MIE243

Final Group Design Project

Wednesday, December 4, 2019

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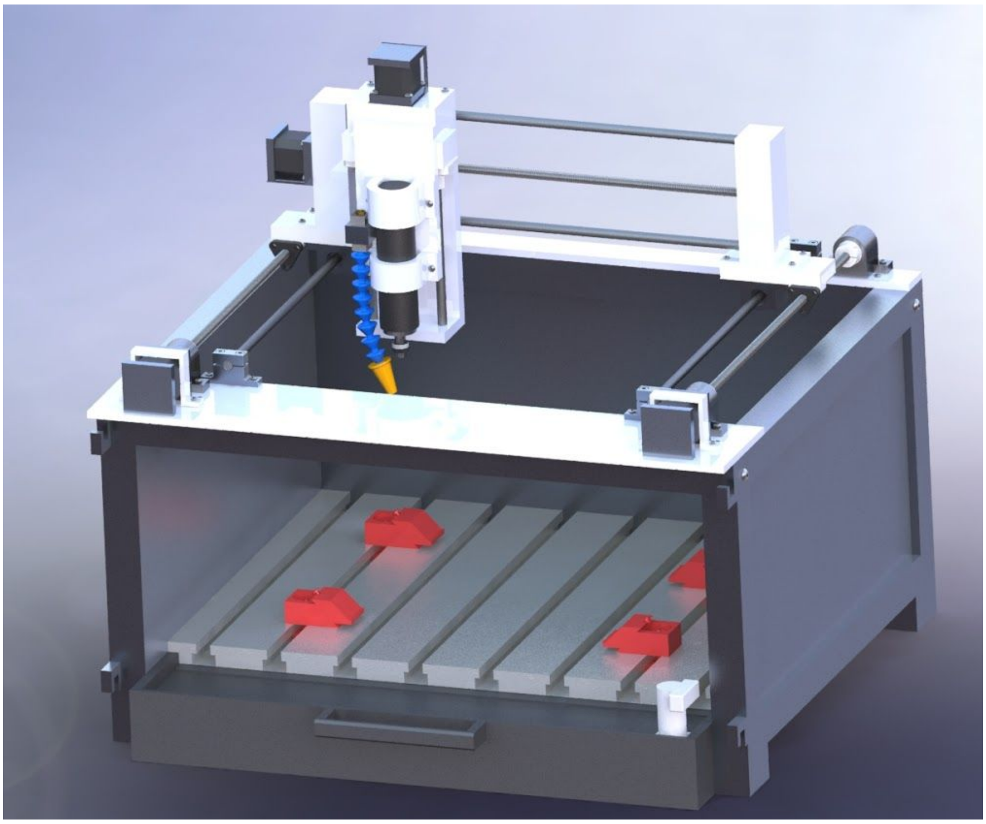

1.0 Introduction And Research

Computer Numerical Control mills, more commonly referred to as CNC mills, are used in a variety of applications. CNC mills uses computerized controls and cutting tools to remove material in individualized patterns to create a unique part. The goal of this design is to produce a kit-type home CNC mill marketable to beginner and hobbyist consumers. With the hobby CNC market on the rise, there is an increasing demand for low cost, simple, and reliable machines. This document will outline the human factors that affect the design, several iterations throughout the design process, and the proposed design with various technical justifications.

1.1 Research

There are many constraints that exist when designing a CNC mill for home-usage. To meet the needs of consumers, the design must be easy to assemble, simple to use, and reliable while also being cost-effective. In addition, users must be able to easily replace components increasing the importance of finding affordable and standardized components. The design will follow the following constraints based on the research in the subsequent sections.

1.1.1 Home Usage and Kit-Type

To be a viable home usage, kit-type milling machine, the design must consider the cost, features provided, technical capabilities, and assembly [1]. The average cost of home usage CNC mills for 10 highly rated machines is approximately $1000 [2]. These machines can range as low as $400 to over $2000. To ensure this design is competitive with the current market, the goal for this design will be to remain under $1400 with a hard constraint of $1600. The less expensive machines generally provide a small working space. For example, the $500 Whittle CNC offers 2” of cutting space in the Z direction and has strict limitations on material selection [3]. To justify the increase in price, the design will provide a large workspace and will be simple to assemble for the average customer. This will be done by ensuring that the assembly will require tools that can be found in a basic toolbox for an average home, including but not limited to multipurpose screwdrivers and wrenches. [4]. The features of this design must include at minimum 3-axes of motion, adjustable clamps to secure the material, a cooling system, and a debris collection system.

The average desk size for an office desk is approximately 40” by 25” [5]. Assuming about half of the desk’s space can be spared for a CNC machine, the limit of the size of the design will be 20” by 15”, with no limit on the vertical distance. Average wooden desks can also hold over 100 pounds, therefore for a kit-type machine, weight will not be strict limiting factor [5]. The goal of the design will be to remain under 100 pounds.

1.1.2 Materials and Drill Bit Types

In order to operate the CNC mill efficiently while remaining within the home usage constraints, the design must accommodate a certain number of materials. The most common materials cut on a CNC machine include aluminum, brass, copper, steel, titanium, wood, foam, fibreglass, and plastic [6]. Our design will not include fibreglass as the debris can be carcinogenic and potentially dangerous if not ventilated properly, for example in a garage. Table 1.1 depicts the acceptable tools, average costs, and specific limitations.

Table 1.1. Materials compared with the tools required and average costs [7]. Average costs are calculated from prices provided by McMaster Carr [8].

Material	Acceptable Tools	Average Cost for a block approximately 4”x4”x6”	Limitations
Aluminum	-High-speed steel (HSS) -Black oxide-coated HSS -Cobalt drill bits (specifically for boring) -Titanium coated HSS	$76	-Liquid coolant necessary

Brass	-Cobalt drill bits	$190	-Liquid coolant necessary
Copper	-Cobalt drill bits	$140	-Repeated cuts will make steel incredibly hot so it is recommended to keep a bucket of water for quenching
Wood	-Black oxide-coated HSS -HSS -Titanium coated HSS	<$40	-No walnut, black locust, or cedarwood as they are hazardous -No pressure-treated woods
Plastic (Polypropylene)	-HSS -Black oxide-coated HSS -Titanium coated HSS	$70	-fan as coolant will work as well as liquid coolant [9]

Analysis of *Table 1.1* helps constrain the design to specified materials by ensuring affordable costs of materials, lower variance of drill bits, and taking into account their respective limitations. This design should cut soft metals (aluminum), woods and plastics. Although there are many alloys of aluminum of varying strengths and hardnesses, the most machinable alloys that are commercially used for hobbyist milling purposes are Al 6061 as well as Al 6063 [9]. These materials as well as wood and plastics are also the lowest in price and are easy to purchase online or in-store. None of these materials have very limiting constraints besides the requirement for liquid coolant or a fan cooling system, which will be finalized later in the design process. Black oxide-coated HSS drill bits are compatible with all the specified materials and is therefore a viable bit type.

They are affordable as they average less than $12 each, are known to resist corrosion, and are durable [8]. This type of drill bit was chosen over ones such as HSS or Titanium coated HSS because of cost and the long lifespan of the bit.

2.0 Engineering Specifications

Engineering specifications outline important conceptual decisions made about the design. The following section will demonstrate major design decisions that the final design will attempt to achieve. These specifications will later be used to determine if a candidate design is viable based on the specified goals, objectives, and constraints. Some of these specifications were generated by the use of the black box method [Appendix A]. The design will maintain a precision of ±0.01in in all areas of the design.

2.1 Motion in the X-Y-Z Plane

The following specification is applicable independently to each axis of motion, where each axis receives separate inputs and outputs.

Input: Rotating, multidirectional (low speed, high torque)

Output: Linear, multidirectional

- Must accurately switch direction of output motion [Appendix A]

Use Cases/Operation: at least one motor to be used per axis with a minimum of 3 axes of motion

- Design must be sturdy to mitigate vibrations or reactionary forces from the material

Flexibility: Can have anywhere above 3 axes of motion

- Can switch direction without needing to switch the input
- Accurate to ±0.01in

Assembly: Must be easy for user to assemble

- Will provide required screws for assembly with clear instructions
- Motor connections should be demonstrated clearly and be easy to comprehend
- User must not be required to purchase additional elements for construction or assembly purposes

2.2 Clamping Mechanism

The clamps should resist the motion of material when being exposed to forces from the drill bit. This mechanism must be non-invasive and must not limit the motion of the drill bit. The clamps must be flexible to various shapes of material defined by the size constraint of the workspace (approximately 15” by 15” at the maximum). They must also be inexpensive and simple for the user to attach and detach to the main machine.

2.3 Spindle Motion

Input: Rotational, continuous

Output: Rotational, continuous (medium to high speed, low to medium torque)

- Must vary in output RPM dependent on the material constraints (around 8000 RPM for aluminum and up to 18000 RPM for plastic and wood [7]).

Use Cases/Operation: Design must be resistant to reactionary forces from material

Assembly: Will be pre-assembled for ease of kit assembly as the spindle is motor driven

2.4 Size of Machine and Workspace

To fit the constraint set from the research, the frame must not exceed an area of 20” by 15” for the base. The vertical distance can vary based on each candidate design in the subsequent sections. This size constraint will influence the resulting workspace. The workspace should be greater than 10” by 10” to ensure versatility in options for the user and to exceed the workspace of competing hobby CNC mills [2]. The center of mass of the machine should be low to ensure stability of the machine at high speeds [10].

2.5 Cooling System

A cooling system is required for the operation of this design for user safety concerns and to ensure a clean and acceptable product. Coolants dissipate high temperatures that can lead to melting, warping, discolouration, or even tool failure [11]. For materials such as wood or plastic, an intensive cooling system is not necessary as it can be cooled by a fan in most cases. However, the design's material constraints include woods, plastics, and aluminums, so a liquid cooling system is required. The coolant must be applied directly to the cutting surface in a continuous or oscillating fashion, depending on the candidate design decisions.

2.6 Cost

To remain competitive with the existing hobby CNC mill market, the design will attempt to remain under a total of $1200. The design must not exceed $1600 as the average cost of CNC mills for home usage is around $1000 [2]. This price constraint limits the design as more affordable materials will be chosen for production. Materials and mechanisms that have a precision of ± 0.01in [12] will be accepted and considered viable.

3.0 Candidate Designs

This section outlines the design ideas generated as viable solutions to the problems presented in the above sections. Through individual brainstorming, over five mechanisms were generated ideas for each engineering specification. A morph chart was then used to combine some of these ideas into three candidate designs [Appendix B]. The fourth candidate was then created through design iteration by combining Candidates two and three. The following four candidate designs were chosen due to their ability to achieve set specifications.

3.1 Candidate 1

This design involves the use of a mechanical arm mechanism for the milling process. The spindle is attached to the end of the arm, which contains 1 degree of rotational freedom on a plane along each of three different joints. . This joint system allows for multiple degrees of cuts and low housing requirements. Through the use of a lead screw mechanism, the arm will be moved along the axis perpendicular to the plane of motion of the arm, with multidirectional motion. There are also linear slots in the base plate to collect the debris left over by the milling process. The clamping mechanisms for this design are “L shaped” systems to secure the working material so that unwanted motion (slipping) is avoided. These clamps will be secured directly to the base plate through the linear slots and can be easily assembled by the user. The workspace will be 15” by 15”, utilizing the entire available area, and the goal of the arm’s height is to be at least 8” tall. There is a liquid cooling system that is attached to the arm that is delivered by a tube and an external system for users to easily refill the liquid when it depletes. The use of lead screws and joint systems for motion provide moderate cost options while meeting the requirements for motion. Should this design be selected for the final candidate, further cost analysis will be done. As is, the design should meet the cost constraints, however, dependent on how much assembly can be done by the user, mechanisms may need to be iterated to become more assembly friendly.

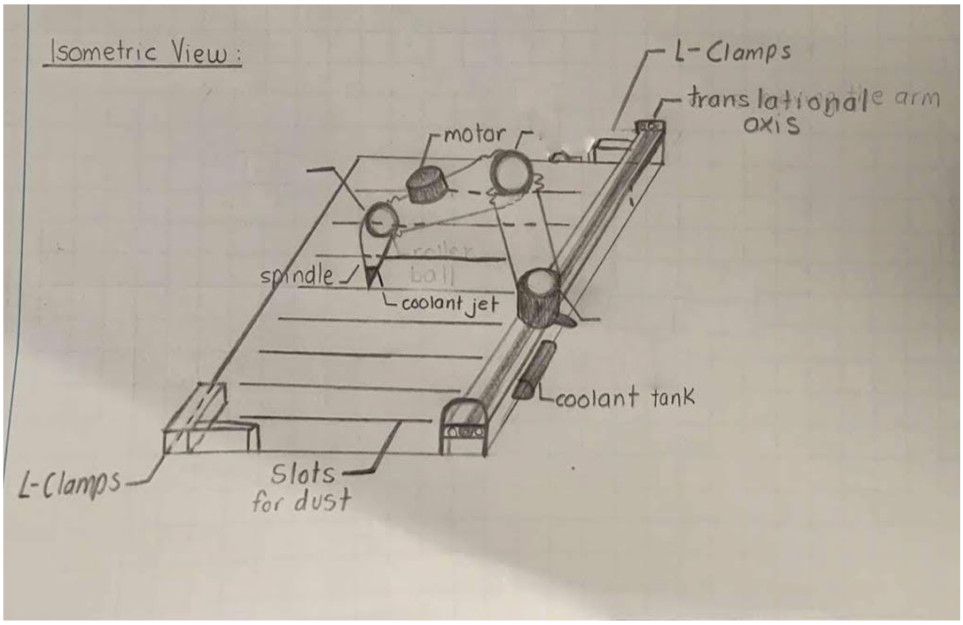

Figure 1.1: An isometric view of the candidate design depicting the joint motion of the arm as well as the horizontal motion using a lead screw.

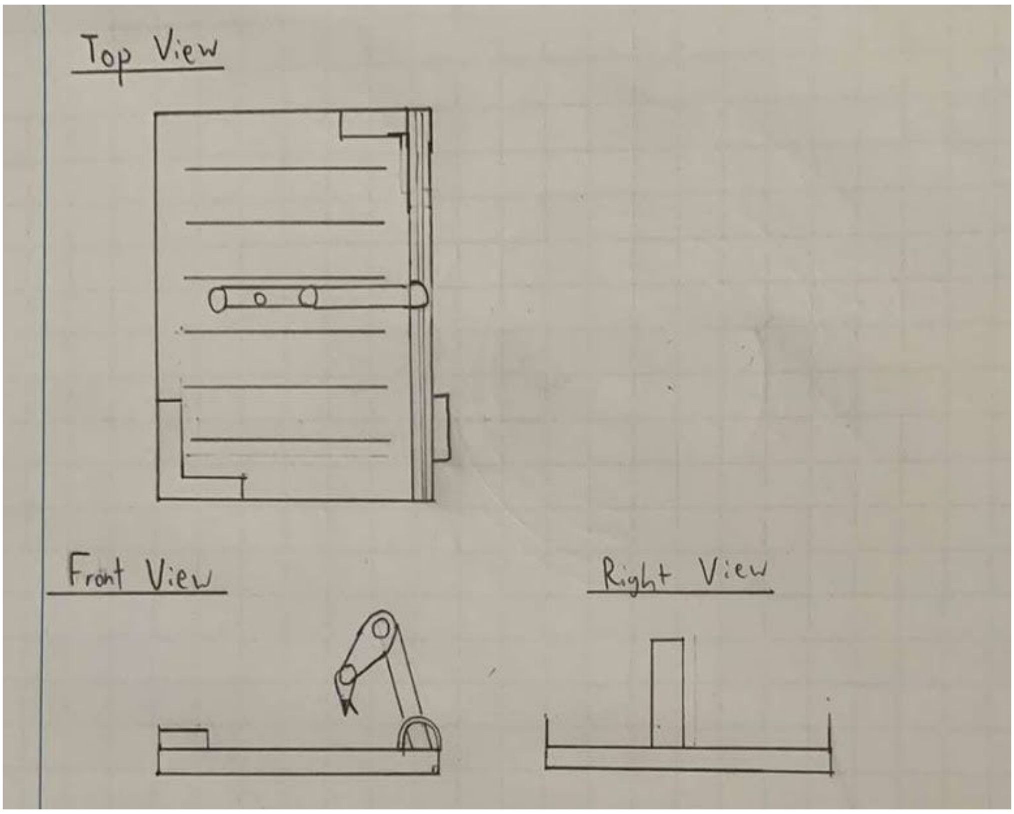

Figure 1.2: Engineering sketches depicting the views of Candidate 1

3.2 Candidate 2

This design involves a rack and pinion system to translate a semi- rigid arc on the horizontal axis. *Figure 1.3* depicts an open rack and pinion system, however, in the final design there will be a case covering the mechanism to ensure debis does not cause severe damage.

