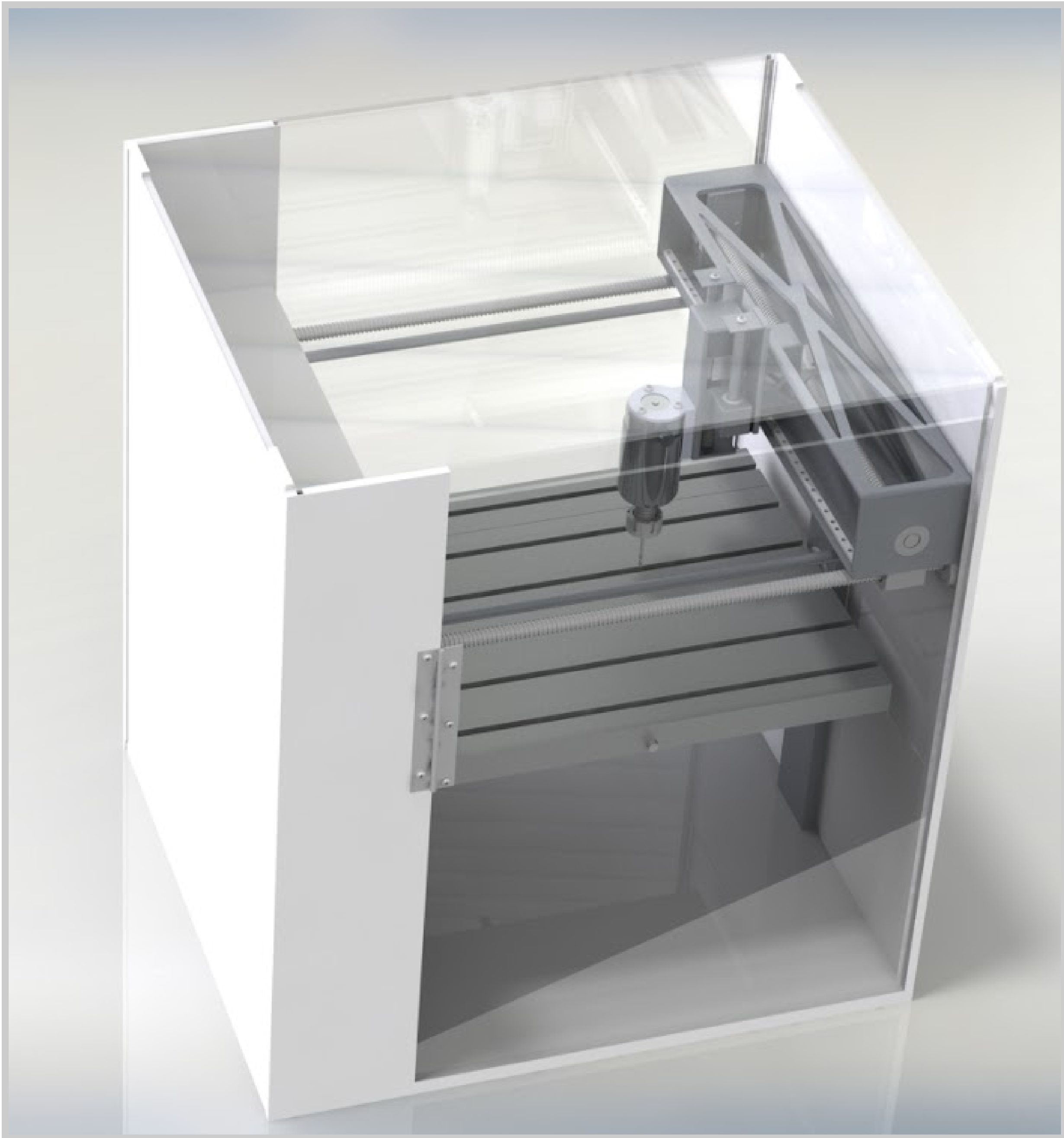
MIE243 Group 47 Project



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Executive Summary

The purpose of this design project is to create a conceptual design for an entry-level professional desktop Computerized Numerical Control (CNC) milling machine. This document details the entire design process from research, creating engineering specifications, candidate designs, and the final design.

Research consisted of identifying professional-level CNC machines currently on the market and their technical specifications. This acted as the foundation for the engineering specifications to be built on.

Afterwards, a set of engineering specifications was created. These specifications detailed the requirements the designs should aim to fulfill, which are as follows:

- ≤ $12, 000 USD, ≤ 92kg
- Able to cut materials up to the degree of soft metals
- Max machine size of 600mm (x) by 700m (x) by 600mm (z)
- Minimum work table size of 220 mm (x) by 120 mm (y) by 100 mm (z)
- Vertical style with 4 or more axes
- Ability to tool swap, and have a feed rate of ≥ 4m/min,
- Overall form must contain debris, minimize noise, and be able to operate on a desktop without specialized mounting.

Prior to the candidate designs, further research was done on the specific mechanisms that are commonly used in CNC machines. This included, rotary to linear motion conversion systems, belts, motors, bearings, gears, guide rail systems, and coolant systems.

Then using the engineering specifications and the mechanism research, three candidate designs were created. These candidate designs are, The Three Rack and Pinion, The Gantry Tipper, and the Mobile Platform. The Three Rack and Pinion design uses rack and pinions as the main mode of motion. The Gantry Tipper is a gantry-style CNC machine with a rotating table. The Mobile Platform has the platform do most of the movement as opposed to the spindle. Then one more major iteration of these designs was done to create two further designs. All these designs were compared to the engineering specifications to arrive at the final design.

The final design chosen was an iteration on the Gantry Tipper. It uses ball screws in the x, y and z axes of motion, and a worm gear in the fourth, rotating axis. This design was chosen for its fulfillment of the engineering specifications. More specifically, how well it contained debris and had a large working area. Finally, a Computer Aided Design (CAD) model for this design was created to demonstrate the functionality of the design.

1. Introduction

A Computer Numerical Control Machine or CNC machine uses code to run a tool and modify material [1]. This design project will be focussed on designing a CNC milling machine, which is a machine that rotates a tool at high speeds to mill out material and create a final product [2]. The following document delves into an analysis of current market options and technologies for entry-level professional CNC milling machines and proposes a design to solve the gap. The following report details the engineering specifications, candidate designs, iterations, proposed design, and CAD model of an entry-level professional CNC machine.

2. Current Market Research

This section outlines the different mechanisms that can be used in CNC milling machines as well as analyzing market opportunities that are available by comparing competition

The search was limited to intermediate level milling machines. This excluded professional grade and hobbyist use as that is not the target demographic. The purpose is to analyze what solutions are currently on the market for professional entry level companies seeking to purchase a CNC milling machine to better understand what the design requires.

The most popular intermediate CNC milling machines are the Tormach PCNC 440, Bolton Tools M4A, the Hass Modular Mini Mill, Bantam Tools CNC Milling Machine, and the CNC Supra Vertical Knee CNC Machine. Table 1 details the comparison between these machines and shows the difference in key features.

Table 1 - Professional level CNC Milling Machines Currently on the market

Category	**Tormach PCNC 440** (Entry Package) [3]	**Bolton Tools 3-Axis CNC Compact Vertical Milling Machine** [4]	**Hass Modular Mini Mill - EDU** [5]	**Bantam Tools CNC Milling Machine** [6]	**CNC Supra Vertical Knee CNC Machine** [7]
Axes	3	3	3	3	3
Cost USD	$6490	$8065	$22995	$4000	$12483
Machine Size	1016mm x 812mm x 1090mm	1100mm × 600mm × 1380mm	914mm x 730mm x 305mm	503mm x 531mm x 493mm	Not specified
Travel Distance	X axis: 254 mm Y axis: 159 mm Z axis: 254 mm	X axis: 220 mm Y axis: 120 mm Z axis: 200 mm	X axis: 406 mm Y axis: 305 mm Z axis: 254 mm	X axis: 117 mm Y axis: 229 mm Z axis: 89 mm	X axis: 860mm Y axis: 292mm Z axis: 114 mm
Feed Rate	X and Y axis: 3.43 m/min Z axis: 2.79 m/min	X and Y axis: 4 m/min Z axis: 4 m/min	X and Y and Z axis: 7.5m/min	X and Y and Z axis: 6.35 m/min	X and Y and axis: 2,53m/min
Torque	Not specified	X axis: 1.5 ft·lbf Y axis: 1.5 ft·lbf Z axis: 2.2 ft·lbf	X axis: 33 ft·lbf Y axis: 33 ft·lbf Z axis: 33 ft·lbf	Not specified	Not specified
Spindle Power	0.56 kW	1 kW	5.6 kW	0.25kW	Not specified
Weight	68 kg (excluding table)	Not specified	227kg	Not specified	Not specified

Coolant	Not included	Coolant Pump	Air Cooled	No	Not included
Desktop	Comes with Table	Comes with Table	Comes with Table	Can put on a table	Comes with Table

3. Problem Statement

CNC machines range from manufacturing scale to hobbyist use. Small scale design companies do not have the resources, funds, or space for an industrial grade machine. However, they require more functionalities than beginner-level machines provide. It is unreasonable for these businesses to outsource every time a prototype needs to be created, and rather they need a machine on-site that is capable.

There are several CNC routers on the market listed at 10K and below for those who are interested for recreational purposes. There are also several industrial grade CNC machines on the market. However, there is a lack of market concentration in CNC milling machines at the 10K price point, with a 4th axis, and is not constrained to a table. Thus, there is an opportunity to develop a CNC machine for entry level professionals looking for rapid prototyping solutions.

4. Service Environment

The designed CNC milling machine will be used in the offices of small-scale professional design companies. The physical environment is an office with minimum room dimensions of 7m^2 as indicated by Ontario's Building code requirements [8], a desktop table with minimum dimensions of 70cm x 60cm, has a room temperature of approximately 20-25 degree celsius, and at least 1 standard 120V electrical power outlet. The virtual environment has internet, whether wireless or ethernet.

5. Engineering Specifications

Based on the market analysis and gap, the following engineering specifications were determined in Table 2. Further reasoning behind these choices are detailed in the rest of this section.

Table 2 - Engineering Specifications

Category	**Specification**
Price Range	$12, 000 USD
Weight	< 92 kg

Permissible Working Materials	Foam, plastics, wood, soft metals
Maximum Machine Dimensions	600mm (x) by 700m (y) by 700mm (z)
Minimum Working Area Size	220 mm (x) by 120 mm (y) by 100 mm (z)
Orientation	Vertical
Axis	4 or more
Tool Swapping	Must permit manual or automatic tool swapping.
Debris	Must contain debris, preventing it from flying into the outside environment.
Noise	Must minimize noise.
Feed rate	≥ 4m/min
Portability	Must be able to operate on a desktop surface without any specialized mounting

5.1 Price Range

Through the preliminary research, CNC milling machines range from $4,000 to $23,000 USD (see Table 1). To stay competitive with the market, our product should be less than $12,000 USD. This is reasonable as the majority of the available CNC machines within this price point are constrained to just 3 axes.

5.2 Weight

Since the CNC Machine will be resting on a desktop surface, we must ensure that the table it rests on is able to withstand the load. We can safely assume that the users would have either a wooden or metal desk in the office. If not, they can be easily purchased commercially. The average wooden desk has a weight load of 96.1kg and the average metal desk has a weight load of 104kg [9]. The CNC machine may be subjected to several rearrangements within the office it exists in as there is not a dedicated room for it. Knowing this, the CNC Machine should be able to be moved with a minimum of 4 people (one to support each corner). The National Institute for

Occupational Safety and Health in the United States states that the average adult can safely lift 23kg, meaning that 4 adults can safely lift 92kg [10]. We take the lower limit of all these values and assign the weight of the CNC machine to be less than 92kg. Compared to the current desktop machines on the market, this value is acceptable.

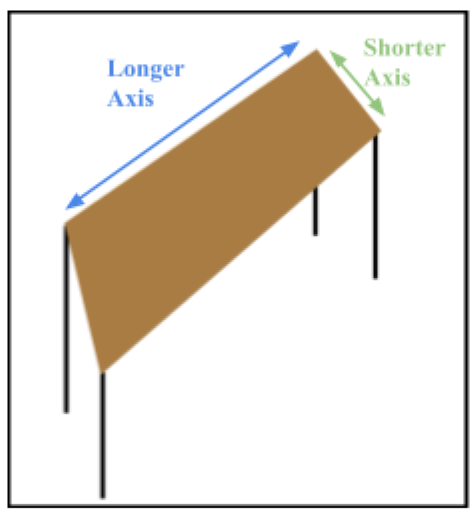
5.3 Permissible Working Materials

Our design is professional grade and not industrial, thus, it will support a range of simple prototyping materials ranging from foam and plastics to soft metals. This is in line with the market research in Table 1.

5.4 Maximum Machine Dimensions

The maximum machine size is 600mm (x) by 700m (y) by 700mm (z). This size was determined by looking at current market options (Table 1), while keeping in mind that the machine must fit on an average desktop. The chosen sizing is within the market range and a reasonable size for a desktop machine. As noted by the dimensions, one of the axes may be longer since it can span across the length of a desktop (see Figure 1 for clarification).

Figure 1 - Many tables are longer in one axis than the other, so the maximum machine dimensions reflect this. The machine can be longer in one axis to take advantage of the longer axis of a table.



5.5 Minimum Working Area Size

The minimum working area size should be 220 mm (x) by 120 mm (y) by 100 mm (z). These values were obtained through market research in Table 8, where the smallest working area size was taken as the engineering specification. This minimum size allows the design of the machine to compete with the current market options of similar type.

5.6 Orientation

Horizontal orientation and vertical orientation mills both have their own benefits. Horizontal mills tend to be more heavy duty and debris is isolated through the work of gravity [11]. However, the main advantages for choosing vertical mills are that they tend to allow for higher visibility of the workspace and are more standardized in terms of tool options and software [12]. Heavy duty milling is not required for this machine, as it is not intended for use at an industrial level, and debris can always be dealt with in other ways. Therefore, vertical mills are far more suitable for the purpose of this design.

5.7 Axis

It is specified by the project guidelines that the machine should operate with greater than three axes. CNC milling machines can sometimes operate with half axis movement, although half axes are mostly due to software limitations [13]. For this project the main focus is on the mechanical aspects, so four or more axes is a suitable engineering specification.

5.8 Tool Swapping

Most, if not all CNC milling machines support tool swapping, whether it is manual or automatic. Automatic tool change (ATC) mechanisms range in size, disk types used for <30 tools and chain types for >30 tools [14]. Both of these options are far too large for the size restriction of this design. However there is the option for ATC systems built into a gantry, which is limited by the size of the gantry [15]. Therefore there is a possibility of implementing an ATC, but due to the size restrictions, this engineering specification will be left more open. As a result, the design must allow for tool changes but it may be manual or automatic.

5.9 Debris

Debris must be contained to prioritize the safety of the users and cleanliness of the office environment. The service environment of the design is an office space with employees working in the general vicinity. Office workers must not need to wear protective footwear and safety goggles when around the operational CNC machine.

5.10 Noise

Since the machine may be operating in an office workspace, the design should minimize noise to prevent disturbance or damage to hearing. Mechanisms should be chosen in the final design to reduce noise as much as possible.

5.11 Feed rate

Based on the market research in Table 1, the feed rate of similar types of machines range from 2.53m/min to 7.5m/min in the x and y plane. Through discussion, it was determined that the design should reach a minimum of 4m/min in order to be on par with the market options.

5.12 Portability

The design is intended to operate in an office setting, where there may be limited space or ther may not be a dedicated workshop. Therefore, the machine must be able to operate on a standard desktop without any specialized mounting or table. This allows the machine to be easily set up and relocated if desired.

5.13 Coolant

Liquid coolant is generally used for industrial CNC machines where working conditions are far more extreme than the scope of this design [16]. The maintenance and complexity of the overall design will increase drastically. Not only will a liquid coolant system need to be integrated into the design but also a filtering system. Filtering the coolant will allow it to be reused, saving lots of expensive coolant. However, it requires high maintenance as the filters will need to be thoroughly cleaned to prevent debris from clogging the system [17]. Furthermore, liquid coolant will make a mess in the working area. Overall, liquid coolants add complexity and lots of maintenance to the design. Which is why compressed air is a considerable option, as it does not require filtration and concentration maintenance, and is preferred to come into contact with some materials (many polymers will experience thermal shock, rapid expansion and contraction) [18]. However, in terms of the scope of this design, it is dispensable as the working materials will not produce enough energy during machining to need any form of coolant. Therefore, we avoided using a coolant system due to its unnecessary costs and complexity it brings to this design.

6. Mechanism Research

This section contains main mechanisms that CNC machines often use. A brief analysis of each mechanism is done.

6.1 Rotary to Linear Motion Conversion Systems

CNC milling machines need to move in the X, Y, and Z axis. In Table 3 are the comparisons of common mechanisms to perform that function.

Table 3 - Types of Rotary to Linear Motion Conversion Systems

Rack and Pinion	
Pros	**Cons**
Rack and pinion systems are low cost, simple to construct, and efficient in power transfer	Rack and pinion systems require large amounts of clearance, do not increase mechanical advantage, and also experience backlash, vibration, and noise.
Ball Screw	
Pros	**Cons**
Ball screws minimize friction, have a low erosion rate, minimal maintenance, and increased durability. They also have low clearance with high precisions, and reduced vibration.	Ball screws are more expensive compared to lead screws and rack and pinion systems.
Lead Screw	
Pros	**Cons**
Lead screws are inexpensive and easily customizable.	Lead screws are prone to corrosion, and require large clearance, backlash, and have lower precision compared to ball screws.

6.2 Belts

The mechanism is overall simple to implement into a design and relatively cheap. Belts can also provide long distance motion transmission and have the option of creating a speed ratio. Additionally, belts can absorb vibration, preventing more expensive/fragile parts from being damaged. However, a belt is elastic and can deform over time, and will need to be replaced more frequently relative to other parts. Belts also require tensioners to ensure they maintain positive contact with the pulleys and do not slip. More information on different types of belts is listed in Table 4.

Table 4 - Types of Belts

Flat Belt	
Pros	**Cons**
Generally the cheapest option for belts.	Only suited for low torque applications.
Timing Belt	
Pros	**Cons**
Timing belts can provide accurate positioning. These belts are also suitable for moderate torque applications.	Faces the general disadvantages of using a belt.
V Belt	
Pros	**Cons**
V-belts have relatively high efficiency and long lifespan. In addition these belts can provide moderate to high torque and low to high speed.	V-belts have more fibres embedded and as a result are less flexible.

6.3 Motor

Every mechanism needs a source of input power, and different types of motors are used based on the application. In Table 5, some motor options are listed along with further information.

Table 5 - Types of Motors

Stepper Motor	
Pros	**Cons**
Stepper motors are ideal for low speed high precision scenarios. The torque of a stepper motor is greater than the torque of the same size servo motor. They are also cheaper than servo motors. They have a long life span because many of the moving parts are frictionless, and are overload safe [19].	Stepper motors have low efficiency, its torque declines rapidly the faster it goes, and can be noisy. Stepper motors are also considered less precise than servo motors. There is also no feedback to notify if steps were missed [19].
Servo	
Pros	**Cons**
Servo motors are highly efficient and accurate with high torque to inertia ratios, and can achieve high speed at high torque values and are relatively quiet.	Servo motors are more expensive and require more maintenance than stepper motors, often require a gear box, and safety circuits.

6.4 Bearings

Bearings are useful for providing motion support and greatly reducing friction between moving parts. Bearings in general are highly standardized, which reduces the design complexity. In Table 6, various types of bearings are examined in further detail.

Table 6 - Types of Bearings

Ball Bearing	
Pros	**Cons**
Ball bearings are good for supporting rotating shafts and can resist against large radial forces. Additionally they are relatively cheap and are suited for high speed applications.	Ball bearings cannot resist against much axial force.
Roller Bearing	
Pros	**Cons**
Roller bearings are good for supporting rotating shafts and can resist against high radial force and moderate axial force.	The rollers have a higher area of contact and in turn produce more heat under heavy operation. Generally, roller bearings are more expensive than ball bearings.
Linear Bearings	
Pros	**Cons**
Linear bearings are good for support along a shaft, or in the axial direction. Other advantages are similar to ball and roller bearings.	Can only support up to moderate speed and moderate loads.

6.5 Gears

Gears are used for motion modification or transmission and are most commonly used to either increase/decrease torque or increase/decrease speed. In Table 7, a few types of gears are evaluated in more detail.

Table 7 - Types of Gears

Worm Gear	
Pros	**Cons**
Worm gears have high load capacity and allow for high reductions in small spaces. They only have unidirectional power transfer, thus it is self locking and beneficial for holding positions.	Worm gears are relatively expensive and have a high operating temperature due to friction.
Spur Gear	
Pros	**Cons**
Spur gears are cheap and highly standardized. Spur gears can be found/made from many different materials (metals, plastics, etc.).	Spur gears have relatively low contact ratio, which results in vibration and noise at high speeds. Backlash is also an issue, it can reduce positioning accuracy and increase wear on the gear teeth.
Helical Gear	
Pros	**Cons**
Helical gears have higher contact ratio than spur gears, so they have less backlash.	Due to the angled teeth of the helical gears, they can produce high axial thrust forces. Helical gears are also typically more expensive.

6.6 Guide Rail Systems

Guide rail systems are important for supporting linear motion in the machine. This support can reduce wear on parts and increase the over lifespan of the machine. Below in Table 8 are the brief notes on the main types of guide rails.

Table 8 - General Types of Guide Rails

Integrated Actuation	
Pros	**Cons**
Cheaper than independent options.	Less design flexibility.
Independent from Actuation	
Pros	**Cons**
Allows for greater design flexibility.	More expensive than integrated systems.

6.7 Coolant Systems

Coolant systems are important to reduce heat and fatigue/wear of the parts due to excessive heat. Using coolant also lubricates the working surfaces, and reduces the risk of corrosion over time [17]. Table 9 delves into the types of coolants and their applications.

