38: Assembly drawing of the x-axis lead screw

Description: The motor (1) was attached to the lead screw (3) through the coupler (2). In order to support the motor, a motor mount (4, 5, 6) was created and attached to the table. This motor mount consists of three components. The X plate 2 (5) was what the motor itself is attached to. X Plate 2 was then attached to the mounting plate, X plate 1 (4), which provided the assembly a means to attach to the table through T-slots. To add strength and stability two L-shaped plates, X plates 3 (6) were welded to the assembly. After the motor and the mounting assembly were created, the lead screw (3) was screwed into the table base (10). Two thrust bearing (7) were mounted onto the lead screw with a flange sandwiched in between. The handle (9) with cap was mounted to the lead screw and allow for easy manual control.

Changes between final design and prototype: The Bellville washer and the nuts were taken off.

Y – Axis



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Table+Base		1
2	yscrew		1
3	yplate1		1
4	motor		1
5	YScrew+Nut		1
6	91253A540		4
7	91251A242		4
8	coupler		1
9	6655K18		1
10	9712K82		1
11	6436K15		1

Figure 39: Assembly drawing of the Y-axis lead screw

Description: The motor (4) was attached to the lead screw (2) through the coupler (8) and it was mounted to the Y plate 1 (3) by four screws (7). The Y plate 1 was mounted to the table base (1) by four screws (6) as well. A backlash removal consisted of a Bellville washer (10), a thrust bearing (9) and a nut (11) were mounted to the lead screw, which was designed to reduce the backlash in the Y axis. The entire table base was attached to the slide base, which was not shown in the drawing by the Y screw nut.

Cost Analysis for Mass Manufacturing

The section discusses the cost that would be involved for mass manufacturing of the product and provides an estimation of the cost.

As justified the section of manufacturing process selection, the production volume for our prototype is estimated to be around 100 units due to it is for research use. The majority of the components will be produced using CNC machine with 6061 aluminum, where the CNC machine will be taken into account as capital cost. The solvent reservoirs would be most cost effective if they are purchased from an outside party rather than manufacturing them. The rest components such as motors, drivers, encoder as well as the fasten components will all be purchased from outside party to reduce the cost. Since the production volume is low, we assume mass manufacturing won't reduce the cost in raw material.

Due to the low production volume, it is recommended to use labor to assembly and test the prototype rather than employ automatic manufacturing line to do that. The estimated time for manufacturing, assembly and testing will be 10 -15 hours.

Table 19 summarizes the estimated cost for the above mass manufacturing plan.

Table 19: Estimated cost for mass manufacturing of automated torque tapping test system

Cost entry	Cost per unit ($)	Unit	Subtotal ($)	Total cost ($)	Cost per product ($)
Aluminum	127.34	100 units	12734	112503	1125.03
Motor and Electrical components	665.34	100 units	66534		
Fastens	116.6	100 units	11660		
CNC machine	6575	1 unit	6575		
Labor	10	1500 hours	15000		

VALIDATION RESULTS

As of this report, preliminary testing has been completed for accuracy, and the table is moving, but needs to be modified. The accuracy results for each axis are as follows:

X-axis accuracy ≈ ±11.5 µm, Y-axis accuracy ≈ ±104.2 µm.

This being said, both axes need to be modified to work correctly with the system. Over the week between submission of this report and submission of our final prototype, we will be continuing modification of the table and programming to improve the system performance.

In order ensure that our design will be functional and perform the way intended we will undergo validation. Our planned methods for this validation are as described below.

Motor Testing

Before we begin assembly, we need to test the motors to verify that the resolution we predicted will be attainable. Each motor should be able to achieve 3200 steps per revolution. With this step revolution, we can attain a system resolution of 0.8 µm. To test the motor, we will be connecting to a rotary encoder with a resolution of at least 3200 counts per revolution. Testing will include advancing single steps to verify that we actually see 0.1125 degrees per step. We will also be testing under different speeds, both starting and stopping to verify that the motor does not skip steps from full speed. If the motor does skip steps when stopping from full speed, we will need to adjust the programming so that the motor decelerates slowly to avoid missing steps.

Before final assembly we can also test the cleaning station. Once the cleaning station has been assembled, we can attach it to the table and run trial tests to verify effectiveness of the cleaning station. This will be evaluated qualitatively by Professor Krauss and Sarang Supekar (The graduate student who will be running tests using our system).

Table Alignment

As soon as the motor mounts are made and the table base has been modified to fit the motors, we can attach the motors and limit switches to the table and begin testing the accuracy and repeatability of the system. The first thing to do is to make sure that the table is mounted onto the base of the MicroTap machine with the axes lined up correctly. While the programming should be able to compensate for any misalignment, it shouldn't have to if we align everything correctly during final assembly. We will be using an optical laser measurement system borrowed from Professor Brei's research group. Once the table is attached to the MicroTap base, we will need to mark clearly on the base of the machine where the edges of the table base need to be for correct alignment, in case the table needs to be removed again.

Testing Accuracy and Repeatability

To test the accuracy of the system, we will be using optical measurements. We will need to measure each axis independently. To measure each axis, we will be moving the table a variety of distances from 1 mm up to 45mm on the Y-axis, and from 1mm up to 50mm on the X-axis. Each axis will be tested in 1 to 5mm increments, and testing the accuracy over 100 tests in order to be able to predict accuracy and repeatability for each axis. The targets for the system will be ±30µm for accuracy and ±1.3µm for repeatability. One other option we are pursuing is finding access to a coordinate measurement machine (CMM). These machines are generally extremely accurate, and may produce a clearer picture of how well we meet our goals.

Limit Switches and Emergency Stop Button

The emergency stop button mounted on the wiring case was tested as soon as we had the motors running, and before we attached them to the system. It stops all motion of the table as soon as it is pressed, as we expected.

The limit switches work, and we have installed mechanical stops on the table as well as a safe guard. If the limit switches fail for any reason , the mechanical stops installed will prevent damage to any other systems as the motors will not be damaged by the attempt of the system to continue motion against the mechanical stops.

Full Scale Testing

Full scale testing will be run in three stages. The first stage of testing will be done as a dry run, only moving the table automatically. This will be done to verify that the table moves as expected and can actually compensate for rotation of the bar or table away from square. An entire bar will be tested without the Microtap machine powered, we will manually manipulate the programs running the system and manually actuate the tap during this verification. Once this test is completed, if we need to make any adjustments we will do so and test again. When we are satisfied with the results of this test, we will move on to stage two of full scale testing.

The second stage of testing will be done using a previously tapped work-piece and a used tap, in case any errors do occur during validation. We will start by running a test on one column of holes, to understand the timing and verify again that all of our controls are working as they should be. Once we are comfortable with how the testing is running on a small scale, we will run at least one full scale test (at least 100 holes), still using a previously tapped work-piece. At this point, if there are any changes to be made to the system we will make them and, time allowing, move on to stage three of full scale validation testing.

Stage three of full scale testing will be on a full bar with a new tap, including all data collection. Ideally, this test will be run by Sarang Supekar (the final user of our system) while we observe and answer any questions he may have during setup and operation.

With or without stage three testing, we will be submitting our final prototype design on April 27th, along with an update including any further changes made to the system, what changes may be made in the future to improve the system, and a full user manual including setup and testing procedure, possible troubleshooting instructions, and the description of the different programs written to control the system.

PROGRAMMING AND CONTROLS

As of this report, the programming for the system is still underway. As such, full documentation is not included in this document. That said, the following gives the requirements by which the program is being written and will be evaluated. A full copy of all code written for the system will be included in the user manual to be delivered along with the final prototype on April 27th.

Program and Controls Specification

Full testing will involve two programs written by outside sources and designed for the machinery which they are controlling. An additional two programs written by our group will be controlling both of these programs to run the full system.

The program written by our group is being designed and written with the following specifications:

1. The interface will be simple and user friendly, and full documentation on all aspects of the custom program will be provided.
2. The user will be required to define work-piece characteristics including defining the hole patterns, either by choosing from presets or by defining a custom pattern, manually input limiting hole locations (top left and bottom right-most holes) and cleaning station location(s).

3. The program must be able to account for table misalignment. If the X and Y axes are not aligned correctly with the tap base, the accuracy of the table movement will not be correct. To correct for any misalignment, the user will input both the characteristic center-to-center distance and the locations of the first and last hole.

The program will allow for randomization as defined by user input from a file. This file must include all of the hole indices to be tested as well as a number indicating at what point in the procedure that a particular hole is to be tested.

-The program will be able to tap at least 100 individual holes, with a goal of 150 holes per test.
-The user will be able to pause or stop the test at any time and resume testing without needing to reset the entire program. The state of any given test will be monitored and recorded. This will allow for multiple tests on a given bar as well as flexibility for timing, errors in testing or the possibility that the tap may need to be changed mid-test.
-In the case that the test does need to be paused or stopped, or if a test does not completely use an entire bar, the user will be provided with both a drawing clearly showing which holes have already been tapped, as well as a file that can be loaded back into the program identifying the same holes so that subsequent tests on a given bar do not repeat holes.
-The program must communicate between the Mach3 motor controller and the WinPCA software controlling the tap. This communication is to avoid table movement while the tapping torque tester is acquiring data. Movement during data acquisition would allow for tap breakage and would be risking breaking the sensors within the machine, which would be an extremely costly mistake.
-An emergency stop button must be included and will stop all movement of the table and associated hardware, as a final failsafe.

The requirements listed above are the minimum goals that must be achieved. Below are the functions we would like to provide if time allows:
-In-test statistical analysis of collected data. This will help in characterizing tap wear and lubricant effectiveness.
-Including a color coding system to identify lubricant types and locations as well as indicate tapped vs. untapped holes.
-Capability to read DXF files to allow for any type of hole configuration. The user would still need to manually identify the limit holes and cleaning station during testing setup, but it would decrease the setup time since a DXF of the plates can be obtained from MicroTap or can be drawn quickly by the user.

These extra goals will not be achievable in this round of testing, though the end users or following student groups may be able to include them in a new program.

These are the specifications by which the program is being written. Full test procedures and program documentation will be included in the final prototype submittal on April 27th.

CHALLENGES

Electrical System
One of the major issues currently is that we are not able to control the air solenoid used during cleaning through the Mach 3 Software. This is because the breakout board states that it has a regulated 5V logic voltage but when we tested the actual voltage it was only 2.7 volts. We had a 5V relay that would receive the signal and switch the 12V Load necessary for the solenoid but because the voltage is lower the relay is not switching. Next we tried to use a MOSFET that switches between 2.0 and 4.0 volts but we still could

not get this to work. This could be caused by incorrect wiring or by a faulty MOSFET. After further research we found that MOSFETs are used mainly for switching resistive loads such as lights and if an inductive load such as a solenoid is switched it requires a diode in parallel with the solenoid to prevent the back EMFs from damaging the MOSFET.

Second issue that arose while testing this was that when the output that controls the solenoid is toggled the emergency state is activated in the software which requires a manual input to click the reset button in the software. This would greatly reduce the automation of the testing process as every time the solenoid is activated to clean the tap the user will have to manually press the reset button before the process will continue.

Third issue is the temperature of the drivers and power supply in the enclosure. We installed a cooling fan to provide air movement through the enclosure and this seems to be working properly right now but after running a full test it is possible that the temperature of the drivers or power supplies can reach temperatures that will damage them. Through our current testing we watched the temperature of the drivers simply by feeling them to see if they were overheating and they still felt cool after an hour of testing. It may be useful to use a thermocouple to measure the temperature of the drivers through three(3) hours of testing to make sure they do not over heat.

Mechanical System

First issue that arose during testing was that the thrust bearing between the X axis handle and the support bracket would bind causing the motor to stall. It was determined that this was caused when the key used to hold the handle in place would stick out into the thrust bearing where it would eventually prevent a ball in the bearing from rotating and bind the entire axis. This was remedied by placing a flat washer between the handle and the thrust bearing. This prevents the key from interfering with any of the balls in the thrust bearing.

Second issue was that when turning the lead screws the lathe was not center and so the end of the shaft that connected to the motor was off center and this caused the table to wobble. This was fixed by milling off the end and drilling an undersized hole into the end of the lead screw. A steel dowel was then pressed into the hole with Loctite® to prevent the dowel from rotating.

Third issue was that during manufacturing a tap broke during tapping on a hole that was used to hold the cleaning station to the support block. To fix this new hole were drilled 3/8” to the side of the original holes. We were able to do this because the position of the clean station along that axis was not as important as any of the other axes.

DESIGN CRITIQUE

Our design as built has some issues that can be addressed. Some of these issues can be fixed before submission of our final prototype, while others will be noted here as future work to be completed as we may not have resources to address them before our due date. Any changes we make to the system will be included in engineering change notices (ECN’s) to accompany the final prototype.

1. Backlash – As of this report, both axes still have a slight problem with backlash, as reflected in our accuracy errors earlier (PXX, LXX). Our use of thrust bearings along with Belleville washers was fairly effective for the X axis, though there is room for minimal improvement. The Y axis will require an entirely different approach, as the screw is mounted to the table base rather than the moving axis. To fix the Y axis, we will need to modify the nut it is running through, though we believe this can be accomplished without affecting the total travel of the axis.

2. The blocks we machined to hold the test bar high enough for the CO_2 delivery system to be functional are off slightly. As a result, the bar is turned slightly (within 5 degrees) from perfectly square with respect to the table. We could reaching the blocks themselves or design new risers to accept the original blocks and allow for adjustment in the Y axis direction so that any discrepancies (off square) can be adjusted for in the system setup.

3. The programming could be refined in the future to make it more user friendly, including combining the setup and configuration program with the LabView program that will be running while performing a test. Improvements should also include the use of dialog boxes and a custom written graphical user interface, and possibly the inclusion of a function to control the motors and solenoids so that Mach3 (the CNC program) could be avoided.

4. The testing and validation of the entire setup could be refined and more closely controlled. Periodic retesting for accuracy and repeatability should be done and procedures need to be developed to define the calibration to be done in the future.

5. The wiring in the enclosure currently looks like a rat's nest with wires running all over the place. With additional time and a larger enclosure the wiring should be cleaned up so that if a component has to be replaced the wires can be located and connected more easily. Evaluation of the cooling for the controllers and power supply could also be beneficial.

6. We need to get the solenoids and switches controlling working for air to both the Microtap machine and the cleaning station so that everything will function properly

7. The cleaning station needs to be redesigned to allow for the CO_2 delivery system to pass under it completely and be rid of the avoidance issues that we are currently struggling with. We also need to verify that the tap is not plunging into the middle of the brass brush in the station itself. Resolution of this issue may require completely remaking the tin can currently designated to hold the brush and acetone solvent for cleaning.

8. The X axis screw needs to be re-turned on the lathe so that the shaft connects with the motor and turns on center. Currently machined end is off-center, so we will be cutting that off and replacing it with a dowel pin pressed into the screw along with Loctite in order to turn the screw on center and resolve this issue.

9. We need to standardize where and how the table will be mounted onto the base of the Microtap machine. Currently we are lining it up by eye, but case the table ever needs to be removed, we need to define exactly where it goes so that we can use the largest possible available area allowed by table movement. This attachment setup needs to be repeatable and will be outlined in the user manual to be included with the final system.

10. A repeatable way to find the hole centers needs to be developed. Currently all alignment with hole centers is done by eye. This could be improved by making a custom fitting that can be loaded into the machine and designed to accept a hole finder similar to those commonly used on a mill in a machine shop.

11. We had talked with Sarang and Professor Krauss about including a shroud to cover the motors. This shroud would be helpful for keeping the tapping oil from splashing unto the table slides, lead screws, and the motors. Over time the tapping oil thickens up and if it gets into the slides or lead screws it will increase the torque necessary to move the table and it could reach a point where

torque surpasses that of the motors. If the oil gets onto the motors, it could decrease their performance, as the motors are not sealed. Given exposure over time, the motors and related electronics could fail from build-up or even exposure to the oils used during testing.

12. The CO_2 delivery system should also be re-evaluated. Currently we are planning on using the hose directly from the CO_2 compressor. Given more time, we would like to redesign to include a jet designed for our system in order to be more accurate with the spray into each individual hole.

RECOMMENDATIONS

Our major recommendation would be to resolve all of the issues covered in the design critique, some of which we will be addressing over the next week. We would advise Professor Krauss and Sarang to consult an individual more experienced in controls to explore ways to improve the programs controlling the system as well as incorporating control of the flow of supercritical CO_2 during testing. The users of this system may benefit from taking the entire system out of the fume hood where it is currently and cleaning both the Microtap machine as well as all interior surfaces of the fume hood, and create a schedule and procedure for maintaining cleanliness of the setup.

CONCLUSIONS

Professor Krauss utilizes a Microtap tap torque machine in order to test the effectiveness of metalworking lubricants. He does this by applying a given lubricant to a predrilled hole and then taps it, recording the torque that was required to do so. These measurements can then be extrapolated to other metalworking processes. Occasionally test lubricants are mixed with supercritical CO_2 and then applied to the work piece. The supercritical CO_2 acts as a coolant, chip evacuator, and a carrier for the other lubricant. Currently, the Microtap machine that is being used does not have an automatic table. This means that the operator must manually align each hole to be tested with the tap. Not only is this process time consuming but it also introduces inconsistent errors in the torque measurements. Because of these reasons we have been tasked with automating the table, along with creating a cleaning station for the tap, and a mount for supercritical CO_2 delivery.

In order to generate concepts we created functions based off of the customer's requirements. Once we had these functions laid out, we created a morphological chart in order to explore all possible solutions to the problems. We then took the possible solutions and developed concepts of ways to implement them. Concepts were created for motor selection, backlash reduction, the cleaning station, the supercritical CO_2 delivery system, and program structure. Once all of the concepts were generated, we ranked each concept against the others for each function. The results of these rankings were organized into Pugh charts. We determined that a stepper motor, Belleville washer, a spring loaded supercritical CO_2 delivery system was and an open loop program were the best of the concepts. The concepts for the cleaning station all rated very equally, and so a combination of those ideas was eventually selected.

After all of the concepts for each function were ranked, we proceeded to develop an alpha design. This design implemented all of the best ideas from the various concepts, and it was also re-evaluated against the concepts to ensure that the combinations implemented in the alpha design were in fact advantageous. This alpha design consists of a stepper motor, a combination of thrust bearings and Belleville washers, a cleaning station that utilizes an air knife and brushes that work in unison with a solvent, and the spring loaded CO_2 delivery system.

We analyzed the alpha design and made changes where needed. This was done through both engineering analysis and reevaluating the customer's specific needs. After each component was finalized, we updated the engineering drawings and developed the initial fabrication plan for the design. The operation conditions of machining have been carefully justified using the machinery's handbook as well as consulting with relevant instructors. We have also put together a validation plan to determine and test how well the requirements will be met in the finished product.

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Sarang Supekar

INFORMATION SOURCES

To obtain an idea of how well our product should perform, we researched similar products that are currently on the market. We researched a few CNC machines with automatic tables [3,6] and as benchmarks analyzed an automatic table from Microtap [2], and the automatic table of a countertop CNC machine [3]. Neither the Microtap nor the CNC machine have ways for cleaning the tools or have a mount for supercritical CO_2. The Microtap also has a very hefty price tag. We then analyzed the current setup of our tap machine and compared it to the other two products. For full benchmarking see the QFD in Appendix A.

To understand how supercritical CO_2 could be used to lubricate, and therefore design an appropriate mount for it, the patent on the delivery system was researched [1]. From this patent we learned that the supercritical CO_2 exists at 31.1°C and 72.8 atm, and acts as a coolant and chip evacuator for the lubricant. Backlash in the table is a major concern, we examined the current table and took the dimension of it and then drew the CAD model to help analyze a feasible solution to remove the backlash. One idea is to replace the table's current screws with ball screws [5], but this would add to the cost. The most feasible design we came up with is to use a combination of Belleville washer and thrust spring. The Belleville washer is a spring that applies pressure to the connection once it is clamped down with proper amount of force [9]. A thrust bearing is a particular type of rotary bearing designed to support high axial load [10].

To design an effective cleaning station, we researched air knife system on the market. Air knife systems utilize compressed air for industrial applications that include drying, removing excess oils and liquids, dust blow off, and cooling [11]. The implementation of air knife would enable the cleaning station to blow the debris on the tap, thus to achieving effective cleaning.

To obtain the optimum machinery operation condition, we looked up an online machinery hand book. [12]

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APPENDIX A: QFD DIAGRAM

System QFD

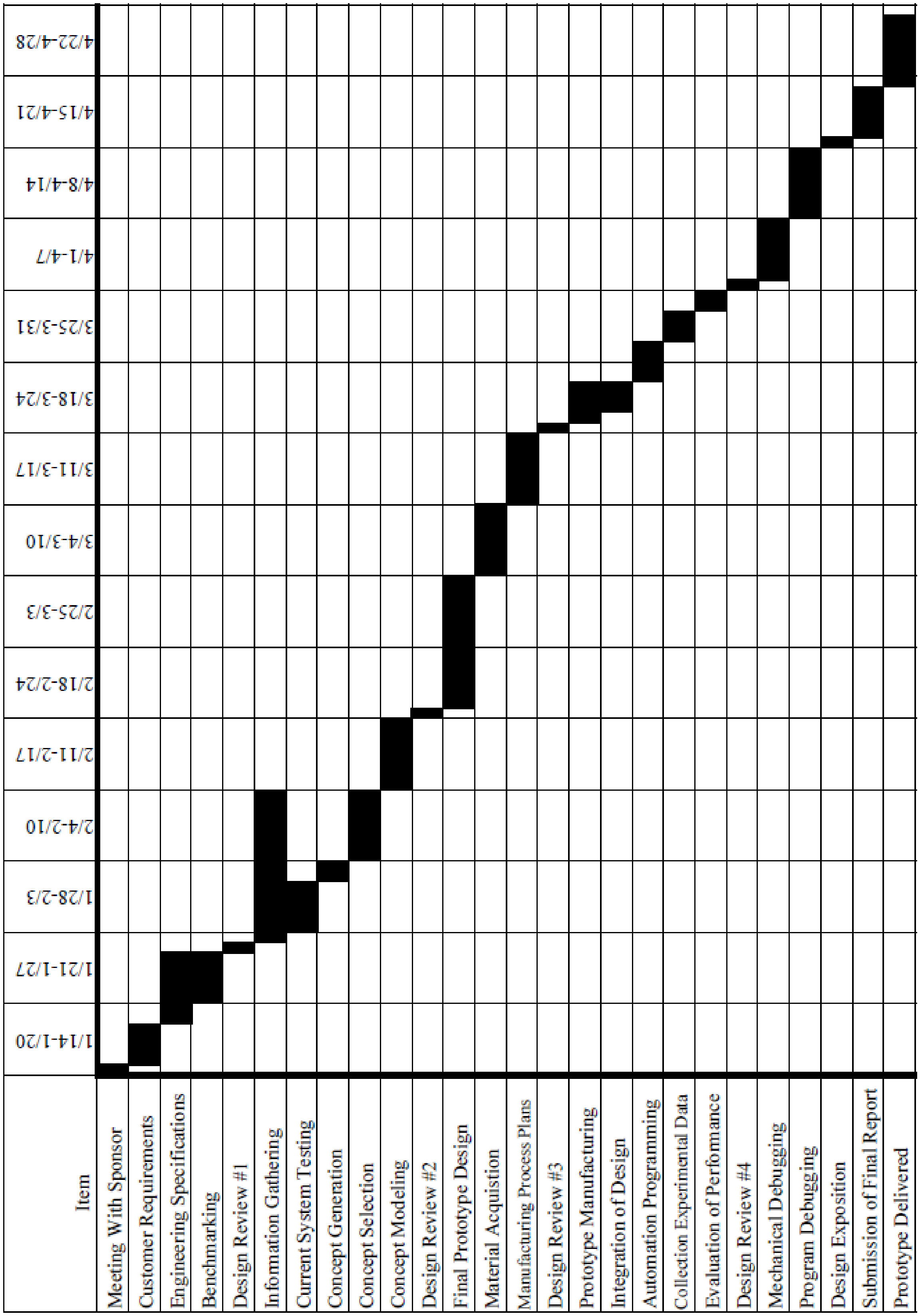
Project:	**Project 25, Automatic Tapping and Cleaning System**
Date:	**1/26/10**

1	Positional Accuracy										
2	Cleanness										
3	Strength										
4	Cost	3	3								
5	Number of Parts	1	1								
6	Preparation time					1					
7	Speed of Motion	1			1	1					
8	Repeatability	3			3						
9	Resolution	3			3				3		
10	Range	9									

Survey Legend	
A	Current product
B	Microtap Autotable
C	CNC Machine

	Customer Needs	**Customer Weights**	Positional Accuracy	Cleanness	Strength	Cost	Number of Parts	Preparation time	Speed of Motion	Repeatability	Resolution	Range	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
			Technical Requirements										**Customer Opinion Survey**				
1	Automatic Control of Table	10	9		1	3	1	1	3	9	9	3					A,B
2	Precise Hole Alignment	11	9			3		1		3	9	1					A,B
3	Automatic Station Cleanning Ability	9		9		3	1						A,B				
4	Super Critical CO2	8											A,B				
5	Low Cost	7	3	1	1	9	3		1	3	3		A	B			
6	Simple User Interface	5						3								A,B	
7	User Manual	4						1									A,B
8	Minimum Modifications	3			3	3	1					1					
9	Manual Control	6	1	1		1	3	1		1							B
		Raw score	216	94	26	168	61	46	37	150	210	44					
		Scaled	1	0.4352	0.1204	0.7778	0.2824	0.213	0.1713	0.6944	0.9722	0.2037					
		Relative Weight	21%	9%	2%	16%	6%	4%	4%	14%	20%	4%					
		Rank	**1**	**5**	**10**	**3**	**6**	**7**	**9**	**4**	**2**	**8**					
		Technical Requirement Units	[µm]	[mL]	[Mpa]	[Dollars]	[#]	[min]	[cm/s]	[µm]	[µm]	[cm]					
		Technical Requriement Targets	0 - 30		>20	<400	<20	5-10	0.5-25	1.3	0.6	27.94-19.05					

APPENDIX B: GANTT CHART



APPENDIX C: DESIGN ANALYSIS ASSIGNMENT

MATERIAL SELECTION

For the motor mounts and for the acetone dish a material selection process was used to find appropriate materials to use.

Motor mounts

The function of the motor mounts is to attach the motors to the xy-table so that the power generated by the motor can be transferred to the lead screw thus making the table move. The objective is to find a material that is low cost yet has the strength to prevent deflections in the material such as bending or yielding, which could cause shaft misalignment. It also has to avoid twisting when the motor torque is applied so that the torque is fully transferred to the lead screw. It also has to resist fatigue damage as it will undergo many cycles of the motor rotating and stopping. It also has to resist possible corrosion due to acetone being splashed onto it.

Using CES EduPack 2009 the following constraints were applied:
Price of less than 2 USD/Kg
Yield strength between 100 to 500 MPa
Nonflammable
Excellent durability to fresh water
Acceptable durability to salt water
Excellent durability to weak acids
Excellent durability to organic solvents
Recyclable

Based on these constraints and ranked from lowest to highest price. Most of the materials are some alloy of aluminum. The top 5 alloys are:

1. Aluminum 6061, wrought, T4
2. Aluminum 6061, wrought, T451
3. Aluminum A356.0 (c): LM25-TB7, cast
4. Aluminum 6061, wrought, T42
5. Aluminum S319.2 (a): LM4-M, cast

Out of these Aluminum 6061 T4 is the best material to use for the motor mounts due to its strength, durability, and having the lowest price of $1.57-$1.73(USD/kg).

Acetone dish

The function of the acetone dish is to hold a capacity of acetone that will be used to clean oil off a tap. A brush will also be installed on the inside to assist with cleaning. The objective is to find a material that can be stamped and fastened without screws. The material must also be resistant to any corrosion that comes from holding acetone or other solvents.

Using CES EduPack 2009 the following constraints were applied:
Price less than 5 USD/kg
Non flammable
Excellent durability to weak acids
Excellent durability to Strong acids
Excellent durability to organic solvents
Excellent durability to oxidation at 500 Deg C
Recyclable

Based on these constraints the top five results ranked for price from lowest to highest are:

1. Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel
2. Stainless steel, ferritic, AISI 409, wrought, annealed
3. Stainless steel, ferritic, AISI 429, wrought, annealed
4. Stainless steel, martensitic, AISI 410S, wrought, annealed
5. Stainless steel, martensitic, AISI 410, wrought, intermediate temper

Form this list the selected material is Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel based off that it is the least expensive material that still meets all the constraints.

DESIGN FOR THE ENVIRONMENT

Motor Mounts

The volume of aluminum used for both the X and Y axis motor mounts is 2.189*10^-4 m^3. The emissions of the aluminum are compared to cast iron, another material that the motor mounts could be produced with. The motor mounts require 0.5977 kg of aluminum 6061 T4 or 1.6091 kg of austenitic cast iron. Using SimaPro and the EcoIndicator 99 method the materials were analyzed to determine their environmental impact. The closest materials in SimaPro used to model those selected are Aluminum 6060 and cast iron NiCr I.

