MIE243: Group Design Project

Entry-Level CNC Machine

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1. Introduction and Research

A CNC milling machine transforms the material into a finished model by removing material from the initial raw material. Computer numerical control (CNC) is programmed code that gives instructions to the mill to carve the final model. The objective of this project is to design an entry-level desktop CNC milling machine that can be used in small engineering firms to cut soft metals (Aluminum and Brass) and wood in order to prototype the first iterations of the design. There are three main sizes of milling machines: micro, benchtop and full size.

1.1 Millable Size/Area

- Millable size/area:
    - 18 x 10 x 4.5 cm [1]
    - 33 x 33 x 4 inches (X xY x Z) [2]
    - 9-1/4" x 7-1/4" x 4" [3]
    - 7″ x 9″ x 3.5 [4]
    - 12" x 16" to 24" x 24" [5]

1.2 Number and Layout of Axis Milling Machines and Limitations [6]

1.2.1 3-Axis CNC Machining

3-axis machines are the most common variety of milling machines and can cut in an X and Y and Z direction. But normally they can not do undercuts (features that cannot be accessed with a standard end mill).

- Ideal for simple tasks which do not require intricate detailing or depth.
- Can be used for cutting sharp edges, boring, milling slots, tapping, and drilling holes.
    - Simple geometries can utilize a 3-axis milling machine.
- Easy to program and operate, which results in excellent accuracy at a low cost.
- The cutting tools have the ability to spin at thousands of RPM, meaning that they can accurately cut the sturdiest of materials.

Layout

The workpiece occupies a stationary position while the cutting tool moves across the X-axis, along with the lathe table, the Y-axis, towards the front/back of the table, and the spindle that drops from the top marks the Z-axis.

Limitations

- The initial capital investment and the installation costs are high.
- It requires highly skilled professionals for operating and maintaining the machine.

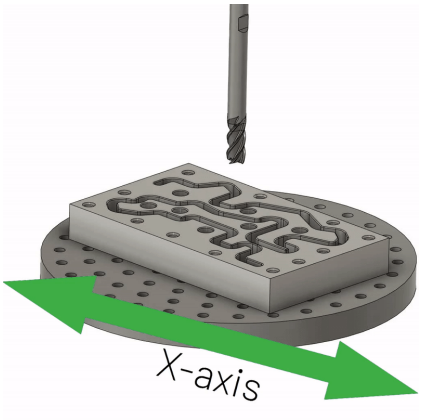


Figure 1: The animation shows different axes on a 3-axis CNC milling machine. [7]

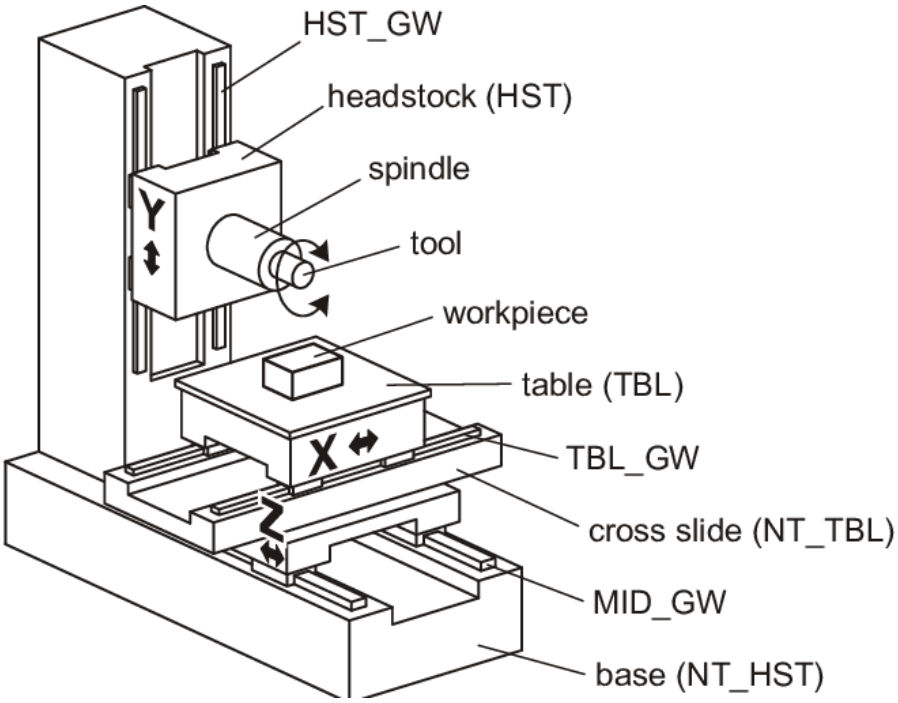


Figure 2: 3-axis milling machine [8]

1.2.2 4-Axis CNC Machining

The 4-axis milling machine is more sophisticated, with the additional ability to rotate on the X-Y plane.

- Useful for cutting holes, cutting along an arc, or carving cutouts, especially on the sides or around a cylinder.
- Useful for high-quality precision engravings, millings, and drillings.
- operation on materials from aluminum and composite board to foam, PCB, and wood.
- Useful for advertising design, art, medical equipment, hobby, industrial applications

Layout

4-axis machining involves an additional axis apart from the usual X, Y, and Z planes. This extra movement is in the form of rotation along the X-axis (X-Y plane), which forms the fourth plane – the A-axis (horizontally).

Limitations

- It does not support continuous machining in practicality as it possesses a fixed set of stops.
- The operators can only use the machine as a pure indexer.
- Quick wear and tear of the worm gear mechanism, especially during high-intensity use.
- The issue of backlash can affect your accuracy or the durability of the machine.

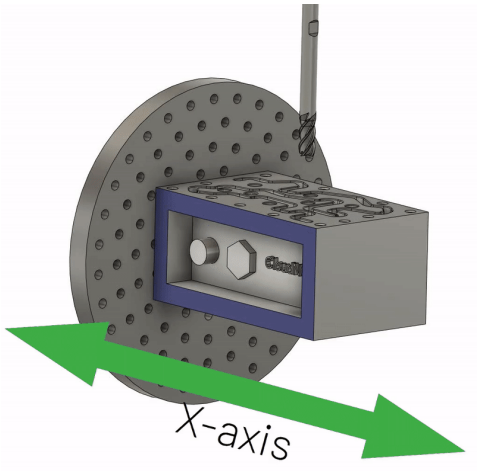


Figure 3: *The animation shows different axes on a 4-axis CNC milling machine.[9]*

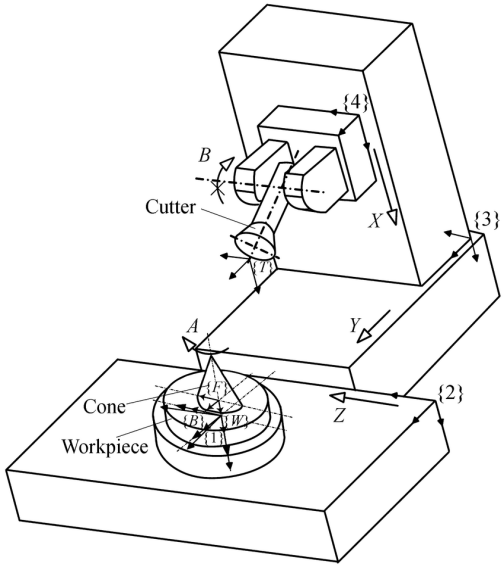


Figure 4: 4-axis milling machine [10]

1.2.3 5-Axis CNC Machining

Allows the operator to simultaneously hit five different sides of a part depending on the design complexities.

- 5-axis milling machines include rotation in both the X and Y-axis.

- Wide usage in medical technology, research and development, architecture, military, automotive industry, aerospace industry, architecture, and creative arts.
- It can hole drilling at compound angles.

Layout

In this setup, the X, Y, and Z-axes are similar to a 3-axis machine layout. The table then rotates along the A-axis, as it does with the 4-axis. The 5-axis machine involves the pivoting action at the joint of the table, followed by rotation along the C-axis.

Limitations

- The CAD/CAM programming for 5-axis machines can be extremely complicated, especially while envisioning the spatial trajectory.
- Since 5-axis milling machines are not that common yet, purchasing and maintaining one is quite a hefty investment.
- The tooling solutions are equally expensive.

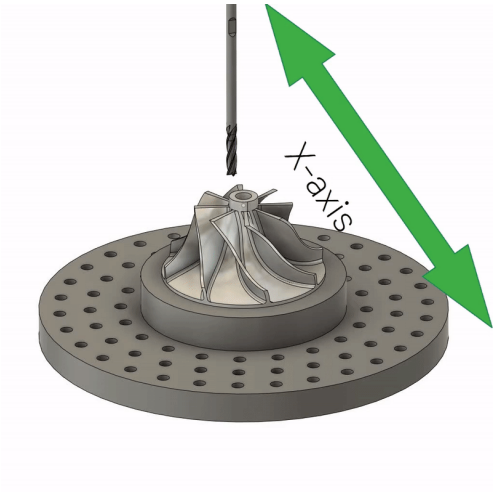


Figure 5: The animation shows different axes on a 5-axis CNC milling machine.[11]

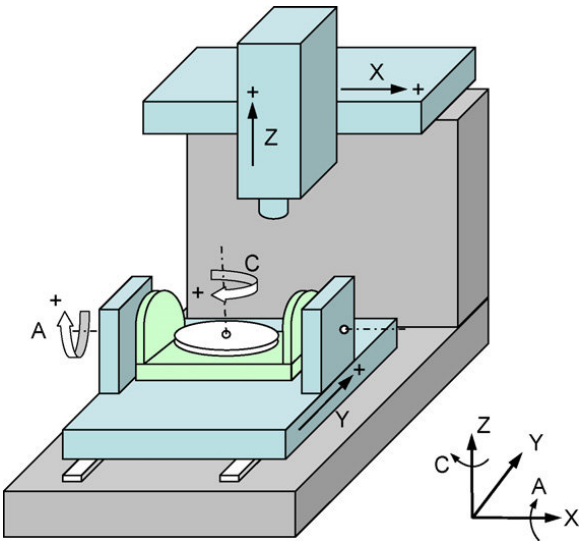


Figure 6: 5-axis milling machine [12]

1.2.4 7-Axis CNC Machining

The 7-axis CNC milling machine can create long, slender, and heavily detailed parts. Also, no need for post-fabrication processes.

