D.I.Y Team: CNC Design Project

MIE243 - Mechanical Engineering Design

Proud Winner of the MIE243 CNC Design Contest

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1. Introduction

CNC milling, or computer numerical control milling, is a computerized machining process that shapes stock materials into user-designed products [1]. The physical milling machine operates by using a rotary tool to remove material; it is guided by a numerical control code that is often created by converting CAD files using special software. This allows users to easily transition their CAD designs into manufactured parts [2][3].

<u>CNC Mill vs CNC Router</u>

The purpose of CNC milling machines is to precisely and efficiently cut metals and other materials using computer automated controls [1]. It was found that for normal home uses, they can be used in a variety of ways especially cutting aluminum for mini projects. Some mechanics enthusiasts can experiment and design engine blocks (the metal cylinder that holds the piston in place) by milling large aluminum blocks. Similarly, the CNC machining can be used to produce other car parts such as suspension components, exhaust parts, carburetor housings. On the other hand, CNC routers are used in a similar fashion, they differ from milling machines in the sense that they cut wood and other soft materials. At home, CNC routers can be used for a variety of wood projects as well as art projects. A common use for CNC routers for enthusiasts is to create pictures and other cool designs by carving into the wood. For home machining, it is often about the joy of creating things; often being custom components for D.I.Y projects. According to most online forums and discussions, most entry level CNC router/milling hobbyists would be willing to spend around 1000-2000 dollars, with routers being the cheaper and preferred option [4]. In general, there is a gray area of overlap between the differences between a CNC mill and a CNC router, as the two operate in the same fundamental way. We will define the difference between the two as:

- CNC Mill: capable of cutting metals, and operate on at least a full 3-axis.
- CNC router: not capable of cutting metals, and may/may not operate on 3-axis

Our Focus

Our design will target the beginner hobbyist market, users that will primarily use the machine for light modelling and prototyping. They will primarily mill common light modelling materials like plastics. Light metals like aluminum are also commonly used in higher fidelity prototypes, which our machine will also cut. Since beginner hobbyists have limited understanding of technical components and likely don't require flagship designs, our machine should be built to be easy to install and operate, and also emphasize on low cost. To cut fully in 3-D, our machine must at least fulfill 3-axis of motion, but no more to reduce complexity and cost. To finalize our focus, the design will categorize as a 3-axis CNC milling machine.

Service Environment

In order to have an ideal design we will also have to take into account the environment that our design will operate in. These include the living and virtual environment around them.

	Environment	**Characteristic**
Living Things	Children if machine used in a house	• Design may be harmful for children and must be kept away from machine
	Pets such as cats and dogs etc.	• Animals in a house might cause hindrance during operation. • They might damage the design
Virtual Environment	Electricity and voltage requirement for design	• Standard voltage in North America Household: 110-120V [7]

Figure 1: The above table describes the service environment of the design.

2. General Engineering Specifications

When designing a CNC machine for hobbyists it is important for the design to be kit-type, compact and affordable. Considering our targeted market, the design must be able to operate in 3 full axes of motion (x,y, and z).

Specification	**Description**
Source of Power	Electric current through portable cable can also be battery powered.
Motion Type	Linear along 1-3 axes (up/down, front/back, left/right)
Output Motion	Continuous rotational motion of the blade
Core Problem	The design must be portable and affordable (Easy Assembly by hand)
Total Dimension	Total dimensions should be minimally greater than the workspace dimension
Workspace Dimension	60 cm x 40 cm x 10 cm[1]

Figure 2: this table shows the overall requirements of the design.

Considering the fact that we are designing affordable, light modelling CNC machines for amateurs and hobbyists, the primary constraints are cost, movement and the compactness of the design.

[1] The area: 60 cm x 40 cm, is determined based on the size of desk in SF3202. The height: 10 cm, is chosen based on the movement height of an existing product: *Shopbot Desktop*

Constraints	Description
Cost	Cost to build machine must not exceed $1000 [9]
Movement	Must be able to operate in at least 3 axes of motion
Compact	Total dimensions of the design must be under 90 x 60 cm (size of table)
Easy to assemble	It must not take more than y time to assemble the design

Figure 3: this table demonstrates the constraints of the design

Since our design is targeted towards applications for light modelling and prototyping, we have compiled a list of common soft materials that our machines will be able to cut in Figure 4.

Aluminum + Aluminum Alloys Ex: 2024-T4/T6, 2014, 6061-T6/T651, 7075-T6
Magnesium Alloys Ex: De-CAt, Extruded
Plastics Ex: Polysulfone, Phenolics, Plastics, Polycarbonate

Figure 4: illustrates a list of soft materials [8]

3. Design Process

The first candidate designs were generated in consideration of our general engineer specifications by extensive research of existing designs and analyzing the possible combinations of motions for the design.

3.1 Style

The initial consideration for our CNC milling machine design is style. This consists of configurations for the bed and gantry that would enable movements in the 3 axes. The bed is where the cutting material will be placed and the gantry contains overhanging assemblies that will cut the material. Depending on the axis, either the gantry or bed could be chosen to be responsible for movement:

- To move in the X direction, either the bed or the gantry could move while the other remains stationary.
- To move in the Y direction, the spindle will slide along the gantry.
- To move in the Z direction, either the bed or the spindle on the gantry could move vertically while the other remains stationary

An initial research through CNC router-building forums and existing machines is conducted, and the most popular configurations have been determined to be the following:

3.1.1 Candidate 1: *Moving Bed and Fixed Gantry*

Goal: To analyze the state of the art CNC designs

As the name implies, candidate 1 features a moving cutting board with a spindle fixed in the x direction. The spindle freely moves in the y-direction and x-direction on the gantry and the cutting board moves in the x-direction to allow cuts to be made in all three axis.

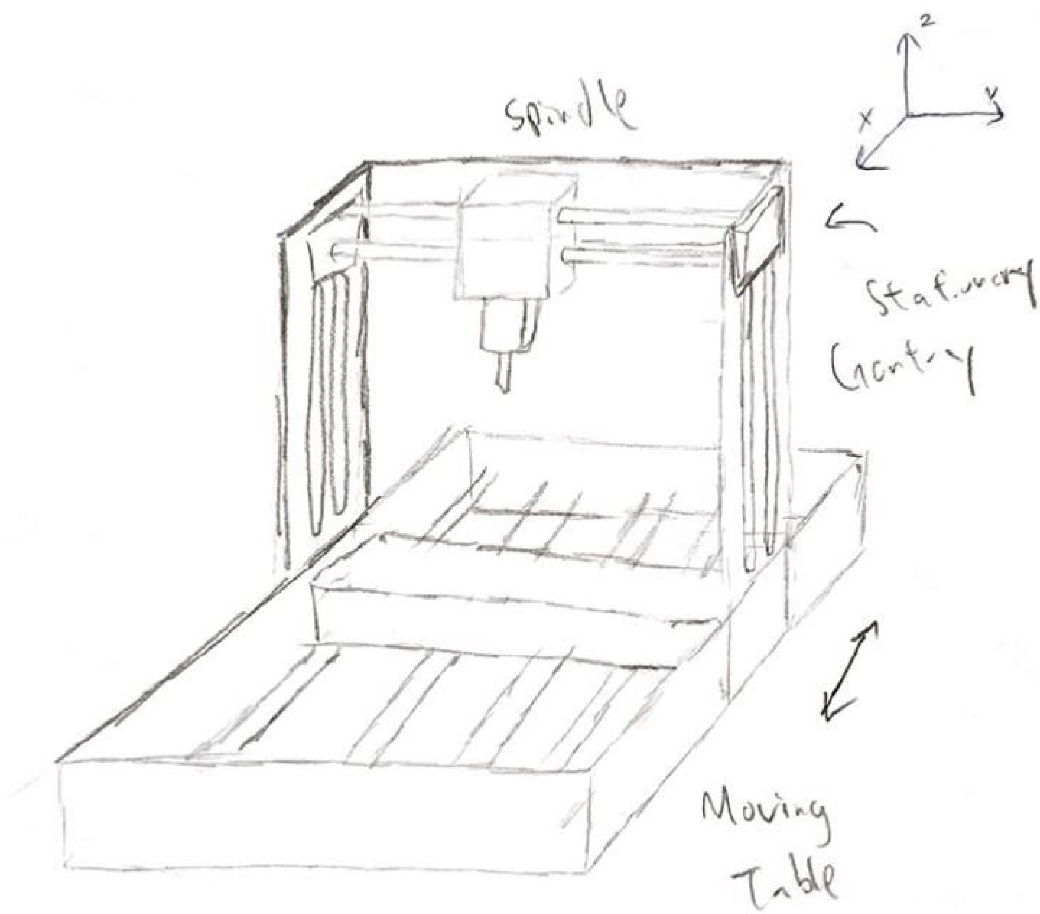


Figure 5: Rough sketch of candidate design 1

Advantages	Limitations
Stationary gantry will result in more stability.	Since this design incorporates a moving base, it requires more space (2x the workspace area) .
More accuracy as both the bed and the spindle will be moving. Better option if precise cutting is required	May require more power to move the whole bed instead of the gantry

	Clamping object on the bed may be a problem as the bed would be in motion frequently
	Larger motion mechanism needed to move bed, might be harder to maintain / lubricate

Figure 6: table describing the advantages and limitations of Candidate 1

3.1.2 Candidate 2: *Stationary Bed and Moving Gantry*

Goal: To optimize the amount of workspace.

Candidate 2 is similar to candidate one except in this case, the spindle does all the moving. The gantry allows the spindle to move in the z and y axes and the table contains a rail that allows the gantry to move in the x direction, thus moving the spindle in the x direction.

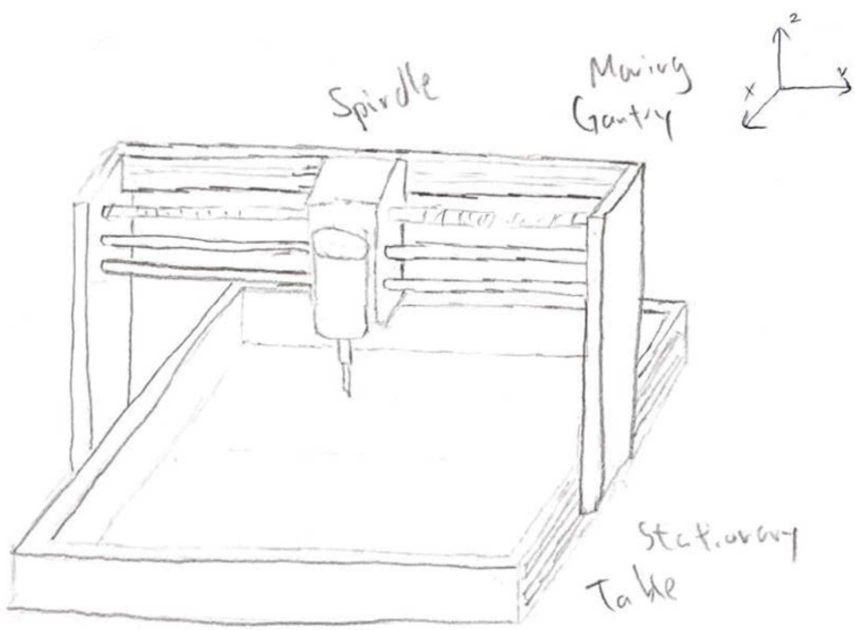


Figure 7: Rough sketch of candidate design 2

Advantages	Limitations
Moving the gantry requires less power than moving the work bed since it weighs less. Thus, a motor with a lower output torque may be used which decreases the manufacturing cost.	Higher chance of the gantry jamming up due to constant motion in potentially more than one axis.
A larger cutting area can be built with a moving gantry since the bed is stationary reducing the combined required length of the sliders	A less stable machine and harder to maintain e.g.frequent lubrication of sliders is required.

Figure 8: Describes the advantages and limitations of Candidate 2

3.1.3 Candidate 2.5: *Modification of Candidate Design 2*

Goal: Mitigate the support and stability of the CNC machine

This design showcases a gantry that allows motion in all three directions. This is an iteration of candidate 2 where we address the issue of support and stability.

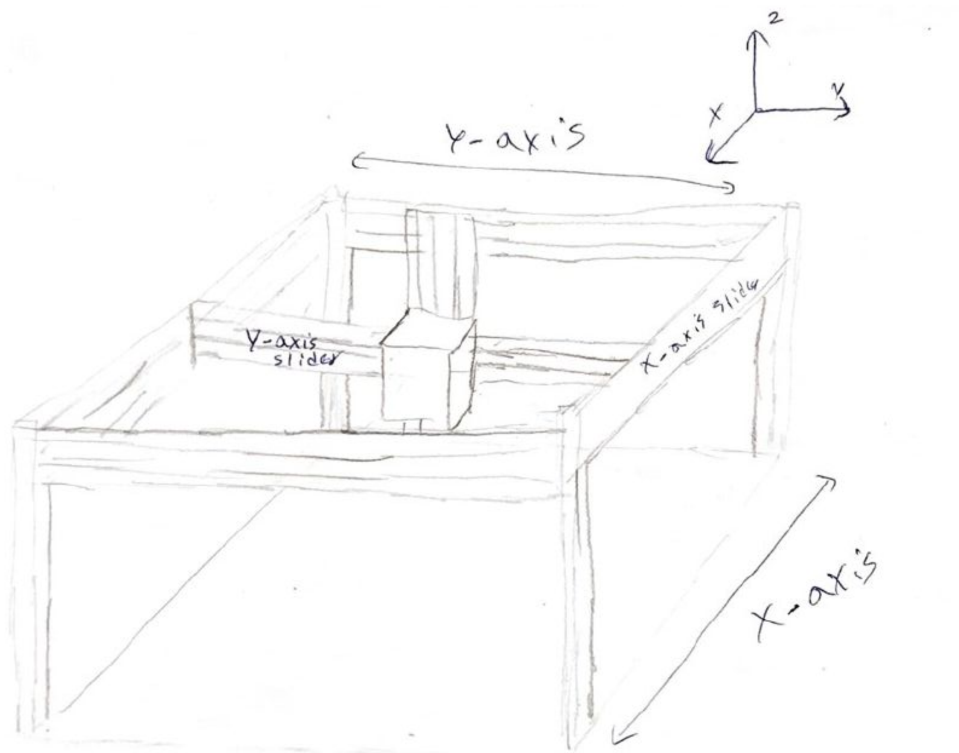


Figure 9: Rough sketch of candidate design 2.5

Advantages	Limitations
Since there is no gantry and the table is not moving the weight of materials being powered by the motor has been reduced significantly.	Friction in the x-axis actuation due to moving the whole mechanism and spindle during the cutting process.
Stability of the design has increased.	
More compact: the design takes up less space compared to other designs.	
Low cost: due to compactness of the design, it uses less materials and since the bed is not moving uses weaker motors which cost less.	

Figure 10: Describes the advantages and limitations of Candidate 2.5

3.1.4 Candidate 3: Circular Bed and Stationary Gantry

Goal: Cuts circular objects and optimizes workspace

This design was the most unique out of the three designs. It features a rotating base and a stationary gantry that allows motions in the z and y direction. All areas on the base can be reached through a combination of rotations and movements on the gantry in the z and y direction.

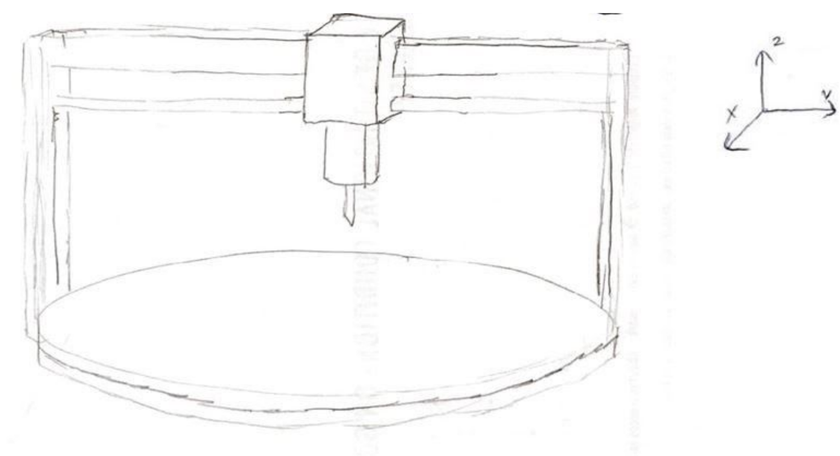


Figure 11: Describes the advantages and limitations of Candidate 3

Advantages	Limitations
Convenient for milling circles	Requires a circular space, might not fit on many workspaces
Increased stability	Might be heavier
Less axes have to move in order to make a cut at a specific spot	Spinning the entire gantry will require more power than just moving spindle

Figure 12: Describes the advantages and limitations of Candidate 3

3.1.5 Selected Style

All candidates were weighed out using our engineering specifications. After thorough consideration, candidate 2.5 was decided to be the most optimal. It saves space and is considerably more stable than the other designs.

3.2 X-Axis Assembly

With the style of the overall design already selected, individual parts of the design are analyzed in a logical order. To begin, the X - Axis (defined by below image) motion mechanism is analyzed. The main purpose of the X-Axis mechanism is to provide stability for the spindle mechanism (section 3.5) and actuate and "allow" the gantry to move freely in the x-axis. This section has been divided into three sections; linear actuator, motor and the guide system. The first part deals with the actuator selection, the second deals with the number of motors and their types, while the last part deals with friction being created as a result of the gantry-holder-shaft and the top-frame as shown by the image below**.** To generate a solution for the X - Axis Motion, an engineering specification is required.

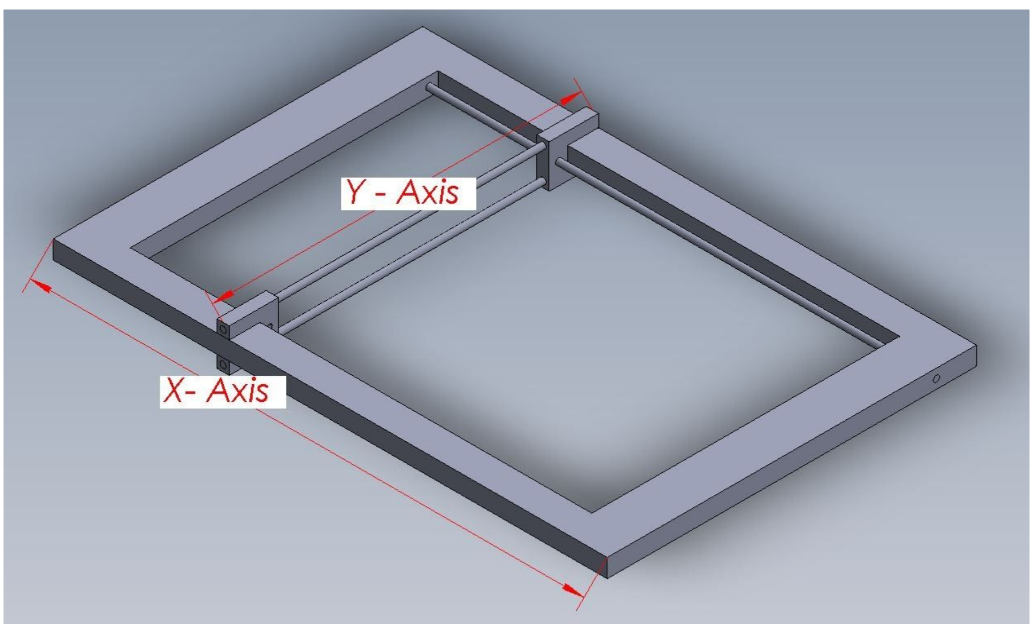


Figure 13: illustrates the upper frame of the design

Engineering Specifications	Details
Input	➔ - Rotational force from the actuator
Output	➔ - actuate, support and allow the gantry to move linearly back and forth
Objectives	➔ Linear Actuator ➔ it must apply high forces and support high loads. ➔ low cost is essential to the design ➔ Motor ➔ produce enough torque to move/ control motion in the x-direction ➔ should be cheap ➔ Support and Allow ➔ allow the gantry mechanism to move freely along the x - axis ➔ decrease the friction being created by the frame and] - shaped supporting shaft ➔ tolerate high force ➔ support medium to high torsion ➔ account for the vibrations being created by the gantry
Constraints	➔ The linear systems must be low-cost (since our primary goal of the project is to design an affordable cnc machine, it is important to select the cheapest guide systems that meet our requirements.) ➔ the linear bearings must be able to support all forces applied by the gantry

Figure 14: communicates the engineering specifications of the X-axis mechanism

3.2.1 Linear Actuator

The linear motion actuators are compared in the table below. The lead screw due to its low-cost, self-locking mechanism, lack of backdrive and low maintenance (self lubricates) has been selected as the optimal linear actuator mechanism for the X-axis.