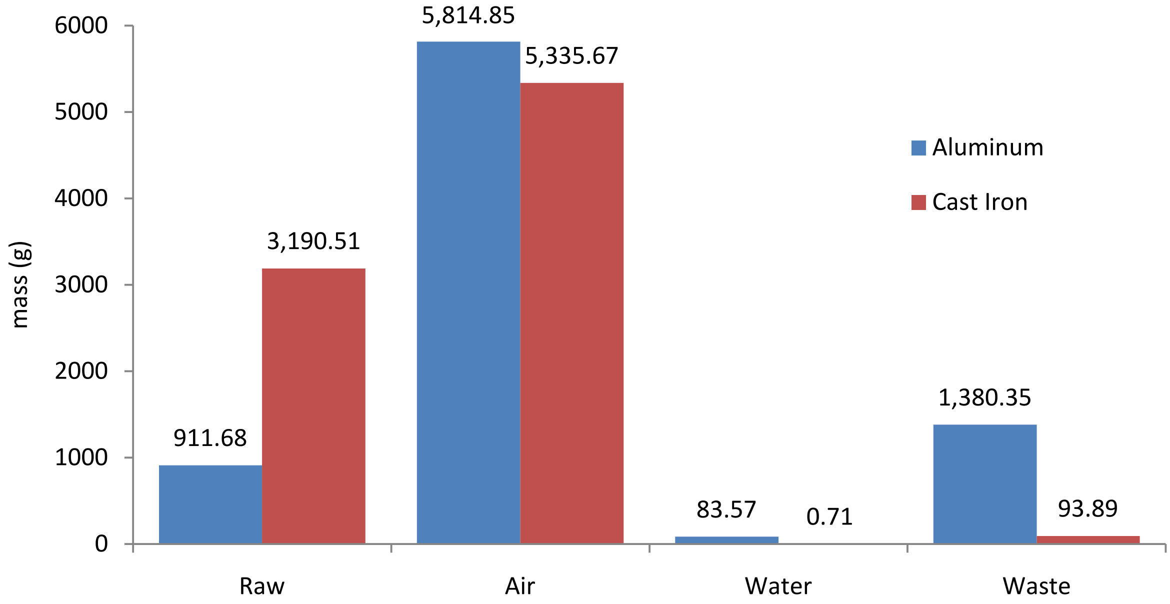


Figure 40: Total emissions broken down into raw material, water emissions, and waste for Aluminum 6060 and cast iron NiCr I

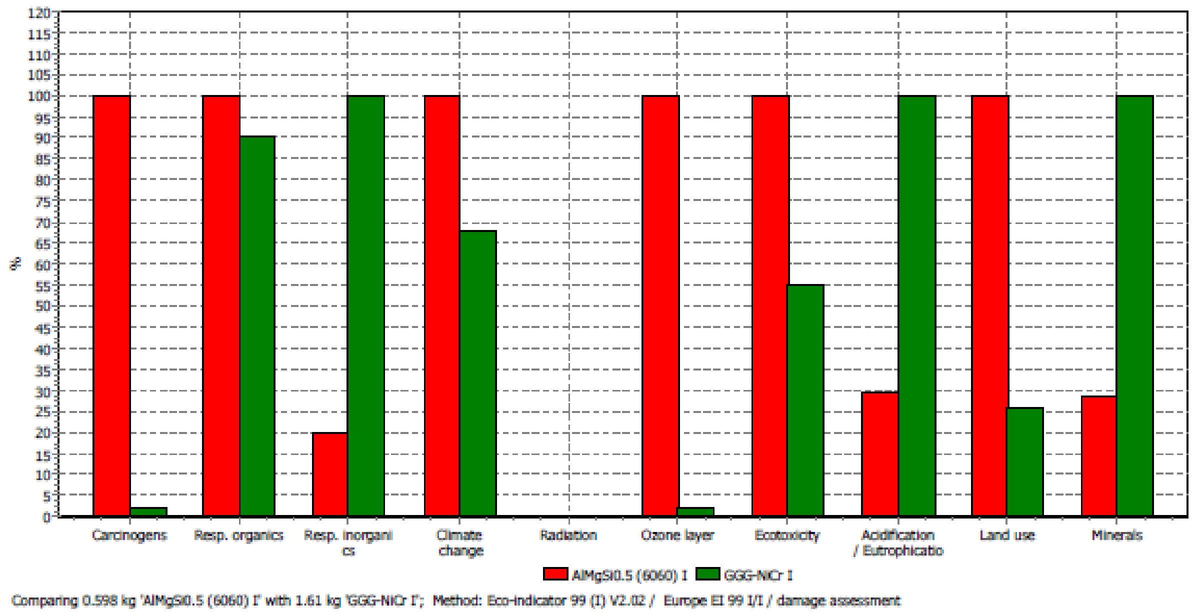


Figure 41: Relative environmental impacts of aluminum 6060 and cast iron NiCr I

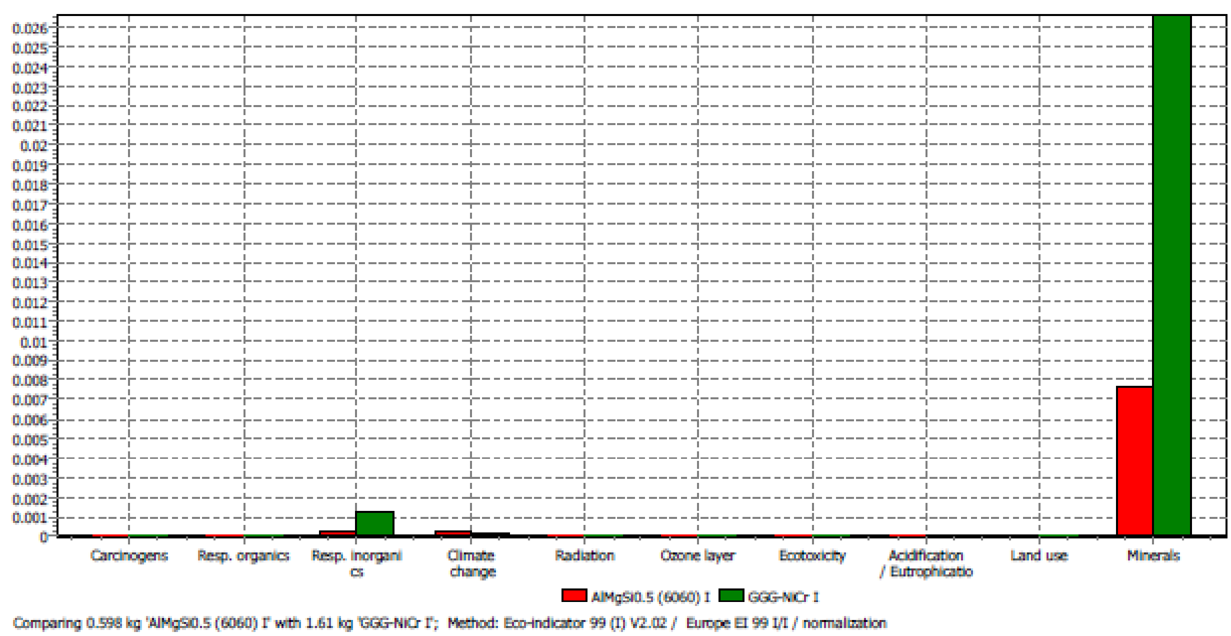


Figure 42: Normalized score of Aluminum 6060 and cast iron NiCr I

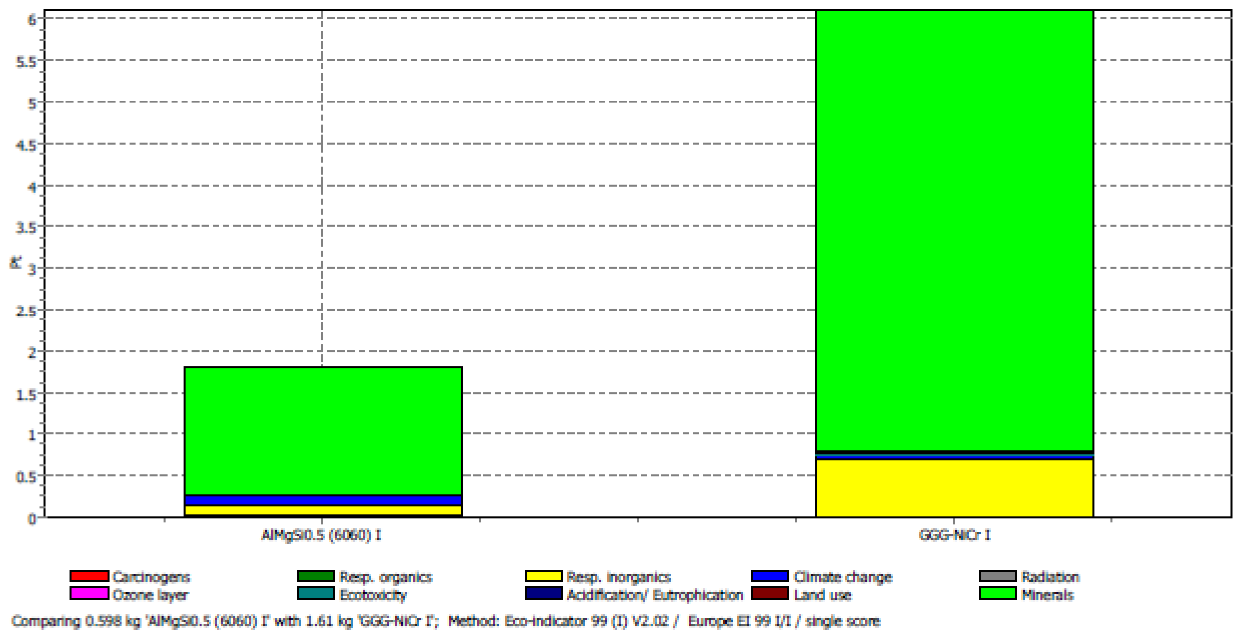


Figure 43: Single score comparison of aluminum 6060 and cast iron NiCr I

Using Figure D2 Aluminum has relative higher scores over cast iron in the categories of carcinogens, respiratory organics, climate change, ozone layer, ecotoxicity, and land use. Cast iron has relative higher scores respiratory inorganics, acidification, and minerals. Using figure D4 the breakdown of the single score that the minerals category contributes most to the score. Cast iron has a point value of 6.1 compared to the point value of 1.8 for aluminum 6060. The results show that Aluminum 6060 over the lifetime of the component will have less of an environmental impact than the identical component made out of cast iron.

Acetone Dish

The volume of material required to produce the Acetone dish is 4.06*10^-5 m^3. The selected material for the acetone dish, stainless steel AISI 405, is compared to stainless steel martensitic 410 to determine if one material will have less environment impact than another. Using the density of the stainless steels 0.3178 kg of 405 was compared to 0.3189 kg of martensitic 410.

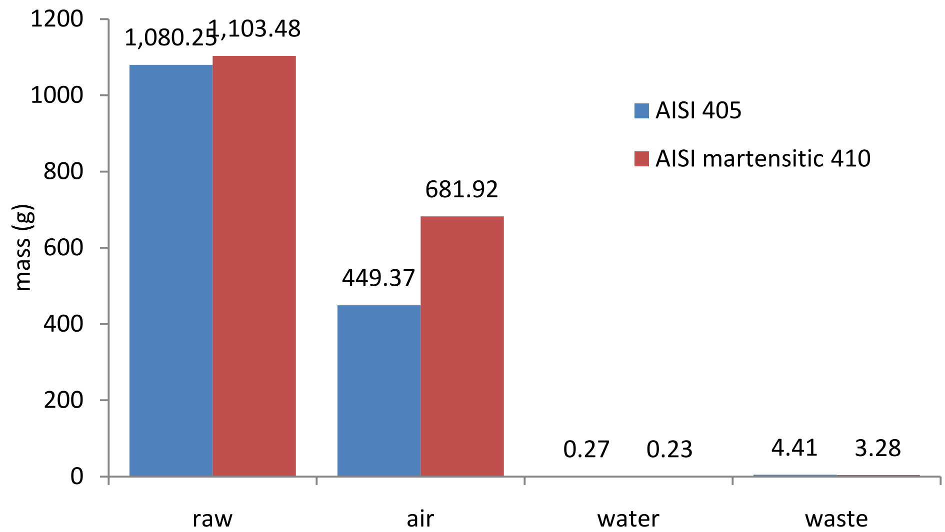


Figure 44: Total emissions broken down into raw material, air emissions, water emissions, and waste for stainless steels 405 and martensitic 410

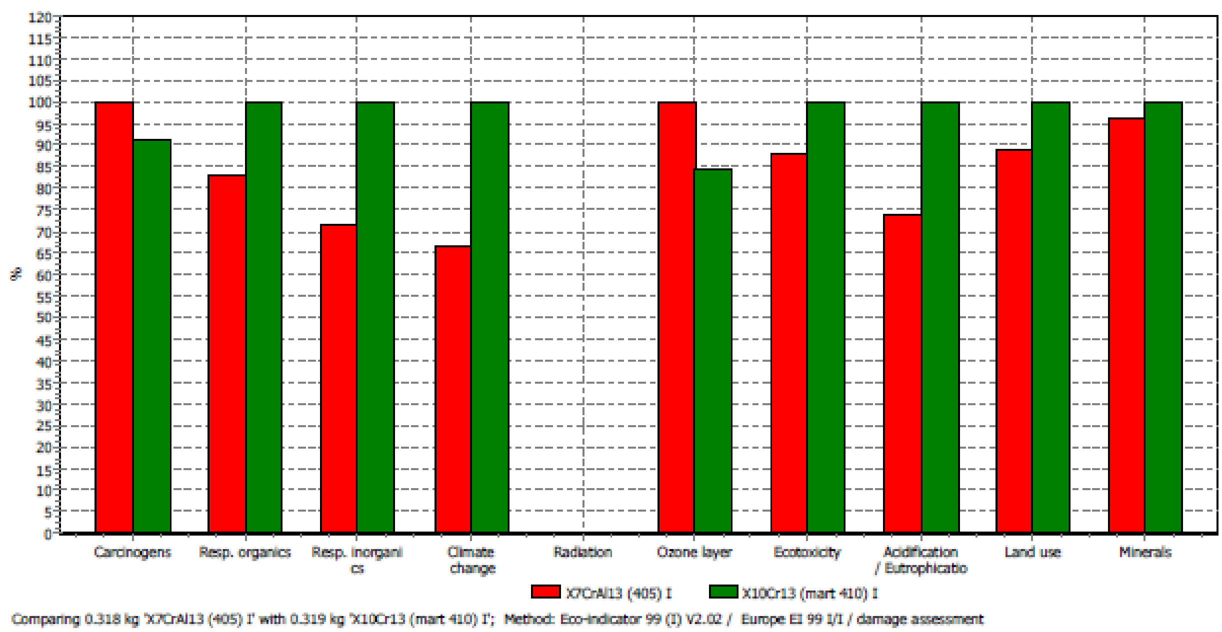


Figure 45: Relative environmental impacts of stainless steels 405 and martensitic 410

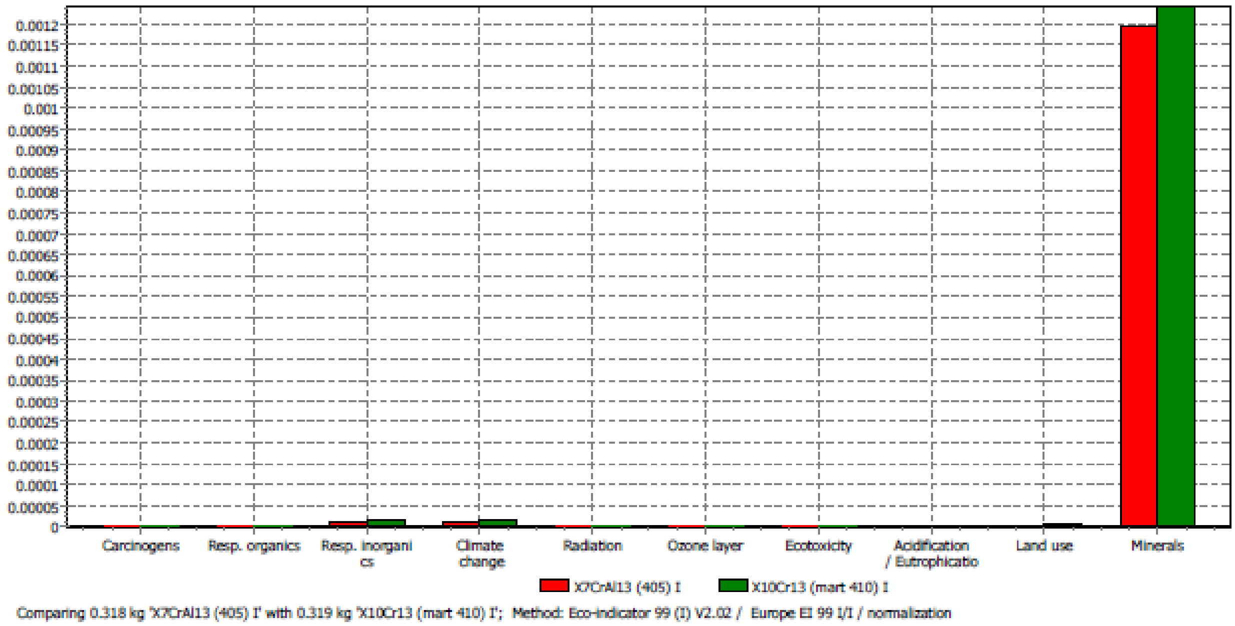


Figure 46: Normalized score of stainless steels 405 and martensitic 410

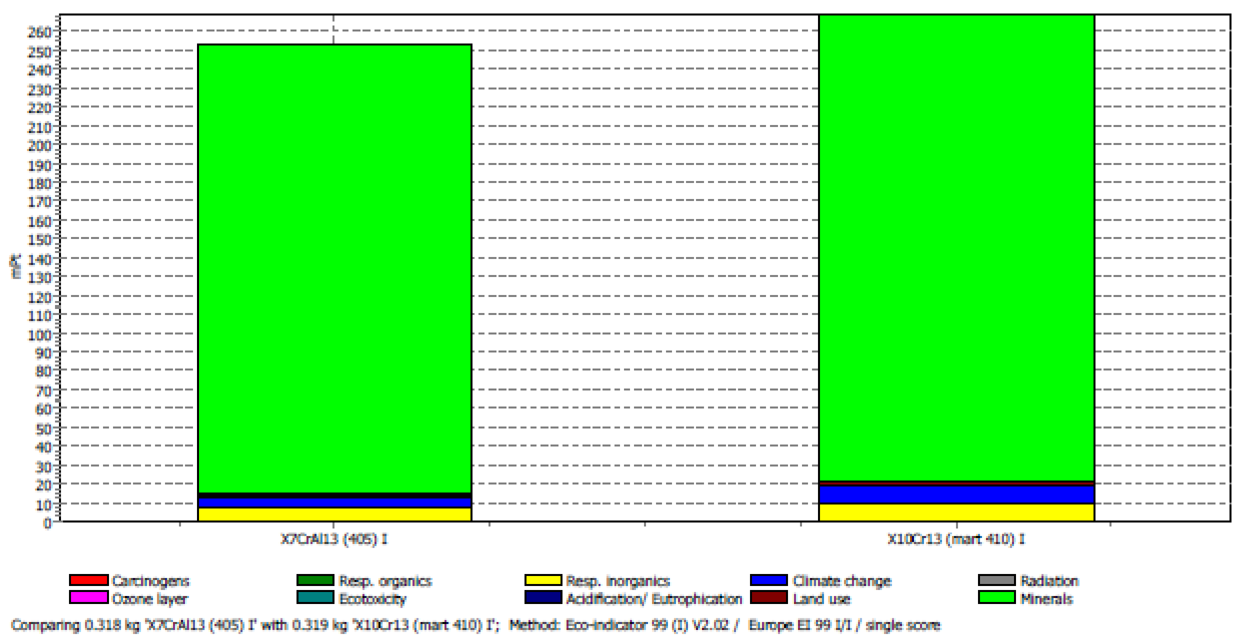


Figure 47: Single score comparison of stainless steels 405 and martensitic 410

Shown in figure D5 both stainless steels have approximately the same mass of raw material while martensitic 410 has 230 grams more of air pollutants. Martensitic 410 has a relative higher score in respiratory organics, respiratory inorganics, climate change, ecotoxicity, acidification, land use, and minerals. 405 has higher relative scores in carcinogens and ozone layer. Based on the normalized scores shown in figure D7 the biggest environmental damage occurs to resources.

Environment Impact of Final Product

By combining the scores of the aluminum 6060 and stainless steel 405 used in the final product it is clear that the aluminum 6060 will have a larger environmental impact. This is shown by the single score of aluminum of 1.8 points while the score of stainless steel is 0.25 pts. Stainless steel does however have a larger amount of raw material of 1080 g compared to 912 g of raw material in aluminum 6060. For both The resources damage category is the most important due to the fact that both aluminum and stainless steel have the highest scores in the minerals category.

MANUFACTURING PROCESS SELECTION

The purpose of our project is to aid in the research of metalworking fluids. Because of this, we estimate that the production volume would only be around 100 units. This is a very low production volume, so when determining which processes to use to manufacture the product, capital investment must be very low. The time it takes to manufacture each unit is not as important because with low production volumes it is usually the capital investment that dominates the cost of each unit.

We have determined with the aid of the Cambridge Engineering Software that it would be most advantageous the motor mounts be produced using 6061 aluminum as discussed above. We have also determined that the solvent reservoir would best be made with AISI 405 stainless steel.

We have decided that it would be most cost effective for all aluminum parts to be created through CNC milling. None of the components are that large, so a relatively small mill machine would be all that is required. 6060 aluminum also does not require a lot of energy to machine with respect to material removed as shown by Figure D9. Once the initial CAM files have been created, the raw material would just have to be loaded into the machine and started by the operator. A high labor commitment is not necessary, and so lower labor costs would be achieved.

For the solvent reservoir created from AISI 405 stainless steel, we have determined that sand casting would be the best way to produce this. Due to the low production volume and relatively cheap cost of sand patterns, the sand casting process would be cheaper than the alternatives. No large machines would be needed since the metal simply needs to be melted and poured into the pattern until it solidifies. It would probably, though, be more cost effective to buy a reservoir, such as a tin can, from an outside party rather than manufacturing them from a primary source.

There are no special steps needed in manufacturing these components such as heat treatment, coatings, etc, nor are any of the mechanical components put under a large amount of stress. Because of these circumstances, the above discussed manufacturing processes would be the most ideal way to create the components.

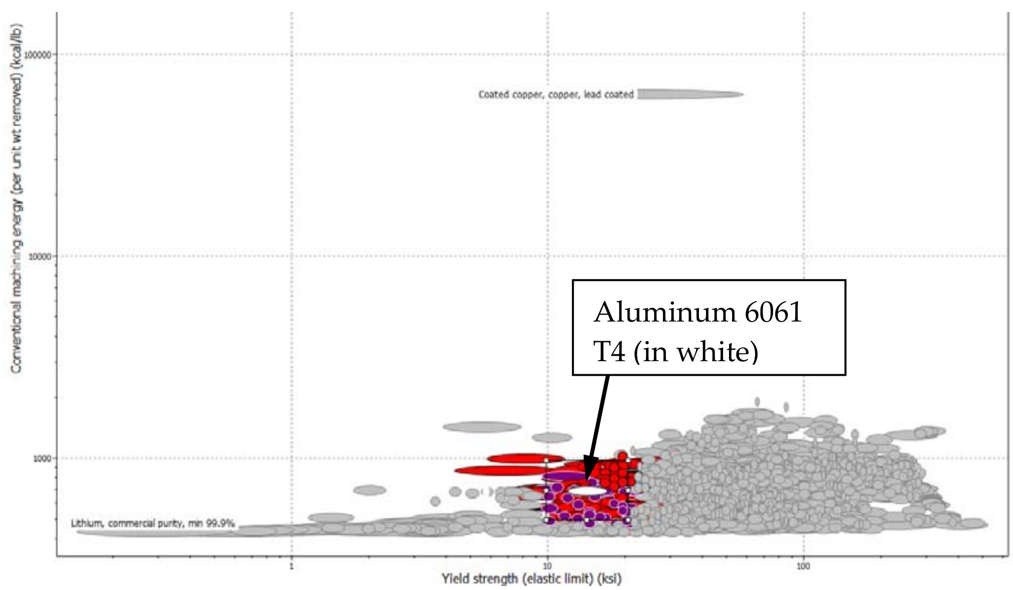


Figure 48: Aluminum 6060 requires a relatively low amount of energy to machine

APPENDIX D: STEP SIZE CALCULATION

Denote the thread size of lead screw to be *X* inch/rev, the step size of a stepper motor to be *Y* 1 rev/step, and the minimum micro-step coefficient to be *N* micro-step/step.

For current system, X=0.1 in/thread=0.1 inch/rev; a typical step size of stepper motor is Y= 1 rev/200 step. So the movement of the table per step, D, can be calculated by Eq. X

$$D = X \cdot Y = 5 \times 10^{-4} \ \frac{in}{step} \qquad \text{Eq. C. 1}$$

The required resolution R=0.6$\mu m = 2.36 \times 10^{-5} \ in$. So the minimum micro step coefficient N can be calculated by,

$$R \geq \frac{D}{N} \qquad \text{Eq. C. 2}$$

which gives

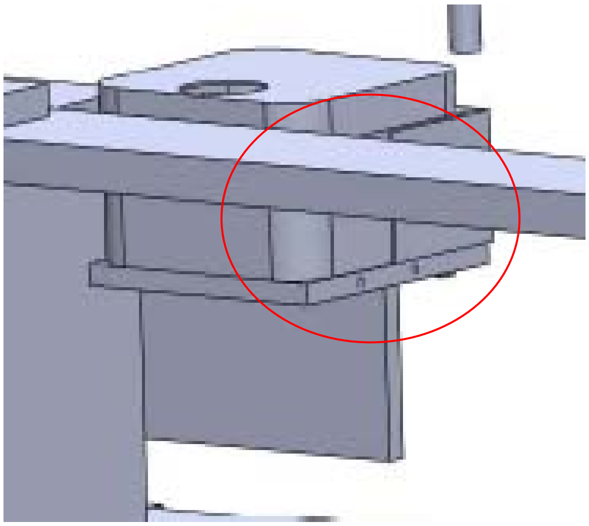
$$N \geq \frac{D}{R} = 23.6 \ Micro - \frac{step}{step} \qquad \text{Eq. C. 3}$$

APPENDIX E: ENGINEERING CHANGES

Change #1

The strike plate was removed to allow for supercritical of the holes in close proximity to the cleaning station. The super critical CO2 delivery hinged plate would hit the strike plate before reaching the holes immediately in front of the cleaning staion.

IS: WAS:



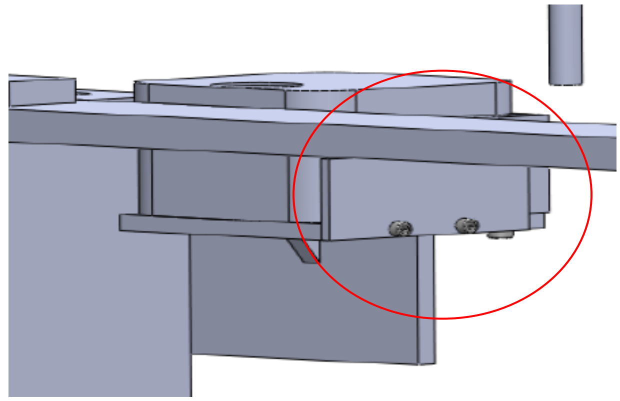


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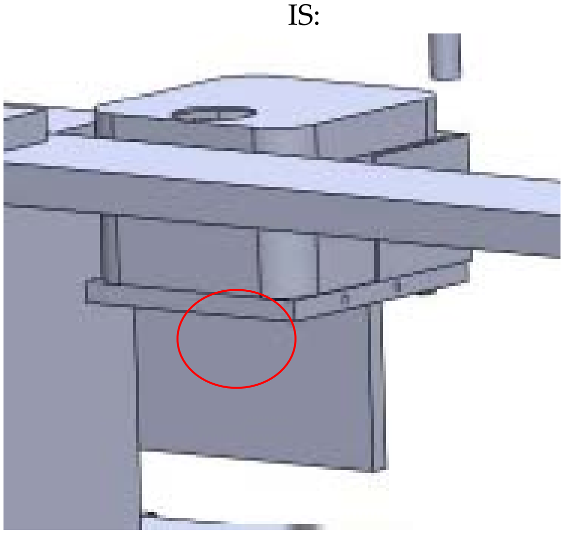
Figure 49: Removal of the strike plate

Change #2

The gusset on the cleaning station mounting bracket was removed to allow for supercritical CO2 delivery of the holes in close proximity to the cleaning station. The gusset was removed because it was causing more interference with the supercritical CO_2 delivery system than the benefit of additional support.

IS: WAS:



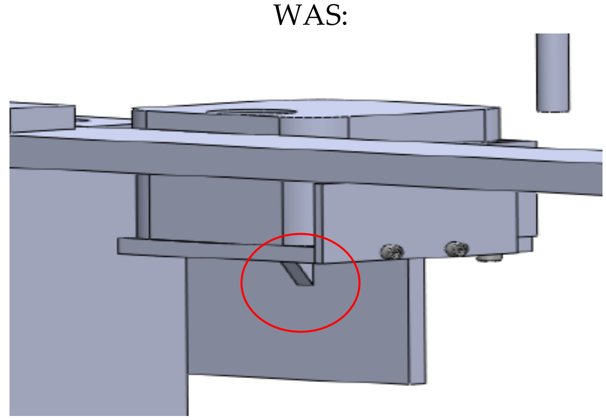


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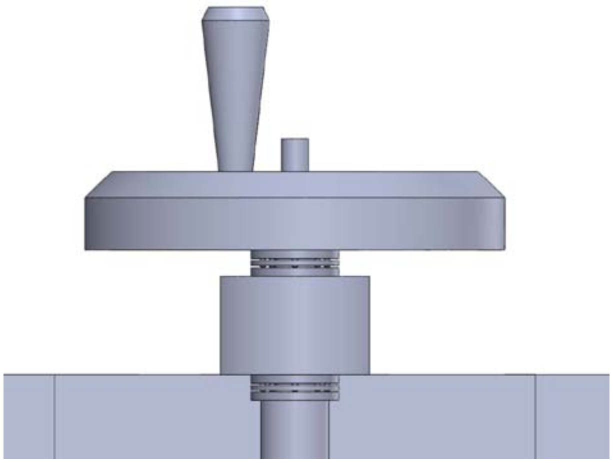
Figure 50: removal of gusset from the cleaning station

Change #3

The ACME nut and Belleville was not installed because of the high price of the ACME nut. The addition of the Belleville washer and ACME nut would have been ineffective as the handle acts as the nut and tightens the assembly down against the bracket to prevent backlash

IS:



WAS:

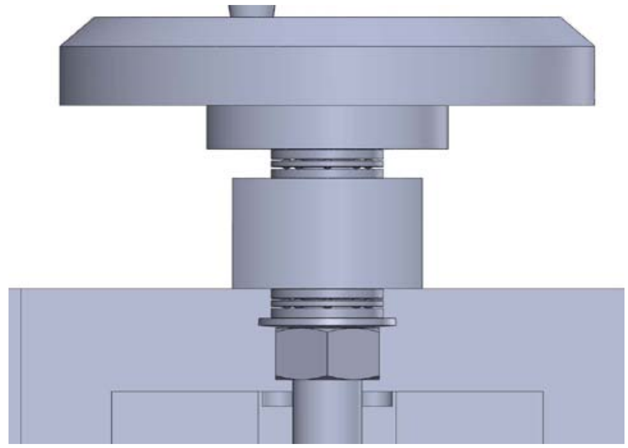


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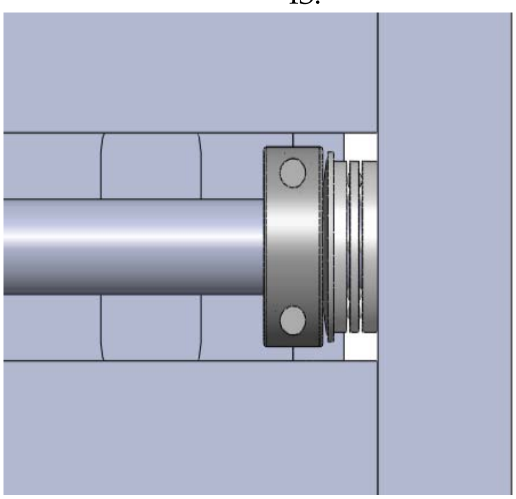
Figure 51: revised backlash removal in X-axis

Change #4

Shaft collar is used in place of the ACME nut. For the Y axis a shaft collar is used in place of the ACME nut due to the high cost of the Acme nut.

IS:



WAS:

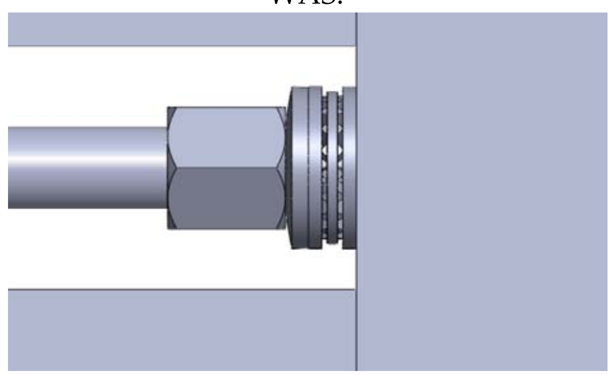


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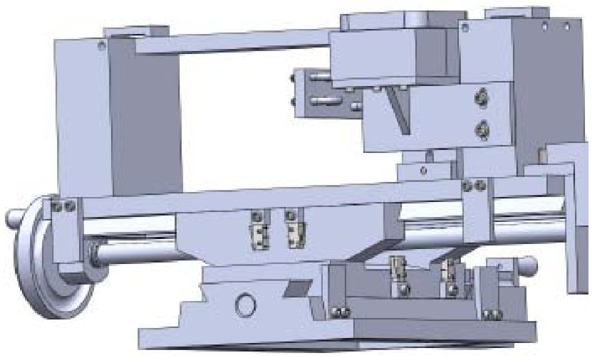
Figure 52: revised backlash removal in Y-axis

Change #5

Limit switches and mechanical stops were installed to prevent damage to the system. This prevents the table from moving to far in the X or Y direction which could ruin the motor mounts

IS:



WAS:

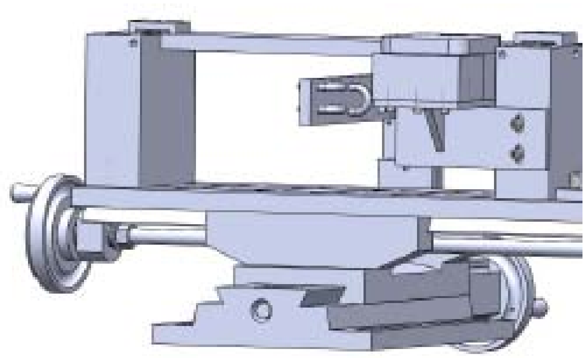


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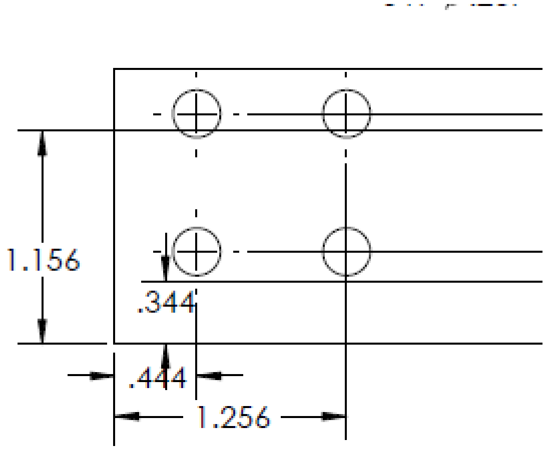
Figure 53: Additon of limit switches

Change #6

The hinge plate of the supercritical CO_2 delivery system was shortened to prevent interference with the cleaning station.