Layout:

The 7-axis CNC milling machine can operate in X-axis (vertical rotation), Y-axis (horizontal rotation), Z-axis (moving the arm up/down), A-axis (rotating at X-axis), B axis (rotating at Y-axis), C axis (rotating at Z-axis), and E axis (twisting the arm). [13]

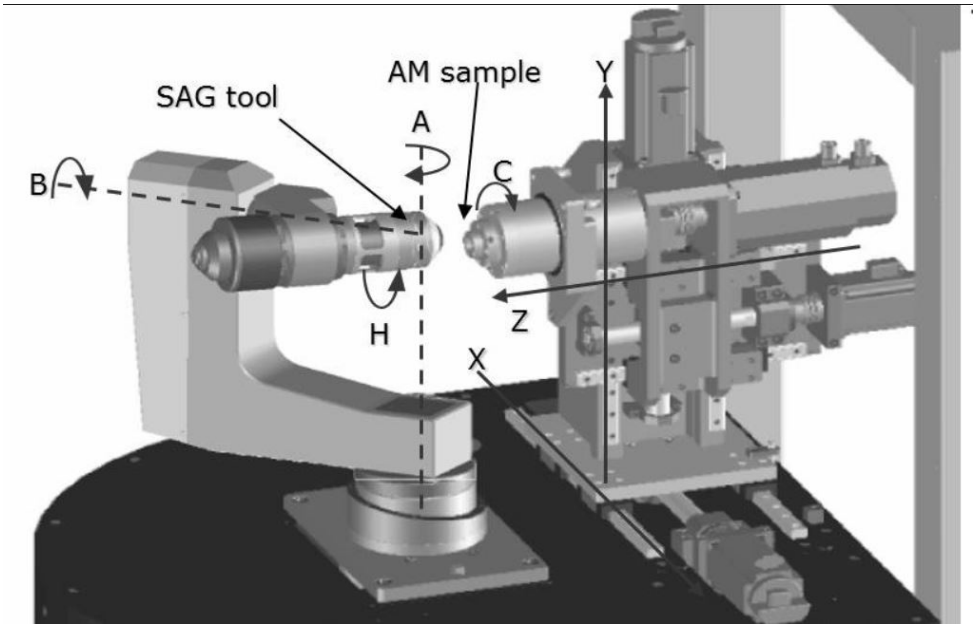


Figure 7: *7-axis milling machine[14]*

1.3 Health and Safety [15]

- All the power buttons should be reachable by the operator during the usage of the machine.
- All the machines should have an emergency button in case of indents.
- Safe for vacuum, brush or rake for cleaning purposes.
- Mills should be removable while the power is disconnected.
- Mills must be sharp to use
- Material pieces must be mounted securely down a flat and stable surface.
- Distance should be kept between the table and the machine while loading materials.

1.4 Coolant [16]

- Air: Cools and clears chips, but has no lubricity purpose.
- Mist: This is a low-pressure coolant that is sufficient when chip evacuation and heat are not major concerns.
- Flood: This is a low-pressure method that creates lubricity and flushes chips from a part to avoid chip recutting.
- High Pressure: This is great for chip removal and evacuation, as it blasts the chips away from the part. However, the pressure can be high enough to break miniature diameter tooling. Often used in deep pocket or drilling operations

1.5 Motors [17]

Electric motors are commonly used in CNC milling matches, especially stepper motors and servo motors. Both convert a non-linear input from the control into linear movement at the spindle shaft and table by turning a screw-like shaft to move the load.

The precision of Motion: [18]

- High degree precision can have accuracy typically around +-0.00508mm.
- Usually, full-size CNC milling machines can have a tolerance of +-0.01mm.

1.6 Types of Milling Machines

- Micro milling machines typically have vertical cutting tools and are usually in the size of 6-9 inches and they should be used on flat surfaces. This machine allows for small and detailed patterns and can be used to bore, cut threads on plastic, wood and thin metals.
- Benchtop milling machines have around 1ftx2ft milling area and can be used to work on more robust metals. They can have horizontal or vertical cutting tools.
- Full-size milling machines are the most expensive of milling machines. They usually are used in professional/industrial setups. They can be as tall as 6 ft and they primarily can be used to bore and cut threads on thick metals such as steel, aluminum and titanium. [19]

Types of milling machines:

- Knee-type: fixed spindle and vertically adjustable work table
- Ram-type: spindle affixed to movable housing(RAM) on the column, machine tool move along X, Y-axis
- Bed-type: worktables affixed directly to the machine bed prevent the workpiece from moving along both the Y and Z axis.
- Planer-type: similar to bed-type where worktable fixed along Y and X axis and spindles capable of moving X, Y, Z axis. Though they can also support multiple machine tools (up to 4), reduce lead time for complex parts

- Specialized: rotary table (circular worktables for roughing and finishing operations), drum(similar to rotary, but work table rotates around horizontal axis), planetary(worktable stationery, workpiece cylindrical)

1.7 Material Capabilities

The following are the commonly used materials used to use milling machine on them:

- metals (alloy, exotic, heavy-duty, etc)
- Plastics (thermosets and thermoplastics)
- Elastomers
- Ceramics
- Composites
- Glass

For the purpose of this project, the only materials used are Aluminum, Brass and wood.

1.8 Standardized Measurements

1.8.1 Cutting Speed

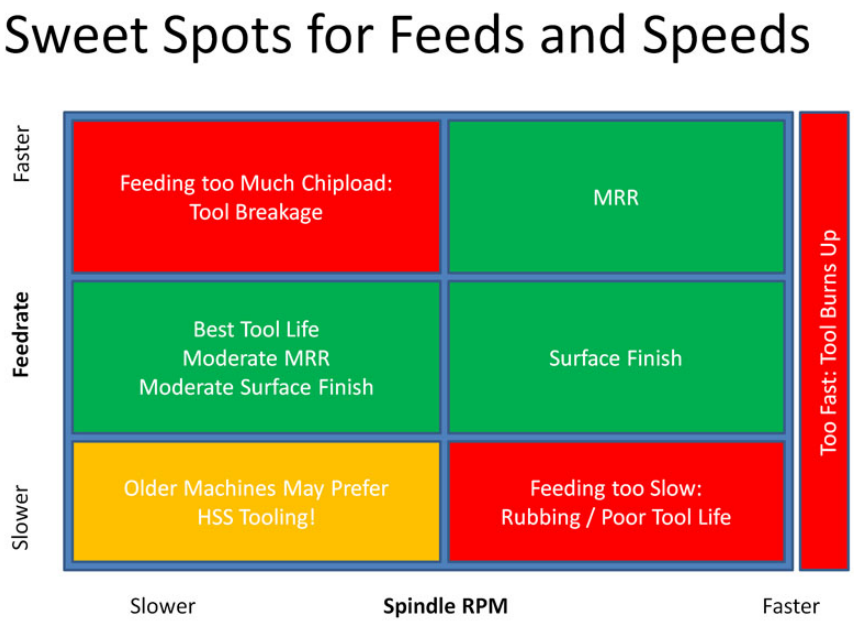


Figure 8: The chart showing the relation between spindle and feed rate speed. [20]

Cutting Speed	$Vc = \frac{\pi \times D \times n}{1{,}000}$	Vc = Cutting Speed (m/min)
		π = 3.14 [The Circular Constant]
Spindle Speed	$n = Vc \div \pi \div D \times 1{,}000$	D = Diameter (mm)
		n = Spindle Speed (min^{-1})
Feed	$Vf = n \times fz \times Z$	Vf = Feed (mm/min)
		fz = Feed per Tooth (mm/tooth)
Feed per Tooth	$fz = \frac{Vf}{n \times Z}$	Z = Number of Flutes

Figure 9: Formulas needed to calculate the cutting speed. [21][22]

- **Aluminum** 1/4″ carbide end mill, 24,000 RPM max, 16,000 RPM ideal [23]
- **Wood** Hardwood: 1500 SFM, Softwood: 1500 SFM, MDF: 1500 SFM, Plywood: 1500 SFM [24]
- **Brass** 1/4″ carbide end mill, 30,560 RPM, 2,000 SFM [25]

1.8.2 Precision

Accuracy 0.05-mm dimensional accuracy

1.8.3 Shank Size

Largest shank size: ¼” or ½”

1.9 CNC Milling Machine Price

Lowest: $6,000

Highest $300,000

Average: $6,0000 [26]

Desktop CNC milling machine price:

Range: $3,000-11,893.35

- The market price of the machine [27]

Type	Hobbyist Grade	Entry Level (3-axis)	Entry Level (5-axis)

Cost ($)	1k - 3k	60k - 100k	200k - 500k

- Operation cost [28] [29][30]

Type	3-axis milling machine	5-axis machine
Approximate Hourly Cost ($)	40	75 - 120

2.0 Engineering Specifications

2.1 General Design Goals:

The design consists of a professional, entry-level desktop milling machine targeted towards small engineering firms which work on wood, plastics, and soft metals such as aluminum, etc with components such as helical metal gears since these generally cannot be made with other alternative methods (ex. 3-D Printing).

2.2 Professional and Entry Level:

The device is to be targeted towards non-hobbyists, where the main target audience of the design consists of small business owners, engineers, and jewellers. The device should be able to have the technical capabilities to mill, cut, drill, engrave, and carve. There are multiple variations of Desktop CNC machines according to their usage. The entry-level desktop CNC routers can range from $150-$500. The hobby-level desktop CNC machine can start with a milling area of 10 cm x 20 cm, with a price range of $1,000- $3,000. The professional desktop CNC milling machines can range from $3,000-$7,000. [31]

The bigger size CNC milling machines which can be used in industrial applications can vary anywhere from $5,000-$500,000. [32]

The difference between the size of the mills in different CNC machines is that the lighter machines use smaller mill sizes to be more accurate and because of the fact that as the machine gets lighter and smaller its tolerance to high torque and vibration decreases hence the size of the mill gets smaller in order to accommodate for fewer vibrations and more accuracy. [33]

2.3 Desktop

- It is seen that the sizes and dimensions of desktop machines vary in range. For the purpose of the design goal and the design purpose, the team has decided to define a desktop milling machine to be within the size defined in section 2.5 Engineering

Specifications, as well as being able to independently support itself, given it being able to move rotary cutting tools in at least three dimensions.

