MIE 243 - Final Project Report

Entry-Level Milling Machine

Project Group 25

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1. Introduction

1. 1 CNC Milling Machine and our Project initiative:

Unlike traditional production machines, CNC (Computer Numerical Control) milling machines stand out in manufacturing industries for their extreme precision capability and the vast pool of parts they can produce compared with other types of mechanical devices. For example, a Punching machine in Detroit can only have one specific car hooding tool, possibly with a few potential variances. In contrast, the NC mine can deliver many possible parts if size, material, and any other minor limitations are imposed [1]. CNC Milling Machine is commonly used in industry for prototyping and manufacturing parts with high precision limited quantity requirements.

CNC milling machines are often used in the industrial market. They are commonly bulky in size [1], many of which require a Three-phase power supply, lubrication at regular intervals, sometimes the additional installation of environment, for example, wastewater pipelines [2]. Many industrial purchases will include installation delivered by the supplier, where groups of engineers will arrive on-site to install with a maintenance contract: standardized maintenance procedures which the buyer shall abide by, procedural maintenance process where the company could send maintenance engineers to, or the when the machine will be sent back to the supplier and then returned, which will take time ranging from 2 weeks to 2-3 months [2]. Small scale CNC Milling machines are with prices ranging from 2,400$ to 7000~9000$[1]

These machines are commonly used in industry to manufacture parts with limited quantity requirements but high precision. Note, however, that functionality is also a need for a potential market outside of industrial usage. There is at present little CNC Milling Machine product available for the individual consumer market. Light users, who have a limited budget for an industry-level CNC machine, do not expect professional installation into the workshop because of limited space for positioning a large-scale product and power source (especially no 3-phase power supply). As a result, they have a reduced expectation of machine precision and production efficiency. Team notes that these customers are often prone to machines with less maintenance [3].

To sum up, the team recognized a need for an entry-level CNC milling machine with reduced cost, size, weight, maintenance, and reduced expectation in precision production efficiency.

1.2 CNC milling machine common application in the market

Most of The team's advanced versions may have a 4th or 5th rotational axis to allow precise shapes of varying dimensions to be machined[4]. With five-axis practices all the basis, the Micec transverse motion directions (x, y, z-axis), and proceed to add on rotation axis) to allow the for the elephant r angled and varying dimensions machining. Aside from those with "cutting" functionality, where the material is held horizontally from the side of the machine, nearly all devices feature their rotary motion system, if applicable, in the lower portion of the device, containing their material to be cut upward. A transverse motion system assembled at the bottom directly moves the rotary motion system horizontally at the side of the machine to achieve side motions and upward downward-moving motions. There are also designs where the transverse motion system is wholly realized at the top of the device [5]. On the machine, the entire ceiling is transverse-motion functional.

The team notices that not all industrial Milling machine practices apply to our design. For example, as seen in this application, [5] the transverse motion is entirely done on the ceiling, the upward-downward movement done onto the design of the spindle, which is expandable and shrinkable. This is hardly applicable in our smaller design since if we make the spindle itself expand and shrink capable, we will risk the torque elevation to reduce spindle precision and overall design reliability. This is not a problem in large-scale design since an object's dimension (length, width, height) amplifies by **2x**, its cross-sectional area amplifies by **4x**, volume amplifies by **8x**. The material's anti-bending capability (stiffness) is related to the cross-sectional area and volume, which increase by **4 – 8x**, but torque is related to length (dimension), which amplifies by merely **2x**. This risky design, as adopted by industrial machines and some function in industrial level CNC machines, **is by nature not replicate-able in our small scale design,** not to mention our consideration of price and light-weight.

This is but a brief hint of what our design should consider. Because of this, a standardized and academic engineering design procedure is to be adopted to create a product that typical individual consumers will love and be willing to buy.

Figure 1.2.1 Representation of How Scale Could Affect Design

Figure 1.2.1 [6]: A hint of how scale can affect design: Recall the difference between elephants and Mice: Mice have petite sizes. Thus, as discussed above, have high surface v.s. volume ratio, this means their heat dissipates quickly, so they have thin skin and high heart rate to maintain their heat, especially compared to elephants, which have rough skin and low heart rate.
Imagine an elephant the size of a mouse, or a mouse the size of an elephant. With thin skin and a high respiration rate, the Mice, being greatly amplified its size, will decrease soon due to overheating. On the other hand, the elephant will pass away due to hypothermia.
This is yet another reason why we should not directly copy industrial machines!!

2. Engineering Specification

From the problem statements and thorough market research, our team has identified several major design requirements for this project. We have also set some necessary assumptions and internal constraints to the product.

INPUT to OUTPUT process in these subtopics.

Overall size:

- The design must be "desktop-size."
- Internal Constraint: the side length of the final casing should not exceed 25 inches.

Operating Principle:

- According to the Problem Statement, the minimum number of axes is 3.
- Internal Assumption: our design should have 4 or 5 axes.

Estimated Cost:

- The design should not be high-end, so the customers should not "afford products at the very upper end of the market price range."
- Internal Constraint: our design should not exceed $5000.

Capabilities:

- Being able to cut material in at least three directions
- The machine should be able to cut wood and metal materials.
- A coolant system should be added to prevent the spindle from being too hot.

Ease of Use:

- The machine should be operated easily by at least entry-level professionals.
- The machine is expected to change the cutting tool automatically and change a minimum number of 5 milling tools.

Health and Safety:

- The machine should be environmentally-friendly, so the dust, cooling fluid, and metal scrap should be recycled in a sealed case.
- The Overall Casing should have high toughness to prevent failure under high vibrations and temperature.
- If a transparent cover is used, it should have high hardness and fracture toughness.