Table 9 - Types of Coolants

Liquid Coolant	
Pros	**Cons**
Highest cooling and lubrication performance. Fends off corrosion effectively. [16][17]	It complicates the design as a filtration system will be needed too. In addition, the concentration of coolant must be monitored as high and low concentrations wear the machine. Furthermore, the filtration system will need to be cleaned to avoid clogging. Thus, high maintenance is required from the user to ensure the two systems are working

	well. [16][17]
Air Coolant	
Pros	**Cons**
Simple design and does not require much maintenance. [16][17]	Lowest quality of coolant: no lubrication and poor cooling efficiency. [16][17]

7. Candidate designs

Based on the engineering specifications and research conducted on mechanisms, three preliminary candidate designs were proposed.

7.1 Three Rack and Pinion

This candidate design consists of 3 rack and pinion mechanisms for the X, Y, and Z axes movement. For the X and Y axes, the rails are stationary and the pinions move back and forth. The pinion is supported by a gear box that is subsequently attached to a rail system for optimal support. For the Z axis, the pinion and gear box are fixed and the rail moves up and down. The rotational axis is achieved using 2 servo motors that attach to the clamping/holding mechanism for the material. See Figures 2-6 for sketches of the design.

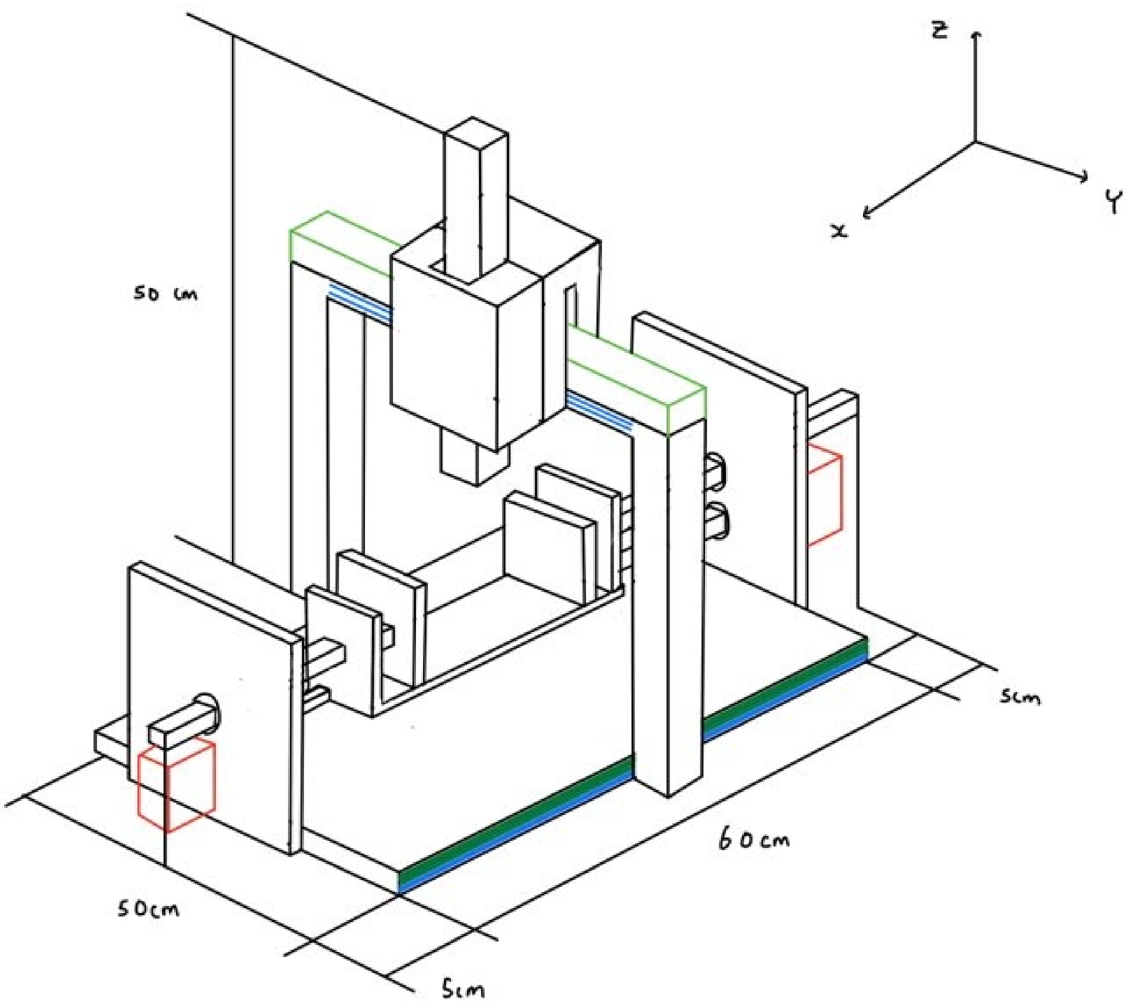


Figure 2 - Isometric view of the Three Rack and Pinion, with rough dimensions.

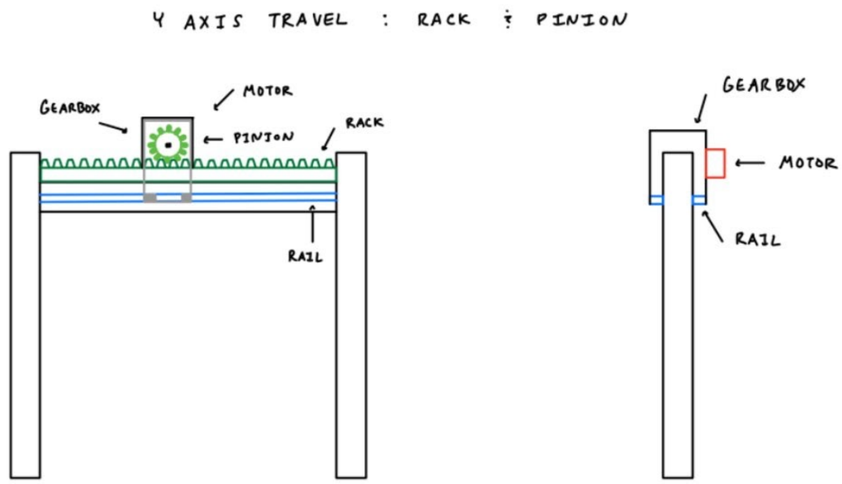


Figure 3 - Side view of the Three Rack and Pinion frame, showing a rack and pinion system setup.

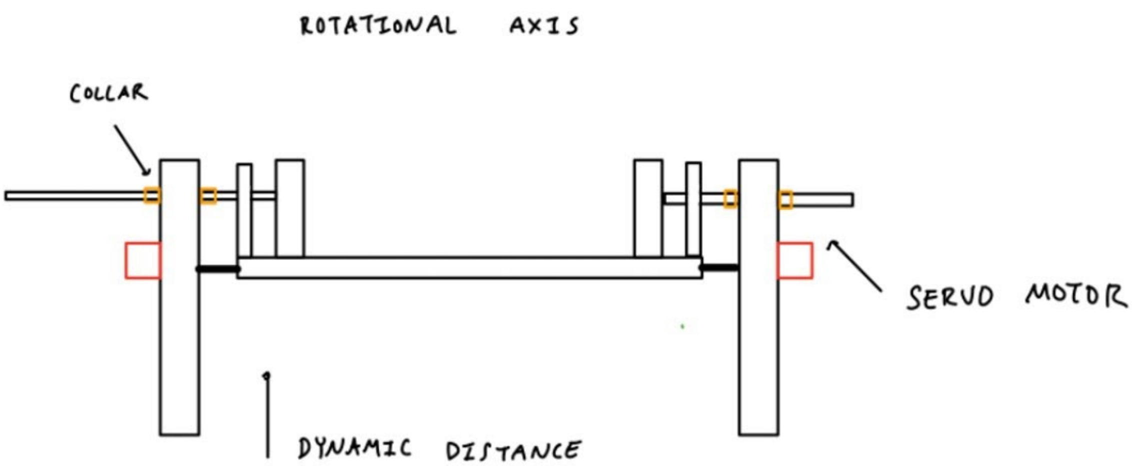


Figure 4 - Side view of the table, with the specialized clamps.

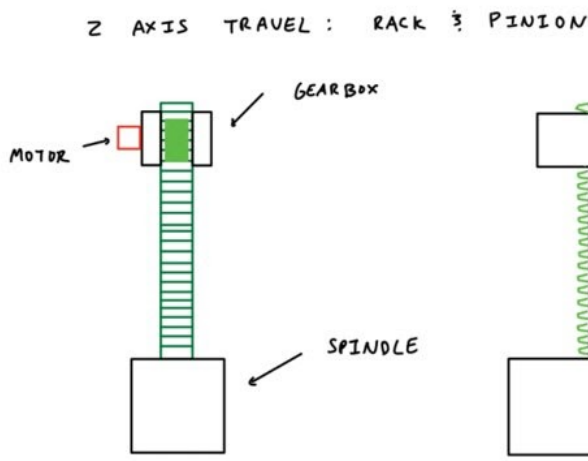


Figure 5 - Isolated views of the z axis travel and the rack and pinion system.

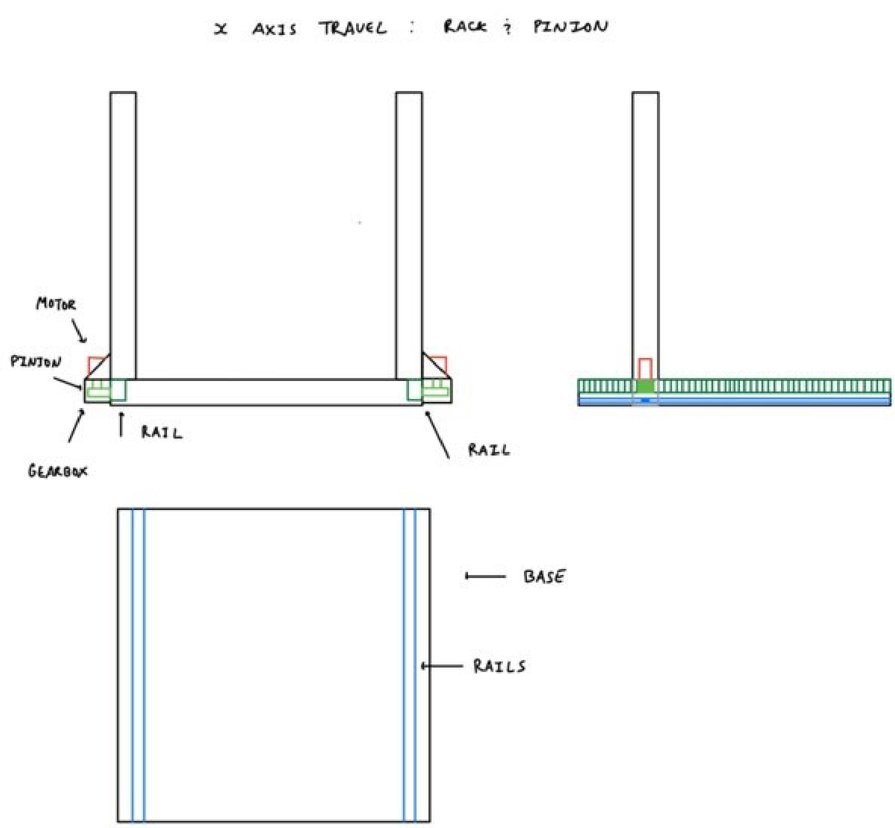


Figure 6 - Isolated views of the x axis travel, with the rack and pinion system.

7.2 The Gantry Tipper

The Gantry Tipper design revolves around the design of a gantry-style CNC machine with a table that can be tilted by a motor. This allows for 4 axis milling with movement axes x along the frame, y along the gantry, z along the spindle, and rotation around the x axis with the table. An additional feature of the tipping table is debris collection via gravity. To aid in debris collection, a compressed air canister and nozzle are attached to the spindle. For motion, the gantry uses rack and pinions to move in x and z directions, and a ball screw to move in the y-direction. These were chosen based on their ability to transform rotational motion into linear motion. The table motor will use a worm gear and worm wheel pair. This allows the motor to control the table while preventing the table from tipping on its own. Figures 7-10 show sketched views of the candidate design.

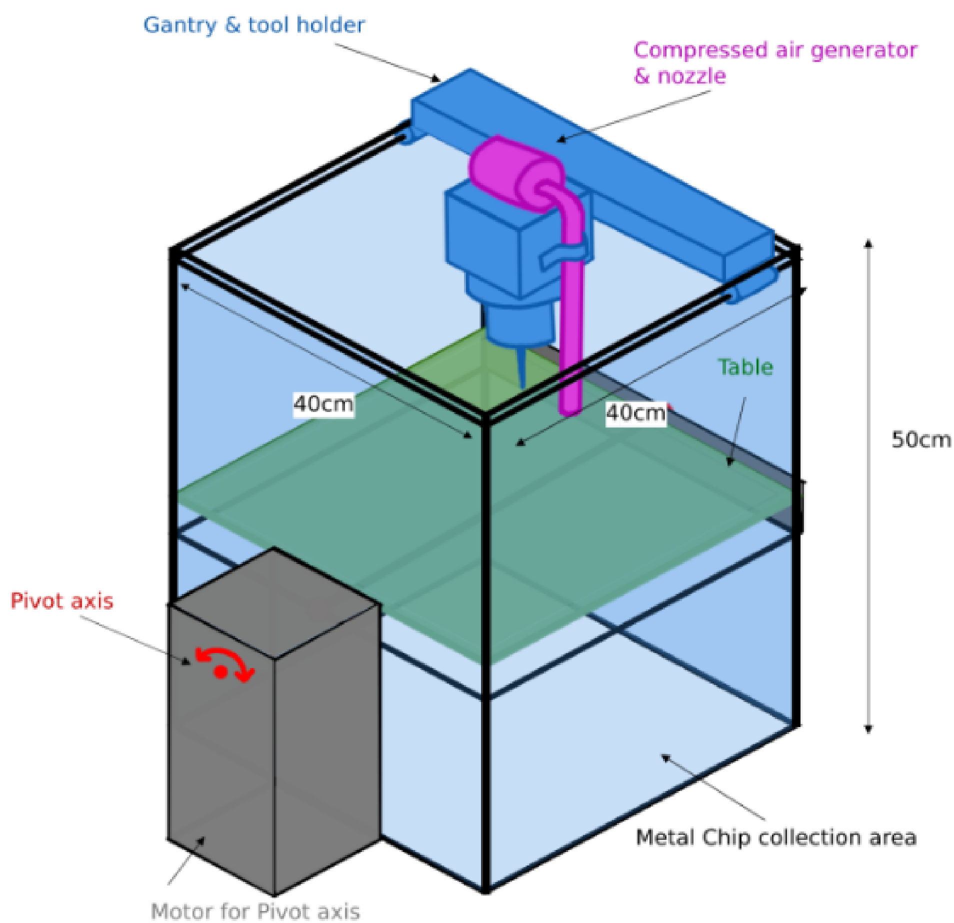


Figure 7 - Isometric view of The Gantry Tipper, with some rough dimensions.

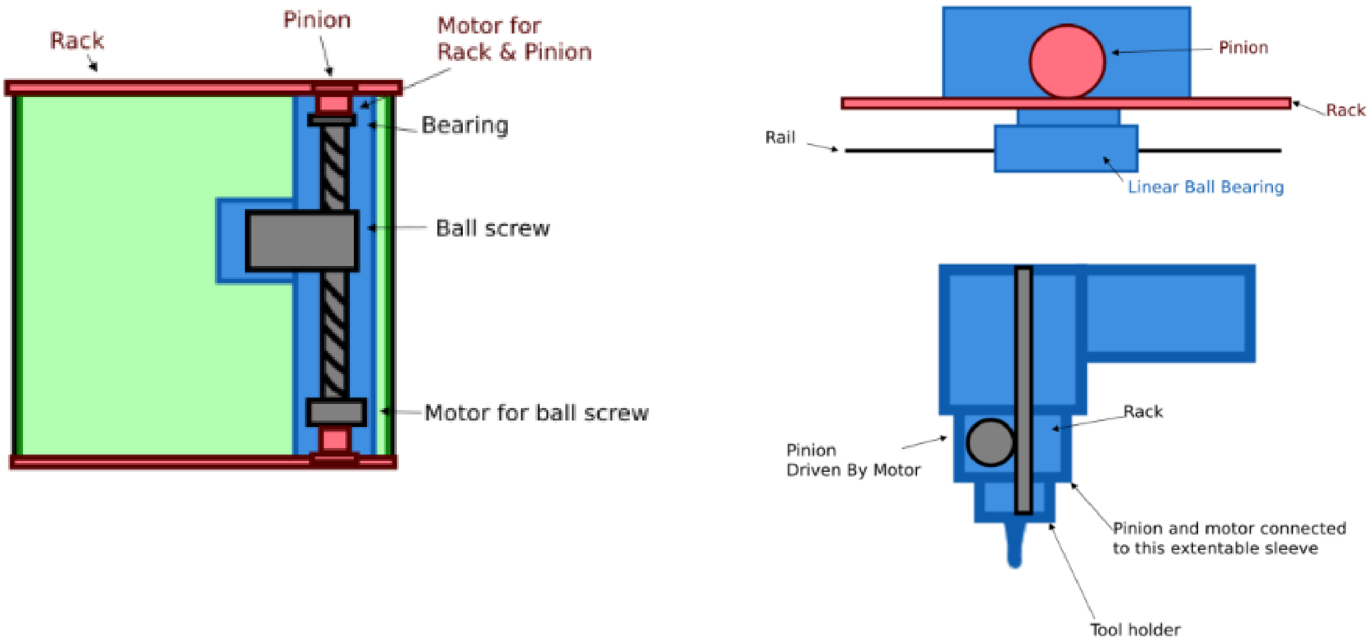


Figure 8, 9 - Top view of The Gantry Tipper alongside the side views of the rail system and z axis movement in the spindle.

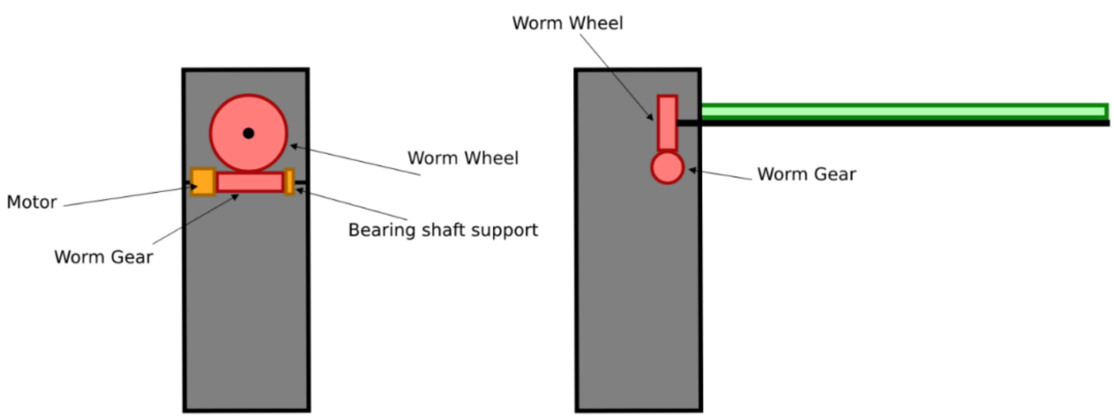


Figure 10 - Isolated views of the system driving the motion of the table.

7.3 The Mobile Platform

The mobile platform is a 3-axis CNC milling machine. In the x-x direction, motion is obtained through a small linear actuator placed inside the main machine housing. This linear actuator is connected to two parallel rods that are ridged along the long axis. The attachment point of the rods to the supporting structure of the linear actuator is constrained in the x,y,z directions, but allows for rotation about the long axis through the use of bearings.

Motion in the y-y direction is achieved through a sequence of motion transmissions. A single motor-gear system provides a rotational input, which is transformed into linear motion via a rack-and-pinion system. The tank thread belt system at the bottom is connected to the two rods, which input the linear motion of the rack and output rotational motion as they rotate around the bearings. On the far end of the two rods is a grooved belt wrapped around, which finally outputs linear motion to the working platform attached on top.

A feature of this design is that 'smooth motion' can be achieved in the x-y plane. That is, the linear oscillator can provide x-x motion at the same time and independently of the rack-and-pinion, since the two grooved rods can slide perpendicular to the rack-and-pinion while the rack-and-pinion is providing linear-to-rotational motion. See Figures 11-13 for different views of the Mobile Platform.

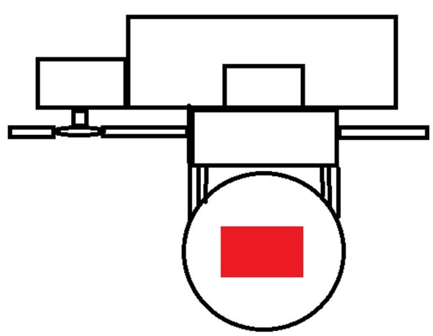


Figure 11 - Top view of the mobile platform.

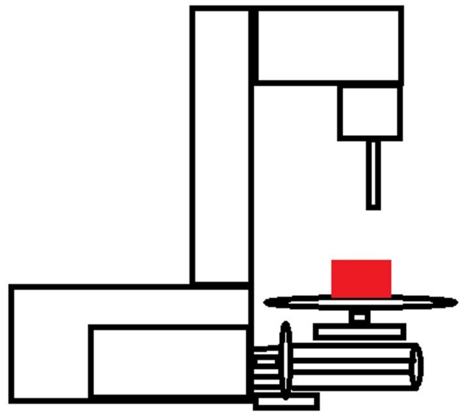


Figure 12 - Side view of the Mobile Platform.

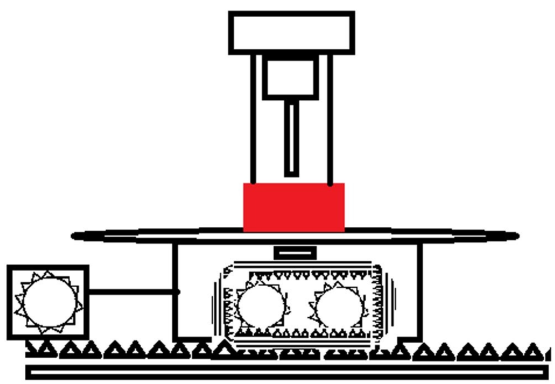


Figure 13 - Front view of the Mobile Platform.