2.4 Material Capability focus

Given that materials such as plastics and wood can be more efficiently milled or produced by other alternative methods such as 3-D printing, where the use of milling machines solely for thermoplastics is not efficient since 3-D printing requires fewer materials. In addition, it is considered that components such as helical or metal gears cannot be easily produced by other methods such as 3-D printing, therefore it is analyzed that our design should focus on milling materials such as metals.

2.5 Engineering Specification:

- General dimension for tabletop CNC milling machine (5-axis milling desktop machine that is able to mill metals) should be within

Relative Size	X (mm)	Y (mm)	Z (mm)
Small	3500	2200	2000

[34]

- Worktable dimension should not exceed 10cm x 10cm
- Shank size: quarter to half an inch

- Precision: 0.01/0.05
- Cost should not exceed $10,000 for a desktop 5-axis design
- There should be at least 5 axes
- Should be able to cut a variety of materials, metals: aluminum, brass or steel; polymers or plastics: Acetal (POM), Acrylics (PMMA), Polycarbonate (PC) and Polypropylene (PP); composites; wood: soft and hard
- Should be able to cut the following basic shapes: Cut-outside-line, Cut-inside-line, Chamfer-online, Engrave-online, Fillet-online, Hole, Pocket-inside-line, Pocket-outside-line, Dog-bones [35]
- DC Motor speed=maximum cutting speed=12500rpm

2.6 Candidate Designs

2.6.1 Candidate #1

Candidate design #1 is a 4-axis CNC milling machine. The mill can move in x, y, z directions and rotate on the x-y plane. The milling area can move in the y-z plane. There are two chain drive linear stages that allow the mill to move in x, y directions. Also, there is a worm drive attached to the spindle which makes the movement in z-direction possible. Four rods are attached to a linear ball bearing for the movement of the milling area. The working area of the Candidate #1 is 30W x 40L x 50H cm. It has a shank size of ½", accuracy with a tolerance of +-0.05mm and is designed to be able to replace different mills. [Figure10] The motor used in this design is a 24V servo motor with a Cutting Speed of 1000 ft/min. The worm drive used in the design for adjusting the height in the mill eliminates any torque and vibration due to the use of worm gear which eliminates the unnecessary vibrations.

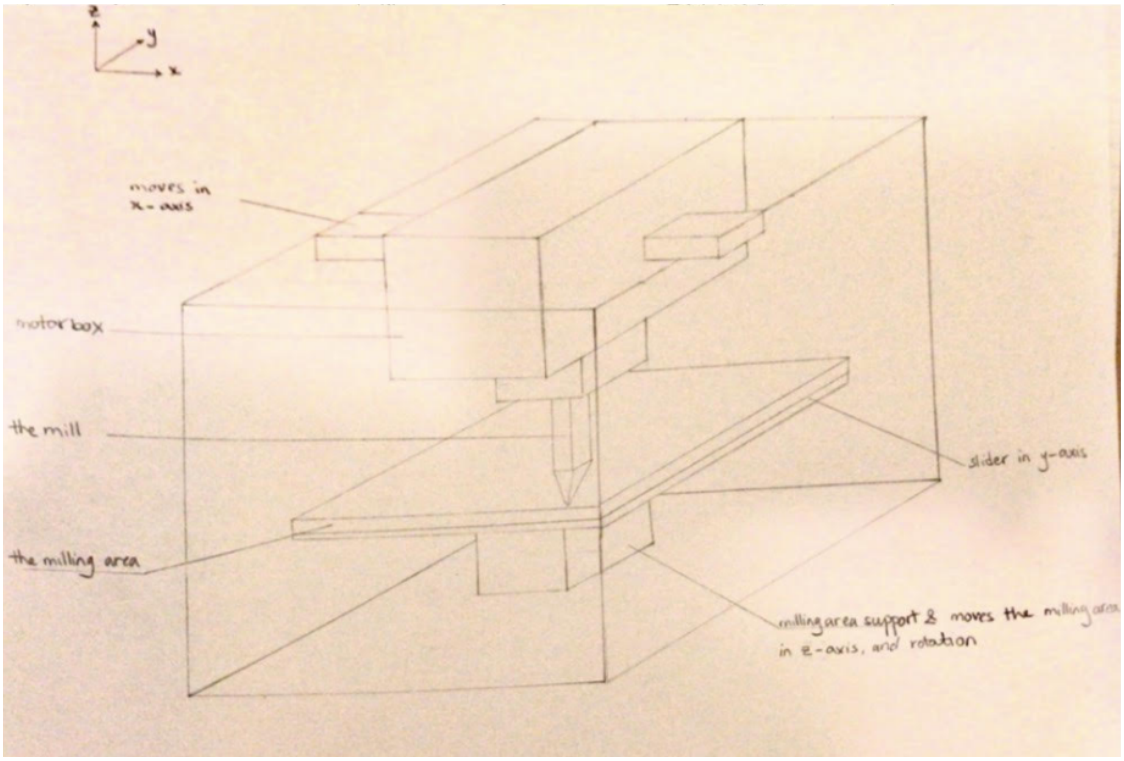


Figure 10: Candidate #1

2.6.2 Candidate #2

This candidate design is a 3-axes CNC milling machine. The CNC milling machine is able to have movements in x, y, and z directions in total. There are 2 main parts of components to this design. First of all, is the top part, is where the drill bit is placed and supports the x and z direction of movements. On the top part of the machine, there are two slides placed in the x-axis on the edges of the top cover of the machine. There is one bar that is placed in the z-direction onto the two slides that allow the bar to transport in the x-direction.

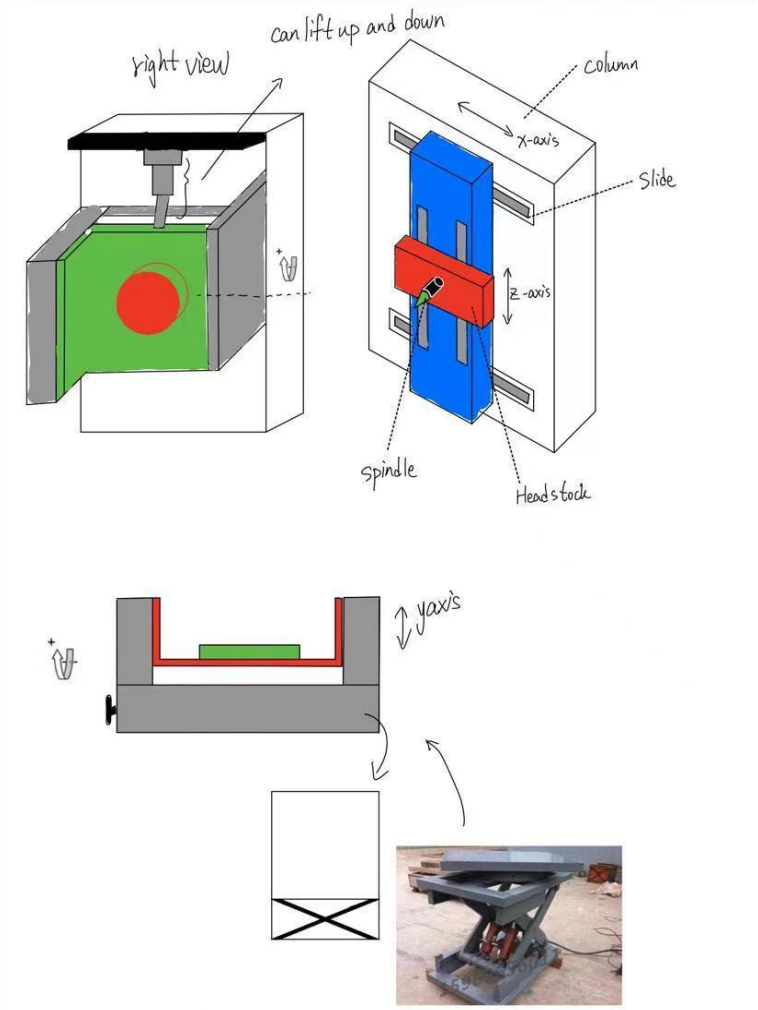


Figure 11: Candidate #2

On this bar, there is a similar mechanism where there are 2 slides in the z-direction on the edges of this big bar. Attached to these 2 slides is one smaller bar which is where the drill bit is directly placed. The second part of the components is at the bottom. The counter is where the specimen of materials can be placed. Below the counter, there is an x-shape scissor lift where 2 x-shapes of a total of 4 bars are placed on two sides. There are 4 pins on each of the tips of the bars and 1 pin in the middle of the cross-section. This mechanism allows the counter to move in the y-direction up and down according to demands. In total, the movement that this CNC milling machine can produce is in x, y, and z-direction.

2.6.3 Candidate #3

Given Candidate #3, the design utilizes a robotic arm machine as shown in *figure 12*. The goal of the design is to provide a lower-cost and greater versatility candidate. As shown in *figure 13*, the first arm of the machine is connected with the machine base with a twisting joint, and the two extended arms are joined by the rotating joint. Each rotating joint is to provide 3 degrees of freedom. The number of axis of movement can be decided depending on the number of robotic arms we choose. Although due to problem identification of this candidate such as vibration issues outlined below, the team did not set additional parameters to decide on the number of machine arms and the exact number of axes of this machine.