3. Candidate Designs

3.1 Candidate Design 1

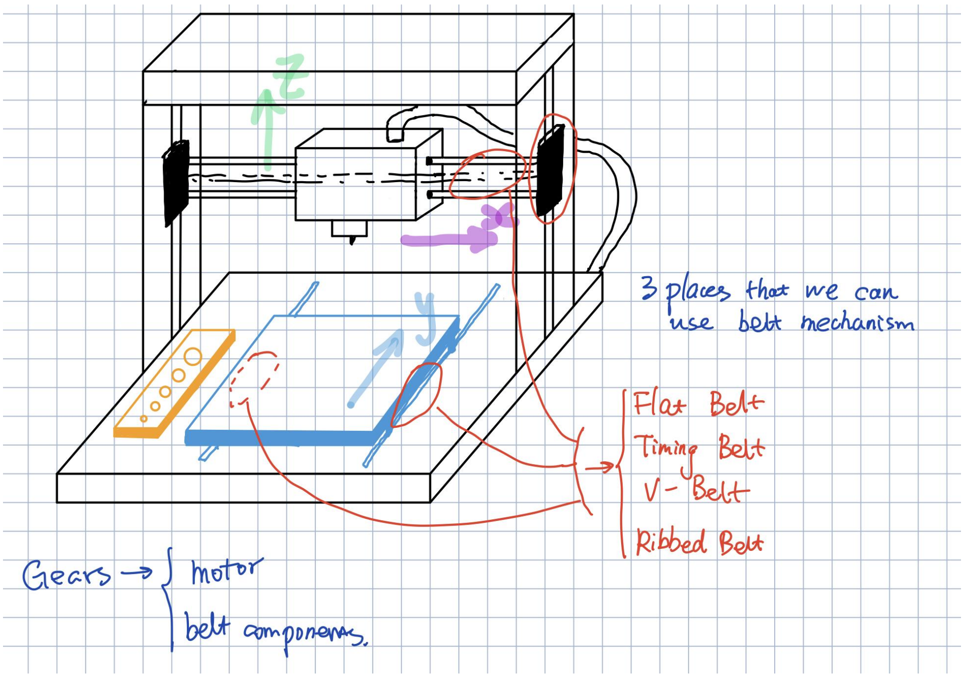


Figure 3.1 Conceptual Sketch of Candidate 1 - *"The 3-axis Design"*

This candidate design is for a three-axis CNC milling machine. The idea is quite minimalistic. Three axes are simply in the x, y, z directions, respectively. The spindle can go up or down (z-direction) and left or right (x-direction). The table on the base can go forward or backward (y-direction).

There is a set of spindle sections on the left side of the base (orange box). For the x and z-direction movement of the spindle, a ball screw mechanism can be used. For the y-direction movement of the table, an electrical sliding table can be used.

- Ball Screw - Move objects in a single direction.
    - Motion conversion: rotation (input) to linear (output)
    - Motion modification: high speed, low torque (input) to high torque, low speed (output)
    - Used for the spindle to perform x and z direction movement.
- Electrical sliding table
    - Motion support: support the object on the machine.

3.2 Candidate Design 2

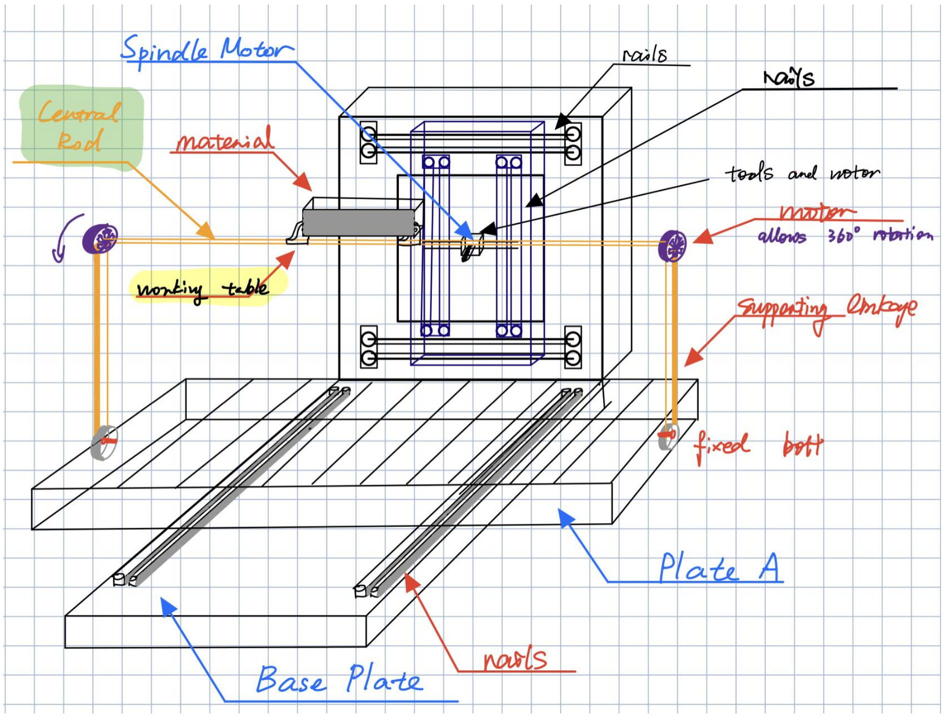


Figure 3.2-1 Conceptual Sketch of Candidate 2 (Version 1) - *"The 4-axis Design"*

Based on the previous 3-axis design, we added one more rotational axis to the working table (shown in orange). Now the material could be mounted between two fixing points on the central rod, and the rotational motion of the rod itself is controlled by one initiative motor on one side of the rod. The followings are some features of this design:

1. The spindle motor is situated on the back wall of the machine on a separated plate (the rectangular shape in Figure 3.2-1). The plate could move vertically on the trails to allow movement in the z-direction.
2. The plate for the spindle motor is on top of two horizontal rails on the back wall so the spindle can also move in the horizontal direction (y-axis).
3. Plate A is located on top of the Base Plate rails would move on the x-axis.
4. The supporting linkage of the central rod is connected to the working table using fixed bolts, so the linkage itself will not rotate.
5. The material (or sample) is mounted to the central rod by a press fit or clamp-related mechanisms.