IS:



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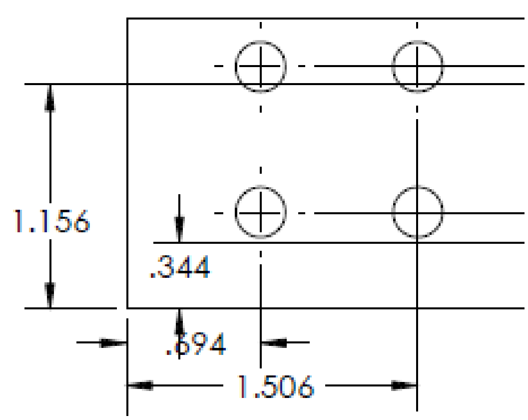

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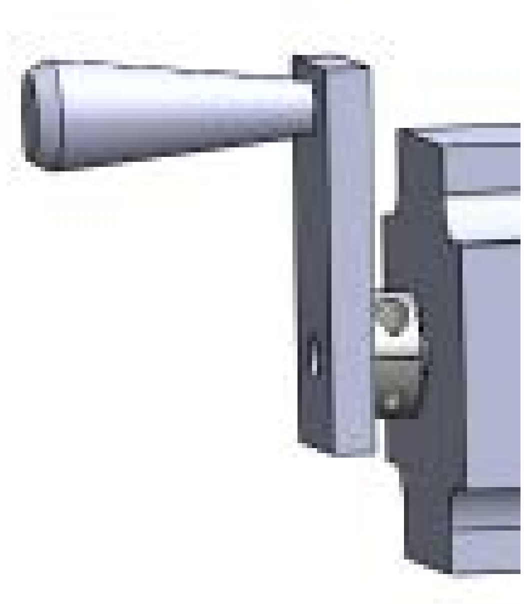
Figure 54: Shortening of CO2 plate 3 by 1/4"

Change #7

The Y- axis handle was changed from one of the original handles to one that is a plate with a shaft collar welded to it. This change was made because the diameter of the original handle was too large to fit unto the motor shaft.

IS:



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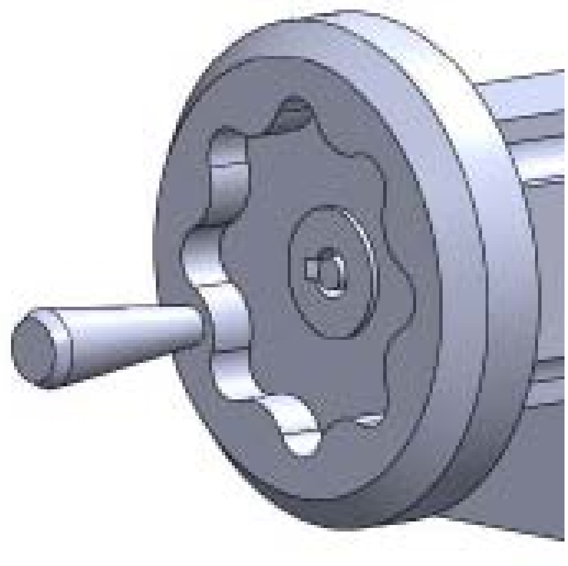

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Figure 55: Change of the handle for the Y-axis

APPENDIX F: BILL OF MATERIALS

Table 20: Bill of Materials

Quantity	Price ea.	Part #	Notes	Distibutor
1	$ 299.95	N/A	2-axis Monster CNC Stepper motor driver kit	Probotix
1	$ 149.00	N/A	Mach3- 45000Hz 6axis controller	CNC4PC
1	$ 24.95	N/A	E-Stop switch	Probotix
4	$ 1.75	N/A	Limit switches	Probotix
1	$ 7.98	N/A	Cooling fan	Newegg
1	$ 33.30	35A-AAA-DDBA-1BA	Solenoid valve	Grainger
1	$ 20.99	N/A	12 VDC power supply 1.5A	Radioshack
1	$ 6.99	N/A	12 VDC auto relay	Radioshack
1	$ 2.64	N/A	5 VDC relay	Radioshack
2	$ 2.59	N/A	6 pin female connector	Radioshack
2	$ 2.59	N/A	6 pin male connector	Radioshack
2	$ 1.99	N/A	2 pin female connector	Radioshack
2	$ 1.99	N/A	2 pin male connector	Radioshack
1	$ 3.49	N/A	Fuse block	Radioshack
1	$ 3.49	N/A	Solder	Radioshack
1	$ 5.97	94135k23	Extension spring pack of 3	McMaster
2	$ 3.21	6655K350	3/8" thrust bearing	McMaster
1	$ 4.62	9712K438	1/2" Belleville washer pack 12	McMaster
1	$ 9.35	99129A325	Hex nut pack 5	McMaster
4	$ 0.66	3201T28	U bolt	McMaster
2	$ 25.66	8975K565	Aluminum 2"x4"x6"	McMaster
1	$ 16.67	8975K371	Aluminum 3/8"x8"x12"	McMaster
1	$ 16.38	9246K11	Aluminum 1/4"x6"x8"	McMaster
1	$ 4.34	7451T19	Brass wire brush	McMaster
2	$ 20.07	61005K311	1/4" shaft coupler	McMaster
1	$ 46.89	33345K9	Flexible blowoff nozzles mag. base	McMaster
4	$ 0.13	91251A540	SHCS 1/4"-20 x 3/4" pack 100	McMaster
5	$ 0.12	91251A196	SHCS #8-32 x 5/8" pack 100	McMaster
8	$ 0.01	91251A242	SHCS #10-24 x 1/2" pack 100	McMaster
4	$ 0.18	91253A540	FHSCS 1/4"-20 x 3/4" pack 50	McMaster
1	$ 0.12	91251A537	SHCS 1/4"-20 x 1/2" pack 100	McMaster
2	$ 0.11	91251A245	SHCS #10-24 x 3/4" pack 100	McMaster
2	$ 0.51	91251A711	SHCS 1/2"-13 x 1" pack 10	McMaster
12	$ 0.10	91251A242	SHCS #10-24 x 1/2" pack 100	McMaster
8	$ 0.10	91251A081	SHCS #2-56 x 1/2" pack 100	McMaster

1	$ 1.75	5047K17	3/8" Tube ID x 1/4" NPT Male pipe fitting adapter	McMaster
1	$ 8.47	5111K308	1/4" Tube OD x 1/4" NPT Male push to connect	McMaster
4	$ 2.31	5111K81	1/4" Tube OD x 1/8" NPT Male push to connect	McMaster
1	$ 2.31	5111K82	1/4" Tube OD x 1/4" NPT Male push to connect	McMaster
1	$ 2.23	4596K51	1/4" pipe coupling	McMaster
1	$ 3.41	51115K2	6mm Tube OD, M5x.8 Male pipe push to connect	McMaster
1	$ 3.50	6436K12	2-piece clamp on shaft collar 1/4" bore	McMaster
2	$ 3.66	6436K15	2-piece clamp on shaft collar 5/8" bore	McMaster
1	$ 10.32	91251A732	SHCS 1/2"-13 x 5"	McMaster
1	$ 6.49	92012A211	Shoulder screw 3/16" x 1-1/2" 8-32	McMaster
3	$ 3.63	6655K18	Thrust bearing 5/8" shaft diameter	McMaster
1	$ 5.83	9712K82	Belleville disc spring .630" ID	McMaster
10	$ 0.91	N/A	Tin can 3.1"x 2"	Specialty Bottle
10	$ 0.12	N/A	3/8" ID air tubing	Stadium Hardware
1	$ 0.79	N/A	1/4" OD air tubing	Stadium Hardware
1	$ 26.07	N/A	Electrical box	Home Depot
1	$ 1.77	N/A	1.5 amp fuses	Home Depot
1	$ 1.77	N/A	3 amp fuses	Home Depot
1	$ 8.47	N/A	Power cord	Home Depot
2	$ 3.22	N/A	Cord connector	Lowes
12	$ 1.27	N/A	Rubber grommets	Lowes