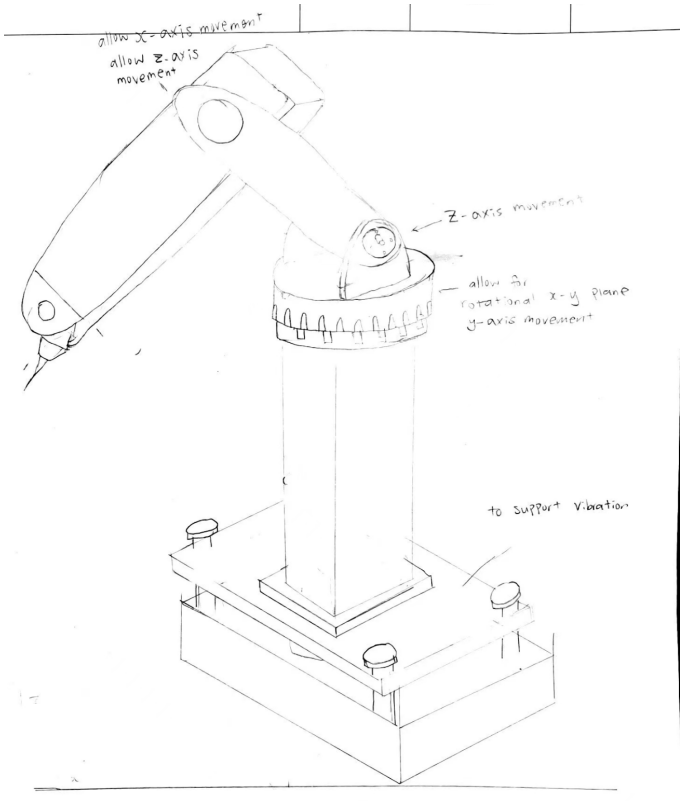


Figure 12: Robotic Arm Milling Machine Sketch

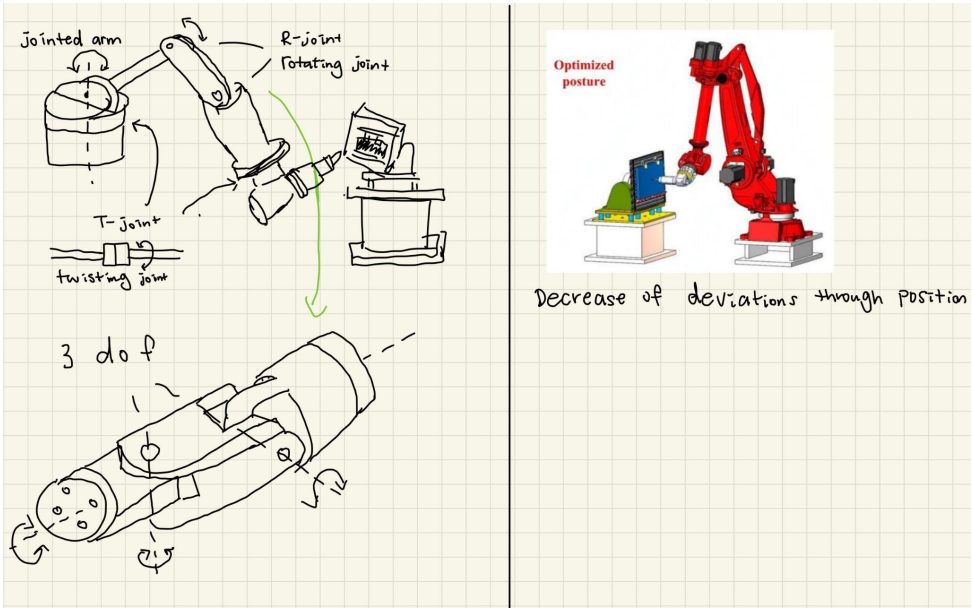


Figure 13: Arm Joints of the Robotic Machine

Though one main challenge of the robotic arm milling machine is the active vibration during milling. The robot arm machines do not provide as much positioning accuracy and can have large vibration onsets from a low capacity of disturbance rejection. [36] In order to reduce the vibrations present, as shown in figure 1, the base of the machine has been added with an extra bed to stabilize the robot arm movements. In addition, by changing the workpiece orientation as shown in figure 3 and figure 4, the direction of the max stiffness created between the milling tool and the workpiece can be adjusted to create the most stable position in order to reduce vibrations. [37]

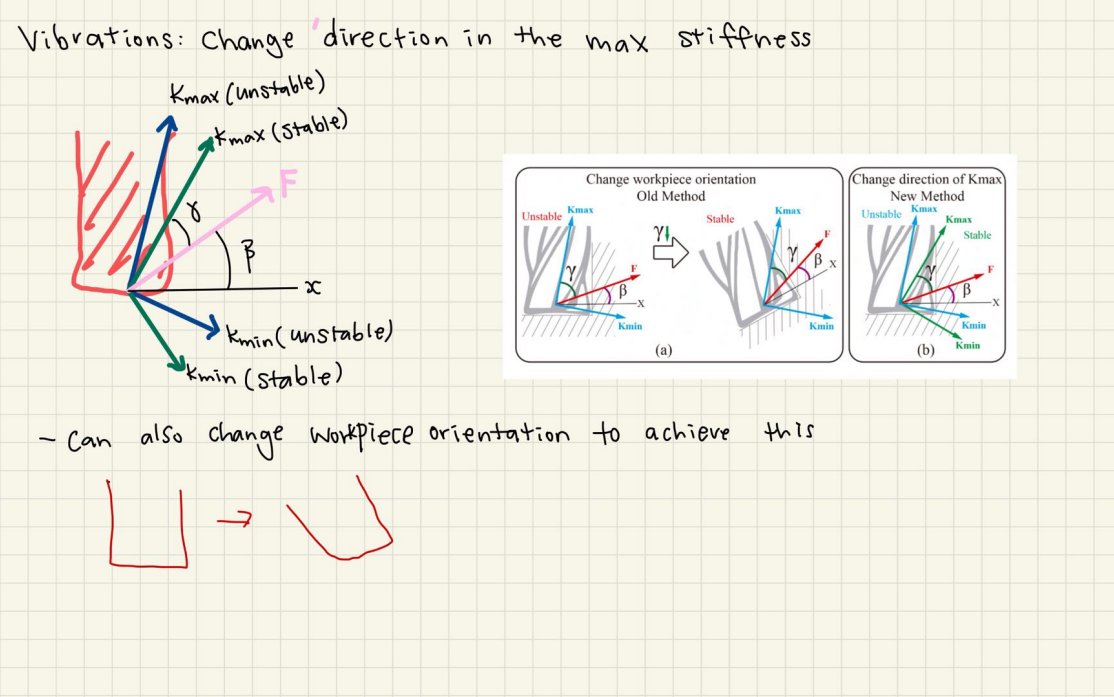


Figure 14: Workpiece Orientation to Reduce Vibrations

Candidate Design Selection

	Vibrance toleration	**Accuracy**	**Movement in 5-axis**	**Price**	**size/dimension**
Candidate Design #1	Can tolerate different radial and axial loads. hence, it can tolerate unnecessary vibrations.	Not super accurate due to the 4 corners might not support the worktable and not having too much vibration while milling the workpiece.	Can move in 4-axis	$5,000-$10,000	Relatively large in order to produce higher precision and fewer vibrations

		(the four corners will have vibrations while milling)			
Candidate Design #2	Can not handle the x-direction load due to the fact that the milling area is vertical (not enough support)	Not super accurate due to having a vertical milling area with no good support.	Can not move in 5-axis, it only moves in 3-axis.	$3,000-$7,000	Can be relatively compact in base area
Candidate Design #3	Can not tolerate the vibrations really well due to the fact that each axis of movement does not have separate support which can ensure the stability of movement during milling.	Not super accurate due to not having a good support for the spindle.	Able to move in 5 axis, although may produce high vibrations	$4,000 <	Requires a relatively large size in order to have stronger support at the base, and is higher in height due to the design

In addition to the comparison, given that design #3 has the least toleration towards vibrations, and through research, it has found no-ideal solution to solve such concerns with our current project need and complexity, therefore candidate design #3 has been eliminated first from the design selection. Regarding candidate #1, most of the design mechanisms are suitable for the final design but the price is too high and also this design can only move in 4-axis and because the

desired CNC milling machine is to have movement in 5-axis, candidate #1 gets eliminated. Therefore, regarding candidate #2, even though it is currently unstable due to vibrations, and is rather hard to operate, there are solutions and potentials to improve on this current design since it can have more flexibility and changes on the structures of the design. Given the comparison between the properties, candidate #2 was chosen to be redesigned and used as the final design.

2.7 Design Analysis and Description

2.7.1 1st Iteration of the initial candidate design 2:

In order to allow for a more stable and flexible movement of the worktable, the swing system was removed, and with replacement of the worktable to be able to rotate in 360 degrees. To allow for more axial movement and flexibility in the design, the spindle is changed from being static to also being able to rotate in 360 degrees in order to mill five faces of the workpiece, with addition of z-axis movement on top of the x and y-axis movement.

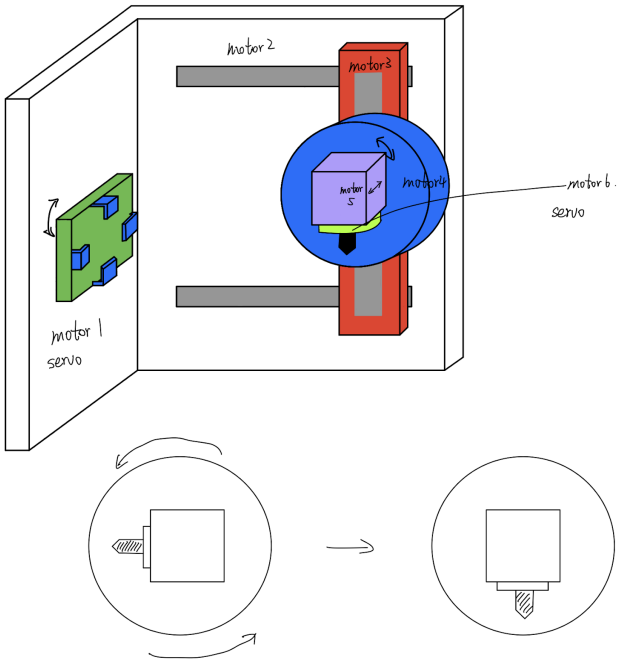


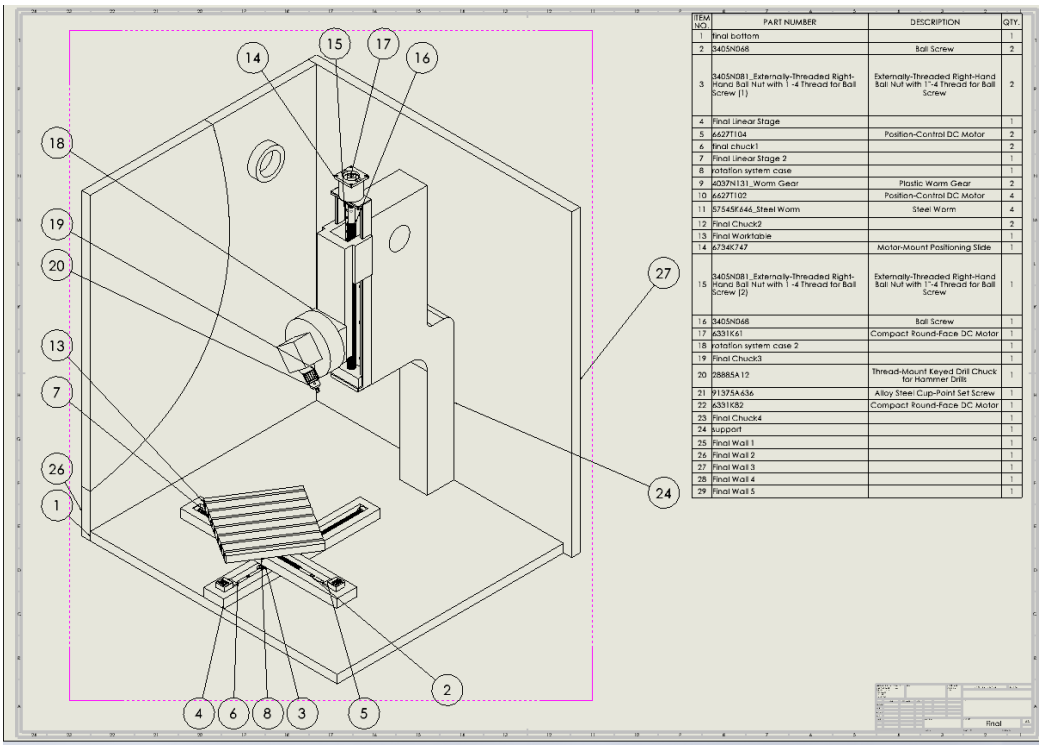
Figure 15. 1st iteration of the candidate design 2