After the first check-in, we realized that the torque from the rotation of the central rod could be too large for the fixed bolts to withstand, so it will possibly lead to the failure of the supporting linkage. Thus, we modified the existing mechanism (see figure 3.2-2).

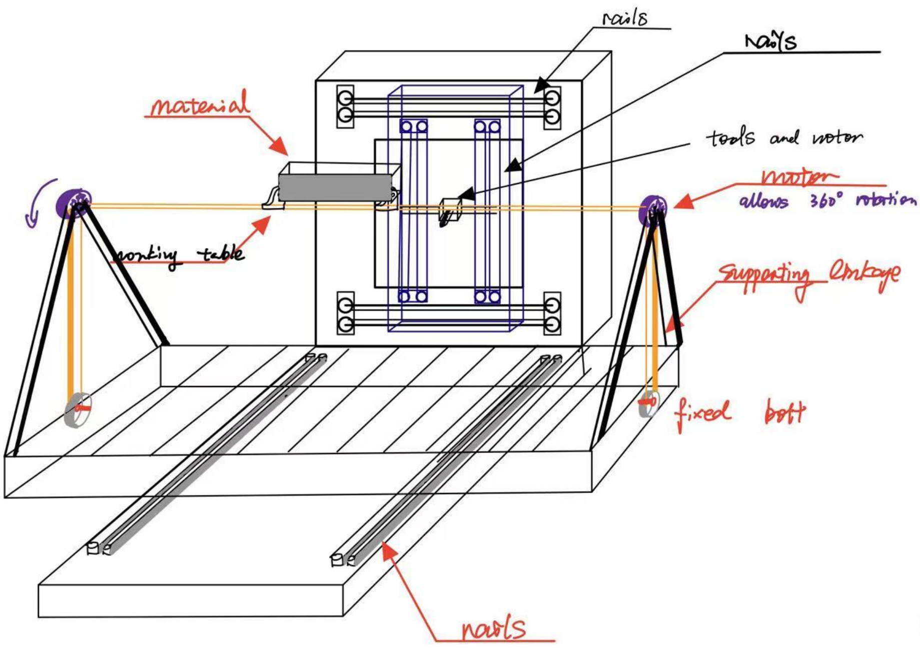


Figure 3.2-2 Conceptual Sketch of Candidate 2 (Version 2) - *"The 4-axis Design"*

- We added two more supporting linkages between the motor and Plate A to separate the torque. In addition, the triangular shape will increase stability.

3.3 Candidate Design 3

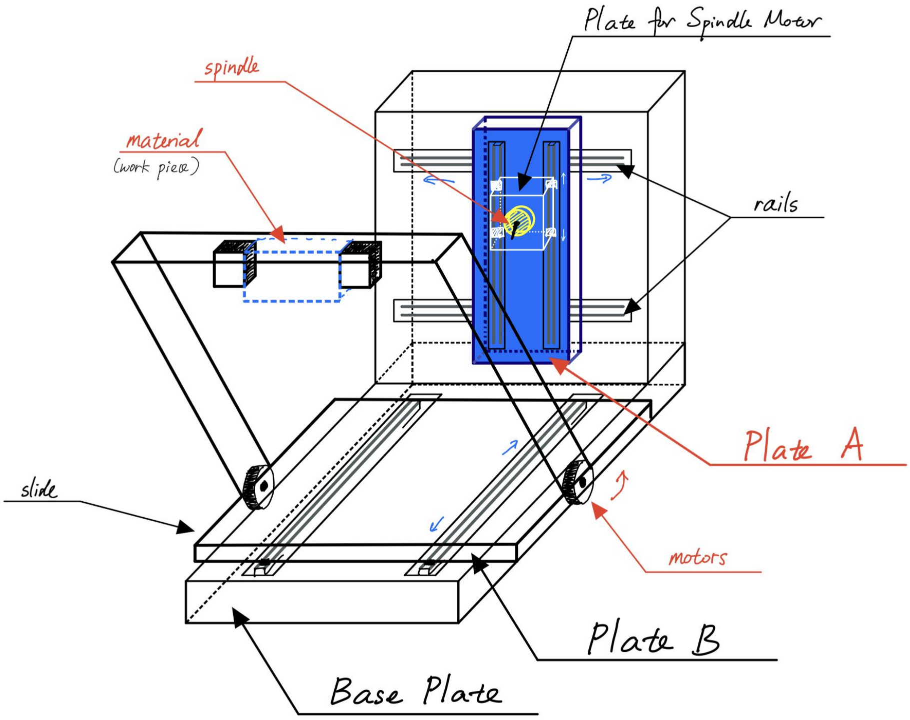


Figure 3.3 Conceptual Sketch of Candidate 3 - *"The 4-axis Design"*

Following a similar approach from Candidate Design 2, we made further modifications in Candidate Design 3. The main goal here is also to rotate the working table and the spindle should locate vertically on the back wall. However, we changed the location of the rotational axis to the base plate so the larger degree of freedom could be reached. The features for this design are listed as follows:

1. The size of the Plate for the Spindle Motor (marked white) is reduced so the linear motion in the z-axis is expanded (the travel distance is increased by more than 50%).
2. The distance between two rails on Plate A is reduced so the horizontal travel distance of the motor is increased.
3. The central beam is in a "U shape" and the material could be mounted on the shaft by press fit or clamp.
4. Two electric motors could control the rotation of the central beam and are moving in the same phase. They are connected to Plate B by bearings.
5. The material for the central beam should have high tensile strength and could withstand large torsional torque.