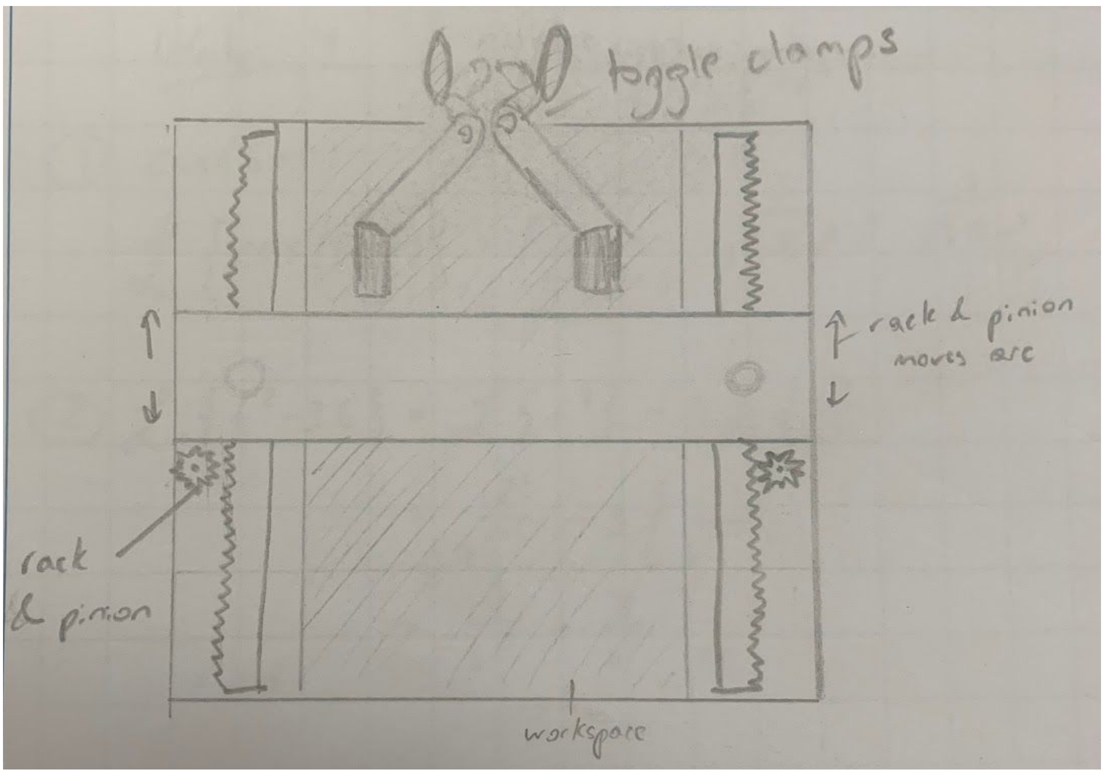

Figure 1.3: Top view of Candidate 2 showing the rack and pinion mechanism

The clamping system for this design will utilize toggle clamps. This allows for a wide variety of sizes as the distance between the arms can be adjusted. This also provides a large amount of support to prevent motion of the material. The spindle is attached to a semi-rigid arc and is moved along the top of the arc by another internal rack and pinion mechanism. The horizontal bar will also be moved vertically by a rack and pinion mechanism. The dimensions of the workspace will be 15” by 12” due to the space taken up by the arc. The design will have a height of 10” to allow for a high versatility in material size options.

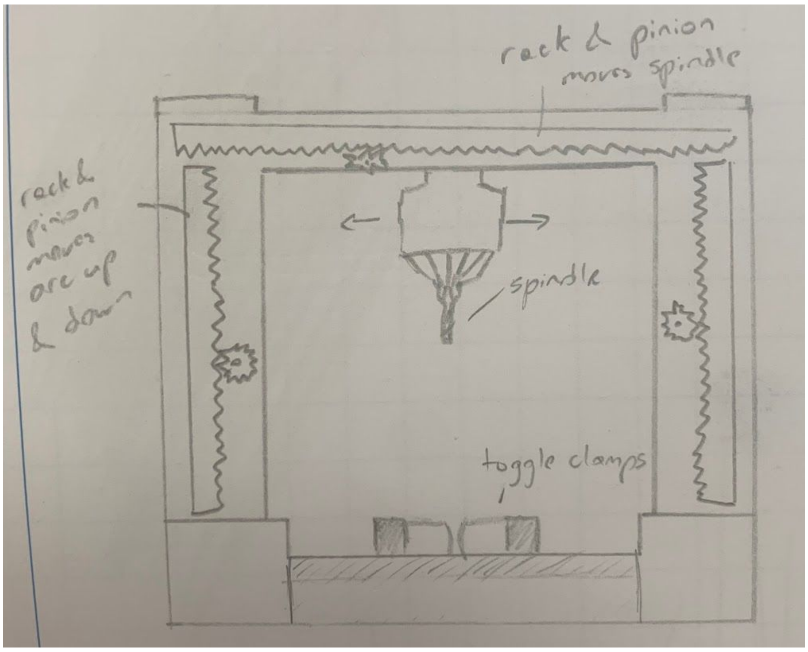

Figure 1.4: Side view of Candidate 2 showing the horizontal and vertical motion of the spindle as well as a closed view of the toggle clamps.

A fan cooling system is attached to the vertical arcs to cool the material continuously. An optional removable exterior casing is provided to contain debris in one single area for easy clean up and to ensure sharp shards do not cause potential harm. The use of several standardized rack and pinion mechanisms helps to minimize the cost. In addition, many manufactured parts are very simple to produce and can be easily assembled by the user, contributing to the minimal cost.

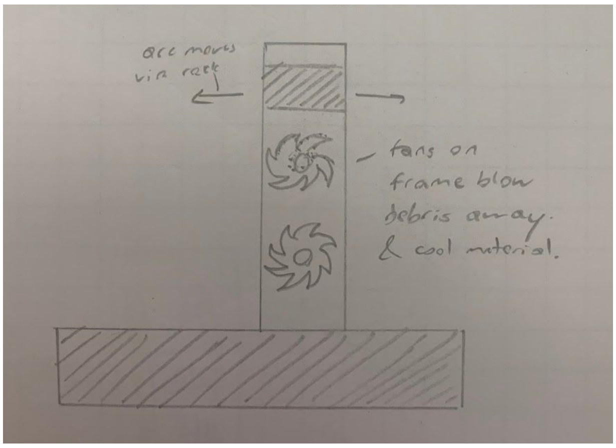

Figure 1.5: Right view of cooling system

3.3 Candidate 3

This design includes lead screw, worm gear, and spur gear mechanisms to control the motion along the X and Y plane. These components are held up by a rigid frame to mitigate vibrations and ensure stability. There is a motor, easily attached manually, to the side of the frame to power the Y axis by rotating a double ended worm gear shaft that each turn a spur gear on opposite sides of the frame. These spur gears are each attached to a lead screw and the lead screws uniformly translate a pair of flange nuts in the Y axis.

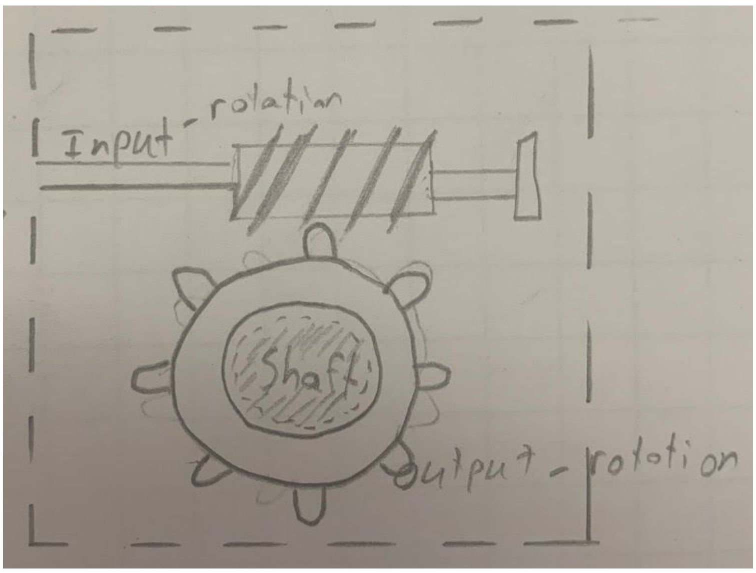

Figure 1.6: Worm gear mechanism producing rotational output to move the lead screw.

Similarly, the x motion is controlled by a lead screw mechanism. A stepper motor is used to power the rotational motion of the lead screw to translate the attached spindle back and forth. Finally, the z axis will be powered by a belt and lead screw mechanism. The belt is powered by a stepper motor to allow for uniform motion along the whole z motion mechanism. Four lead screws are attached to the belt and rotate uniformly to move the plate up and down.

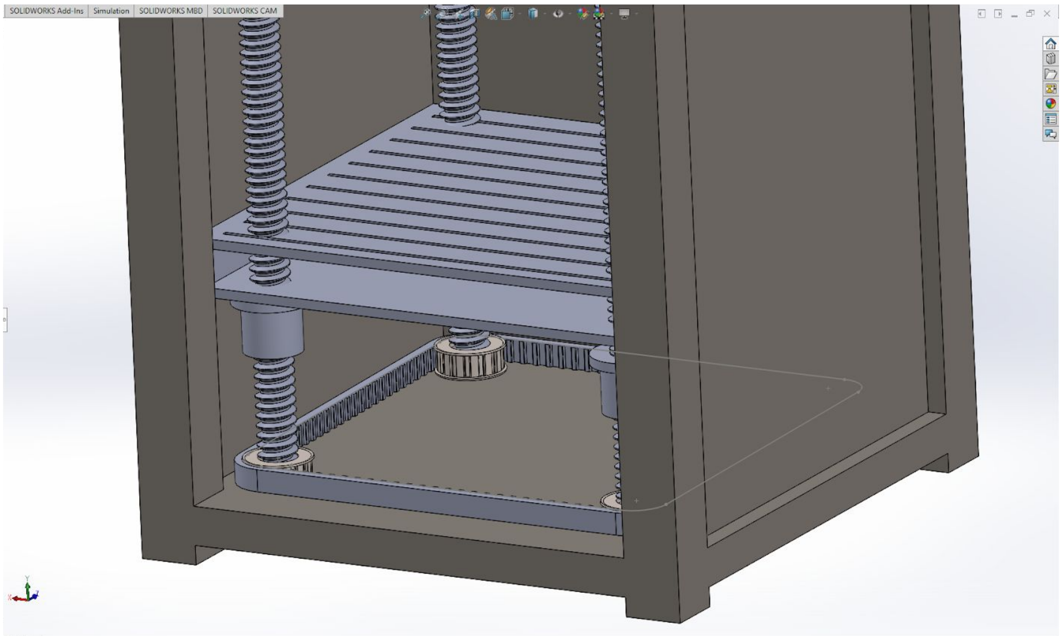

Figure 1.7: Rough CAD drawing of belt mechanism to power motion in the z direction.

The spindle will be rigidly attached to the X axis lead screw, and will cut into the material by the vertical motion of the base plate. There will be a non-invasive clamping mechanism with two block sections and two actuating lead screw like components. One block will be fixed onto the base plate, while two threaded shafts run parallel to each other, connecting the second block that can be brought closer (to clamp) or further (to release) by manually turning these threaded shafts. The 13" by 13" base plate will optimize the working area and the lead screw will lift the plate up approximately 10". The base plate will have linear slots to collect dust. The dust will fall into a dust collecting tray that can be easily removed by the user to allow easy disposal of waste. The use of standardized lead screw mechanisms as well as a belt will help to minimize the total cost of the final design. The parts used in this design are highly standardized including the lead screws, worm gears, spur gears, support shafts, belt, and several other components. The limited number of custom made parts further contribute to the minimal cost of this design. There is a liquid cooling system not depicted in the engineering sketches that will be implemented through a tube along the path of the lead screw to effectively cool the cutting surface. There will be an optional safety net that can be attached to the front open area to prevent material shards from exiting the workspace or liquid coolant from splashing on the external surfaces.

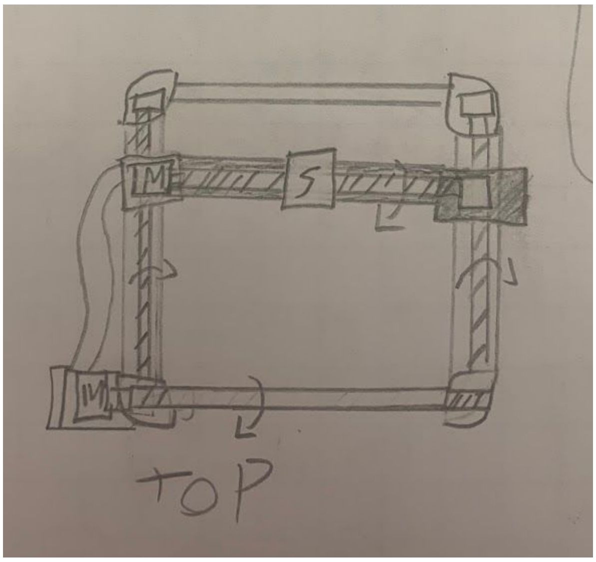

Figure 1.8: Top view of Candidate 3 depicting the motion on the X and Y planes through lead screw mechanisms and a hidden worm gear mechanism.

3.4 Candidate 4

This design comes from an iteration combining the optimal components of Candidates 2 and 3. The design will contain a rigid frame with each motion component sitting on top. This design includes lead screw mechanisms to control the X, Y, and Z motion, with the Y motion defined as the two parallel sides along the frame of the body. The two lead screws along the

Y axis will be powered by 2 individual stepper motors to allow accurate uniform motion back and forth of their respective flange nuts. A stepper motor will rotate the X axis lead screw and move the plate attached to the spindle along its path of motion. Attached to this lead screw will be a manufactured plate containing another lead screw mechanism that will move the spindle up and down to cut into the material. The spindle will be fixed to a plate attached to the lead screw mechanism powered by its own motor. Each axis will have 2 smooth support shafts to support the linear motion. The base plate fixed at the bottom will have a working space of 8” by 8” with the z axis moving up to 4” vertically. The base plate will have a t shaped structure to allow for the connection of dust. There is also a removable dust collection tray with a mesh netting above a liquid coolant reservoir to allow for an automatic refill system and easy disposal of waste by the user. These thin T slots are used to place and secure side clamps onto the base. This is accomplished by using a square nut that prevents rotation in the slot, combined with a screw to secure the side clamp to the slot. Each clamp also has a secondary screw, angled on top to manually actuate the jaw, which pushes on the material from the side, and secures the material in place.

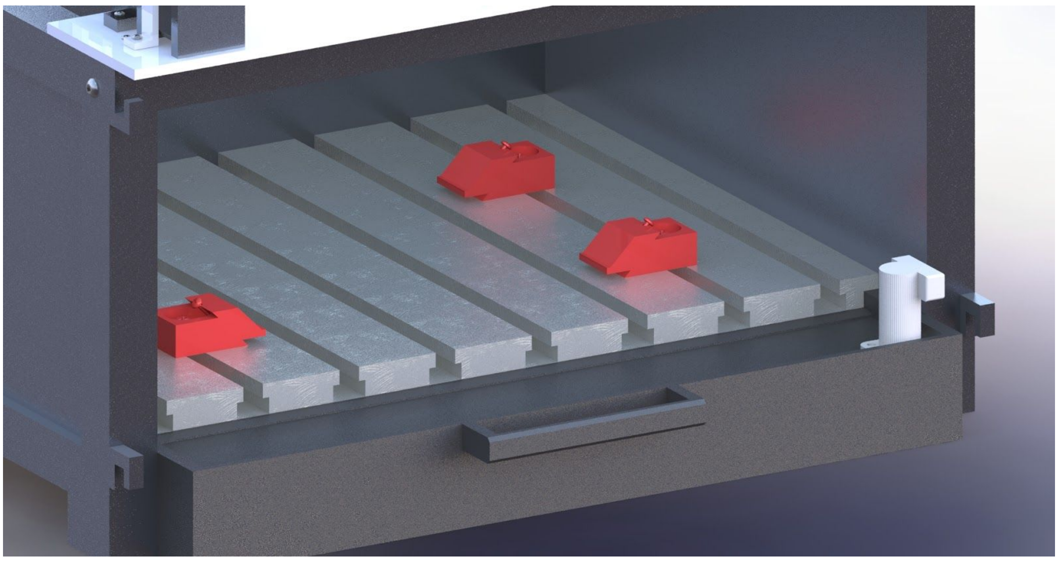

Figure 1.10: T plate with view of automatic coolant refill system

The use of several lead screw mechanisms helps to minimize the overall cost of the final product as these mechanisms are very inexpensive. This design allows for many easily assemblable parts by the user themselves which will further lower the cost of manufacturing as each part is simple and easy to understand how it is incorporated. Not including the simple custom manufactured frame, the design will attempt to contain all standardized parts to contribute to the low cost of the design.

4.0 Design Analysis and Description

Although all 4 candidate designs met the set specifications, candidate design 4 outperforms the other candidates in all aspects. The best aspects of designs 2 and 3 were used to iterate design 4. As such, design 4 does not have the same limitations as designs 2 and 3. Each of the designs were analyzed in terms of how well each met the set engineering specifications. The chief deciding factors that helped to determine which design best satisfied the conditions were: ease of assembly, resistance to reactionary forces and precision.