2.7.2 2nd Iteration of the candidate design 2:

Due to concerns of vibration and instability from the first iteration, the worktable is changed from vertical to horizontal, since when it is attached to the base, it is more stable, which means less vibration which can cause errors or accidents during the milling process. In addition to the vibrations caused by the spindle moving in x, y, and z-axis causing less precision, the spindle movement is being removed with sole movements in the z-axis and replaced by adding them to the work table. Support is being added to the z-axis linear stage (spindle) to also reduce excessive vibrations. This second iteration provides us with the foundation of our final design.

2.7.3 Explanation of Device Operation

Our design is a 1200 mm × 1200 mm size 5-axis CNC milling machine with a work table of size 400 mm × 400 mm and it is capable of cutting through metals. The gear ratio of the design is 1 : 1. Thus, the input motor has a rotational speed of 12500 rpm implies the output speed is also 12500 rpm. In order to implement the requirement of 5 axes, there are 3 sliding bars inside the design. In figure 16, underneath the work table, there is a pair of cross sliding bars which allows linear transportation in X and Y direction. On the side where the shank and motor box is, there is the third sliding bar that allows the shank and the motor to linearly transport in the Z direction. The other 2 axes are rotational. The rotational axes one is at the work table and the other is at the shank.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	final bottom		1
2	3405N068	Ball Screw	2
3	3405N081_Externally-Threaded Right-Hand Ball Nut with 1 -4 Thread for Ball Screw (1)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	2
4	Final Linear Stage		1
5	6627T104	Position-Control DC Motor	2
6	final chuck1		2
7	Final Linear Stage 2		1
8	rotation system case		1
9	4037N131_Worm Gear	Plastic Worm Gear	2
10	6627T102	Position-Control DC Motor	4
11	57545F646_Steel Worm	Steel Worm	4
12	Final Chuck2		2
13	Final Worktable		1
14	6734K747	Motor-Mount Positioning Slide	1
15	3405N081_Externally-Threaded Right-Hand Ball Nut with 1 -4 Thread for Ball Screw (2)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	1
16	3405N068	Ball Screw	1
17	6331K61	Compact Round-Face DC Motor	1
18	rotation system case 2		1
19	Final Chuck3		1
20	28885A12	Thread-Mount Keyed Drill Chuck for Hammer Drills	1
21	91375A636	Alloy Steel Cup-Point Set Screw	1
22	6331K82	Compact Round-Face DC Motor	1
23	Final Chuck4		1
24	support		1
25	Final Wall 1		1
26	Final Wall 2		1
27	Final Wall 3		1
28	Final Wall 4		1
29	Final Wall 5		1

Figure 16. The full detailed drawing of the design.

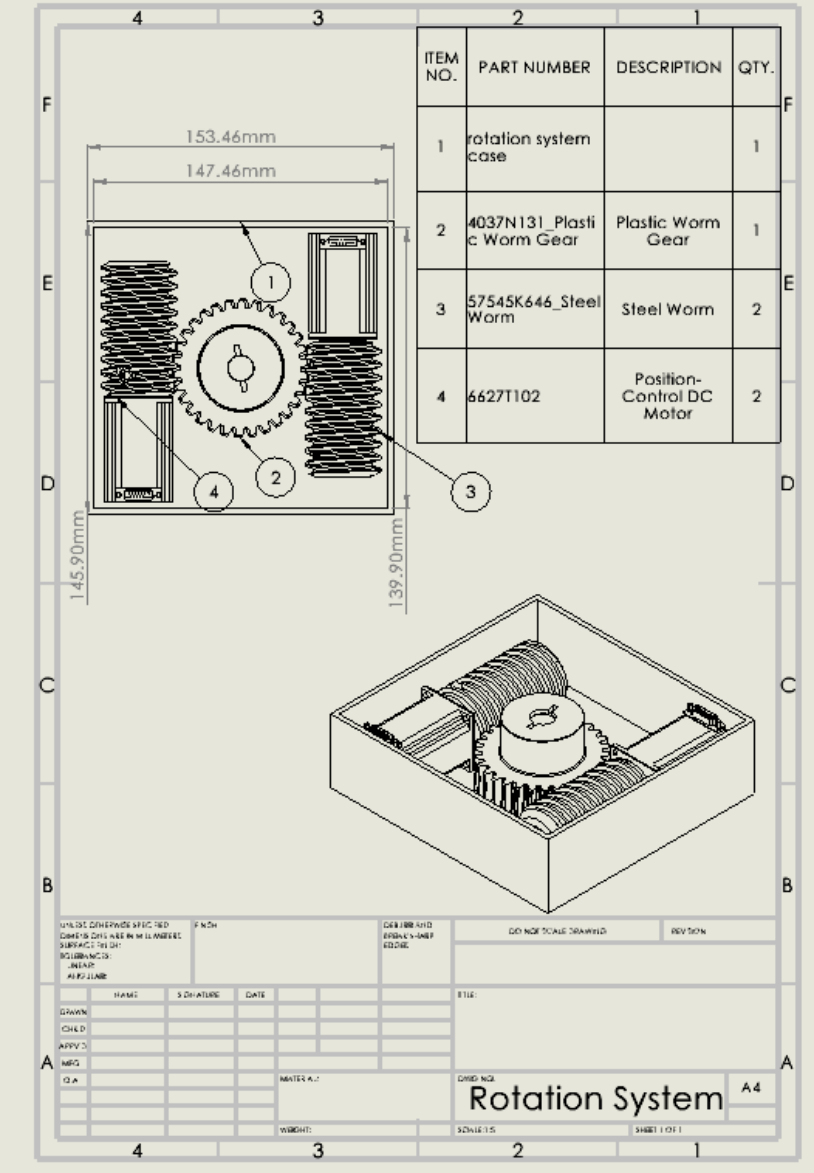


Figure 17. Worm gear box as the rotational system.

The mechanism behind the rotation system is the worm gear box. This allows the work table to rotate on the X - Y plane like in figure 3, and the motor box to rotate in the Y - Z plane.

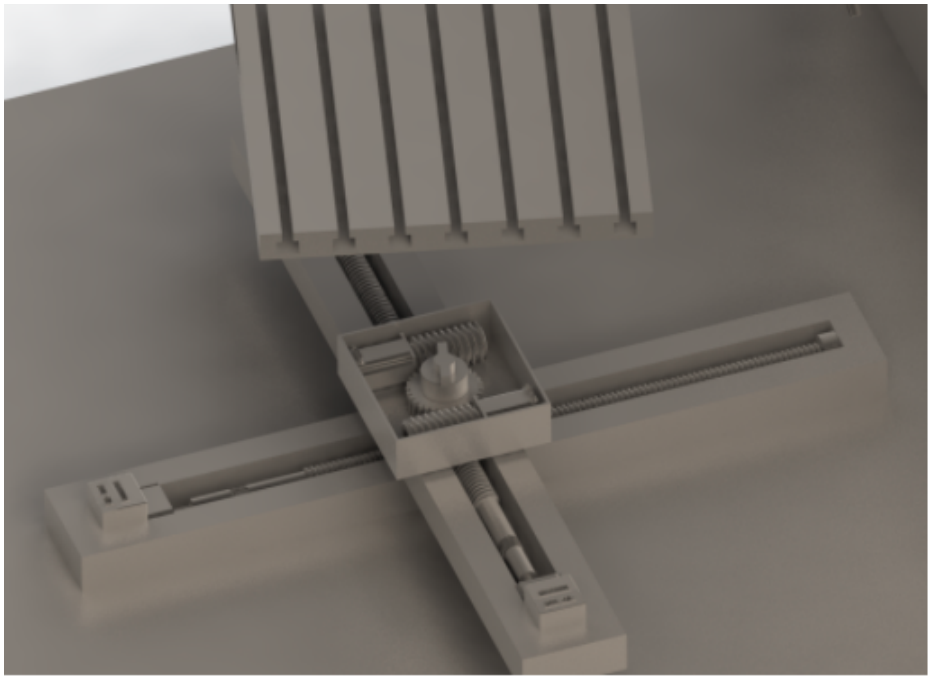


Figure 18. The rotation mechanism of the work table.

Since a CNC milling machine is capable of cutting through metals, as being operated, safety is a crucial factor in designing a machine like this. Hence, there is an emergency button added in case of accidents, it instantly stops the machine. The red emergency button is visibly present within reach of the operator. The emergency button instantly stops the machine when an emergency situation occurs.