3.4 Candidate Design 4

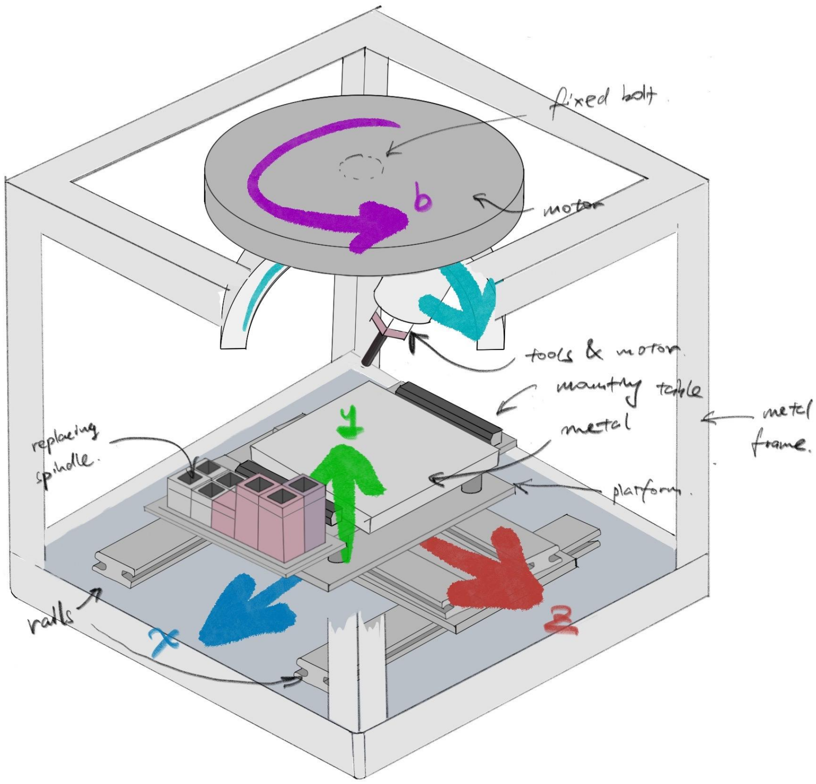


Figure 3.4 Conceptual Sketch of Candidate 4 - *"The 5-axis Design"*

Figure 3.4 demonstrates Candidate Design #3, a 5-axis proposal with three sizable axes transverse + 2 axes rotational motion. Note that the mechanism that facilitates movement gathers either at the top or bottom of the invention in this design, with transverse motion exclusively at the bottom and rotational motion solely at the top. The design features:

1. Rotation of the spindle in a plane(notated using the Cyan arrow) perpendicular to the **clamping table** while having the spindle tip maintained roughly at the same geometric position, simplified as the light grey downward-placing Arc at the upper portion of the design in Figure X1.
2. A rotary platform holds the former and allows it to spin(notated using the purple arrow) around the y axis, thus rotating the plane. The spindle can be positioned to provide a well-rounded angled cut. This is simplified as a grey cylinder "motor" in Figure X1.

This candidate has the most relevance to our final design proposal. However, this design still suffers the drawback of the following aspects:

1. Two sides of the arc obstruct the potential movement of the **clamping table**.

2. Designing for the arc to be motion-precise is complex and can potentially involve too many customized parts, which drastically increases manufacturing cost, thus market price.

This was a good approach as it intuitively expressed and inspired the advantage of designing 3-transverse 2-rotation mode and proved it being doable in the case of desktop design. This candidate has the most relevance to our final design proposal: where the latter mainly focuses to resolve the potential instability of the top mechanism (the mechanical structure supporting and rotating the spindle).

4. Detailed Designs

The team has divided the project into three major mechanisms, with different team members in charge of corresponding research, justification, and CAD processes. The major mechanisms are identified as follows:

- The rotary table and its supporting component
- The spindle with the coolant
- The overall outer casing

Thus, this section will introduce the explanation and justification of component selection for those three major mechanisms.

4.1 The External Support of the Rotary Table

4.1.1 Selection of main power/motion source/input in the rotary system

The team went into depth to decide which power input they needed for the mechanism that provides the two rotary motions of the material (lower portion of the design).

The team first eliminated the use of hydraulics. Not only because they are not covered in lectures that we are not familiar with, but also because our motion output or rotational motion requires high-precision and motion control. Hydraulics only offers linear motion and thus is hard for it to drive a rotary motion either when directly connected to the potential circular plate, 2. Connected with rack and pinion to turn linear to rotational, since still, the precision of hydraulic is doubtable at CNC machine precision standard, we think hydraulics is actually only suitable for two-stage motions: expand, and shrink, any intermediate state is hardly controllable. This limits our input source to motors.

The team waived all **chemical motors**, as they require manual energy input (gasoline/diesel), emit gas, sound, cause vibration, and smell like motor oil, it also cannot provide effective positioning. Its smell also eliminates itself from being used in our spindle system.

The team did not choose a **Direct-Drive motor**, though they deliver high torque and acceptable precision, high torque high precision models often mean greater size and weight, which is not tolerable in desktop CNC machines. These motors are mostly used in turn, so they are not within the function our machine aims for [7].

The main struggle team was between Brushless Servo Motor and Stepper motor. A stepper motor typically delivers higher torque at low speed (<1000rpm) than a servo motor, and provides usable detent torque since most of them have high pole count, usually between 50 and 100, significantly more than a servo motor, with pole count between 4-12 [8]. This means the stepper motor is capable of holding the shaft exactly still for a moderate amount of torque. Also given its peak torque at 0 velocities, it can even better hold the shaft static given constant power input.

Servo motor delivers a constant torque throughout the potential increase of angular speed. This means as the torque of the stepper motor decreases towards 0 with higher rpm, the servo motor offers the same torque constantly. As seen below.