APPENDIX G: ENGINEERING DRAWINGS

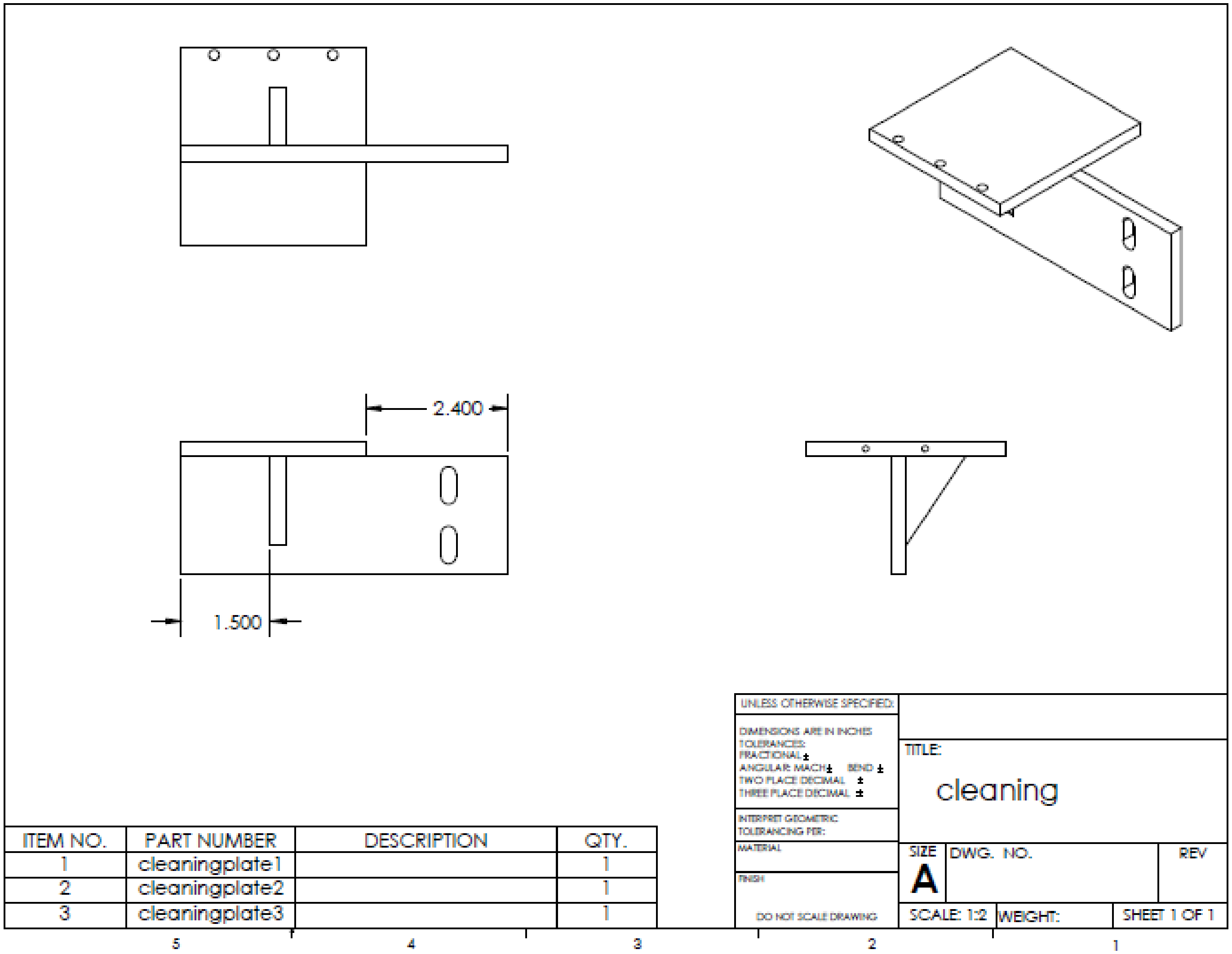


Figure 56: engineering drawing of cleaning station mounting bracket assembly

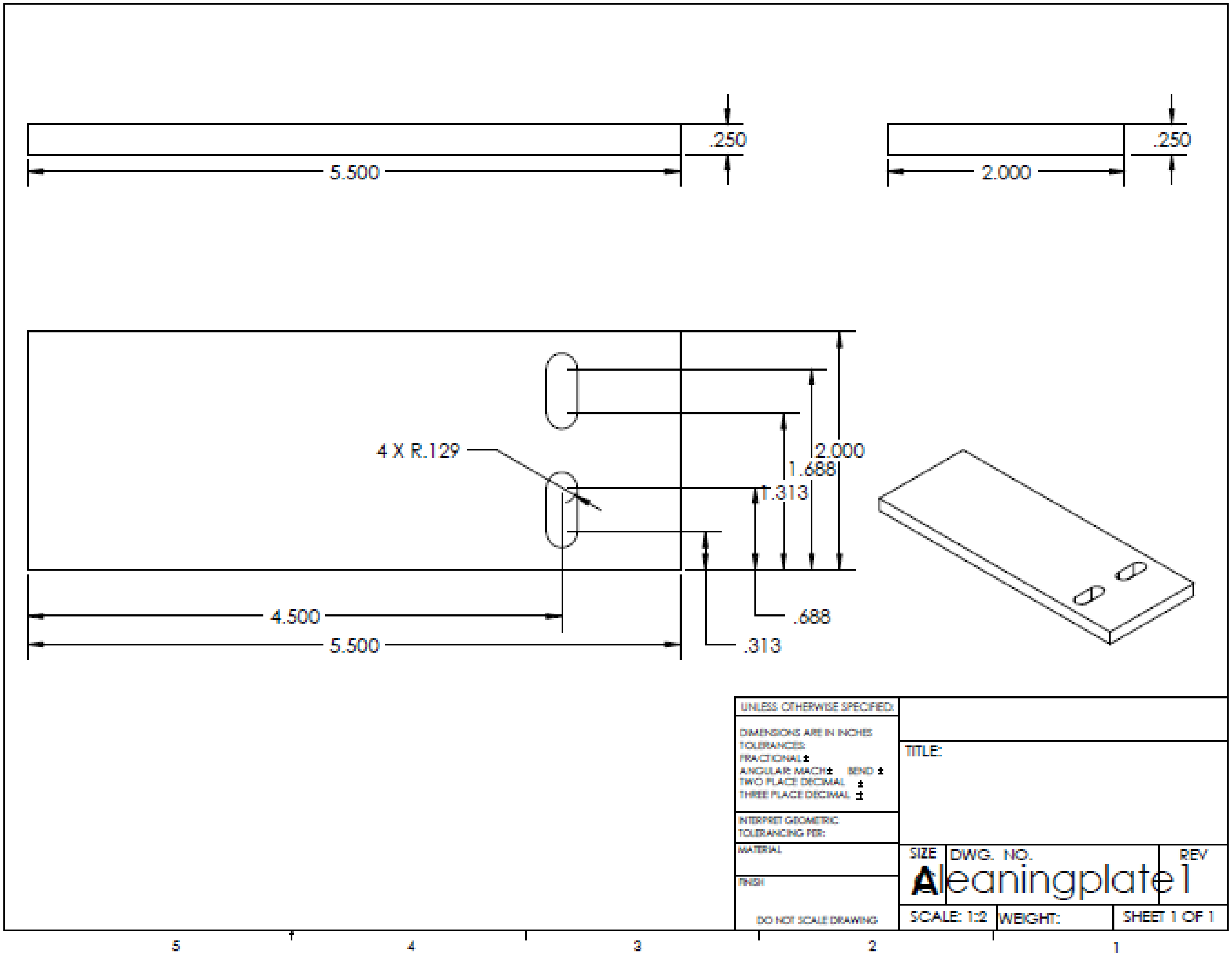


Figure 57: Engineering drawing of cleaning plate #1

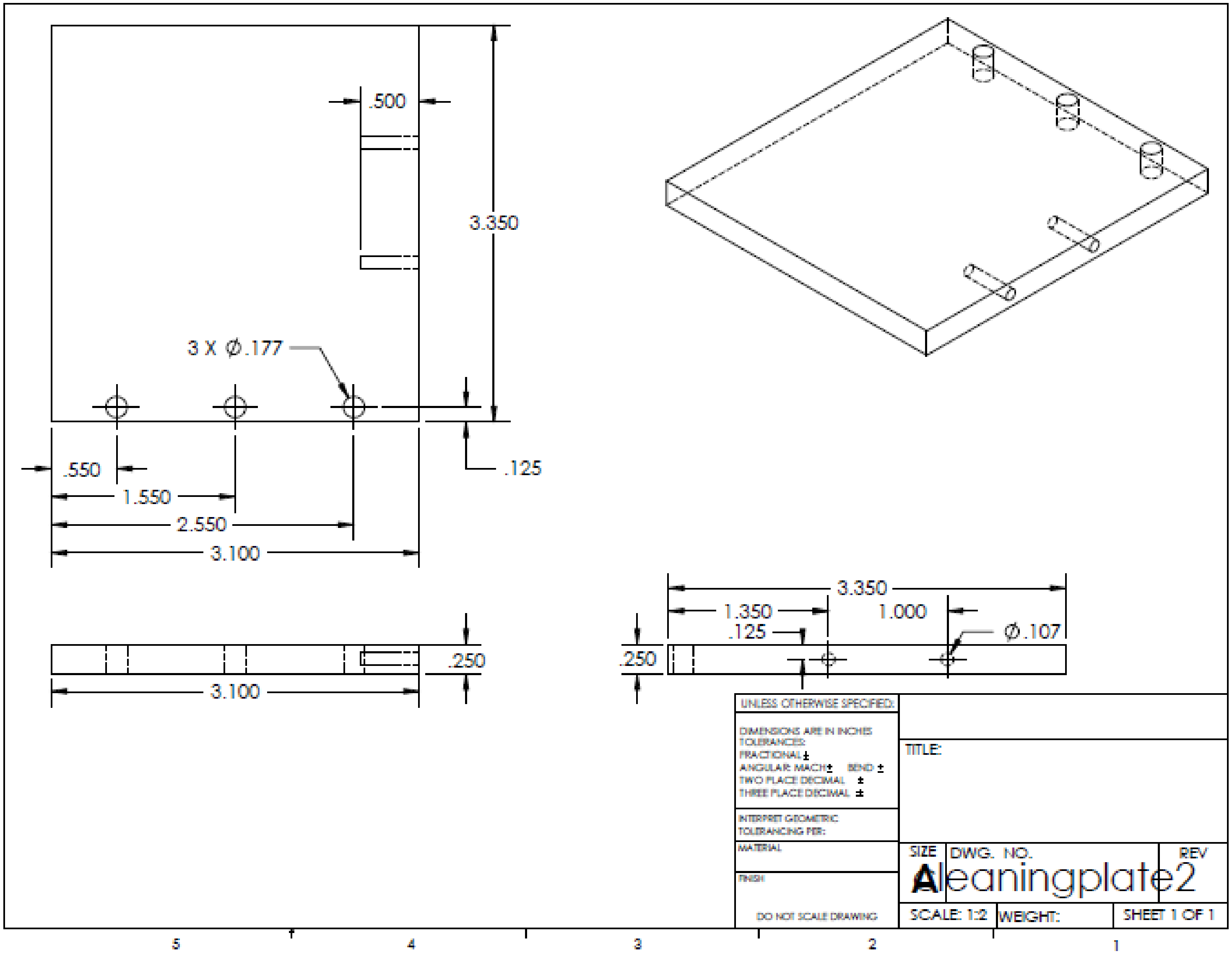


Figure 58: Engineering drawing of cleaning plate #2

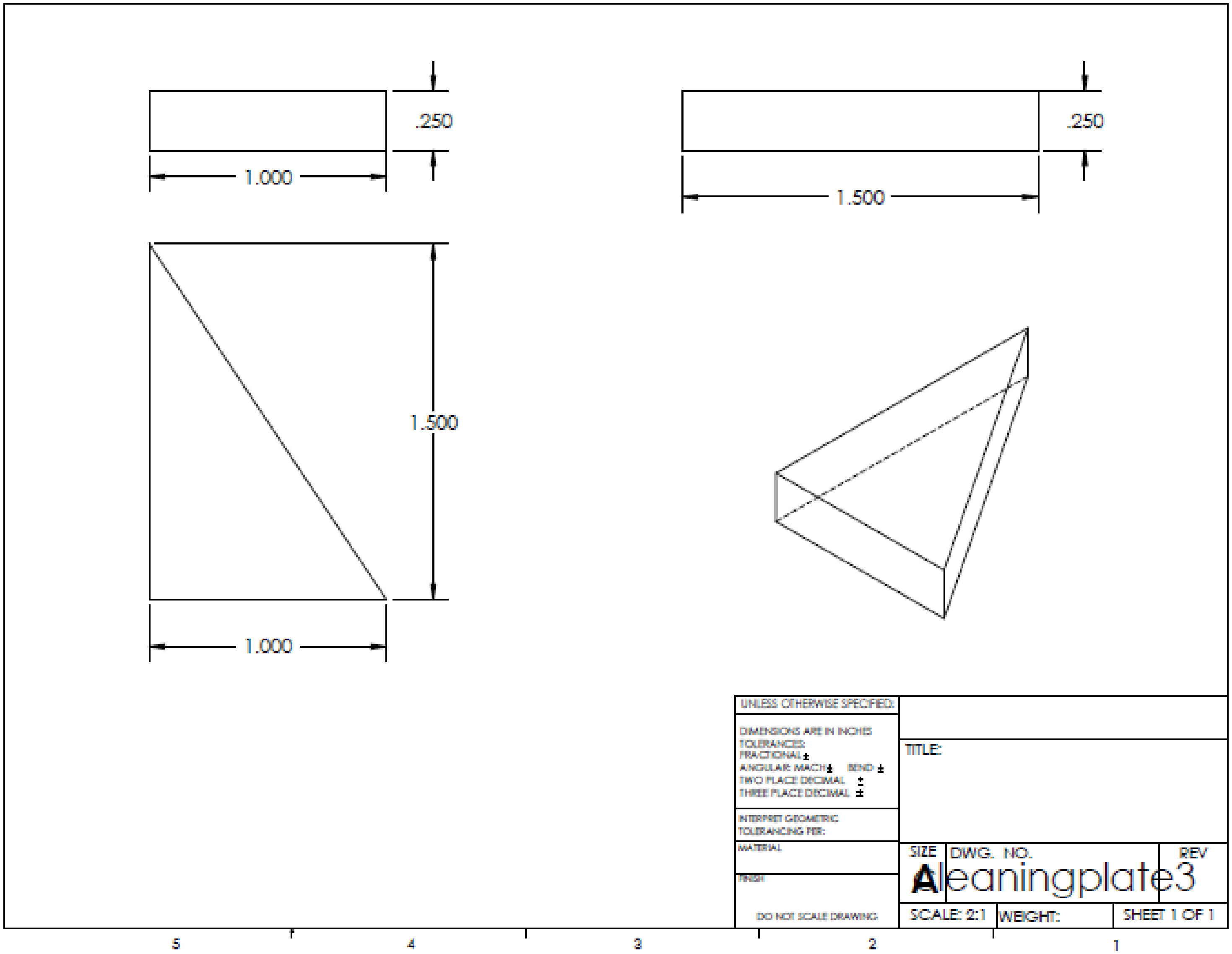


Figure 59: engineering drawing of cleaning plate #3

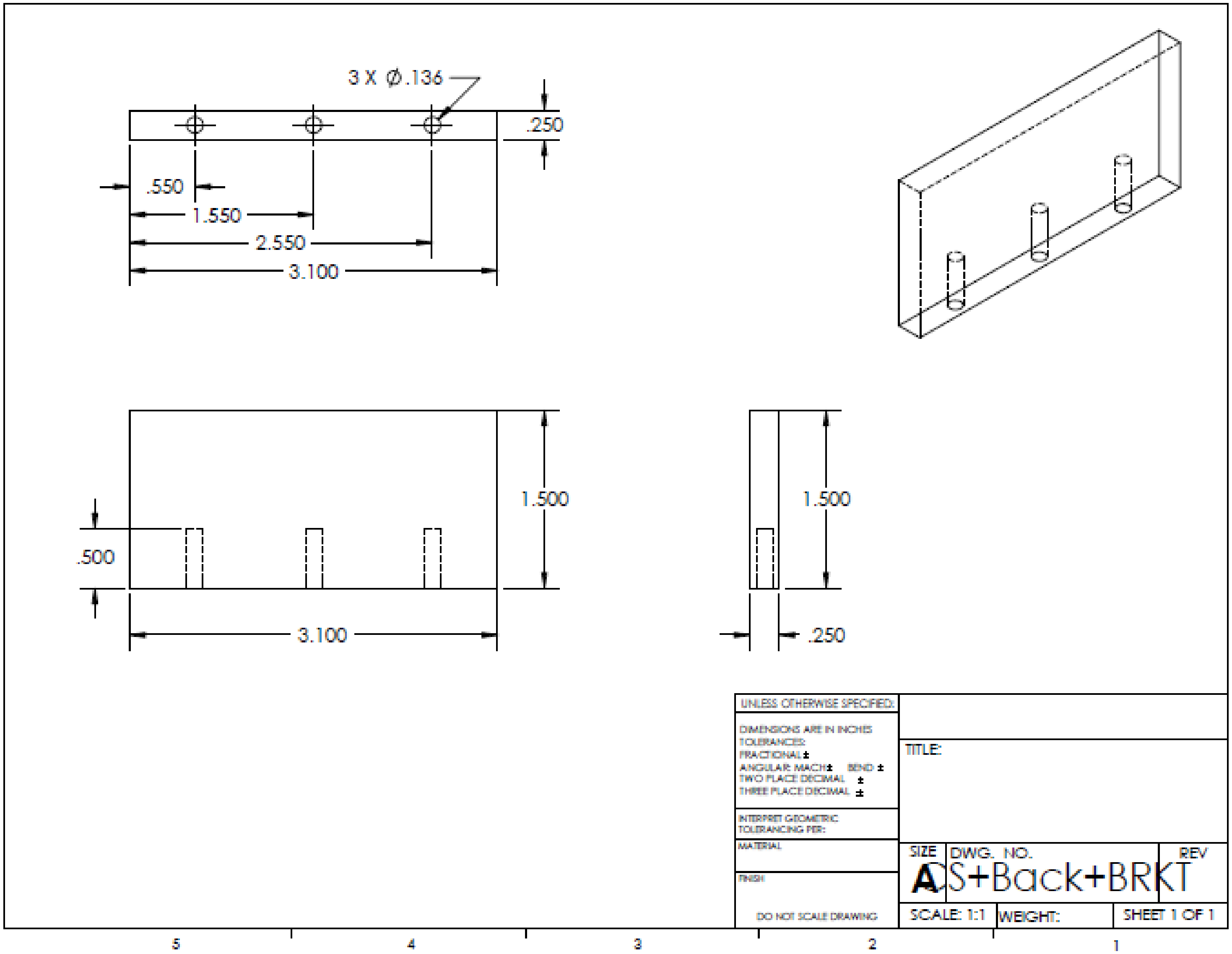


Figure 60: Engineering drawing of tin can mounting bracket

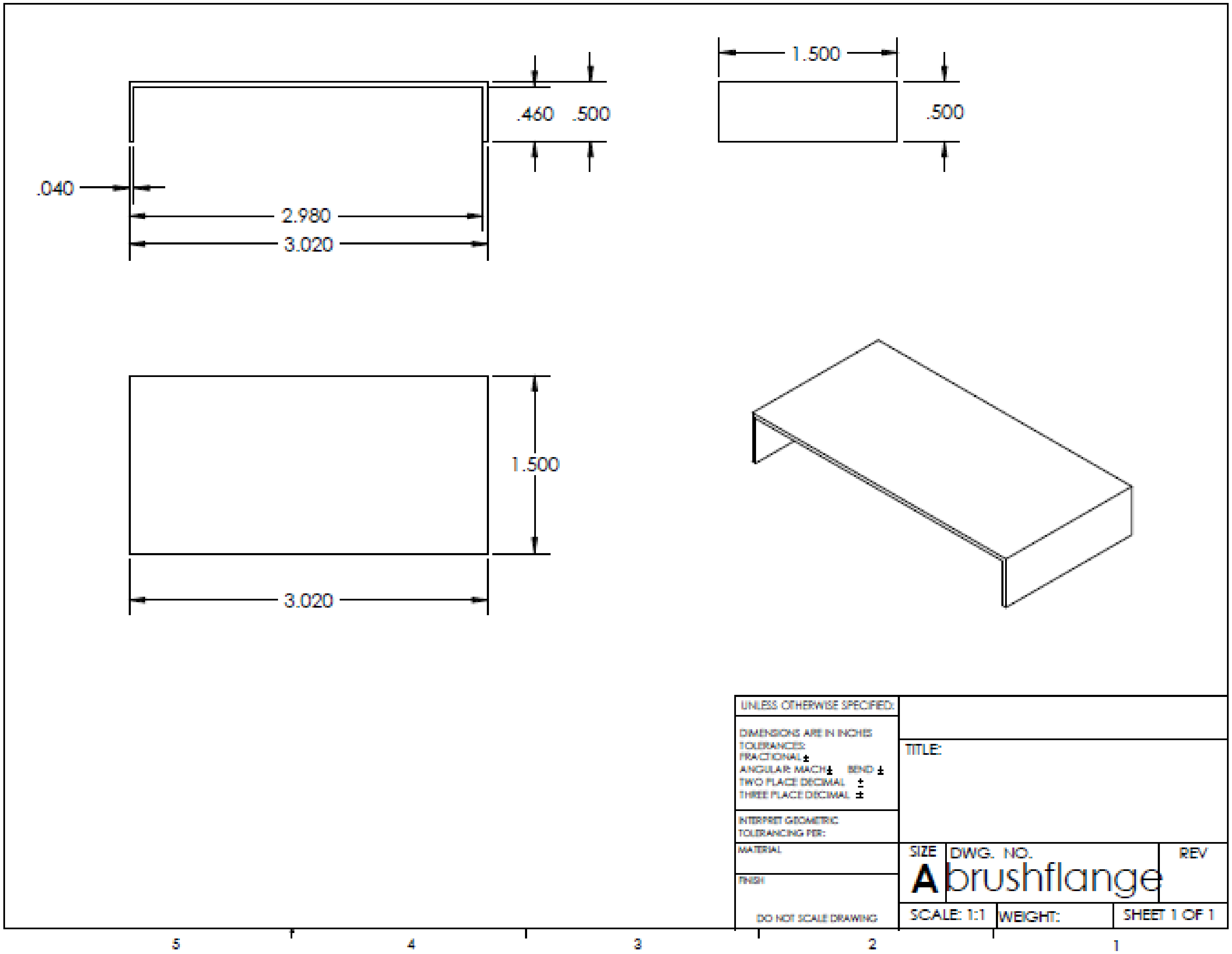


Figure 61: Engineering drawing of the brush mounting flange

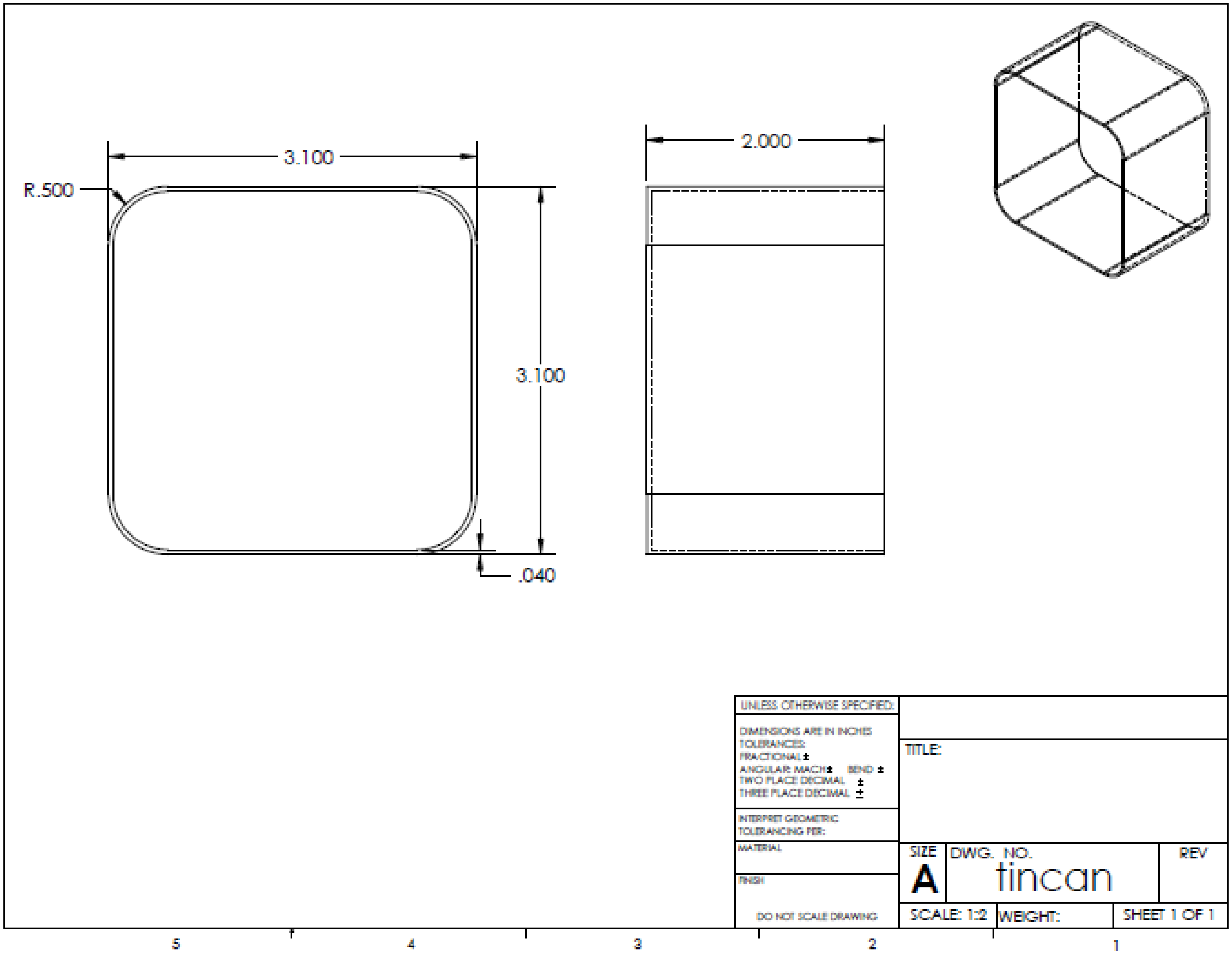


Figure 62: Engineering drawing of the purchased acetone dish

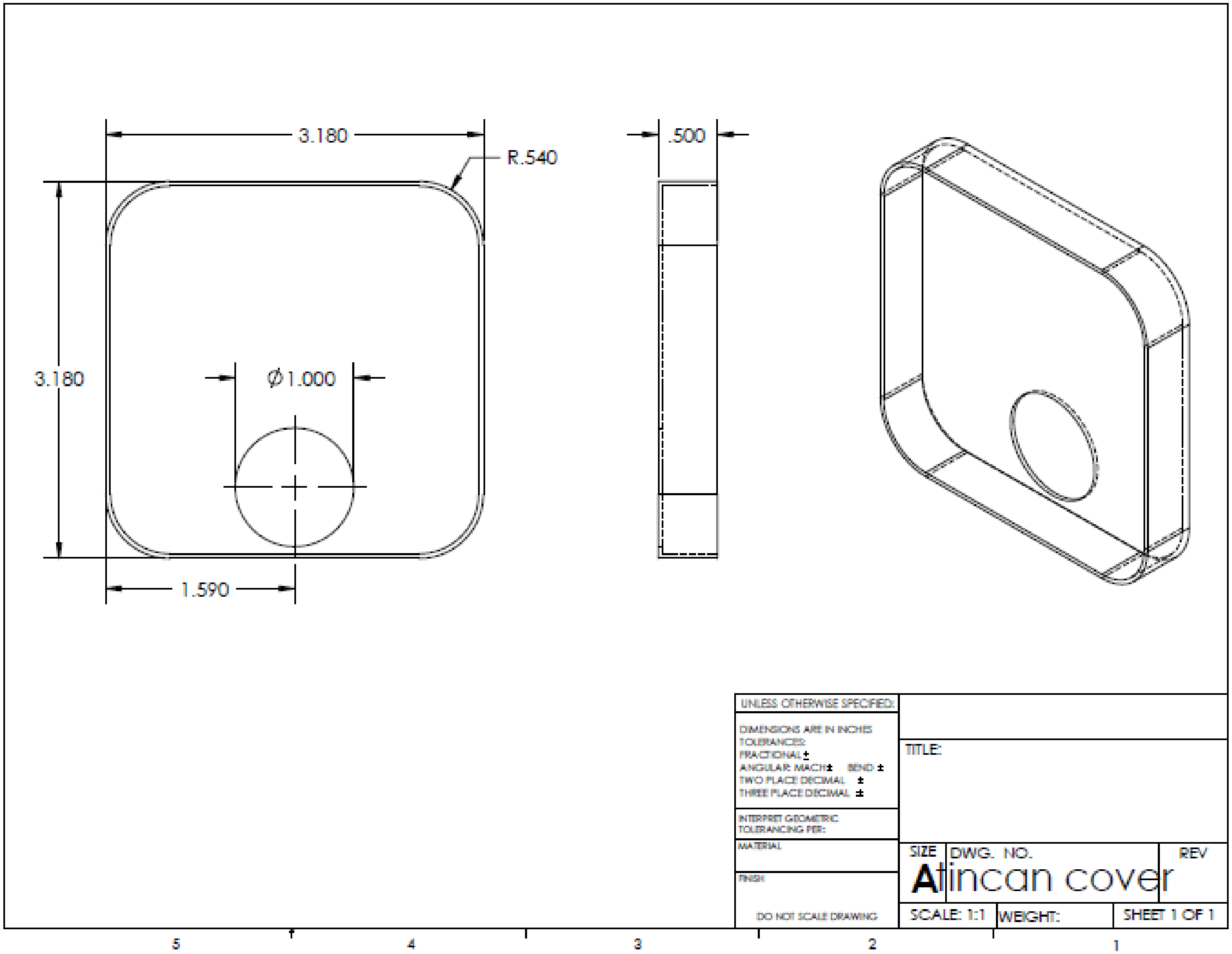


Figure 63: Engineering drawing of the acetone dish cover

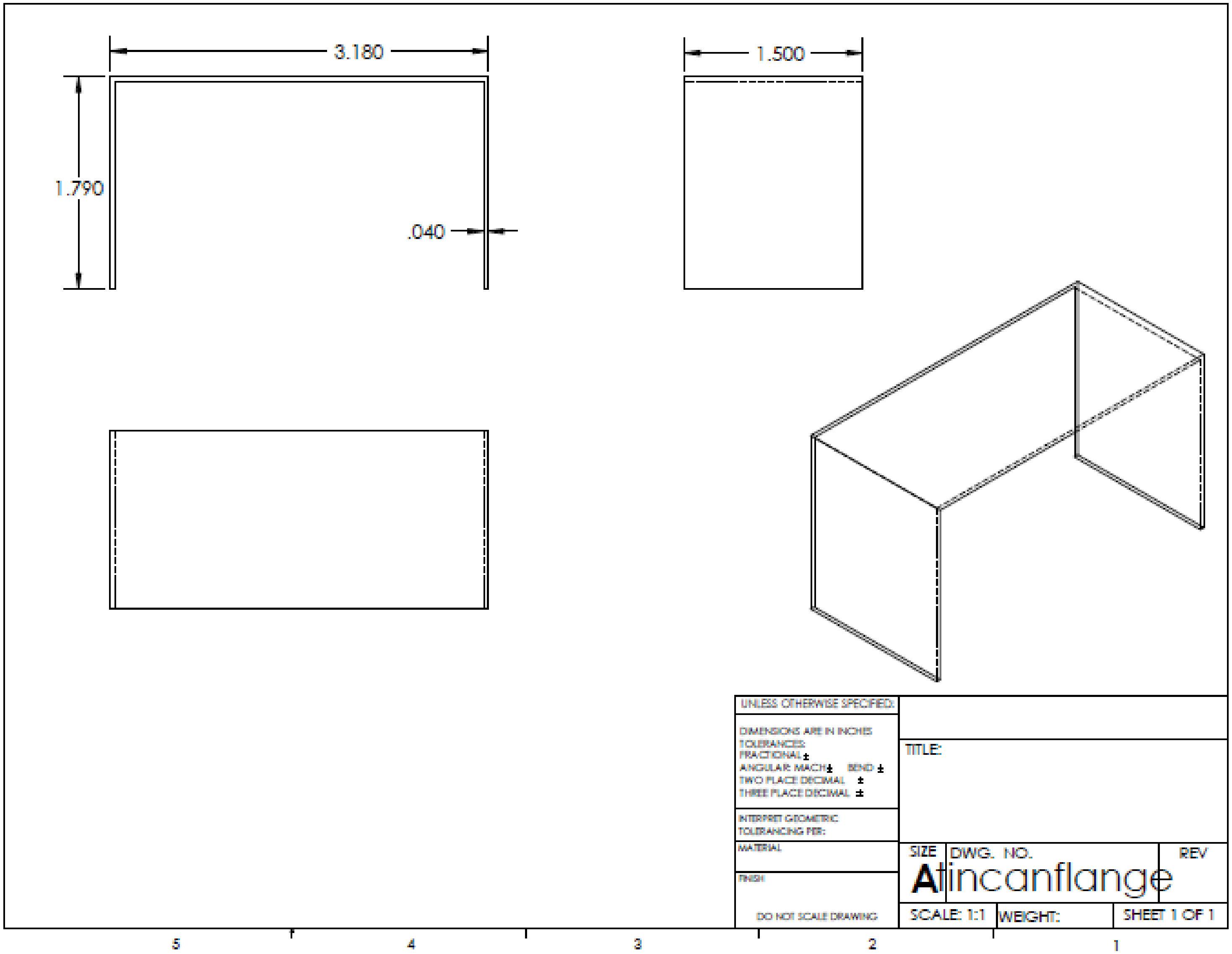


Figure 64: Engineering drawing of the acetone dish mounting flange

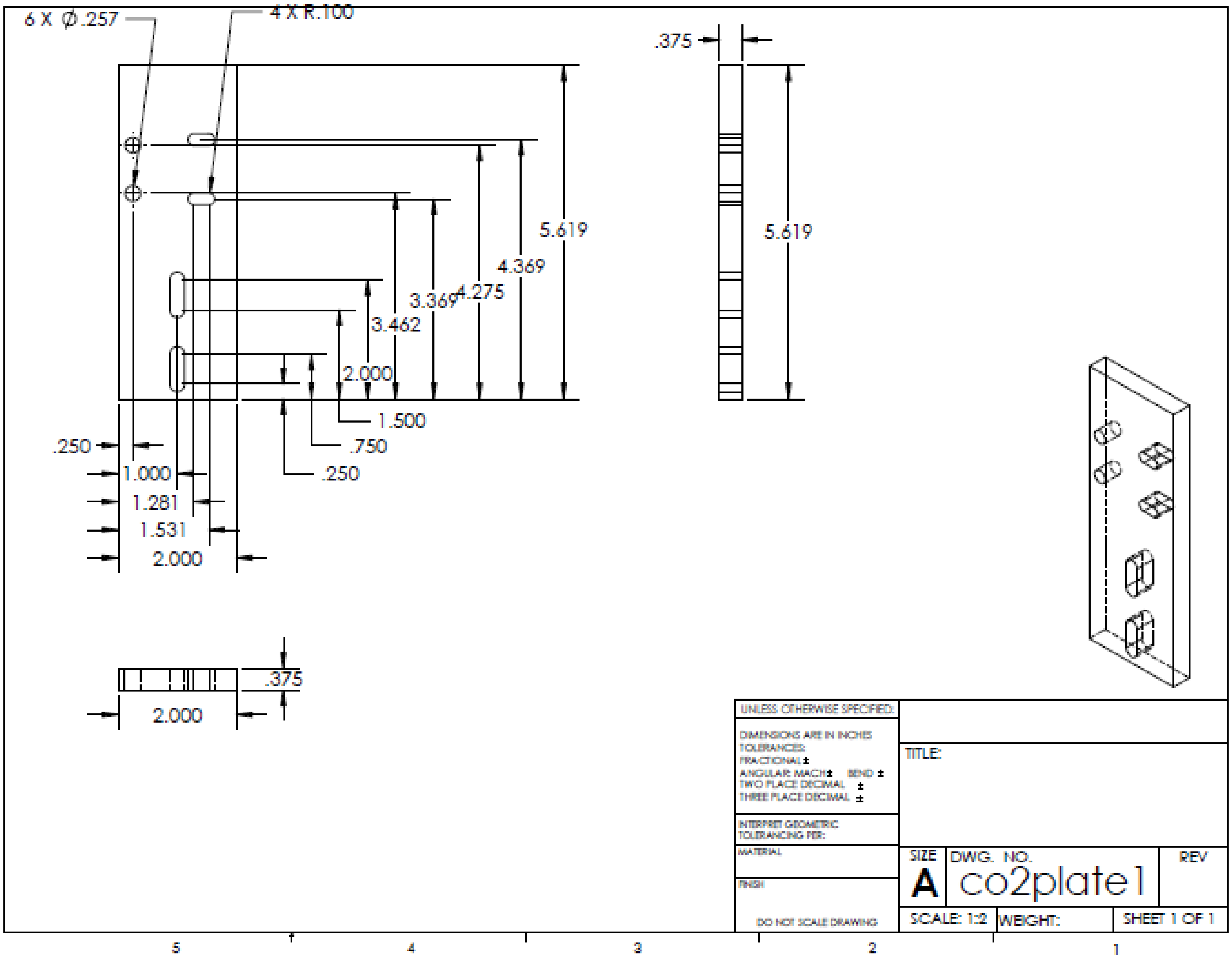


Figure 65: Engineering drawing of teh supercritical CO_2 plate #1

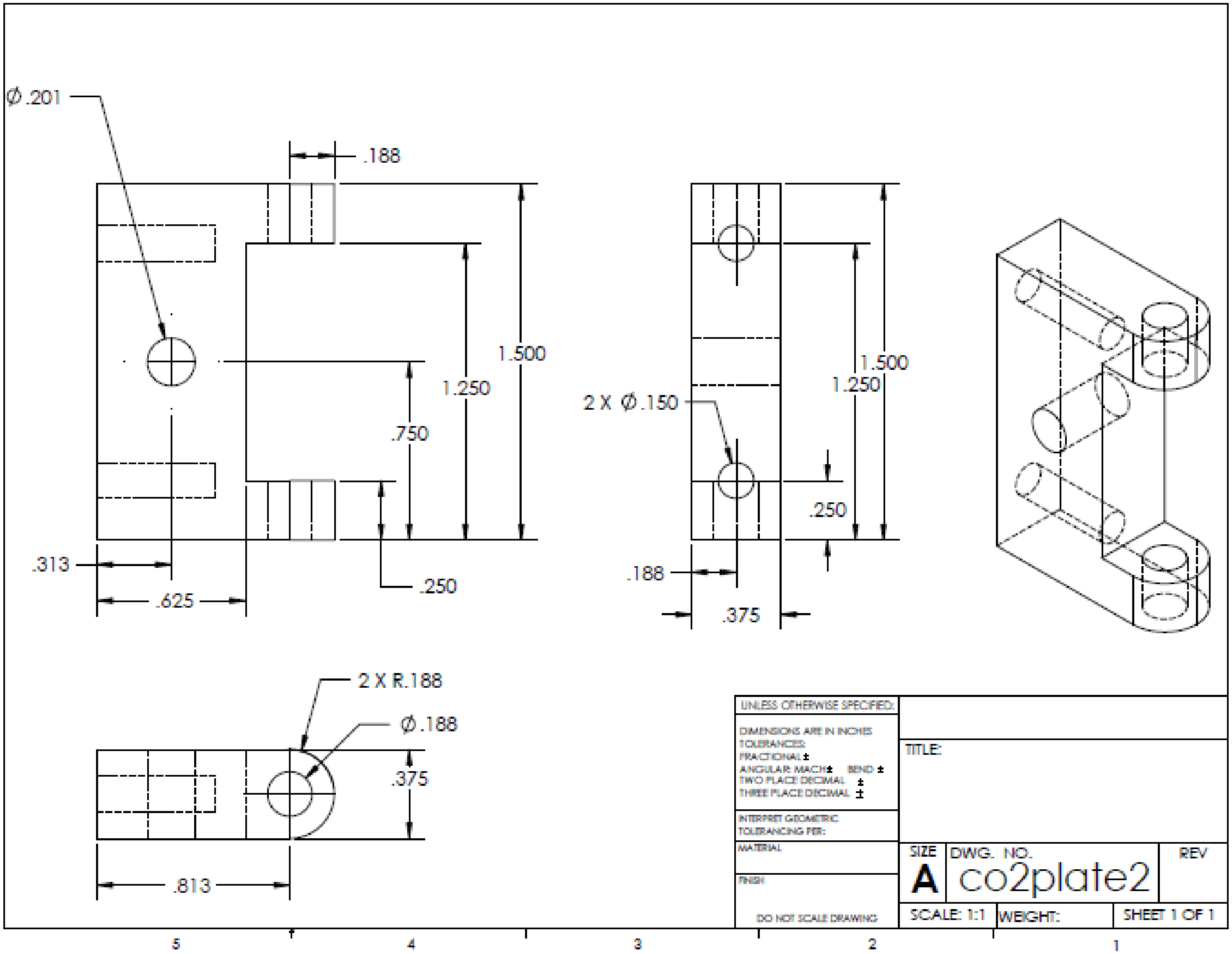


Figure 66: Engineering drawing of the supercritical CO_2 plate #2

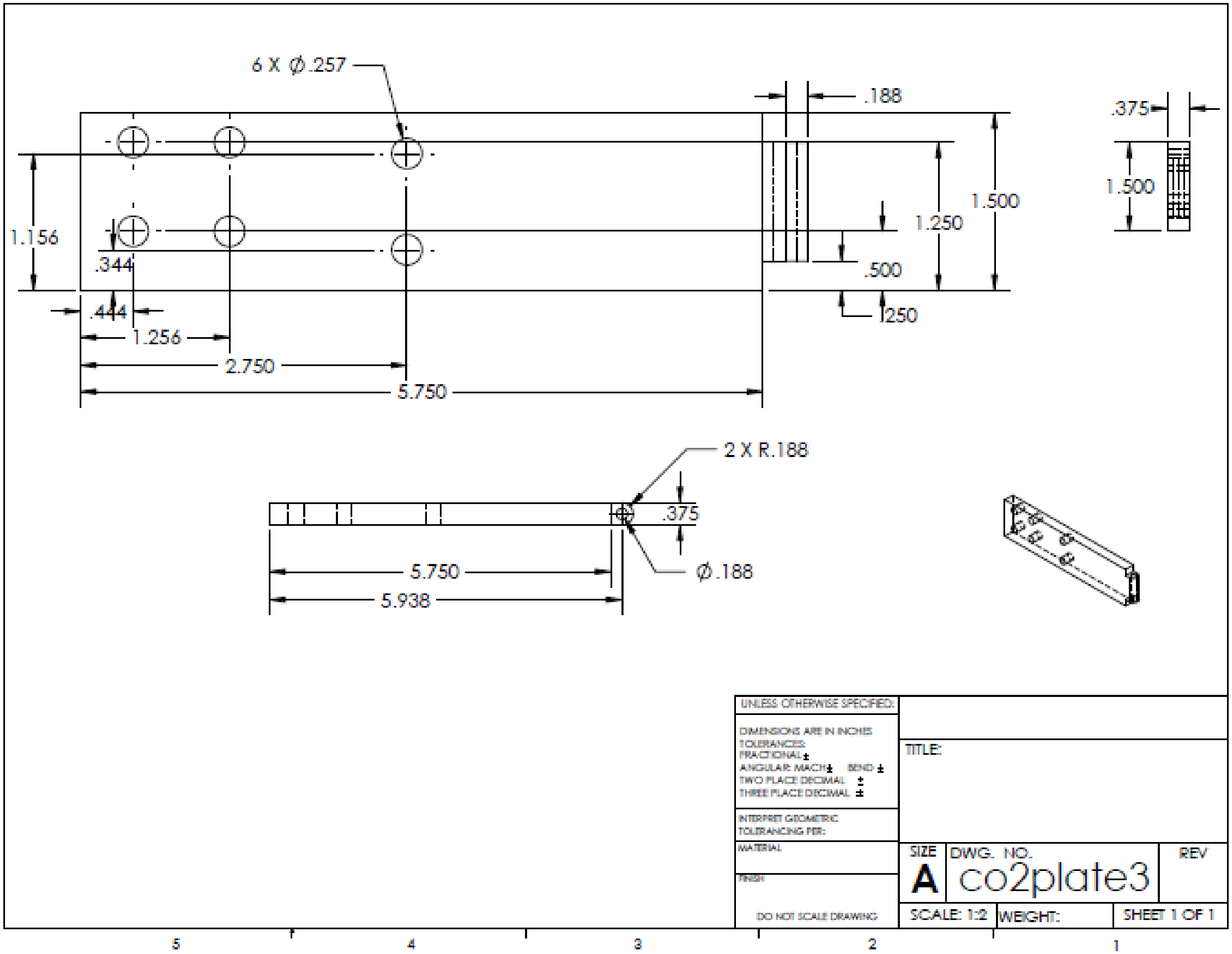