7.4 Candidate Designs Tested Against Engineering Specifications

After the candidate designs have been sketched, they must be compared to the engineering specifications to see if they meet them. If a design does not meet a specification, further iteration can be done to remedy the issues. Table 10 lists the engineering specifications and compares the candidate designs to them.

Table 10 - Candidate Designs and their Fulfilment of the Engineering Specifications

Category	**Engineering Specification**	**Candidate Design 1: (3 Rack and Pinion)**
Price Range	$12,000	Reasonably within
Weight	< 92 kg	Within weight limits
Permissible Working Materials	Foam, plastics, wood, soft metals	Can mill foam, plastics, wood, soft metals
Maximum Machine Dimensions	600mm (x) by 700m (y) by 700mm (z)	700 mm (x) by 500 mm (y) by 500 mm (z)
Minimum Working Area Size	220mm (x) by 120mm (y) by 100mm (z)	350 mm (x) 450 mm (y) 200 mm (z)
Orientation	Vertical	Vertical
Axis	4	4
Tool Swapping	Must permit manual or automatic tool swapping	Manual tool swapping
Debris	Must contain debris, preventing it from flying into the outside environment	Debris containment with a removable plastic cover
Noise	Must minimize noise.	Noise can be minimized, but the rack and pinions must be addressed.
Feed rate	≥ 4m/min	Likely can be achieved, this would be further examined in detailed design.
Portability	Must be able to operate on a desktop surface without any specialized mounting.	Can operate on a regular desktop without specialized mounting.

Table 10 (continued)

Category	Candidate Design 2: (Gantry Tipper)	Candidate Design 3: Mobile Platform
Price Range	Reasonably within	Reasonably within
Weight	Within weight limits	Within weight limits
Permissible Working Materials	Can mill foam, plastics, wood, soft metals	Can mill foam, plastics, wood, soft metals
Maximum Machine Dimensions	400mm (x) by 400m (y) by 500mm (z)	700 mm (x) by 500 mm (y) by 500 mm (z)
Minimum Working Area Size	350 mm (x) by 450 mm (y) by 100 mm (z)	220 mm (x) by 120 mm (y) by 100 mm (z)
Orientation	Vertical	Vertical
Axis	4	3.5 axis
Tool Swapping	Manual tool swapping.	Manual tool swapping.
Debris	Debris containment via enclosure and storage system.	Debris can be contained with an outer covering/shell.
Noise	Noise can be minimized with proper mechanism choices.	Noise can be minimized, but the rack and pinions must be addressed.
Feed rate	Likely can be achieved, this would be further examined in detailed design.	Likely can be achieved, this would be further examined in detailed design.
Portability	Can operate on a regular desktop without specialized mounting.	Can operate on a regular desktop without specialized mounting.

8. Iteration of Candidate Design

After comparing the candidate designs to the engineering specifications, further iterative designs were created to address the gaps in the designs. The following subsections will detail these new iterations and their functionality in detail.

8.1 Iterative Design 1

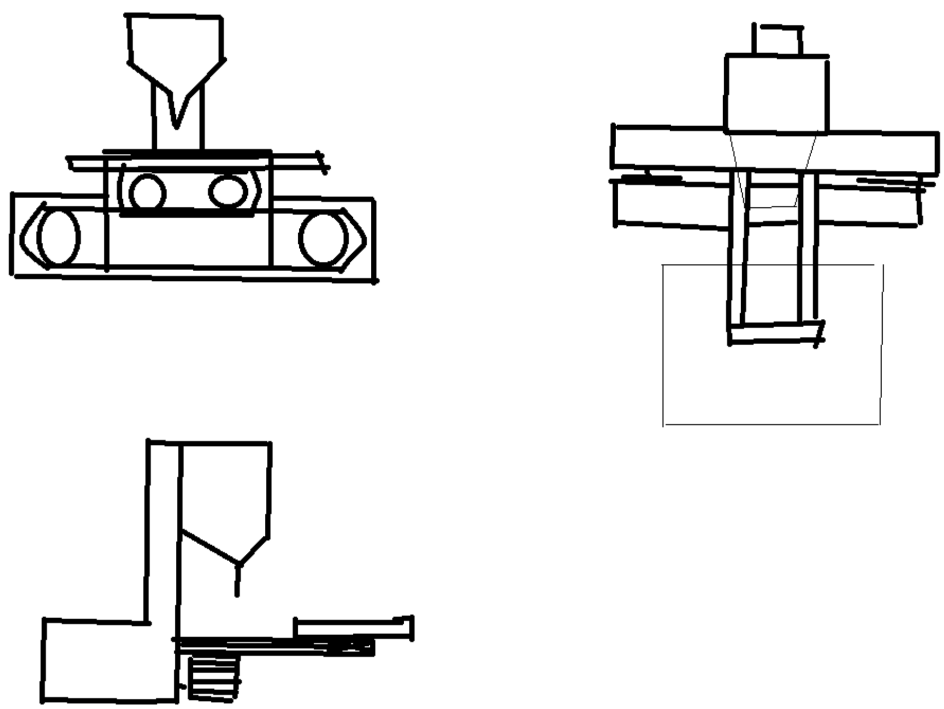


Figure 14 - Front, top and side view of the Iterative Design 1, based on the Mobile Platform.

We removed the rotation element of the base as the movement in the three axes can accomplish the same without it. Therefore, the rotational mechanism overcomplicates the design and is an unnecessary cost. Furthermore, we improved the rack and pinion mechanism at the bottom of the design by changing the rack into a belt, therefore, avoiding the long linear extensions of the rack. This will help minimize the space the machine occupies when operating. As a result, the entire movement mechanism will have to be shifted up slightly to accommodate for the small dimensional changes of changing the rack into a belt. See Figure 14 for sketches.

8.2 Iterative Design 2

This design iteration is a combination between “The Gantry Tipper” and the “3 Rack and Pinion” designs. It uses the table system from the “3 Rack and Pinion” design and the overall shape and functionality of the CNC machine is from “The Gantry Tipper” (see Figure 15). This design also uses a timing belt for one of its axes to reduce cost. However, a timing belt still satisfies the design requirements, and is notably accurate with positioning applications. Idle rollers have also been added to increase the tension and positive engagement between the belt and pulley. The compressed air system was determined to be unnecessary and was removed from this iteration. The z axis movement was changed to a ball screw to provide better positioning accuracy and reduce noise due to backlash. Stepper motors the gantry due to the discrete increments, which drastically increases the accuracy of the positioning.

Furthermore, the table is a custom designed table (not pictured in detail in the sketch), that is modular. It consists of one core piece, two end pieces, and 4 add-on pieces that slide into one another and are secured by a threaded rod. This allows users to dynamically change the table depending on material size to get a 180° rotational access. The table is driven by a motor connected to a worm gear and wheel pair. This is ideal for high torque scenarios and since this mechanism is used for rotating the table, clamps, and material to be milled, a lot more power is needed to move the large load. Additionally, the worm gear can easily rotate the wheel but not vice versa, so the position of the table will be precise, see Figure 10. See Figure 16 for sketches of the other mechanisms.

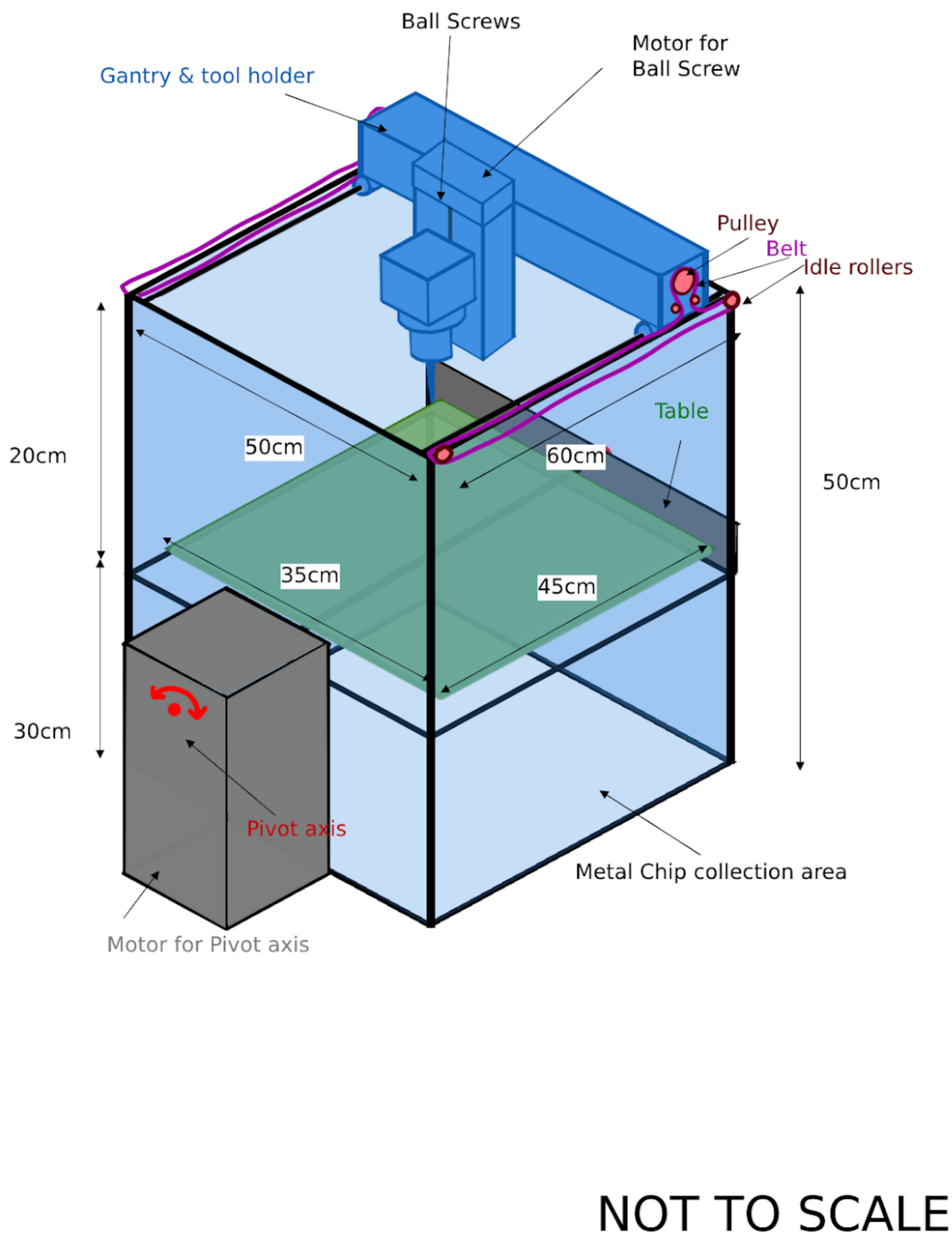


Figure 15 - Isometric view of the Iterative Design 2, based on the Three Rack and Pinion and The Gantry Tipper. Note that the clamps for the Three Rack and Pinion are not displayed here to keep the image less crowded.

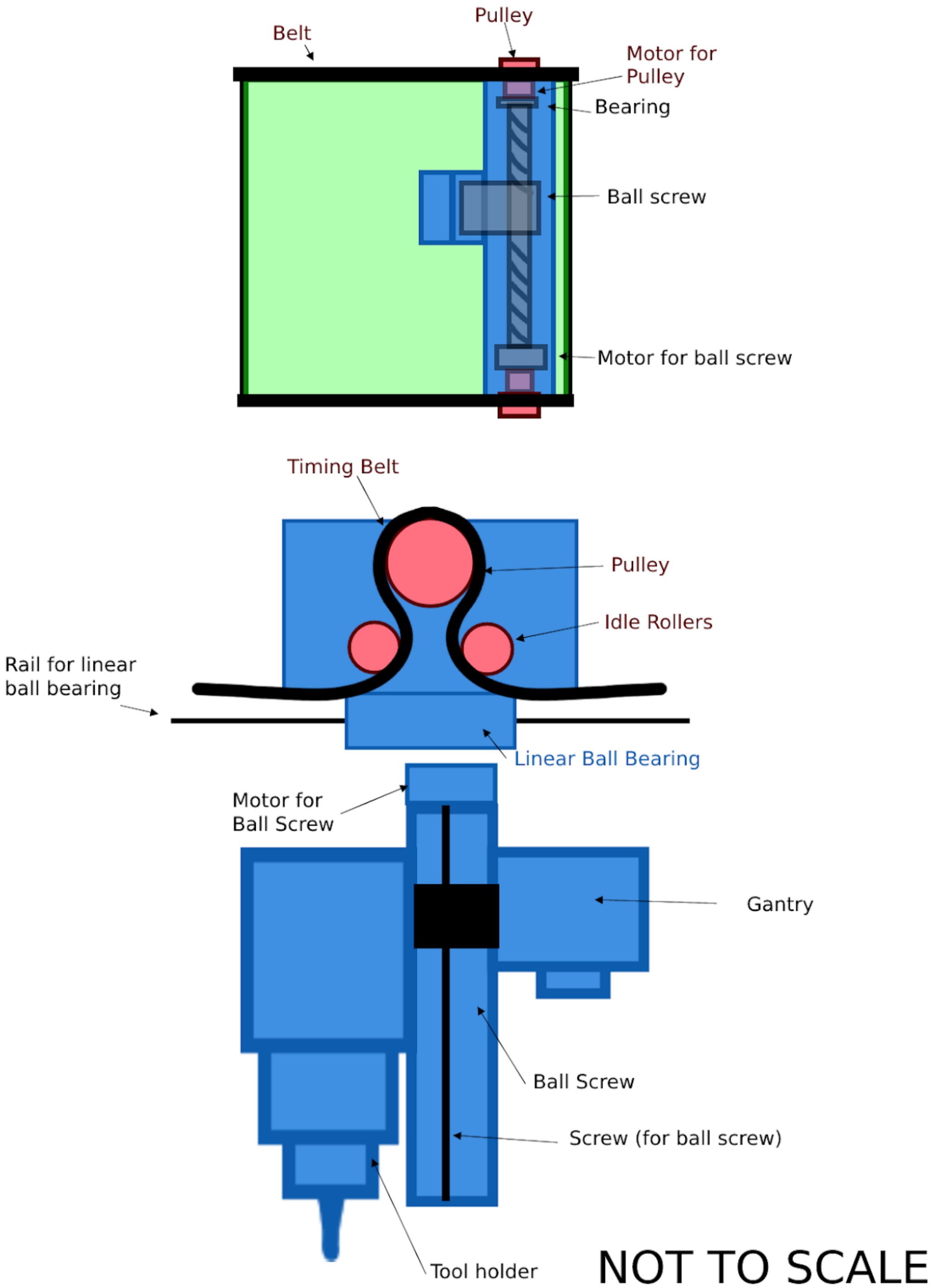


Figure 16 - Top view of Iterative Design 2, and isolated views of the rail system and z axis movement with the spindle. The movement along one of the axes has been changed to a timing belt.

8.3 Iterated Designs Comparison Against Engineering Specifications

Once again, after these designs have been sketched out, they must be compared to the engineering specifications. At this point, the comparison to the engineering specifications allows the team to choose the best design to move forward with in the project. Table 11 details the comparison to the engineering specifications.

Table 11 - Iterated Designs Compared to Engineering Specifications

Category	**Candidate Design A (Rack & Pinion + Gantry Tipper)**	**Candidate Design B: Mobile Platform 2**
Price Range	Reasonably within	Reasonably within
Weight	Within weight limits	Within weight limits
Permissible Working Materials	Can mill foam, plastics, wood, soft metals	Can mill foam, plastics, wood, soft metals
Maximum Machine Dimensions	500mm (x) by 600 mm (y) by 500 mm (z)	700 mm (x) by 500 mm (y) by 500 mm (z)
Minimum Working Area Size	350 mm (x) by 450 mm (y) by 200 mm (z)	350 mm (x) by 450 mm (y) by 200 mm (z)
Orientation	Vertical	Vertical
Axis	4	3.5 axis
Tool Swapping	Manual tool swapping.	Manual tool swapping.
Debris	Debris containment via enclosure and storage system.	Debris containment through removable cover.
Noise	Noise can be minimized with proper mechanism choices.	Noise can be minimized with proper mechanism choices.
Feed rate	Likely can be achieved, this would be further examined in detailed design.	Likely can be achieved, this would be further examined in detailed design.

Portability	Can operate on a regular desktop without specialized mounting.	Can operate on a regular desktop without specialized mounting.

9. Final Design

The final design of the CNC machine is a 4-axis gantry style milling machine based on the *Iterative Design 2,* but with a number of changes. In Figures 17 and 18, there are images of the CAD model and rendered model. More detail about the mechanisms, design choices, and material selections are detailed in the following sections.

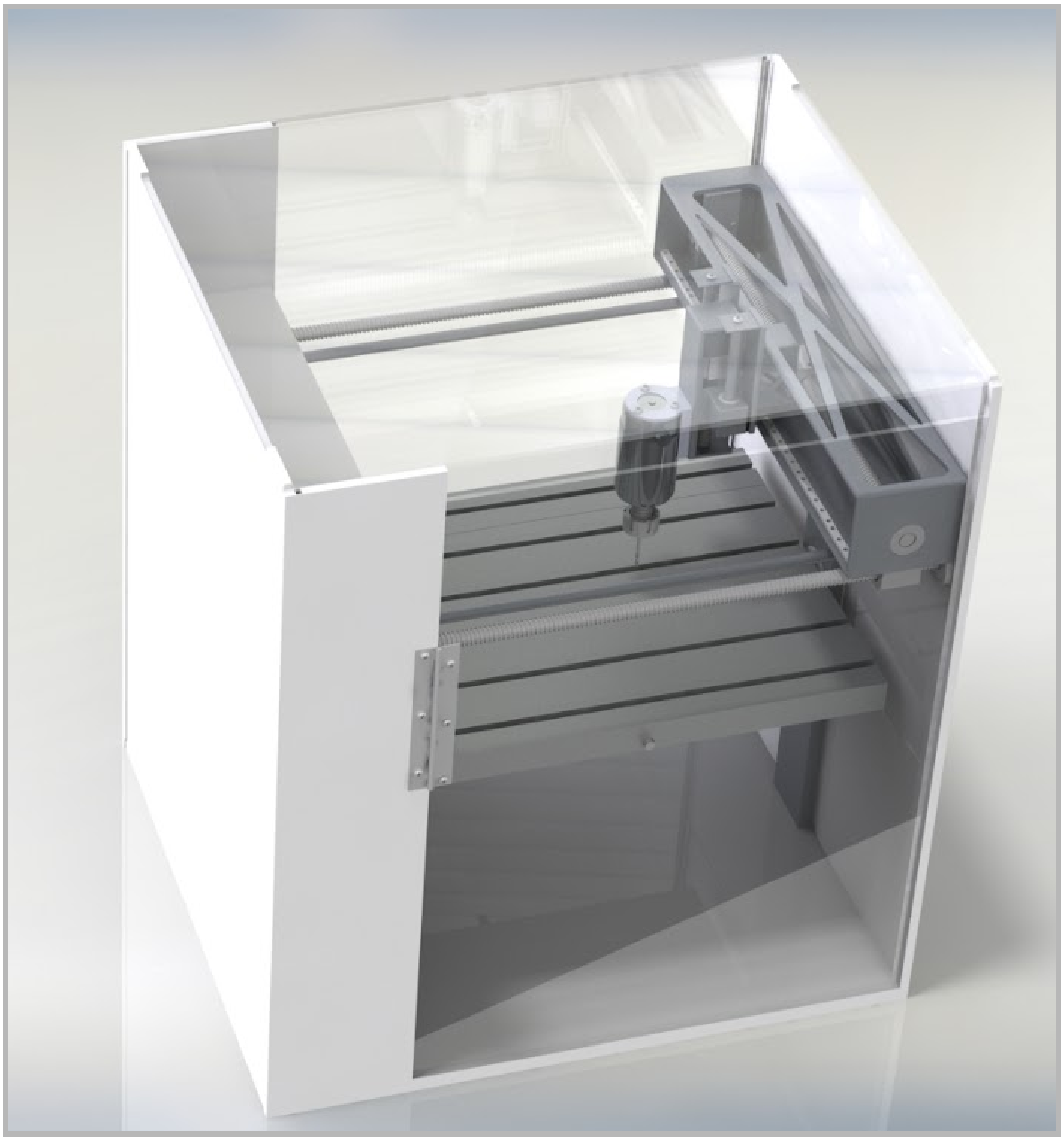


Figure 17 - Rendered CAD model of the CNC machine.