4.1 Justification

Candidate #1 consists of many crucial parts that would require pre-assembly as they are too complex for the end-user to put together. This in turn would mean that the final product is not modular. Replacing parts would be relatively difficult and potentially expensive for this design. In addition, the clamping mechanism used to secure the material to the base plate must be attached in predetermined increments. This can potentially pose a limitation to the user's material selection because it may be hard to find materials containing very specific dimensions. Even though this aspect of the design can be viable, Candidate Design 4 has greater versatility in material size options.

Candidate #2 used rack and pinion gears for motion in all 3 directions. In accordance with the engineering specifications, the CNC machine must be able to resist reactionary forces.

However, the motion of the rack and pinion can be reversed by applying forces to the rack. For example, for motion in the z-direction, the weight of the material and the force of the spindle will push down on the rack which will, in turn, move downwards as the rack and pinion are reversible.

Candidate #3 was developed while designing against the limitations of the previous designs. As such, this design is easy to assemble and it resists reactionary forces to a higher degree. However, the precision in the z-direction of candidate 3 did not reach the objective of being accurate to 0.01 in. The z motion of candidate #3 is controlled by 4 lead screw mechanisms that are all connected to a belt which causes identical motion in all 4 lead screw mechanisms. However, the forces that act in the negative z-direction causes this belt to deflect which in turn distorts the accuracy of the z-axis by displacing the belt. In accordance with the calculations [Appendix C], it takes only 1.43 N (in the negative z-direction) to displace the belt by 0.04 in. This potential displacement is larger than the set precision of 0.01 in. It is very likely that a force of 1.43 N will be experienced by the belt as this is a very small force. As well, the feed force from the spindle acting in the negative z-direction has a magnitude of greater than 450 N [Appendix G]. Given this information, this design cannot be considered viable due to the high chance of displacement outside of the design's overall precision.

4.2 Detailed Analysis of the Final Design

Candidate 4 was chosen as the final design as it excels in comparison to the other candidates based on the engineering specifications. This design optimizes the working space while maintaining a precision ±0.01. The use of lead screw mechanisms provide a low cost and efficient option to power the X, Y, and Z axes. This mechanism maintains the required precision for motion to accurately cut woods, plastics, and soft metals such as aluminum 6061 to the desired shape. This will be done through USB connection and G code from any compatible CAD software. The use of adjustable, rigid clamps allows for the user to purchase a wide variety of sizes of material while maintaining the integrity of the position. The design's compact size allows for increased portability and is able to fit comfortably on an average hobbyist's desk. In addition to it being ideal for home-use, the frame structure, removable dust collection tray, and mesh netting system contains most, if not all, of the debris and liquid coolant. The cooling system, next to the spindle, easily cools the material directly at the cutting surface. The spindle provides a variable RPM output, dependent on the material it is cutting. Due to the high amount of standardized parts and simple but efficient mechanisms, the cost of the final design meets the specifications. This provides a competitive and desirable option for customers seeking home-use, kit type CNC mills.

4.2.1 Detailed Analysis of X, Y, and Z Motion

The motion of the spindle is controlled in the three axes through the use of several lead screw mechanisms and a variety of accompanying parts to further enable the range and ease of motion. As described in section 3.4, the Y axis involves two uniformly rotating, lead screws that with a flange nut that is guided along it. To achieve this movement with the precision of 0.01" and to withstand the resulting moment, the use of additional supports are needed as well as a means to transmit the input energy throughout the screw. We chose a Nema 17 stepper motor [13] in order to effectively and precisely rotate the lead screw at the max calculated speed of 50 inches per minute, and calculated linear resolution of 0.00025 inches [Appendix H] [14] . The motor is secured with a custom component that resists the axial movement of the motor. On the opposite side is a precision flexible shaft coupler [8] that allows for minimal backlash and are optimal for accuracy. Extending through the opposite end of the coupling is an ultra-precise lead screw [8] that has a low backlash within the range of our guaranteed accuracy. The 12" lead screw was chosen for its standardized size that still allowed a wide range of workspace for the spindle to move. On its opposite ends, the screw is supported by two bearing housings that support a thrust bearing each. The needle-roller thrust bearing is optimal for resisting the axial forces that arise from the helical nature of the screw, while permitting the easy rotation of the mechanism. The thrust bearing is prevented from sliding in the direction of the lead screw by a helical shaft collar on the lead screw. As the lead screw rotates via the motor, the flange-nut of the same thread size (¼-20) is restricted from rotating and therefore translates along the axis. The flange nuts of the 2 parallel lead screw mechanisms move simultaneously to fully control the motion of the spindle in the Y axis. These components, as with all flange nuts in this design, were chosen with a spring designed to mitigate backlash from the reversal of the direction of motion.

Atop these flange nuts is where another similar lead screw mechanism takes place. To support these forces and potential moment, there are two linear guide shafts per axis that support against such forces. On the Y-axis, these two guide shafts were also placed on opposite sides to prevent any significant rotation of the mechanisms above. The linear motion guide shafts [8] were selected to be accompanied by a linear bearing with a platform to slide along the shaft. The shaft being made of 1566 carbon steel makes it ideal for loading when fixed at its 2 ends by base-mounted shaft supports [8] where it is unnecessary for these shafts to rotate. To synchronize the motion of each pair of flange-nut and linear bearing, A custom plate is implemented that connects to these two mechanisms, as well as providing a base for further housing necessary for the X and Z axis.

Above each of these two plates sits a custom housing unit designed for another lead screw mechanism. On one extreme, there are 2 holes of depth 0.5” that act as a press fit slot for the two guide shafts. These shafts were calculated to be a minimum of 3” apart in order to stay within our accuracy constraint [Appendix I]. Between these two shafts sits another 12” lead screw mechanism similar to the one described above where the thrust bearings are fit in the housing and secured by the shaft collar. On the opposite side of the housing lies a similar setup of the same guide shafts and lead screw, but there exists a hole to fit the precision flexible coupling and connect it to a Nema 17 motor on the outside of the housing. This motor is supported by a standardized L support that is screwed into the housing for security.

Translating along the lead screw is another ultra-precision flange nut that is designed to control the movement in the X direction. This nut is secured to a plate that houses the lead screw for the Z- axis. To mitigate further forces and moments from the lead screw itself, the platforms on the linear bearings are also attached to the same plate. This plate is secured to two blocks that make up the housing for the Z axis. Similar to the X axis, there are two guide shafts and a lead screw that attach into two blocks on opposite ends where a motor is supported and fixed above the lead screw to control the rotation of the lead screw. Each of the shafts and lead screw in this component of the design have a flange nut that uniformly move vertically when fixed together with a plate across the three top surfaces The flange nuts were chosen as opposed to the linear bearing platforms due to their smaller size and ease of installation in the Z-axis. This plate attaches to a different vertical plate where the spindle is directly attached. The linear bearings in this mechanism greatly mitigate the reactionary forces of the spindle while accounting for the machine's accuracy.

The three sets of lead screw mechanism are fully automated and controlled by four NEMA 17 motors that collectively control the precise motion of the spindle in 3D space while also prioritizing the machine's resistance to the effect of forces on the mechanisms. This allows total motion of 8x8x4 in the X,Y, and Z directions, respectively. These are the two driving reasons for every specific choice in component.

4.2.2 Detailed Analysis of Clamping Mechanism

The selected clamps are non-invasive side clamps that operate by sliding into the T shaped cuts in the base plate [15] and use screws to push the jaw outwards to clamp the piece; the jaw can resist up to 1670 lbs of force [8] while leaving the top exposed. These clamps satisfy the engineering specifications because they hold the material being cut from its side from a relatively low side profile, meaning that the14 drill bit motion is not constrained, without invasively affecting the material. By using 4 individual clamps, the positions of the clamping forces can be moved to flexibly support materials of different shapes and dimensions, while fitting within the workspace. The installation and placement of the side clamps are simple for the user, as they just need to be slid into the base plate's cuts and manually tightened with a screwdriver.

4.2.3 Detailed Analysis of Spindle Motion

The pre-assembled spindle for this CNC machine uses a stepper motor, rated to 1500 W and an rpm range of 8000-24000 while providing a rotational, continuous output [16]. This is ideal for the materials being cut as their maximum RPM requirements are 8556.8 for aluminum and 19862 for wood/plastic, which were calculated using

$$RPM = \frac{12(surface\,feed\,per\,minute)}{pi*d}$$

[Appendix D for sample calculations][17]. Since the spindle has an integrated motor, the original engineering specifications regarding the spindle input are resolved while meeting the desired output, as well as facilitate user assembly since the spindle just needs to be attached to the rest of the CNC machine, through a C shaped clamp. The reactionary forces the spindle will encounter are mitigated by the z-plate the spindle is mounted to, as the plate provides a lip that arches over the spindle which will take on the majority of the load and prevents the spindle from moving out of place.

4.2.3 Detailed Analysis of Size and Workspace

The size of the assembled CNC machine is 18” x 15”. The weight of the assembled CNC machine is approximately 50 lbs. The objective of this design is to be able to be used as a home CNC kit. In order to do so, it was established that the dimensions of the design needed to be within 20” x 15” and needed to have a mass of less than 100 lbs. The final design accomplishes both these objectives. Due to it’s small size and portable nature, this design is perfect for home use and can be placed on an average wooden desk.

4.2.4 Detailed Analysis of Cooling System and

Coolants dissipate high temperatures that can lead to melting, warping, discolouration, or even tool failure [10]. For materials such as wood or plastic, an intensive cooling system is not necessary. However, this CNC machine will also be machining aluminum. Aluminum does require the application of coolant while being worked on to prevent any warping or tool failure. The final design incorporates a soluble oil cutting fluid as this type of cutting fluid is best for machining aluminum [18]. The tank of cutting fluid is connected to the dust collection tray of the CNC machine. The fluid is pumped from the reservoir to a tube that has a nozzle in close proximity with the spindle [19]. Due to issues modelling a flexible tube in Solidworks, the clear tube that connects the pump in the reservoir to the connector and nozzle could not be modelled in SolidWorks. As the spindle works on the aluminum, cutting fluid is sprayed onto the material intermittently. The cutting fluid gathers in the collection tray and is filtered by a fine metallic mesh before re-entering the reservoir. This fine metallic mesh also demonstrated difficulties and is not modelled in the final CAD. The collection of fluid allows for efficient and non-wasteful use of materials and eliminates extra cost for the user. In addition to the metallic net, another mesh is placed on the open face in order to keep any chips or debris within the interior of the walls. This mesh is removable and adjusted to the hooks in the corners in order to insert and remove material.

4.2.5 Detailed Analysis of Cost

After cost analysis, the design's total cost is approximately $1590. This does not meet the design's goal of remaining below $1400 but does stay within the strict constraint of $1600. This increase in price is justified by the increased stability of the machine. The design ensures a great amount of stability and is precise. It also provides a large working space, greater than the design's goal.

Table 1.2 Bill of materials (see [Appendix E] for cost analysis with bill of materials)

Item Number	Part #	Description	Vendor	Vender Number	Quantity
1	001	Side Panels	Custom	-	2
2	002	Base Frame	Custom	-	1
3	003	Back Panel	Custom	-	1
4	004	Front Rod	Custom	-	1
5	005	16''x12'' Base Plate	World of Clamping	A1744	1
6	006	Dust Tray With Tank	Custom	-	1
7	007	Easy-Access Base-Mounted Shaft Support	Mcmaster Carr	1865K100	4
8	008	Needle-Roller Thrust Bearings	Mcmaster Carr	5909K230	8
9	009	Needle-Roller Thrust Bearings Washers	Mcmaster Carr	5909K231	8
10	010	Right-Hand Threaded Flange Nut	Mcmaster Carr	6350K208	3

11	011	Right-Hand Threaded Ultra-Precision Lead Screw (12’’)	Mcmaster Carr	6350K696	3
12	012	Right-Hand Threaded Ultra-Precision Lead Screw (6’’)	Mcmaster Carr	6350K689	1
13	013	Mounted Linear Sleeve Bearings	Mcmaster Carr	6374K115	4
14	014	Flange-Mounted Linear Ball Bearings	Mcmaster Carr	6483K610	2
15	015	Aluminum Helical Flexible Set Screw Precision Flexible Shaft Couplings	Mcmaster Carr	9861T431	4
16	016	18-8 Stainless Pan Head Phillips Screws (¼’’’)	Mcmaster Carr	91772A030	73
17	017	18-8 Stainless Pan Head Phillips Screws (¾’’)	Mcmaster Carr	91772A113	4
18	018	18-8 Stainless Pan Head Phillips Screws (⅝’’’)	Mcmaster Carr	91772A112	8
19	019	18-8 Stainless Pan Head Phillips Screws (1 ¼’’’)	Mcmaster Carr	91772A116	3
20	020	18-8 Stainless Pan Head Phillips Screws (½’’)	Mcmaster Carr	91772A194	2
21	021	Steel Square Nut	Mcmaster Carr	94855A278	4
22	022	316 Stainless Steel Pan Head Phillips Screw (1’’)	Mcmaster Carr	91735A542	4
23	023	Low Profile Side Clamps	Mcmaster Carr	8958A11	4

24	024	12’’ Linear Motion Guide Shaft (¼’’ Diameter)	Mcmaster Carr	1555T122	4
25	025	6’’ Linear Motion Guide Shaft (¼’’ Diameter)	Mcmaster Carr	1555T121	2
26	026	½ HP Coolant Pump For CNC Lathe Machine	Amazon	TC-2180	1
27	027	Clamping ACME Lead Screw Collar	Mcmaster Carr	6698K51	6
28	028	1500W Air Cooled CNC Milling Spindle and Motor	Automation Technology inc	KL-1500A	1
29	029	NEMA 17 Stepper Motor	Newegg	17HS4401	4
30	030	Coolant Spray System Unit	Amazon	13010300GQ	1
31	031	Spindle Holding Clamp A	Custom	-	1
32	032	Spindle Holding Clamp B	Custom	-	1
33	033	Spindle Plate	Custom	-	1
34	034	C Plate Top	Custom	-	1
35	035	C Plate Bottom	Custom	-	1
36	036	C Plate Side	Custom	-	1
37	037	X Motion Support	Custom	-	2
38	038	Connector Plate	Custom	-	1
39	039	Lead Screw Plate	Custom	-	2
40	040	Top Plate A	Custom	-	1
41	041	Top Plate B	Custom	-	1
42	042	Flange Connector	Custom	-	1

43	043	Bearing Housing	Custom	-	4
44	044	Metallic Mesh	Mcmaster Carr	1023A75	1
45	045	Diamond Net Mesh Tool Spool Roll	Amazon	B00SE867WA	1
46	046	Hose and Connection	Amazon	13010300GQ	1

5.0 Conclusion

The purpose of this design is to create a CNC mill for home-usage with a kit-type assembly. This design will accomplish precise cutting of woods, plastics, and soft metals. Engineering specifications were generated to set achievable criteria that the design should achieve. Through research, idea generation and the creation of a morphological chart, three initial candidate designs were chosen. Iteration of the second and third candidates introduced the fourth candidate which was ultimately chosen as the final design. Candidate 4 was chosen as the final design as it meets all the set specifications. It provides a viable cost option, effectively uses precise mechanisms to move the spindle, and stays within the space constraints.

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6.0 Appendices

Appendix A: Morphological Chart for Candidate Design Generation

The morphological chart allows for the combination of numerous mechanisms in order to create candidate designs. Below is the chart and the three initial combinations made.

MORPH CHART

Mechanism	Idea #1	Idea #2	Idea #3	Idea #4	Idea #5
Drill Spindle/axis control (with layout of structure)	Roller ball mechanism with arm with each axis	Framework side support system	Framework top support system	Base plate moves via gear system	Rigid L arm
Clamping system to secure block	Wedge Clamping	Magnetics	L-side clamping	*Scissor side clamping*	Non invasive side clamps
Cooling System	Liquid coolant attached to drill part	CPU Cooling Pump * is drainage system also	Circular Spray Microjets attached to spindle	Coolant shot from base onto metal	Fans attached to sides/top of structure
Dust Collection/ Draining system	Cutting Dust Skirt/ graphite vortex	DH-dense hole pattern in plate	Fan blowing dust to side	*Compressed air hose blowing at cutting direction*	Vacuum attached to drill
Guard system (optional)	Universal Safety shields	Adjustable Visor Guard	No guard	Rectangular guard that fits over the base	Maybe a heavy ish cloth to stop pieces from flying outwards but won't really get in way
Way to drive spindle	*Gear driven spindle*	*Belt driven*	Motor driven (small motor on top of spindle)	Gears	Drive shafts

Appendix B: Pairwise Comparison

	Cost	Resistance to Reactionary Forces	Ease of Assembly	Precision	Workspace	Total
Cost	**-**	**0**	**0**	**0**	**1**	**1**
Resistance to Reactionary Forces	**1**	**-**	**0**	**1**	**1**	**3**
Ease of Assembly	**1**	**1**	**-**	**0**	**0**	**2**
Precision	**1**	**0**	**1**	**-**	**1**	**3**
Workspace	**0**	**0**	**1**		**-**	**1**

As seen by the pairwise comparison above, resistance to reactionary forces is the most important factor closely followed by precision. These 2 qualities of the design are of utmost importance. Hence why some mechanisms were favored over others. In order to improve resistance to reactionary forces, a scissor lift mechanism was abandoned. In order to improve precision, a belt mechanism was abandoned. For example, one of the candidate designs involved a robotic arm but was not selected to be the final design as it was not easy to assemble for the end user.