Figure 67: Engineering drawing of the supercritical CO_2 plate #3

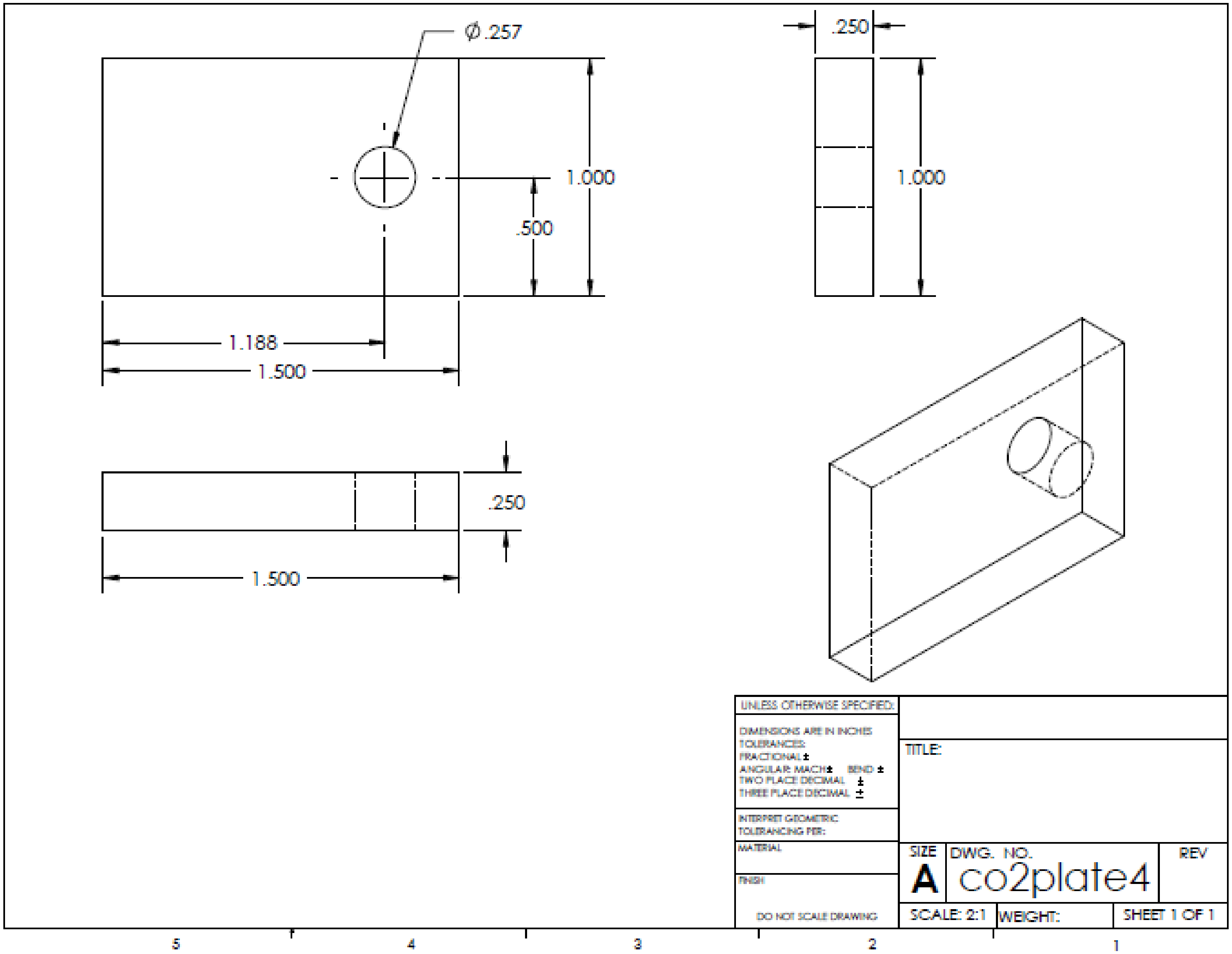


Figure 68: Engineering drawing of the supercritical CO_2 plate #4

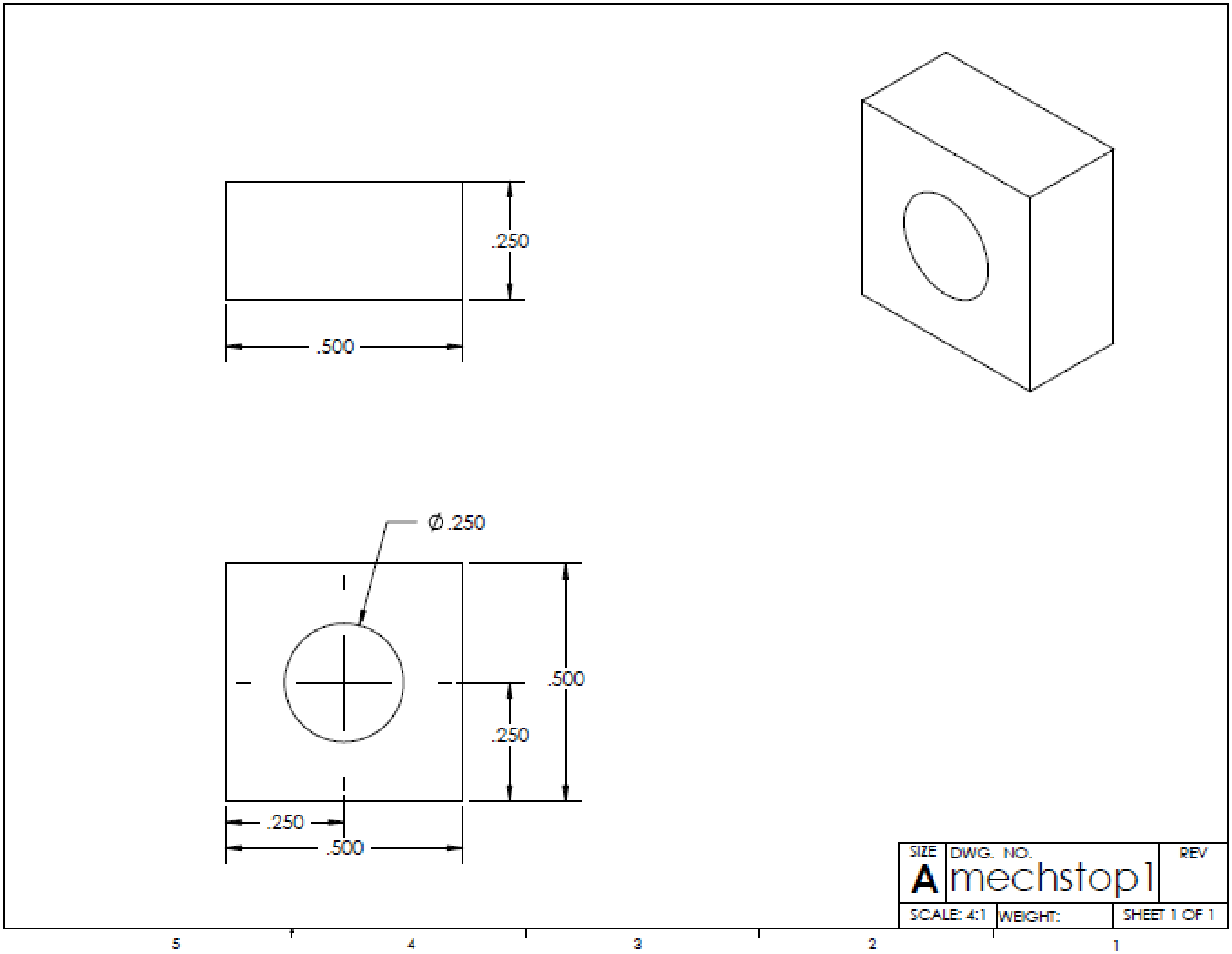


Figure 69: Engineering drawing of the mechanical stop plate #1

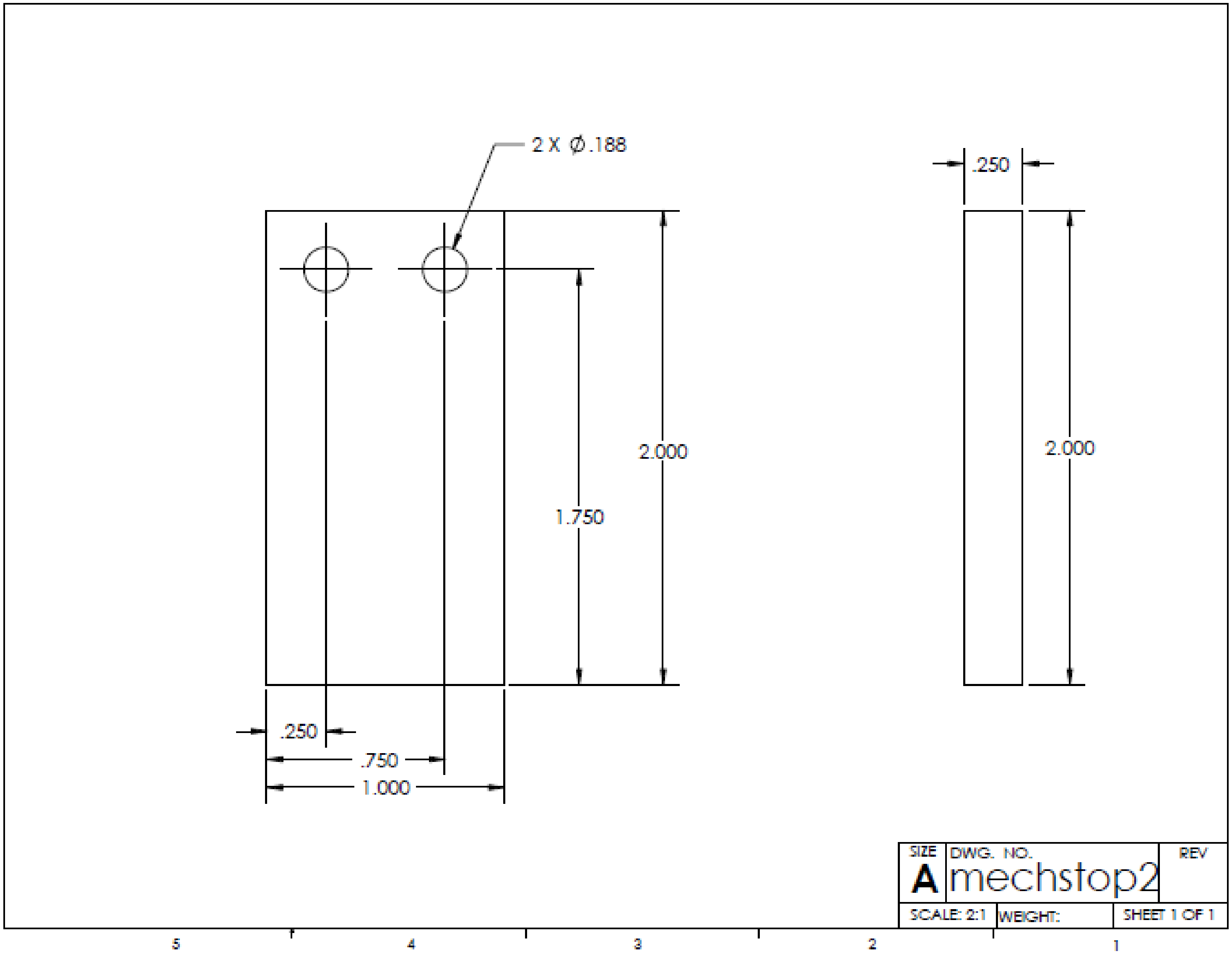


Figure 70: Engineering drawing of mechanical stop plate #2

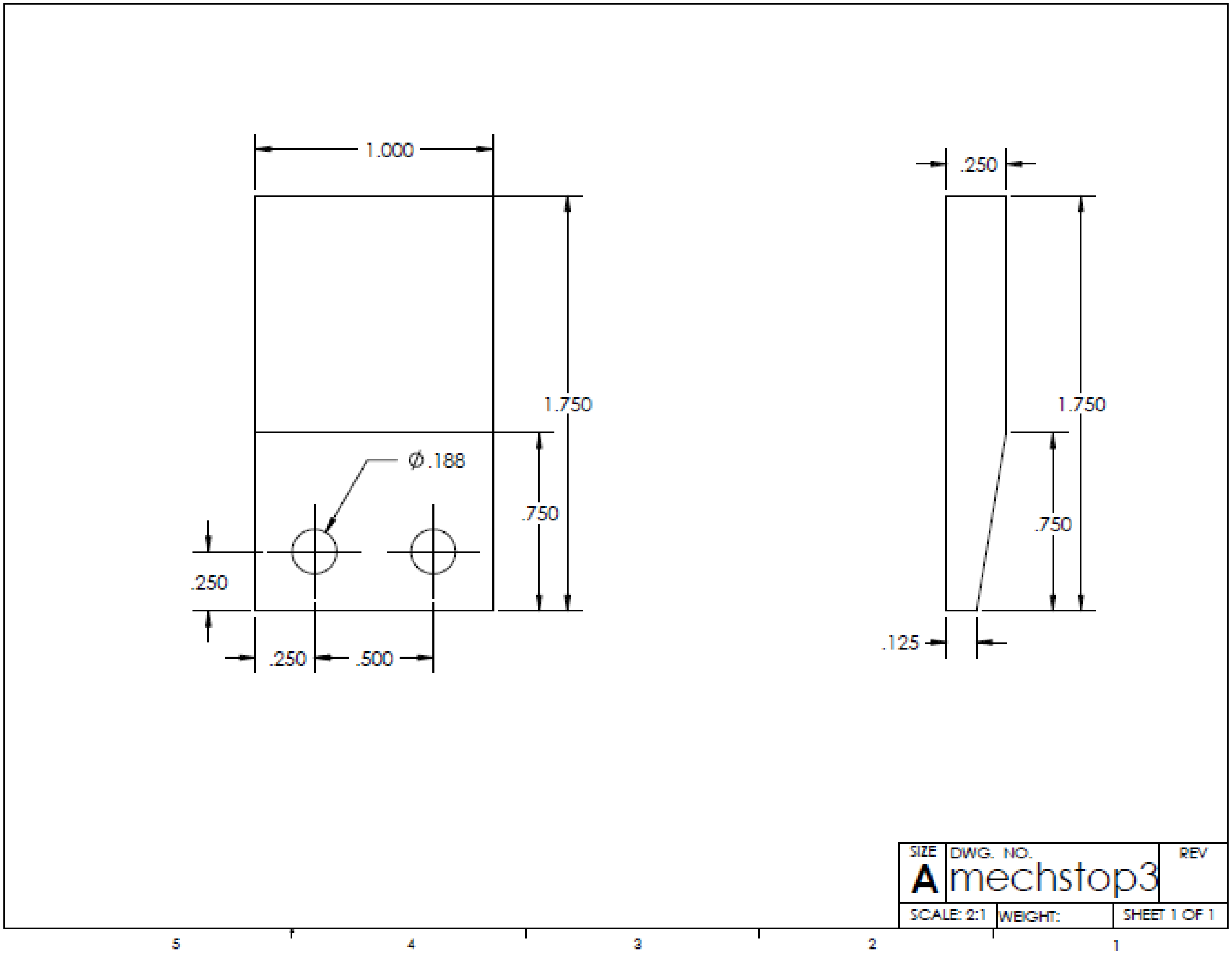


Figure 71: engineering drawing of mechanical stop #3

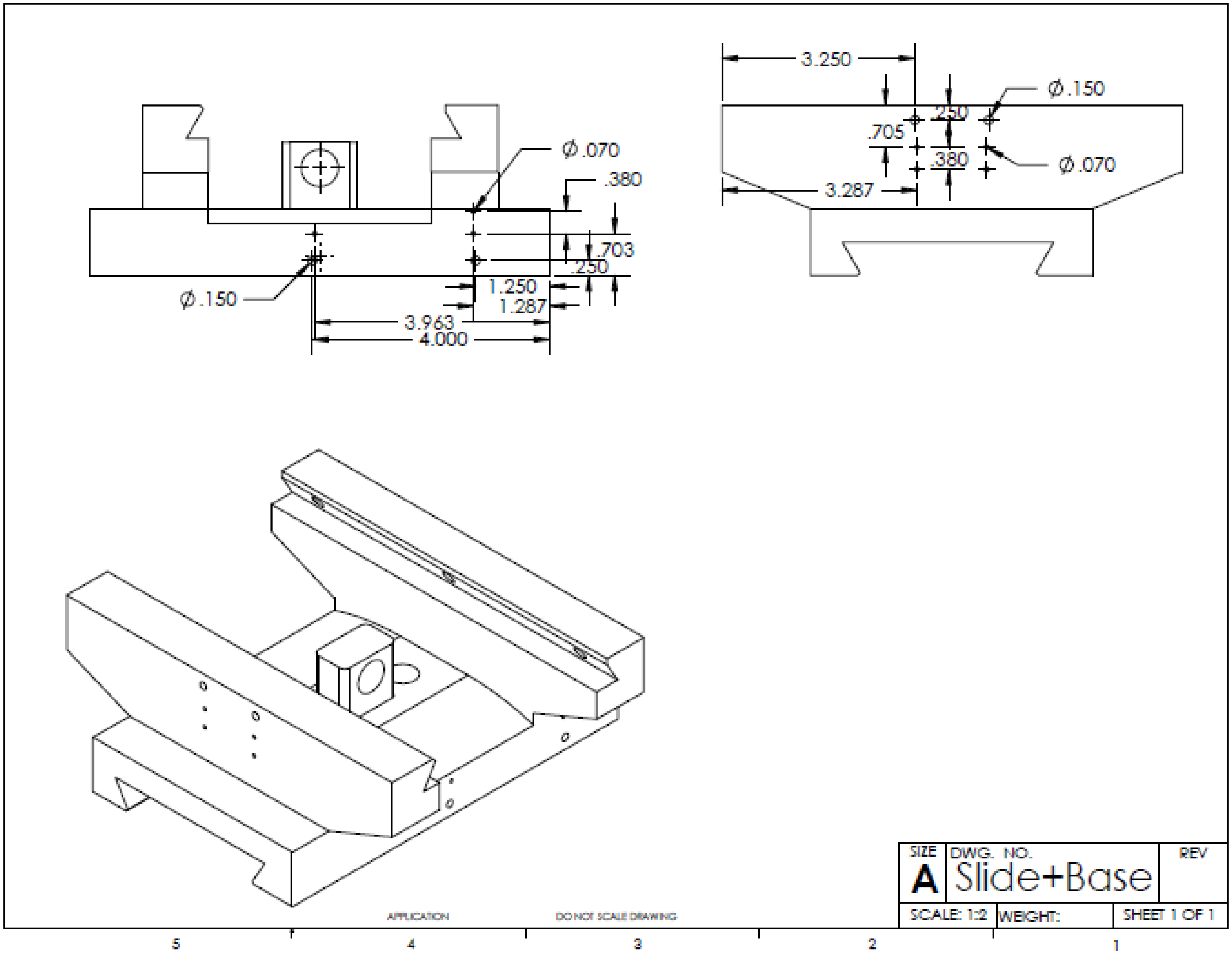


Figure 72: Engineering drawing of the revisions needed on the slide base for limit switches

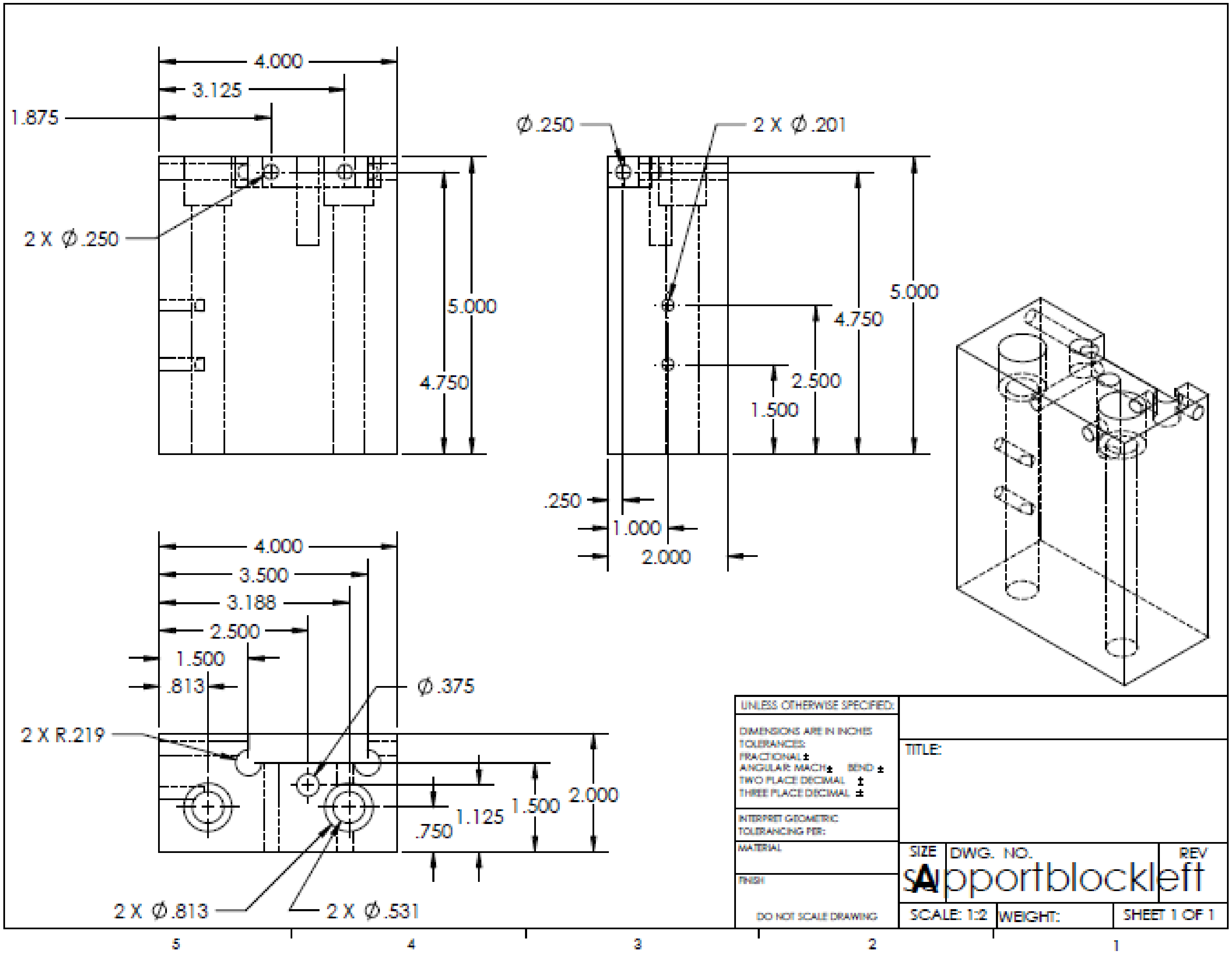


Figure 73: Engineering drawing of the left support block

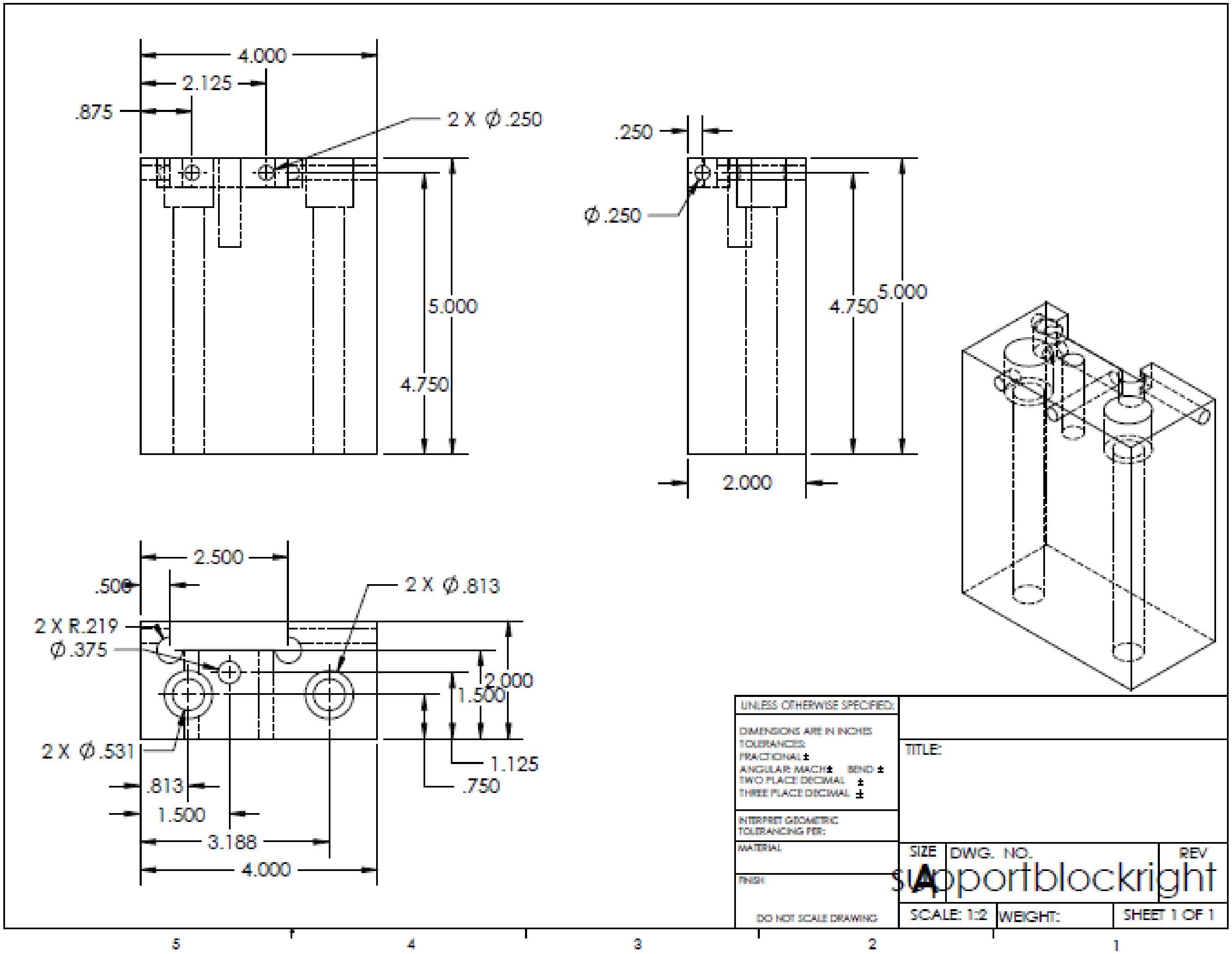


Figure 74: Engineering drawing of the right support block

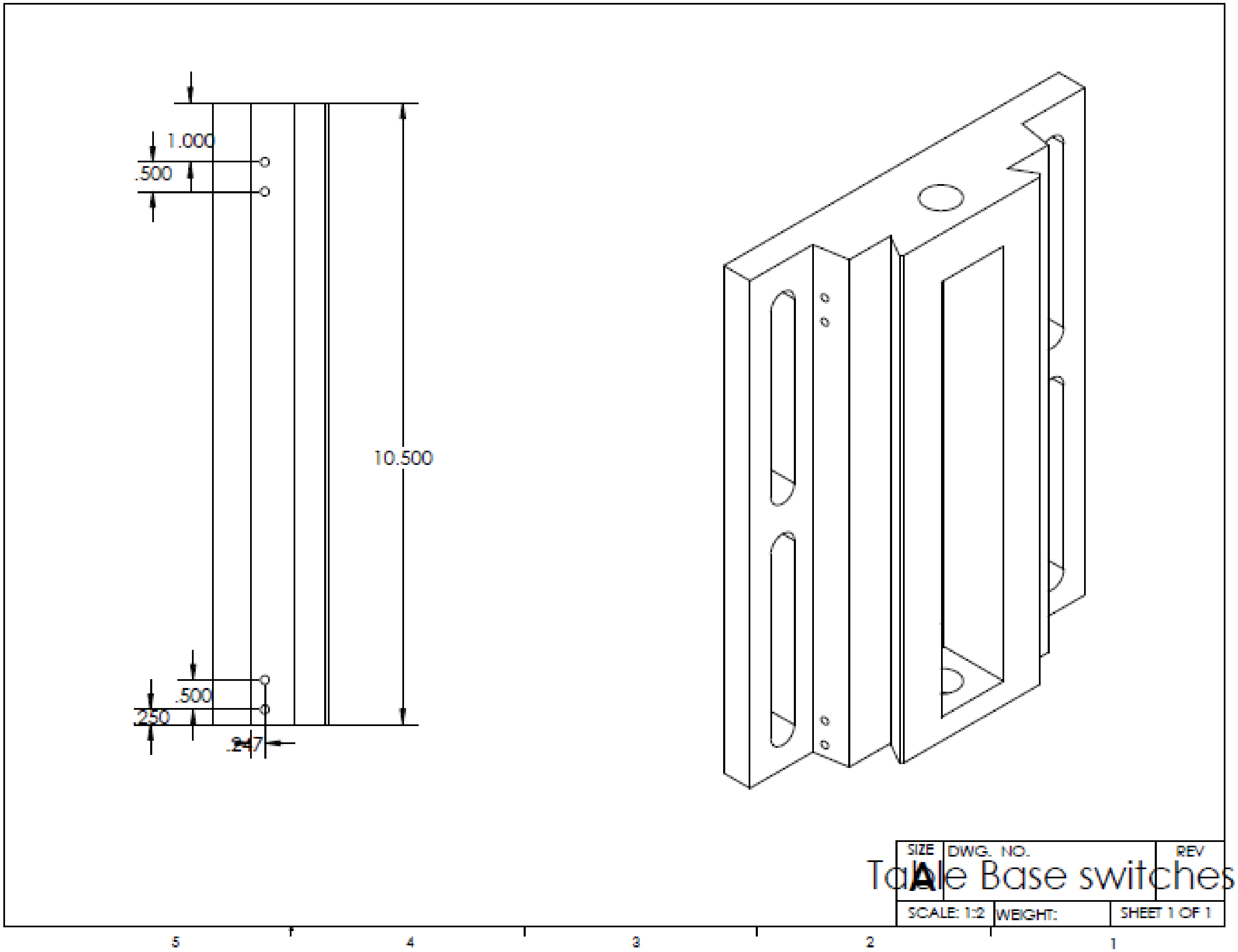


Figure 75: Engineering drawing of the revisions needed on the table base for limit switches

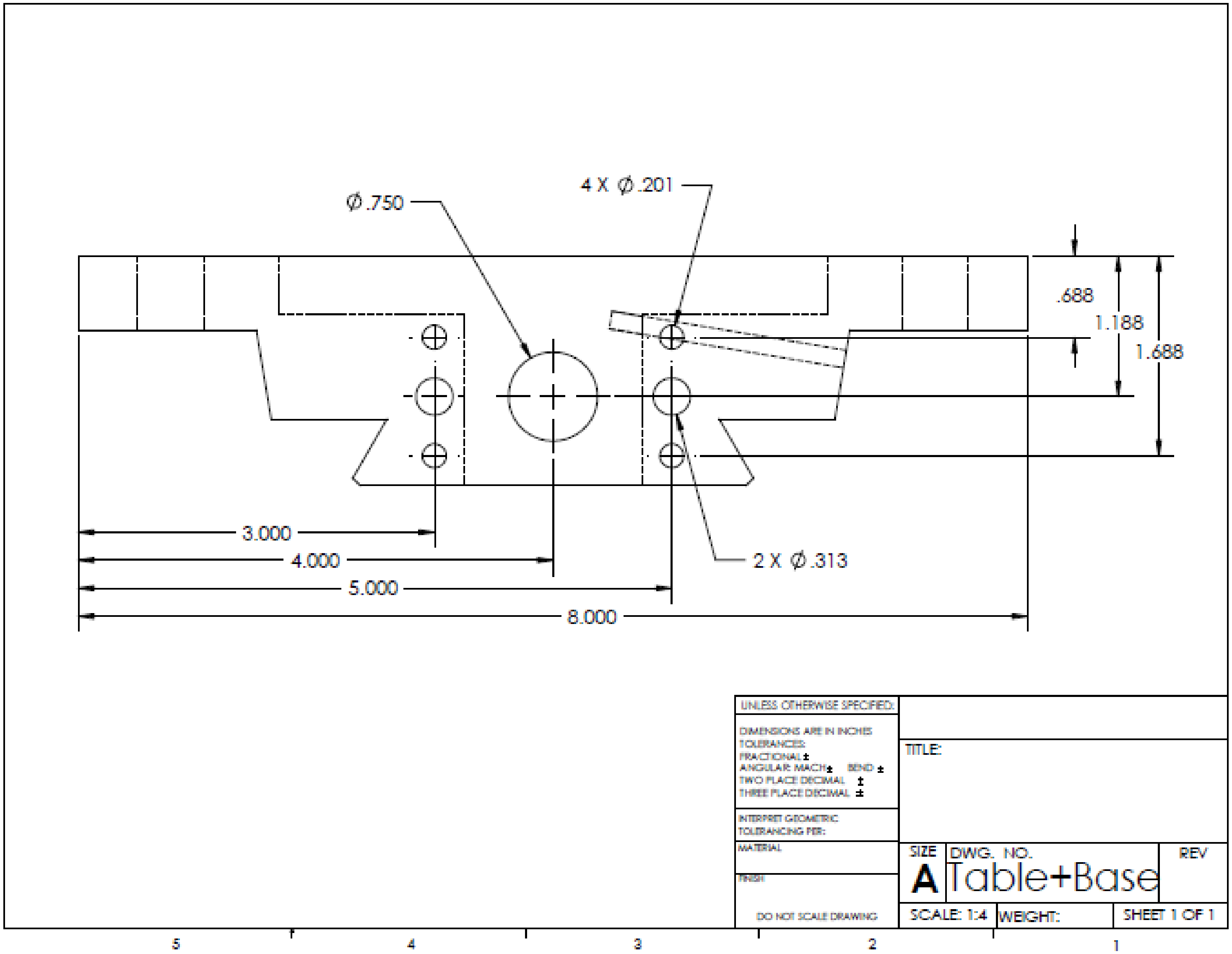


Figure 76: Engineering drawing of the table base revisions needed for the motor mount

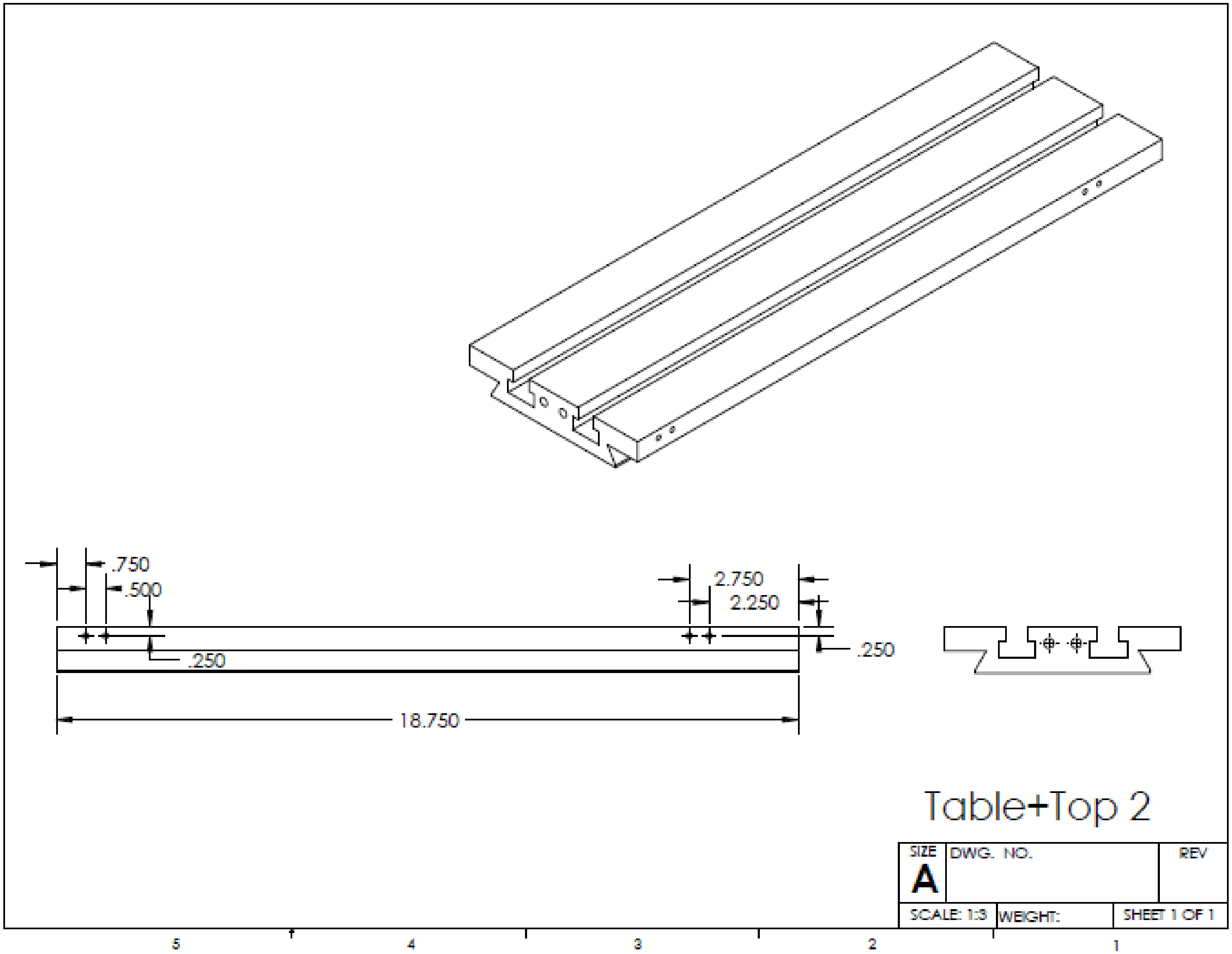


Figure 77: Engineering drawing of the revisions needed on the table top for limit switches