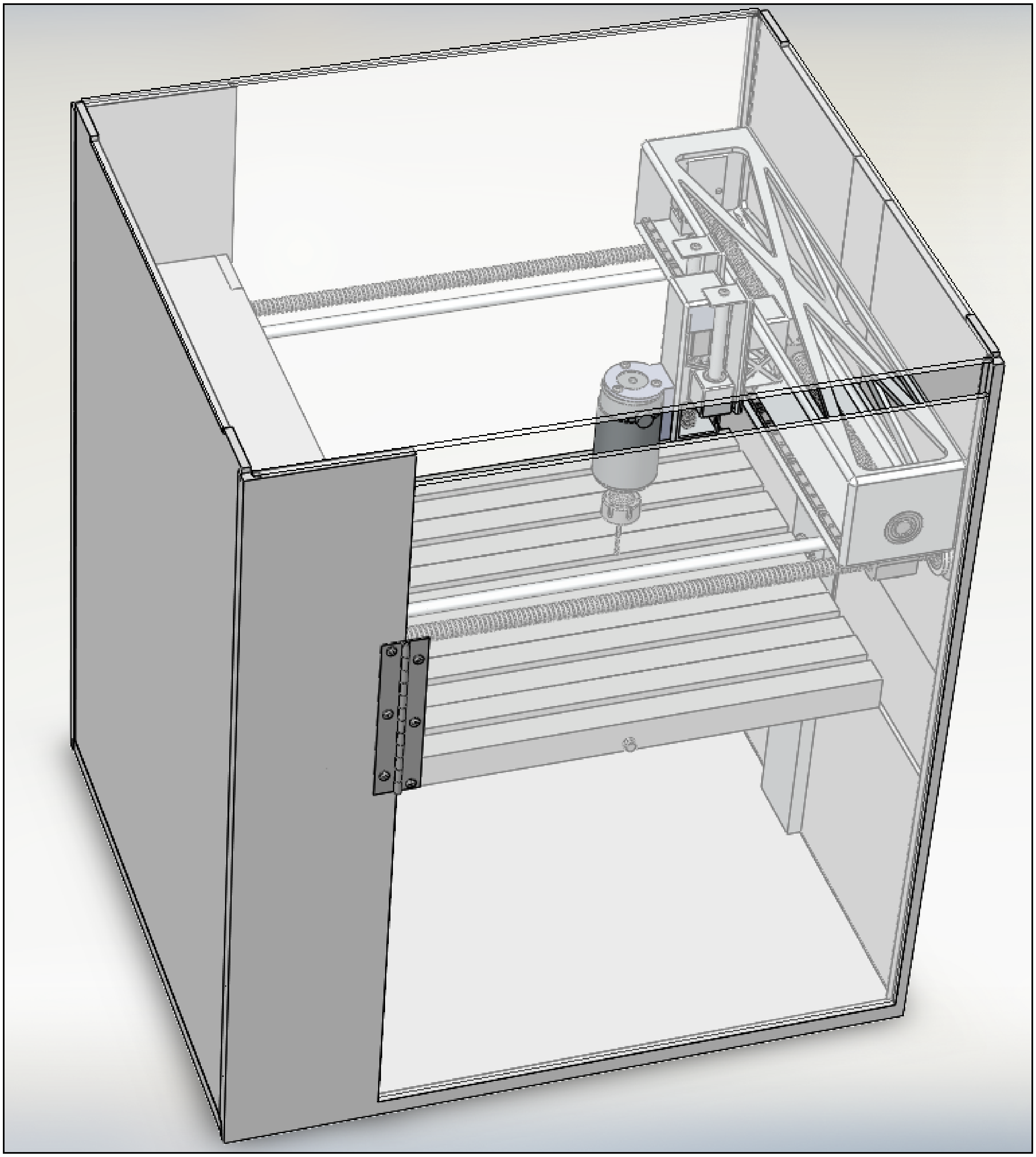


Figure 18 - CNC machine CAD model.

9.1 Description

Along the x, y, and z axis, the machine moves using ball screws. Ball screws were chosen due to their high level of positioning accuracy, low friction, and part standardization. In addition, stepper motors were chosen to drive the ball screws to further increase accuracy of the machine. The stepper motors controlling the ball screws are assumed to be connected to a 2:1 gear reduction system for the x and y axis, however it is important to note this is not visible in the CAD model, and the motors currently in the model are placeholders. The z axis is also a 2:1 speed reduction, powered by a motor with 2250 RPM, and a spindle with an RPM of 3000.

The fourth axis, which is a revolution around the x-axis and is also driven by a stepper motor for the same reason. The stepper motor selected had adequate torque, but there is still design flexibility and the option to select a motor with greater power. The table is attached to a worm wheel, which meshes to a worm gear connected to the motor. This allows the motor to drive the table's rotation without the table backdriving the motor.

One of the main issues encountered when designing for the fourth axis was how the milling of smaller material sizes could be achieved without the table intruding. In order to combat this issue, the table was designed to be modular, so that the width in the y direction could be adjusted to the approximate material size. Moreover, the tabletop has standard sized M6 t-slots which allow for the user to choose their own clamping system [20]. The user can remove and add more table sections/modules by opening the door of the machine and using the slide-up panels on the side to remove and add the parts.

Overall, the machine is mostly modular, and can be disassembled fairly easily. This was an intentional design choice to allow the user to diagnose issues and perform maintenance on the machine easily. While longevity of the parts was taken into consideration and the machine was designed to be robust, one cannot truly predict the issues that may occur. Therefore, it was an important decision to ensure that the machine was modular to allow for easy repairs by the user.

As seen in the new design model, some aspects have changed from the candidate design. These design choices are relatively small, but overall improve the quality of the design. The clamping system was changed to be more standardized, and the top of the machine is covered to ensure safe operation. However, the idea of workspace transparency was carried through, and acrylic panels are used in the tops and sides of the machine to allow for high visibility of the workspace. This is important as non-industrial milling machines may not often be used for mass/repetitive production. As a result, it is important that the user is able to see the milling operation clearly, since one time milling jobs can be experimental and require close observation.

9.2 Design Choices

Overall, the final design was generally similar to the candidate designs it was derived from. However there were some changes that need to be addressed and explained. Moreover, the final mechanisms that were chosen for the design were done so for specific reasons, which are explained in Tables 12 to 14.

Table 12 - Major Changes from the Candidate Design

Mechanism/Feature	Purpose and Justifications
Ball screw replacing belt	After a meeting with the TA, it was decided that the axis movement controlled by the belt would be changed to ball screws. Since both the x and y axis are planar axes, it is important that the level of accuracy between these two axes was the same. While ball screws are more expensive, it is the better choice in terms of longevity and robustness, thus the choice of ball screws over belts.
Table clamps removed	The table clamps used in the “3 Rack and Pinion” design were originally planned to be used in the final design. However, upon further discussion and iterations, it was decided that this specialized mechanism was not required. Instead, a much more standardized t slot table configuration is used to allow the user more flexibility in choosing clamping mechanisms.
Gearbox placement	The gear box has been moved inside the machine to keep the overall design more compact. This design choice was made in order to reduce the amount of desk space used and to ensure the vital machine components were secure from the outside environment.

Table 13 - Shell Mechanisms/Features

Mechanism/Feature	Purpose and Justifications
Removable Wall	A simple design where one of the walls along the y-axis is inserted into the metal frame from the top. The metal frame is closed at the bottom but the top remains uncapped, allowing for the wall to slide up and out of the frame whenever needed. The purpose of this feature is to help the user to attain more access to the working areas and make any adjustments needed.
Door	The other shell wall along the y-axis can be opened and closed like a door due to a hinge mechanism. The purpose of this mechanism is the same as that of the removable wall.
Two Sliding	These two small slits are capable of sliding up into the main wall giving access to the table. The sides of the table can then slide out.

Table 14 - Rotating Table Mechanisms/Features

Mechanism/Feature	Purpose and Justifications
Worm Gears	The table will need to transmit a large amount of torque because it needs to be able to rotate and support the forces from the table and the material that needs to be cut. Thus, worm gears were selected as they can transmit large amounts of torque and are unidirectional which will ensure accurate positioning. It is a 40:1 speed reduction.
Stepper Motors + Support	Since precision is needed, a stepper motor was selected over a servo motor for cost purposes. The motor is supported by a bracket as well as screwed into the gearbox housing.
Shaft + Couplers	The worm and worm gear is attached to its shaft through square keys which is ideal for medium to high torque applications. The worm shaft and the motor shaft have a rigid coupling; it can transmit high torque and there is no designed angular or parallel misalignment.
Bearings	All ball bearings are shielded to prevent debris and are press-fit into the housing. Ball bearings are also cost efficient.

Spacers + Collars	Spacers and collars are used to maintain the position of the gears.

Table 15 - Gantry Mechanisms/Features

Mechanism/Feature	Purpose and Justification
Linear Bearings + Rails	The linear ball bearings and rails were chosen since they fit the gantry well and are easy to connect to the shell. In addition, two rails were needed to properly support the gantry motion, so this cheap guide rail system was the ideal mechanism choice.
Ball Screw + Step Motor	Ball screws were used in two axes of motion (x and y) to ensure consistent accuracy, and part standardization.
Inner Guide Rail + Carriage	The inner guide rail and carriage type was chosen for its flat profile and low cost. The spindle connecter and spindle are relatively light, so this guide rail, although it is low profile, is still sufficient support.

Table 16 - Z axis Mechanisms/Features

Mechanism/Feature	Purpose and Justification
Ball Screw + Motor	The step motor rotates to provide an accurate method of linear motion.
Linear Bearings + Rails	The rails provide motion support to the spindle assembly as it translates in the z-axis. The rails were mounted on an H-shaped platform attached to a platform between the gantry horizontal ball screw and the spindle vertical ball screw.
Nut + Collet Chuck	The collet chuck sits between the threaded rod and an adjustable nut (with an opening exposing the top of the collet chuck). When

	the nut is tightened on the rod, the pressure exerted on the chuck causes it to contract, and enables it to firmly grasp tool bits of a variety of sizes.
Spindle Motor	The spindle motor sacrificed accuracy for power and torque compared to the step motor, and it was selected to fit the size constraints imposed by the other components of the finished CNC machine.

9.3 Technical Drawings

The following section displays assembly and part drawings of the design.

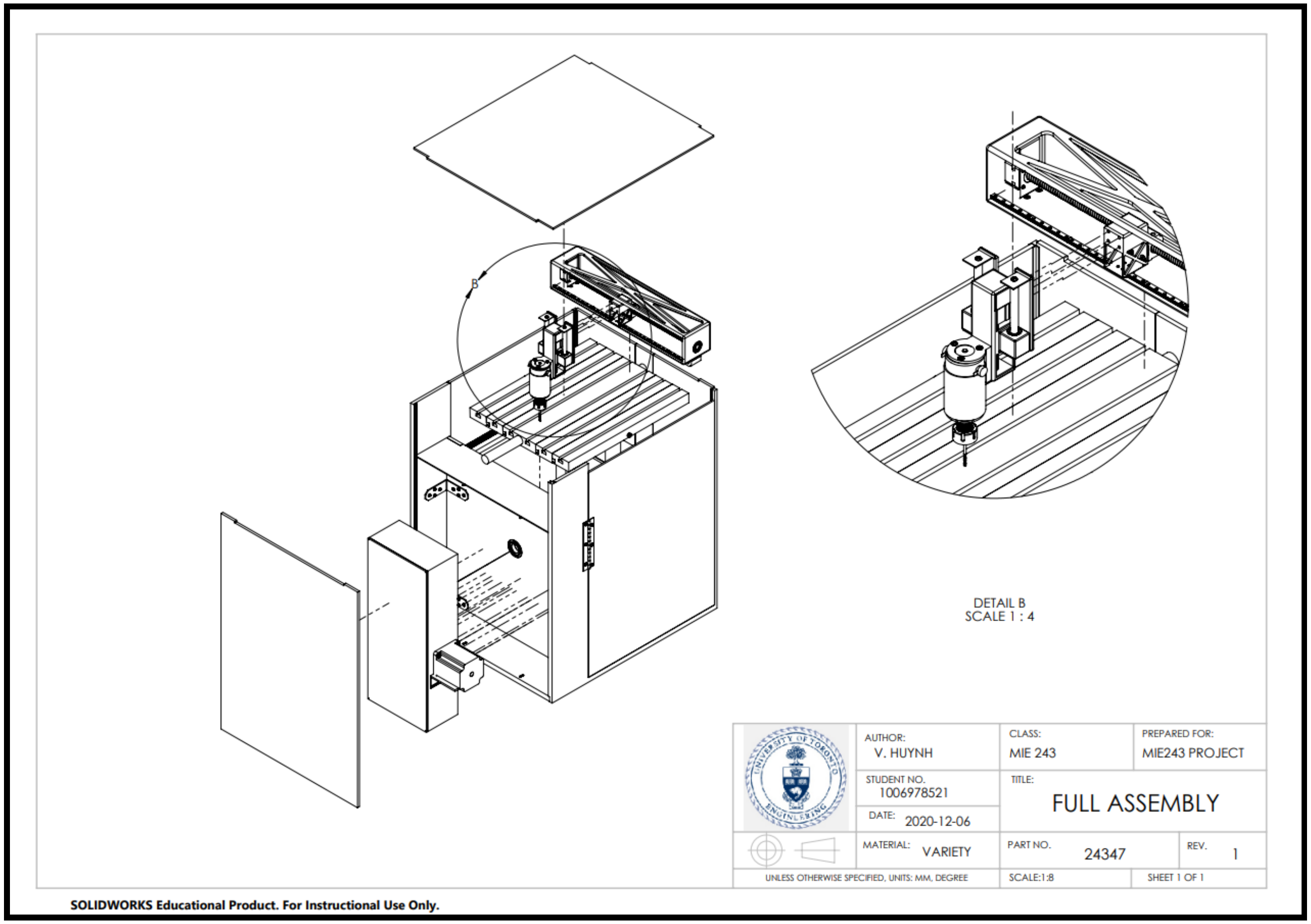


Figure 19 - Full assembly drawing, more detailed parts drawing below.

Shell Components

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	24347A1	FRONT ALUMINUM WALL	1
2	24347A2	ALUMINUM FRAME	1
3	24347A3	GANTRY ALUMINUM GUIDERAIL	2
4	24347B1	ALUMINUM BOTTOM BACK WALL	1
5	243474	REMOVABLE ACRYLIC SIDE WALL	1
6	24347A5	ACRYLIC BASE	1
7	24347A6	ALUMINUM SHAFT SUPPORT BACK WALL	1
8	24347A7	ACRYLIC SIDE DOOR	1
9	1586A34	SURFACE-MOUNT HINGE WITH HOLES	2
10	1586A34	SURFACE-MOUNT HINGE CONNECTING ROD	1
11	24347A8	ACRYLIC LID	1
12	6624K69	BALL SCREW	2
13	2349K414	PERMANENTLY LUBRICATED BALL BEARING	2
14	91772A192	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW, 8-32 THREAD, 3/8" LONG	6
15	91772A205	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW, 8-32 THREAD, 2" LONG	2
16	91771A205	PASSIVATED 18-8 STAINLESS STEEL PHILLIPS FLAT HEAD SCREW, 82 DEGREE COUNTERSINK, 8-32 THREAD, 2" LONG	2
17	24347B3	ACRYLIC SLIDING BACK WALL	2
18	24347B2	ALUMINUM SHELLED RIGHT TOP WALL	1
19	24347B5	ALUMINUM SHELLED LEFT TOP WALL	1
20	24347B4	SHAFT SUPPORT FRONT WALL	1

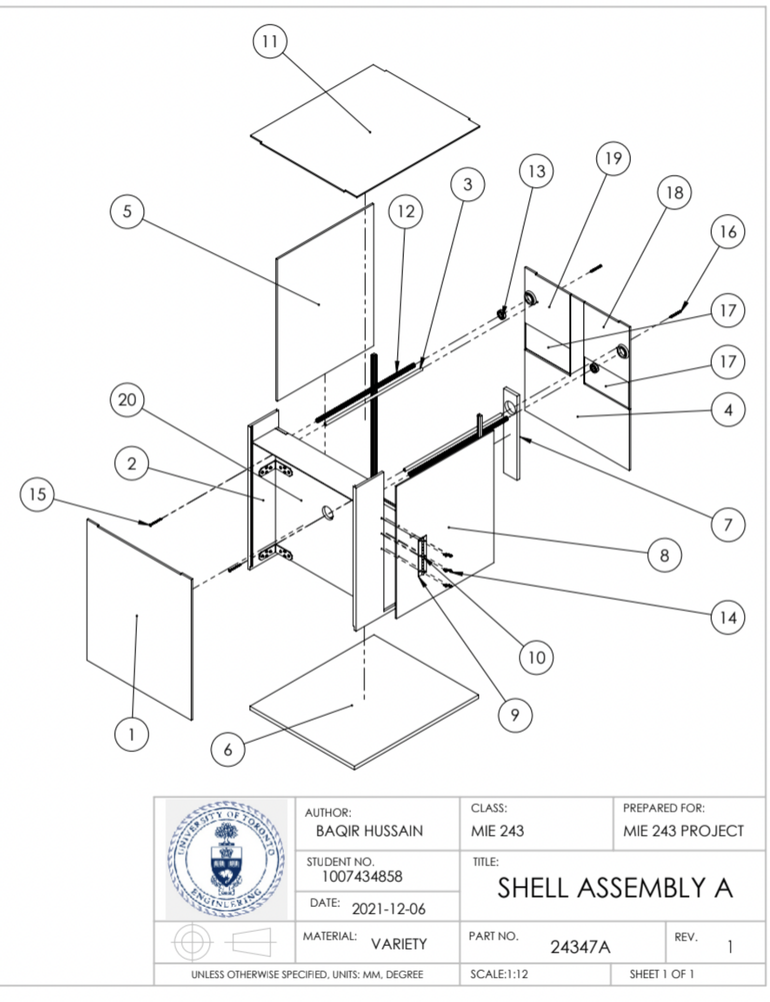
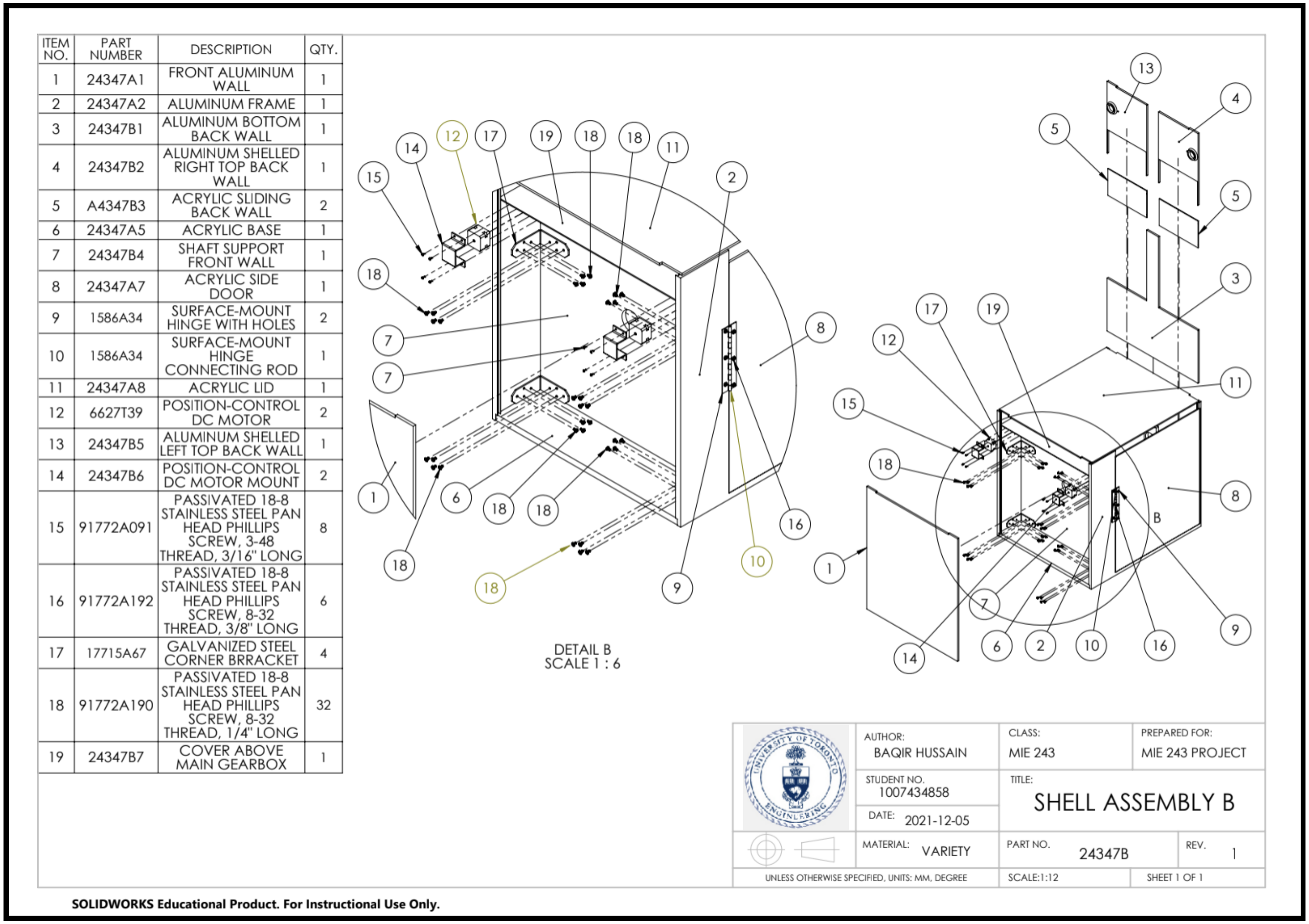


Figure 20 - Shell assembly part A.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	24347A1	FRONT ALUMINUM WALL	1
2	24347A2	ALUMINUM FRAME	1
3	24347B1	ALUMINUM BOTTOM BACK WALL	1
4	24347B2	ALUMINUM SHELLED RIGHT TOP BACK WALL	1
5	A4347B3	ACRYLIC SLIDING BACK WALL	2
6	24347A5	ACRYLIC BASE	1
7	24347B4	SHAFT SUPPORT FRONT WALL	1
8	24347A7	ACRYLIC SIDE DOOR	1
9	1586A34	SURFACE-MOUNT HINGE WITH HOLES	2
10	1586A34	SURFACE-MOUNT HINGE CONNECTING ROD	1
11	24347A8	ACRYLIC LID	1
12	6627T39	POSITION-CONTROL DC MOTOR	2
13	24347B5	ALUMINUM SHELLED LEFT TOP BACK WALL	1
14	24347B6	POSITION-CONTROL DC MOTOR MOUNT	2
15	91772A091	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW, 3-48 THREAD, 3/16" LONG	8
16	91772A192	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW, 8-32 THREAD, 3/8" LONG	6
17	17715A67	GALVANIZED STEEL CORNER BRRACKET	4
18	91772A190	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW, 8-32 THREAD, 1/4" LONG	32
19	24347B7	COVER ABOVE MAIN GEARBOX	1

Figure 21 - Shell assembly part B.