Mechanism	**Features**
Candidate 1: Belt drive [10][11] 	➔ Ideal for long-stroke movements ➔ Suited for horizontal movements ◆ Vertical movements would require breaks to prevent free fall in case of power loss ➔ Accommodates low to high speed and accuracy ➔ Poor positioning accuracy ◆ Belt stretches over-time ➔ Low noise ➔ Low maintenance
Candidate 2: Chain drive [11] 	➔ Can support high loads ➔ Generates more noise and vibration than belt drive ➔ Requires regular lubrication

Candidate 3: Ball screw [10]

	➔ Ideal for vertical applications
	    ◆ Self locking
	    ◆ No backdrive (most circumstances)
	➔ Can support high loads
	➔ Highly accurate and precise
	➔ Very efficient due to minimal rolling resistance
	➔ Prone to noise from ball movements
	➔ Requires regular lubrication
	➔ Very expensive

Candidate 4: Lead screw [11] [12]

	➔ Can support high loads, though less than ball screws
	➔ Ideal for vertical applications
	    ◆ Self locking
	    ◆ No backdrive (most circumstances)
	➔ Not noisy
	➔ Not as efficient as ball screws due to friction
	➔ Not ideal for long distance movements
	➔ Low maintenance
	    ◆ Self lubricating
	➔ Low cost

Candidate 5: Rack and Pinion [11]	➔ Highly accurate over long distance travels ➔ High friction requires frequent maintenance ◆ Lubrication ➔ Rack length must be accomodated ➔ Prone to backlash due to need of clearance ➔ Helical ➔ Higher speeds and load capacity ➔ Quieter

Figure 15: describes, compares and contrasts the linear actuator mechanisms.

The use of lead screw as the linear actuator for a CNC machine gives rise to the problem of there being uneven distribution of force if only one lead screw is to be used along an axis meaning that the side on which the lead screw lies must have more support than the other or the other side has to be heavier. Hence why, two lead screws shall be used, one on each side of the top frame for proper load distribution and design simplicity.

3.2.2 Motors

There are two main types of motors that are considered for actuation of motion in the x or y-axis. 1) Stepper motors 2) Servo motors. Stepper motors are very appealing to our design as they are cheaper than servo motors, but offer relatively the same amount of accuracy. Furthermore, they do not require encoders unlike servo motors, which could fail often. Also, one may ask the question, “If two lead screws are to be used, are they going to be powered separately or by a single motor?”. The disadvantages of both options are tabulated below.

Using 2 motors	Using 1 motor
Motors may fight against each other	Has to be put on 1 side, and the motion has to be transmitted along the whole length of the y axis. This requires a belt drive, two bearings, and an axle at least which amount to the cost of

	an extra stepper motor.
Introduce extra vibrations to the system.	If an axle has to be run along the whole length of the y axis, it could twist. Meaning that the machine’s tracking would not be the same going forward as going backward. Even if the motor is mounted in the middle, the backlash problem still exists.
Need to be perfectly in sync.	If only one motor is used to actuate motion along two lead screws, it has to be larger and heavier than a motor which actuates motion along only one lead screw. This leads to an extra required time for the gantry to ramp up or reverse direction which may not seem significant however could lead to a large accumulation of wasted time in long cuttings.

Figure 16: describes the disadvantages of using 2 motors vs 1 motor [13]

Weighing the disadvantages and ease of assembly for each scenario against each other, we decided that using one motor per lead screws is a better option.

Motor choice (NEMA 23) justification

The average machining force which is converted to torque through the lead screw is 47 lbs (weight of the gantry). After converting this load to lead screw torque, we find that the magnitude of the required torque for the lead screw is 31.6 oz.in. The average operating rpm of the x-axis is around 10 rpm. Knowing this, we can check the torque vs rpm, whether or not the 31.6 oz torque can be provided by the motor at that rpm.

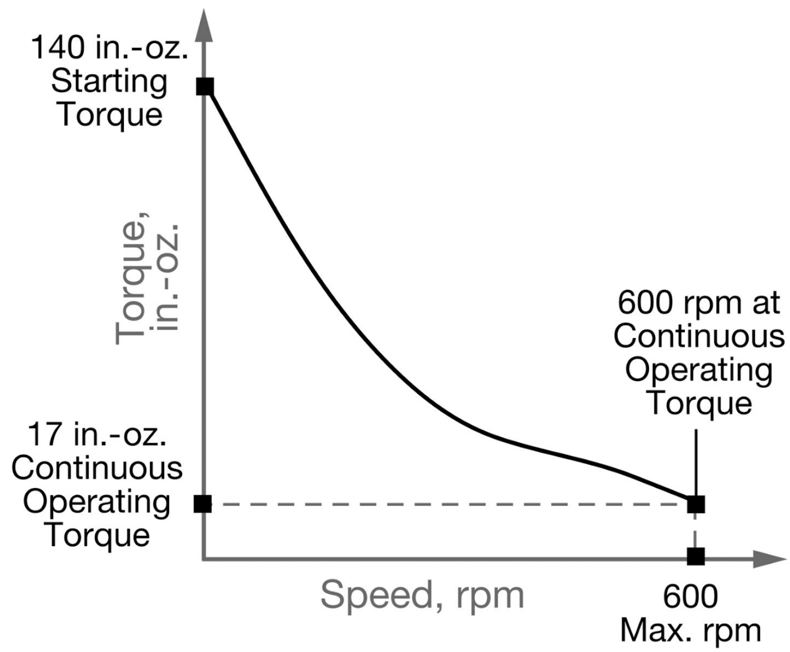


Figure 17: Torque vs Speed graph

The point (31.6 oz.in, 10 rpm) lies under the graph thus the choice of the 23 NEMA motor is appropriate.

3.2.3 Support Mechanism

The main purpose of this section is to deal with the friction created by the green **]** - shaped support (referring figure 17 below) and the grey top frame in addition to supporting any forces applied by the gantry.

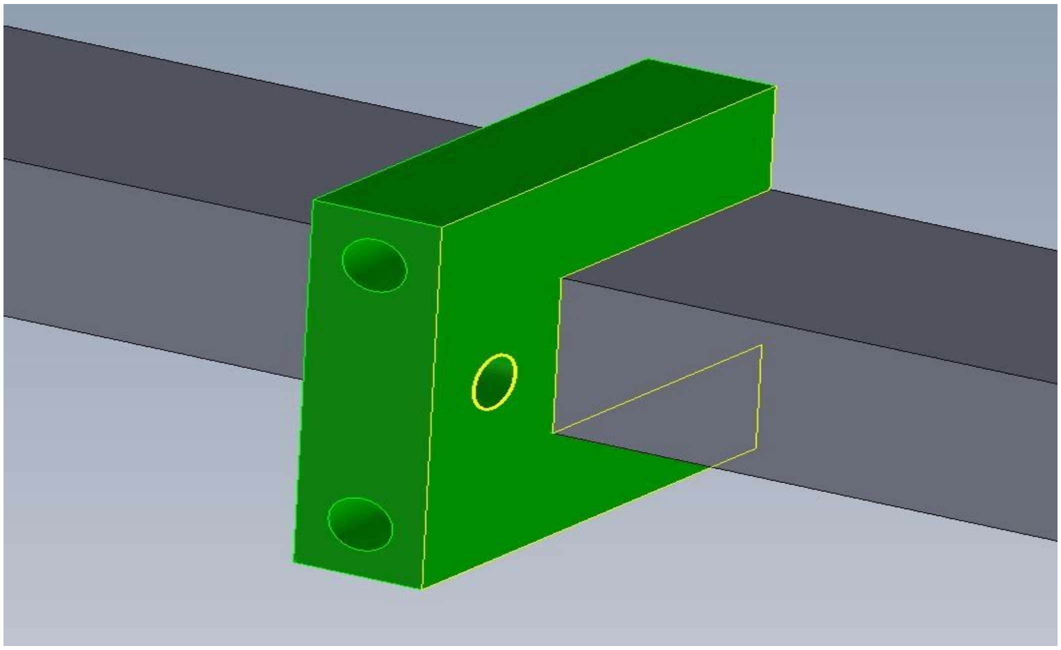
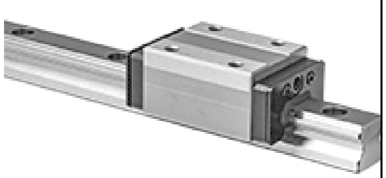


Figure 18: **]** *- shaped support diagram*

To eliminate the friction, the below 4 categories of solutions are analyzed. These 4 categories are mostly used for linear guide systems.

Mechanism	Features
Candidate 1: Linear Ball Bearing Carriages and Guide Rails [14] 	➔ support high loads up to 38000 N ➔ high moment loads up to 27.6 Nm ➔ low friction and high stiffness ➔ available in single and dual rails ➔ high cost and high noise level ➔ high speeds
Candidate 2: Sleeve Bearing Carriages and Guide Rails [15] [16]	➔ no lubrication needed ➔ maintenance free ➔ best at handling impact and vibration ➔ low noise

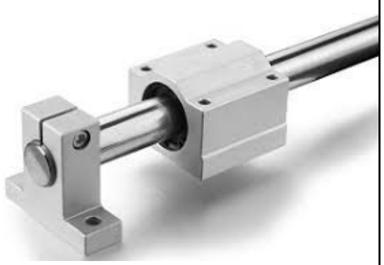
	➔ cheaper than linear ball bearing carriage ➔ create more friction ➔ suitable for static roll moment of less than 250 ft-lbs ➔ have low load capacity
Candidate 3: Track Roller Carriages and Guide Rails [17] 	➔ high load capacity ➔ support lateral and moment forces ➔ perform smooth operation ➔ low friction ➔ High speeds
Candidate 4: Ball-bushing bearing Carriage and round rails [18] 	➔ round rails are cheaper than square rails ➔ round rails operate more smoothly than square rails ➔ less accuracy, load capacity and static roll moment

Figure 19: Describes, compares and contrasts the guide mechanisms.

Upon comparing the above categories using the engineering specification of the guide system mentioned in the beginning of this section and analyzing the standardization of these mechanisms, the track roller mechanism was chosen. This mechanism is the cheapest mechanism and it's highly standardized. Track roller carriage supports high load and moderate roll moments and can operate with low friction at relatively high speeds. The track roller selected is standardized and can be ordered from McMaster-Carr. To view the track rollers refer to the Bill of Materials Section.

<u>Linear coupling choice justification:</u>

A linear coupling is required to attach the motor shaft to the lead screw and transmit the rotational motion. There are two types of linear couplings: flexible and rigid. We are using flexible couplings with a ¼” input and output shaft diameter just so it is a perfect fit for the lead screw and motor shaft which are both 1⁄4” as well. A flexible coupling can compensate for misalignments which are quite common in CNC applications causing noise and reducing the life of the coupling [19]. However, a rigid coupling requires both shafts to be in absolute perfect lateral and radial position which is very difficult to achieve.

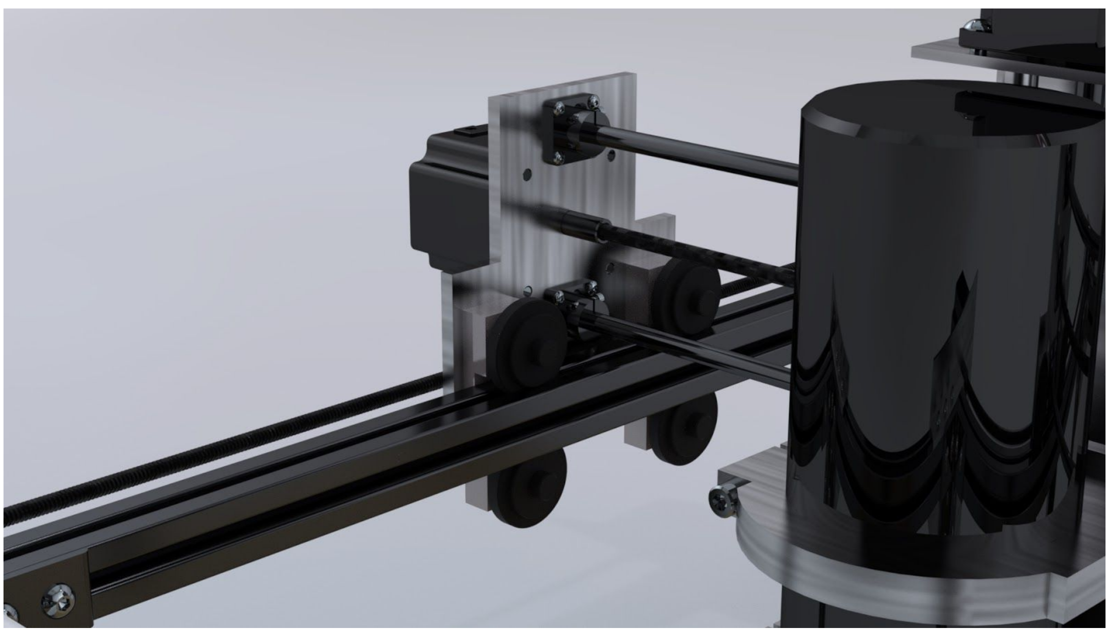


Figure 20: x-axis motion mechanism

3.3 Y-Axis Assembly

In this section of the report we have discussed the y-axis motion of our design. Similar to the x-axis motion, the y-axis mechanism allows motion of the gantry in the y-direction. Unlike the x-axis mechanism, the y-axis mechanism does not travel a long distance and is supported on one side only but still needs to support the spindle. Therefore our objective is to design it in such a way that it can be actuated efficiently but is also sufficiently supported in order to hold the spindle.

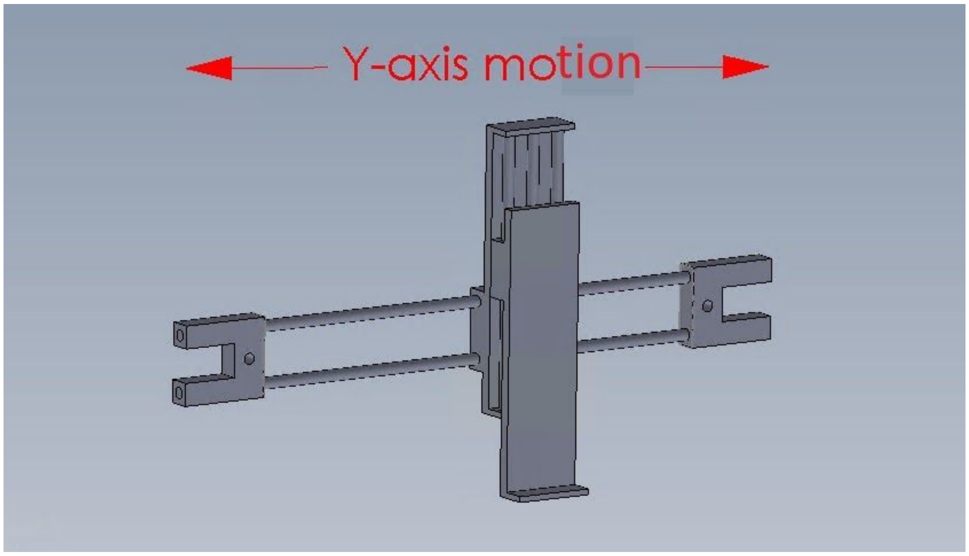


Figure 21: y-axis motion mechanism

Engineering Specifications	Details
Input	Rotational Motion
Output	Linear Motion of y - axis back and forth
Objectives	➔ Efficient motion of the mechanism throughout the axis ➔ Reduce friction and other external forces ➔ Reduce wear and tear in the mechanism so that it does not need to be replaced regularly
Constraints	➔ Cost must be minimized ➔ Must fully support the spindle and z - axis mechanism

Figure 22: communicates the engineering specifications of the Y-axis mechanism

3.3.1 Linear Actuator

For actuation a stepper motor similar to the x-axis mechanism would be ideal as it is cheap and has relatively good accuracy. For Linear actuator that will provide the motion, we have selected some ideal mechanisms in the x-axis section for the task and will further narrow them down according to our requirements.

Referring to figure 15 which includes a list of all the mechanisms, rack and pinion and chain drive mechanism will be very heavy for our application and have a lot of backlash. The belt drive is not very ideal for high force applications. Out of the Ball screw and the lead screw, the Ball screw has more advantages but, due to our cost constraint, it will be difficult to implement it in our design and the ideal option is to implement the lead screw.

3.3.2 Support Mechanism

To support the lead screw it is ideal that we attach support shafts on top and bottom of the mechanism so that it is able to support the spindle on top and not be affected by any moment [20]. One disadvantage of doing so is that it will take up space in the y-axis but this sacrifice will ensure that are design is rigid and moves smoothly.

3.3.3 Motor

The selected motor will be the same as the one used in the X axis assembly, NEMA-23. For explanations, refer to the X-axis assembly section.

3.4 Z-Axis Assembly

The Z-axis assembly serves to enable vertical movement of the spindle assembly direction so that the CNC machine can cut in the Z direction. It is designed in the form of a linear motion system that consists of three primary mechanisms (see Figure 23):

- support mechanism — to support cutting cutting moments from the spindle

- linear actuator — to drive the vertical movement of the spindle assembly and support its weight
- motor — to drive the linear actuator

In our chosen style of design, the Z-axis assembly is attached to the Y-axis assembly and allowed to move in the Y direction.

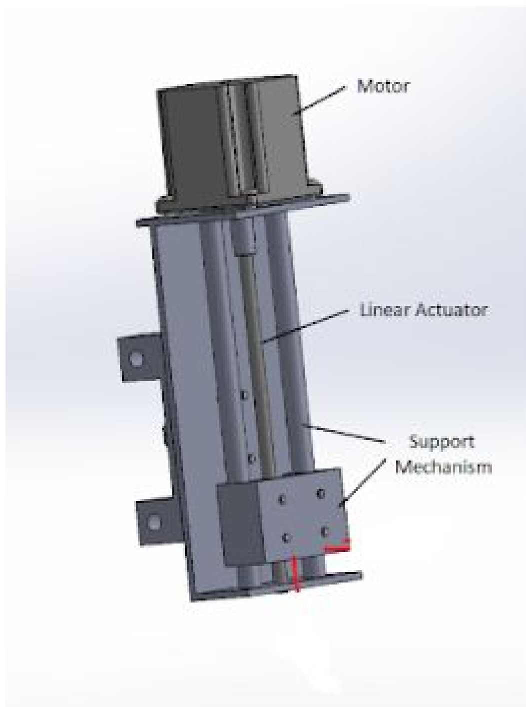


Figure 23: Illustration of Z-axis assembly

Engineering Specifications	**Details**
Input	Rotational motion
Output	Linear motion (vertical)

Objectives	Overall ➔ Design should reduce the moment generated by the cutting force acting: ◆ Distance between the two z-axis motion supports (D2) ~ maximize ◆ Distance between the two y-axis motion supports (D1) ~ maximize ◆ Length of spindle mounting bracket (D3) ~ minimize ◆ Also involves thickness of materials: ◆ Thickness of mounting bracket (D6) ~ sufficiently increase ➔ Cost should be minimized
Constraints	➔ Design must endure the moments caused by external cutting forces applied to the spindle and not flex.

Figure 24: Engineering specs for Z-axis assembly

3.4.1 Support Mechanism

From the list of guide rails in Figure 19, the selected candidate is the round guide rail. In the application of a milling machine, the cutting forces applied onto the spindle will exert moment loads on the guide rails. (see Figure 25). These will be applied primarily in the X and Y axis. In general, round guide rails are better suited to support moment loads than profiled rails [21].

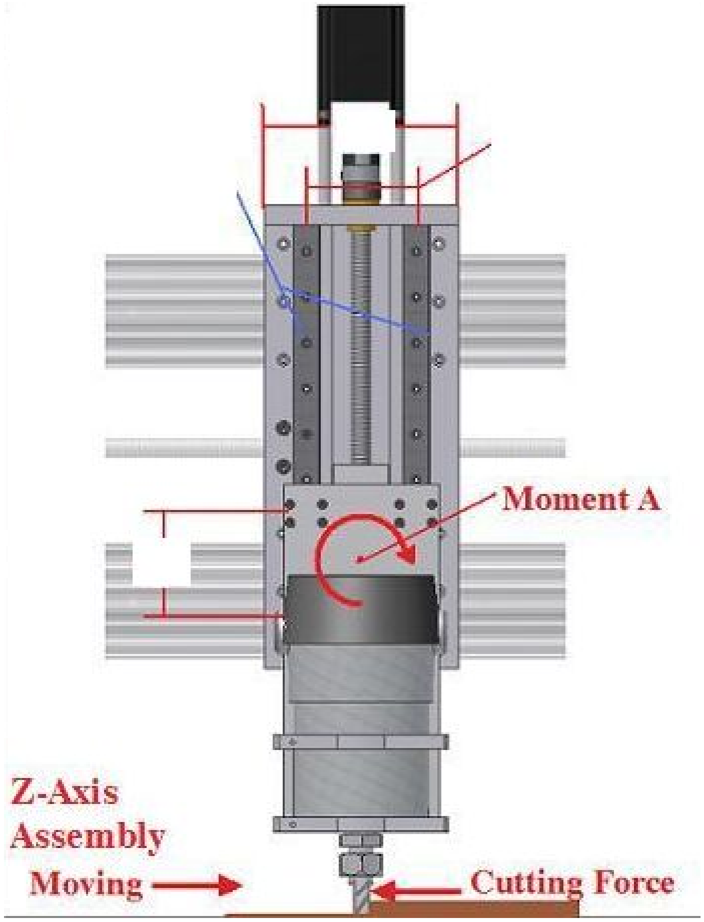


Figure 25: The cutting force exerts a moment load (Moment A) on the guide rails [22]

Although profiled guide rails offer more rigidity, stiffness, and positioning accuracy, they are more expensive. As our design primarily focuses on low cost, we can afford to sacrifice a bit of accuracy for a lower cost. Our design will feature a dual round guide rail system in Figure 25. A bearing platform where the spindle mount will be attached to will operate on the two guide rails.