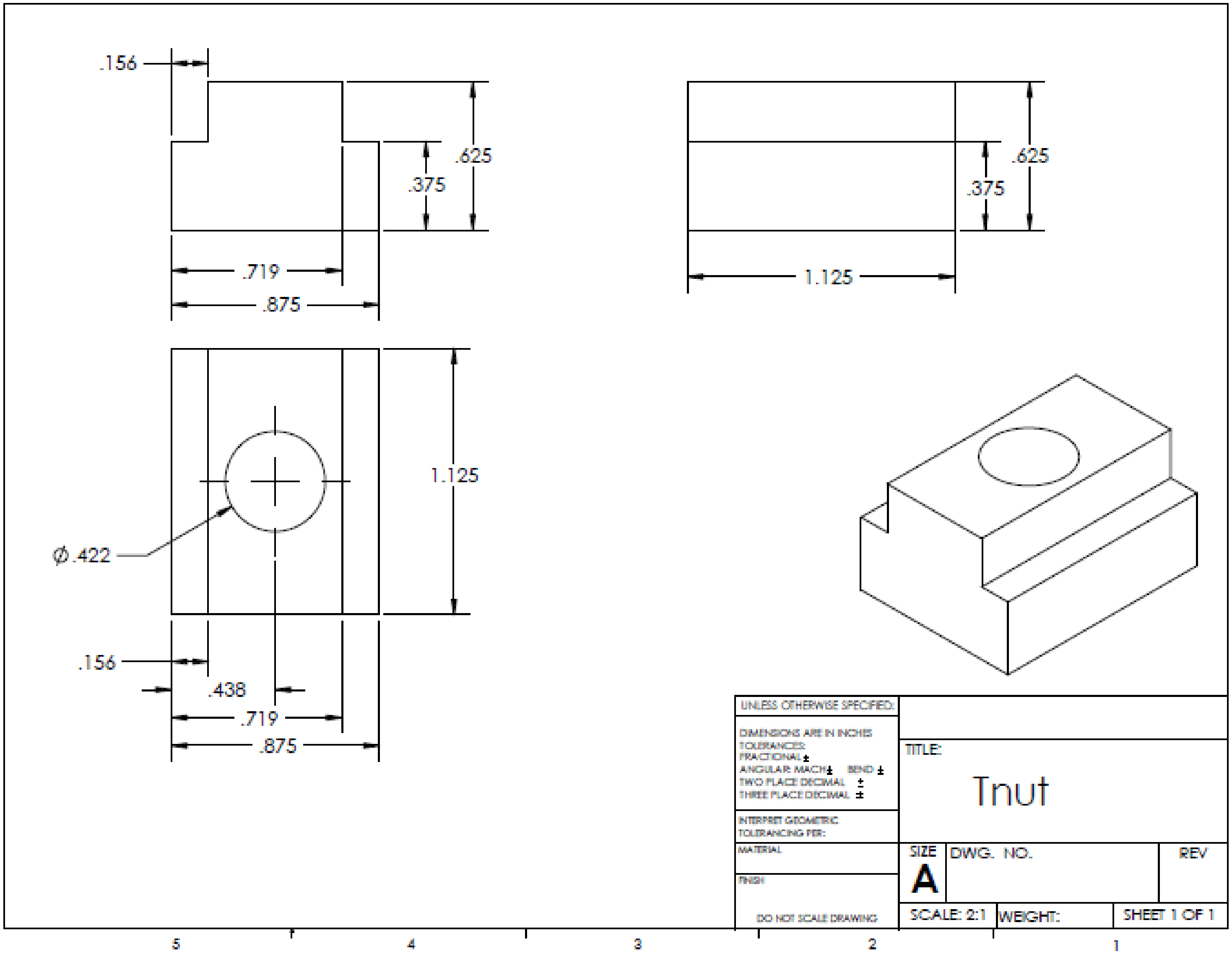


Figure 78: Engineering drawing of the T-slot nut

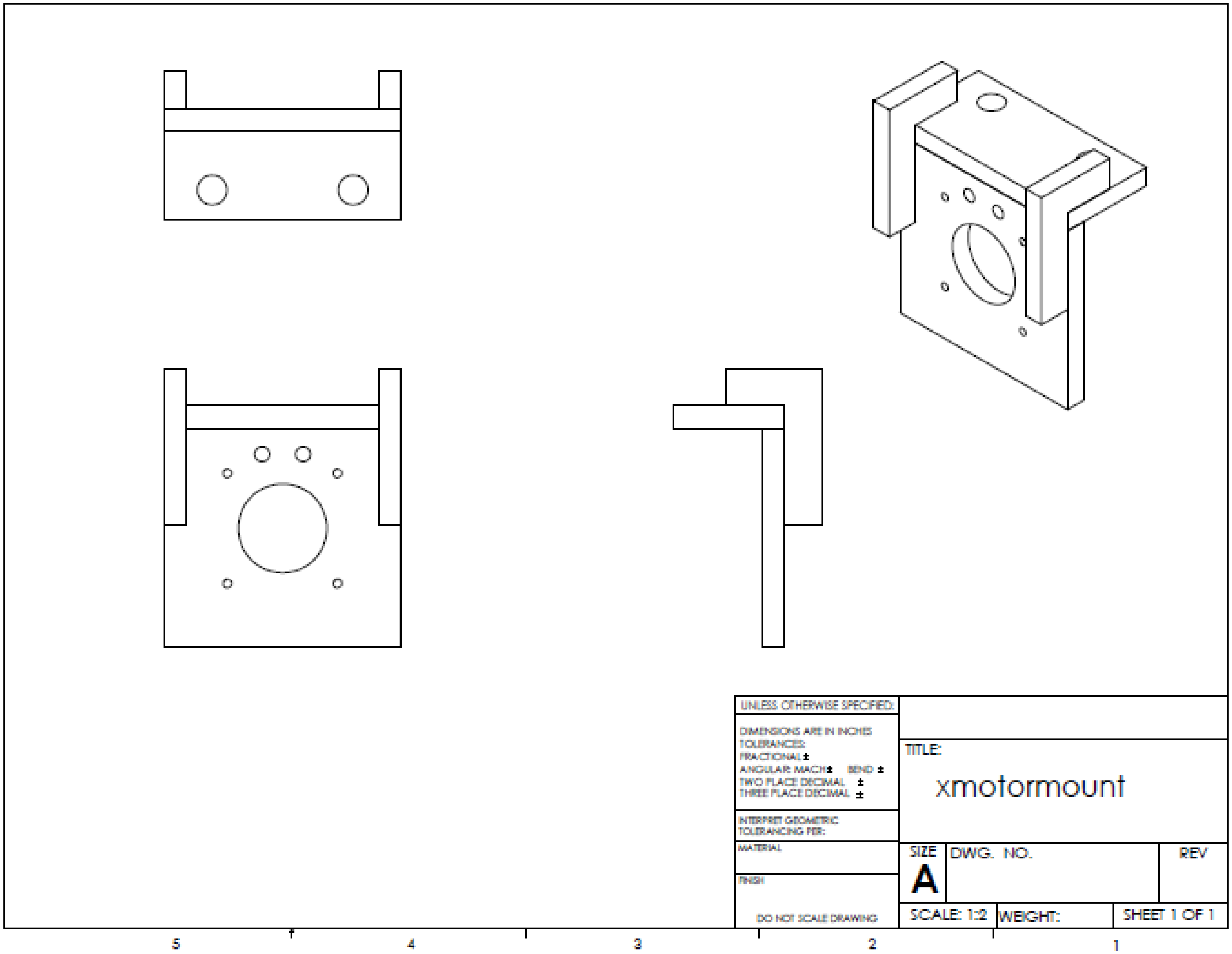


Figure 79: Engineering drawing of the X-axis motor mount assembly

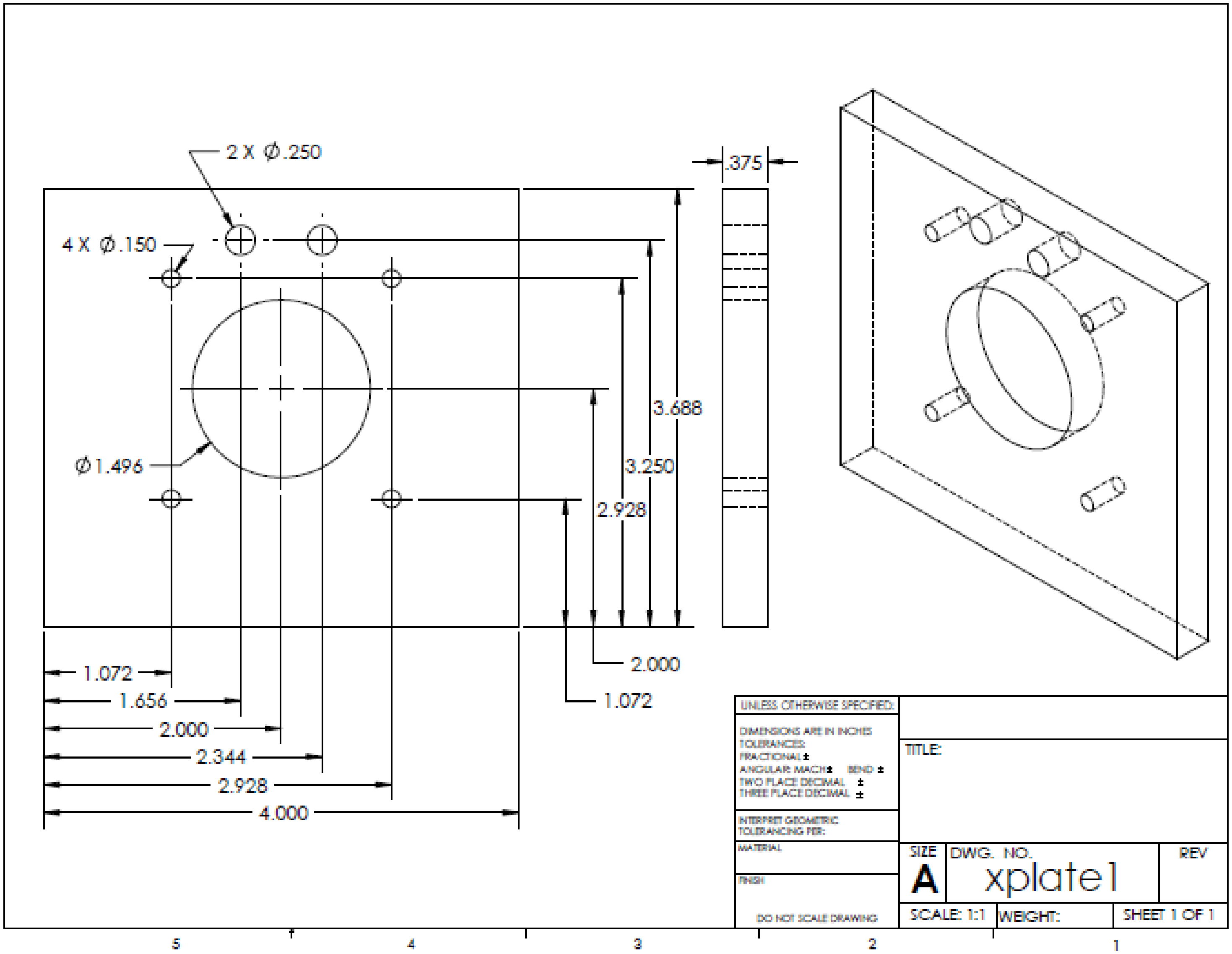


Figure 80: Engineering drawing of the X-axis motor mount plate #1

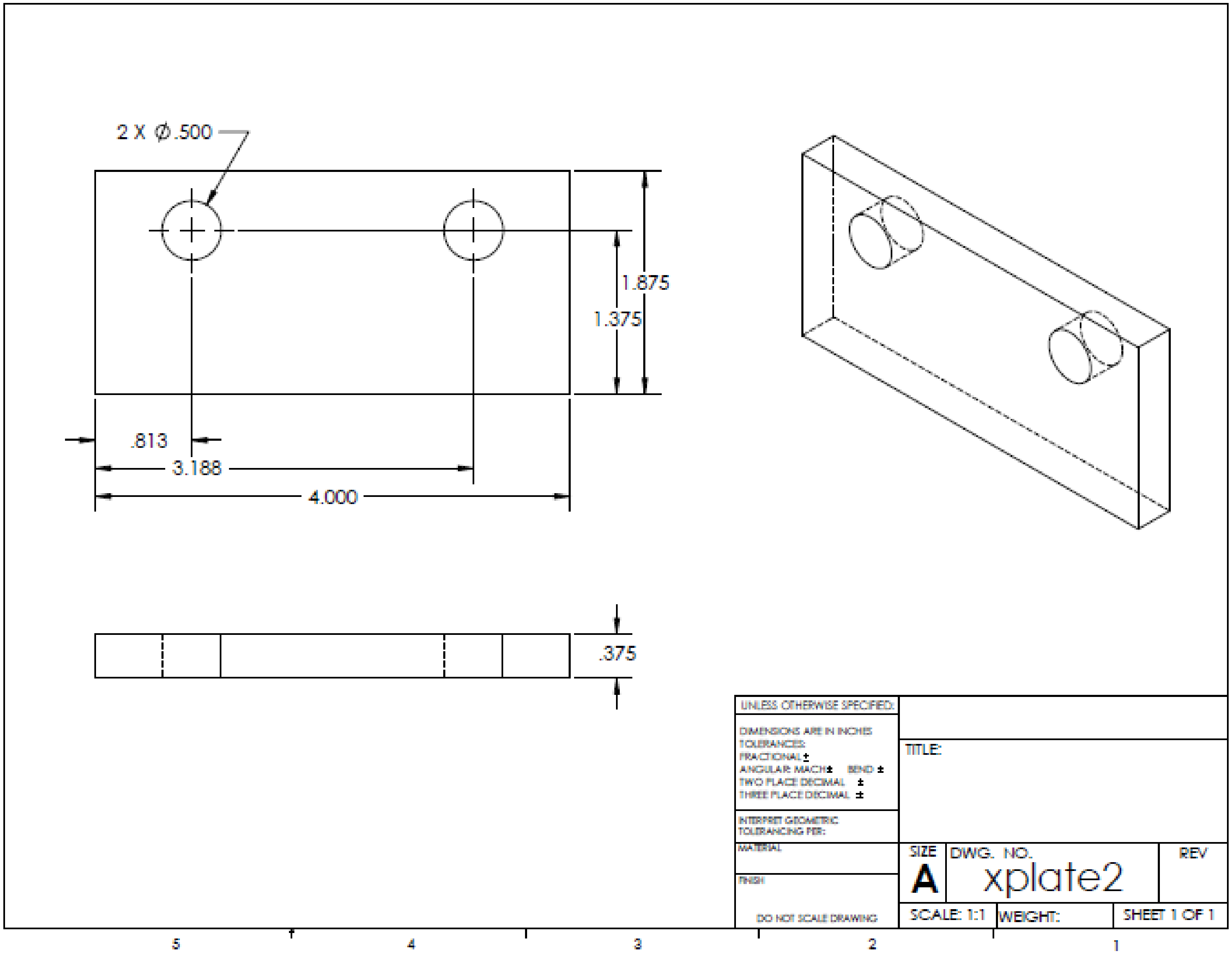


Figure 81: Engineering drawing of the X-axis motor mount plate #2

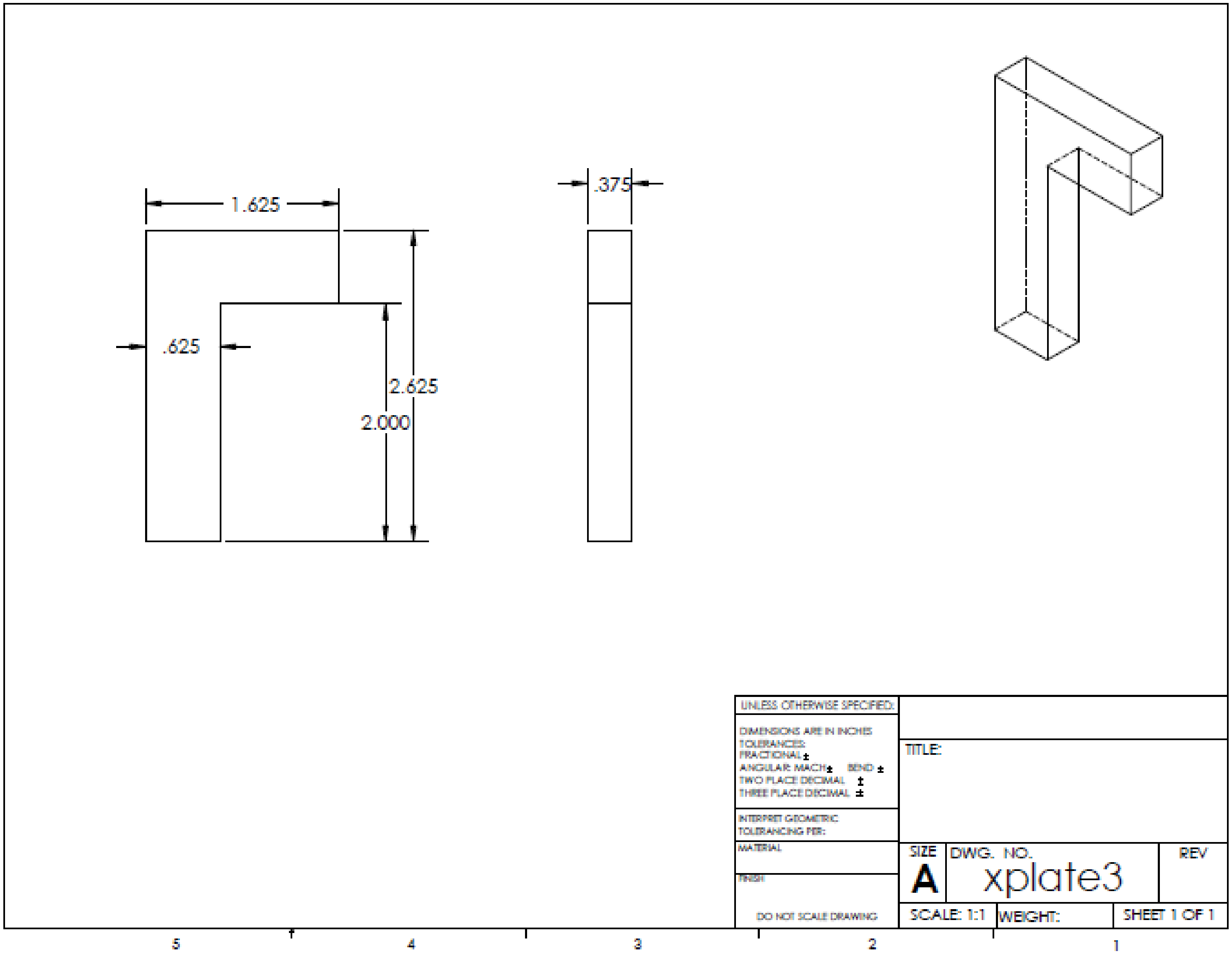


Figure 82: Engineering drawing of the X-axis motor mount plate #3

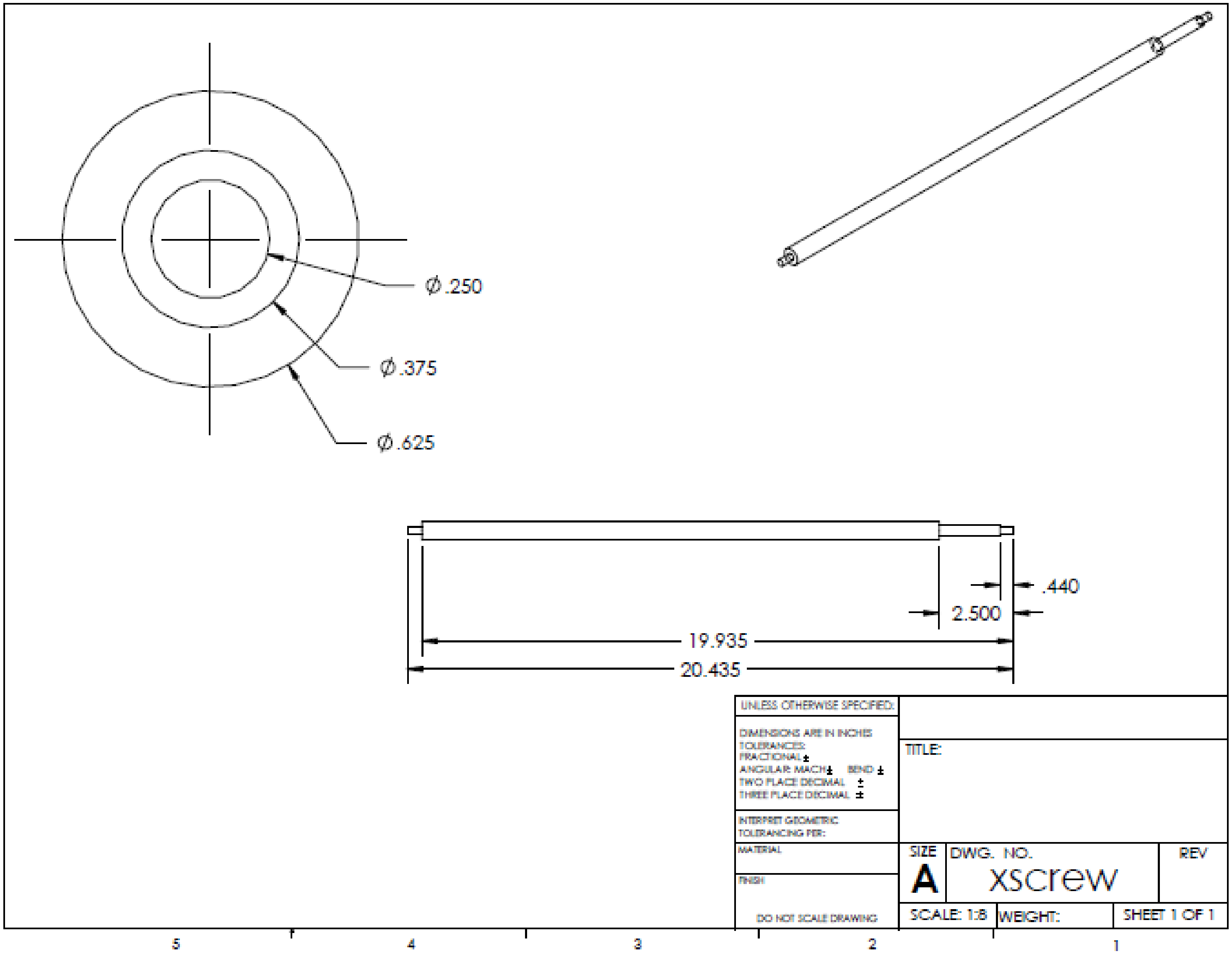


Figure 83: Engineering drawing of the modified X-axis lead screw

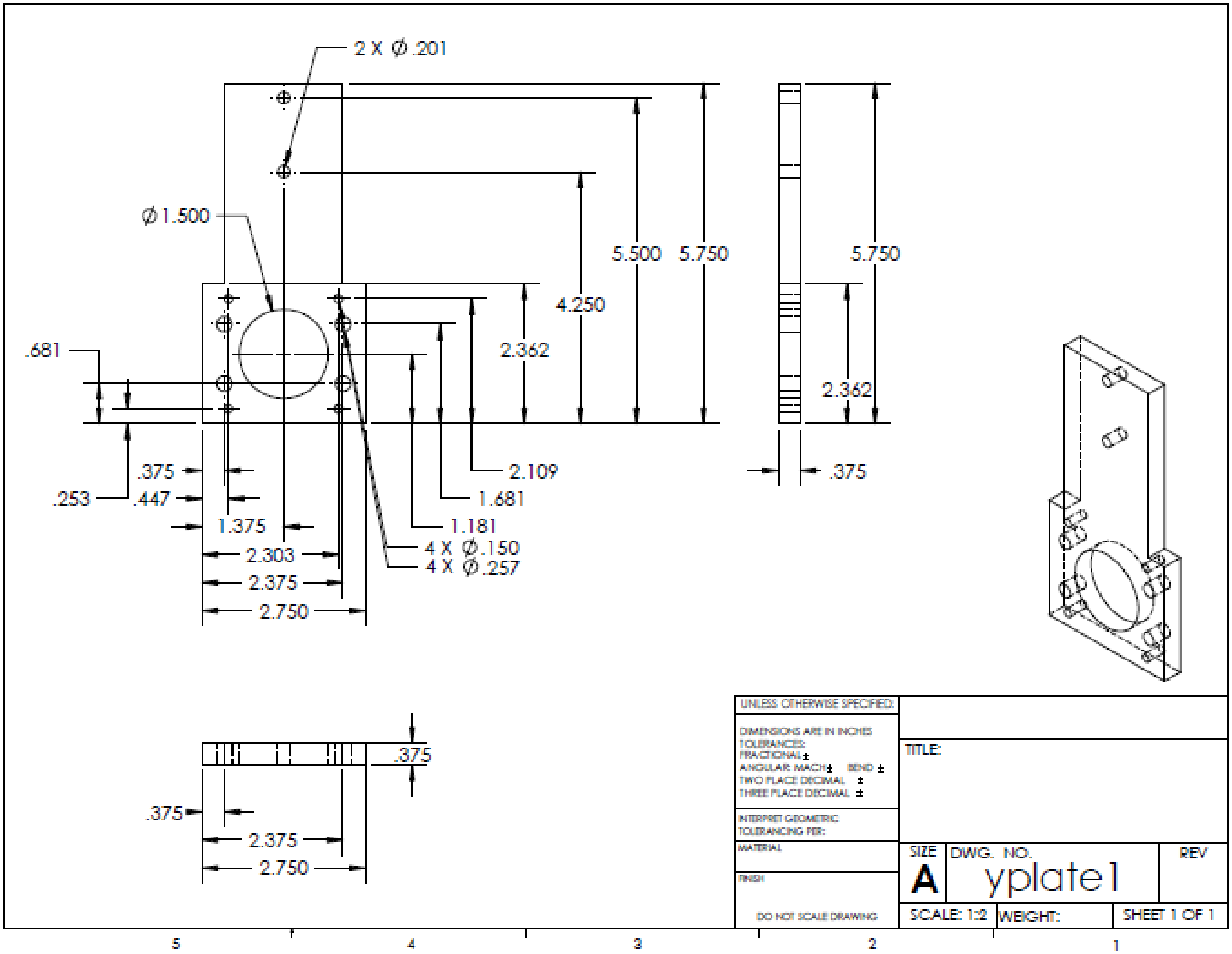


Figure 84: Engineering drawing of the Y-axis motor mount plate #1

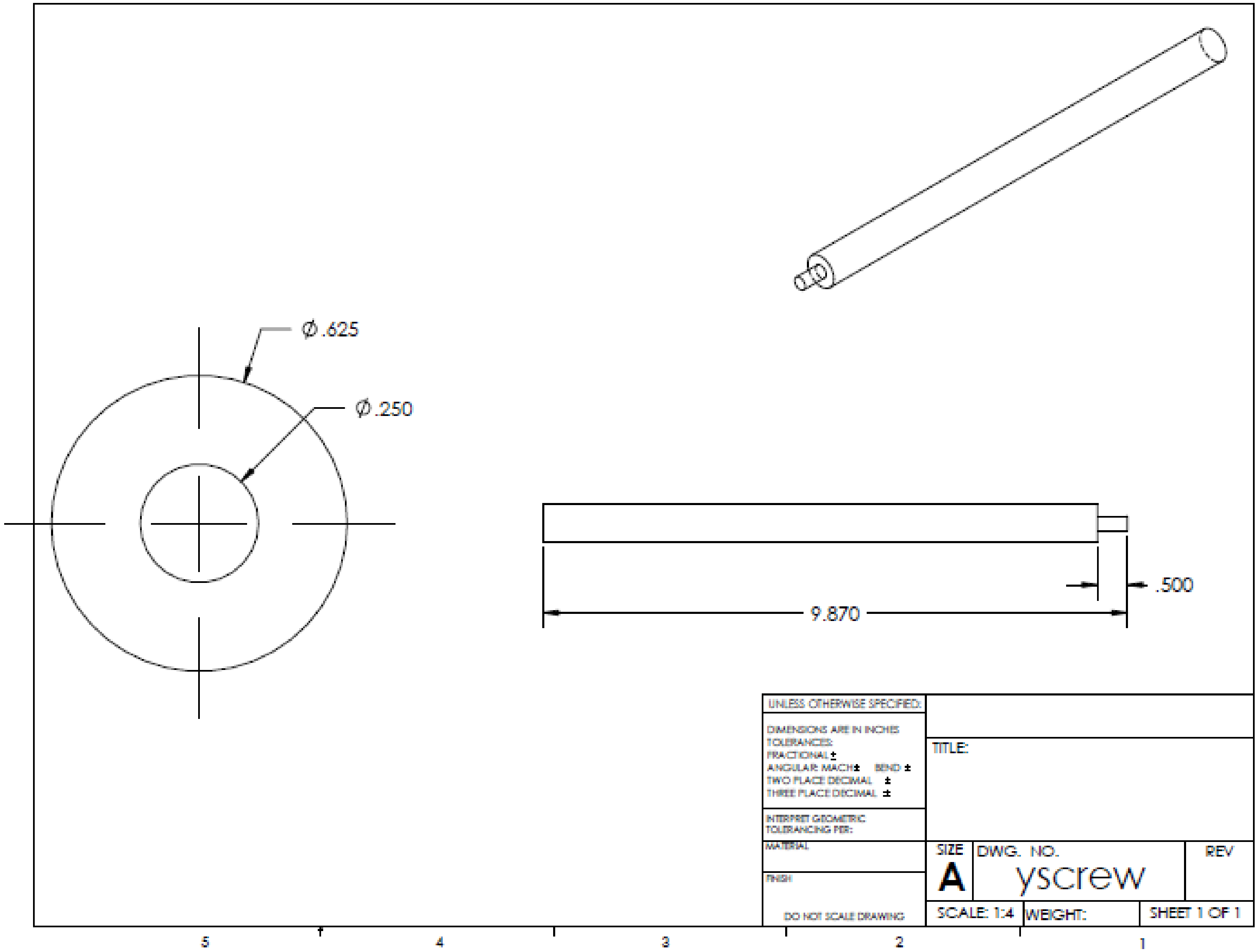
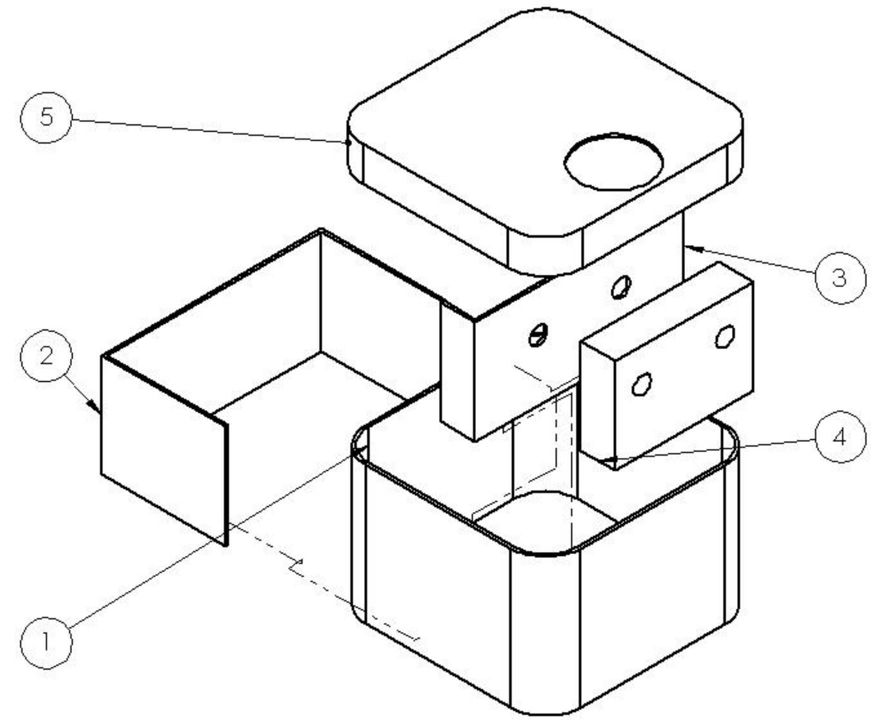


Figure 85: Engineering drawing of the modified Y-axis lead screw



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	tincan		1
2	tincanflange		1
3	brushflange		1
4	brush		1
5	tincan cover		1

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

TITLE:
acetonetrayexpl

SIZE A | DWG. NO. | REV
SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

Figure 86: Assembly drawing of the acetone dish sub-system

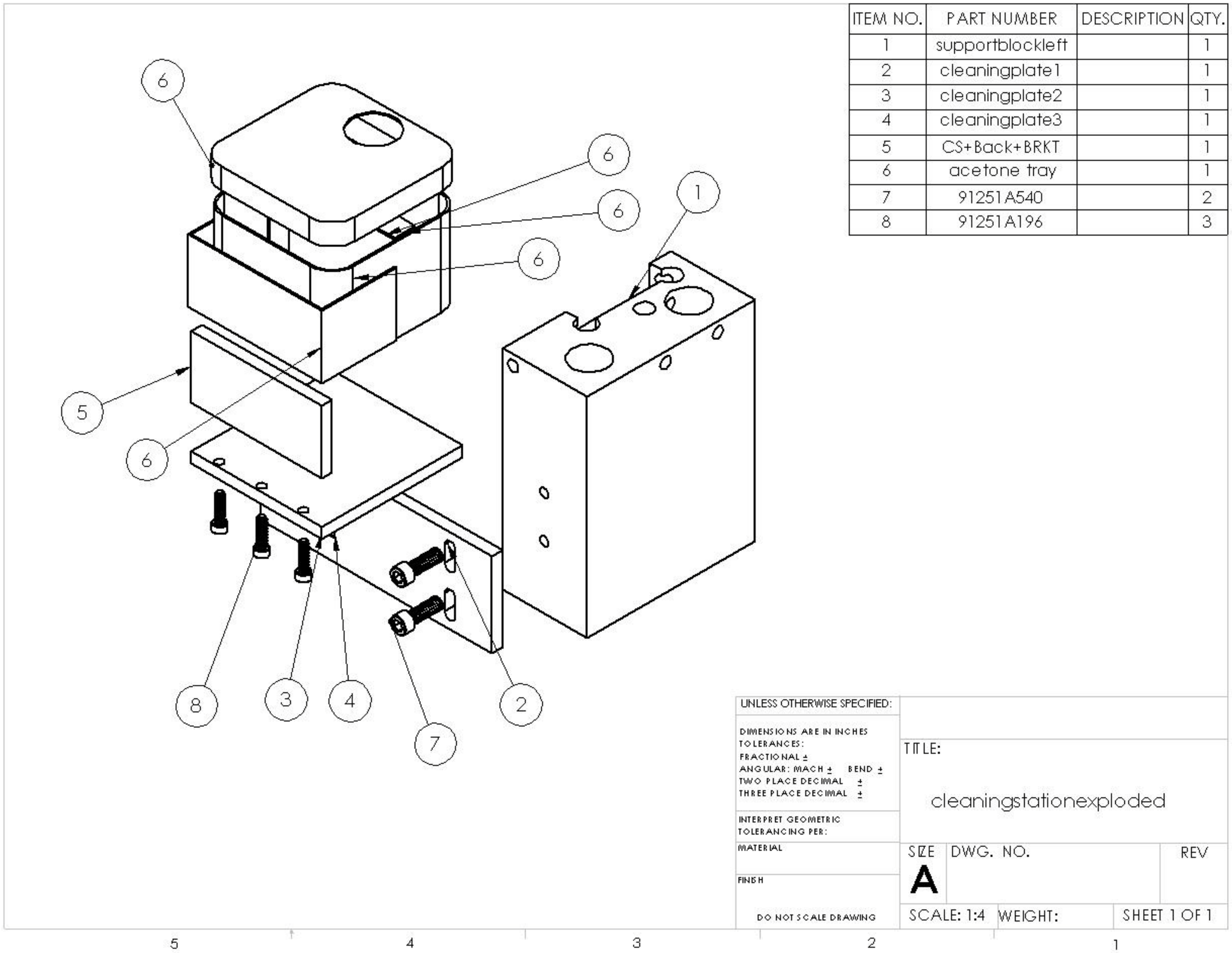
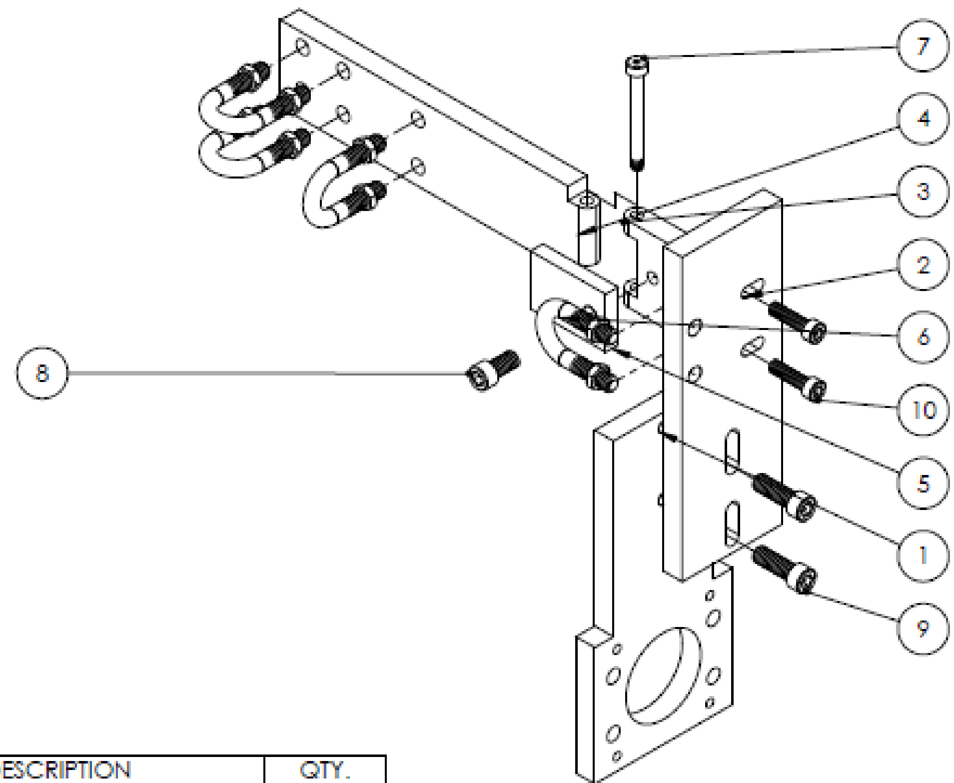


Figure 87: Assembly drawing of the cleaning station sub-system



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	yplate1		1
2	co2plate1		1
3	co2plate2		1
4	co2plate3		1
5	co2plate4		1
6	3201T28		4
7	92012A211		1
8	91251A537		1
9	91251A540		2
10	91251A245		2

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

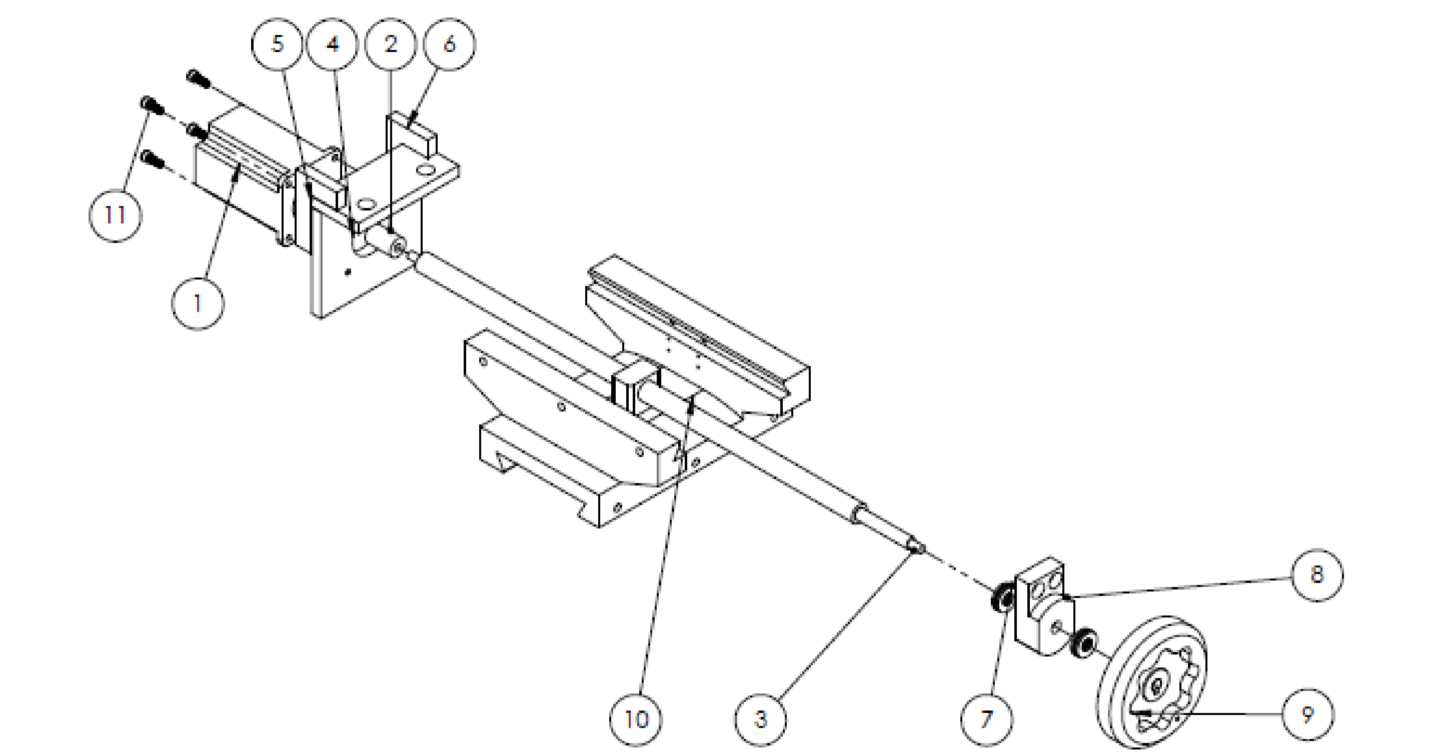
TITLE: Co2assem

SIZE A | DWG. NO. | REV

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

5 4 3 2 1

Figure 88: Assembly drawing of the supercritical CO_2 delivery sub-system



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	motor		1
2	coupler		1
3	xscrew		1
4	xplate1		1
5	xplate2		1
6	xplate3		2
7	6655K35		2
8	XScrew+flange		1
9	handle		1
10	Slide+Base		1
11	91251A242		4