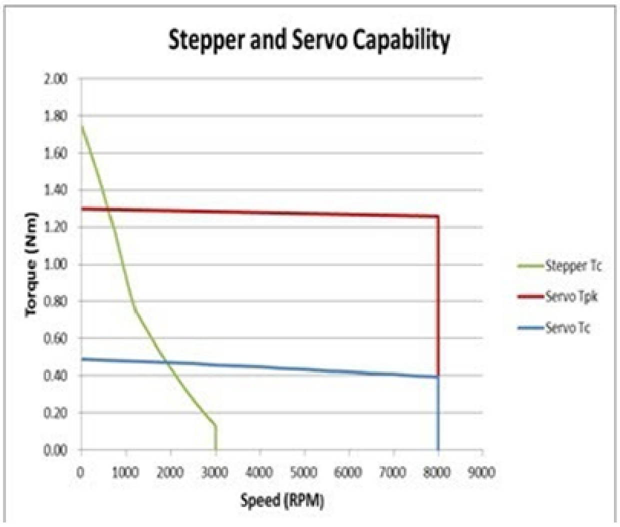


Figure 4.1.1: Stepper and Servo Torque v.s. speed General demonstration

Servo motor also benefits from its fundamental control principle: it adopts a closed-loop control system, which means if excess torque is applied and step loss occurs, the servo motor is able to compensate by rotating more, but Stepper motor, due to its open-loop system, won’t even notice its step loss. One way to prevent this overload scenario is to increase the engineering torque limit of the motor, presumably by 3 times [9], but this increase in size and weight and power does not worth it, since overload condition is not normal usage, using 3 times better Stepping motor for only 1% time usage is a waste of torque and money.

Servo motor also outweigh Stepper motor since it operates silently and with no vibration, since Stepper motor has these issues, especially when operating in low-speed condition (~300rpm) --- our thought on using a stepper motor, seeing its drop-in torque effect(Regard Figure Z1) is to limit it to operate under 1000rpm, but this has a chance to result in 1. vibration of the motor, 2. noise and 3. potential heating, which significantly complexed the discussion.

We noticed, though, that the above function of the servo motor comes with a significant increase of weight and motor volume: since a servo motor always comes with its own encoder, and has a higher market price than a stepper motor.

This was really a tough decision, both servo and stepper motor have almost balanced pros and cons. We then decided to postpone this decision to a later session: Motors are inputs, **knowing input is high-speed low-torque rotational motion, we will only decide which one to use once the functional mechanism is designed.**

4.1.2 Swinger support part selection justification:

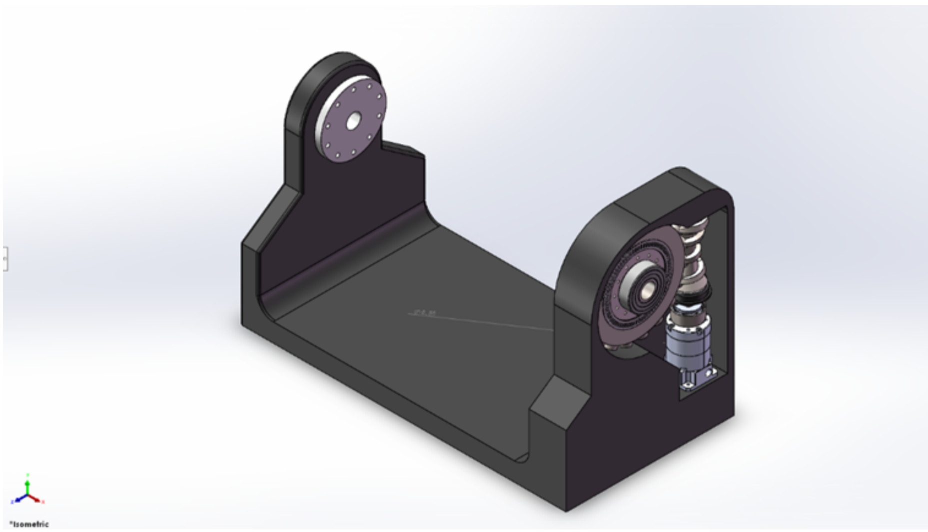


Figure 4.1.2: Swinger support Isometric View

Below is the part justification of Swinger support (dark U-shaped hold mounted onto the bottom of our milling machine, under the Swinger).

The swinger support section is designed to <u>1. hold the swinger</u> and <u>2. drive the swinger to achieve rotational motion along the Z-axis, and hold the swinger rigid at any position within the given angular displacement limit (θ=(+/-)90°). Therefore, this requires</u>

1. a supporting mechanism to stand the total weight of swinger (including mechanism assembly inside of swinger) + rotary table + weight of potential material to be cut + minor downward (-Y direction) point force delt by spindle during the milling operation.

2. a mechanism that spins the rotary table by first rigidly connecting onto the swinger and applying rotary motion/torque to initiate and maintain rotative motion. This torque required is **low speed and high torque**, and is **non-constant** as the swinger starts from static to motion, and as the swinger rises from the lowest position(marked as θ=0°) to a given angular displacement limit.

The swinger support must fit into a given dimensional requirement of design as specified in Engineering Specification: 20 inch x 20 inch x 20 inch.

The swinger support must be able to be mounted onto the transverse moving system to move along the Z direction.

Below is the Justification of parts by category. NOTE: FOR SAMPLE-SPECIFIC SPECS. OF ALL PARTS, REGARD THE CHART AT THE END OF THIS PORTION, THERE IS NO MENTIONING OF WHY 0.5 INCH SHAFT AND FOR E.G. 0.85 INCH PITCH CIRCLE GEAR IS USED RATHER THAN 0.75 INCH PITCH CIRCLE. THAT IS TOO MUCH WORK AND RESEARCH FOR 2ND YEAR STUDENTS.

4.1.3 Justification of SwingerSupportCase

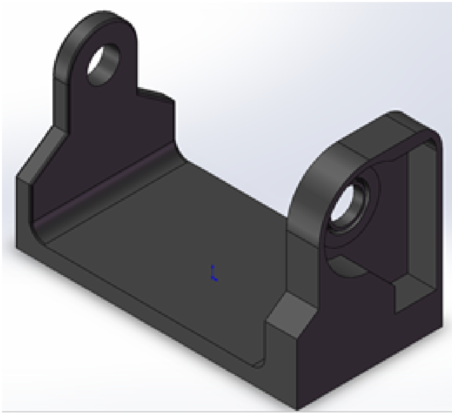


Figure 4.1.3: SwingerSupportCase Isometric View

1. Justification of Overall Shape: This part provides the exterior structure of the entire Swinger Support, every mechanism used to utilize a function in the Swinger Support is to be mounted onto this structure. As seen above, The system should allow a swinger to rotate along an axis. The SwingerSupportCase is designed to be U-shaped just like the swinger since this shape allows 1. two points of attachment that are collinear to the designated axis of rotation of the swinger, 2. The swinger to swing passed the case without physical conflict. 3. at the bottom of the U-shape, is a flat surface that can be attached onto a potential transverse motion system.