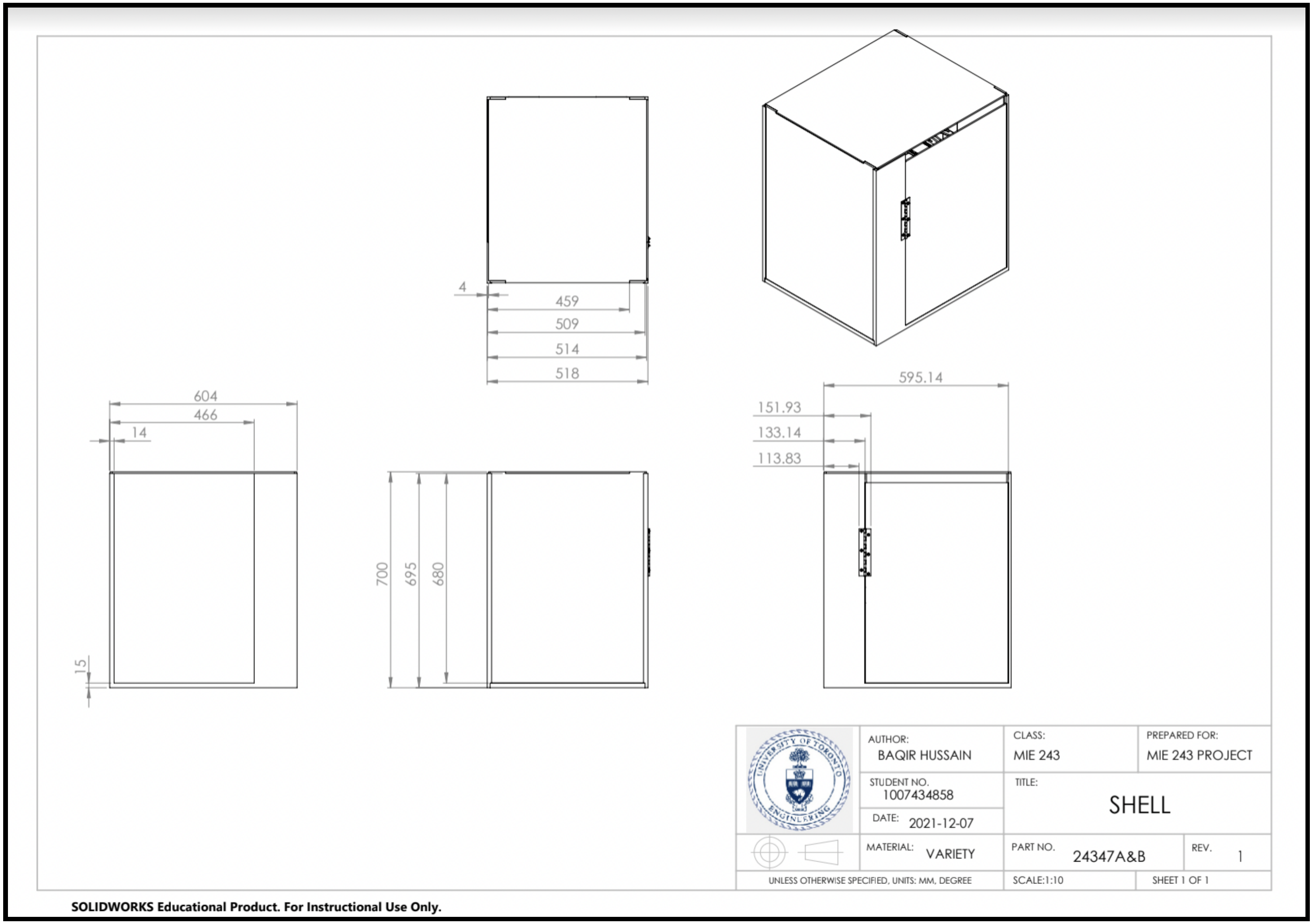
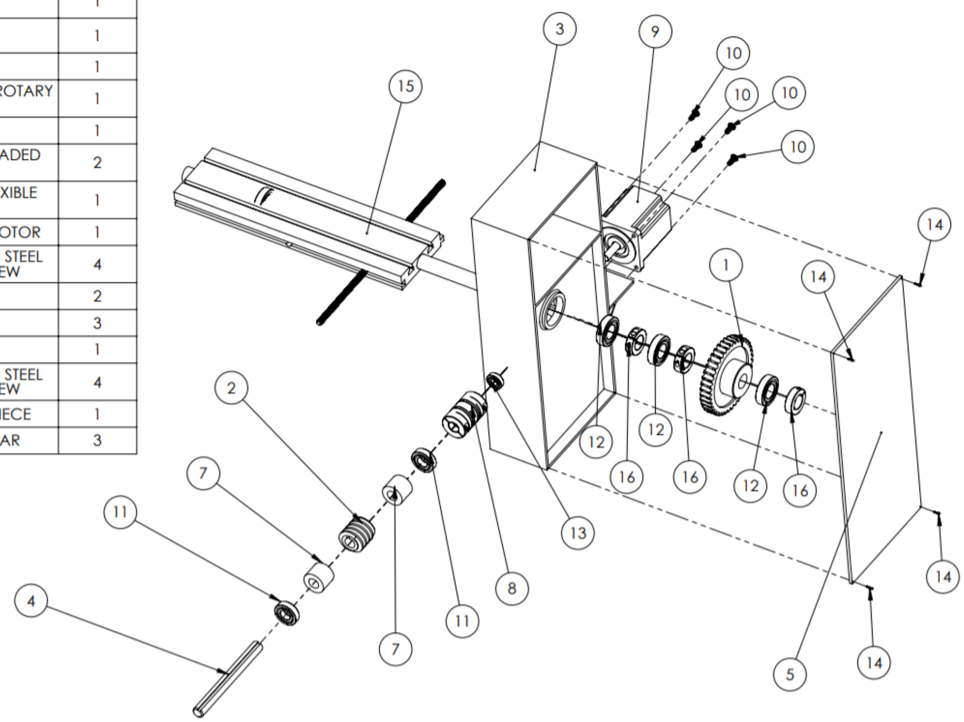


Figure 22 - Shell part drawing.

Modular Gearbox Component

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	57545K315_METAL WORM GEAR	METAL WORM GEAR	1
2	57545K327_METAL WORM	METAL WORM	1
3	24347C1	TABLE GEAR BOX	1
4	1497K116	1045 CARBON STEEL KEYED ROTARY SHAFT	1
5	24347C2	GEAR BOX COVER	1
7	94639A964	OFF-WHITE NYLON UNTHREADED SPACER	2
8	6208K696	CLAMPING PRECISION FLEXIBLE SHAFT COUPLING	1
9	6627T57	POSITION-CONTROL DC MOTOR	1
10	91772A539	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	4
11	60355K603	BALL BEARING	2
12	60355K605	BALL BEARING	3
13	60355K601	BALL BEARING	1
14	91772A057	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	4
15	24347D1	MODULAR TABLE CORE PIECE	1
16	6435K18	CLAMPING SHAFT COLLAR	3



AUTHOR: CRYSTAL JIN
CLASS: MIE 243
PREPARED FOR: MIE243 PROJECT
STUDENT NO. 1006998867
DATE: 2021-12-05
TITLE: TABLE GEAR BOX ASSEMBLY
MATERIAL: VARIETY
PART NO. 24347C
REV. 1
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE
SCALE 1:6
SHEET 1 OF 1

Figure 23 - Assembly for Modular Table Gearbox

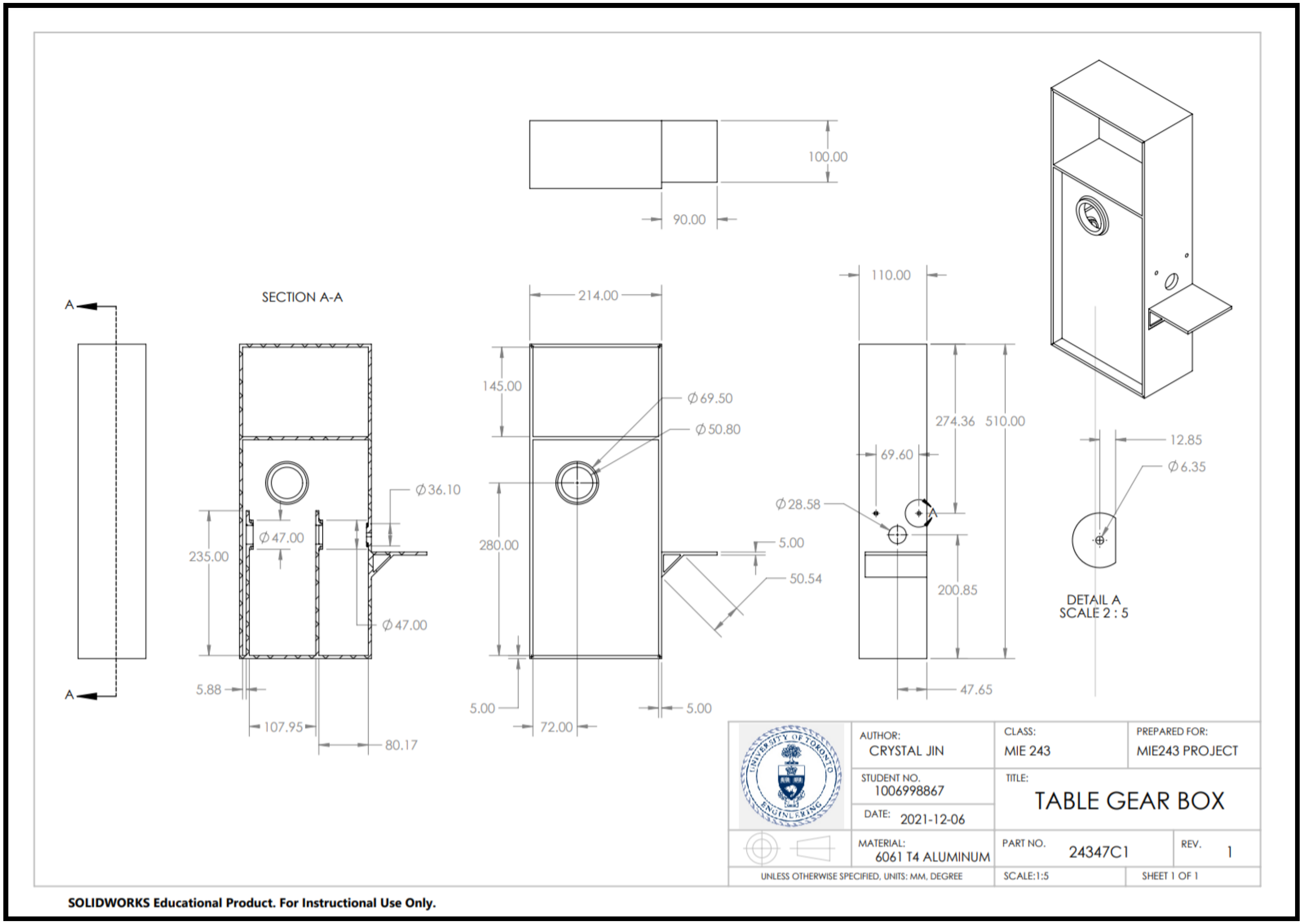


Figure 24 - Gearbox for Modular Table

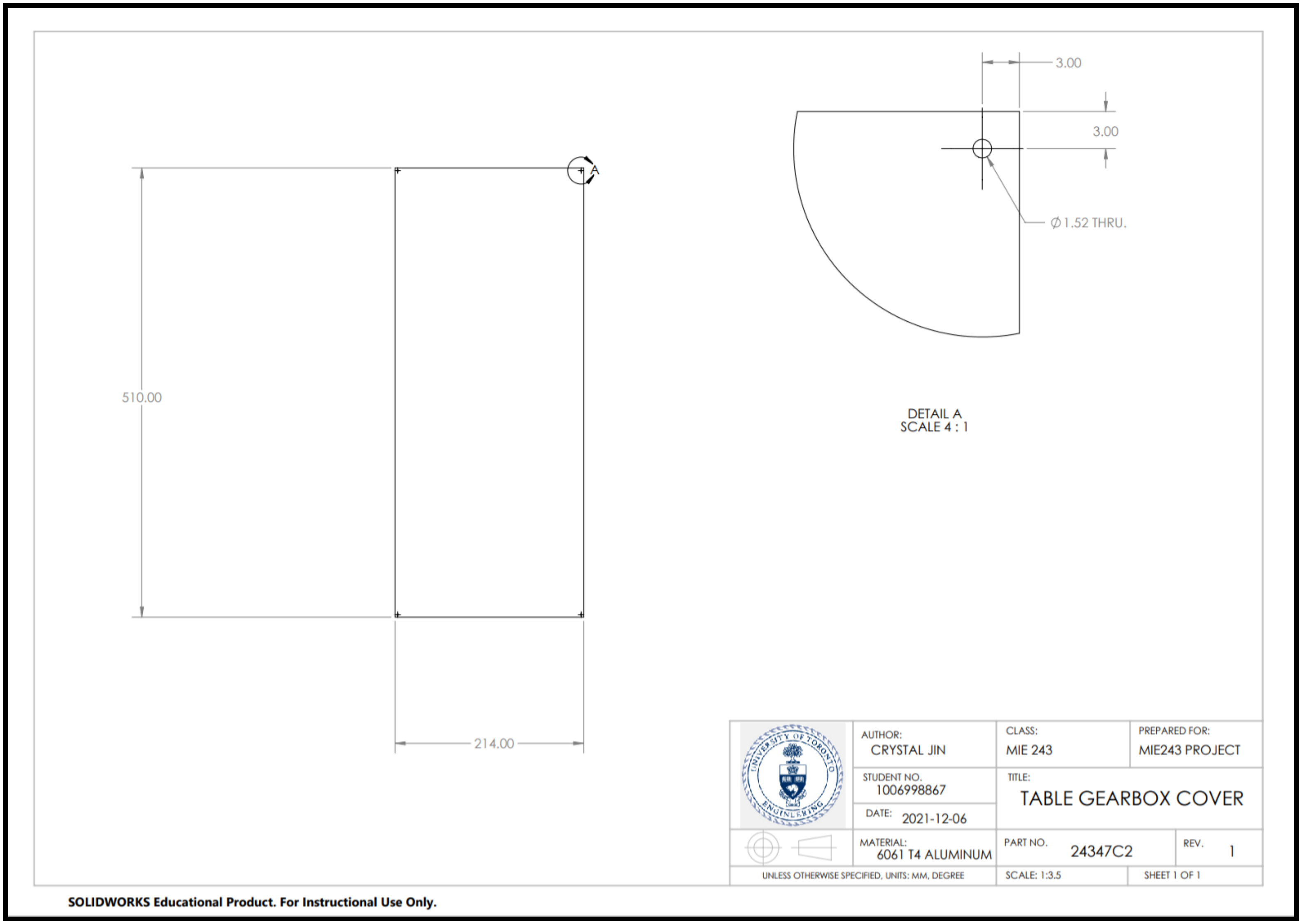
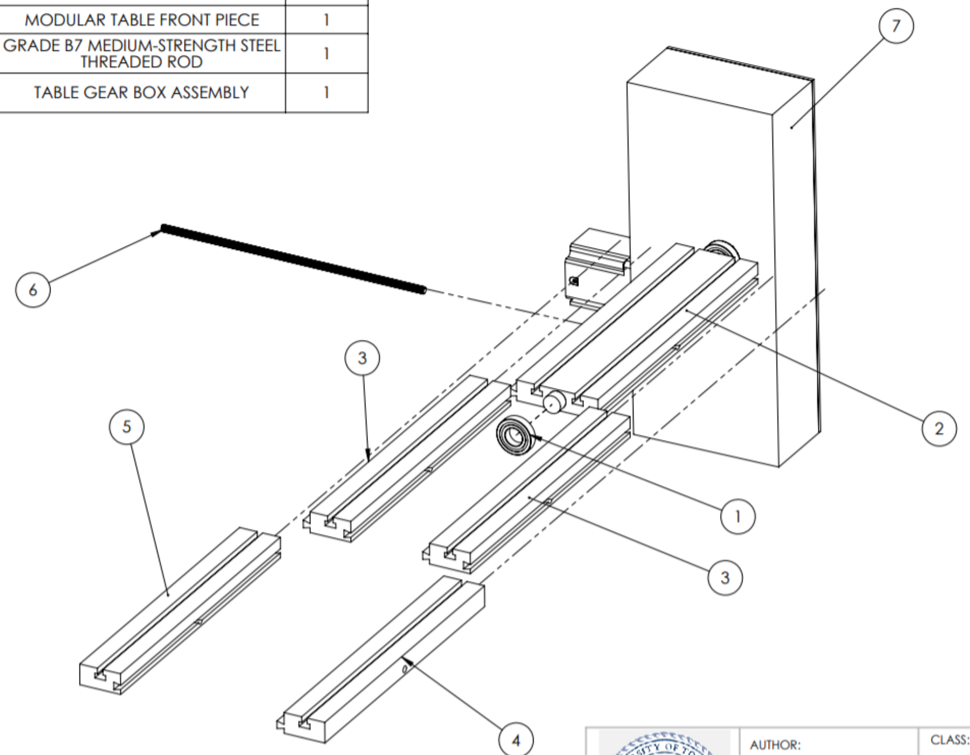


Figure 25 - Gearbox Cover for Modular Table

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	60355K605	BALL BEARING	1
2	24347D1	MODULAR TABLE CORE PIECE	1
3	24347D2	MODULAR TABLE REGULAR PIECE	2
4	24347D3	MODULAR TABLE BACK PIECE	1
5	24347D4	MODULAR TABLE FRONT PIECE	1
6	98957A133	GRADE B7 MEDIUM-STRENGTH STEEL THREADED ROD	1
7	24347C	TABLE GEAR BOX ASSEMBLY	1



AUTHOR: CRYSTAL JIN	CLASS: MIE 243	PREPARED FOR: MIE243 PROJECT	
STUDENT NO. 1006998867	TITLE: MODULAR TABLE ASSEMBLY		
DATE: 2021-12-06			
MATERIAL: VARIETY	PART NO. 24347D	REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE	SCALE: 1:5	SHEET 1 OF 1	