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

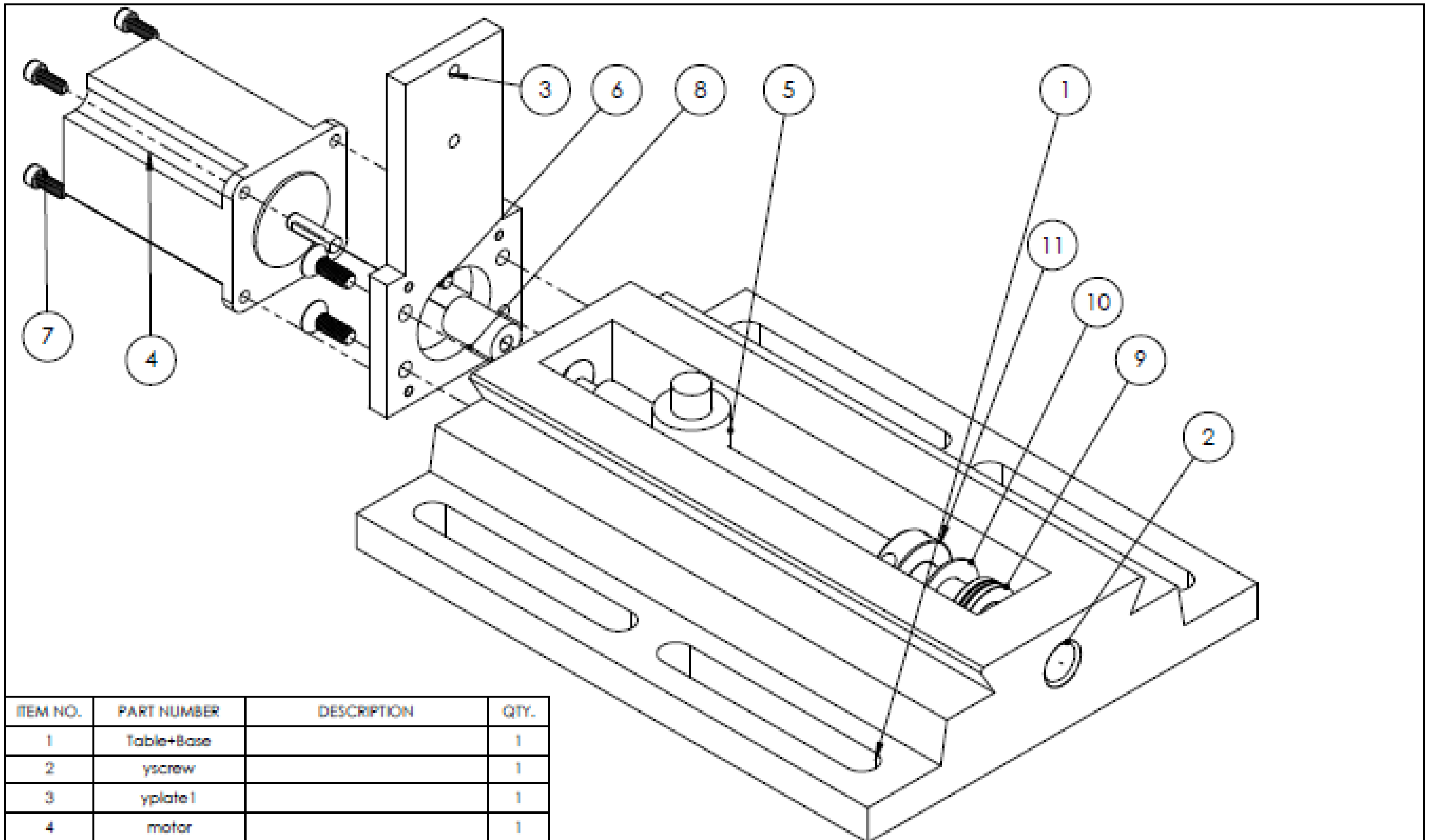
TITLE: xaxis

SIZE A | DWG. NO. | REV

SCALE: 1:12 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

Figure 89: Assembly of the X-axis sub-system



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Table+Base		1
2	yscrew		1
3	yplate1		1
4	motor		1
5	YScrew+Nut		1
6	91253A540		4
7	91251A242		4
8	coupler		1
9	6655K18		1
10	9712K82		1
11	6436K15		1

Figure 90: Assembly of the Y-axis sub-system

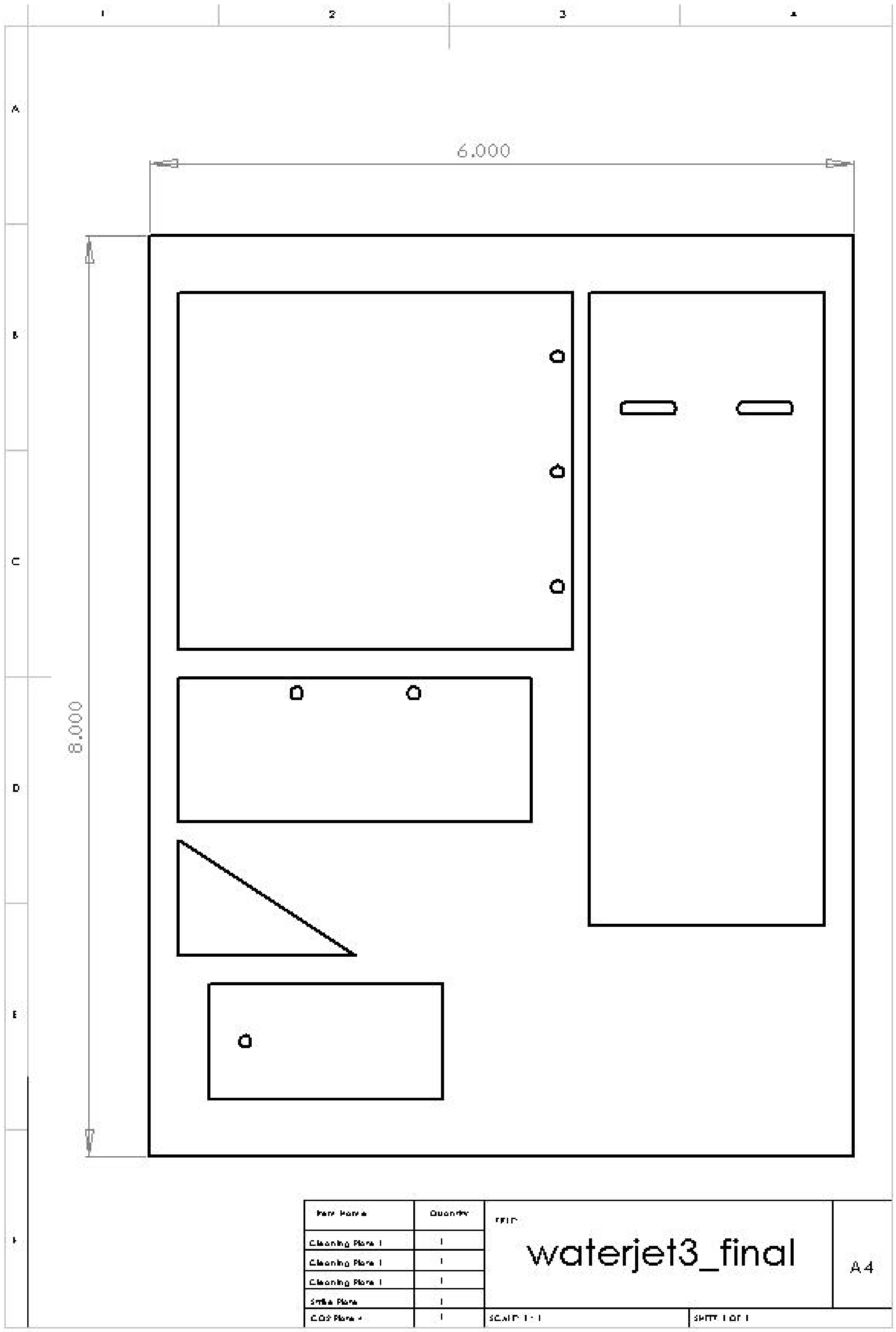


Figure 91: Water jet cut layout #1

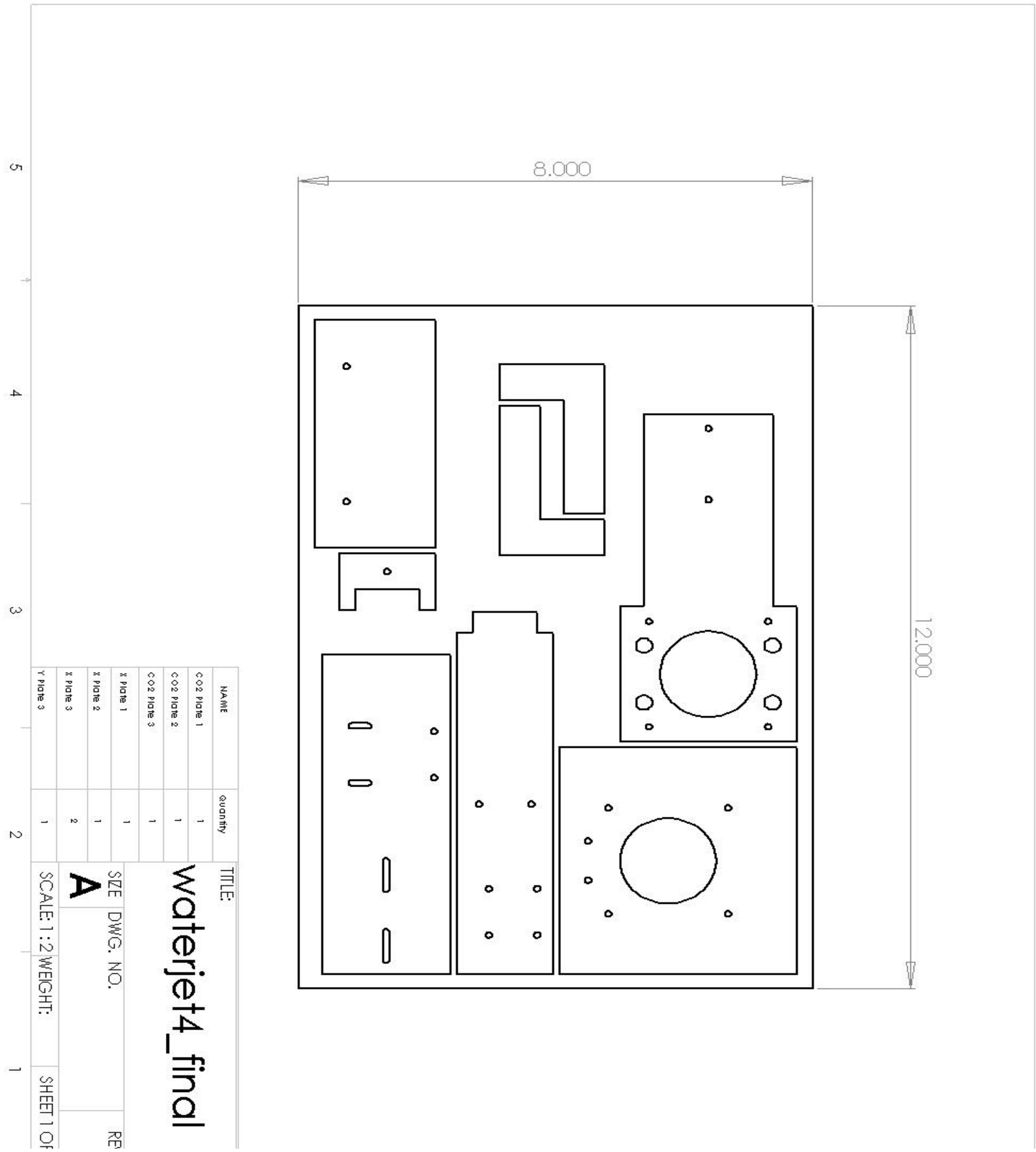


Figure 92: Water jet cut layout #2

APPENDIX H: CIRCUIT DIAGRAM

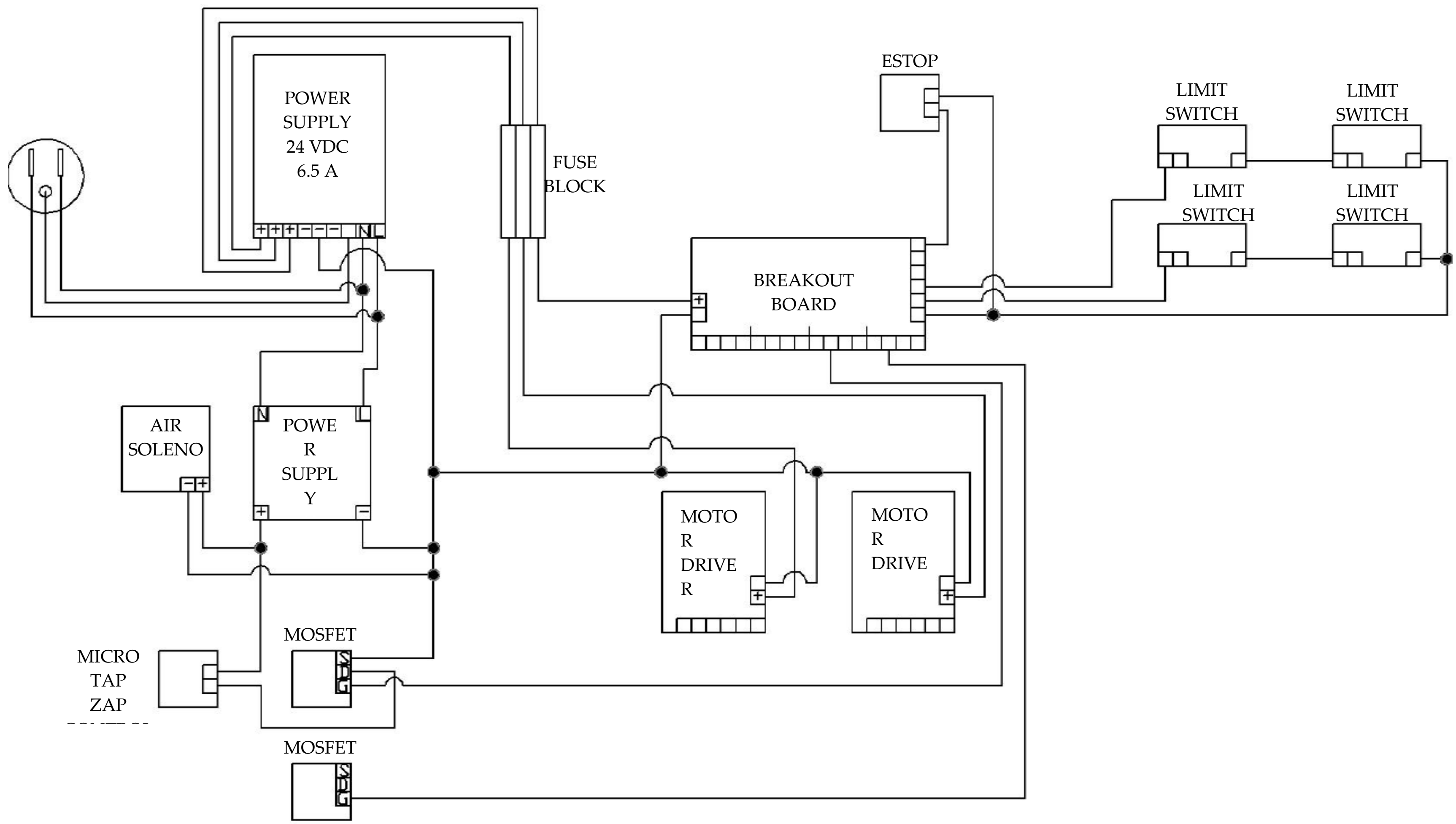


Figure 93: Circuit diagram

APPENDIX I: PORT PIN LAYOUT

Table 21: Port pin layout

Port:	03xBC
Pins:	**Signal**
1	Not in use
2	X Step
3	X Direction
4	Y Step
5	Y Direction
6	Flood output: air solenoid cleaning station
7	Not in use
8	Mist output: air Micro Tap ZAP system foot pedal
9	Not in use
10	Y Limit
11	Not in use
12	Not in use
13	E-stop
14	X Enable
15	X limit
16	Y Enable
17	Not in use
18	GND
19	GND
20	GND
21	GND
22	GND
23	GND
24	GND
25	GND

APPENDIX J: PURCHASED ELECTRONICS DATASHEETS

Stepper motor data sheet

probotix™

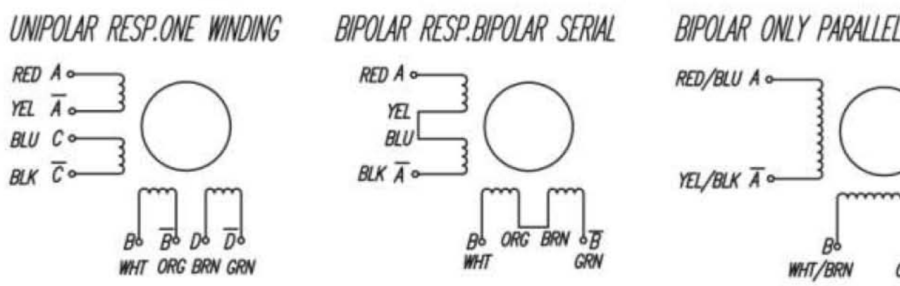
THE GREEN MONSTER

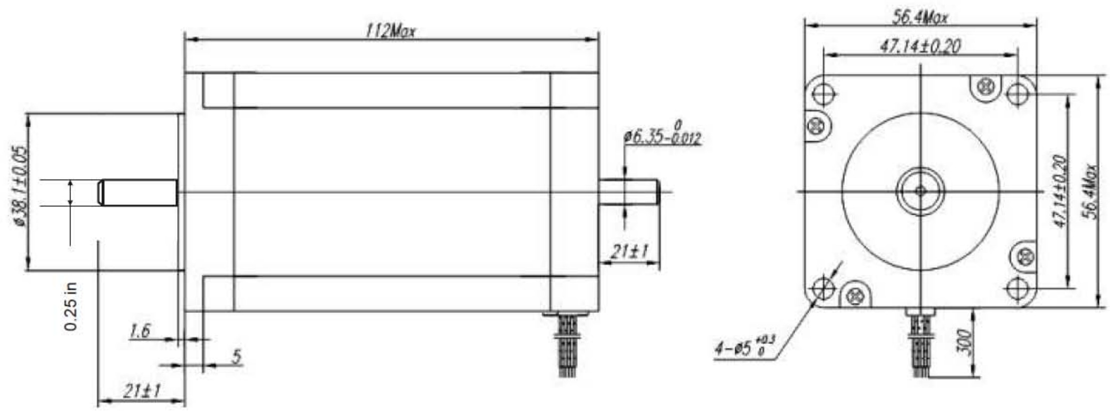
HT23-400-8

High Torque Stepper Motor

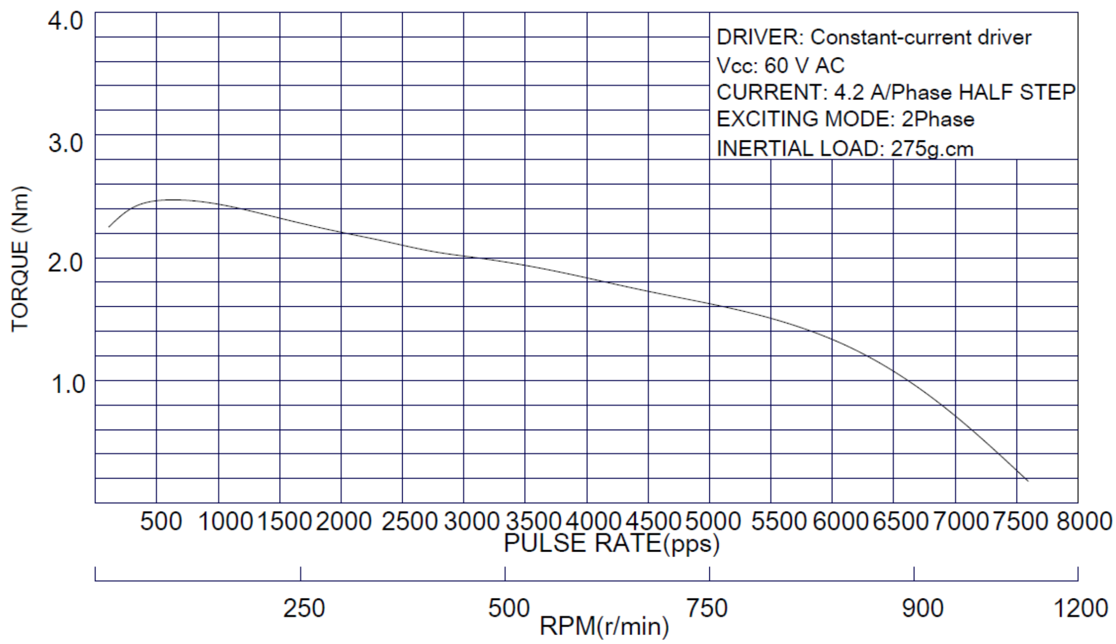
400 OzIn Hybrid Design
1.8 deg / 200 Steps Per Revolution

	Parallel	Series	UniPolar
Holding Torque (N.m +-10%)	2.8	2.8	2.0
Rated Current (Amps/phase)	4.2	2.1	3.0
Resistance (ohm/phase +-10%)	0.8	0.8	1.6
Inductance (mH/phase +-20%)	3.8	15.2	3.8
Rotor Inertia (g.cm 2)	480		
Motor Weight (kg)	2.0		
Motor Length (mm)	112		
Number of Wires	8		





HT23-400-8 Torque Curve



Bipolar stepper motor Driver kit user Manual

probotix

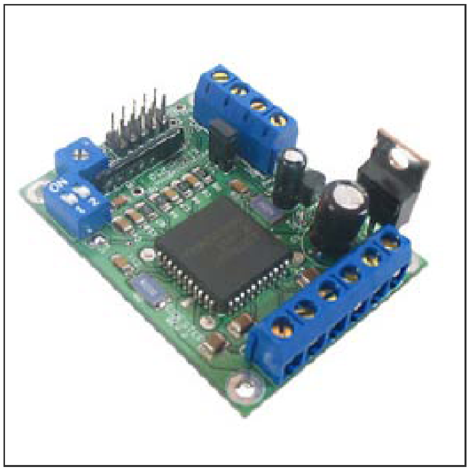
3-Axis Bi-Polar Stepper Motor Driver Kit
User Manual

Version 2.0

Model: SideStep

Stepper Motor Microstepping Driver Specs:

- Chopper Current Driver
- .5 - 2.5 Amp Current Limiting
- Dual H-Bridge Configuration
- Full, Half, Quarter, & Eighth Microstepping Resolution
- 8V - 32V Supply
- Optional Integrated Charge Pump for 5V Logic Side



Description

The SideStep is a complete microstepping motor driver and control system with a built-in translator. It is designed to operate bipolar stepper motors in full-, half-, quarter-, and eighth-step modes, with output drive capability of 32 V and up to 2.5 A. This driver utilizes the Allegro A3977 chip which includes a fixed off-time current regulator that has the ability to operate in slow-, fast-, or mixed-decay modes. This current-decay control scheme results in reduced audible motor noise, increased step accuracy, and reduced power dissipation. The SideStep is one of the smallest stepper driver boards in its class, making it ideal for incorporating into robots and other industrial control equipment.

Bipolar Chopper Drivers

Bipolar chopper drivers are by far the most widely used drivers for industrial applications. Although they are typically more expensive to design, they offer more performance and increased efficiency. Bipolar chopper drivers use an extra set of switching transistors to eliminate the need for two power sources. Additionally, these drivers use a four transistor bridge with recirculating diodes and a sense resistor that maintains a feedback voltage proportional to the motor current. Motor windings, using a bipolar chopper driver, are energized to the full supply level by turning on one set (top and bottom) of the switching transistors. The sense resistor monitors the linear rise in current until the required level is reached. At this point the top switch opens and the current in the motor coil is maintained via the bottom switch and the diode. Current "decay" (loss over time) occurs until a preset position is reached and the process starts over. This "chopping" effect of the supply is what maintains the correct current voltage to the motor at all times.

Features

- Hardware or software selectable phase, enable, and direction signals
- Current limit adjustable by potentiometer
- Wide range of motor power (5-35 V)
- Power (for logic) indicator LED
- ±2.5 A, 35 V Output Rating

Automatic Current Decay Mode Detection/Selection Mixed-, Fast-, and Slow-Decay Modes

- 3.0-5.5 V Logic Supply Voltage Range
- Home Output
- Synchronous Rectification for Low Power Dissipation
- Internal UVLO and Thermal-Shutdown Circuitry
- Crossover Current Protection

Flexible Design

The SideStep was designed with flexibility in mind with features including:

- Internal synchronous-rectification control circuitry is provided to improve power dissipation during PWM operation.
- Internal circuit protection includes thermal shutdown with hysteresis, under-voltage lockout (UVLO), and crossover-current protection. Special power-up sequencing is not required.
- The logic signals are brought out to a .1" pin header on one side, allowing for use of an IDC cable to connect your boards. Every other pin on the IDC header is connected to ground, which acts to shield the control signals from noise. Noise in a stepper control system can cause miss stepping, which can damage your equipment, cause injury, and ruin your work piece.
- The Vref signal and HOME signals are brought out to this header to allow advanced connections to control devices, such as a microcontroller which can adjust the driver's output current on-the-fly.
- The dip switch can be left uninstalled or removed and wired to a microcontroller to change the step resolution mid-motion for advanced speed ramping.
- The main control signals, STEP, DIRECTION, and ENABLE, as well as a GND connection, are brought out to WAGO type screw clamps for easy wiring to common devices, such as parallel port breakout boards.
- A two-stage, noise filtered, charge pump section is included. The first stage is regulated to 12 V, and has a header for a 12 V DC cooling fan. The second stage drops this 12 V down to 5 V which powers the driver's logic. This allows the logic supply to be driven from the same 12-24 V supply that the motor drive section is powered from. The logic supply has a power-on LED indicator.
- Alternately, the 12 V regulator can be left uninstalled or removed, allowing separate supplies for the logic and drive sections. The fan connector can be used for the power supply input.
- Both regulator sections can be left uninstalled or removed, to allow a single logic supply to be fed to the driver through the IDC pin header, such as from our PBX-1 breakout board with integrated charge pump.
- Additionally, the 5 V pin on the pinheader can be used to feed other boards from a single board, or to feed pull-up resistors for limit and home switches, provided that the current limits of the 7805 regulator are not exceeded.
- An 8-pin SIP resistor acts as the pull-ups for the logic signals. The eighth pin acts as a bridge in the event that your application requires reversed logic to the step and direction signals. Simply, cut off the necessary pin(s) from the SIP resistor before installing. A provision for an inline resistor and a decoupling capacitor has been included for noise filtering on the STEP signal.
- A solder jumper on the SR signal, which disables the drivers built-in synchronous rectification, allows for wiring external diodes for reduced heat dissipation. Wire one side of the jumper to +5V to disable synchronous rectification, or install the jumper to ground to enable this internally on the driver.
- A large ground plane exists for heat dissipation however, the layout of the components of this driver board allows for the use of a standard 1" square BGA heatsink. The board's large ground plane makes a heatsink unnecessary in many applications; however, use of a heatsink is recommended, especially when driving motors at higher than 1.5 amps per phase.
- An under-voltage lockout circuit protects the A3977 from potential shoot-through currents when the motor supply voltage is applied before the logic supply voltage. All outputs are disabled until the logic supply voltage is above 2.7V; the control logic is then able to correctly control the state of the outputs. Thermal protection circuitry turns off all the power outputs if the junction temperature exceeds 165°C. As with most integrated thermal shutdown circuits, this is intended only to protect the A3977 from failure due to excessive junction temperature and will not necessarily protect the IC from output short circuits. Normal operation is resumed when the junction temperature has decreased by about 15°C.

Setting Current Limit

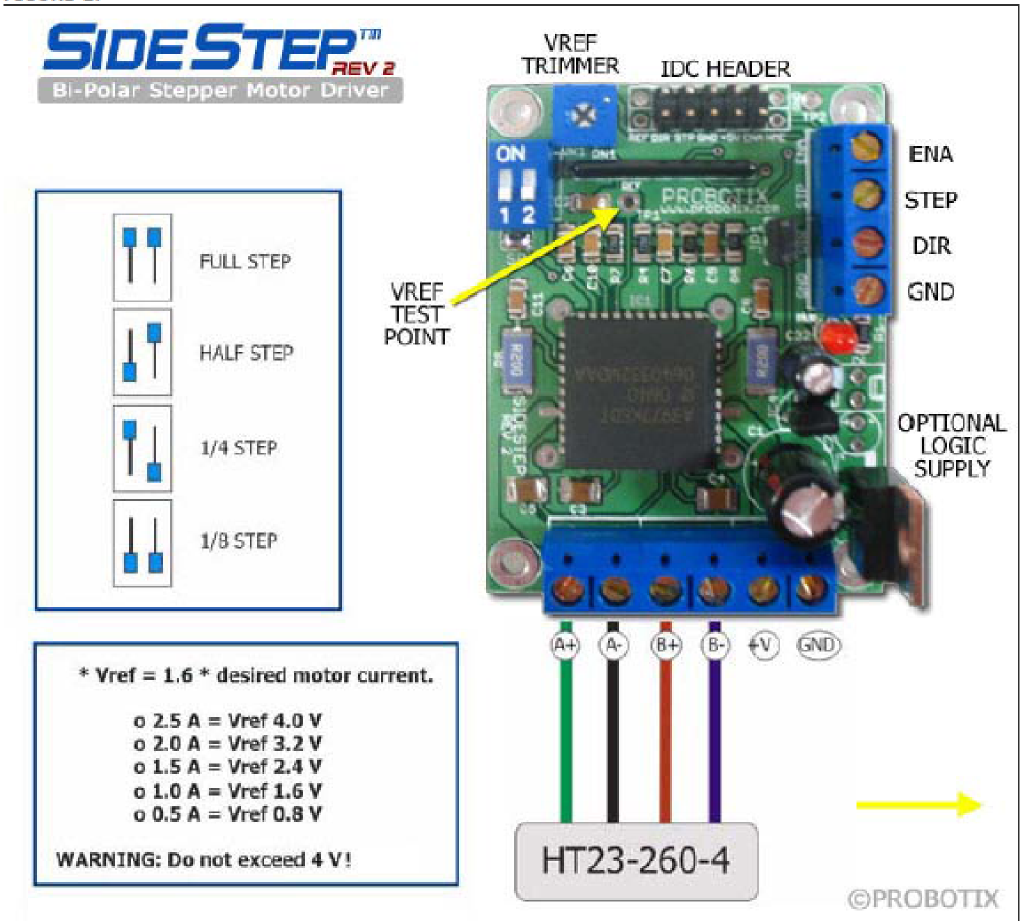
- Measure the DC voltage between the Ref Pin and GND, and adjust the trimmer as follows: Vref = 1.6 * desired motor current.
    - 2.5 A = Vref 4.0 V

- 2.0 A = Vref 3.2 V
- 1.5 A = Vref 2.4 V
- 1.0 A = Vref 1.6 V
- 0.5 A = Vref 0.8 V

WARNING: Do not exceed 4.0 V!

1. Determine the step resolution you wish to use, and set the dip switches according to Figure 2.
2. If driving your motors at more than 1.5Amp, install a BGA heatsink over the driver chip. Contact us if you need heatsinks.
3. Apply power.
4. Connect a voltmeter between the VREF signal and GND and adjust the current trimmer to the desired voltage determined above.