3.4.2 Linear Actuator

From the list of actuators in Figure 15, the two viable candidates we've considered are the lead screw and ball screw, as they are both self locking, which prevents vertical backdrive in case of power loss. Similar to the decision between profiled and round guide rails, the primary decision factor will be low cost. The lead screw comes at a lower cost than ball screw, at the tradeoff of higher accuracy that is not required for our budget machine. The lead screw will fit in between the two guide rails and will be driven by a motor.

3.4.3 Motor

The selected motor will be the same as the one used in the X and Y axis assemblies, NEMA-23. For explanations, refer to the X-axis assembly section.

3.5 Spindle Assembly

The spindle assembly on the CNC milling machine consists of the spindle and its mounting bracket which would be mounted on the Z-axis assembly.

3.5.1 Spindle

The functionality and quality of the CNC machine heavily depends upon the selection of the respective spindle, as the spindle is responsible for the cutting of materials. Our spindle must be chosen such that it is capable of cutting the materials determined in the general engineering specifications.

Calculations for the spindle speeds and power requirements are conducted because these are the primary specifications used to differentiate products in the marketplace. It involves using recommended charts [Appendix B, Appendix C] that originate from industry experimental data to determine cutting speed, chip load, and unit horsepower for a given material. The chart values are based on the selected milling bit, and depths of cut:

- ➔ The selected bit for our design is ¼” 3-flute end-mill bit.
- ➔ Assuming a maximum cut — a full slot cut — the radial and axial depths of cut are equal to the diameter of the bit, which is 0.25”.

Inserting these parameters (cutting speed is averaged) into the formulas in Appendix D calculates the feed-rate, material removal rate, and most importantly — the spindle speed and power.[2] A standard machine efficiency of 80% is applied to the power to find the overall required power. This calculation is conducted for each material within the design scope and the respective speed and power required for the spindle are tabulated in Figure 27.

Material	**Required Spindle Speed (RPM)**	**Required Power (hp)**
Aluminum + Aluminum Alloys	21400	4.0
Magnesium Alloys	15300	1.4
Plastics[3]	6100	0.9

Figure 27: Required spindle speed and power to cut materials

The engineering specifications for the spindle are:

[2] A sample calculation for *aluminum + aluminum alloys* for can be found in Appendix D.
[3] Unit horsepower for plastics is not given, so the value for magnesium alloys is used instead in the calculation. The assumption is made because plastic is a softer material.

Spindle Specifications	Description
Objectives	➔ The cost of the spindle should not exceed $500 CAD ➔ The size and weight of the spindle should be minimized
Constraints	➔ Must satisfy the required spindle speed and power in Figure 25: ◆ Speed: 21400 RPM ◆ Power: 4.0 hp ➔ The spindle's voltage rating should be 120V

Figure 28: Engineering specifications for the spindle

<u>Chosen Spindle</u>

The spindle that we have chosen is available from AliExpress for $350 (see Figure 29). It has a speed and power rating of 0-24000 rpm and 4.0 hp, respectively, which satisfies our cutting requirements. It is air-cooled, which we have chosen over water-cooled variants to reduce maintenance and minimize additional parts; this ultimately simplifies the operation for the end user. Although it operates at 240 V, the spindle must be used in junction with a variable frequency drive (VFD) and other electrical components that can be chosen to operate on 120 V outlets. The selection of these components are beyond the scope of this report

The primary criterion for choosing the spindle is to meet our spindle constraints, particularly the speed rating and power rating. The dimensions and cost are secondary since these parameters are dependent on spindle capabilities (i.e. a spindle with a comparatively higher power rating will be larger and more expensive). Furthermore, we will pivot the rest of our design based on the chosen spindle.

Figure 29: The chosen spindle from AliExpress, available at [23]

Spec	**Description**
Cooling Method	Air-cooled
Power Rating	4.0 hp (3 kW)
Speed Rating	0-24000 RPM
Voltage Rating	240 V
Dimensions	Mid-body diameter: 105 mm; Length: 233 mm
Cost	$500 CAD ($350 + $150)[4]

Figure 30: Specs for the chosen spindle

[4] The spindle itself costs $350. The $150 accounts for the estimated cost of the variable frequency drive and other additional electronic components required for the spindle to operate.

3.5.2 Mounting Bracket

To complete the spindle assembly, the spindle must be attached onto a mounting bracket, which acts as a fixed support and must prevent the spindle from sliding or rotating at all times. The mounting bracket is attached onto the plunge arm of the Z-axis assembly. Ideally, the bracket should be a lightweight and standardized product to reduce both initial cost and also potential replacement cost in the future for the user. As such, the following engineering specifications have been developed.

Specification	**Description**
Objectives	➔ Lightweight ➔ Standardized ➔ Reduce hole clearance after attaching spindle
Constraints	➔ Must fit the spindle ➔ Must hold the spindle in place to resist translation and rotation at all times

<u>Chosen Mounting Bracket</u>

The chosen mounting bracket is specifically designed for spindles with a 105 mm diameter, and is available from AliExpress for $16 (see Figure 31). It is made of cast aluminum. Although plastic brackets were also considered as they are even lighter than aluminum, they were ruled out because they are not available as a standardized part.

Figure 31: The chosen mounting bracket from AliExpress, available at [24]

Specification	Description
Material	Cast aluminum
Dimensions	105 mm hole; refer to Appendix D for complete dimensions
Cost	$20 CAD

3.6 Base and Frame

3.6.1 Material Selection Frame

The two main considerations for the machine frame include the stiffness and damping ability [25]

- ➔ Frame should resist distortion as cutting and other forces are applied
- ➔ Frame should dampen any unwanted vibrations to avoid rough cuts or chattering [26]

If the frame bends too much when cutting forces are applied, it can lead to

- ➔ Lower lifespan
- ➔ Poor cutting accuracy
- ➔ Poor surface finishes
- ➔

Possible Frame Material	Description and Benefits
Polymer Concrete	➔ Very good damping abilities ➔ Not very rigid ➔ Light weight
Epoxy Granite Fill [27]	➔ Mixture of epoxy resin and granite pebbles/grains ➔ Very good damping abilities ➔ Not very stiff and rigid

Cast Iron	➔ Excellent damping and rigidity [28] ➔ Contains internal stresses ➔ Heavy ➔ Most commonly used
Steel	➔ Stiff but poor damping ability ➔ Contains internal stresses
Aluminum	➔ Much better damping ability than steel ➔ Does not have much internal stresses ➔ Relatively lightweight ➔ Relatively commonly used

Figure 32: describes, compares and contrasts the use of different materials for the base

The choice comes down to either cast iron or aluminum. Since the machine is for home-use, maybe cast iron would be too heavy and too sturdy for the purposes of a hobbyist. Aluminum on the other hand is lightweight and has many other desirable properties and therefore is going to be the final choice for the material of the frame.

Screws

The common options for screw selections include steel, copper, aluminum and titanium [29]. Titanium screws can be ruled out right away since they are much too strong and expensive for the purposes of a CNC milling machine. Copper can also be eliminated since the biggest benefit for using a copper screw is to prevent corrosion. Corrosion in a CNC machine is really never a huge issue since they will probably not be used in extreme long terms and the machine is likely not being exposed to water and other materials that cause corrosion. The remaining two options are steel and aluminum. Aluminum is lighter than steel but is much weaker than steel, for this reason, steel will be the final choice for screw materials. The specific type of screw that is used comes from a company called Servocity, which will be further explored in the frame support mechanism[30].

Base/Cutting Board

It was decided that the base must be expendable due to accidental cuts into the base, replacements should be relatively cheap. In this case, a relatively inexpensive, common and sturdy material should be used as the base. After considering many types of wood, an engineered wood product called MDF (medium density fibreboard) was chosen due to the fact that it has no grains, making it easy to cut and drill without damaging or drastically affecting the structural properties and strength [31]. The MDF will be pre-drilled at certain points to allow an easy assembling process.

3.6.2 Support Mechanisms

The design of the support mechanisms will be based off of the engineering specifications of the frame.

	Engineering Specifications
Objectives	➔ Must be able to support a maximum force of 183.75 N (Weight of gantry times a safety factor of 1.25) ➔ Frame must be able to support a screw drilled through ➔ Must have a yield stress of at least 184 MPa when safety factor of 1.5 is used [32].
Constraints	➔ Size ◆ Must not be taller than the height of the spindle ➔ The cost of the frame should be optimized

Figure 33: communicates the engineering specifications of the support mechanism

It was decided that the material for the frame is going to be aluminum. After thorough research into aluminum beams and rails, a company called 80/20 was researched and their products will be used in the frame and frame support. All the products referred to below are products from 80/20.

T-Rails will be used as the beams for the frame. A total of 8 beams will be used to create the frame.

Since we have chosen a design that does not incorporate a moving gantry, our vertical rails would be rigid in order to reduce vibrations in the structure and will be situated at the corners of the working space so that the spindle can approach most of the area. We have two ways to attach the supporting rails to the workspace, by welding them or by screwing. The better option would be to screw them in as it would be easier to manufacture however it will slightly increase the assembly time for the machine [33].
The 4 legs acting as the supporting rails is secured using the specific parts from the company as shown in the diagram, the top frame will be secured together using the same parts [34]. Additionally, rail brackets shown in 6.3.1 and 6.3.2 will be used for extra support for the top frame.

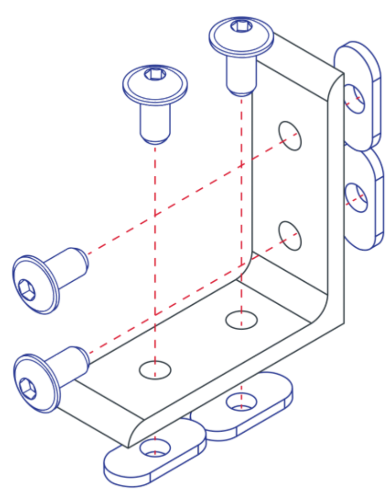


Figure 34: Diagram of how supporting rails will be secured with a raised perpendicular mount and socket head screws [35] [36]

Figure 35: Diagram of the T-Rail

Out of the 4 top rails two of them would have to be fully supported as they will drive the spindle in the x direction and two do not need to be fully supported. Additional brackets can be used for further support [37]. Cutting space attached to the exterior frame through screws so that the frame does not get damaged during milling and board could be replaced.

4. Final Design

To tackle this project, we came up with a general engineering specification and categorized the functions of the machine. By doing so, we were able to come up with specific engineering specifications for each assembly of the final design and generate potential candidates which we then carefully analyzed and compared against each other to decide on the best design choices. After comparing all the potential candidates for style, motion assemblies and all the relevant subsections in the three axes, we propose the D.I.Y CNC mill:

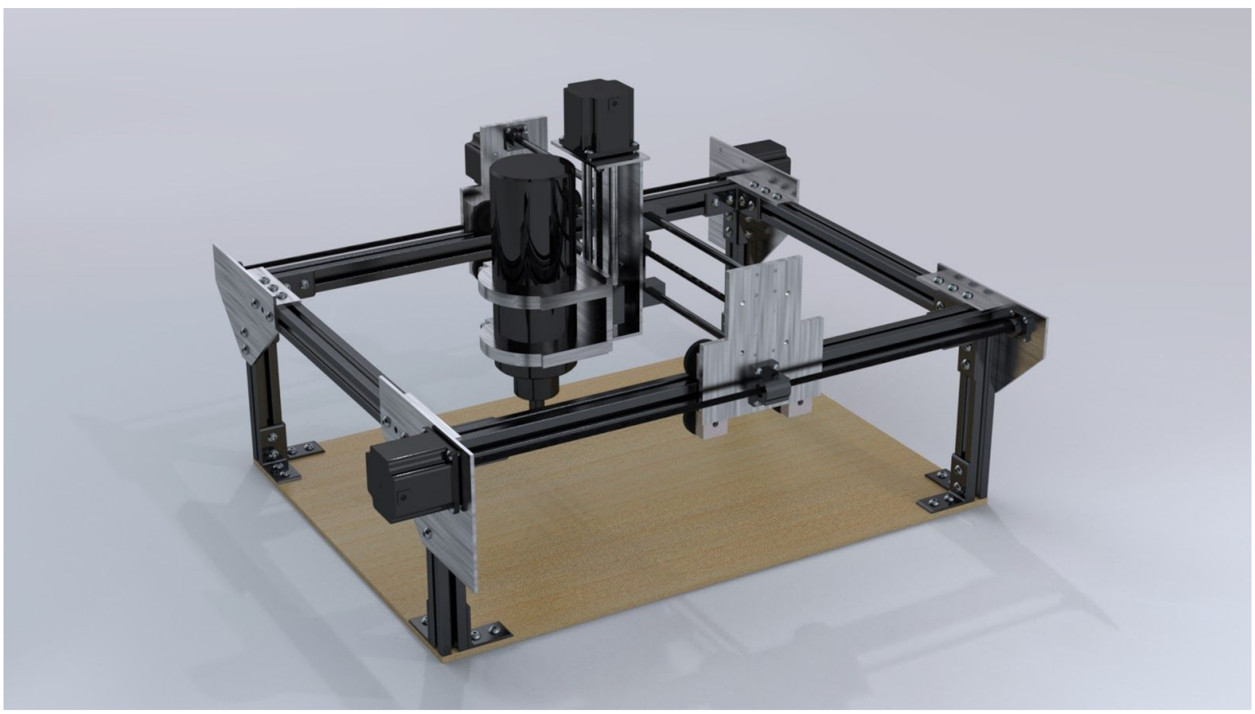


Figure 36: CAD drawing of final design

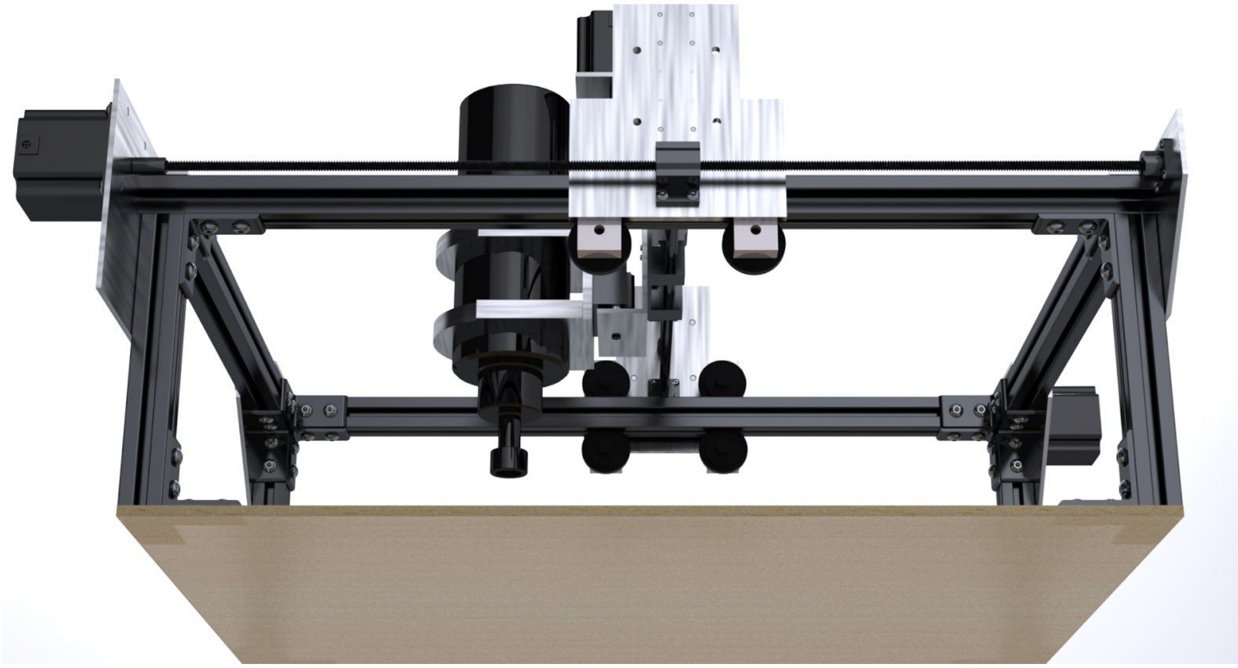


Figure 37: side view

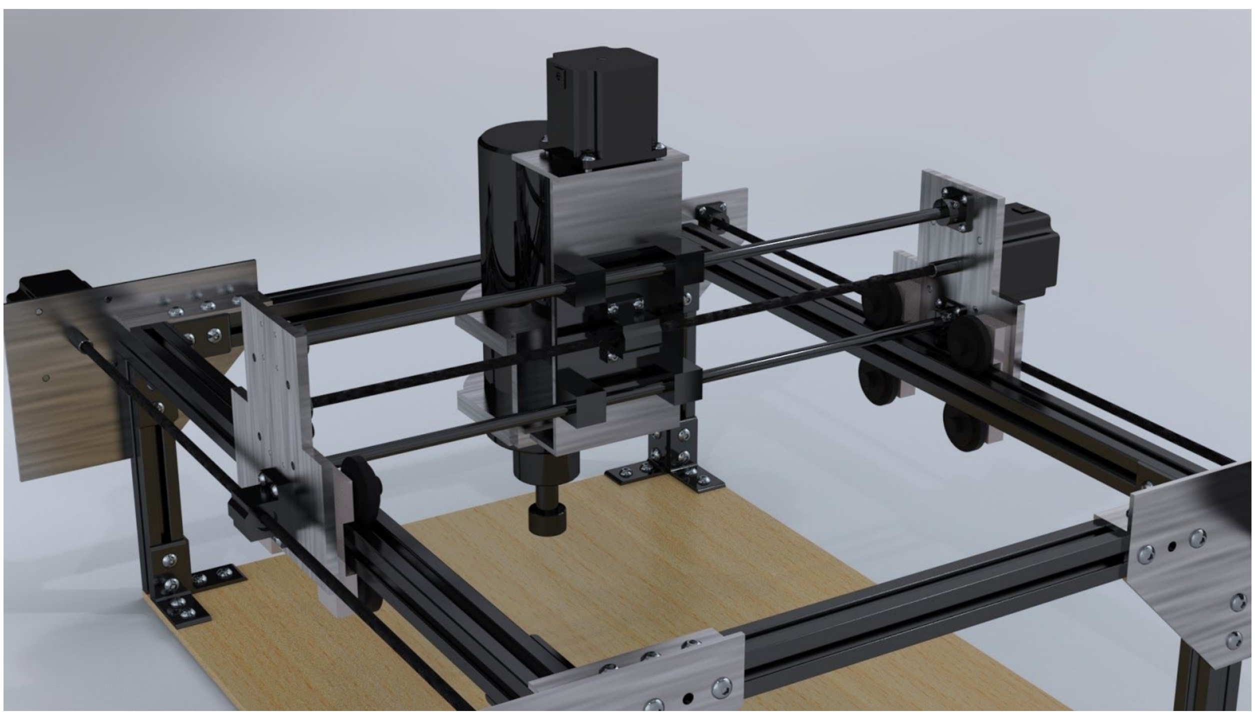


Figure 38: close-up top view

4.1 Bill of Materials

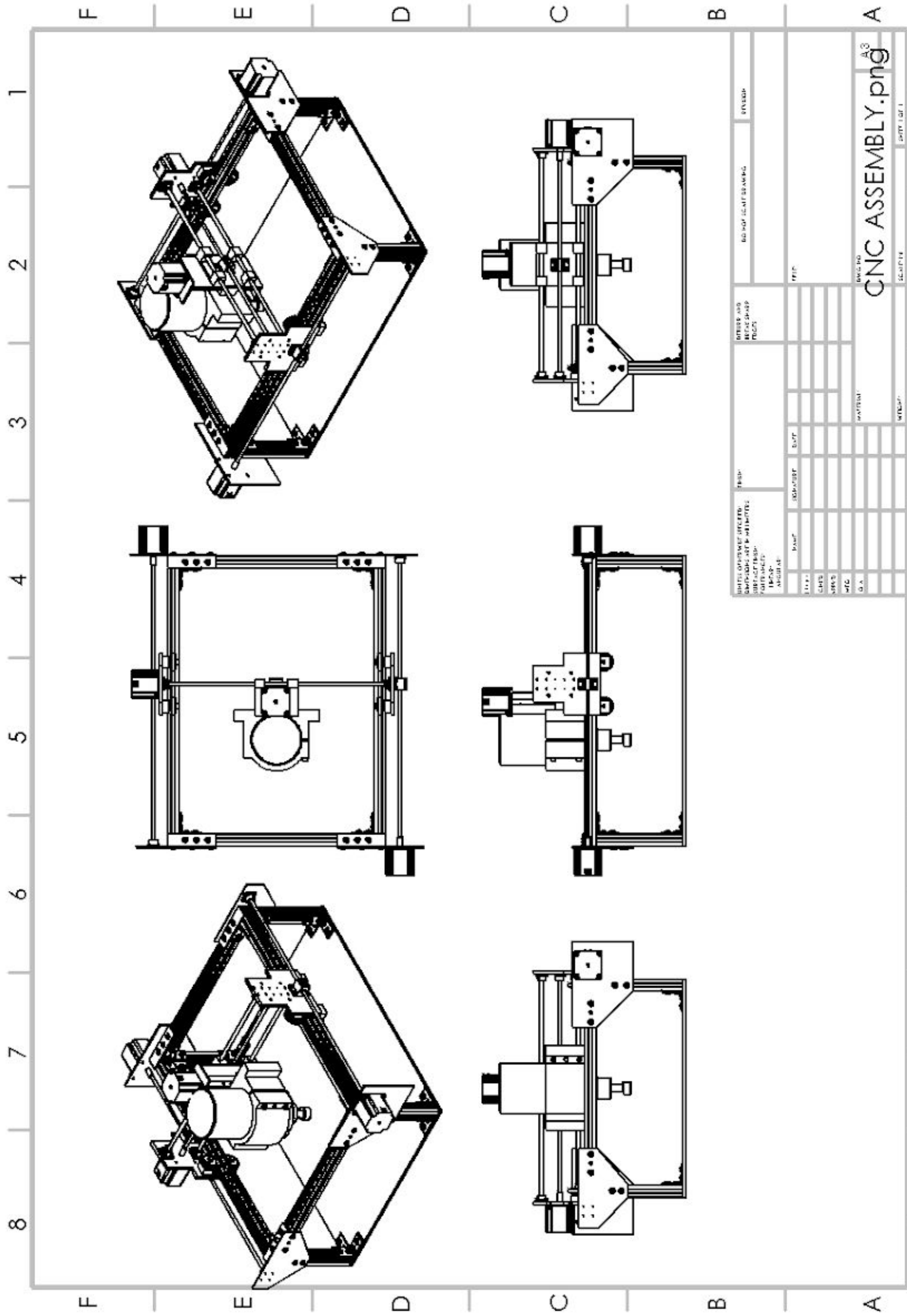
The table below contains all the parts used in the D.I.Y CNC machine. Due to the complexity of the design, the labeled exploded view was eliminated. To understand the name and its purpose please read the description below or refer to CAD drawings.