Figure 26 - Modular Table Assembly

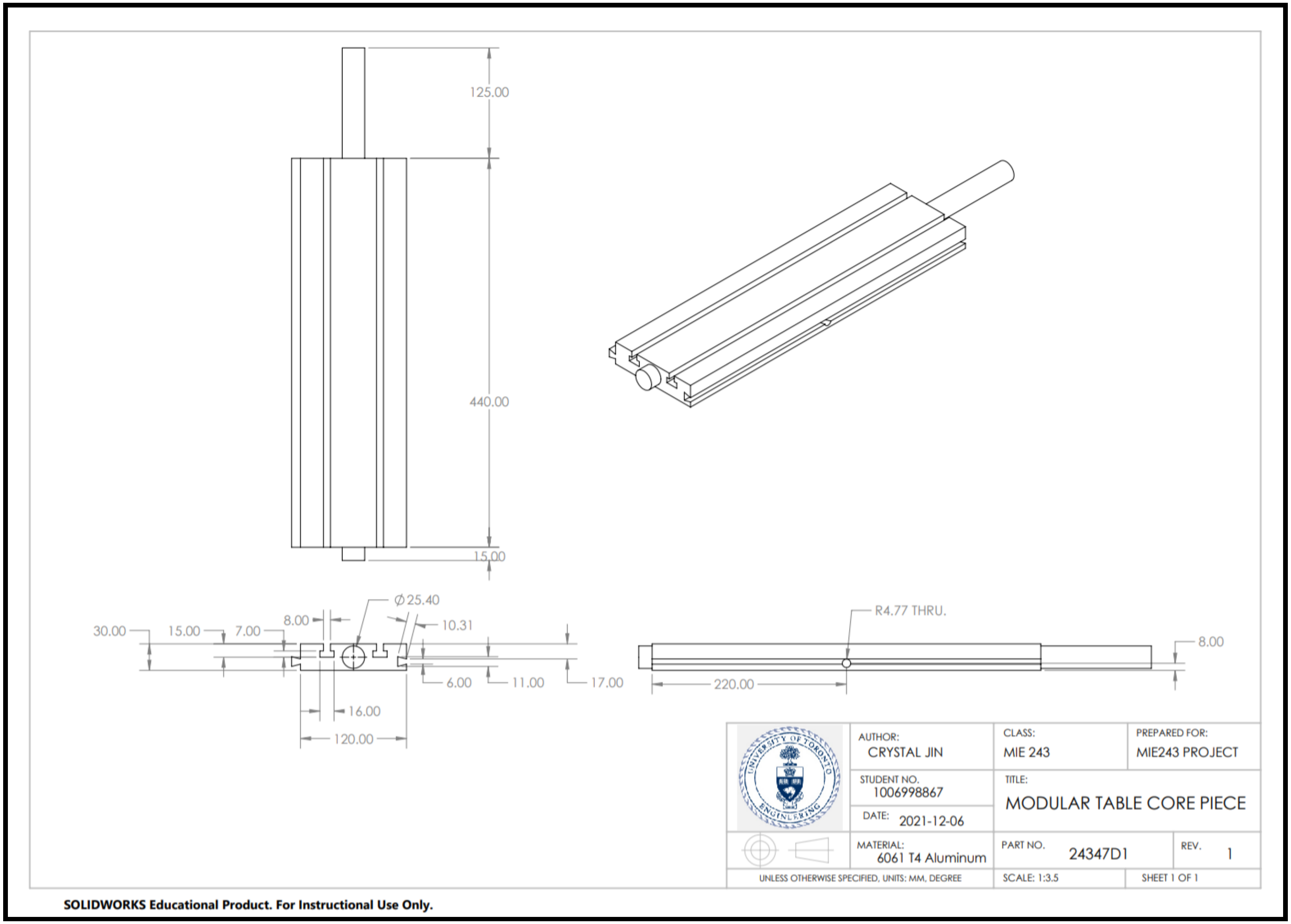


Figure 27 - Modular Table Core Piece

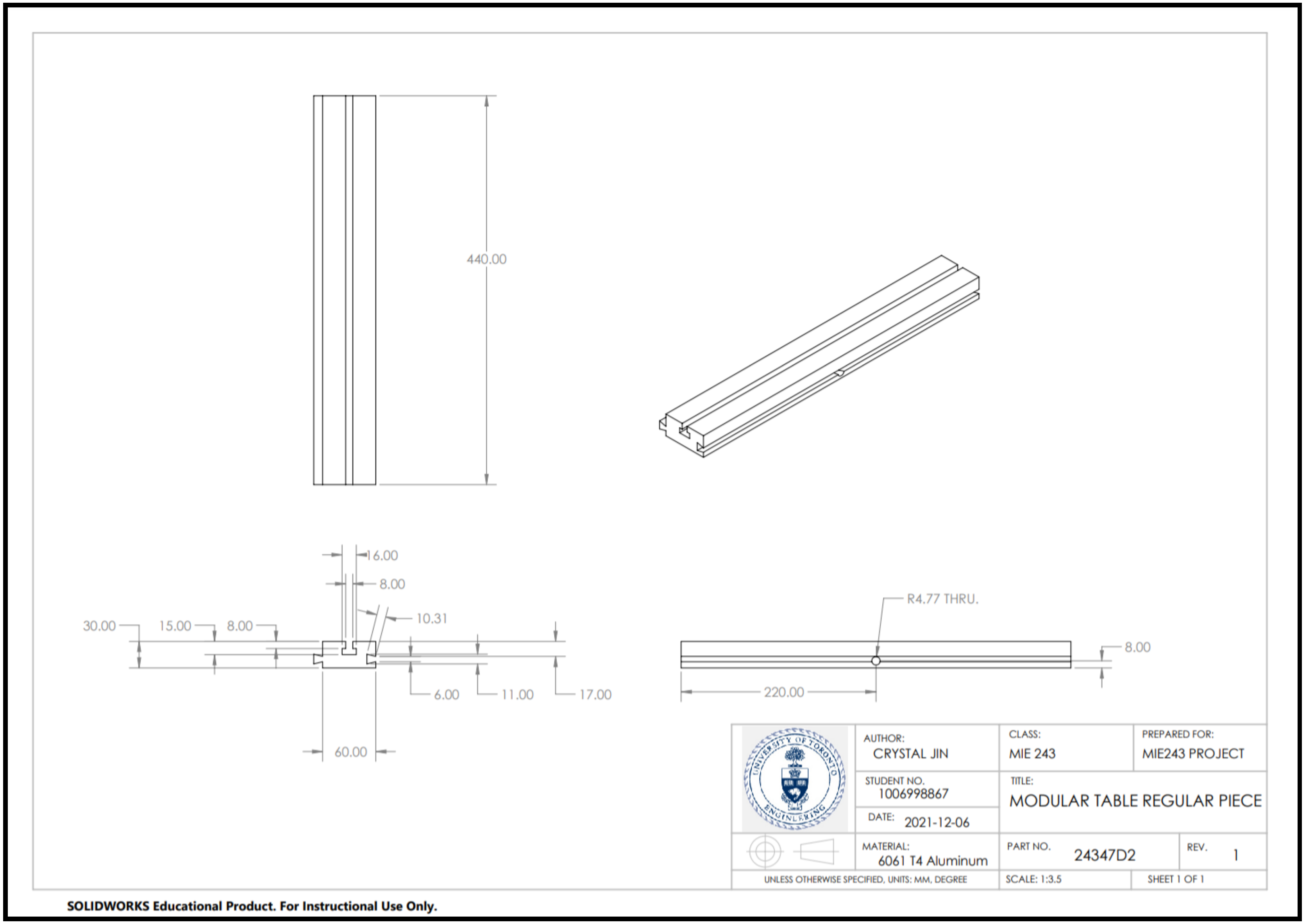


Figure 28 - Modular Table Regular Piece

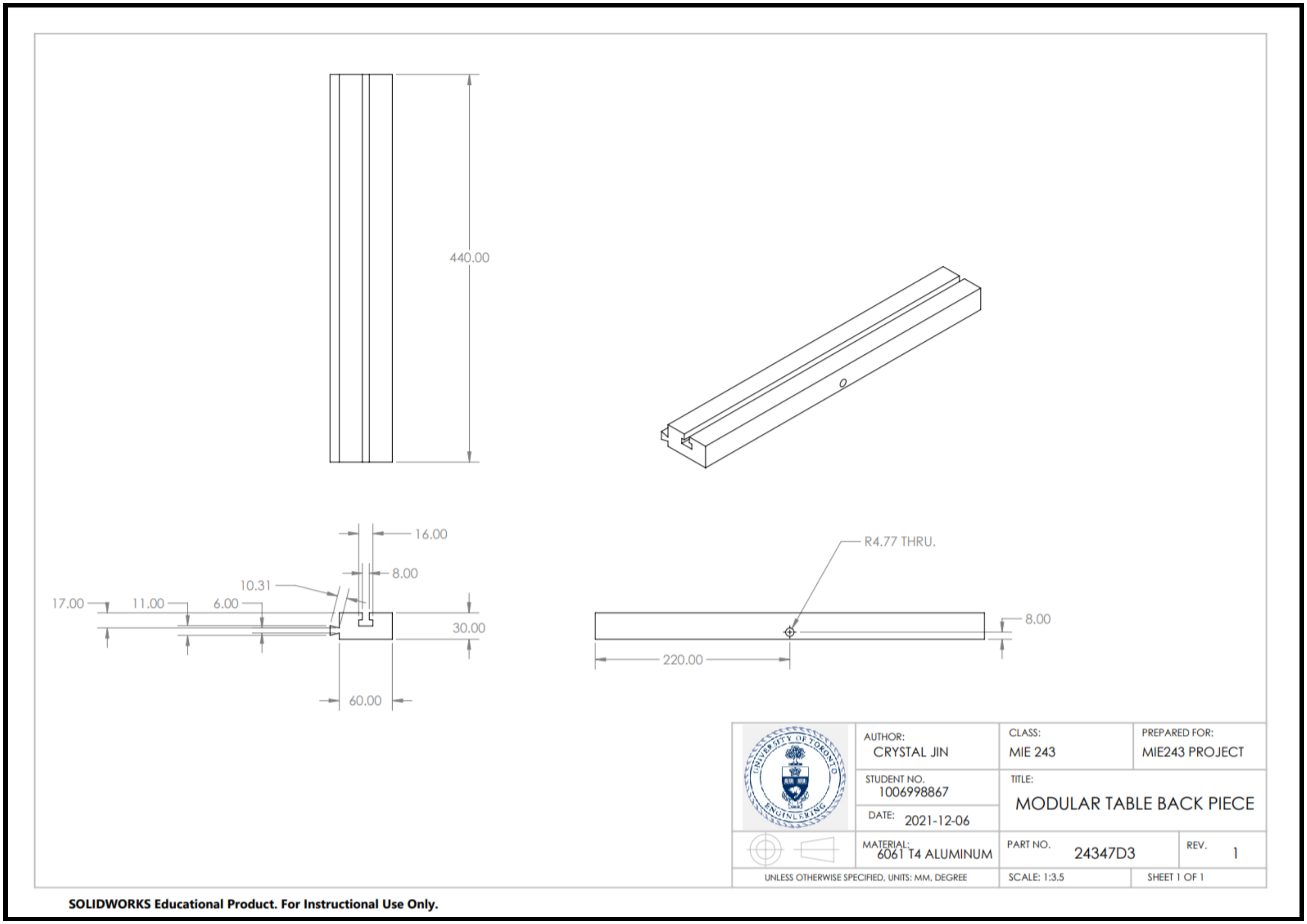


Figure 29 - Modular Table Back Piece

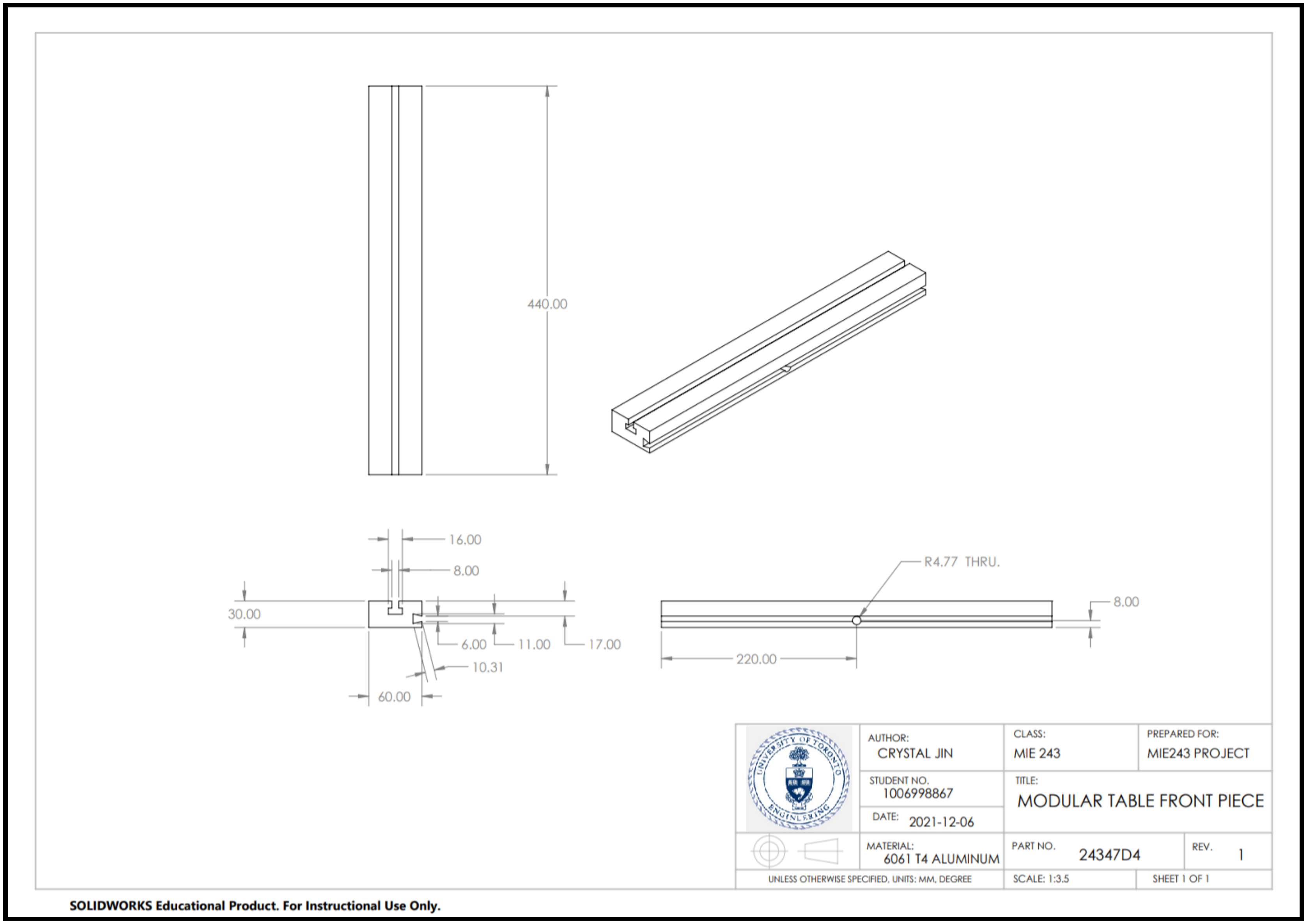
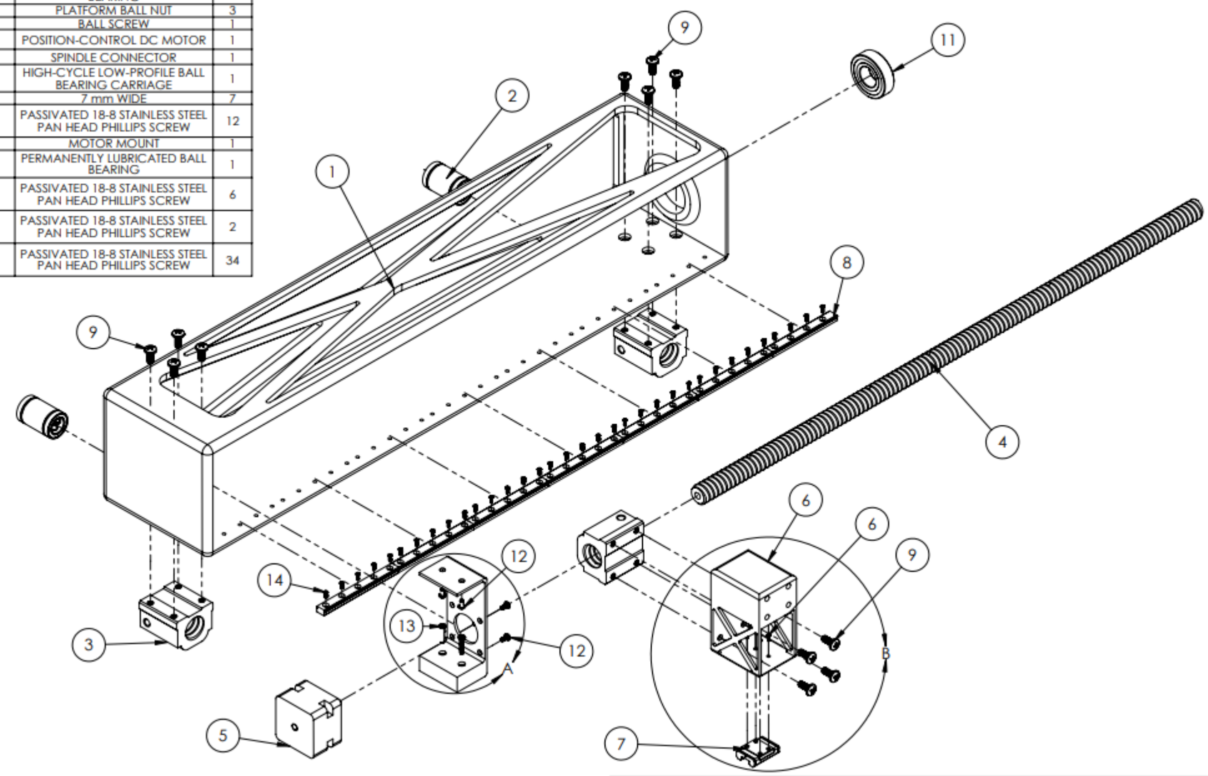


Figure 30 - Modular Table Front Piece

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	24347E1	GANTRY	1
2	3766N15	FIXED ALIGNMENT LINEAR BALL BEARING	2
3	6624K73	PLATFORM BALL NUT	3
4	6624K69	BALL SCREW	1
5	6627T39	POSITION-CONTROL DC MOTOR	1
6	24347E2	SPINDLE CONNECTOR	1
7	7917N11	HIGH-CYCLE LOW-PROFILE BALL BEARING CARRIAGE	1
8	7917N28	7 mm WIDE	7
9	91772A192	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	12
10	24347E3	MOTOR MOUNT	1
11	2349K414	PERMANENTLY LUBRICATED BALL BEARING	1
12	91772A091	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	6
13	91772A096	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	2
14	91772A051	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	34



AUTHOR: V. HUYNH	CLASS: MIE 243	PREPARED FOR: MIE243 PROJECT	
STUDENT NO. 1006978521	TITLE: GANTRY ASSEMBLY		
DATE: 2020-12-06			
MATERIAL: VARIETY	PART NO. 24347E	REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE	SCALE:2:5	SHEET 1 OF 2	

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Figure 31 - Full assembly of all the gantry parts.

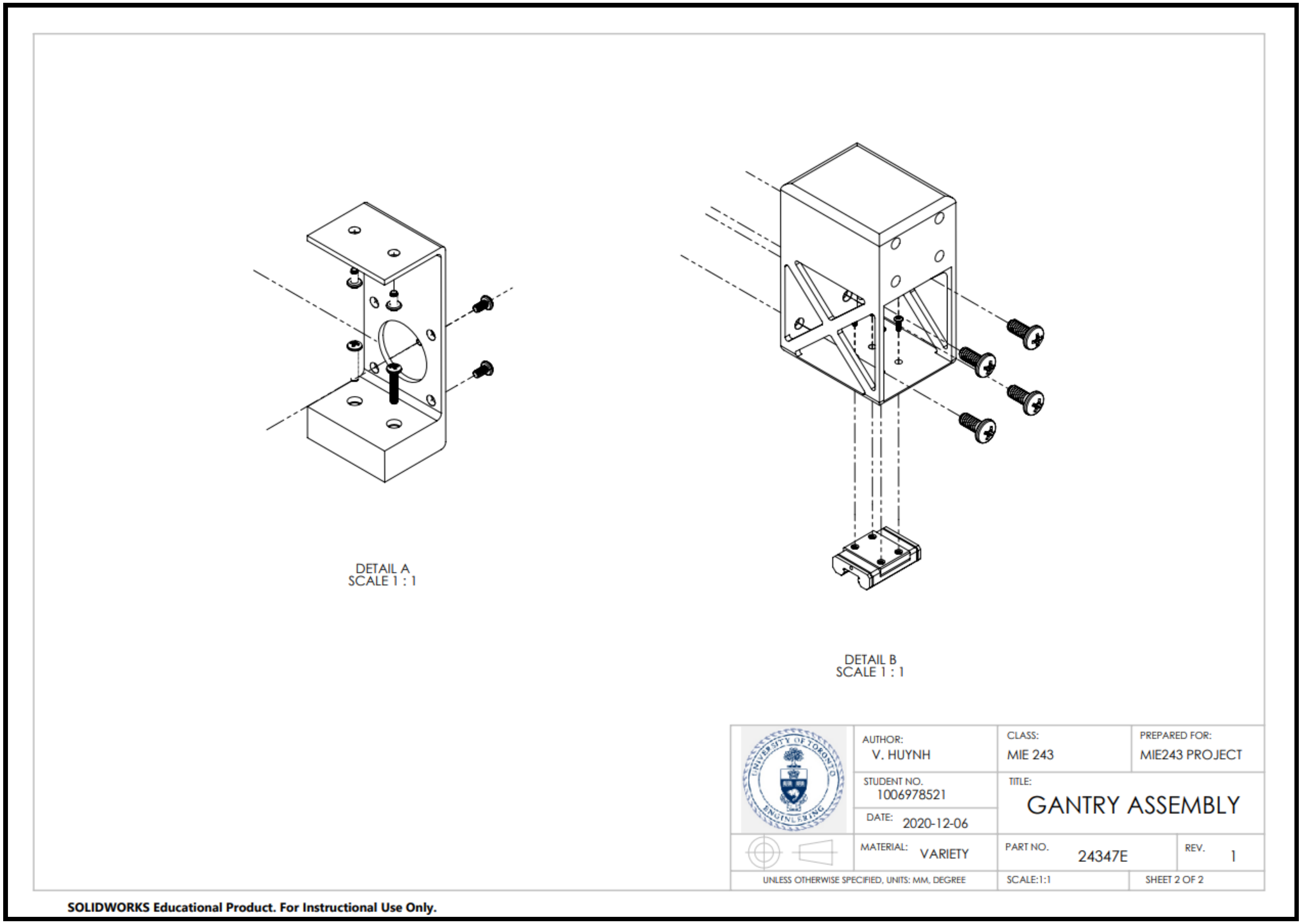


Figure 32 - Sheet 2 of the full gantry assembly, it covers the detailed views of sheet 1.

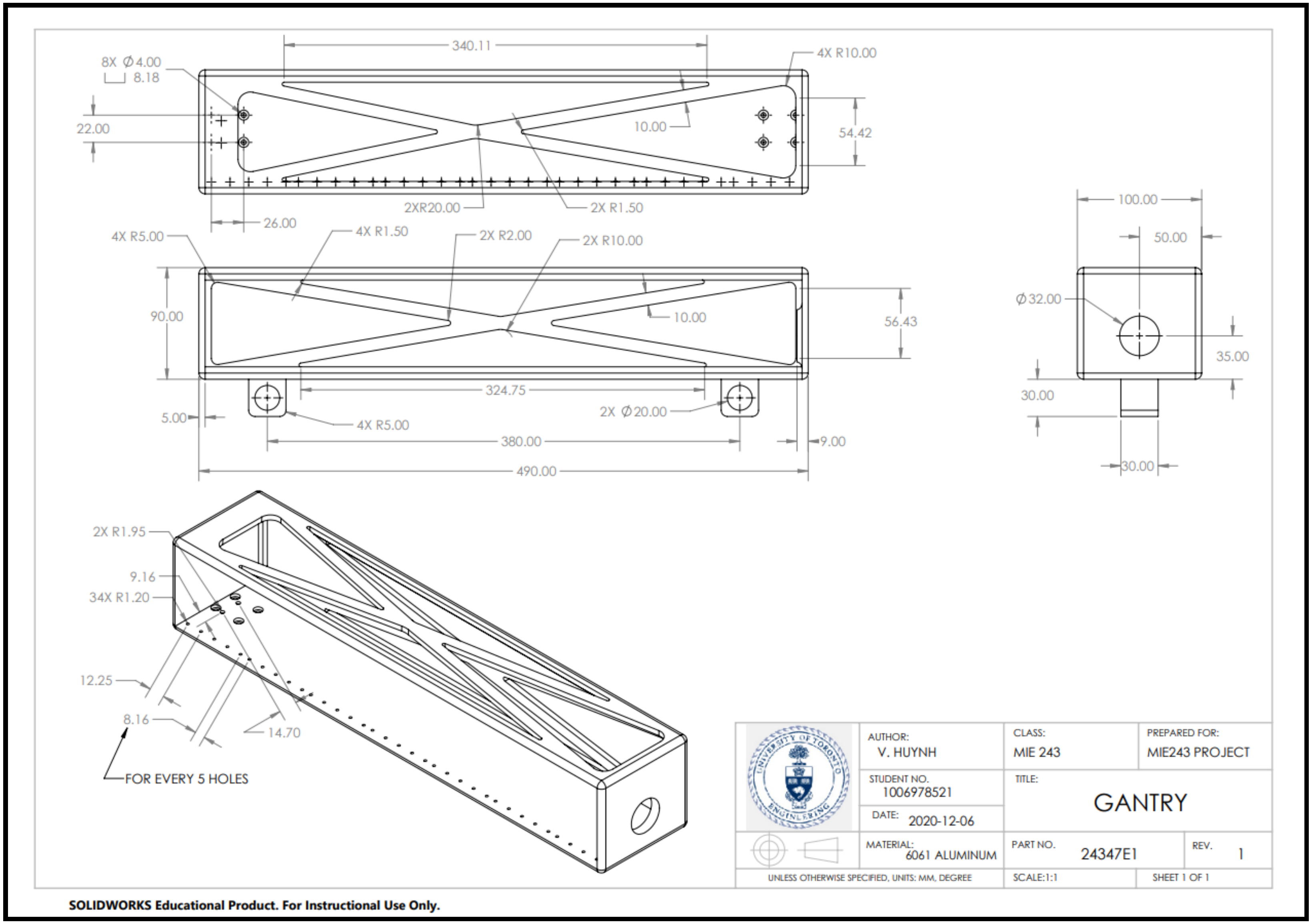


Figure 33 - Gantry part drawing.