Appendix C: Force Required to Displace Belt

$\varepsilon = \Delta L/L$ = strain

*Note that the length of the belt is 45 inches

$\varepsilon = 0.04/45$

$\varepsilon=8.89\times10^{-4}$

*Plug strain into $\sigma=E\varepsilon$=stress where E=0.0025 GPa for the rubber of the belt [8].

$\sigma=(0.0025\text{ GPa})(8.89\times10^{-4})$

$\sigma=2.22\times10^{-3}$ MPa

*Plug the stress into $\sigma=F/A$ to find the force.

$F= (2.22\times10^{-3}\text{MPa})(645.16\text{mm}^2)$

Force Required = 1.43 N

Appendix D: RPM of Spindle for aluminium and wood/plastic

Formula used: RPM = [12*Sfm/pi*(diameter of bit)]

*Sfm=smallest drill bit size

RPM FOR ALUMINIUM	RPM FOR WOOD/PLASTIC
=(12*280)/(pi*0.125) =8556.8 RPM	=(12*650)/(pi*0.125) =19862 RPM

Appendix E:

Item Number	Part #	Description	Vendor	Vender Number	Quantity	Unit Cost
1	001	Side Panels	Custom	-	2	9.04
2	002	Base Frame	Custom	-	1	6.34
3	003	Back Panel	Custom	-	1	15.84
4	004	Front Rod	Custom	-	1	1.50
5	005	16’’x12’’ Base Plate	World of Clamping	A1744	1	129.00
6	006	Dust Tray With Tank	Custom	-	1	0.49

7	007	Easy-Access Base-Mounted Shaft Support	Mcmaster Carr	1865K100	4	12.17
8	008	Needle-Roller Thrust Bearings	Mcmaster Carr	5909K230	8	2.80
9	009	Needle-Roller Thrust Bearings Washers	Mcmaster Carr	5909K231	8	1.12
10	010	Right-Hand Threaded Flange Nut	Mcmaster Carr	6350K208	3	29.92
11	011	Right-Hand Threaded Ultra-Precision Lead Screw (12’’)	Mcmaster Carr	6350K696	3	44.43
12	012	Right-Hand Threaded Ultra-Precision Lead Screw (6’’)	Mcmaster Carr	6350K689	1	18.91
13	013	Mounted Linear Sleeve Bearings	Mcmaster Carr	6374K115	4	51.08
14	014	Flange-Mounted Linear Ball Bearings	Mcmaster Carr	6483K610	2	29.11
15	015	Aluminum Helical Flexible Set Screw Precision Flexible Shaft Couplings	Mcmaster Carr	9861T431	4	37.91
16	016	18-8 Stainless Pan Head Phillips Screws (¼’’’)	Mcmaster Carr	91772A030	73	7.70 (pack of 100)
17	017	18-8 Stainless Pan Head Phillips Screws (¾’’)	Mcmaster Carr	91772A113	4	4.95 (pack of 100)
18	018	18-8 Stainless Pan Head Phillips Screws (⅝’’’)	Mcmaster Carr	91772A112	8	4.32 (pack of 100)
19	019	18-8 Stainless Pan Head Phillips Screws (1 ¼’’’)	Mcmaster Carr	91772A116	3	6.57 (pack of 100)

20	020	18-8 Stainless Pan Head Phillips Screws (½’’)	Mcmaster Carr	91772A194	2	7.54 (pack of 100)
21	021	Steel Square Nut	Mcmaster Carr	94855A278	4	8.47 (pack of 100)
22	022	316 Stainless Steel Pan Head Phillips Screw (1’’)	Mcmaster Carr	91735A542	4	9.50 (pack of 25)
23	023	Low Profile Side Clamps	Mcmaster Carr	8958A11	4	43.81
24	024	12’’ Linear Motion Guide Shaft (¼’’ Diameter)	Mcmaster Carr	1555T122	4	15.00
25	025	6’’ Linear Motion Guide Shaft (¼’’ Diameter)	Mcmaster Carr	1555T121	2	8.25
26	026	½ HP Coolant Pump For CNC Lathe Machine	Amazon	TC-2180	1	98.00
27	027	Clamping ACME Lead Screw Collar	Mcmaster Carr	6698K51	6	6.83
28	028	1500W Air Cooled CNC Milling Spindle and Motor	Automation Technology inc	KL-1500A	1	149.00
29	029	NEMA 17 Stepper Motor	Newegg	17HS4401	4	17.26
30	030	Coolant Spray System Unit	Amazon	13010300GQ	1	16.88
31	031	Spindle Holding Clamp A	Custom	-	1	2.67
32	032	Spindle Holding Clamp B	Custom	-	1	3.54
33	033	Spindle Plate	Custom	-	1	1.96
34	034	C Plate Top	Custom	-	1	1.41
35	035	C Plate Bottom	Custom	-	1	1.29

36	036	C Plate Side	Custom	-	1	1.61
37	037	X Motion Support	Custom	-	2	2.97
38	038	Connector Plate	Custom	-	1	3.14
39	039	Lead Screw Plate	Custom	-	2	1.66
40	040	Top Plate A	Custom	-	1	3.81
41	041	Top Plate B	Custom	-	1	2.26
42	042	Flange Connector	Custom	-	1	0.98
43	043	Bearing Housing	Custom	-	4	3.32
44	044	Metallic Mesh	Mcmaster Carr	1023A75	1	7.03
45	045	Diamond Net Mesh Tool Spool Roll	Amazon	B00SE867WA	1	3.65
46	046	Hose Connecting Support	Custom	-	1	1.12

Appendix F: Cutting Force

K_{ci}=650 N/mm^2 for aluminum [20]

$K_c = K_{ci} * h_m$^($-m_c$)

Kc = 650*(0.254)^(-0.25)

Kc = 915.598 N/mm^2

Appendix G: Machining Force

*Note that assuming area of chip □ 1mm^2.

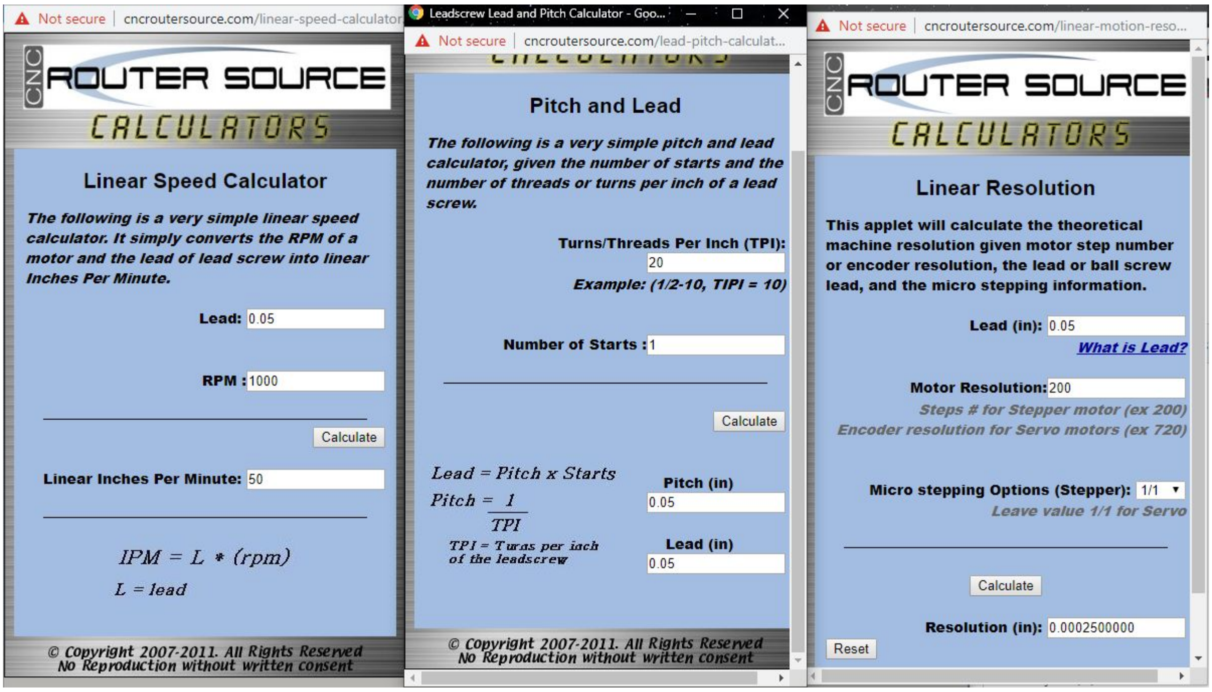
Fc = Kc = machining force

Therefore Fc = 915.598 N (Machining Force of Aluminum)

Ff = 0.5Fc = 457.499 N (Feed Force)

Fp = 0.5Ff = 228.9 N (Passive Force)

Appendix H: Approximate Linear Speed and Resolution for Lead Screws



Appendix I: Calculations of L1 and L2

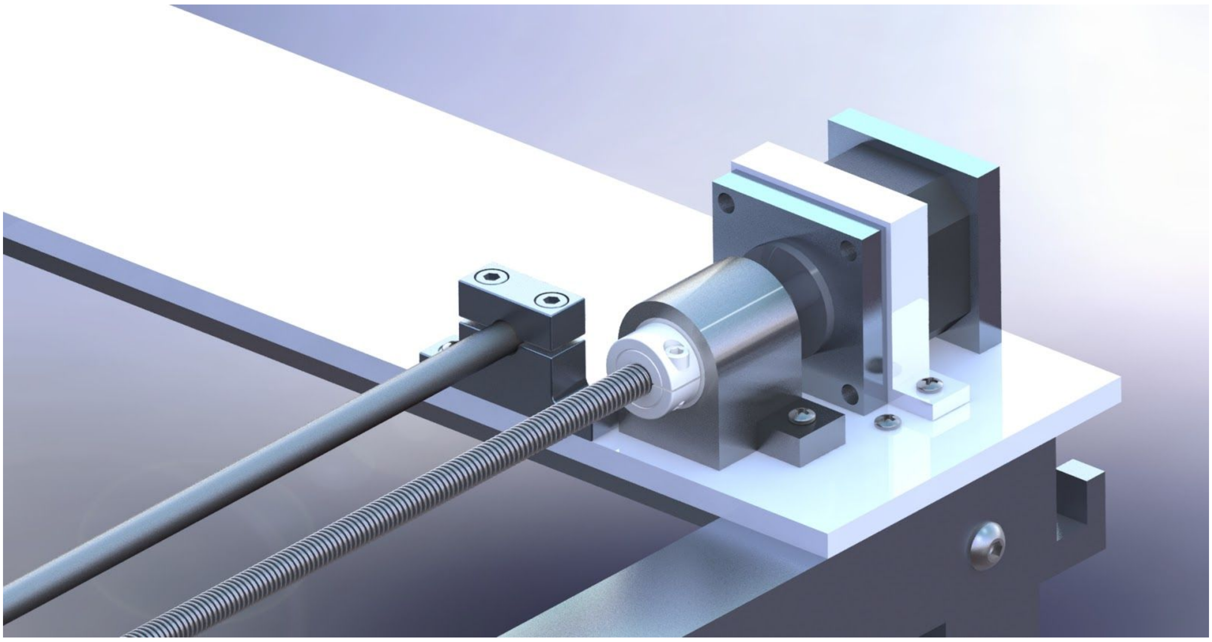
(L2/L1)*2δ= unwanted movement

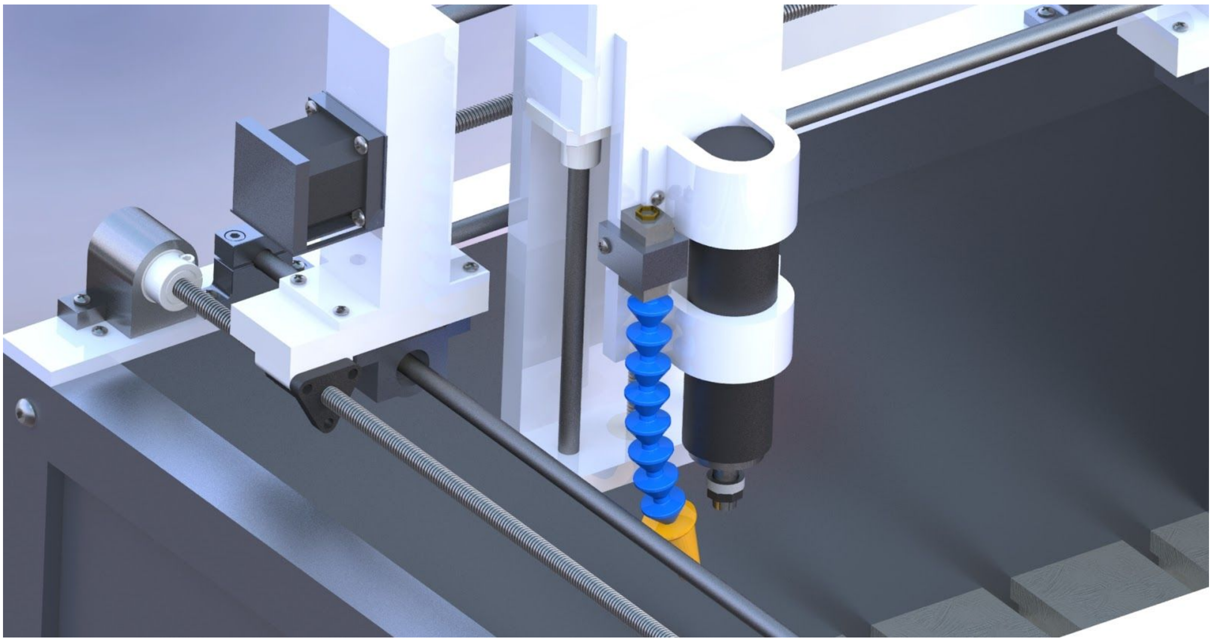
When L1=L2, the unwanted movement is 2*0.0015=0.003”

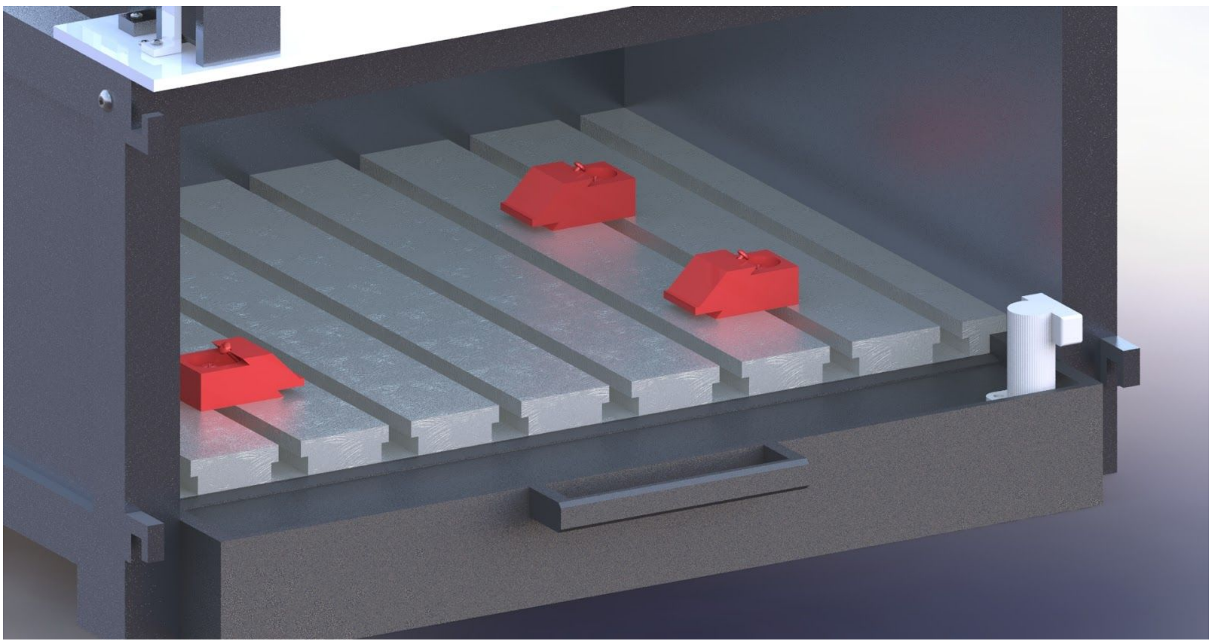
We optimized the vertical distance while maintaining the precision accordingly:

L1=3, L2=9, giving an error of 0.009” (within our precision of 0.01”)