ITEM NO.	PART NAME	DESCRIPTION	QTY	Cost
1	L-Bracket	4-hole tall inside corner 90 degrees bracket	20	$82
2	xRail	23.5” 1.00” X 1.00” T-Slotted Profile	2	$10.8
3	yRail	15.7” 1.00” X 1.00” T-Slotted Profile	2	$7.2
4	zRail	7" 1.00” X 1.00” T-Slotted Profile	4	$6.5
5	Rail Bracket	Custom made can be CNC-milled or 3D printed	2	
6	Rail Bracket2	Custom made can be CNC-milled or 3D printed	2	
7	Motor	NEMA 23 stepper motor	4	$324.36
9	X-axis Lead Screw	23", ¼” lead screw	2	$40.48
10	Track Rollers	Standardized from Mcmaster Carr	4	$230

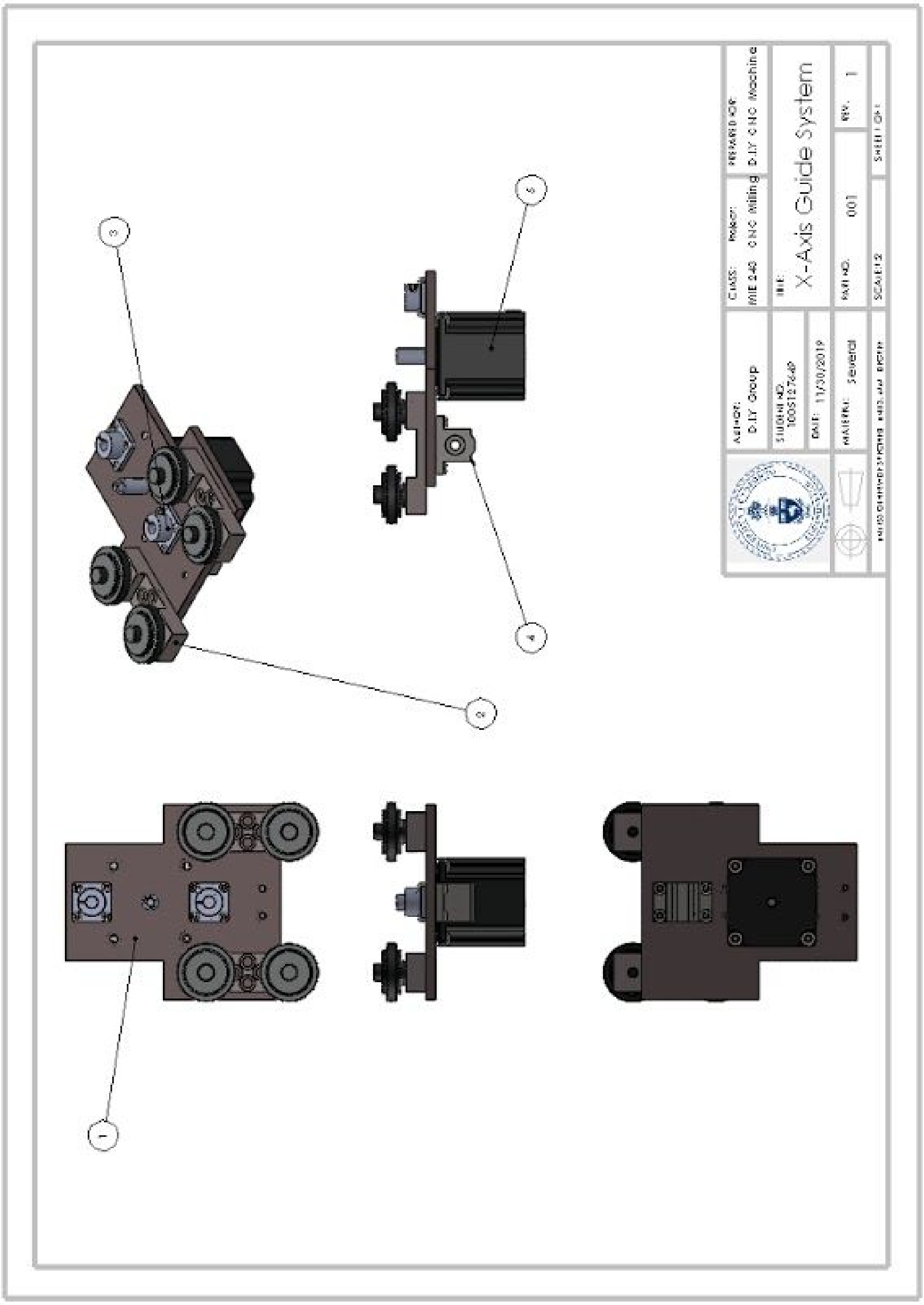
11	Y-axis mount	Custom made can be CNC-milled or 3D printed	2	
12	Circular Rail	⅜” diameter, 18.25" length	2	$24.72
13	Rail end mount	Custom made can be CNC-milled or 3D printed	4	
14	Lead screw end mount	Custom made can be CNC-milled or 3D printed	3	
15	Linear Bearing		4	$183.6
16	Y-axis Lead Screw	18", ¼” lead screw	1	$16.6
17	Backing		1	
18	Z-axis bracket		1	
19	Spindle Mount		1	$14.5
20	Spindle	Air Cooled 3kW 0-24000 RPM Spindle	1	$282
21	Z-axis Lead Screw	6.31", ¼” lead screw	1	$16.6
22	Linear coupling		4	$169.12
23	Bolt Assembly	1/4-20 x .500" Black BHSCS and Slide-In Economy T-Nut - Centered Thread - Black Zinc	108	$43.2

24	SBHC-SCREW	0.164-32x0.375-HX-N	12	
25	SBHCSCREW	0.19-32x0.375-HX-N	12	
26	SBHC-SCREW	0.19-32x0.5-HX-N	4	
27	SBHCSCREW	0.125-40x0.375-HX-N	20	$20
28	SBHCSCREW	0.125-40x0.25-HX-N	8	
29	HX-SHCS	0.25-20x1.5x1-N	2	
30	HX-SHCS	0.112-40x0.5x0.5-N	4	
31	SBHCSCREW	0.164-36x0.5-HX-N	4	
32	Base	60cmx40cmx1/4” Wood Base	1	$44.5
33	Custom Parts	All parts without price are custom CNC-milled parts or 3D printed parts	17	$100
		Total Cost	1	$1606