2. Justification of Dimension:

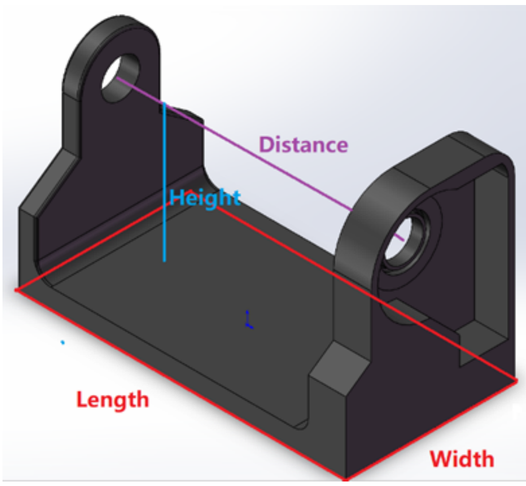


Figure 4.1.4: SwingerSupportCase with dimension suggested

This design aims for desktop size, so the size of the machine(the entire milling machine) should not exceed 20inch x 20inch x 20 inches. We started with the assumption that the rotary motion system will resemble a circular boss as a rotary table, with machinery A under it to drive it rotational along its centerline, with another machinery B driving rotary table, and machinery A rotational along a line perpendicular to the previous centerline.

As shown in Figure Z3, the team estimated the entire rotary motion system will occupy roughly rectangular space, since the dimension limit of the entire design is 20inch, the **length of the rectangle is limited to about 18 inch.** with the width of the rectangle more than but around the diameter of the rotary table, so as to reduce potential conflict with the spindle transverse motion system. The **width is set to be about 8 inches**.

The **height** of extruded holes is determined by the lowest possible position of the swinger (We built the swinger prior to the Support Case, regarding the previous section for Justification of Swinger), this is when the swinger is tilted diagonally: see Figure Z5.

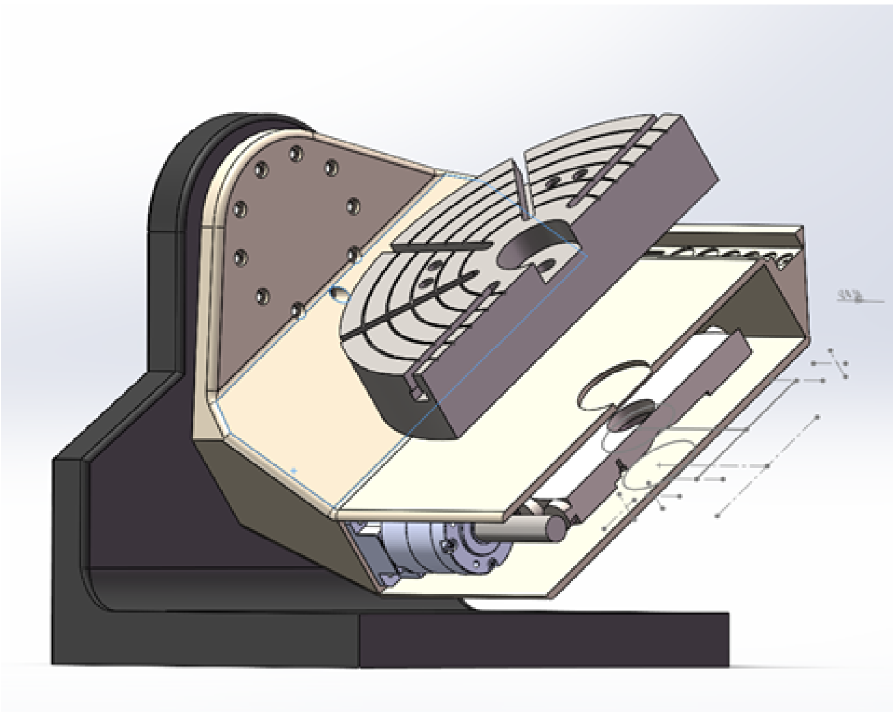


Figure 4.1.5: Sectional view of Swinger + SwingerSupport swinger is tilted,

note the clearance we have at the swinger bottom

We reserved 1-inch clearance (note the gap between Swinger and Support) for safety concerns.

The **Distance** between two inner surfaces of support is determined by referring to the swinger's total width, adding 1-inch clearance.

4.1.4 Justification of inward-concave at +X side:

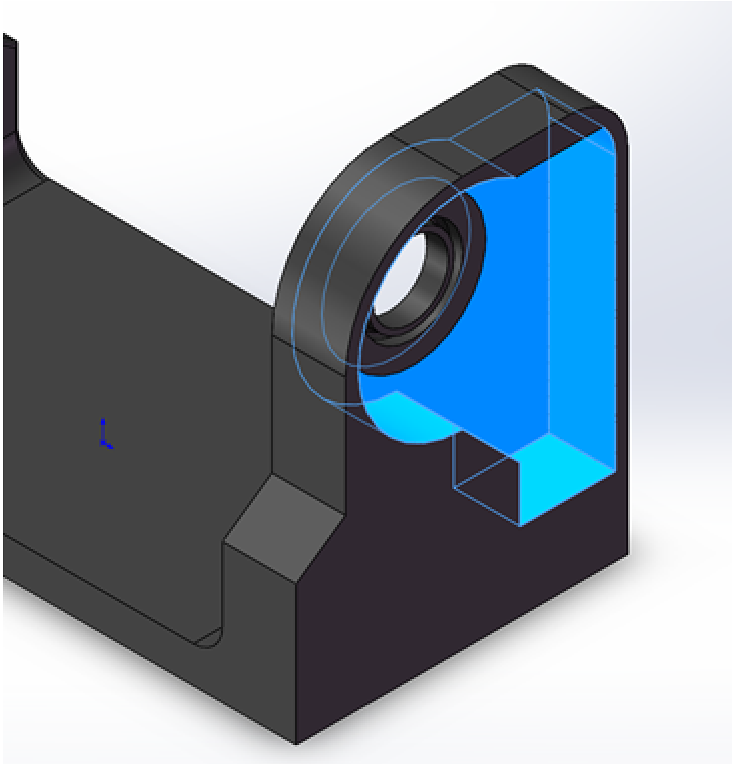


Figure 4.1.6: inward-concave Highlight

In some early prototypes (Regard Figure 4.1.6), we have planned to only use Swing support as pure support with solid inside, with mechanisms that drive the rotary motion mounted externally outside of the support.