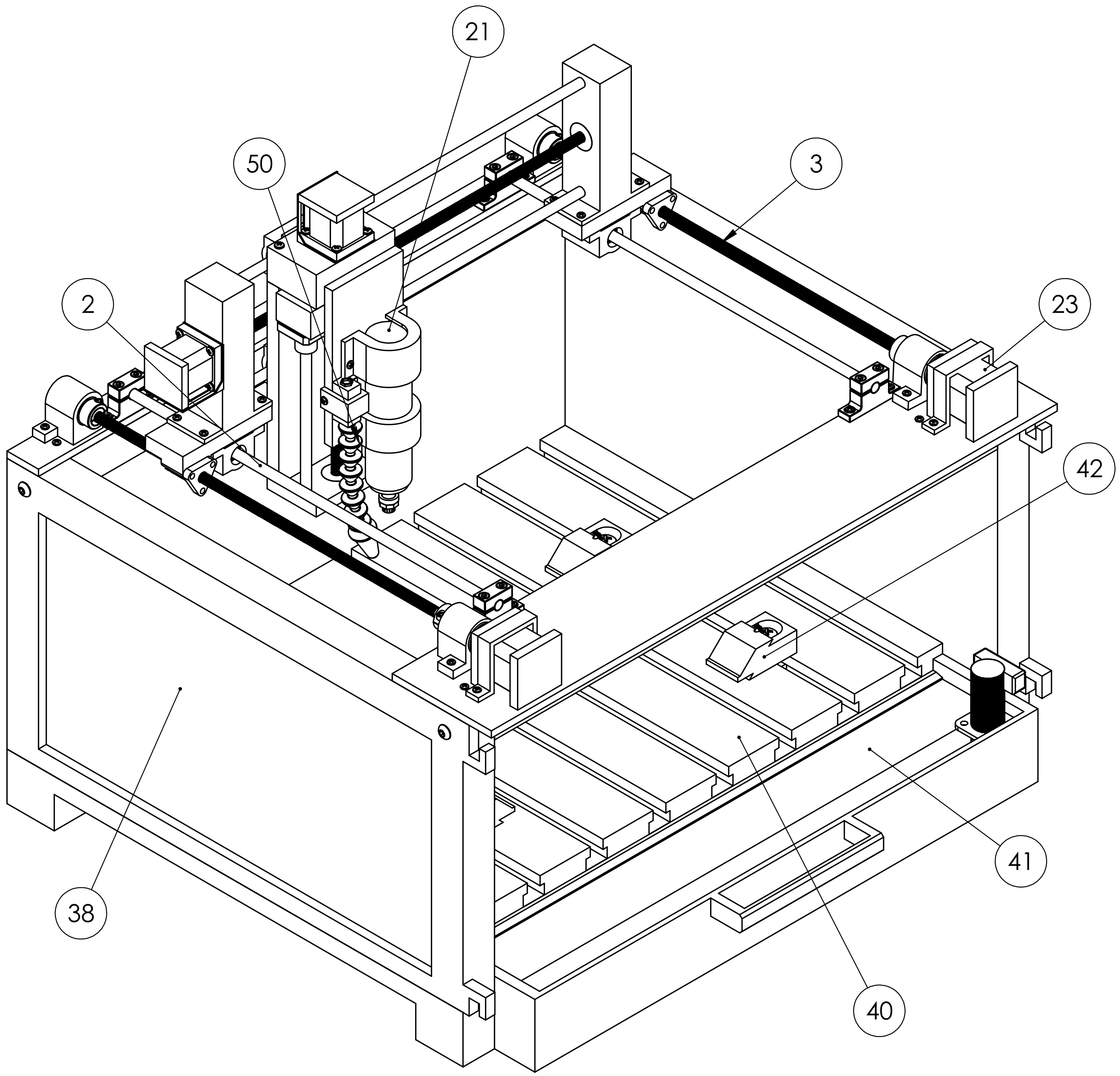
Appendix J: Drawings and Rendered Images



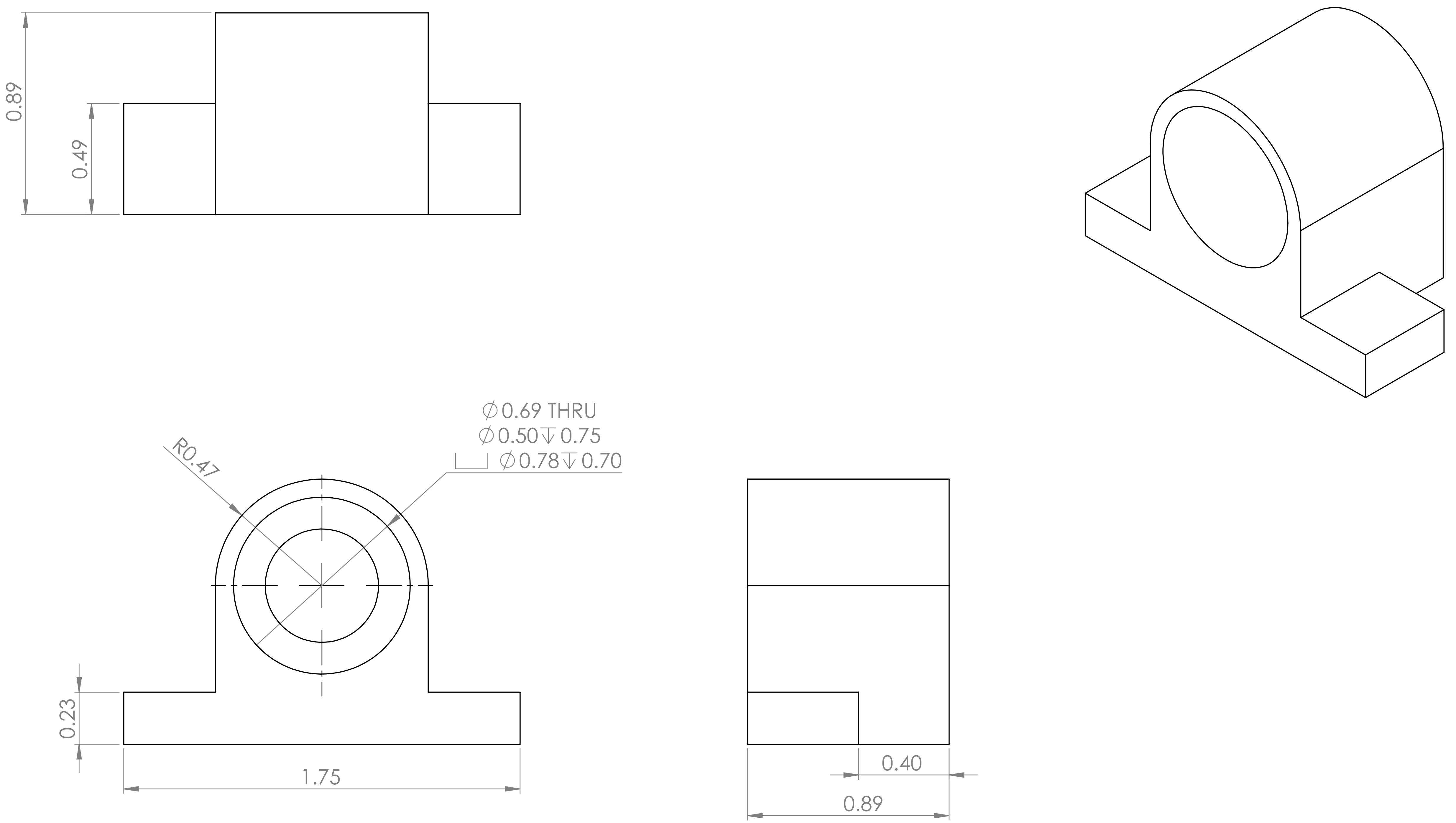




ITEM NO.	PART NAME	DESCRIPTION	QTY
2	SUPPORT SHAFT	SUPPORT BAR FOR LEAD SCREW MECHANISM	6 (AT DIFFERENT LENGTHS)
3	LEAD SHAFT	LEAD SCREW MECHANISM	4
21	SPINDLE	SPINDLE TO DRIVE CUTTING	1
23	MOTOR	NEMA 17 STEPPER MOTOR	4
38	FRAME	ASSEMBLED FRAME	1
41	DUST COLLECTION TRAY	TRAY WITH BUILT IN RESERVOIR TO COLLECT AND REUSE FLUID	1
42	CLAMPS	BASEPLATE CLAMPS	4
50	COOLING TUBE	AUTOMATIC REFILL COOLING SYSTEM	1



AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: ASSEMBLY DRAWING		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 10 OF 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:3		SHEET 1 OF 2



NOTES:
1. ITERATION OF THIS DESIGN WITH CLOSED 17.53IN HOLE FOR BEARING WITHOUT COUPLING

AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: BEARING HOUSING		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 5 OF 10		REV. 1
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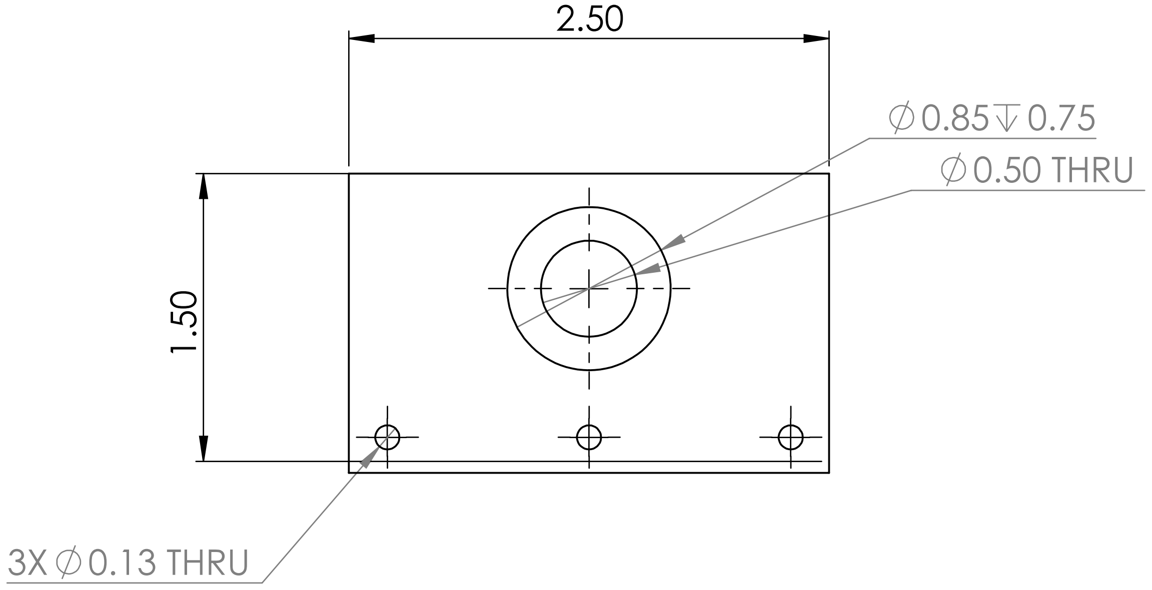

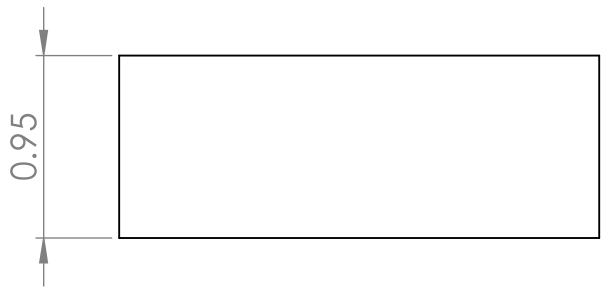

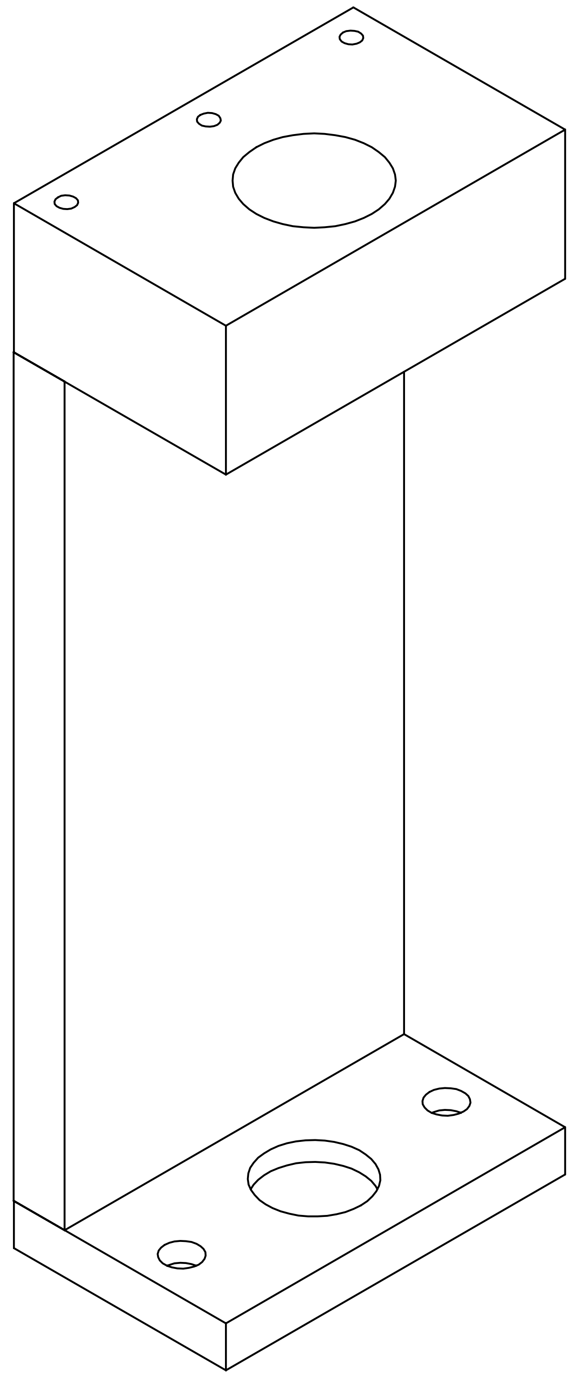

NOTES:
1. ITERATION OF DESIGN FOR BOTTOM PLATE WITH IDENTICAL DIMENSIONS EXCEPT MISSING THRU HOLE FOR COUPLING AND HEIGHT REDUCED TO 0.3IN

AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: C BAR FOR Z MOTION BOTTOM/TOP PLATE		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 4 0F 10		REV. 1
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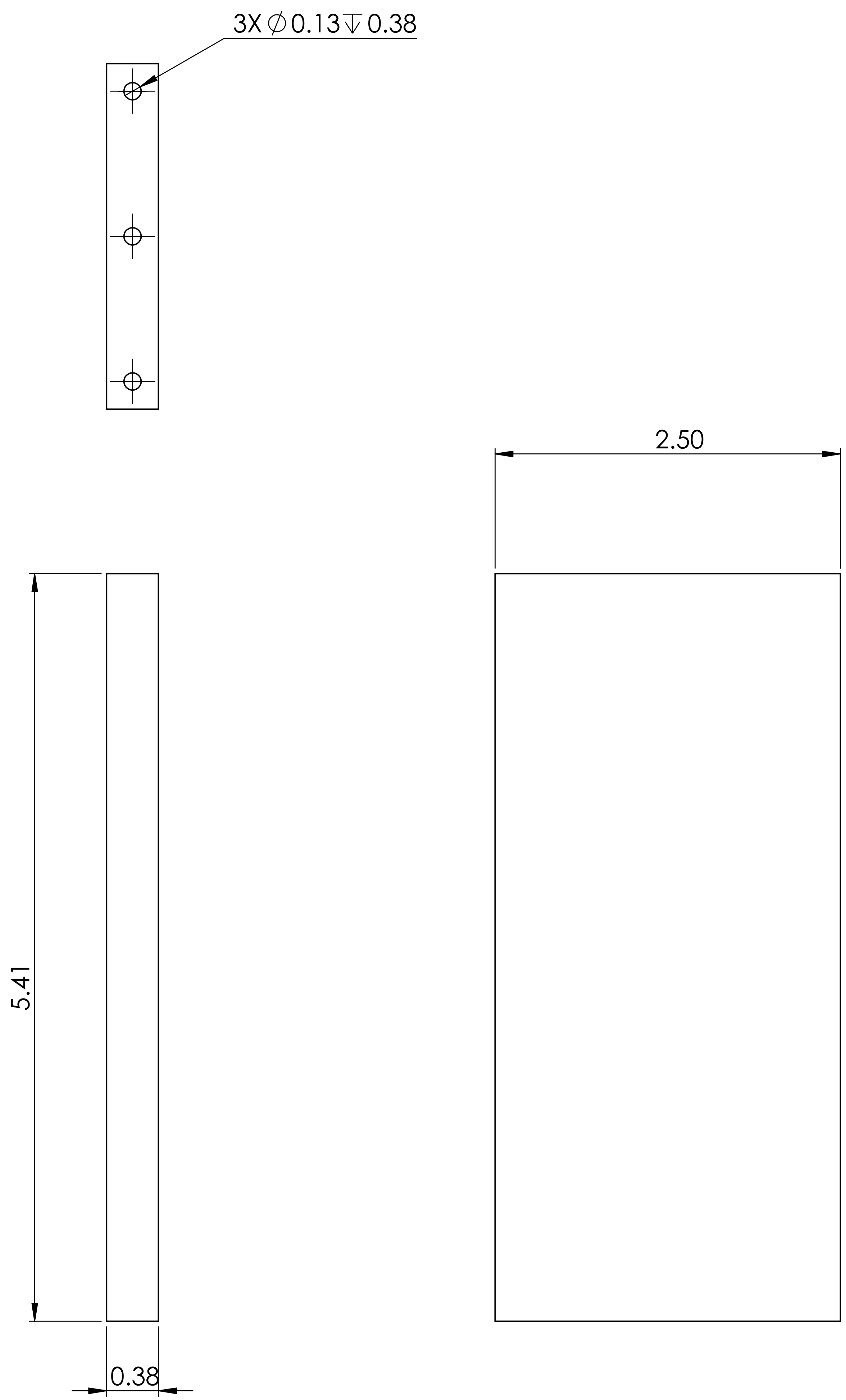