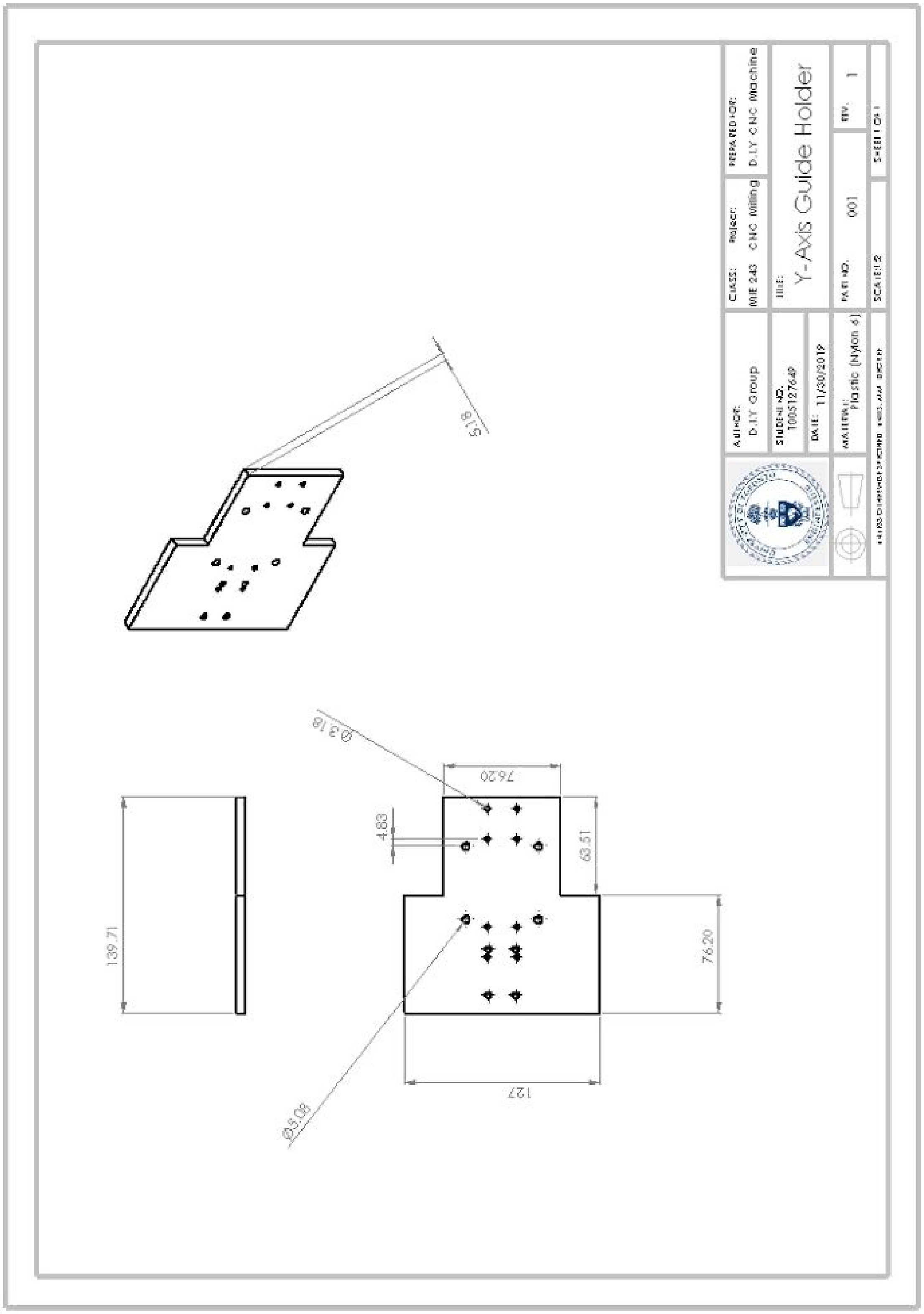
5. Drawings



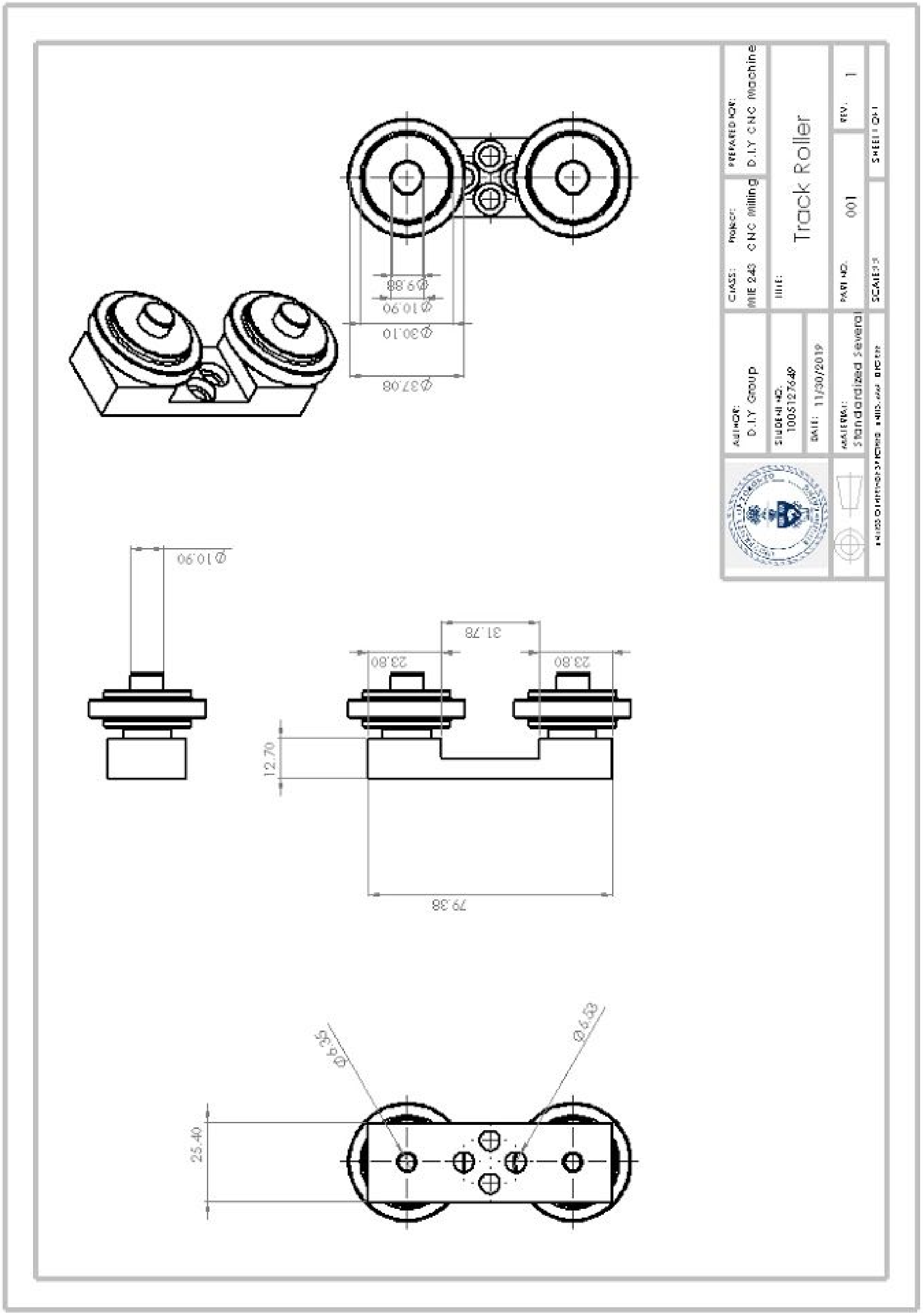
5.1 X-Axis Guide System Drawing



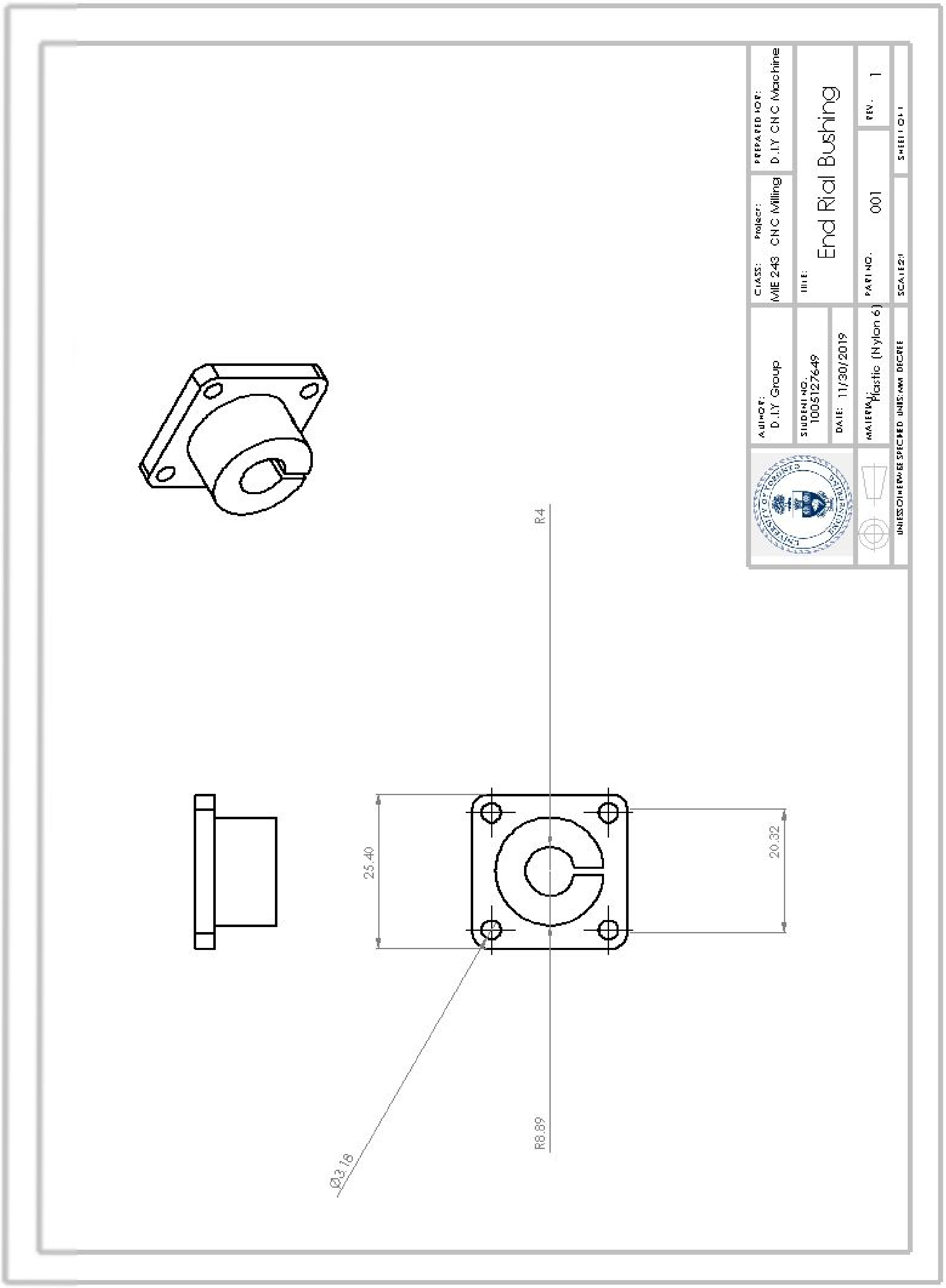
5.1.1 Part 1: Y-Axis Mount



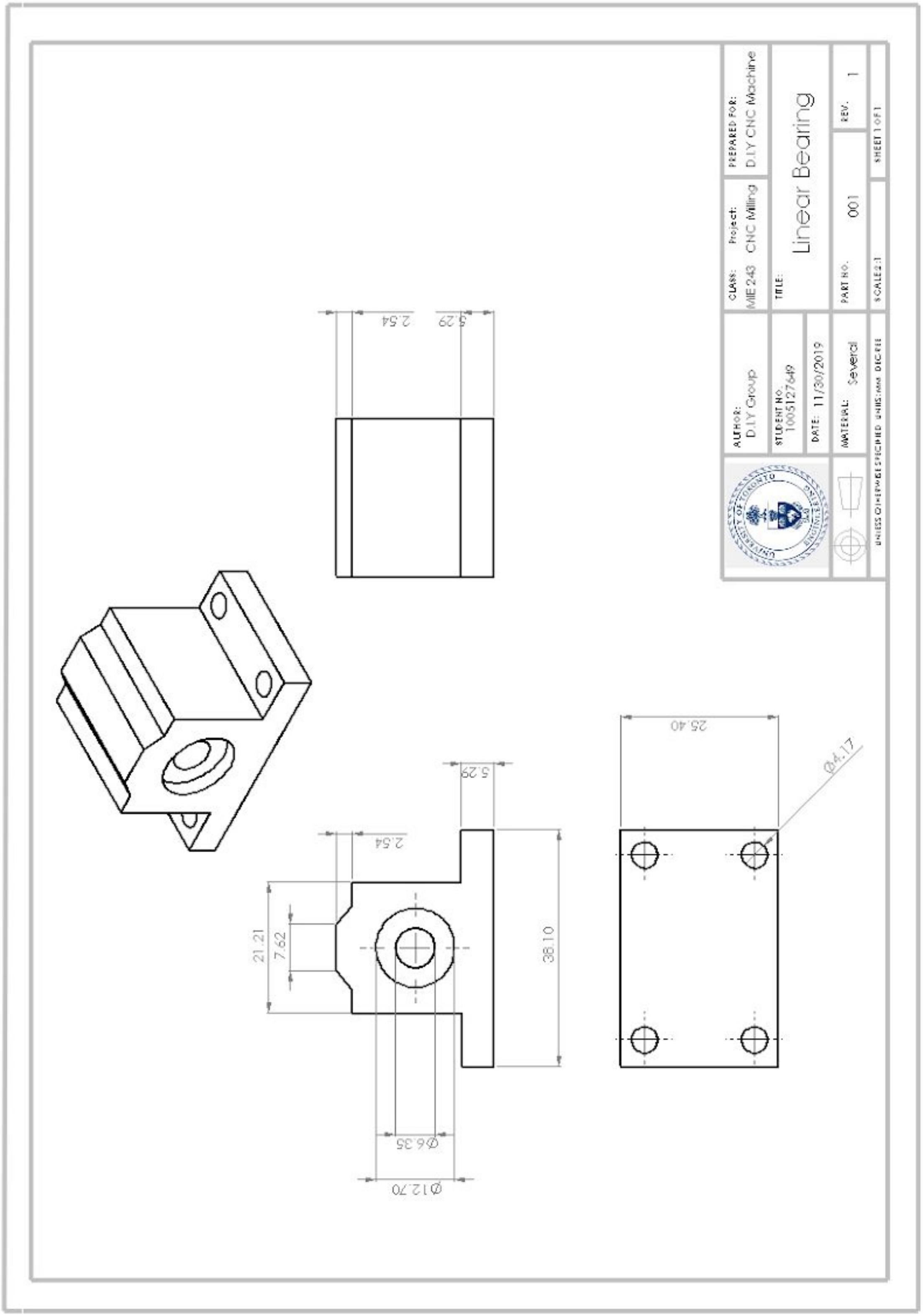
5.1.2 Part 2: Roller



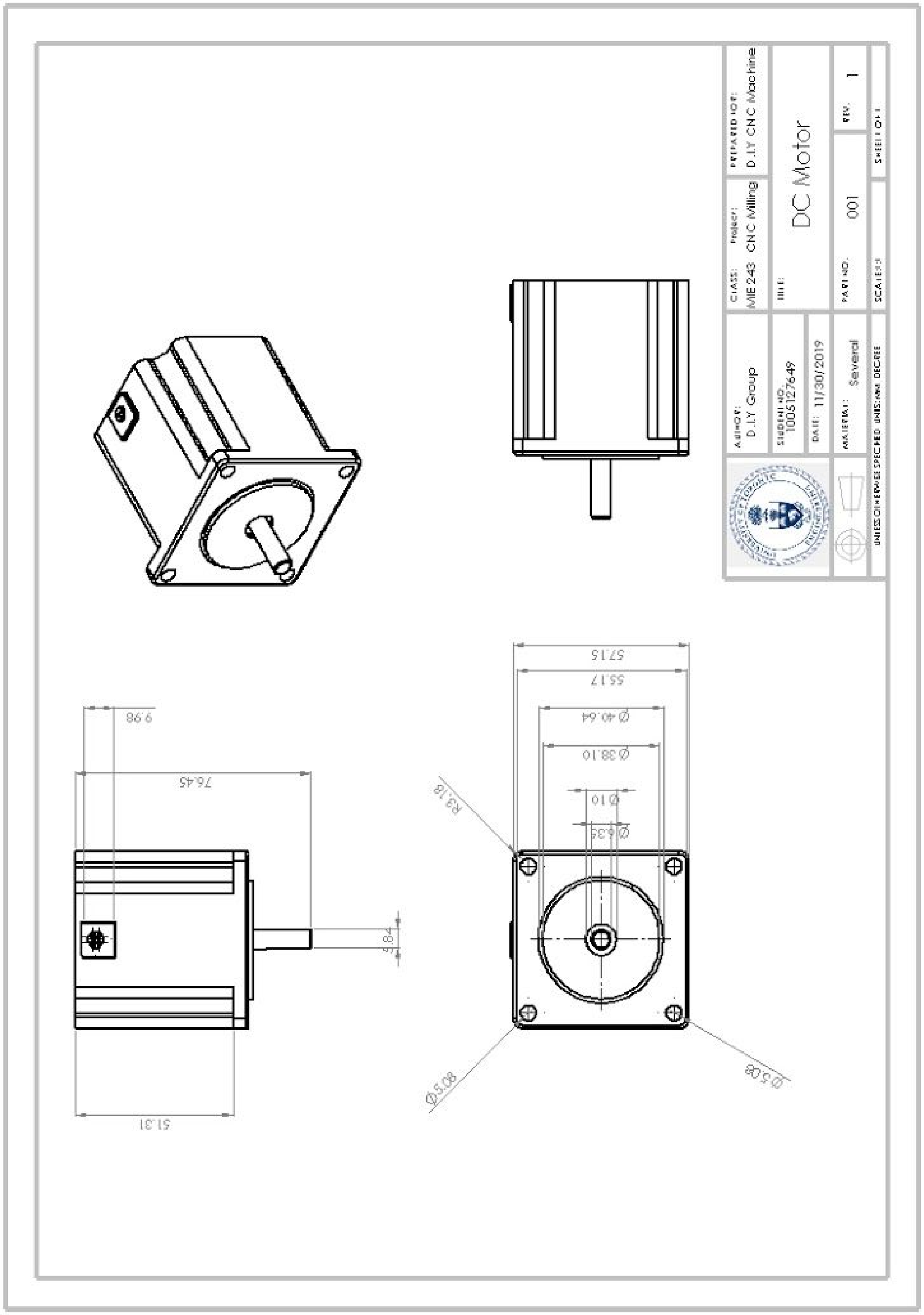
5.1.3 Part 3: Rail end mount



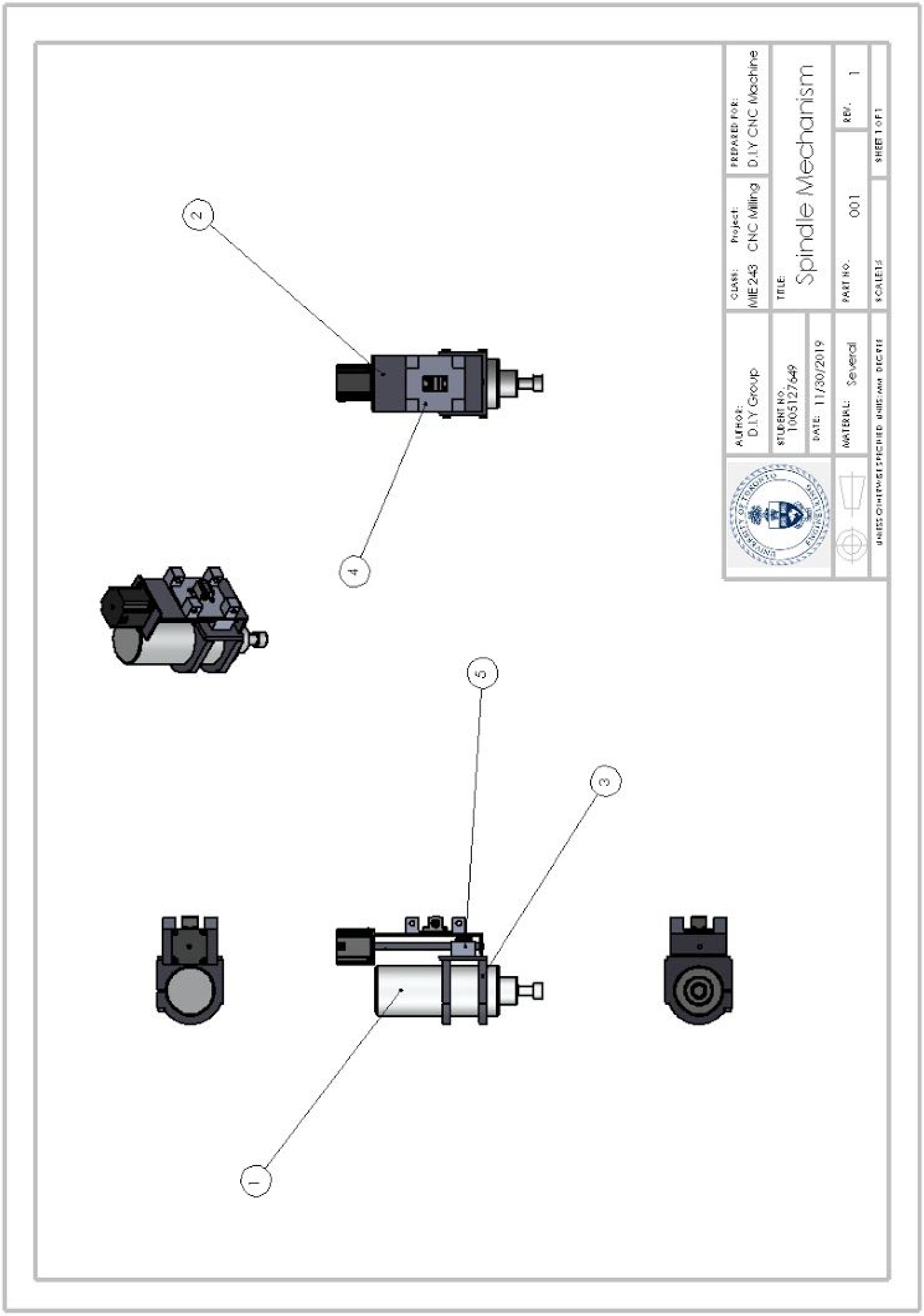
5.1.4 Part 4: Linear Bearing



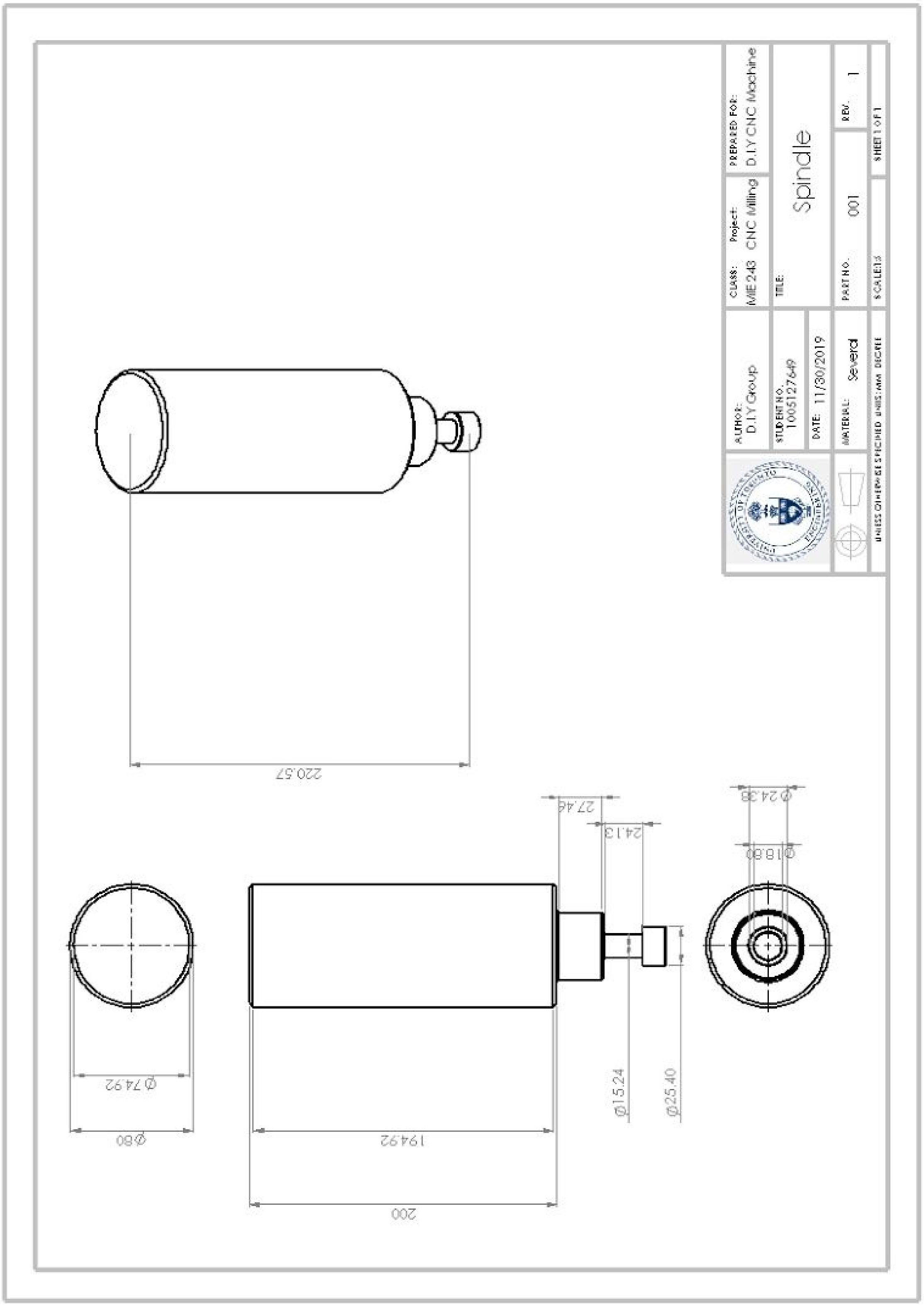