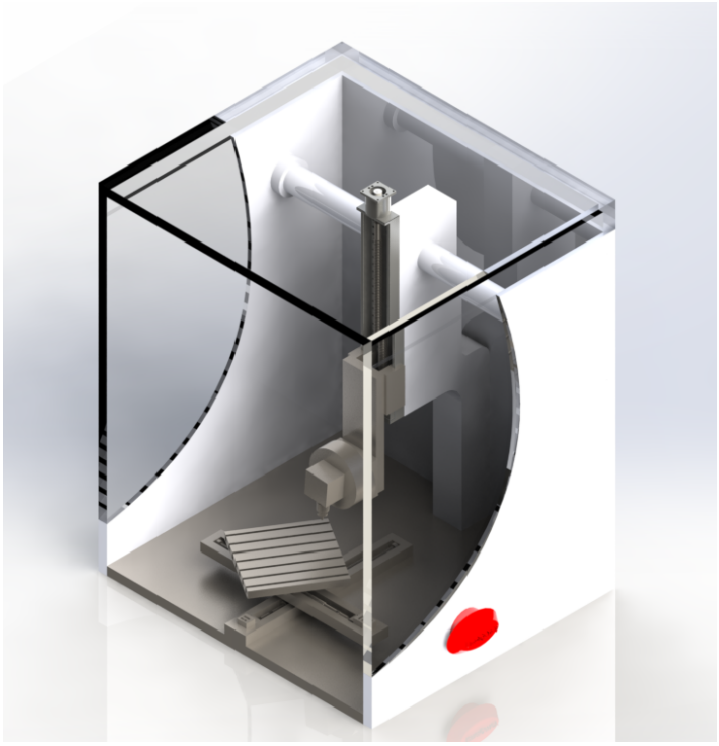


Figure 19. Final Design

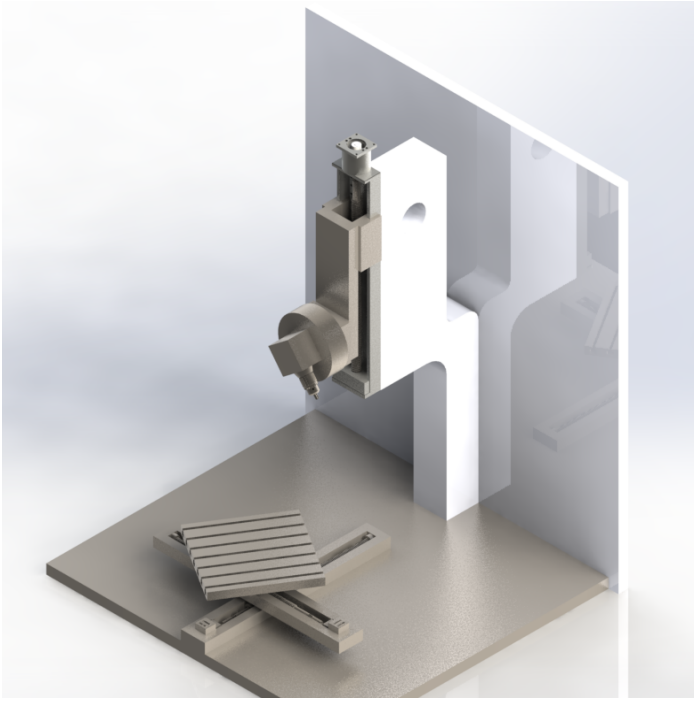


Figure 20. Final Design without casing

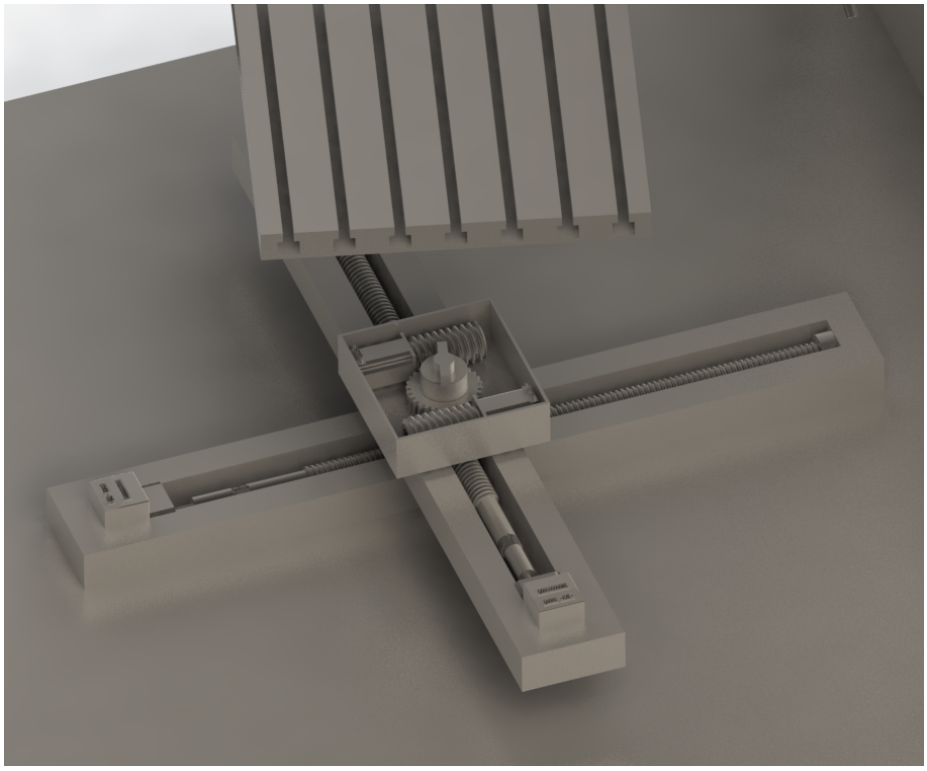
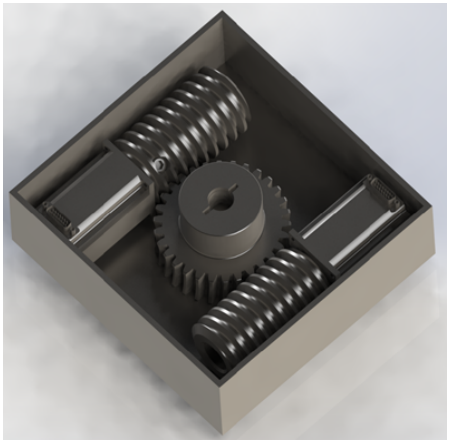
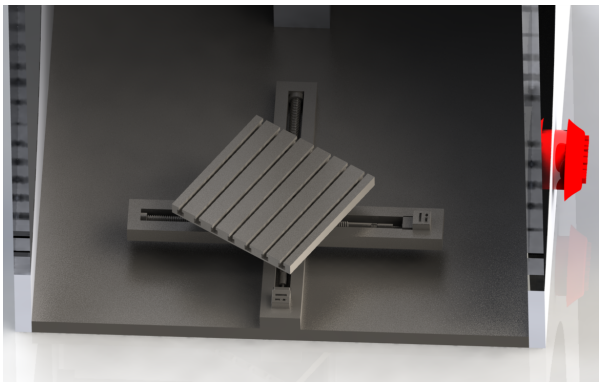


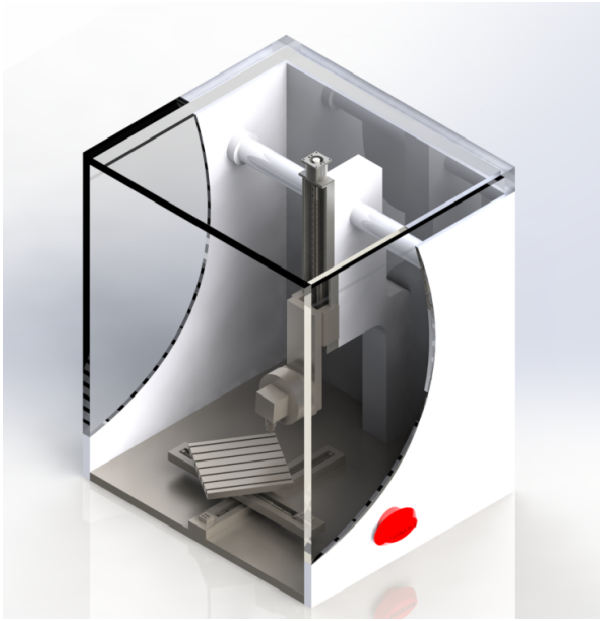
Figure 21. Final Design worktable

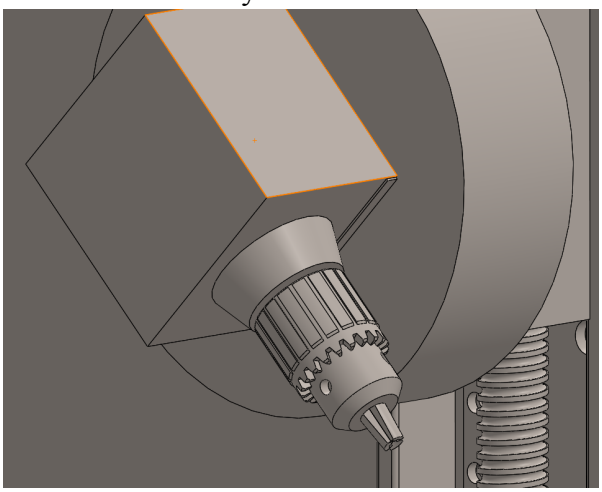
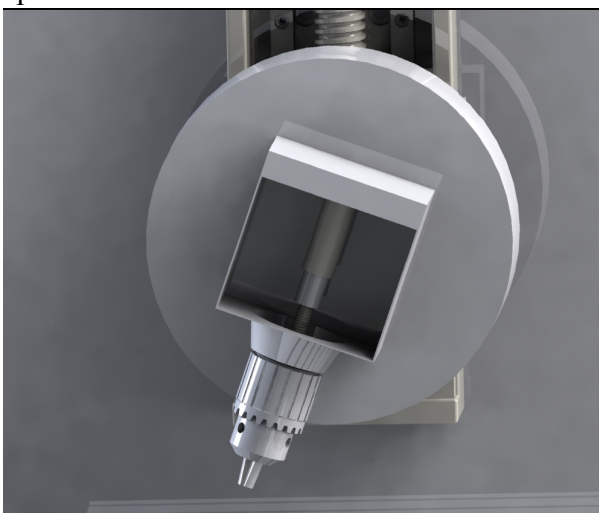
2.8 Justification of Component Selection