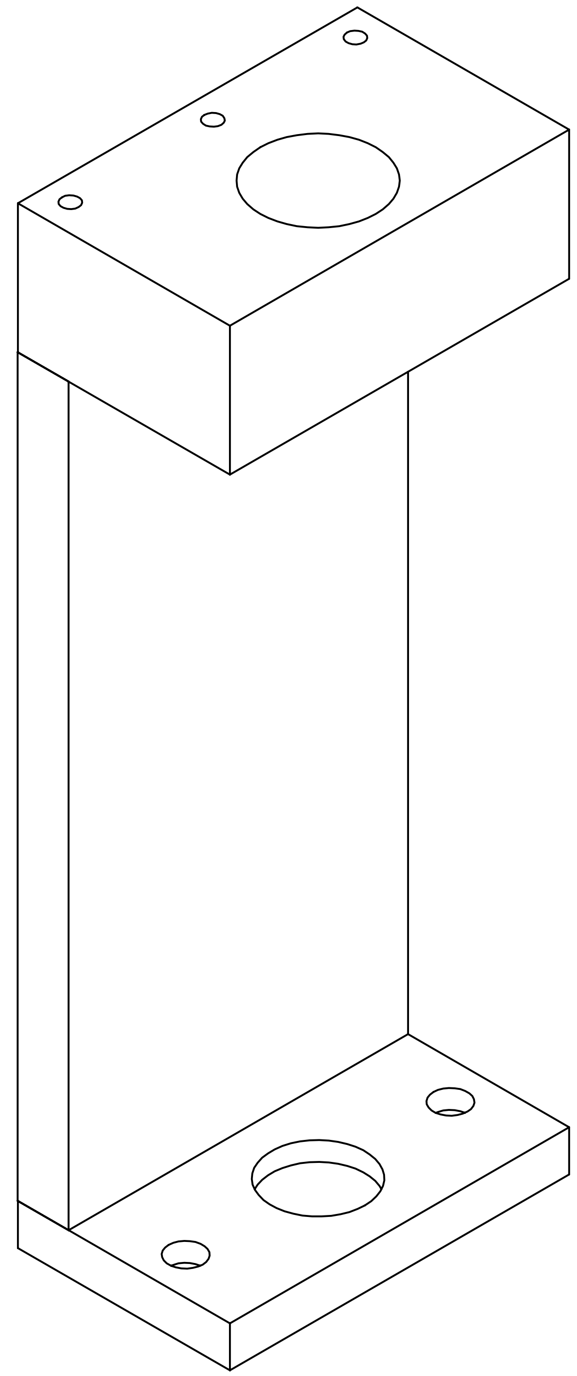

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DATE: 10/18/2019			
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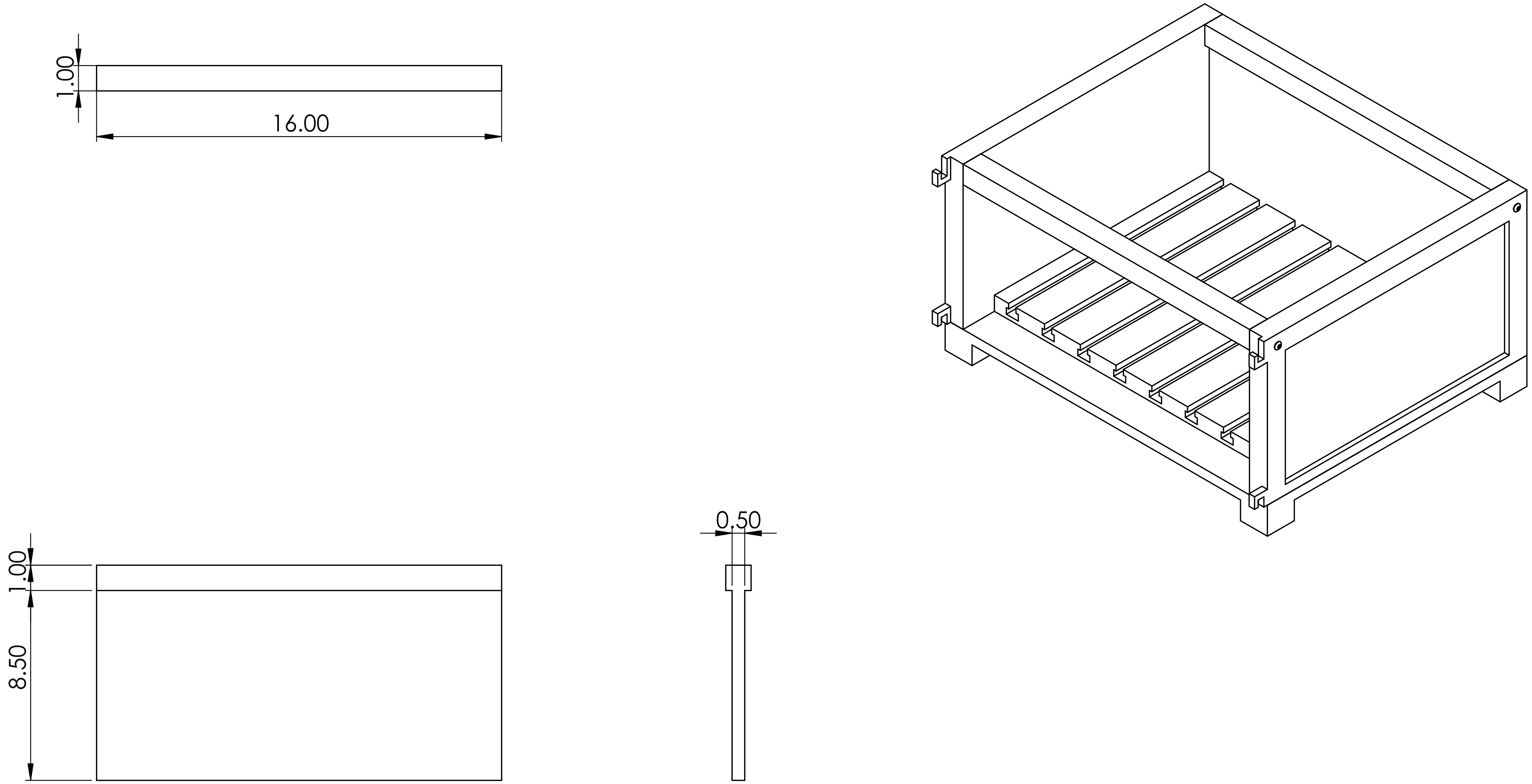

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STUDENT NO. 1004808498	TITLE: FRAME ASSEMBLY		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 7 OF 10		REV. 1
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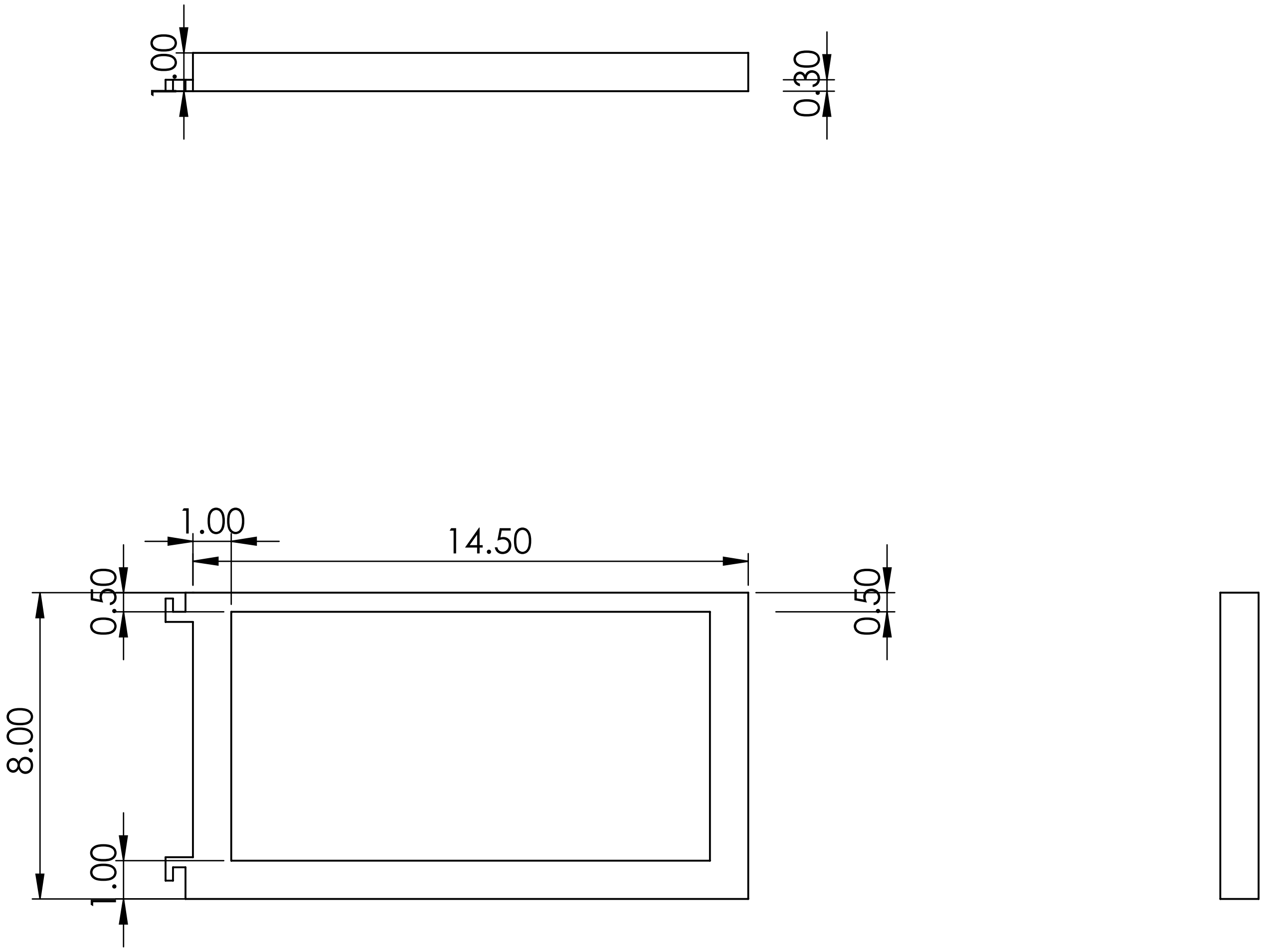
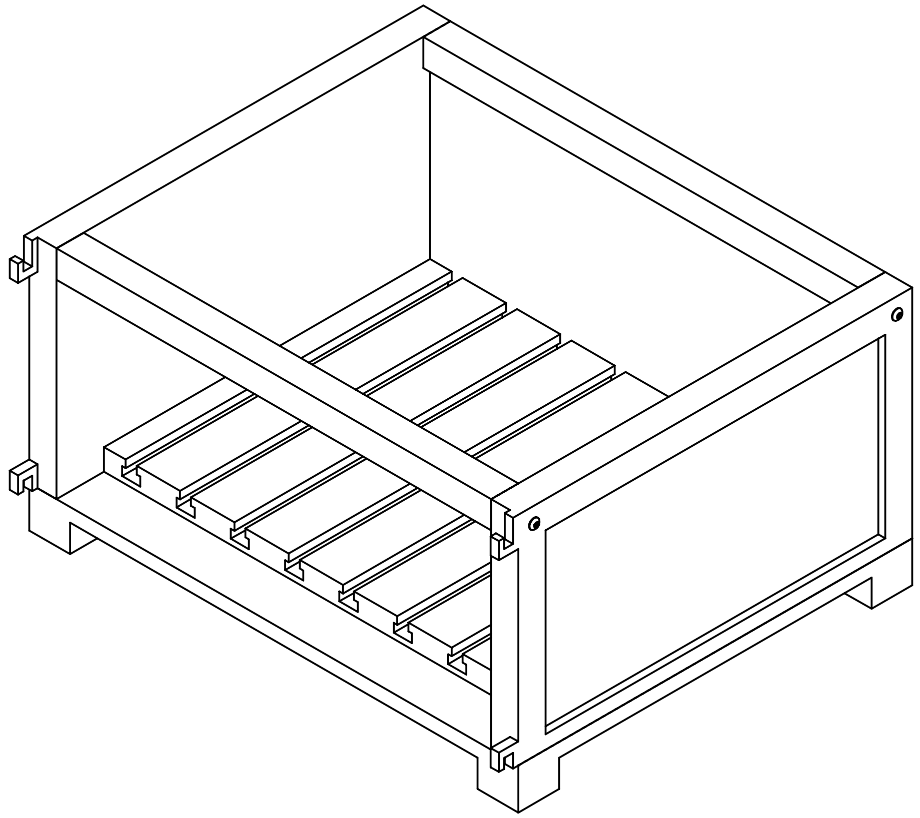
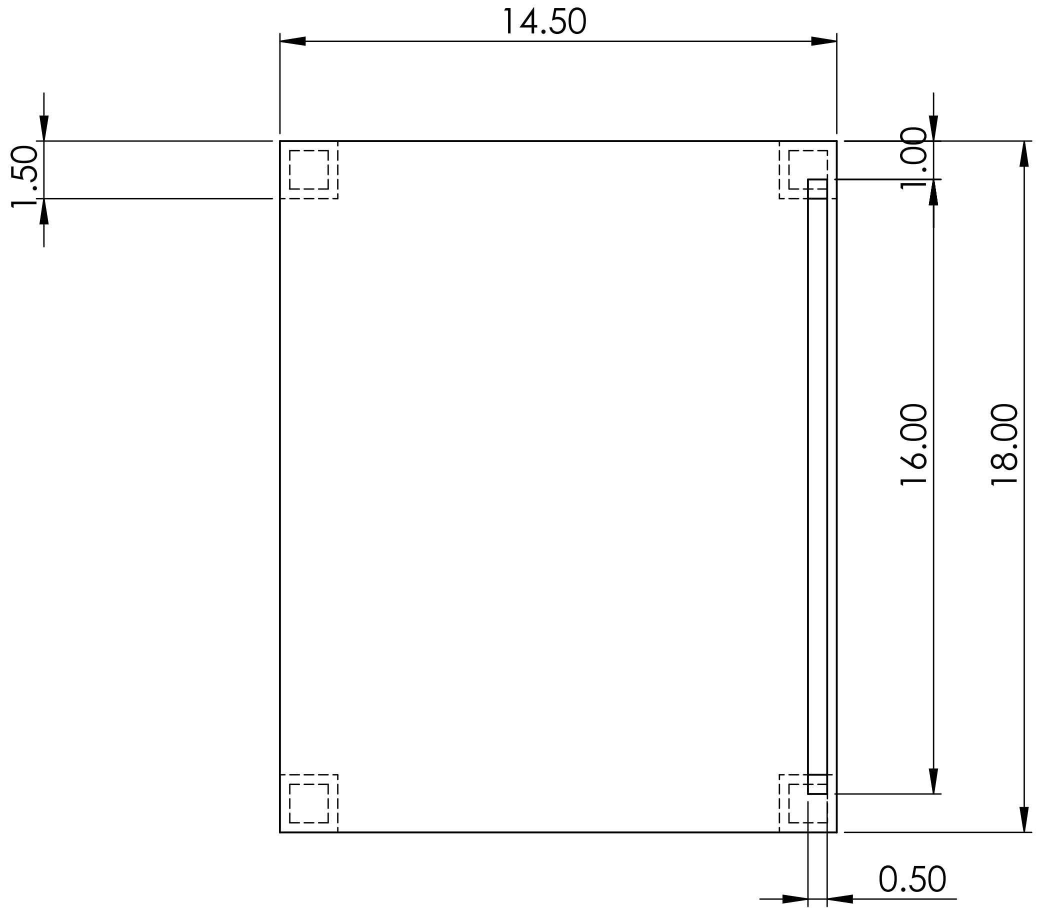
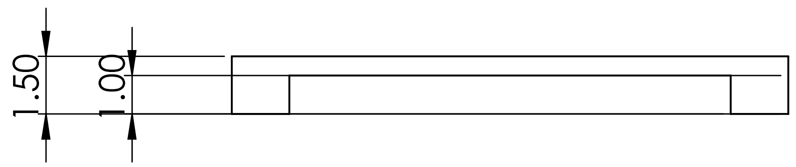
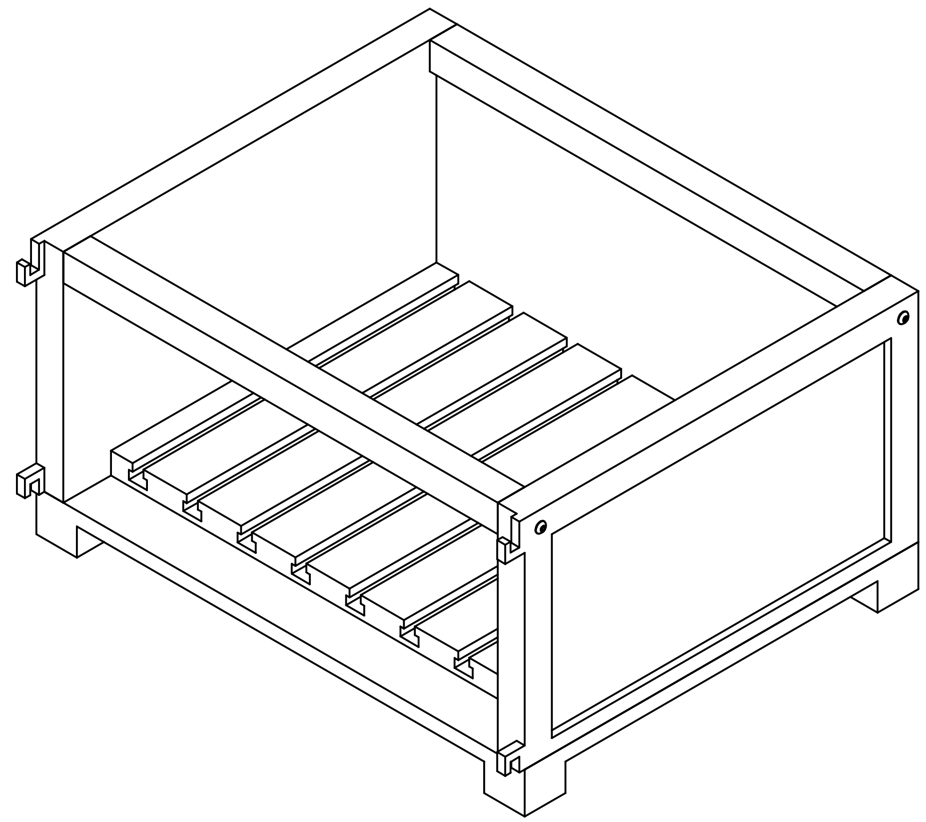