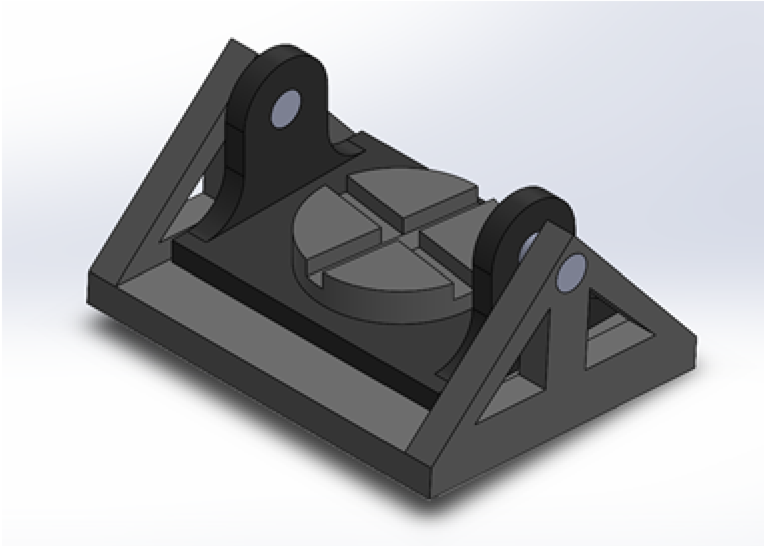


Figure 4.1.7, Prototype in Early interactions

However, the team then realized that if they were to embed the parts into the structure, the machine can be more compact; also because parts exposed to the exterior environment can be susceptible to damage such as corrosion (we have decided the design will be using liquid coolant when a milling job is present).

The reason why the inward-concave roughly features a circle and a rectangle is because of how we decided the parts will be arranged. The team noted that if the motor is mounted in line with the rotary axis since dimensions of motors (especially servo and stepper, paired with gearbox) are typically longer at their axial direction, the length of the motor will greatly occupy the reserved length of support, which is constrained to be 18inch. This will otherwise shrink the angle we reserved for the swinger, thus inflicting potential conflict between spindle and swinger, or will shrink the diameter of the rotary table, which is even more unacceptable.

Mounting the motor perpendicular and non-coaxial to the output shaft also has a hidden benefit, because of mechanisms like worm-and-gear which 1. have a high gear ratio and 2. By nature, preventing backward movement requires the input and output shaft to be non-coaxial and perpendicular.

4.1.5 Justification of **“Roller Cam (WormGear)” and “WormPole”:**

We note a difference in the required rotational motion output with the input. Since we decided that we will be using electric motors, especially stepper and servo, **these motors** (or literally any motors) **typically have high speed and low torque**. We need to decelerate the motor speed thus to increase torque, with **input and output better not be collinear**, as discussed above, this is due to the nature of motors and our machine arrangement.

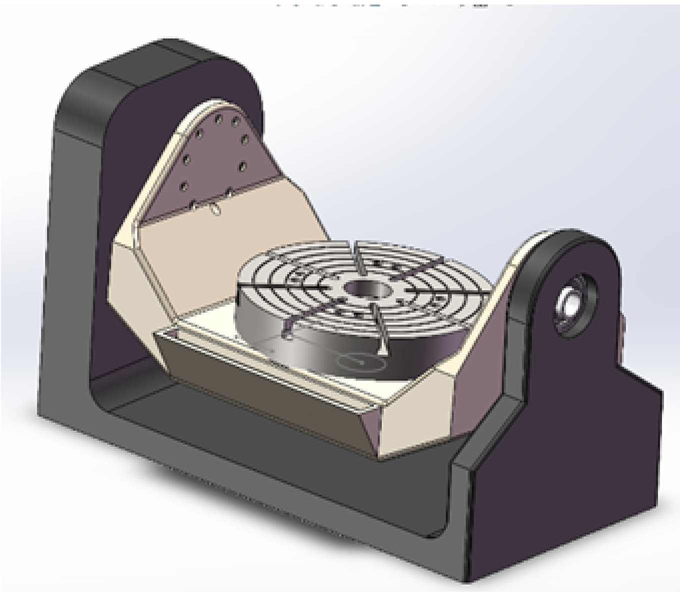


Figure 4.1.8: our arrangement

Since this design is limited to desktop size, we started the design by building the outer shell. Referring to Figure Z8, if the motor is placed coaxial with the output shaft, it will essentially increase the width of the design, which is not what we wish for as a desktop-sized design.

When the input and output shaft is non-coaxial and perpendicular, our choice of motion moderation mechanism is naturally induced toward the worm gear mechanism.