Component	Justification
Worm Gearbox with two worm gears and one worm wheel 	● The worm gearbox was used for the transformation of the milling area and spindle. ● Two worm gears and a worm wheel were used to make the rotation in the x-y plane possibly because they have a large speed ratio which allows the milling area to adjust its speed as needed when milling the material. Also, not being able to reverse power transfer is an extra point for the worm gears because the milling area should be stable and this property in addition to its ability to withstand external forces helps the milling area to be stable and make the final engraved material accurate.
Ball screw linear stage with servo motor on the top	● Creating stable controlled movement along the axis ● Includes a position feedback control

	system for position-control, therefore provides the ability to hold the motor at specific angular positions, which is ideal in the motion control of the spindle piece
Two perpendicular Ball screw linear stage with stepper motor(24 Volts DC, 8,574 rpm @ 2.62 in.-oz round-faced motor) at the base 	• Stepper motor provides the ability to position, therefore being able to use for transportation of the work table • Able to brake between angular steps • This provides resolution to form the linear stage with the worm gear • Given that the work table requires • Two perpendicular ball screw linear staging with stepper motor was used to move the movement of the milling area in the x, y direction possible. The ball screw was used because it allows for the movement to be accurate and have the minimum amount of torque transmitted which causes the milling area moment to be very accurate and causes the overall outcome to have high accuracy. In

	addition,+ they are efficient ball screws and they transmit less torque, they have lower friction and run at cooler temperatures which is an extra plus. On the other hand, frequent lubrication is required for these components and they should be changed frequently due to wear-out. [38] ● Since the stepper motor used is less expensive than that of the servo motor, it is also beneficial to use this as the functions of the stepper motor already sufficiently fit the need of the transportation of worktable.
Motor-Mount Positioning Slides and Ball Screws	● The slides are used as a vertical linear stage ● Ball screws are used due to their feature of roller balls within the helical grooves, this provides the ability to reduce wear due to mechanical contact within the screw assembly

	• The sliding friction is replaced with rolling friction [39]
Acrylic Sheet Casing 	• The clear acrylic sheet casing provides the ability to see through the milling operation more clearly for safety and procedural reasons • The acrylic sheet material is also less expensive compared to other clear casing materials such as glass and is also lighter in weight, which helps in the opening and closing of the casing • The casing also provides means of filtering and blocking external dust from going into the machine. • Acrylic sheet is a transparent plastic with outstanding strength, stiffness and optical clarity. Acrylic sheets are easy to fabricate. [40]
Material use of Stainless steel	• Majority of the materials being used for the design are stainless steel, given its ability to resist corrosion and withstand

	high temperatures, this help prevent the constant replacement of the components
Drill Chucks & Keys 	• Milling chunk is used to hold different spindles and give the user an open option to choose different spindles.
Spindle 	• The spindle is attached to one of the walls in the casing in order to give less vibration when milling and cause high accuracy. • A ball screw linear staging was used to give the machine the access to move in the z-direction. It allows for the movement to be accurate and have the minimum amount of torque transmitted which causes more accuracy. • Attached to a maximum 12500 rpm dc motor

Nuts	• Ball nuts are used in order to transmit forces to loads, ball nuts provide this transmission with high accuracy and precision. [41]
Emergency Button 	• The red emergency button is visibly present in order to ensure the safety and health standards of the machine • The emergency button instantly stops the machine when an emergency situation occurs

2.9 Total Cost Estimation

Due to considerations of cost, the majority of the components used within the design utilizes existing components, the custom parts includes the 400 x 400mm work table, as well as the supporting pole for the motor-mount positioning slides.

Name	Serie Number	Price ($)	Quantity
Ball Screws [42]	3405N068	535.40	3
Nuts [43]	3405N081	129.08	3

Worm Wheel [44]	4037N131	29.17	2
DC Motors[45]	6331K61	113.41	1
Worm Gears [46]	57545K646	88.06	4
Position-Control DC Motors with Integrated Driver and Controller [47]	6627T102	632.46	4
2x Position-Control DC Motors with Integrated Driver and Controller [48]	6627T104	682.14	2
Motor-Mount Positioning Slides	6734K747	1936.31	1
Drill Chucks & Keys [49]	28885A12	92.97	1
Total: $8456.72			

In order to reduce the cost and to provide an estimation of the cost of the design, most materials are chosen from existing parts within Mcmaster Carr. From the components used, the overall cost of the design is around $9000 considering the addition of some minor customized parts including the work table and the supporting pole. It is believed to be within a reasonable price range given from the research and engineering specification, given a design for a 5 axis desktop-milling machine. A part of the price rise is due to various implementations regarding consideration of a long-lasting design such as the choice of materials (using stainless steel to prevent corrosion and heating,) the use of ball screws to prevent wear from within, having casings to prevent debris and dust from getting into the machine, etc. The team believes that such implementations are necessary, and the price is reasonable given the quality and accuracy of the 5-axis design.

2.10 Drawings

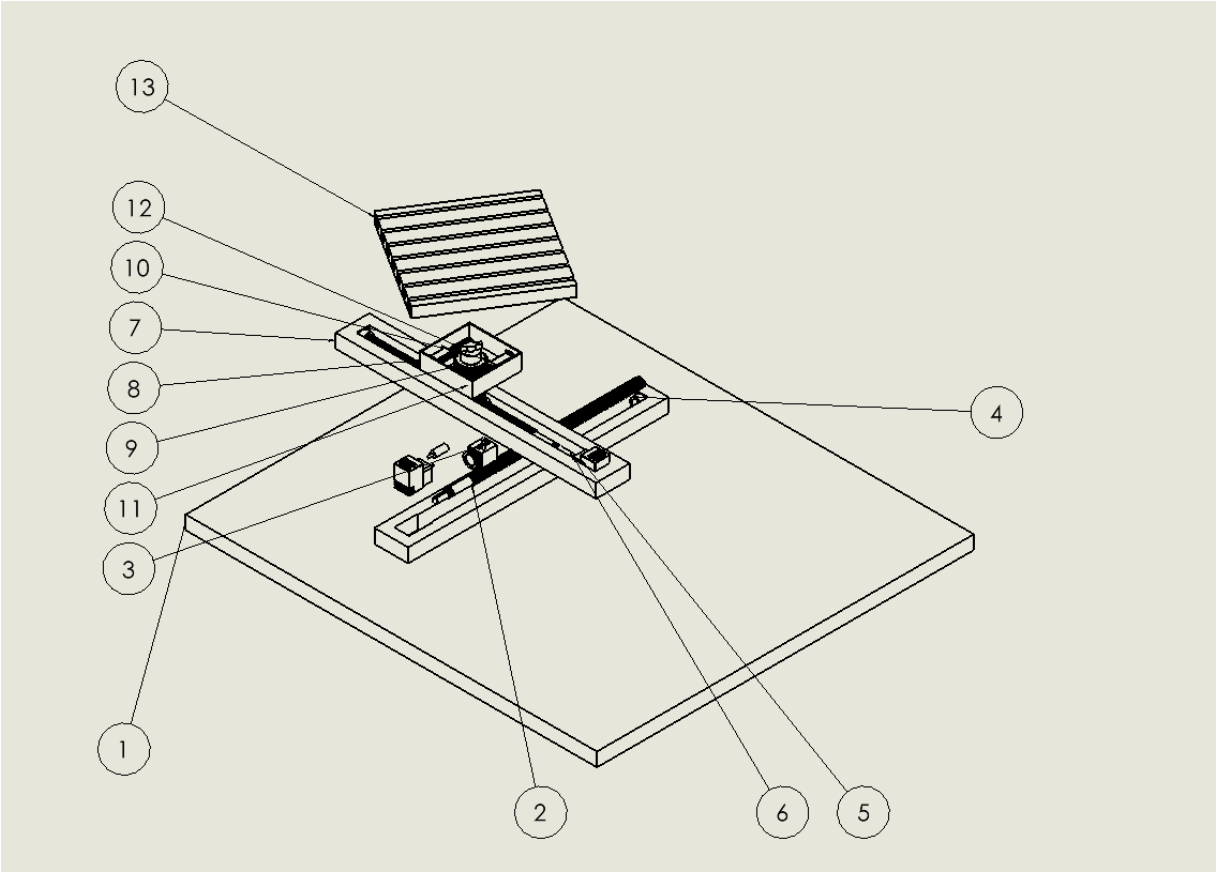


Figure 7. Drawing of the exploded view of worktable

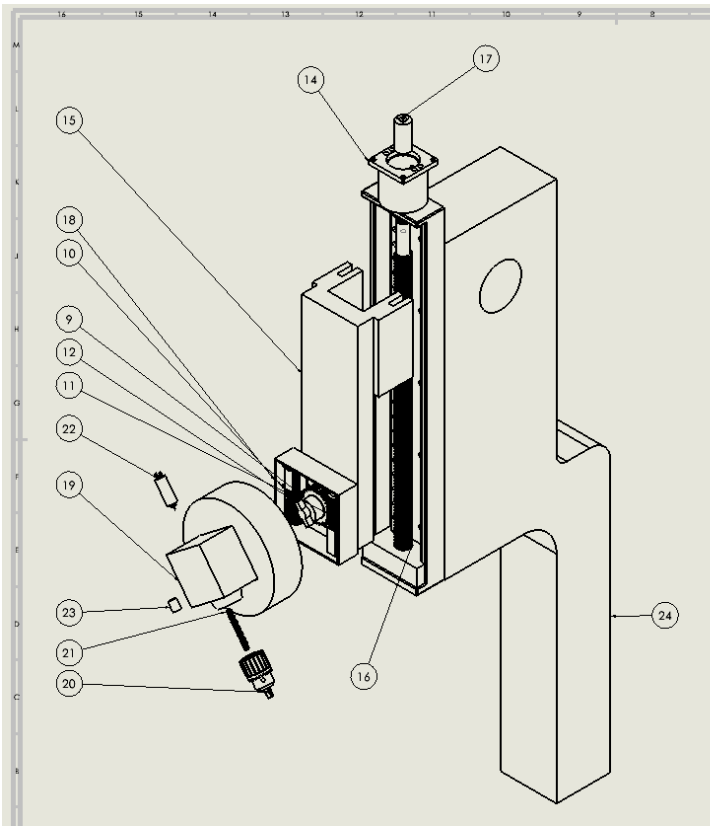
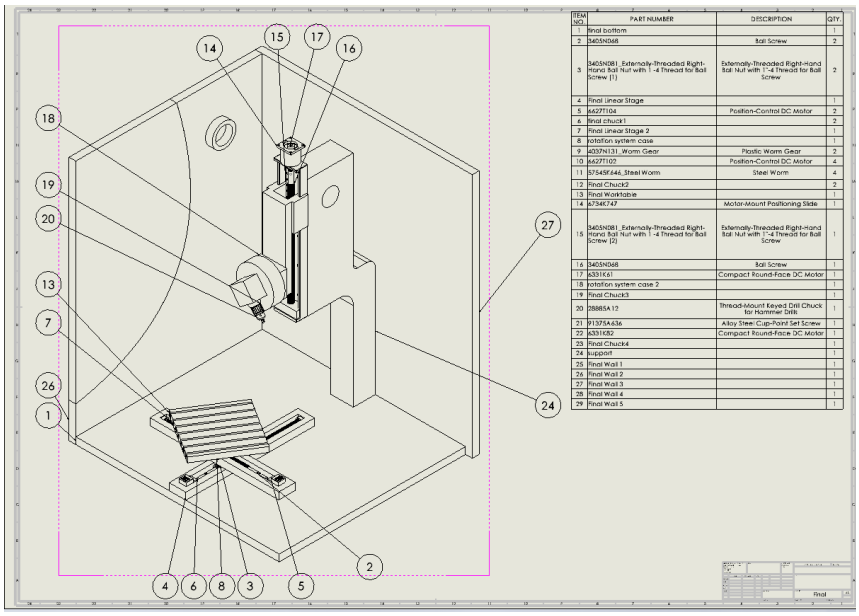