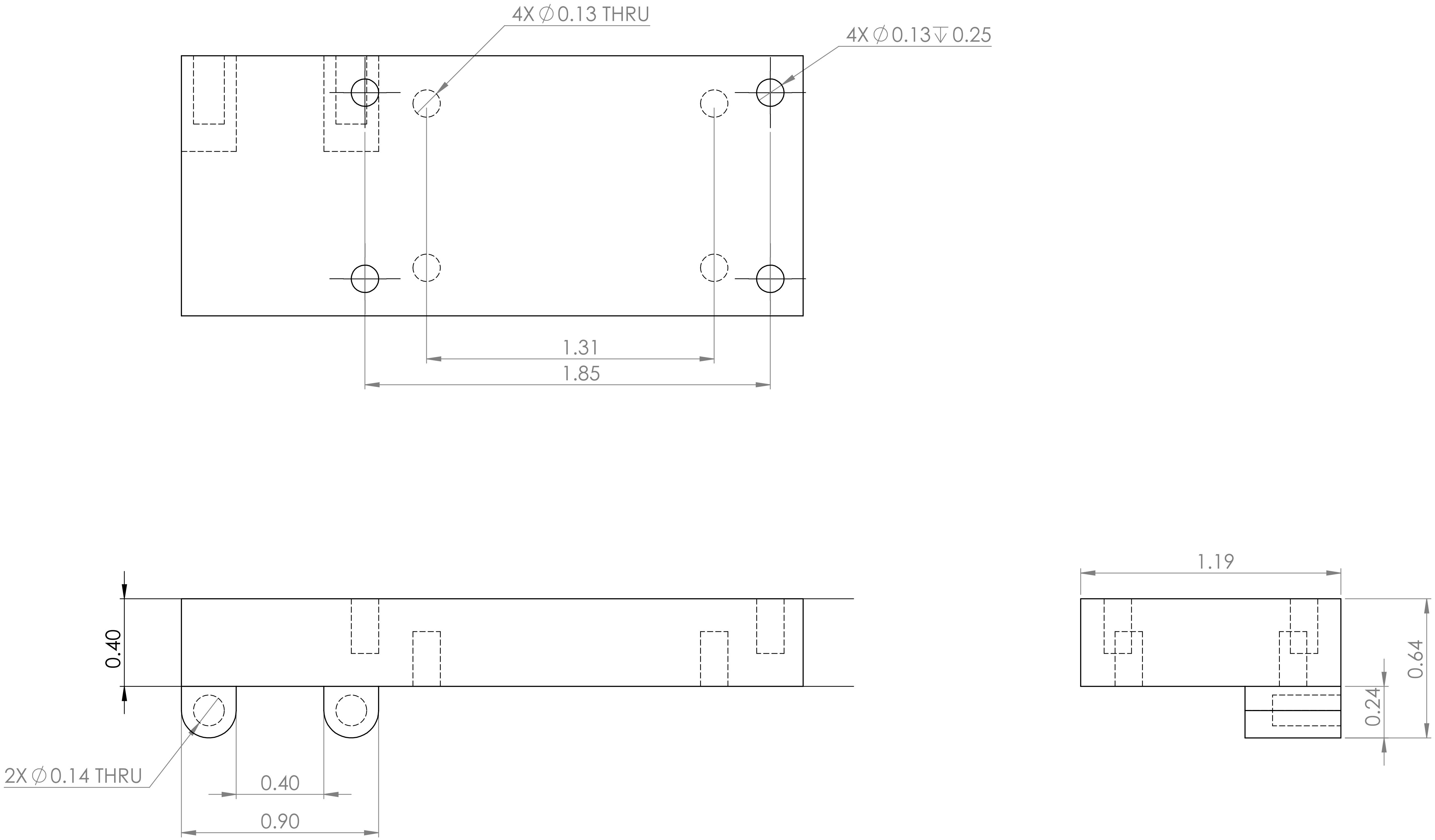
AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: FRAME ASSEMBLY		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 7 0F 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:5	SHEET 3 OF 3	



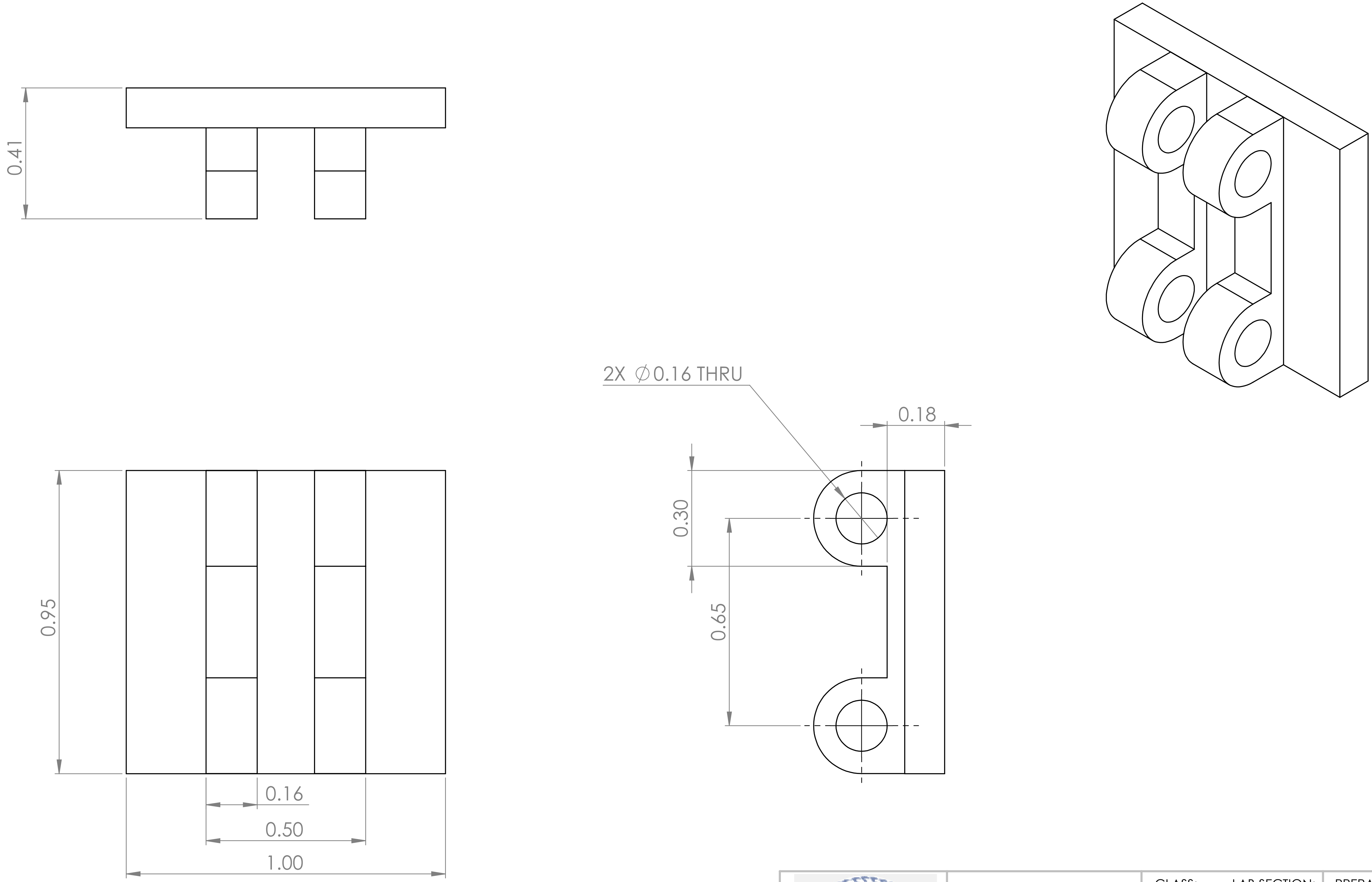




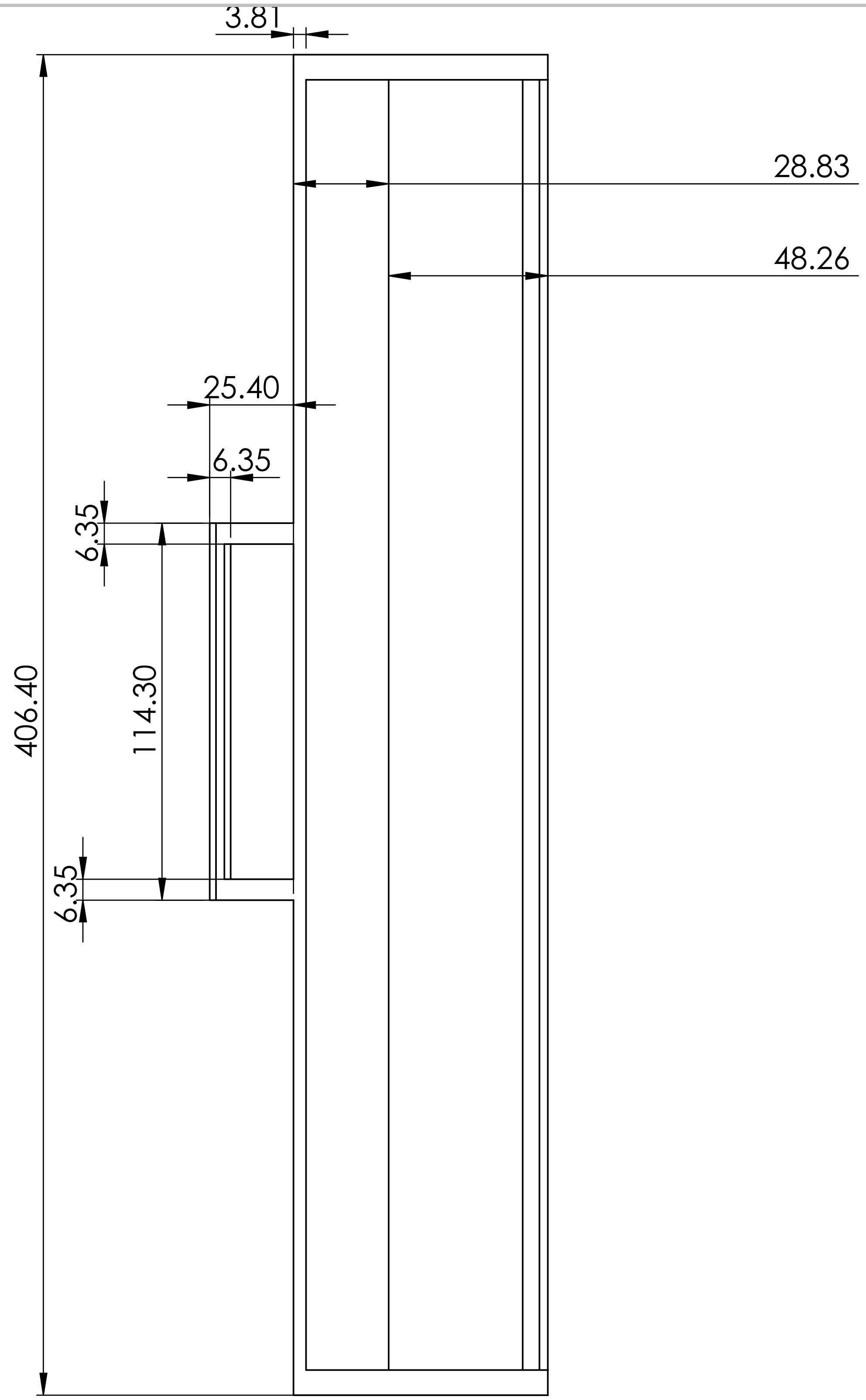
AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: FRAME ASSEMBLY: BOTTOM		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 7 0F 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:5	SHEET 1 OF 3	

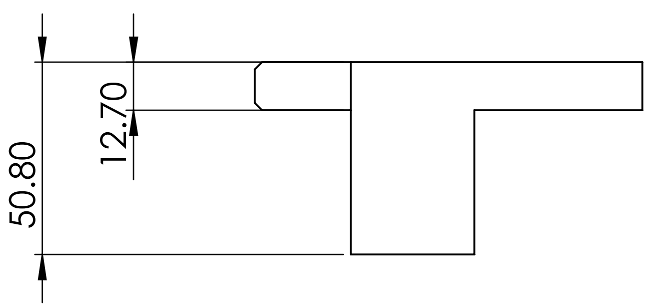


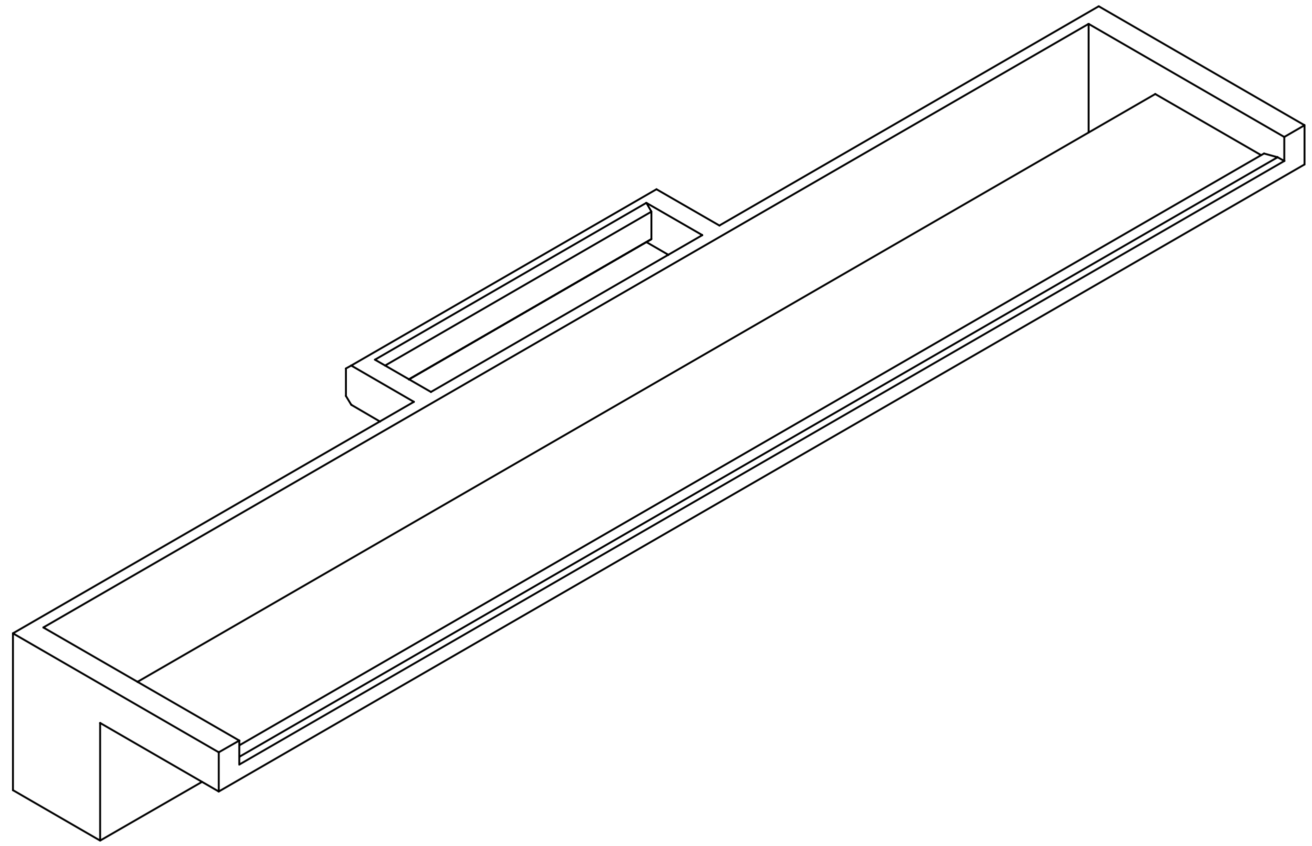
AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: HOUSING ATTACHMENT		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 3 0F 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:2:1	SHEET 1 OF 1	