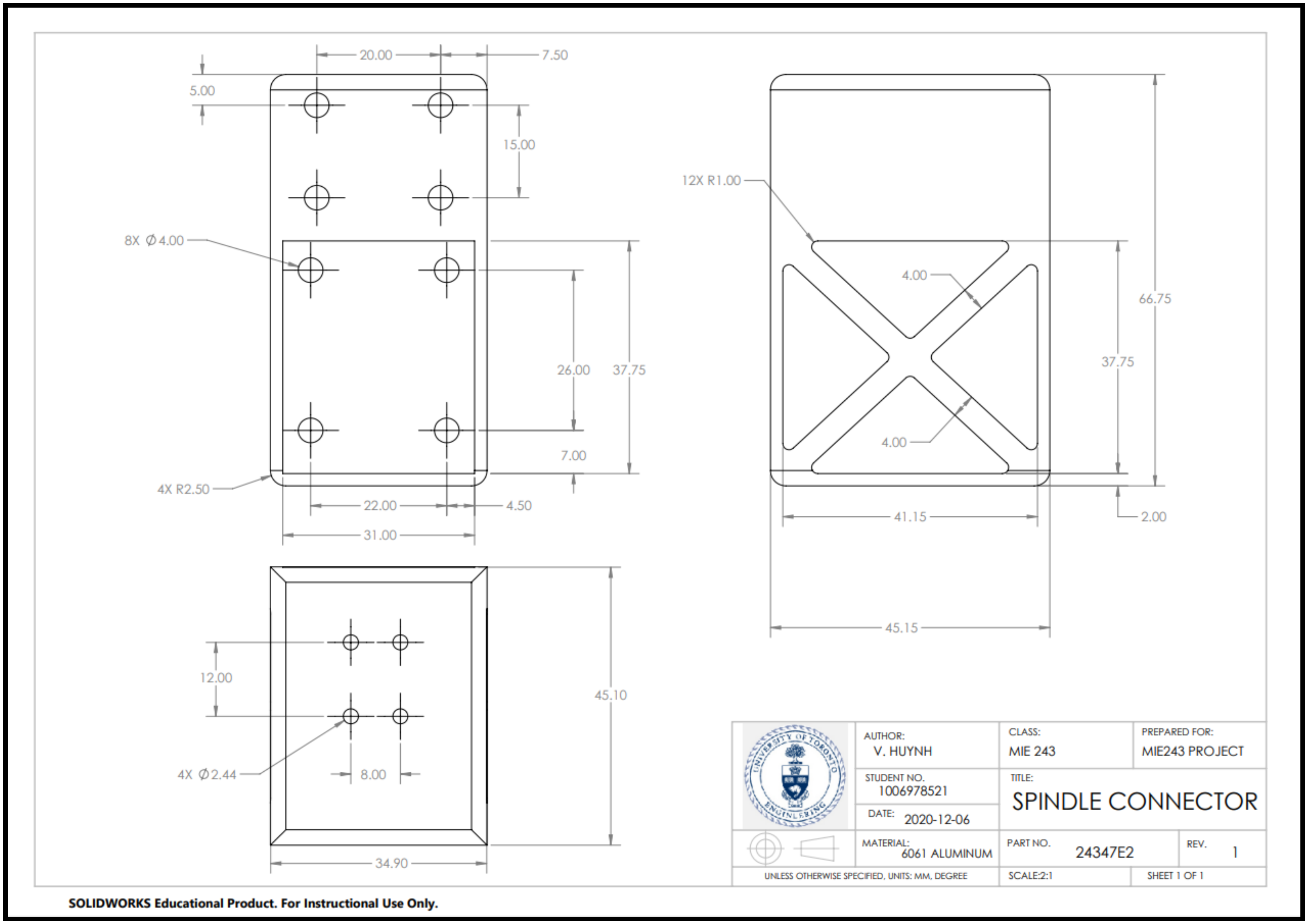


Figure 34 - Spindle connector part drawing.

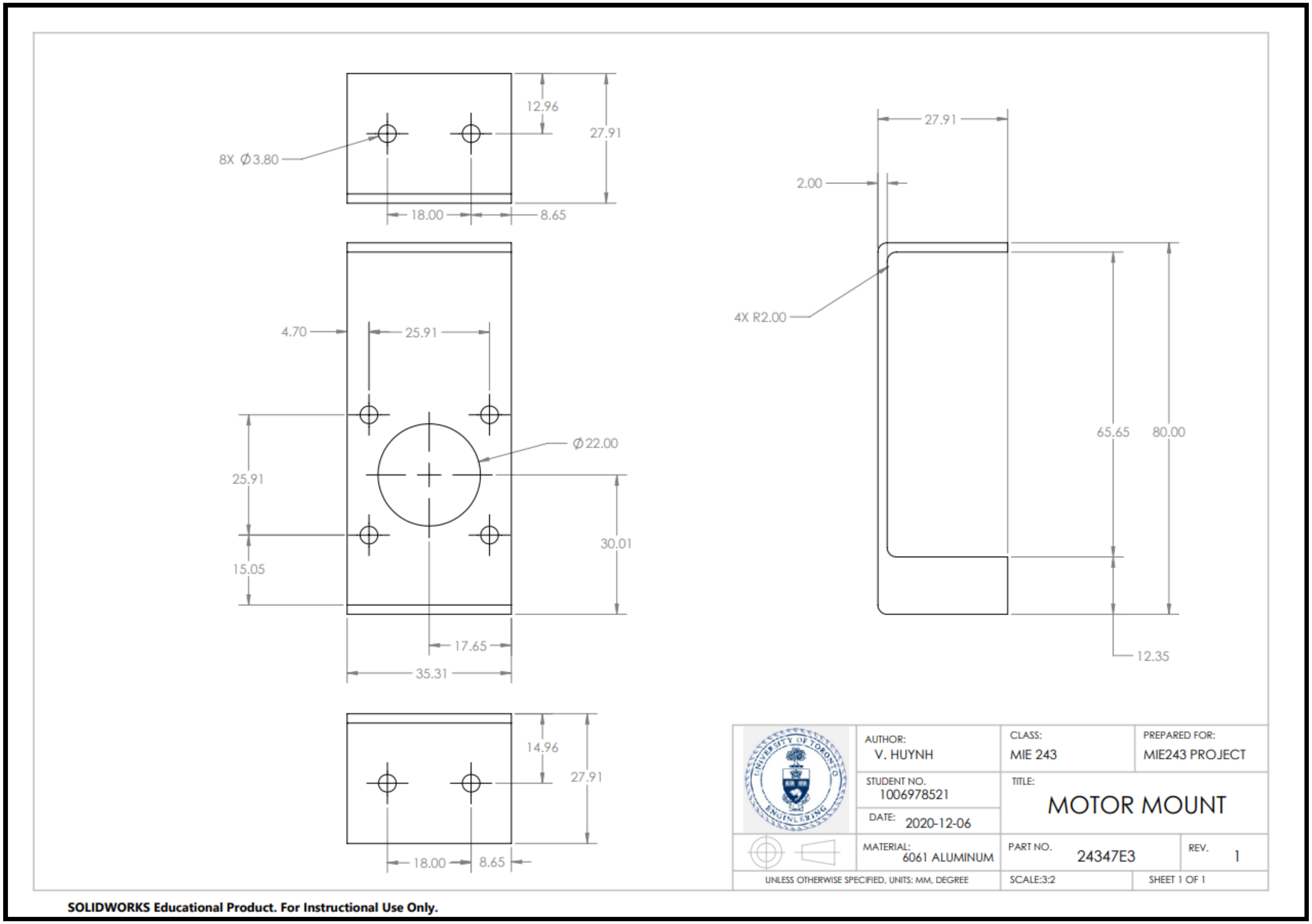
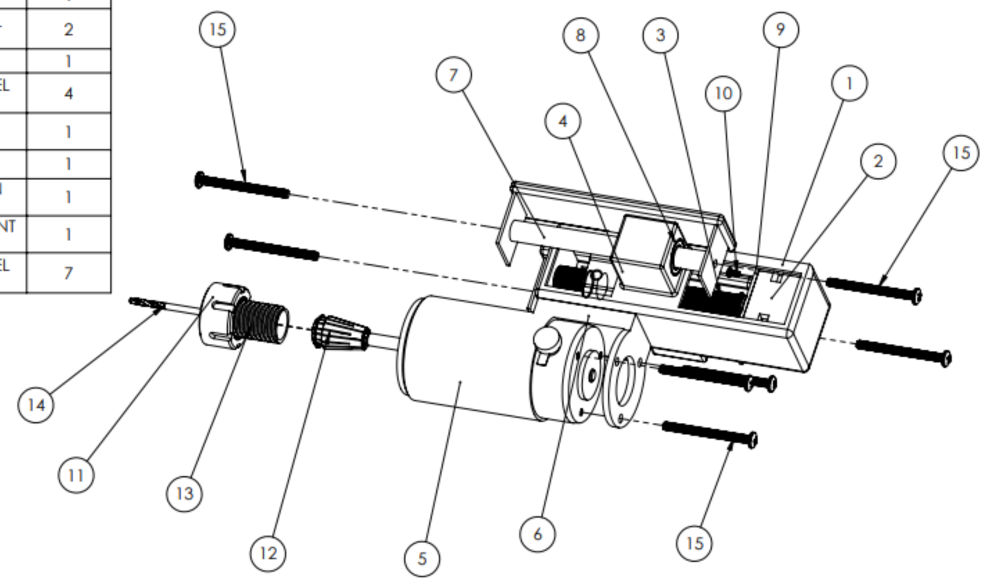


Figure 35 - Motor mount part drawing

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	24347F1	HOUSING	1
2	6627T39	POSITION-CONTROL DC MOTOR	1
3	6624K69	BALL SCREW	1
4	6624K73_PLATFORM BALL NUT	PLATFORM BALL NUT	1
5	6331K13	COMPACT ROUND-FACE DC MOTOR	1
6	24347F2	CURVED ATTACHMENT	1
7	24347F3	RAILS	1
8	3766N15	FIXED ALIGNMENT LINEAR BALL BEARING	2
9	24347F4	MOTOR MOUNT	1
10	91772A091	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	4
11	6163N112_COLLET CHUCK	COLLET CHUCK	1
12	3215A308	ER-16 COLLET	1
13	98980A395	304 STAINLESS STEEL PRECISION ACME LEAD SCREW	1
14	2396N507	CARBIDE DRILL BIT WITH COOLANT HOLES	1
15	91772A524	PASSIVATED 18-8 STAINLESS STEEL PAN HEAD PHILLIPS SCREW	7



AUTHOR: DOMINIK ADAMIAK	CLASS: MIE 243	PREPARED FOR: MIE243 PROJECT	
STUDENT NO. 1007359895	TITLE: Z AXIS AND SPINDLE ASSEMBLY		
DATE: 2021-12-07			
MATERIAL: VARIETY	PART NO. 24347F	REV. 1	
UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE	SCALE:1:5	SHEET 1 OF 1	

Figure 36 - Z Axis and Spindle Assembly

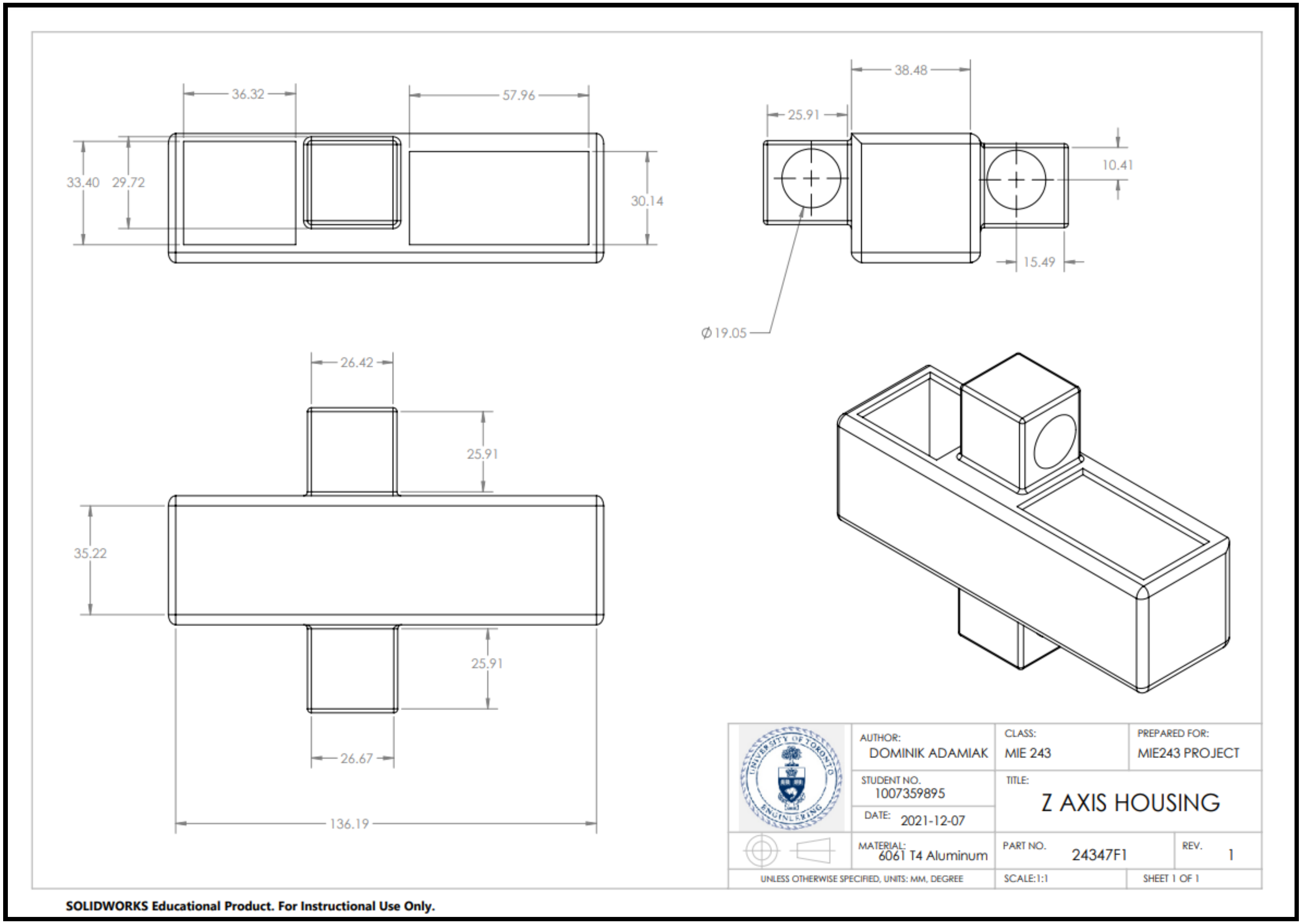


Figure 37 - Z Axis Housing

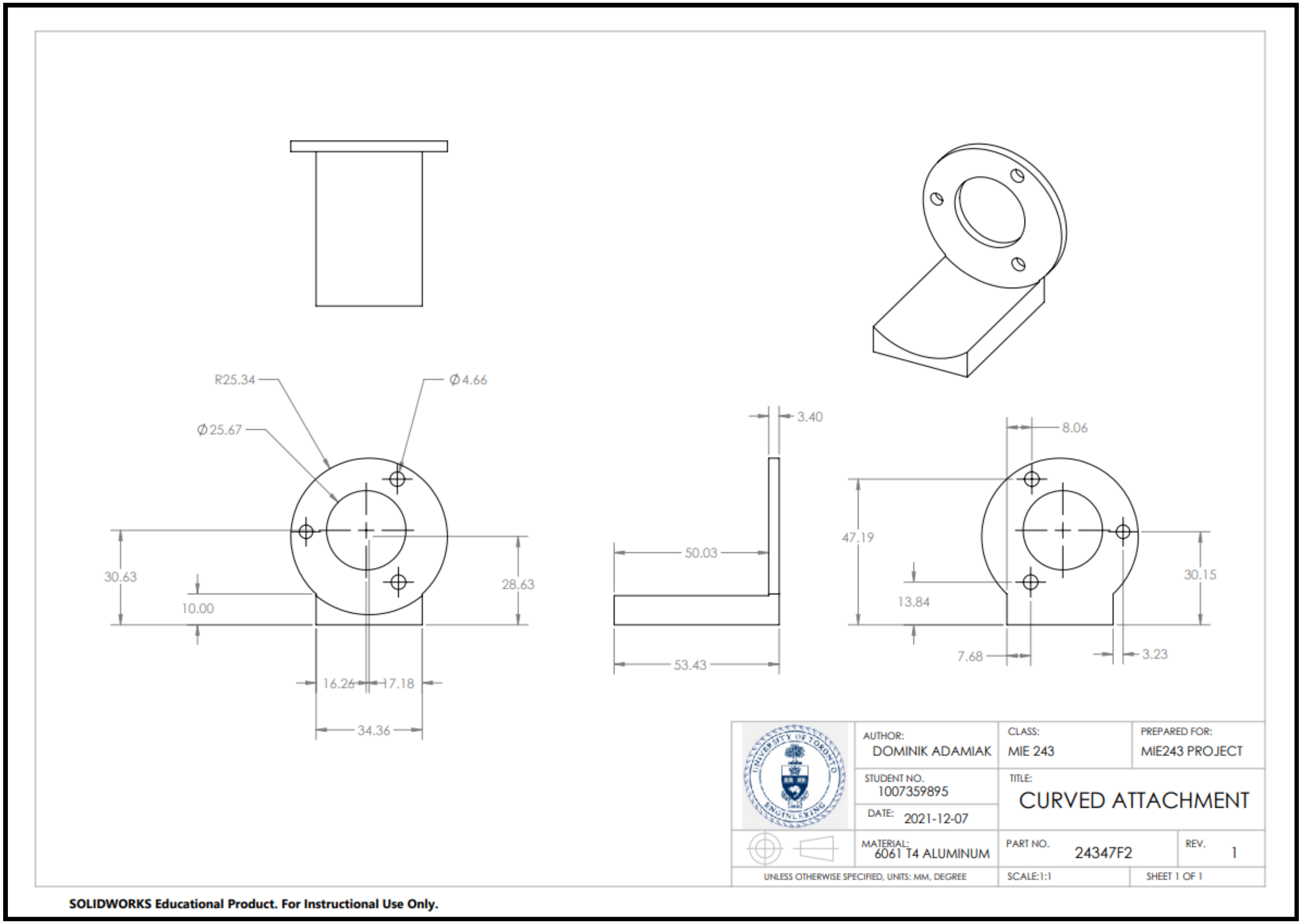


Figure 38 - Curved Attachment.