5.1.5: Part 5: Motor



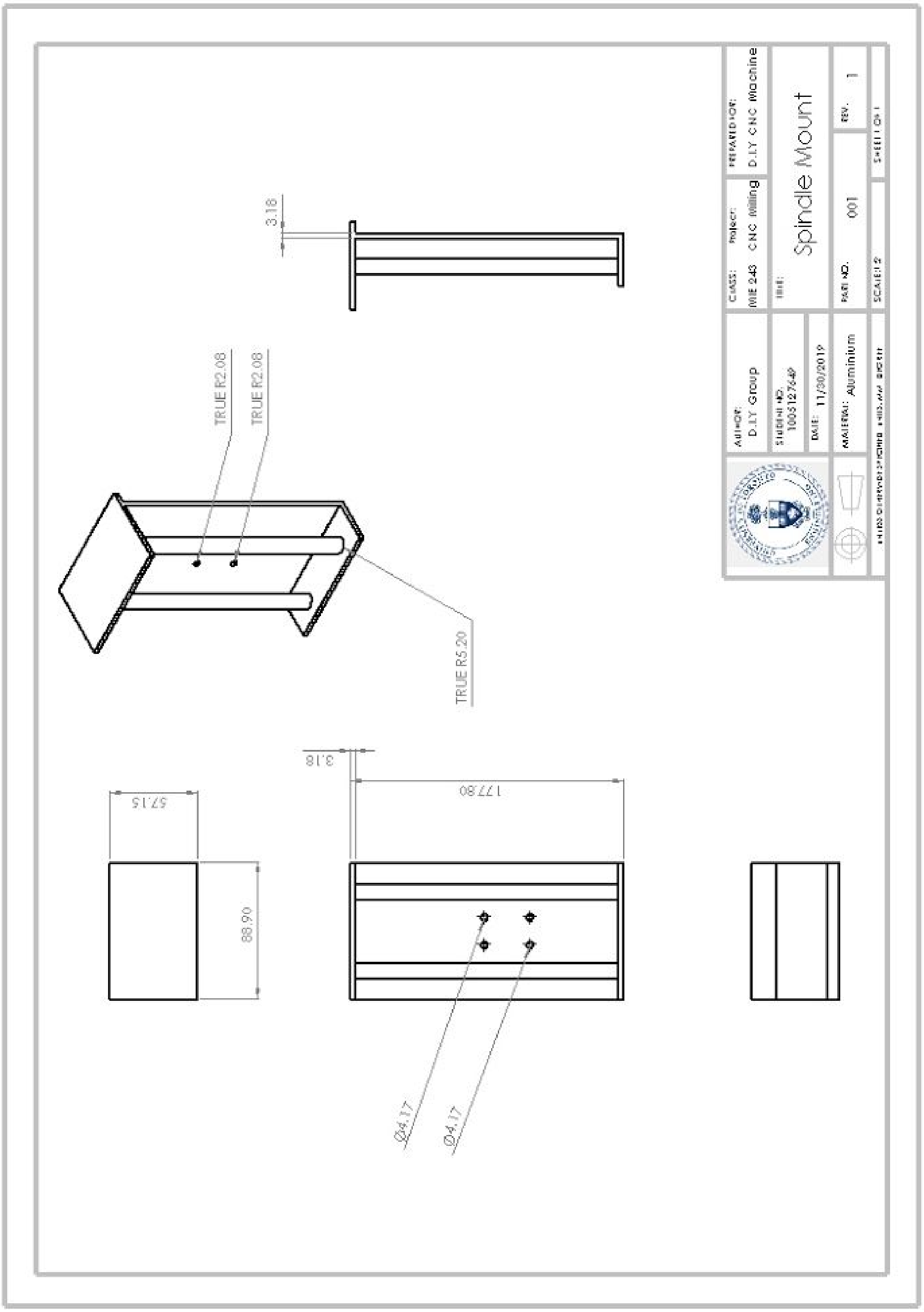
5.2 Spindle Mount Mechanism



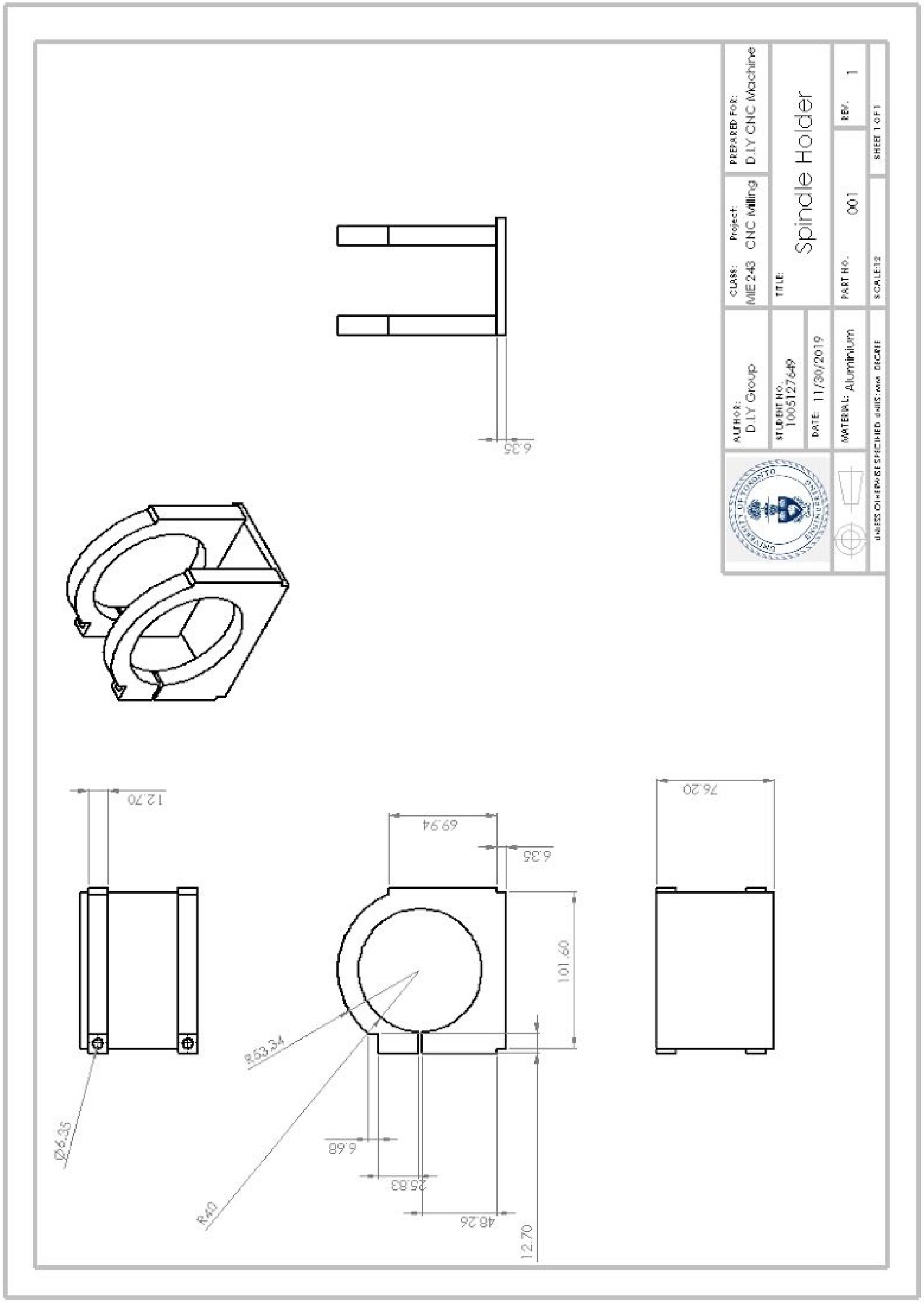
5.2.1 Part 1: Spindle



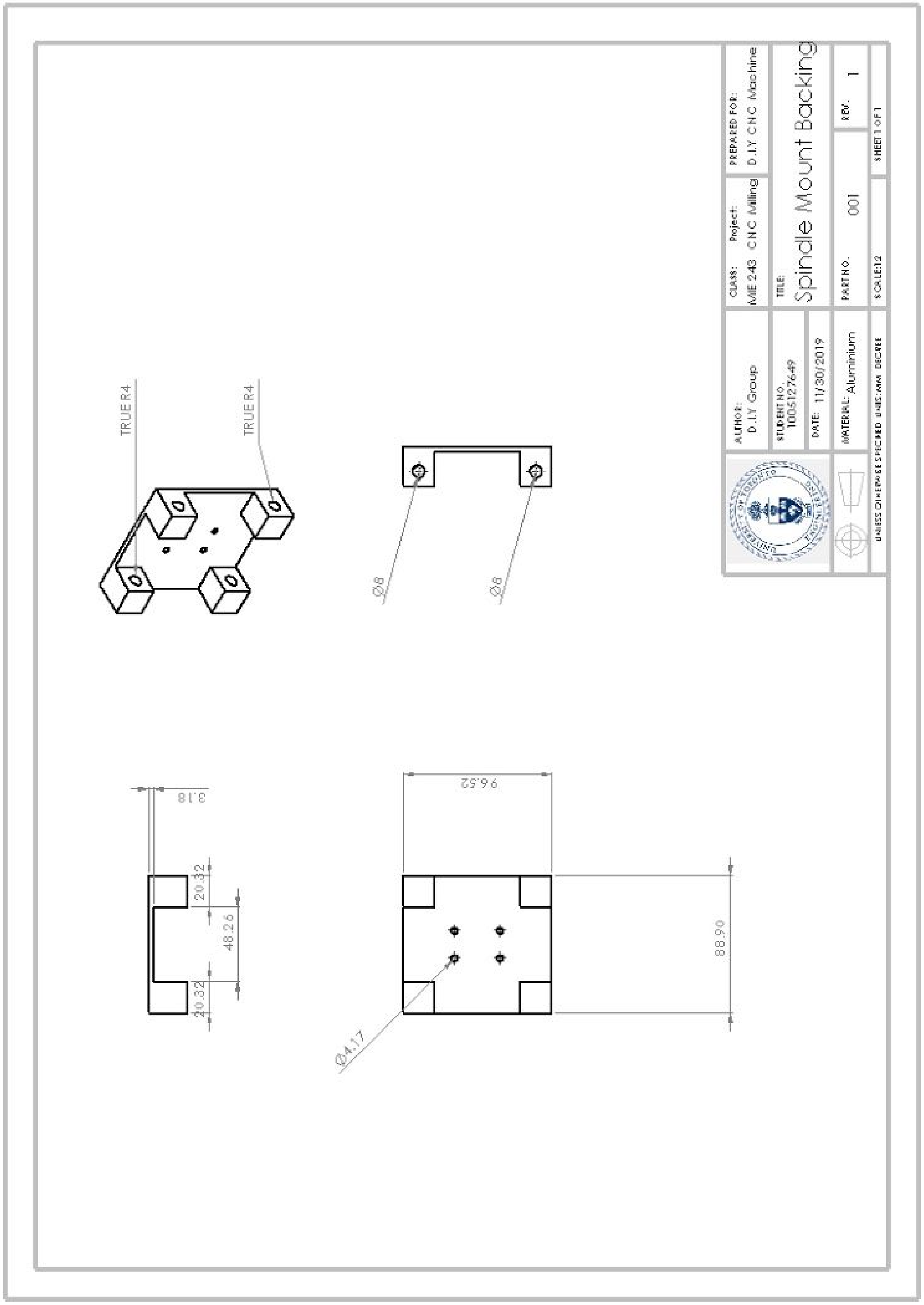
5.2.2 Part 2: Backing



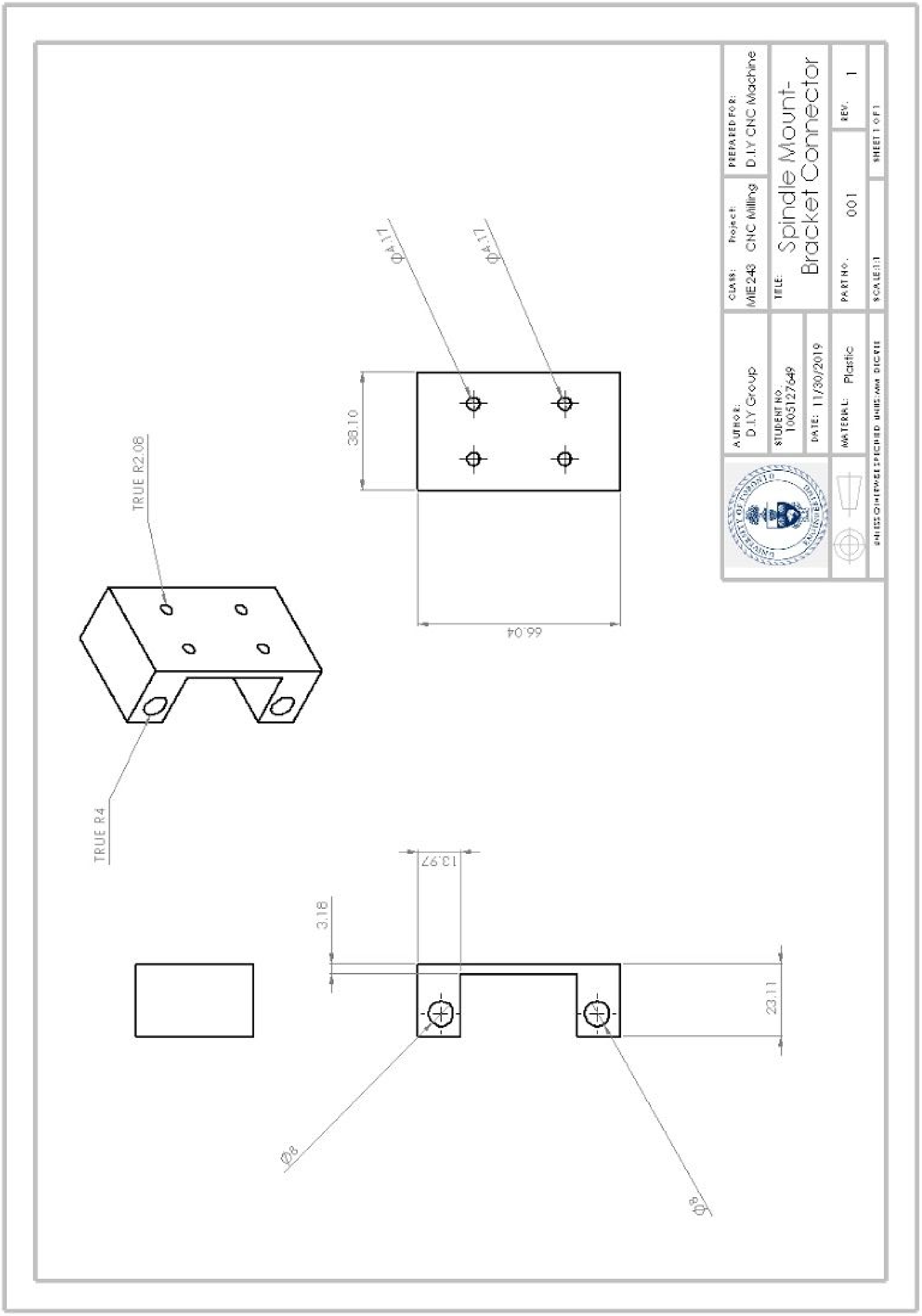
5.2.3 Part 3: Spindle Mount



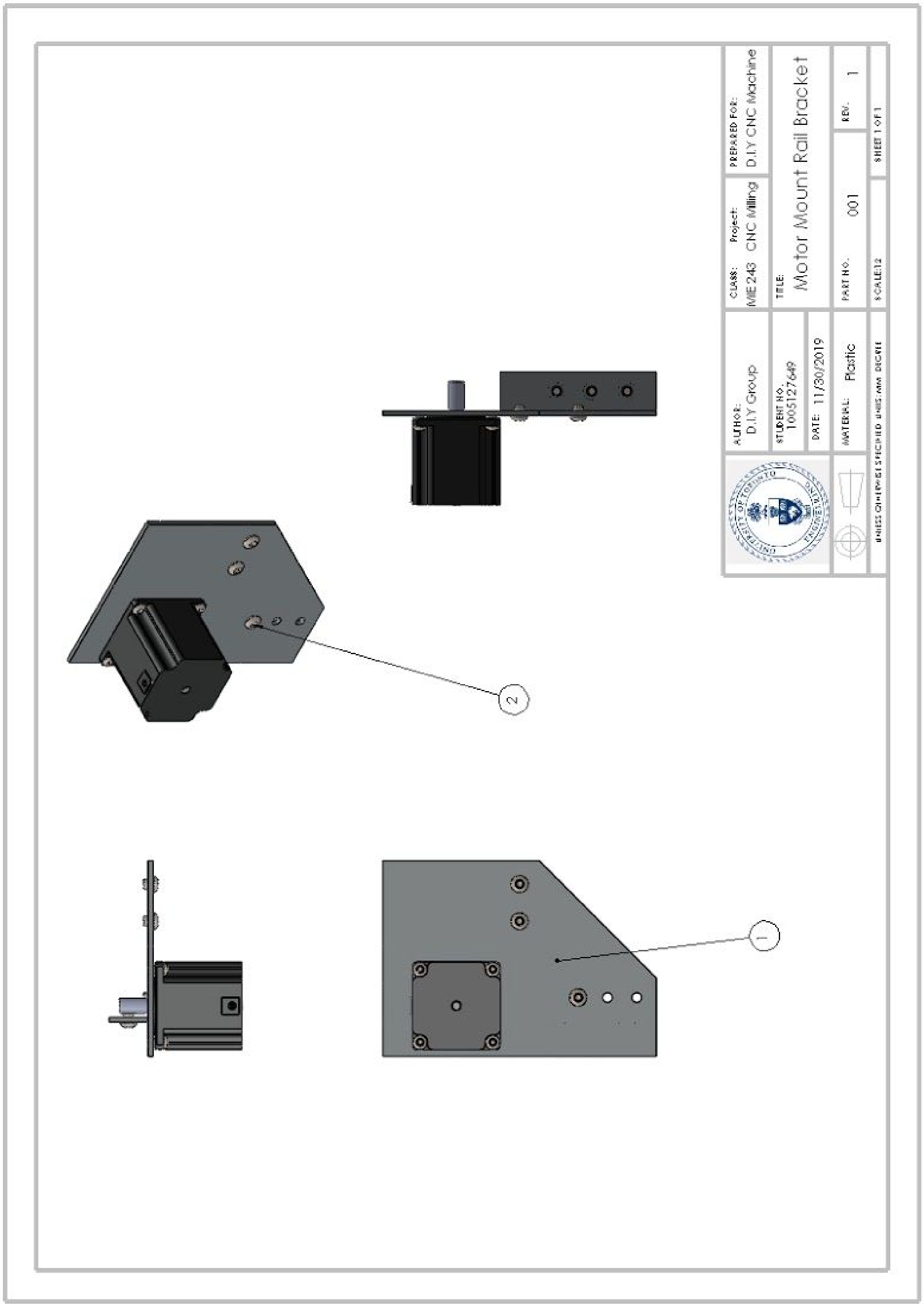
5.2.4 Part 4: Z-axis Bracket



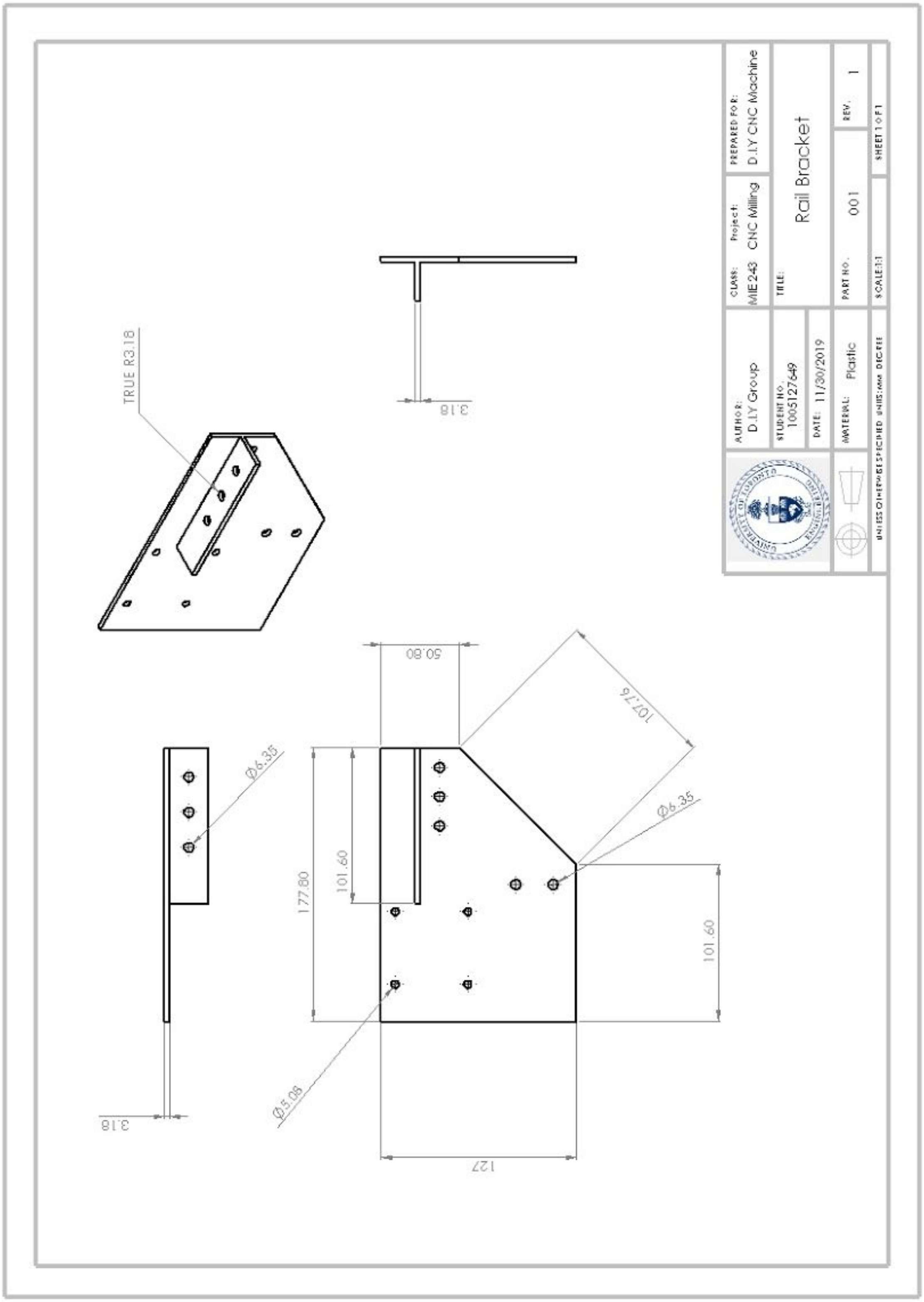
5.2.5 Part 5: Spindle Mount Bracket Connector