FIGURE 2:



WARNING: The SideStep has an optional on board voltage regulator section for supplying the logic side of the driver when NOT using one of our breakout boards or as a stand-alone stepper motor driver. JP1 must be removed when supplying the 5V logic voltage through the IDC cable header. Applying 5V through the IDC header, for example, when using on of our breakout boards, with this jumper installed will destroy your board and void your warranty!

WARNING: Never remove a connection to the stepper motor with power applied. There is a HIGH probability the A3977 IC will be damaged. The A3977 is rated for 35V DC max. The power supply voltage should be limited to ~32V DC to allow for back EMF generated by the stepper.

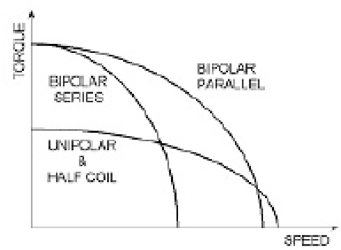
WARNING: If the motor is connected during this adjustment, excessive heating may occur. Most motors can NOT experience temperatures above 100°C. At these temperatures internal melting and seizure may occur. Short-term current overdrive will, in general, not harm most motors.

Motor Wiring

Unipolar and Bipolar Half Coil, because we're using less turns, doesn't give us great low speed torque, but because of the low inductance, holds the torque out to high speeds.

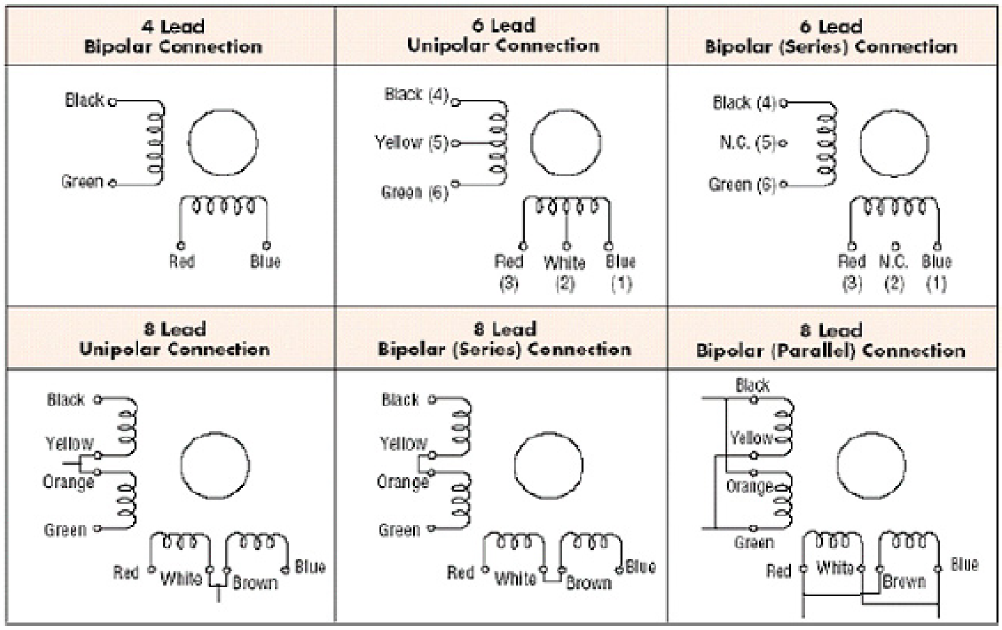
Bipolar Series uses the full coil so it gives very good low speed torque. But because of the high inductance, the torque drops off rapidly.

Bipolar Parallel also uses the full coil so it gives good low speed performance. And its low inductance allows the torque to be held out to high speeds. But remember, we must increase current by 40% to get those advantages.



Connections	Resistance (Ohms)	Inductance (mH)	Current (A)	Voltage (V)	Holding Torque (oz-in)
Unipolar	Same as NamePlate	Same as NamePlate	Same as NamePlate	Same as NamePlate	Same as NamePlate
Bipolar Series	NamePlate X 2	NamePlate X 4	NamePlate X 0.707	NamePlate X 1.414	NamePlate X 1.414
Bipolar Half Coil	Same as NamePlate	Same as NamePlate	Same as NamePlate	Same as NamePlate	Same as NamePlate
Bipolar Parallel	NamePlate X 0.5	Same as NamePlate	NamePlate X 1.414	NamePlate X 0.707	NamePlate X 1.414
Driver	**Motor Choices**	**What to Do**	**How to Do It**		**End Result**
Unipolar (6 Leads)	6 Lead Motor	Use as is (Unipolar)			6 Leads
	8 Lead Motor	Convert to Unipolar	Tie yellow and orange together and use AND Tie white and brown together and use		6 Leads
Bipolar (4 Leads)	6 Lead Motor	Convert to Series	Tape off yellow and white leads and don't use		4 Leads
		Convert to Half Coil	Tape off black and red leads OR Tape off green and blue leads		4 Leads
	8 Lead Motor	Convert to Series	Connect yellow and orange and tape off AND Connect white and brown and tape off		4 Leads
		Convert to Parallel	Tie black and orange together AND Tie yellow and green together AND Tie red and brown together AND Tie white and blue together		4 Leads
		Convert to Half Coil	Tape off black, yellow, red, and white OR Tape off orange, green, brown, and blue		4 Leads

Wire Connection Diagrams



A chopper drive allows a stepper motor to maintain greater torque or force at higher speeds. The chopper drive uses Pulse Width Modulation and current sense feedback to regulate a constant current output of the drive transistors. The chopper gets its name from the technique of rapidly turning the output voltage on and off (chopping) to control motor current. Low impedance motor coils will deliver the best performance for a chopper driver. The chopper drivers main benefit is allowing you to overdrive your motors with a higher than rated supply voltage, which will charge the coils faster. So long as you do not exceed the breakdown voltage of the stepper motors coils, and do not exceed the rated voltage of the drives, you will benefit from faster acceleration and higher top end speeds, without harming your motors.

Microstepping electronically divides a full step into smaller steps by holding the stepper motors phases "in between" it's physical steps. For example, if a stepper motor provides 200 steps per revolution, then a eighth step micro-step driver would deliver 1600 steps per revolution. Micro-stepping increases step resolution and also reduces losses due to audible distortion and resonance. This results in a stronger, smoother operating drive. When microstepping, you must multiply the number of steps per unit by the micro-step resolution in the CNC control software.

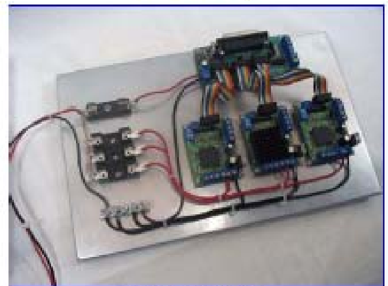
Microstepping effectively reduces the step increment of a motor at the cost of accuracy, because the electronic resolution does translate exactly to physical resolution. Therefore you should not rely on microstepping to increase your accuracy, but instead adjust your drive screw pitch when you need closer tolerances.

Installation Instructions

Step 1: Choose and mark off mounting locations for the components. The drivers will need to be close enough to the breakout board to connect the supplied IDC cables.

Step 2: Mount the Breakout Board and Drivers using 4-40 standoffs.

Click To Enlarge



Click To Enlarge

Step 3: Next mount the fuse and grounding blocks.

Step 4: Wire the power and ground wires. Use a ground block as pictured to connect all of the grounds to a single location. Do not connect the motors, yet.

Click To Enlarge

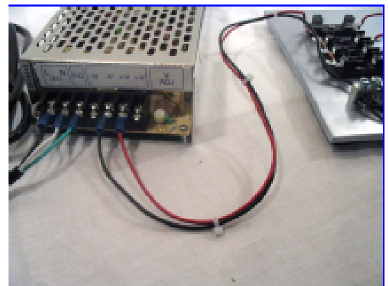
Step 5: Connect the power supply to the fuse and grounding block.

- Whack the female end off of the power cable.
- Strip back 2" of the outer jacket. Separate the 3 wires. You should have a Black (L) and a White (N) and a Green ground (G).
- Clip back the string.
- Strip off 1/2" of insulation from each of those.
- Trim down some screw eyes so they will fit into the slots in the power supply connectors.
- Remove the screws on the power supply connectors.
- Crimp on the connectors and screw them down.
- Plug in the power cable and verify that you have 24 Volts across V+ and V-
- Then, Disconnect the power cable
- Crimp connectors in the same way as above to your power wires that lead to your fuse blocks and screw them down.

Click To Enlarge

Step 6: Install the fuses in the fuse blocks.

Click To Enlarge



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Step 7: Connect the power and set the VREFs as described above. Disconnect the power when finished.

Step 8: Connect the motors

Step 9: Install the DB25 cable between the breakout board and your PC

Step 10: Configure your software. Refer to the breakout board manual for software configuration and limit and e-stop wiring.

Step 11: Test the system with your software.

Control Software Setup

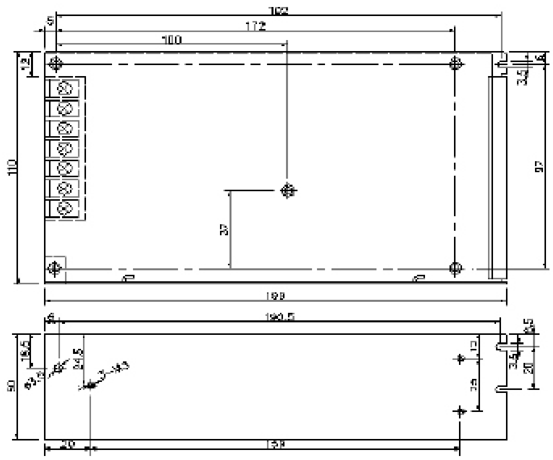
The SideStep is negative logic. The STEP, DIRECTION, and ENABLE lines should be inverted in your software. Please contact us if you need help configuring your software.

Minimum pulse width for the step pulse is 5 uS. Maximum step frequency is 40 kHz. You may destroy your drivers if you try to exceed 40kHz. Most steppers torque really drop above 1 kHz at full step, or 8 kHz if you're using the eighth-step mode.

Power supply datasheet

METAPO

Industrial Power Supply IM150W Series



SPECIAL FEATURES

AC input range selected by switch
High efficiency
DC adjust range
LED Power indicated
Output reverses protection
Free air cooling convection
199* 97* 50 mm
Weight 0.73 kgs/pcs
1 year warranty

SPECIFICATION

Output
Maximum power..............150 Watts
DC adjust range..............± 10% of rating output voltage
Hold-up time...................> 20 ms at 230Vac / 50Hz
Rise time.........................< 20ms
Over Voltage Protection...110% ~ 135% of rated output
Over Power Protection......105% ~ 150%, auto-recovery
Short Circuit Protection......shut off, AC recycle to restart
Connector.....................7P / 9.5mm pitch terminal block

Input
Input range...........90~132Vac/180~264Vac selected by switch
Frequency............47-63Hz
AC inrush current...Cold start, 30A @ 115Vac; 60A @ 220Vac
EMI/RFI................FCC Part 15J, Class A & CISPR 22 Class A

Operating temperature
0℃ to +40℃ @100%; -10℃ @ 80%; 50℃ @ 60% load
Storage temperature: -20℃ to +80℃
Free air cooling convection

Model	IM151C12-1M	IM151C24-1M
Output	V1	V1
Voltage	+12V	+24V
Max. Load	12.5A	6.5A
Efficiency	>80% @115Vac/60 Hz	>80% @ 115 Vac/60 Hz

Break out board datasheet

PBX-2 CNC Parallel Port Breakout Board User Manual

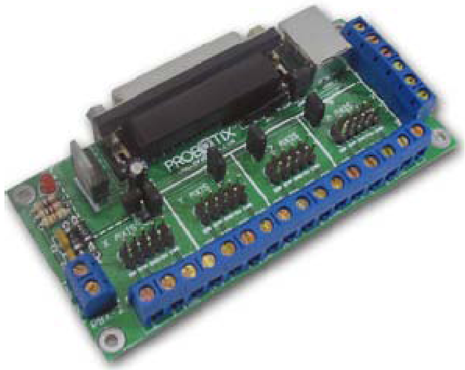
Parallel Port Breakout Board

Version 1.0
preliminary

Model: PBX-2

Breakout Board Specs:

- DB25 Female
- All Pins Brought Out
- Jumper Enabled Input Pull-up Resistors
- Integrated 5V Logic Supply Regulator
- PROBOTIX Pinheader & Screw Clamp Terminals
- Experimental USB Powered Logic Supply



Description

The PBX-2 is a Parallel Port breakout board designed specifically for Hobby CNC machines. It is compatible with a variety of Parallel Port CNC Control Software.

The PBX-2 has a built in LM317 based voltage regulator section that will supply 1.5AMPS @ +5V to the driver outputs of this interface. It also connects to the limit switch and e-stop inputs through a jumper connected 1K pull-up resistor network. The pullup resistors are needed in most cases when switching the logic inputs through physical switches.

The LM317 is rated for 40VDC, so you can wire it up to the same power supply as the motors. You may want to run it off of a WalWart to provide an additional layer of protection and to limit noise. Make sure to test the polarity of the the wires from the WalWart, and make sure it is not an AC output device. Any voltage between 6 and 40 volts should work.

The PBX-2 has an experimental USB power supply jack. This jack can supply the +5V logic supply side of your drivers. **Do not plug in a USB cable without disconnecting JP6**. JP6 isolates the LM317 based regulator section from the rest of the circuit, including the logic power indicator LED.

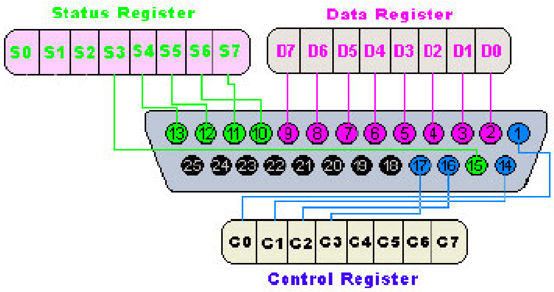
The USB specification allows the USB port to draw 100mA, without needing to enumerate. It is very likely that your PC's USB port is protected from current overdrive. Your results may vary, and I assume no liability for your PC. However, I have been using it for quite some time, on my PC. It probably would not protect you from spikes, so USE AT YOUR OWN RISK! I would recommend driving it through an externally powered USB hub.

The IDC cables can supply logic side power to your driver boards. Some of our drivers also have on-board logic supply regulators. **Use the jumpers to ensure that both regulator sections are not connected at the same time.**

The Parallel Port was primarily designed for controlling printer devices, so on some pins the logic inside of the PC is inverted for different reasons. The built in parallel port on your PC generally shows up at address 0x378, but that is determined by your BIOS

The PBX-2 is not an isolated breakout board. We strongly reccomend that you use an add-on parallel port card. Be aware that hose $10 MOSCHIP NM9805 Chipset driven boards will initialize at non-standard addresses. The Windows XP drivers will not let you change the address. This is not a problem for EMC or Mach3, but currently KCam will not allow you to use a non-standard parallel prot address.

Here is a pinout of a DB25 parallel port:

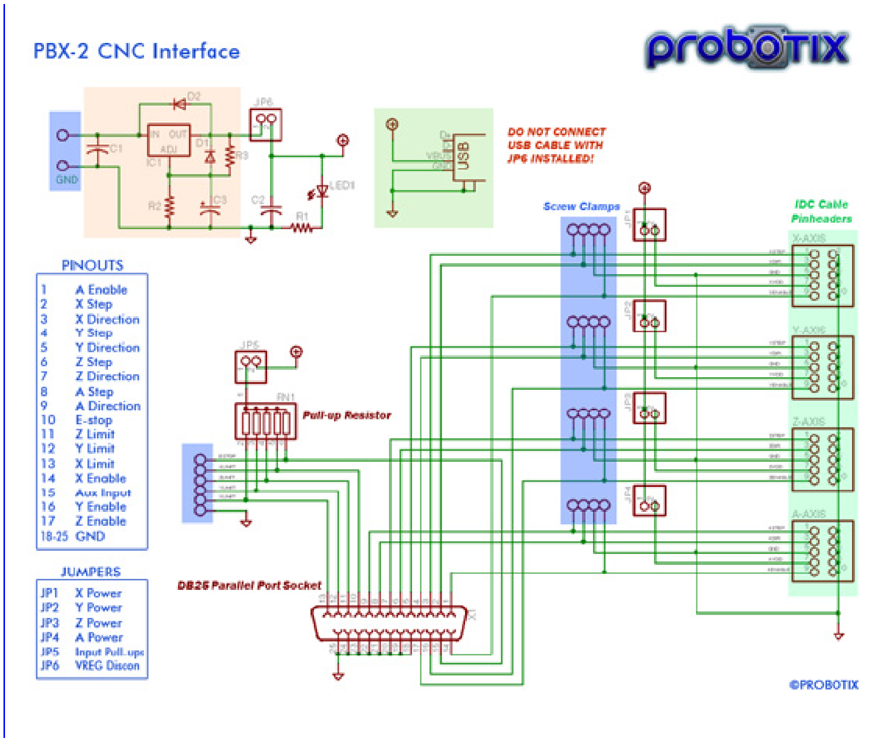


Pin No (DB25)	Signal name	Direction	Register - bit	Inverted
1	nStrobe	Out	Control-0	Yes
2	Data0	In/Out	Data-0	No
3	Data1	In/Out	Data-1	No
4	Data2	In/Out	Data-2	No
5	Data3	In/Out	Data-3	No
6	Data4	In/Out	Data-4	No
7	Data5	In/Out	Data-5	No
8	Data6	In/Out	Data-6	No
9	Data7	In/Out	Data-7	No
10	nAck	In	Status-6	No
11	Busy	In	Status-7	Yes
12	Paper-Out	In	Status-5	No
13	Select	In	Status-4	No
14	Linefeed	Out	Control-1	Yes
15	nError	In	Status-3	No
16	nInitialize	Out	Control-2	No
17	nSelect-Printer	Out	Control-3	Yes
18-25	Ground	-	-	-

Please note how they are designated inputs, outputs, or both. Also, some of them are inverted. Depending on the software you choose to control it, the configurations may need to be inverted on certain inputs or outputs. Without going into the details, just know that you may have to try different settings to get your machine to respond properly.

Here is the intended and typical pinout of the PBX-2 cnc interface:

PIN	Signal
1	A Enable
2	X Step
3	X Direction
4	Y Step
5	Y Direction
6	Z Step
7	Z Direction
8	A Step
9	A Direction
10	E-stop
11	Z Limit
12	Y Limit
13	X Limit
14	X Enable
15	Aux Input
16	Y Enable
17	Z Enable
18	-25 GND



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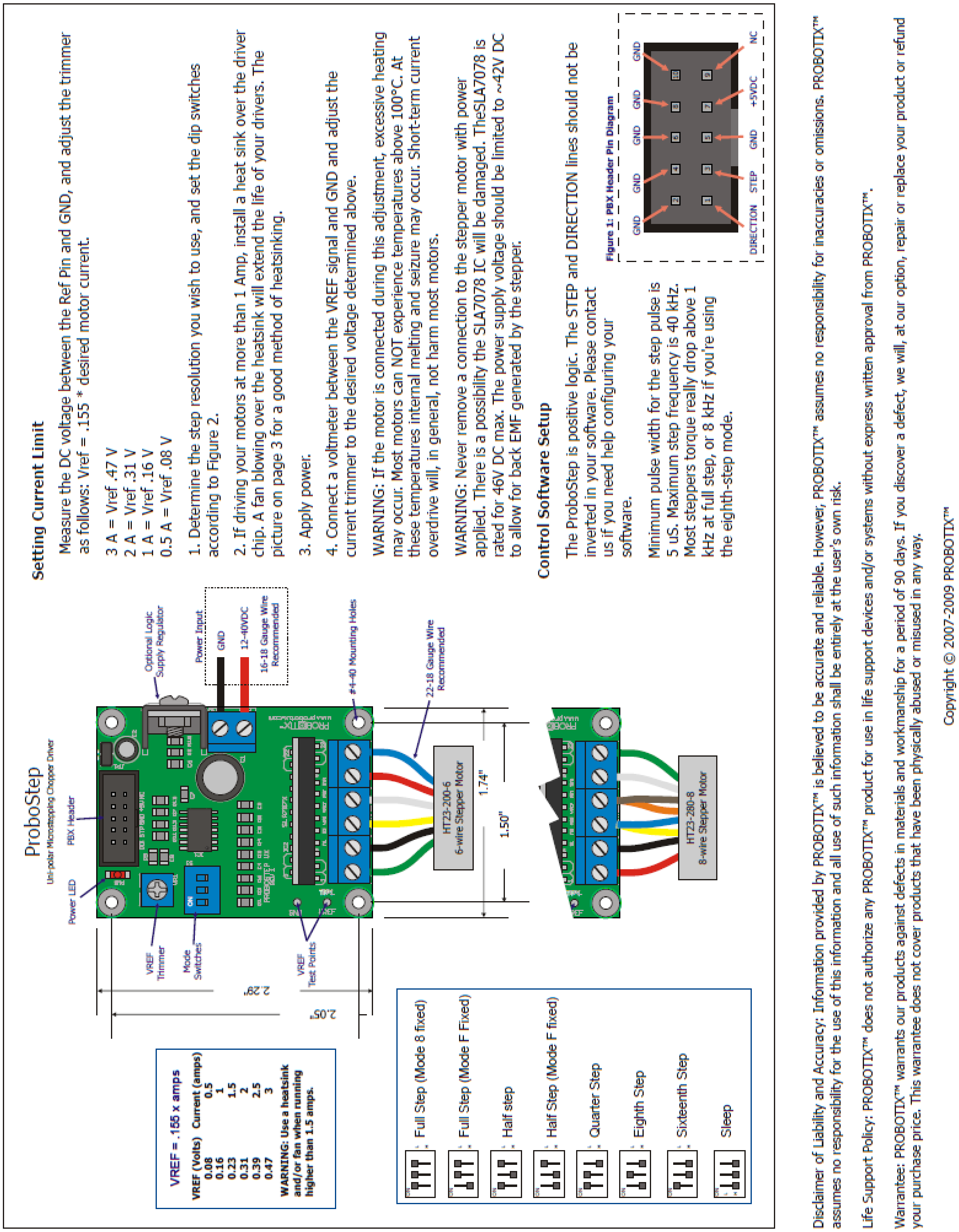
Warrantee: PROBOTIX™ warrants our products against defects in materials and workmanship for a period of 90 days. If you discover a defect, we will, at our option, repair or replace your product or refund your purchase price. This warrantee does not cover products that have been physically abused or misused in any way.



ProboStep

Uni-polar Microstepping Chopper Driver

VREF (Volts)	Current (amps)
0.08	0.5
0.16	1
0.23	1.5
0.31	2
0.39	2.5
0.47	3

VREF = .155 x amps

WARNING: Use a heatsink and/or fan when running higher than 1.5 amps.

Setting Current Limit

Measure the DC voltage between the Ref Pin and GND, and adjust the trimmer as follows: Vref = .155 * desired motor current.

3 A = Vref .47 V
2 A = Vref .31 V
1 A = Vref .16 V
0.5 A = Vref .08 V

1. Determine the step resolution you wish to use, and set the dip switches according to Figure 2.

2. If driving your motors at more than 1 Amp, install a heat sink over the driver chip. A fan blowing over the heatsink will extend the life of your drivers. The picture on page 3 for a good method of heatsinking.

3. Apply power.

4. Connect a voltmeter between the VREF signal and GND and adjust the current trimmer to the desired voltage determined above.

WARNING: If the motor is connected during this adjustment, excessive heating may occur. Most motors can NOT experience temperatures above 100°C. At these temperatures internal melting and seizure may occur. Short-term current overdrive will, in general, not harm most motors.

WARNING: Never remove a connection to the stepper motor with power applied. There is a possibility the SLA7078 IC will be damaged. TheSLA7078 is rated for 46V DC max. The power supply voltage should be limited to ~42V DC to allow for back EMF generated by the stepper.

Control Software Setup

The ProboStep is positive logic. The STEP and DIRECTION lines should not be inverted in your software. Please contact us if you need help configuring your software.

Minimum pulse width for the step pulse is 5 uS. Maximum step frequency is 40 kHz. Most steppers torque really drop above 1 kHz at full step, or 8 kHz if you're using the eighth-step mode.

Figure 1: PBX Header Pin Diagram

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Warrantee: PROBOTIX™ warrants our products against defects in materials and workmanship for a period of 90 days. If you discover a defect, we will, at our option, repair or replace your product or refund your purchase price. This warrantee does not cover products that have been physically abused or misused in any way.

Stepper motor driver datasheet

ProboStepVX

Uni-polar Microstepping Chopper Driver

Model: ProboStep VX

Stepper Motor Microstepping Driver Specs:

- Chopper Current Driver
- 0.5 - 3 Amp Current Limiting
- Short-circuit & Open-circuit Protection
- Full, Half, Quarter, Eighth & Sixteenth Microstepping
- B uffered Step & Direction Lines
- 10V - 42V Supply
- For 5-, 6-, and 8-wire Stepper Motors

Description:

The ProboStep is a complete microstepping motor driver and control system with a built-in translator. It is designed to operate uni-polar stepper motors in full-, half-, quarter-, eighth-, and sixteenth-step modes with output drive capability of 44V and 3.0 A. This driver utilizes the Sanken SLA7078MPR chip which includes built-in sense current detection and load circuit short or open protection provide lower loss and lower thermal resistance.

Features:

- Hardware or software selectable step and direction signals
- Current limit adjustable by potentiometer
- Wide range of motor power (10-42V)
- Power (for logic) indicator LED
- 3 A, 42 V Output Rating
- Fixed-offtime PWM blanking circuit reduces ringing
- 3.0-5.5 V Logic Supply Voltage Range
- Synchronous Rectification for Low Power Dissipation
- Internal UVLO and Short & Open Circuit Protection
- Crossover Current Protection

Flexible Design:

The ProboStep was designed with flexibility in mind with features including:

Internal synchronous-rectification control circuitry is provided to improve power dissipation during PWM operation.

Internal circuit protection includes short-circuit and open-circuit protection. Special power-up sequencing is not required.

The logic signals are brought out to a .1" pin header on one side, allowing for use of an IDC cable to connect your boards. Every other pin on the IDC header is connected to ground, which acts to shield the control signals from noise. Noise in a stepper control system can cause miss stepping, which can damage your equipment, cause injury, and ruin your work piece.

A schmitt trigger IC buffers the high voltage driver from your sensitive parallel port, and filters noise.

Unlike the SideStep, the driver chip, the ProboStep does not have thermal protection, so a heatsink must be used when driving motors at greater than 1 amps.

An under-voltage lockout circuit protects the A3977 from potential shoot-through currents when the motor supply voltage is applied before the logic supply voltage. All outputs are disabled until the logic supply voltage is above 2.7V; the control logic is then able to correctly control the state of the outputs.

Patented short and open circuit protection.

Unipolar Chopper Drivers:

Unipolar chopper drivers are the simplest form of stepper motor control. A set of four sink drivers control the current to each of the four half-phases of a stepper motor. The circuit includes recirculating diodes and a sense resistor that maintains a feedback voltage proportional to the motor current. The high side of the supply is split out to one side of each half-coil, and the other end of each half-coil is routed to the low-side transistor switches. Motor windings, using a chopper driver, are energized to the full supply level by turning on one set the switching transistors. The sense resistor monitors the linear rise in current until the required level is reached. At this point the switch opens and the current decays until a preset position is reached and the process starts over. This "chopping" effect of the supply is what maintains the correct current voltage to the motor at all times.

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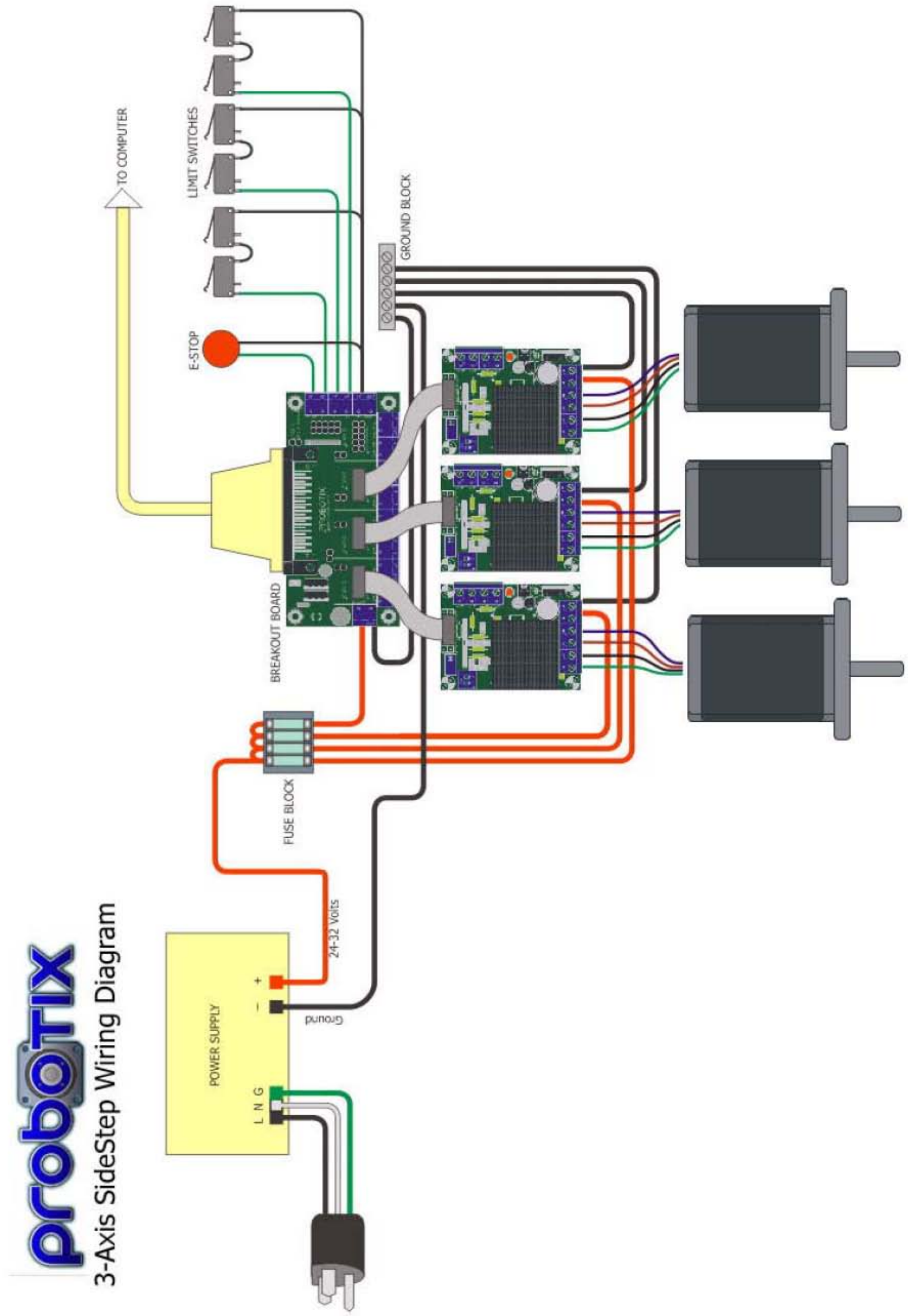
Wiring diagram



APPENDIX K: BIOS

Ryan Braun

Ryan is from Macomb, MI and graduated from Dakota High School in 2006. He decided in high school that he was going to major in engineering, and in his sophomore year at U of M chose mechanical engineering. He is interested in the automotive industry and manufacturing. After obtaining a Bachelor's of Science in Mechanical Engineering degree he plans on attending grad school for a master's degree, but is not sure whether it will be in mechanical engineering.

Yi Chen

Yi Chen is a student of the University of Michigan in his senior year, his major is mechanical engineering. He also studied at Shanghai Jiaotong University (SJTU), Shanghai, China before he transferred to U of M. He is interest in field of control and automobiles. When not working, he likes basketball and watching game videos. Yi Chen can be reached via davidsky@umich.edu

Nate Hinkle

I grew up in the Kalamazoo area in Michigan, and was homeschooled from kindergarten through all of high school. I was the typical kid that loved to take apart anything I could get my hands on (VCR's were my most common victims). I chose mechanical engineering because it seemed to be the broadest of engineering disciplines, allowing me to be able to explore many different topics and engineering approaches. While graduate school is possibly a future option, at the moment I am looking forward to graduating in April and moving into a full time position at that time. Fun fact: I am the 6^{th} of 7 children.

John Prins

John is originally from Holland, MI, graduating from Holland Christian High School Class of 2006. His interest in mechanical engineering began by the interest of the mechanical systems of cars, trucks, tractors, and ATV's and the design of these vehicles. After graduating John would like to work in the off-road equipment industry and particularly in agriculture equipment. After a few years of working he may return to get a masters degree in mechanical engineering.