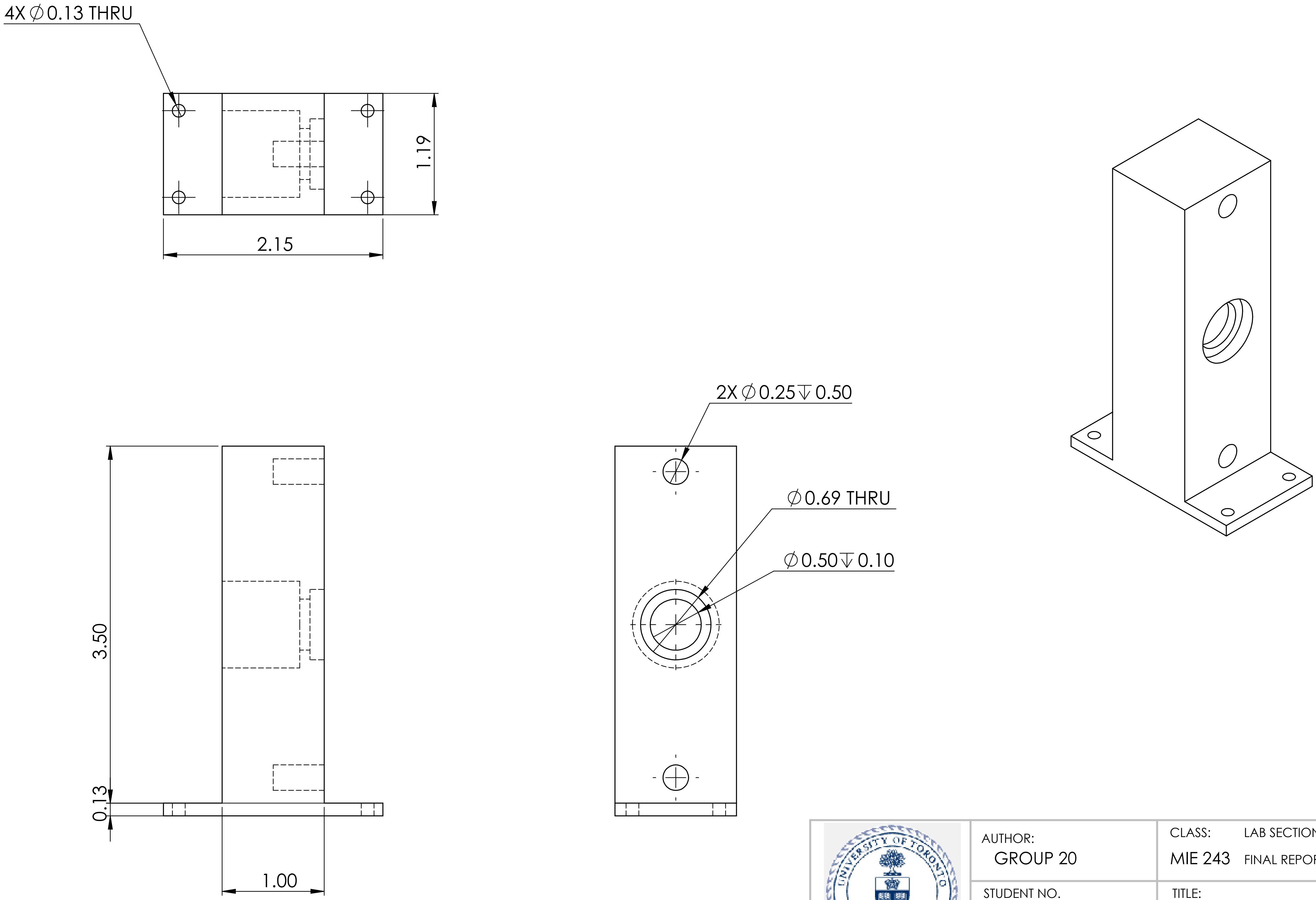
AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: LEAD SCREW ATTACHMENT		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 6 OF 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:3:1		SHEET 1 OF 1



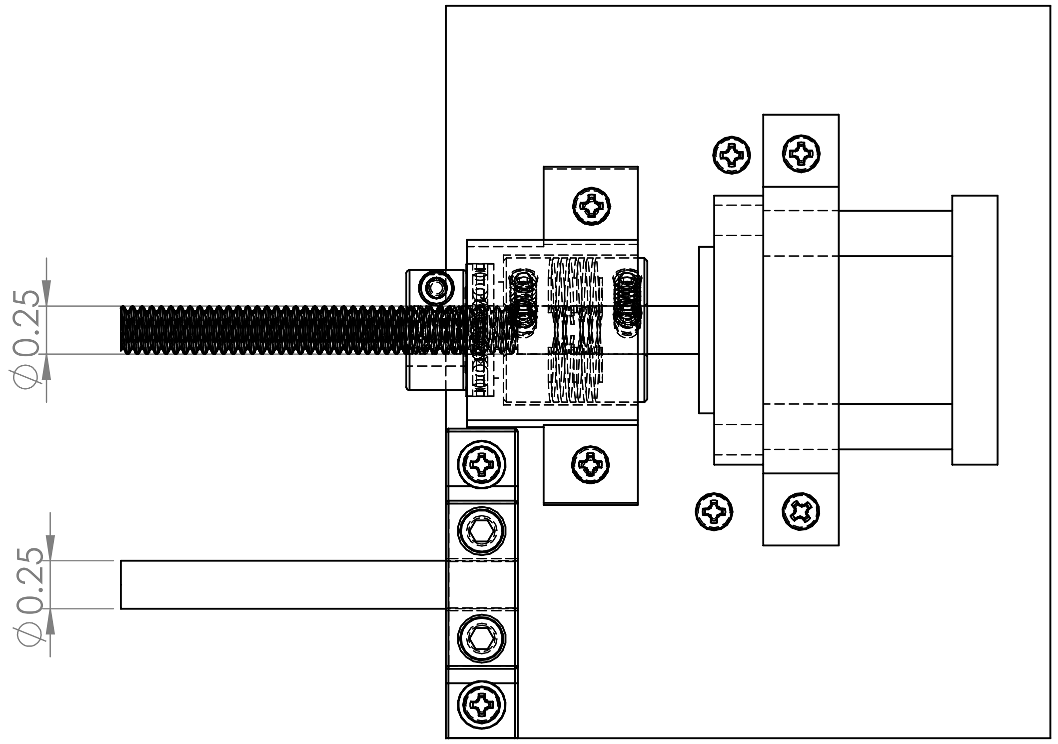


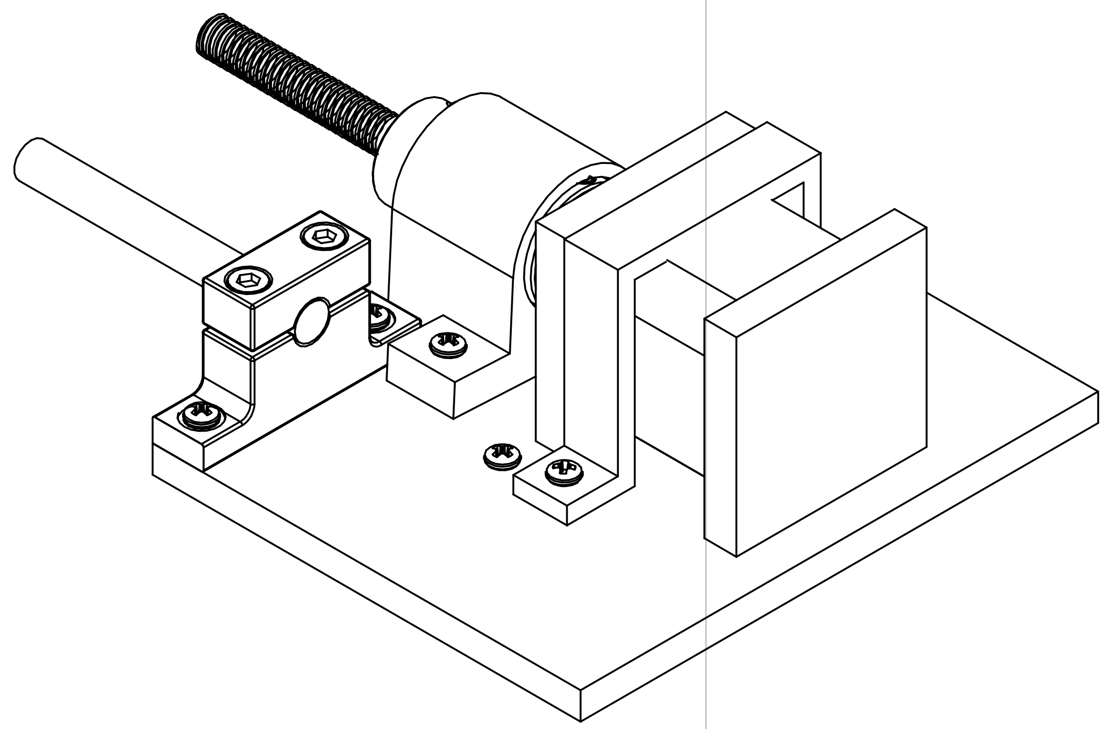


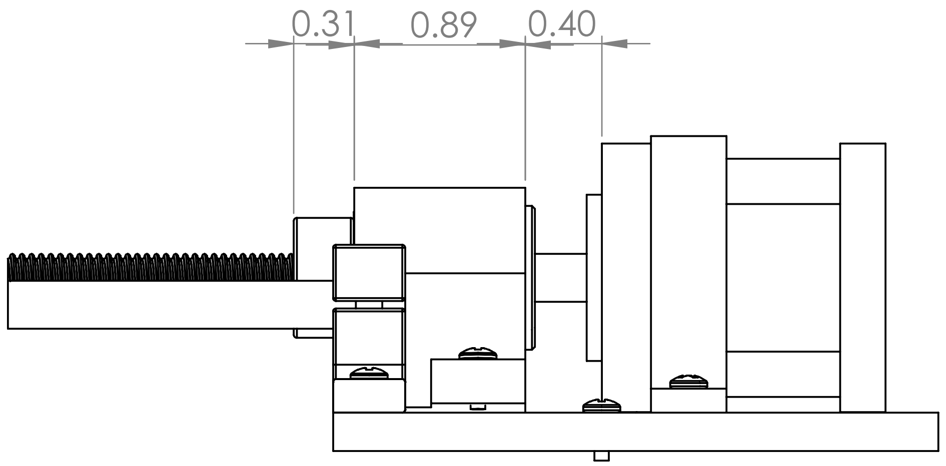
AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: DUST COLLECTION TRAY		
DATE: 10/18/2019			
MATERIAL: PLASTIC	PART NO. 1 0F 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:2	SHEET 1 OF 1	

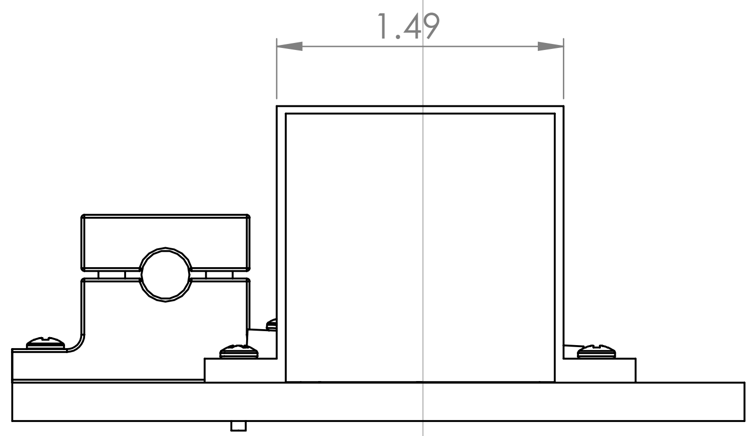


AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS	
STUDENT NO. 1004808498	TITLE: HOUSING FOR X AXIS			
DATE: 10/18/2019				
MATERIAL: ALUMINUM	PART NO. 2 0F 10		REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1		SHEET 1 OF 1	

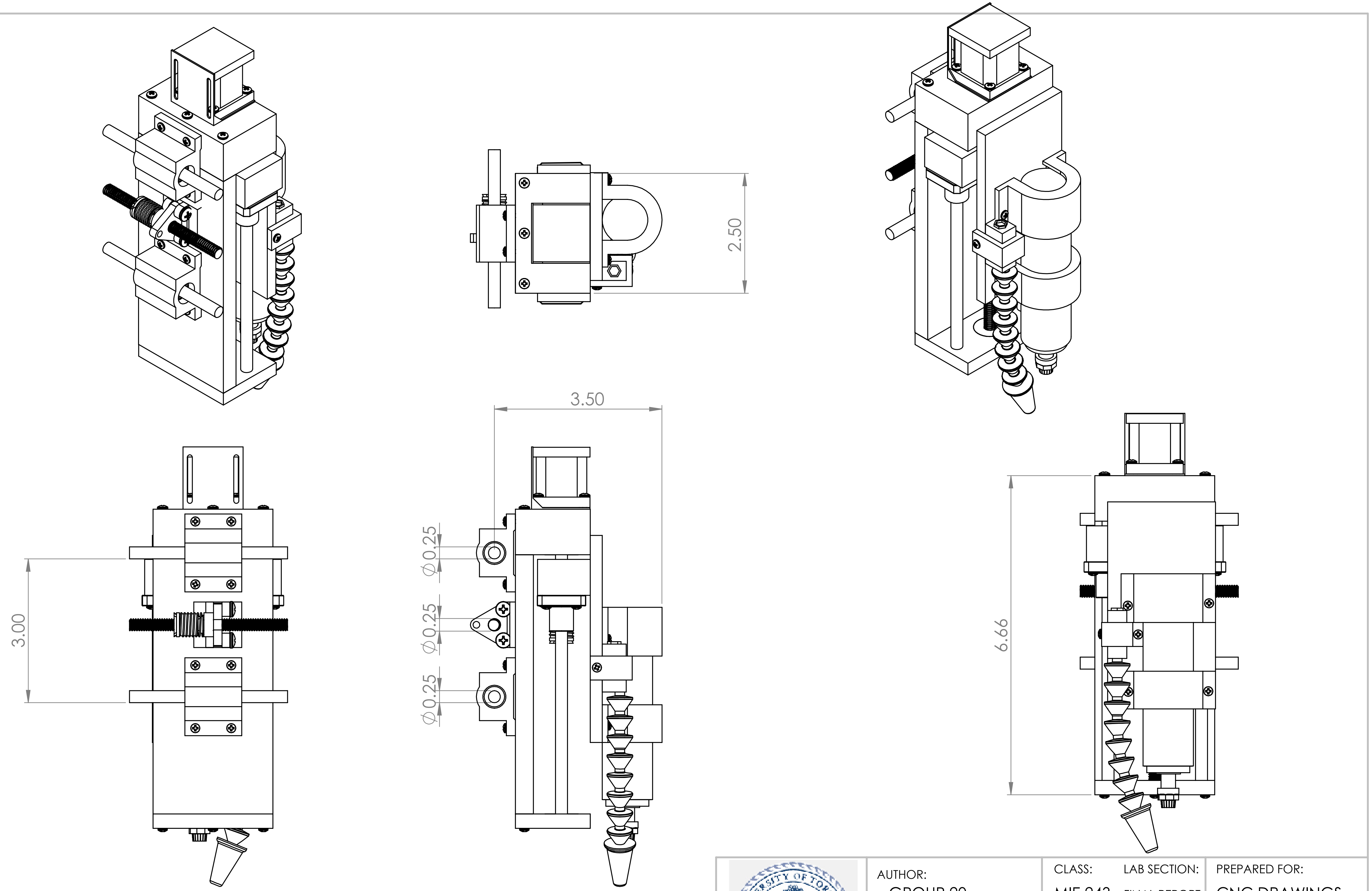








AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: LEAD SCREW MECHANISM		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 8 OF 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:1		SHEET 1 OF 1



AUTHOR: GROUP 20	CLASS: MIE 243	LAB SECTION: FINAL REPORT	PREPARED FOR: CNC DRAWINGS
STUDENT NO. 1004808498	TITLE: SPINDLE MECHANISM		
DATE: 10/18/2019			
MATERIAL: ALUMINUM	PART NO. 9 0F 10		REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: IN, DEGREE	SCALE:1:2		SHEET 1 OF 1