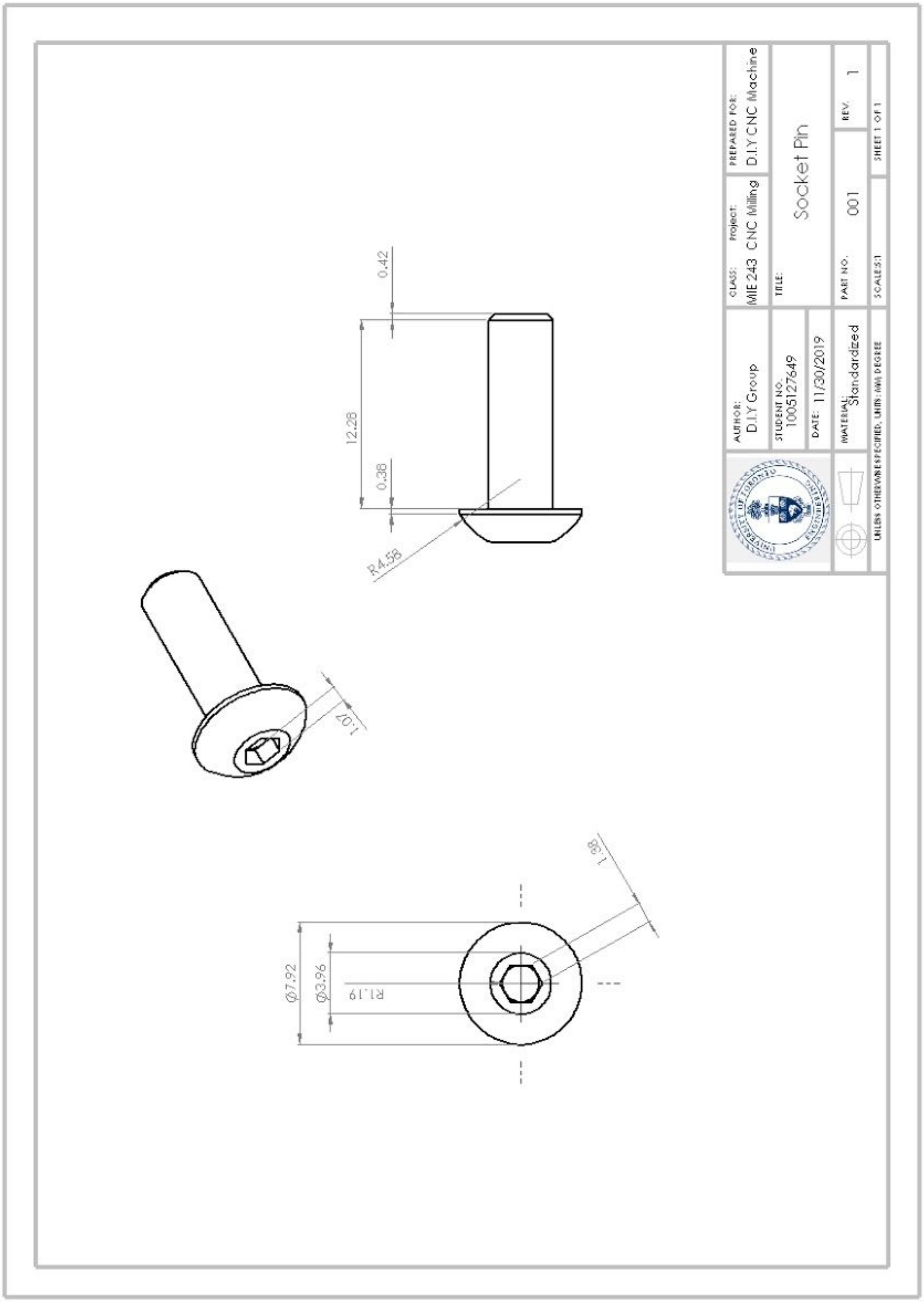
5.3 Motor Mount Rail Bracket Mechanism



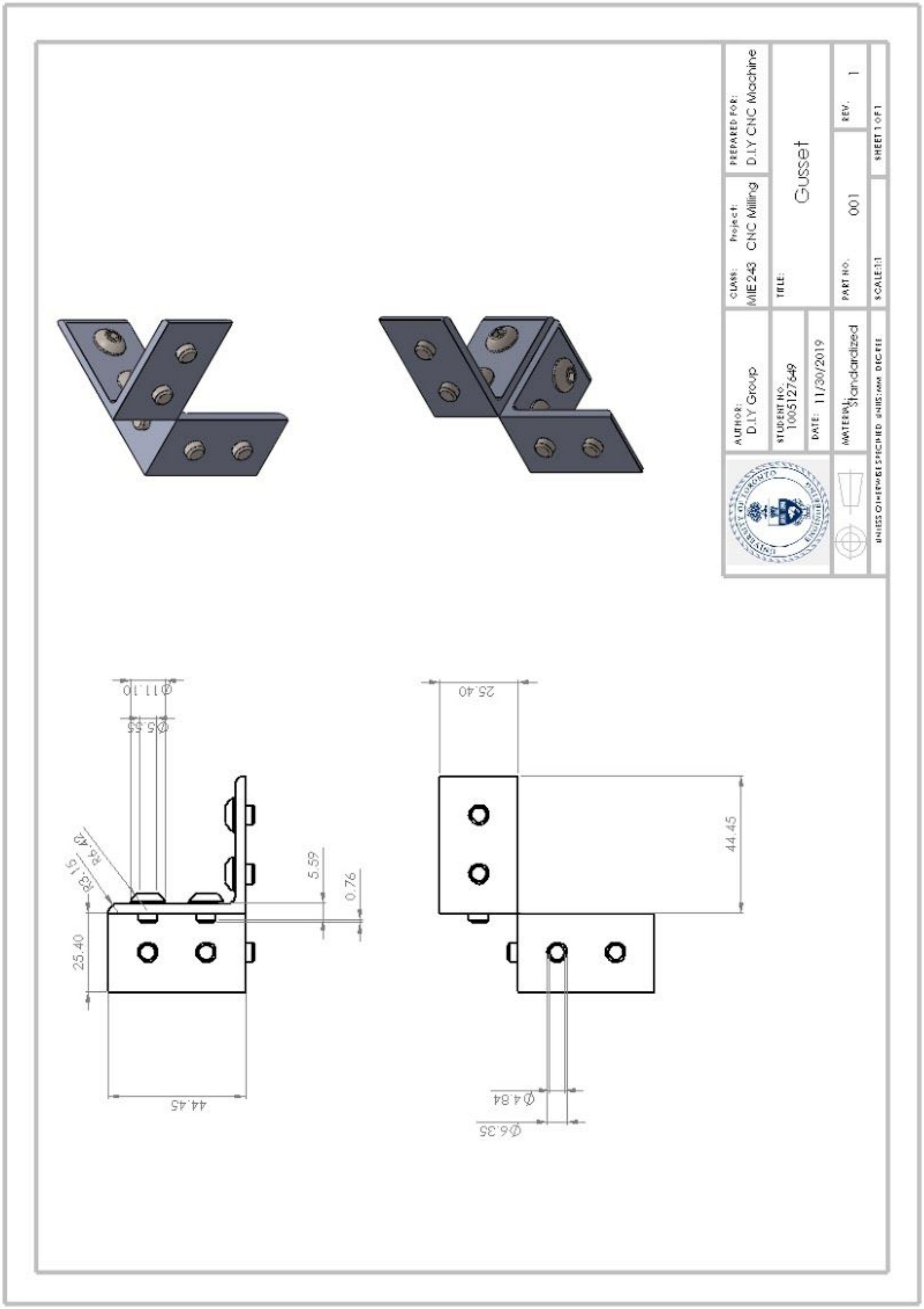
5.3.1 Part 1: Rail Bracket



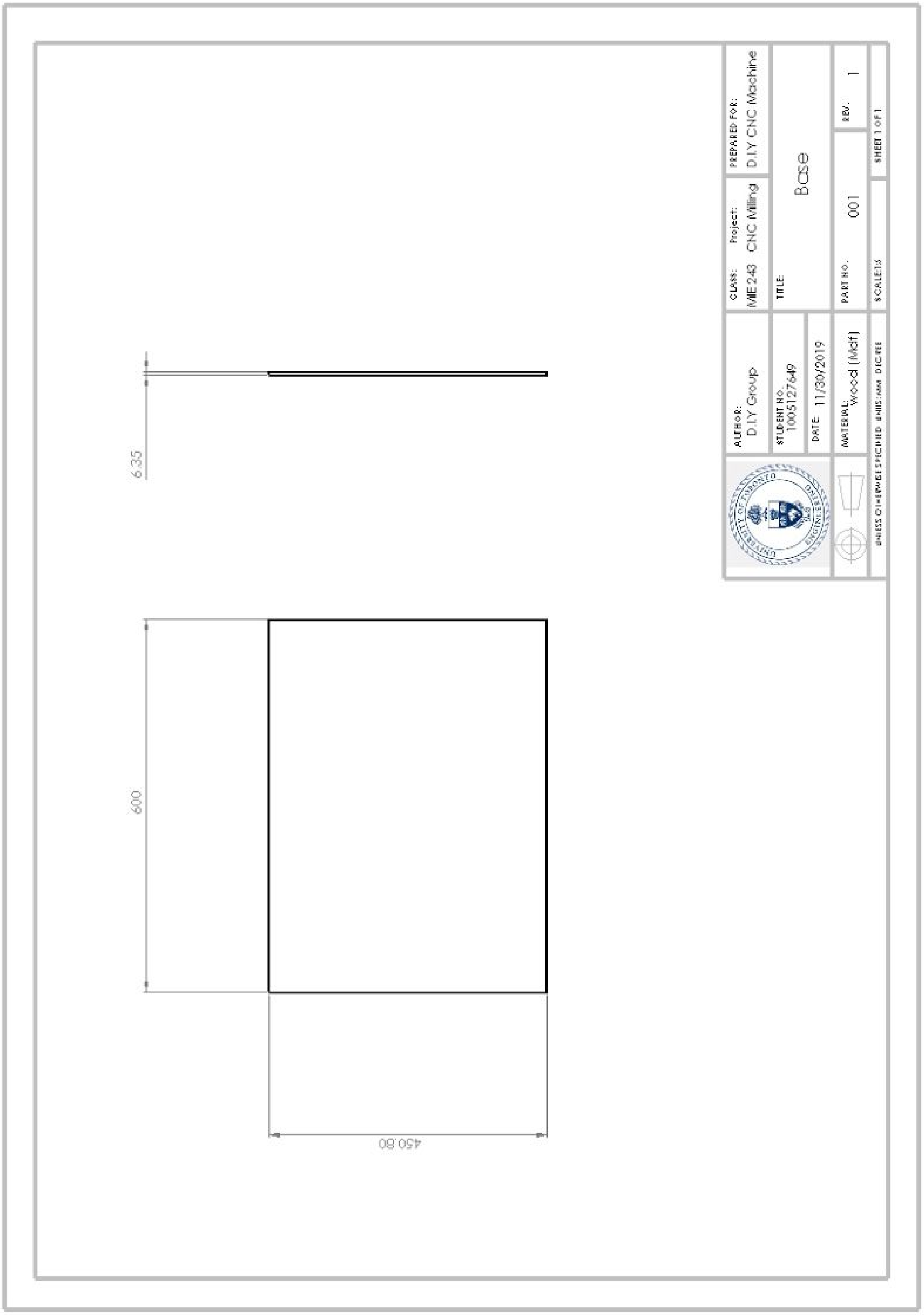
5.3.2 Part 2: Socket Pin



5.4.0 L-Bracket

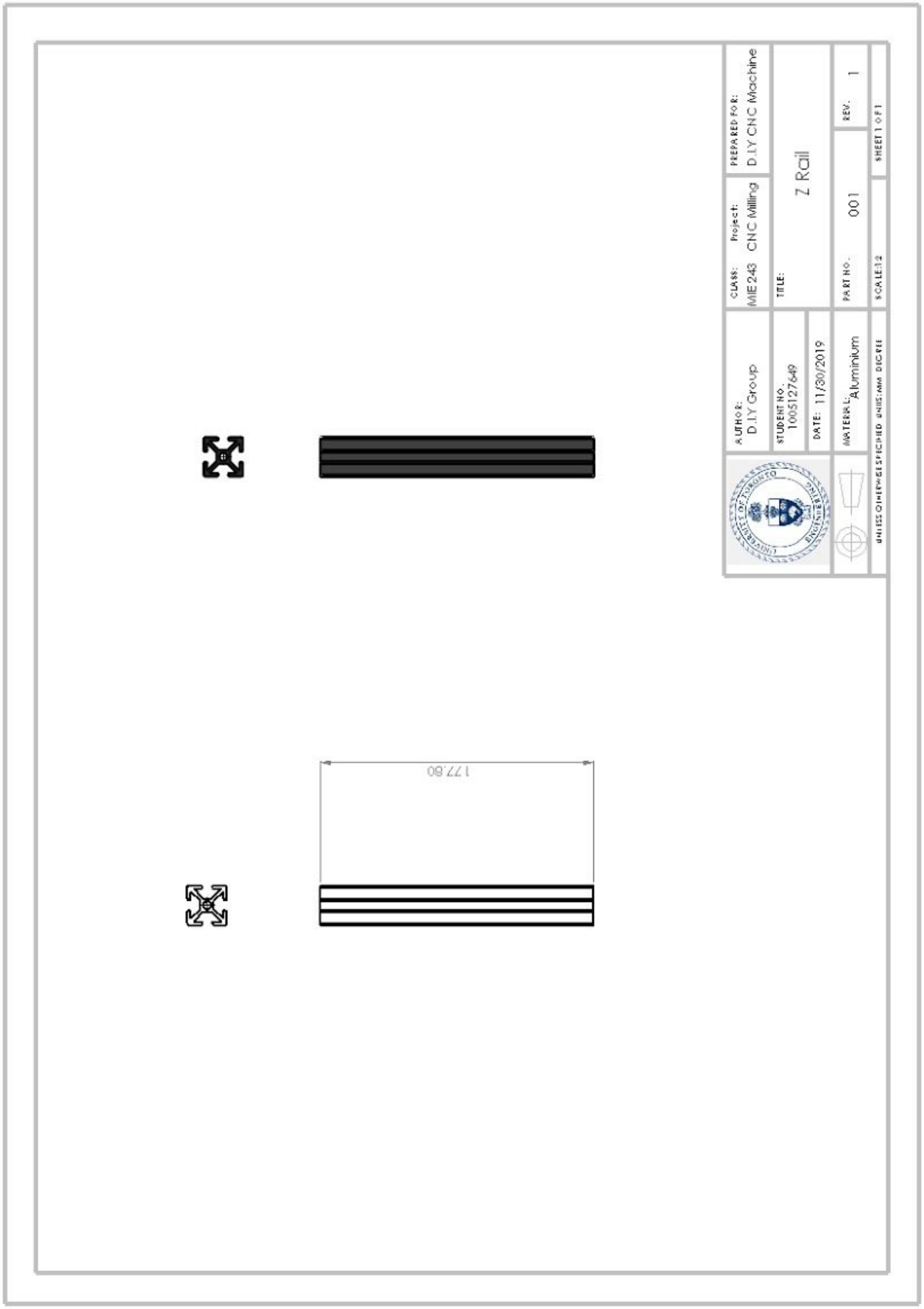


5.5.0 Base

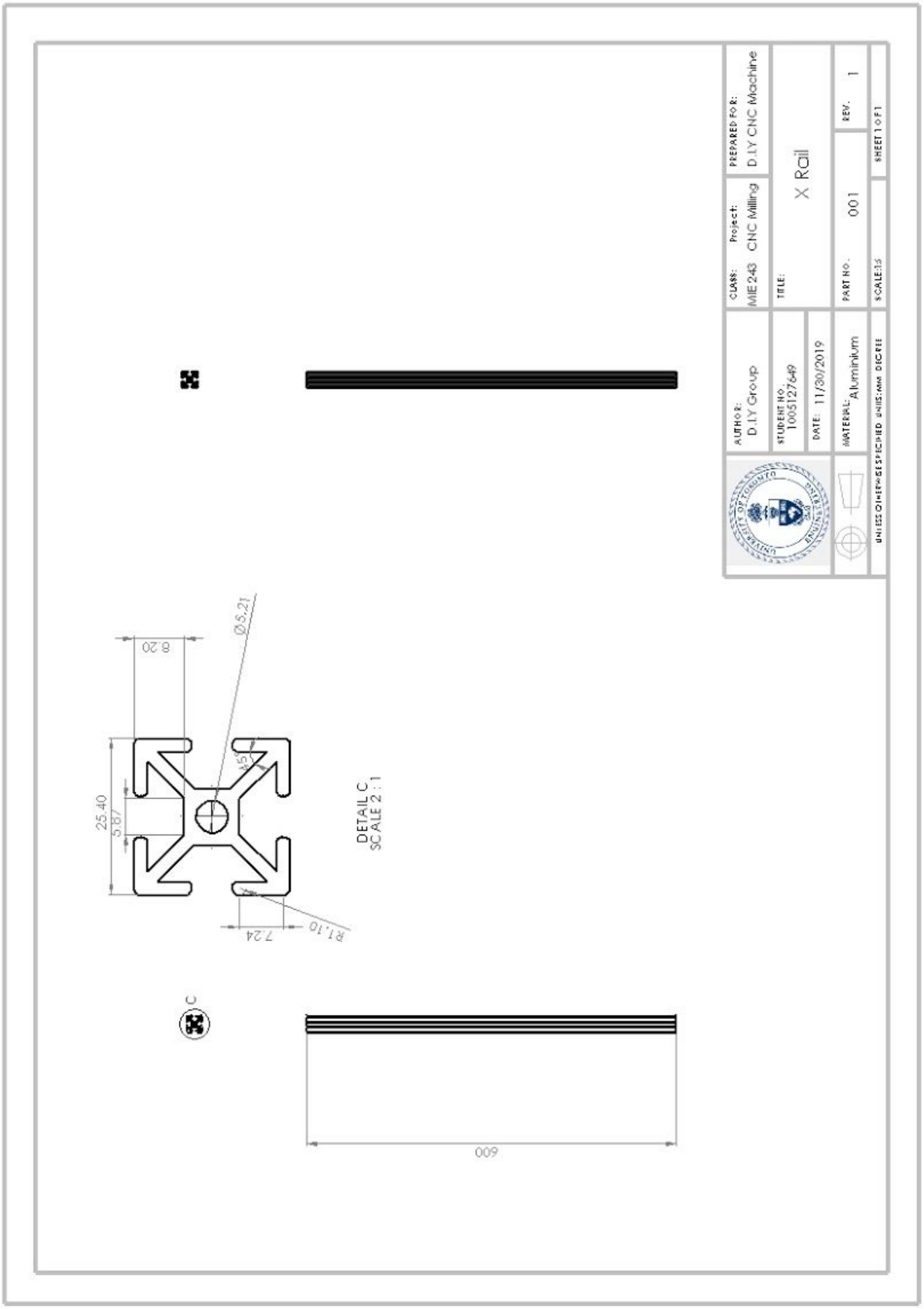

6.35
600
450.80
AUTHOR: D.I.Y Group
STUDENT NO. 1005127649
DATE: 11/30/2019
MATERIAL: Wood (Mdf)
CLASS: MIE 243
Project: CNC Milling
PREPARED FOR: D.I.Y CNC Machine
TITLE: Base
PART NO. 001
REV. 1
SCALE:1:5
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED UNITS: MM DEGREE

5.6 Rails and Supports

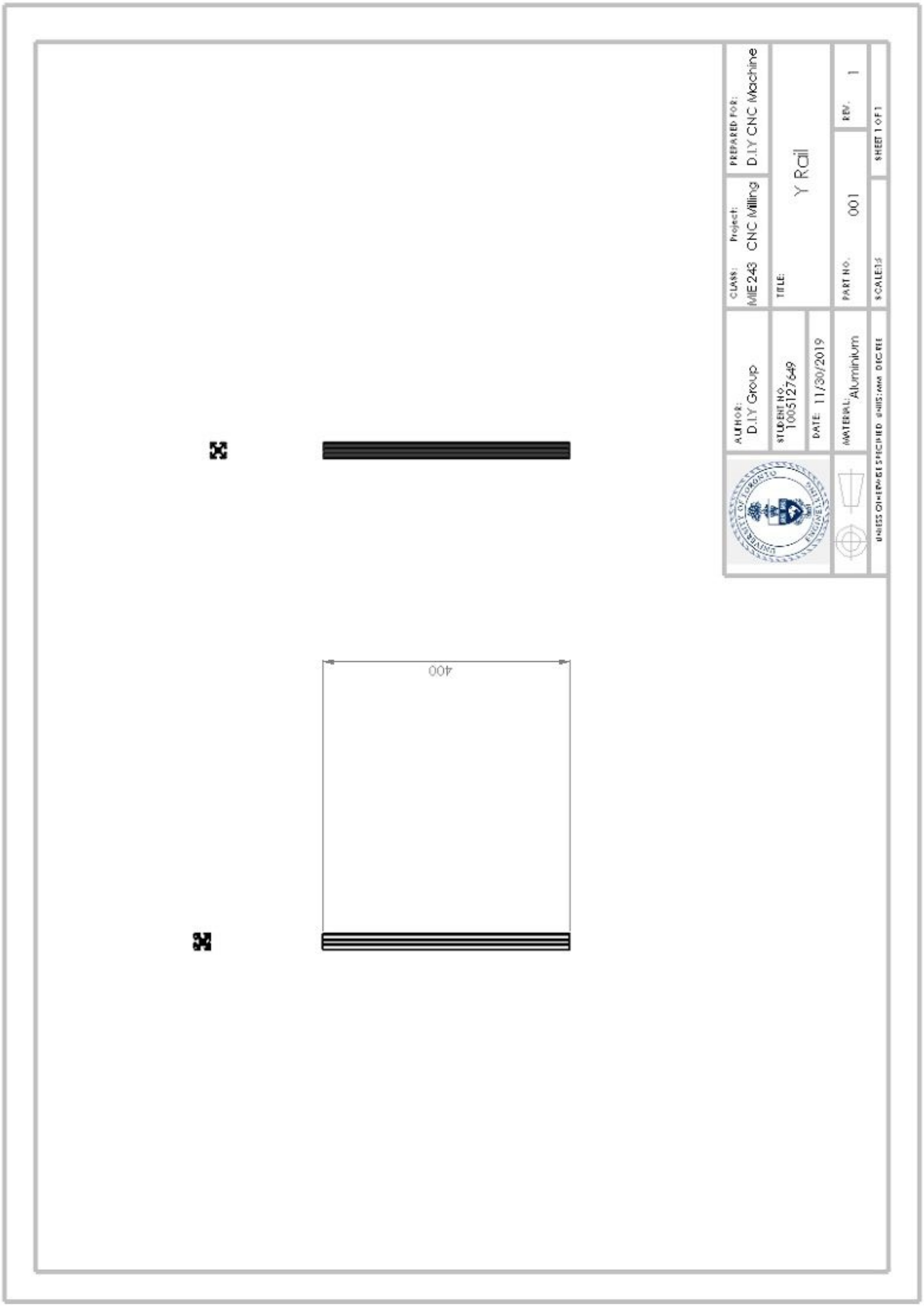
5.6.1 Z Rail: Used as supports



5.6.2 X Rail: used as the long sides of the top frame



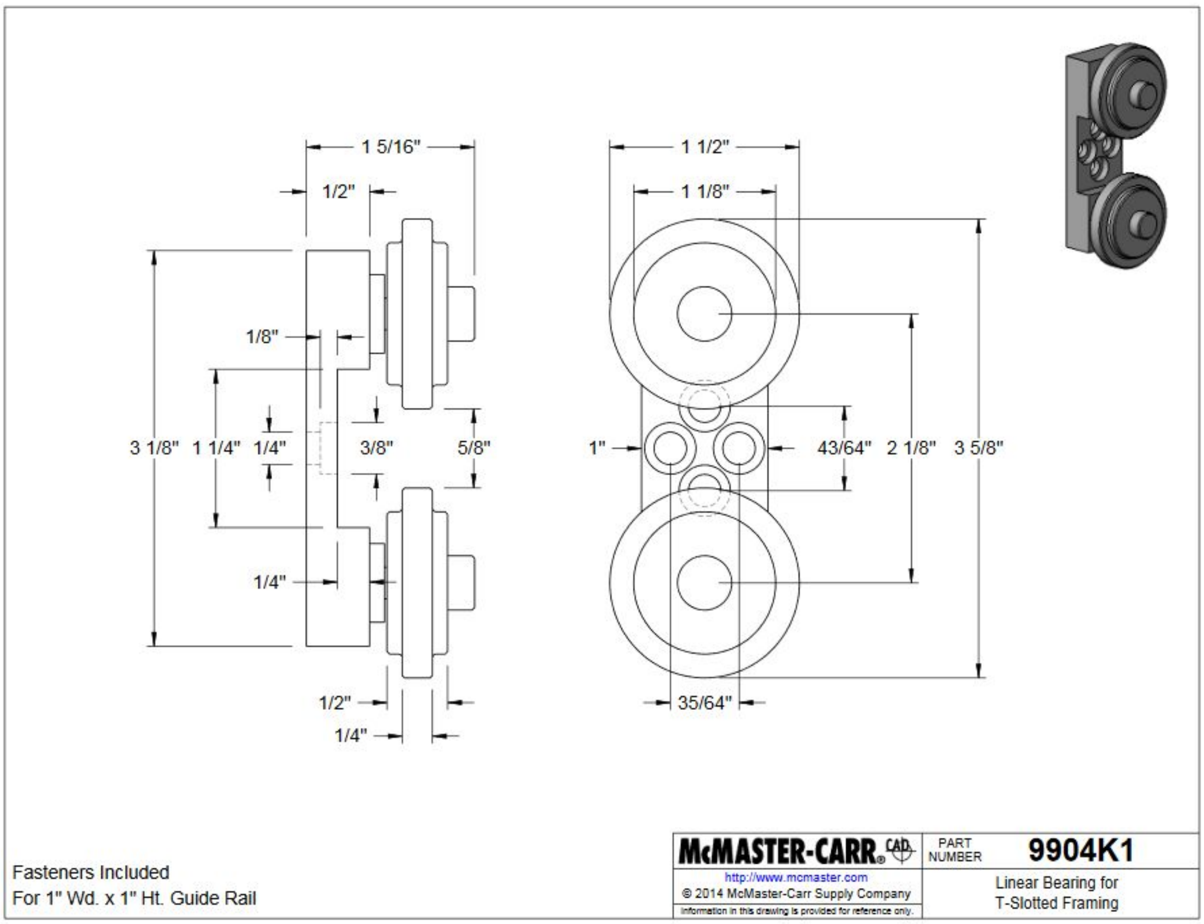
5.6.3 Y Rail: used as the short sides of the top frame