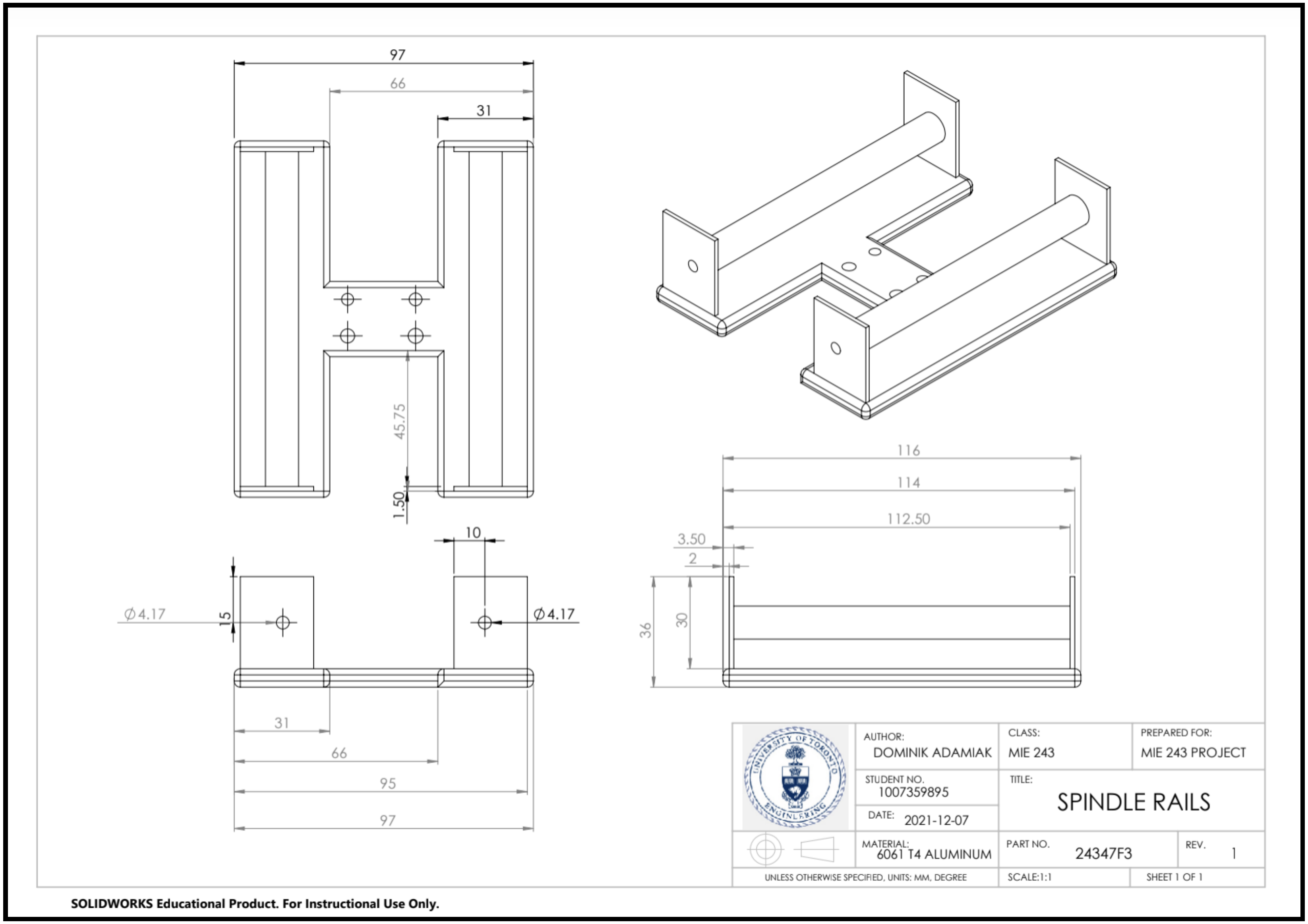


Figure 39 - Spindle Rails

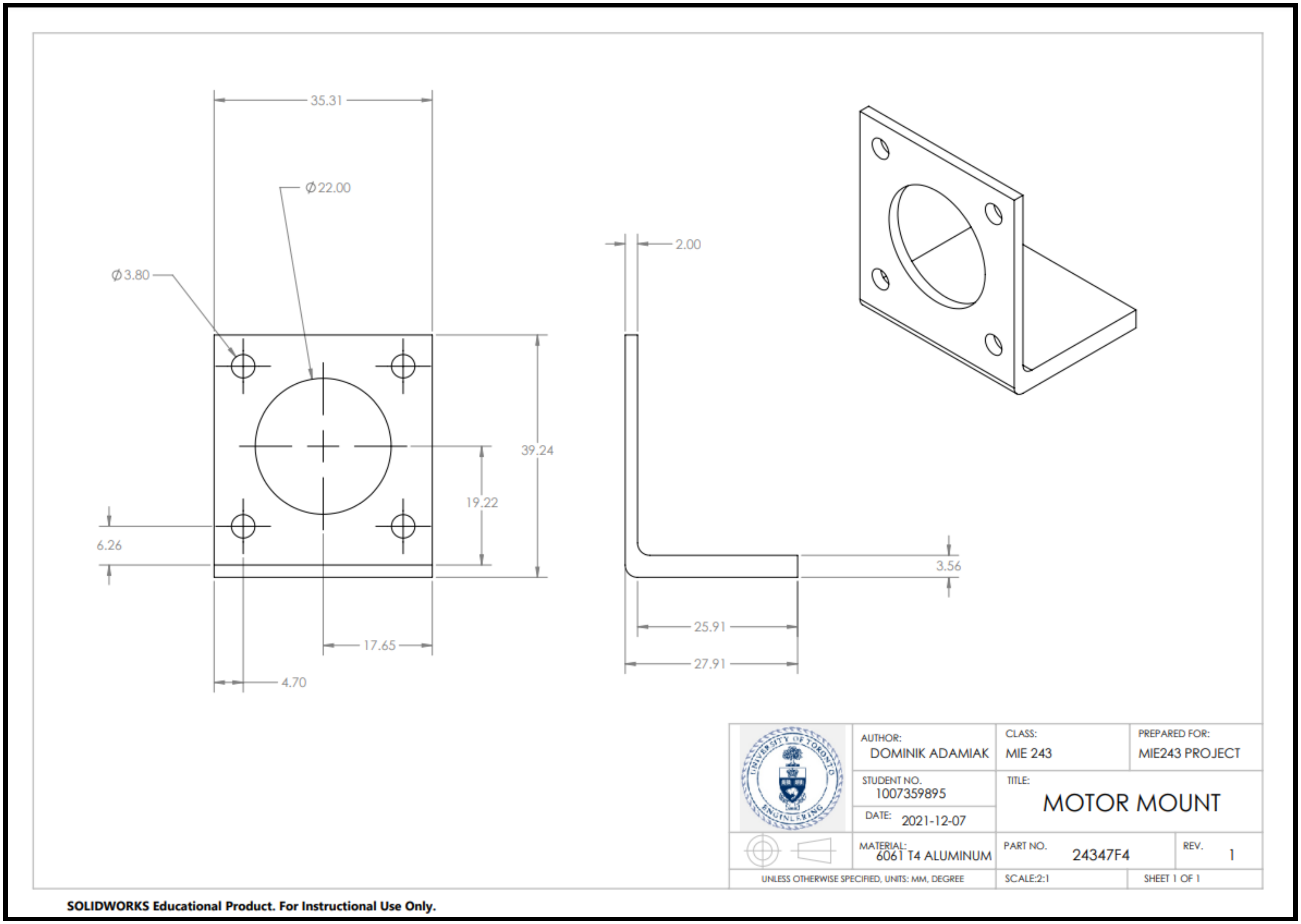


Figure 40 - Z Motor Mount

9.4 Bill of Materials

In order to fully evaluate the final design against the engineering specifications, the overall cost must be determined. In Table 15, the quantity and cost of the standard parts are listed. Some parts are custom parts made from raw materials, so for the sake of estimation, they are only priced by their raw material cost.

Table 17 - Materials Listed with Supplier, Quantity, and Price

Item	Supplier	Quantity	Price per unit
Shell			
Front Aluminum Wall	Custom	1	$11.53
Aluminum Frame	Custom	1	$9.54
Gantry Aluminum Guide Rail	Custom	2	$0.24
Aluminum Bottom Back Wall	Custom	1	$5.88
Aluminum Shelled Right Top Back Wall	Custom	1	$0.60
Aluminum Shelled Left Top Back Wall	Custom	1	$0.60
Acrylic Sliding Back Wall	Custom	2	$0.28
Removable Acrylic Side Wall	Custom	1	$6.29
Acrylic Base	Custom	1	$15.08
Aluminum Shaft Support Back Wall	Custom	1	$1.53
Aluminum Shaft Support Front Wall	Custom	1	$14.26
Acrylic Side Door	Custom	1	$4.34
Acrylic Lid	Custom	1	$5.17
Position-Control DC Motor	Custom	2	$0.04

Mount			
Cover Above Table Gearbox	Custom	1	$0.86
Surface-Mount Hinge With Holes (including pin) 1586A34	McMaster Carr	2	$5.59
Position-Control DC Motor 6627T39	McMaster Carr	2	$72.30
Ball Screw 6624K69	McMaster Carr	2	$96.08
Permanently Lubricated Ball Bearing 2349K414	McMaster Carr	2	$24.46
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 3-48 Thread, 3/16" Long 91772A091	McMaster Carr	Pack of 100	$8.00
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 8-32 Thread, 3/8" Long 91772A192	McMaster Carr	Pack of 100	$8.25
Galvanized Steel Corner Bracket 17715A67	McMaster Carr	4	$3.86
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 8-32 Thread, 1/4" Long 91772A190	McMaster Carr	Pack of 100	$7.71
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 8-32 Thread, 2" Long 91772A205	McMaster Carr	Pack of 50	$11.89

Passivated 18-8 Stainless Steel Flat Head Phillips Screw, 8-32 Thread, 3/8" Long 91771A205	McMaster Carr	Pack of 50	$12.03
Rotating Table			
Threaded Rod 98957A133	McMaster Carr	1	$6.17
Modular Table	Custom	1 Core piece, 1 front piece, 1 back piece, 2 regular add on pieces	$24.57
Modular Table Gearbox	Custom	1	$14.49
Worm Gear 57545K215	McMaster Carr	1	$217.18
Worm, Keyed Bore 57545K327	McMaster Carr	1	$81.55
Stepper Motor 6627T57	McMaster Carr	1	$253.04
Motor Controller 6627T68	McMaster Carr	1	$738.60
Motor Driver 6627T62	McMaster Carr	1	$547.93
Clamping Shaft Collar 6435K18	McMaster Carr	3	$3.80
Shaft Coupler 6208K696	McMaster Carr	1	$107.31
Carbon Steel Keyed Rotary Shaft 1497K116	McMaster Carr	1	$21.21

Spacer 94639A964	McMaster Carr	2	$5.14
Shielded Ball Bearing 1 inch 60355K605	McMaster Carr	4	$13.08
Shielded Ball Bearing 0.75 inch 60355K603	McMaster Carr	2	$11.45
Shielded Ball Bearing 0.5 inch 60355K601	McMaster Carr	1	$7.51
Stainless Steel Pan Head Phillips Screw 1/4"-20 Thread, 5/8" Long 91772A539	McMaster Carr	4 (Pack of 50)	$7.36
Stainless Steel Pan Head Phillips Screw 0-80 Thread, 3/8" Long 91772A057	McMaster Carr	4 (Pack of 100)	$7.87
Gantry			
Shielded Ball Bearing Inner Diameter 15mm 2349K414	McMaster Carr	3	$24.46
Linear Ball Bearing 3766N15	McMaster Carr	2	$43.47
Ball Screw Rod/Shaft 6624K69	McMaster Carr	3	$96.08
Platform Ball Screw/Nut 6624K73	McMaster Carr	3	$254.90
Stepper Motors 6627T54	McMaster Carr	3	$120.11
Stepper Motor Controllers 6627T68	McMaster Carr	3	$738.60

Stepper Motor Drivers 6627T62	McMaster Carr	3	$547.93
Guide rail carriage 7917N11	McMaster Carr	1	$57.15
Guide Rails 7917N28	McMaster Carr	7	$24.50
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 5/32” 91772A051	McMaster Carr	1 pack	$6.05
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 3/16" 91772A091	McMaster Carr	1 pack	$8.00
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 1/2" 91772A096	McMaster Carr	1 pack	$9.77
Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 3/8" 91772A192	McMaster Carr	1 pack	$8.25
6061 T4 Aluminum	Custom	1.6 kg	$3.36
Z-Axis and Spindle			
Ball Screw	McMaster Carr	1	$96.08
Platform Ball Nut 6624k73	McMaster Carr	1	$254.90
Passivated 18-8 Stainless Steel Pan Head Phillips Screw 8-32 Thread Size, 1-7/8" Long 91772A524	McMaster Carr	8	$10.03 (Pack of 50)
Passivated 18-8 Stainless Steel Pan Head Phillips Screw 3-48 Thread, 3/16" Long 91772A091	McMaster Carr	4	$8.00 (Pack of 100)

Fixed Alignment Linear Ball Bearing 3766N15	McMaster Carr	2	$86.94
Curved Attachment	Custom	1	
Collet Chuck 6163N112	McMaster Carr	1	$40.91
Collet 3215A308	McMaster Carr	1	$32.00
Stainless Steel Precision Acme 98980A395	McMaster Carr	1	$153.64
Rails	Custom	1	$0.40
Housing	Custom	1	$0.36
Stepper Motors 6627T54	McMaster Carr	1	$120.11
Stepper Motor Controllers 6627T68	McMaster Carr	1	$738.60
Stepper Motor Drivers 6627T62	McMaster Carr	1	$547.93
Spindle Motor 6331K13	McMaster Carr	1	$112.03
Spindle Motor Speed Controller 7793K12	McMaster Carr	1	$215.46
Grand Total			$11,110.46

See Appendix A for cost estimations.

9.5 Material Justification

Table 18 - Material justification for custom parts

<table>
<tr><th colspan="3">Acrylic</th></tr>
<tr><td rowspan="4">Shell</td><td>Base</td><td rowspan="4">Acrylic is used for parts that are useful if transparent and are not needed as a support. The reason why Acrylic was chosen is because it has high strength and hardness while having low density and costs. These properties are required for containing the projectile debris from the working materials during machining while maintaining low costs. Furthermore, Acrylic has the useful property of being transparent. This is very helpful for the user as they will be able to survey the working areas at all times allowing them to adjust when necessary.</td></tr>
<tr><td>Door & Removable Wall</td></tr>
<tr><td>Top/Lid</td></tr>
<tr><td>Sliding Back Walls</td></tr>
<tr><th colspan="3">Al 6061 T4</th></tr>
<tr><td colspan="2">All Remaining Custom Parts</td><td>Al 6061 T4 is used for parts that are used as supports, and thus, undergo considerable amounts of stress. The reason why Al 6601 T4 was chosen is because of its high specific properties, low cost and is highly standardized.</td></tr>
</table>

See Appendix A for material properties and selection.

9.6 Motor Calculations

When choosing a motor, there are two important factors to consider, speed, and torque. The speed of the motor dictates the feed rate of the machine, or how fast the spindle can move across the working area (not to be mistaken with the spindle spin speed) [21]. The torque of the motor is also important to consider since heavier components, and faster moving components require more torque to move and stop [22].

This design uses ball screws used for the x and y axes that move 4mm per full rotation of the screw with an error of +- 0.210mm per 300mm. The stepper motor chosen for the design is a NEMA 23 stepper motor with a speed of 2,250rpm and a max torque (also known as startup torque [22]) of 165 in-oz. In addition, a 2:1 speed reducing gearbox would be used in the final design. Note that the gearbox and this specific motor are not the same in the CAD model, the ones in the CAD model are placeholders. Therefore the speed of the machine in the x and y axes is given by:

$$\left(\frac{2{,}250rpm}{2}\right)(0.004m/rotation) = 4.5m/min$$

The max feed rate in the x and y axis is 4.5m/min, which is within the market researched machines feed rate range, whose speeds range from 3.43m/min to 15.2m/min (see Table 8). Furthermore, the max torque of this motor and gearbox configuration would yield a torque of:

$(165\ in - oz)\ (2) = 330\ in - oz$

Converting the torque to lb-ft, the motor and gearbox system produces a max torque of approximately 1.7lb-ft. The current market torque ranges from 1.5lb-ft to 3.3lb-ft (see Table 8), so this system is comfortably within the market range. However, further iterations and prototyping would be required to fully determine if the motor rpm and torque is sufficient for this design.

The current torque of the motor for the modular table is 80in-oz. The worm gear to worm ratio is 40:1. The modular table thus has a torque of 3200in-oz or 21 Nm. The table has a mass of 11.7kg or 115N. If we simplify the force to be acting on the center of the table downwards, the distance is approximately 11cm or 0.11m away. Note that torque is equal to the cross product of force and the distance from the rotational axis. Thus, the necessary torque can be calculated to be 12.65 Nm. Therefore, the motor and gearbox mechanism has enough power to rotate the table. Furthermore, there is 8.35 Nm remaining, assuming that the center of gravity for the materials to be cut can be represented as a force acting downwards on the center of the table, the materials can be upwards of 75N or 7.65kg.

In analysing the spindle z-axis movement, the necessary torque required was calculated to be the [mass of objects being lifted in the z-direction by the step motor] * [distance from step motor to the centre of gravity]. Both the mass and COG of the spindle assembly were evaluated in Solidworks. This was evaluated to be 5.17 inches * 31.74 oz = 180.95 inch-oz. Thus a gear reduction ratio of 2:1 was selected, in order to allow the selection of the NEMA 23 motor, similar as in the x and y axis. This allows the RPM to remain relatively high, while preserving part comminatility with the other axis of motion. As in the previous case, the gear reduction is not modeled in the SolidWorks assembly.

9.7 Comparison to engineering specifications

Once more, this design, the final design, must be compared against the engineering specifications. Table 16 outlines the final design and how it compares to the engineering specifications.

Table 19 - The Final Design Compared Against the Engineering Specifications

Category	Engineering Specification	Final Design
Price Range	$12 000	$11,110.46
Weight	< 92 kg	59 kg
Permissible Working Materials	Foam, plastics, wood, soft metals	Foam, plastics, wood, soft metals
Maximum Machine Dimensions	600mm (x) by 700mm (y) by 700mm (z)	600mm (x) by 500m (y) by 600mm (z)
Minimum Working Area Size	220mm (x) by 120mm (y) by 100mm (z)	440mm (x) by 360mm (y) by 110mm (z)
Orientation	Vertical	Vertical
Axis	4 or more	4 axes
Tool Swapping	Must permit manual or automatic tool swapping.	Manual tool swapping is possible.
Debris	Must contain debris, preventing it from flying into the outside environment.	The design has a workspace that is well contained and prevents debris from being ejected.
Noise	Must minimize noise.	The design uses mechanisms with low noise output, minimizing noise as much as possible.
Feed rate	≥ 4m/min	12m/min

Portability	Able to operate on a desktop surface without any specialized mounting.	The design does not need any specialized mounting.

The final design meets all the engineering specifications, so it is a viable design in theory. Further steps to verify the viability of the design would include prototyping and testing.

10. Conclusion

In summary, based on market research, the central aim is to design a CNC machine for entry level professionals in need of rapid, on-site prototyping. The main specifications being under $12,000 USD, minimum 4 axis, and the ability to cut materials ranging from foams to soft metals. Research into common mechanisms used in CNC machines led to three candidate designs, analyzing them against the engineering specifications then transitioned into two more iterative candidate designs, to finally our proposed conceptual design “The Gantry Tipper”. Future steps for this design involve further iterations to refine the detailed design and incorporate advisor feedback

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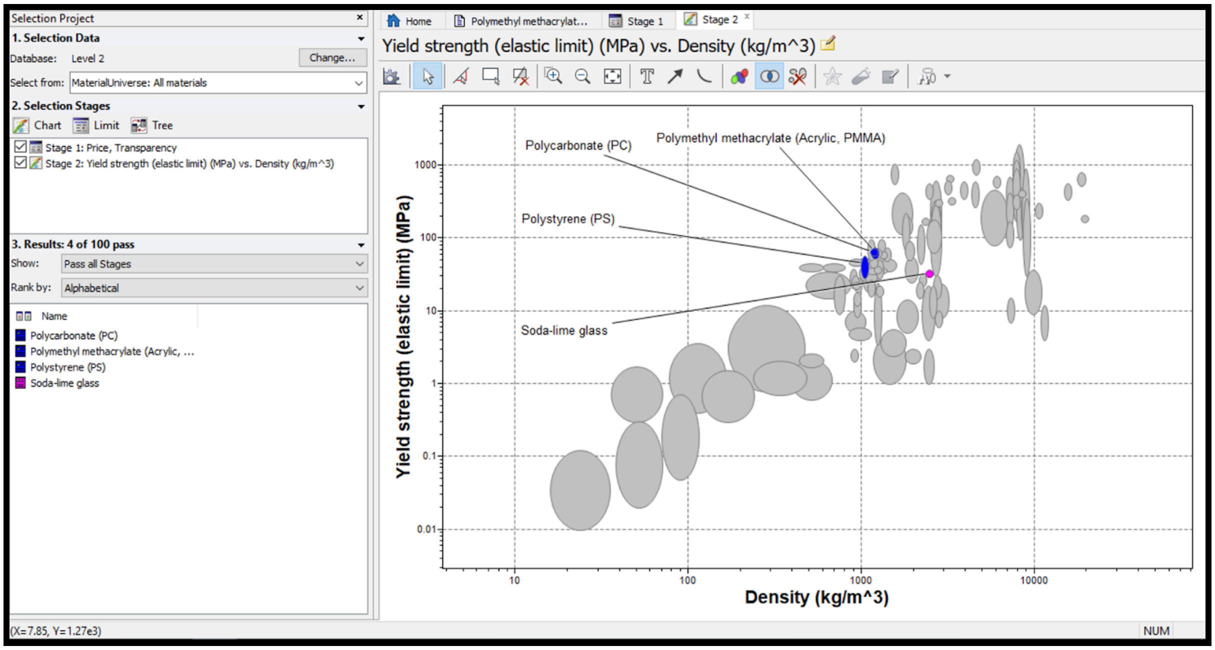
Appendix A



Material Selection - σ_y vs. density with cost and optical constraints of max 3 USD/kg and transparent respectively from CES EduPack 2018 database.

General properties

Density	1.16e3	-	1.22e3	kg/m^3
Price	* 2.76	-	2.87	USD/kg
Date first used	1933			

Mechanical properties

Young's modulus	2.24	-	3.8	GPa
Shear modulus	0.803	-	1.37	GPa
Bulk modulus	4.2	-	4.4	GPa
Poisson's ratio	0.384	-	0.403	
Yield strength (elastic limit)	53.8	-	72.4	MPa
Tensile strength	48.3	-	79.6	MPa
Compressive strength	72.4	-	131	MPa
Elongation	2	-	10	% strain
Hardness - Vickers	16.1	-	21.9	HV
Fatigue strength at 10^7 cycles	* 15.2	-	32.7	MPa
Fracture toughness	0.7	-	1.6	MPa.m^0.5
Mechanical loss coefficient (tan delta)	* 0.0105	-	0.0179	

Acrylic properties from CES EduPack 2018 database.

Price					
Price	ⓘ	* 2.02	-	2.17	USD/kg
Price per unit volume	ⓘ	* 5.44e3	-	5.93e3	USD/m^3
Physical properties					
Density	ⓘ	2.69e3	-	2.73e3	kg/m^3
Mechanical properties					
Young's modulus	ⓘ	66.6	-	70	GPa
Specific stiffness	ⓘ	24.5	-	25.8	MN.m/kg
Yield strength (elastic limit)	ⓘ	92.6	-	108	MPa
Tensile strength	ⓘ	206	-	240	MPa
Specific strength	ⓘ	34.1	-	39.8	kN.m/kg
Elongation	ⓘ	16	-	23	% strain
Compressive modulus	ⓘ	67.9	-	71.3	GPa
Compressive strength	ⓘ	* 92.6	-	108	MPa
Flexural modulus	ⓘ	* 66.6	-	70	GPa
Flexural strength (modulus of rupture)	ⓘ	* 92.6	-	108	MPa
Shear modulus	ⓘ	25.6	-	26.9	GPa
Shear strength	ⓘ	138	-	163	MPa
Bulk modulus	ⓘ	* 66.6	-	70	GPa
Poisson's ratio	ⓘ	0.325	-	0.335	
Shape factor	ⓘ	39.6			
Hardness - Vickers	ⓘ	74	-	87	HV
Hardness - Brinell	ⓘ	62	-	68	HB
Elastic stored energy (springs)	ⓘ	63	-	85.1	kJ/m^3

6061 T4 Aluminum properties from CES EduPack 2018 database.

Appendix B

Cost Calculations

The custom materials for the modular table, gearbox, and gantry are constructed out of 6061 T4 Aluminum. The average price of 6061 T4 Aluminum is 2.10 USD/kg. Some parts of the shell are made out of Acrylic. The average price of Acrylic is $2.82.

i. The mass of the modular table is 11.7 kg. Thus, the raw material cost is $24.57.

ii. The mass of the gearbox is 6.9 kg. Thus, the raw material cost is $14.49.

iii. The mass of the custom parts in the gantry are 1.42 kg, 0.05 kg, 0.13 kg for a total mass of 1.6kg. Thus, the raw material cost is $3.36.

iv. The mass of the aluminum custom parts in the shell are 22.15 kg. Thus the raw aluminum material cost is $46.52. While the acrylic custom parts in the shell are 11.15 kg. Therefore, the raw acrylic material cost is $31.44. The total raw material cost for the shell is $77.96.

v) The custom parts of the 0.36kg for a total raw material cost of $0.76