Figure 8. Drawing of the exploded view of Spindle



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	final bottom		1
3	5405N068	Ball Screw	2
5	5405N081_Externally-Threaded Right-Hand Ball Nut with 1-4 Thread for Ball Screw (1)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	2
4	Final Linear Stage		1
5	6627T104	Position-Control DC Motor	2
6	final chuck1		2
7	Final Linear Stage 2		1
8	rotation system case		1
9	6537N131_Worm Gear	Plastic Worm Gear	2
10	6627T102	Position-Control DC Motor	4
11	57545F446_Steel Worm	Steel Worm	4
12	Final Chuck2		2
13	Final Worktable		1
14	6734K747	Motor-Mount Positioning Slide	1
15	5405N081_Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw (2)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	1
16	5405N068	Ball Screw	1
17	6331K61	Compact Round-Face DC Motor	1
18	rotation system case 2		1
19	Final Chuck3		1
20	28885A12	Thread-Mount Keyed Drill Chuck for Hammer Drills	1
21	91375A636	Alloy Steel Cup-Point Set Screw	1
22	6331K82	Compact Round-Face DC Motor	1
23	Final Chuck4		1
24	support		1
25	Final Wall 1		1
26	Final Wall 2		1
27	Final Wall 3		1
28	Final Wall 4		1
29	Final Wall 5		1

Figure 9. Drawing of the Final Design

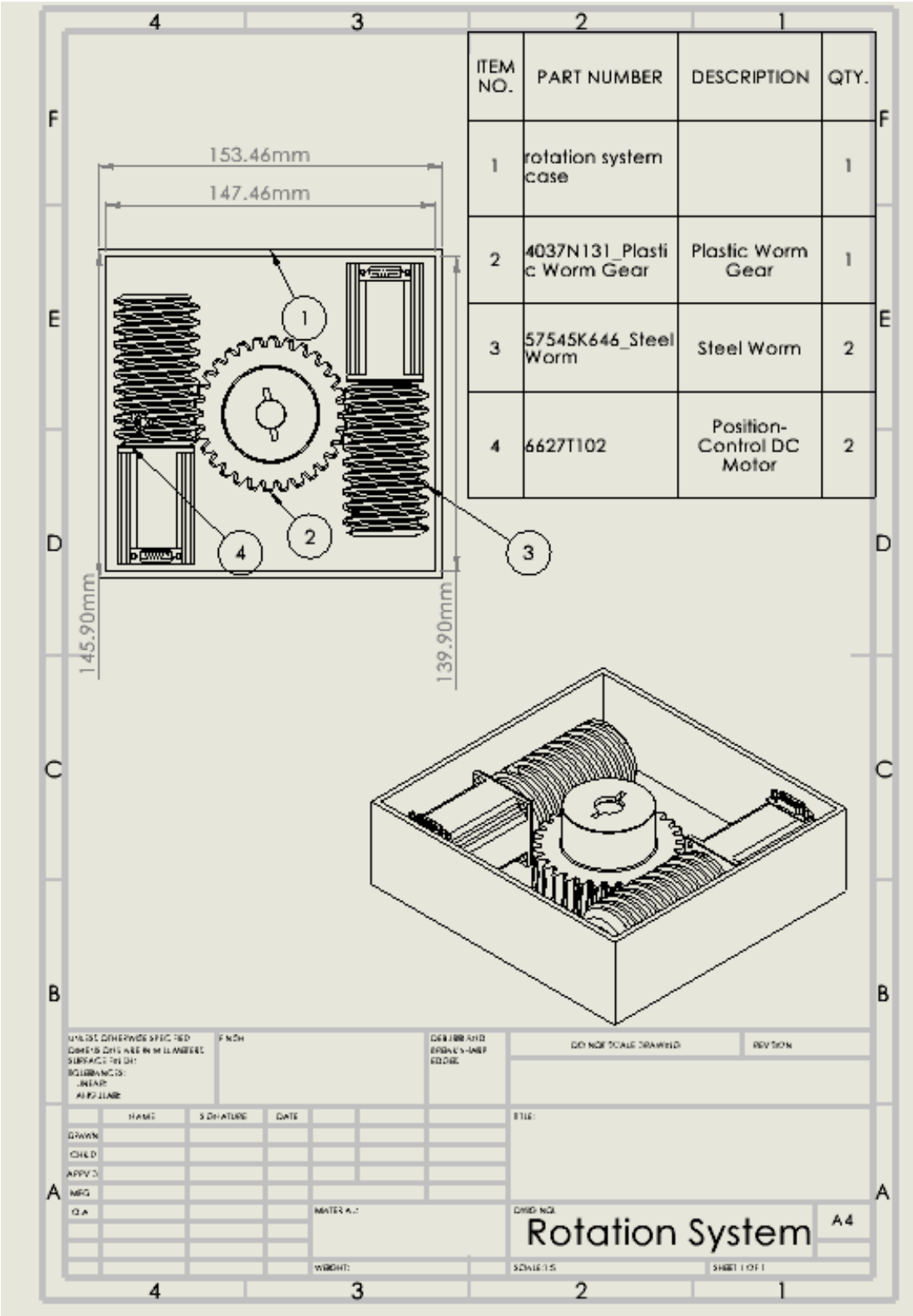


Figure 10. Drawing of the Rotation System

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	final bottom		1
2	3405N068	Ball Screw	2
3	3405N081_Externally-Threaded Right-Hand Ball Nut with 1 -4 Thread for Ball Screw (1)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	2
4	Final Linear Stage		1
5	6627T104	Position-Control DC Motor	2
6	final chuck1		2
7	Final Linear Stage 2		1
8	rotation system case		1
9	4037N131_Worm Gear	Plastic Worm Gear	2
10	6627T102	Position-Control DC Motor	4
11	57545K646_Steel Worm	Steel Worm	4
12	Final Chuck2		2
13	Final Worktable		1
14	6734K747	Motor-Mount Positioning Slide	1
15	3405N081_Externally-Threaded Right-Hand Ball Nut with 1 -4 Thread for Ball Screw (2)	Externally-Threaded Right-Hand Ball Nut with 1"-4 Thread for Ball Screw	1
16	3405N068	Ball Screw	1
17	6331K61	Compact Round-Face DC Motor	1
18	rotation system case 2		1
19	Final Chuck3		1
20	28885A12	Thread-Mount Keyed Drill Chuck for Hammer Drills	1
21	91375A636	Alloy Steel Cup-Point Set Screw	1
22	6331K82	Compact Round-Face DC Motor	1
23	Final Chuck4		1
24	support		1
25	Final Wall 1		1
26	Final Wall 2		1
27	Final Wall 3		1
28	Final Wall 4		1
29	Final Wall 5		1

Figure 11. Bill of Materials

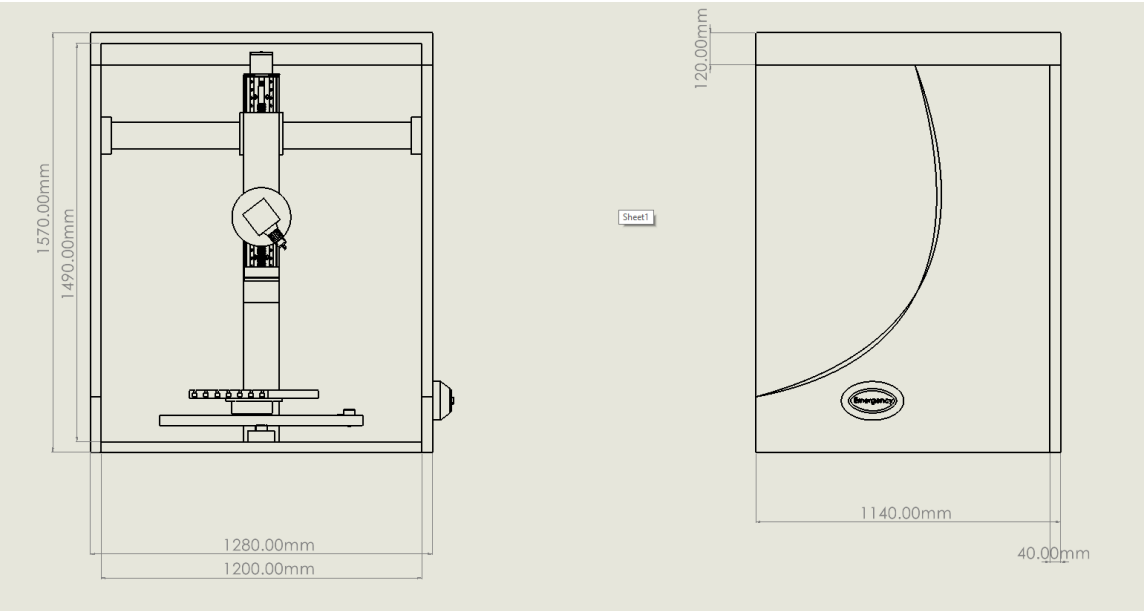


Figure 12. Drawing Front view and Right view of Final Design

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