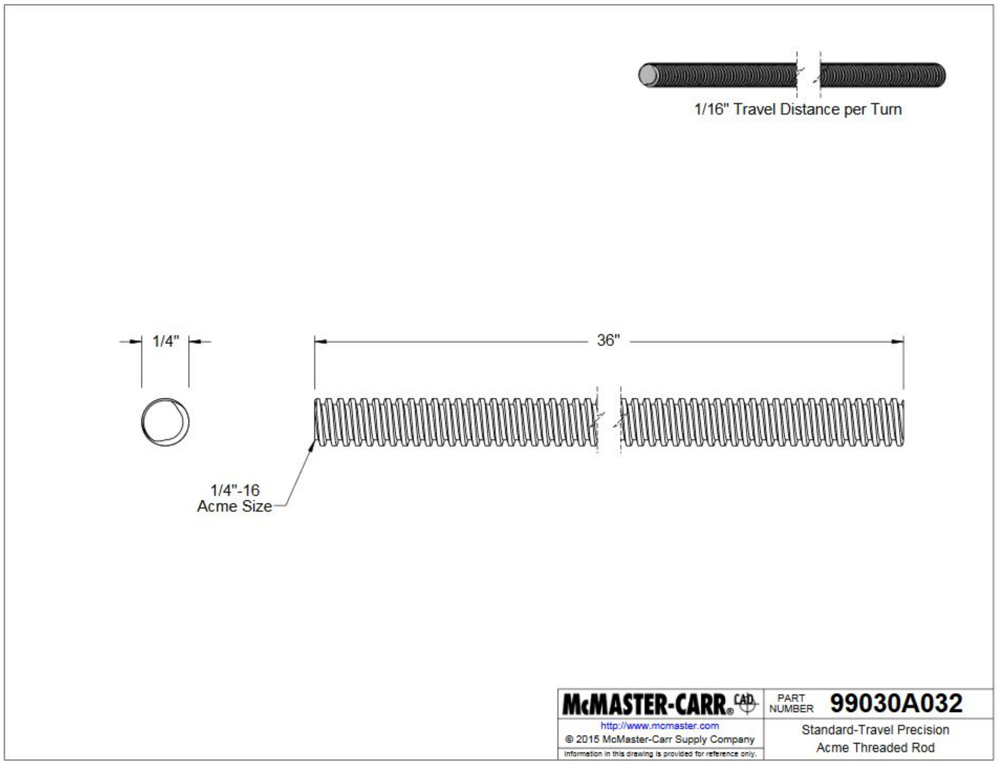
5.7 Non- trivial Standardized Parts

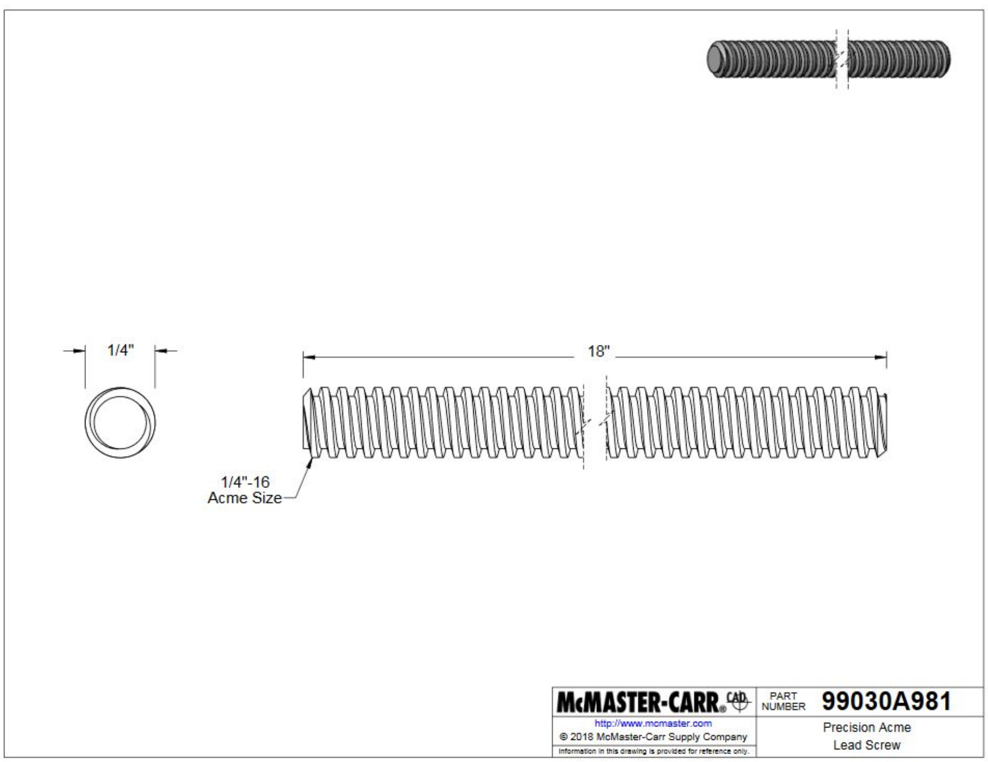
Here you can find the CAD drawings provided by the seller for the most important standardized parts (the ones which are specific, complex and not easily found on the market) used in the design of the CNC machine.

5.7.1 Track Roller

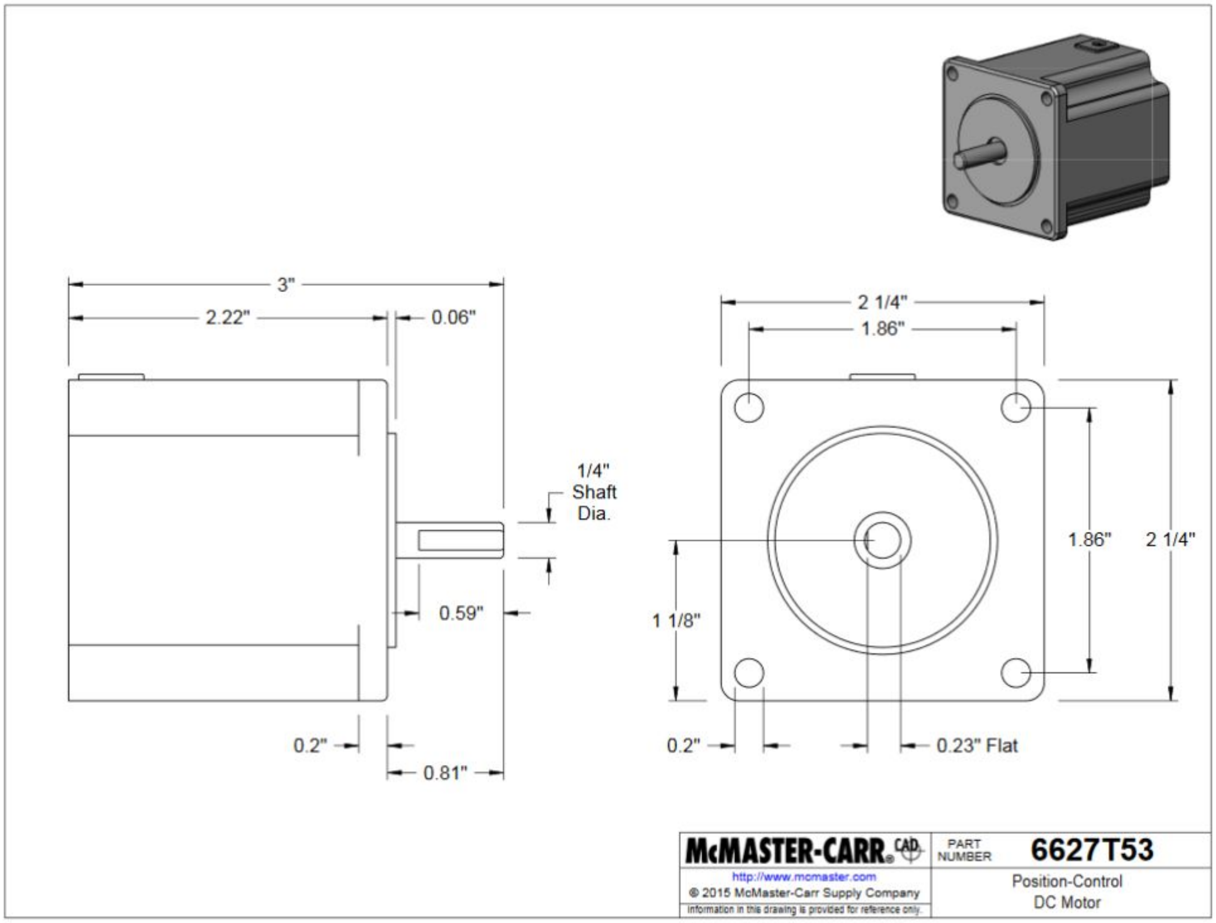


5.7.2 Lead Screw (For X-axis, Y-axis, and Z-axis)

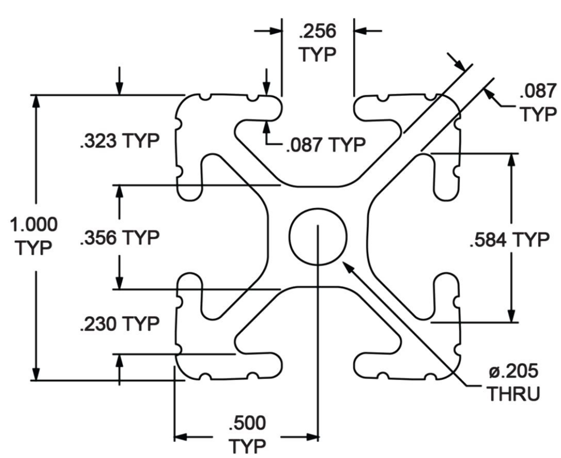




5.7.3 Motor



5.7.4 T- Profile Rails



6. Conclusion

For this project we were tasked to design a CNC milling machine for hobbyists. After some initial research of existing designs we generated an engineering specification and by following the engineering design process, we generated minimally viable conceptual designs that fulfilled our engineering specification. From these designs we chose the design that took up the least space and was the most stable. After further iteration we produced final conceptual design where we chose lead screws as the linear actuators for all three axis and 4 Nema 23 stepper motors to generate the motion for each axis. For motion transmission and motion support we used linear couplings and simple ball bearings respectively. Our estimated cost of materials added up to approximately $1600 which is in the range of a hobbyist CNC milling machine ($1000 - $3000). Although we used 4 stepper motors that raised the cost of our design, our proposed design implements mostly standardized parts for easy assembly and is an economical option for our targeted users.

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Appendix A: Cutting Speeds and Feeds Chart [8]

Materials Soft Grades	**Speed** S.F.M. Under 32 HRC	**Materials** Hard Grades	**Speed** S.F.M. Over 32 HRC	Feed (Inch/Tooth) End Mill Diameter							
				1/8"	3/16"	1/4"	3/8"	1/2"	5/8"	3/4"	1"
NONFERROUS MATERIALS											
Aluminum + Aluminum Alloys 2024-T4/T6, 2014, 6061-T6/T651, 7075-T6	800-2000	440, 356, 380, C61300	500-1000	.001	.002	.002	.003	.004	.005	.006	.007
Copper Yellow Brass, High Lead Brass, Red Brass	800-1500	Navel Brass, High Silicon Bronze, A-17, C-17200	800-1000	.001	.001	.002	.0025	.003	.004	.004	.005
Copper Alloys Alum/Bronze, Low Silicon Bronze	800-1000	Nickel Silver, Beryllium Copper, Oxygen-Free Copper	700-1000	.001	.001	.002	.0025	.003	.004	.004	.005
Magnesium De-CAt, Extruded	1000 min	Nickel Silver, Beryllium Copper, Oxygen-Free Copper	700-1000	.001	.002	.002	.003	.004	.006	.008	.009
Plastics, Acrylics, Phenolics Polysulfone	200-600	Polycarbonate	200-500	.001	.002	.003	.004	.006	.008	.010	.015
Carbon, Graphites	200-400			.004	.004	.006	.008	.010	.010	.015	.020

Appendix B: Average Unit Horsepower (UHP) Chart

5.9 AVERAGE UNIT POWER REQUIREMENTS

HORSEPOWER PER CUBIC INCH/MINUTE

MATERIAL	HARDNESS BHN	UNIT POWER* Horsepower/Cubic Inch/Minute		
		TURNING P_t HSS & CARBIDE TOOLS FEED .008 TO .010 IPR	DRILLING P_d HSS DRILLS FEED .002 TO .010 IPR	MILLING P_m HSS & CARBIDE TOOLS FEED .004 TO .008 IPT
STEELS - *wrought & cast* Plain Carbon Alloy Steels Tool Steels	85-200	1.2	1.0	1.2
	35-40 R_C	1.6	1.4	1.5
	40-50 R_C	2.0	1.7	2.0
	50-55 R_C	2.2	2.0	2.2
CAST IRONS Gray, Ductile and Malleable	110-190	1.0	1.0	1.0
	190-320	1.8	1.6	2.0
STAINLESS STEELS - *wrought & cast* Ferritic, Austenitic and Martensitic	135-275	1.5	1.3	1.4
	30-45 R_C	1.5	1.4	1.6
PRECIPITATION HARDENING STAINLESS STEELS	170-450	1.5	1.4	1.7
TITANIUM	250-375	1.0	1.0	1.2
HIGH TEMPERATURE ALLOYS Nickel & Cobalt Base	200-360	2.0	2.0	2.5
REFRACTORY ALLOYS Tungsten	321	3.5	3.3	3.6
Molybdenum	229	2.4	2.0	2.5
Columbium	217	2.2	1.7	2.3
Tantalum	210	2.7	2.1	2.7
NICKEL ALLOYS	80-360	2.2	2.2	2.6
ALUMINUM ALLOYS	30-150 500 kg	0.3	0.2	0.4
MAGNESIUM ALLOYS	40-90 500 kg	0.2	0.2	0.2
COPPER	80 R_B	1.2	1.1	1.2
COPPER ALLOYS	20-80 R_B	0.8	0.6	0.8
	80-100 R_B	1.2	1.0	1.2

*Power requirements at spindle drive motor, corrected for dull cutter and 80% spindle drive efficiency.

Appendix C: Required Spindle Speed and Power Calculation [38]

$$n = \frac{12 V_c}{\pi D} \quad (1)$$

$$V_f = n f_z z \quad (2)$$

$$MRR = V_f \cdot RDOC \cdot ADOC \quad (3)$$

$$P = MRR \cdot UHP \quad (4)$$

Substituting (1) → (2) → (3) → (4)

$$\boxed{P = \frac{12 V_c f_z z}{\pi D} RDOC \cdot ADOC \cdot UHP} \quad (5)$$

D ~ tool diameter (in)
n ~ spindle speed (RPM)
V_c ~ surface cutting speed (feet/min)
f_z ~ chipload (in/tooth)
z ~ # of flutes on endmill
V_f ~ feedrate (in/min)
MRR ~ material removal rate (in³/min)
RDOC ~ radial depth of cut (in)
ADOC ~ axial depth of cut (in)
P ~ spindle horsepower (hp)
UHP ~ unit horsepower (hp/in³/min)

Sample Calculation (Al + Al Alloys)

Using a 1/4" endmill (3-flute),

$V_c = 1400$ ft/min
$f_z = 0.002$ in/tooth
$z = 3$ flutes
$D = 0.25$ in

Assuming a full slot cut (max),

$RDOC = ADOC = 0.25$ in
$UHP = 0.4$ hp/in³/min

$$P = \frac{12(1400)(0.002)(3)}{\pi(0.25)}(0.25)(0.25) \times (0.4)$$

$$\boxed{P = 3.2 \text{ hp}}$$

calculation is continued on next page...

$P = 3.2\ hp$

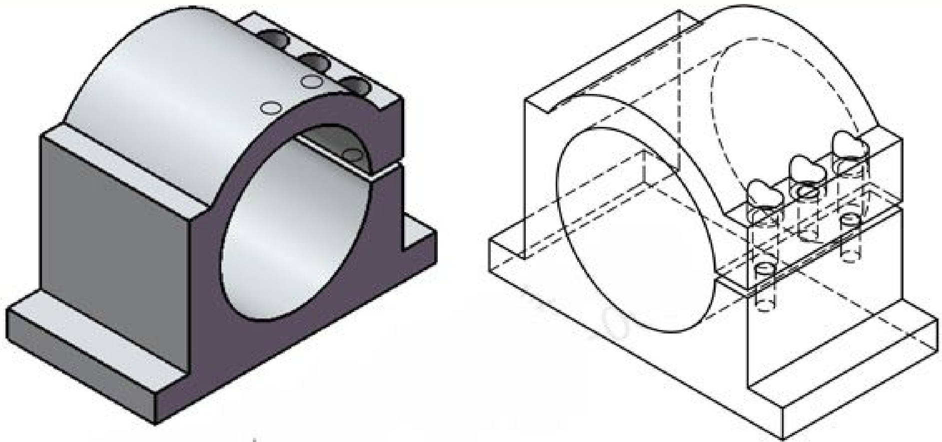
Considering a standard 80% machine efficiency,

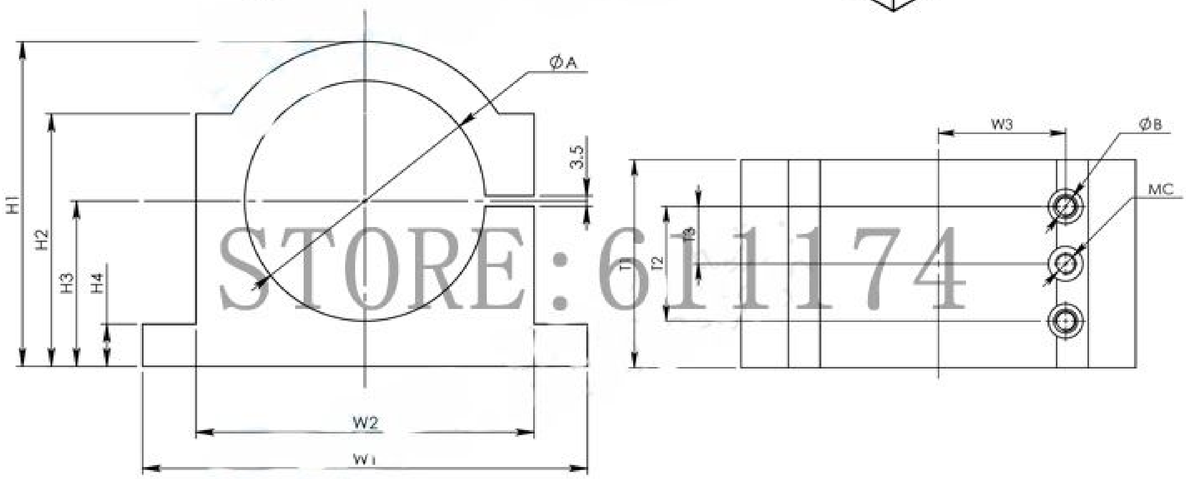
$$\boxed{\text{Required } P = \frac{3.2}{0.8} = 4.0\ hp}$$

$$n = \frac{12\,(1400)}{\pi\,(0.25)} = 21400\ RPM$$

$$\boxed{\text{Required Speed} = 21400\ RPM}$$

Appendix D: Dimensions of Mounting Bracket for Spindle [24]





	D62	D65	D80	D80W	D85	D100	D105	D110
W1	130	130	148	150	150	168	175	186
W2	100	100	112	114	114	130	135	148
W3	38	38	47.75	47.75	47.75	56.5	59	66.5
H1	85.8	86.2	107	108	108	121	126.5	138
H2	71.2	71.5	83	84	82	91	100	105
H3	43	45	50	55	55	59.5	62.5	70
H4	15.5	16	14	14	14	16	24	18
T1	78	78	77.5	98	78	82.5	84	120
T2	46	46	43	70	43	49.5	54	90
T3								
A	62	65	80	80	85	100	105	110
B	9	9	9	9	9	9	9	9
C	8	8	8	8	8	8	8	8

**referencing D105 column*

Appendix E: Further Research for Material Selection

Furthermore, the specific type of aluminum can also be chosen. After considerable amounts of research, it was narrowed down to 3 different choices:

- Aluminum 1100
- Aluminum 2014
- Aluminum 2018

Aluminum 1100 is commonly used for kitchen utensils and other sheet metal work. It is easily machined and can be cut without the use of any substances. Aluminum 2014 is a precipitation hardened alloy, and has good strength once heat treated (annealed). This aluminum is much stronger, it use normally used for aircraft structures and truck frames. Lastly, Aluminum 2018 is an age hardened (precipitation hardened) material with high strength. This aluminum is definitely the strongest among the three listed; it is commonly used in the manufacture of aircraft engines and other heavy duty pistons. According to many online retailers, the three Aluminums cost around 2-3 dollars/kg. Since price is not the deciding factor, the use case will determine the final material. Since Aluminum 2018 is a bit too sturdy (and harder to cut) and Aluminum 1100 might not be strong enough for a CNC, Aluminum 2014 would be the final choice for the frame material. However, aluminum 2014 is not easily available and would require tedious amounts of work to acquire, therefore Aluminum 6061, a similar aluminum with similar use cases will be used instead. Aluminum 6061 is heat treated, easily machined and can be used in heavy duty structures such as truck components, pipelines etc.