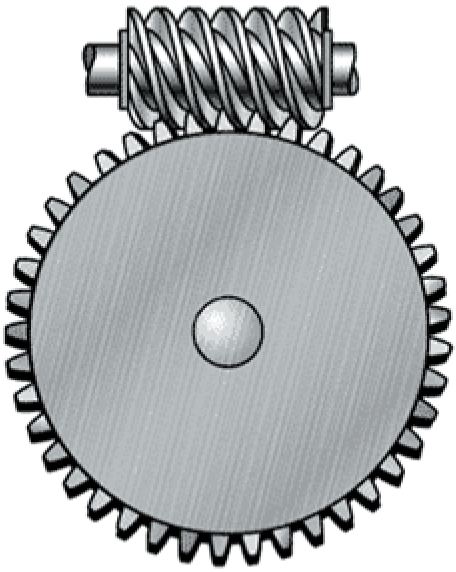


Figure 4.1.10: A typical Worm Gear design

This kind of design benefits the design by High gear ratio which effectively transform High-Speed low torque to Low-speed High torque, this kind of design also helps because as discussed during lectures, they are very good at dealing with reverse motion: in our case, the motor can drive the worm thus rotate the gear at high torque thus rotate the swinger with high power, yet the torque done by gravity coming back from the swinger will have a hard time affecting the motor performance.

In our design, we used a part called roller cam or roller gear cam, which is similar to the worm gear, the only difference is their tooth is replaced by needle roller bearings which rotate around the edge of the tooth of the worm pole upon contact [10].

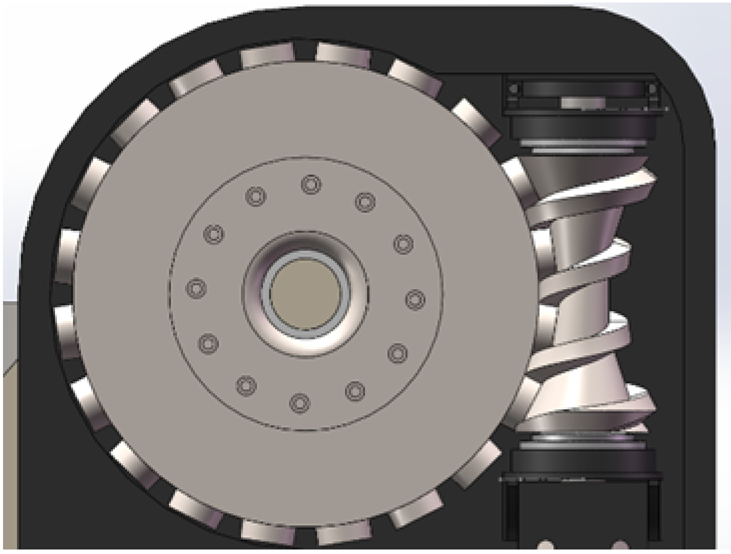
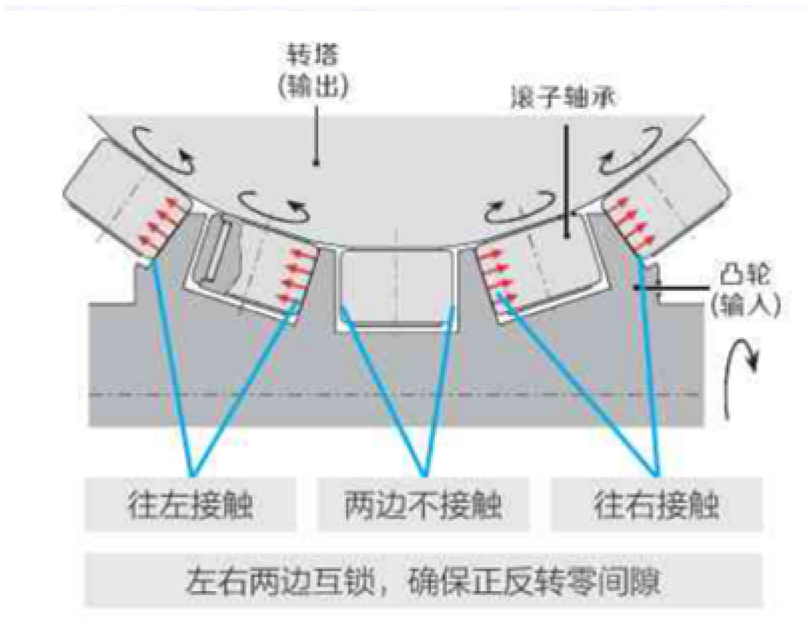


Figure 4.1.11: Team's design arrangement of Roller Cam drive

Due to the fact of how they are manufactured [Figure 4.1.11], the mechanism utilizes needle roller bearings to transmit torque between the roller cam and the worm pole. When coupled with pre-compression [11], these mechanisms can deliver down to zero backlashes. Regarding Figure Z10, one may note that these cam drives are paired such that the point of contact and internal forces are symmetric at the center of connection. This implies that ~zero backlash can be delivered by the mechanism spinning either clockwise or ccw, at any torque within Engineering limits[11]. This is ideal in our use case since it will be utilized in motion control and the swinger will deliver backward torque.



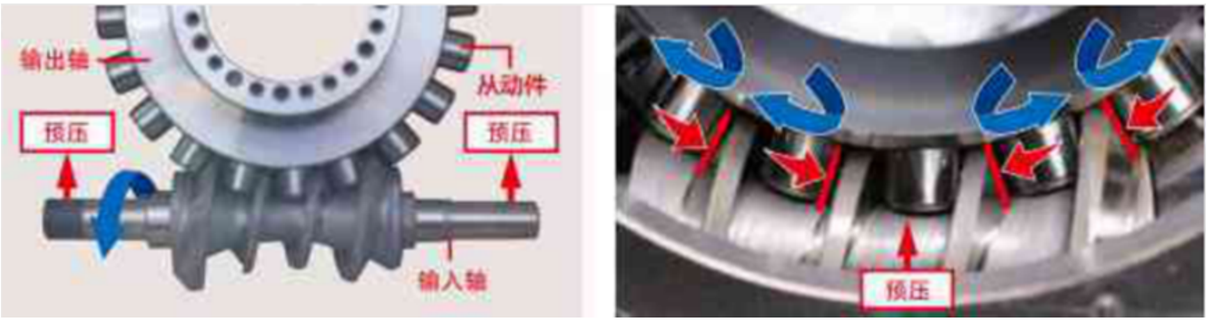


Figure 4.1.12: Graphic demonstration of Roller Cam Drive, Source from supplier[12], note the direction that red arrow points

the use of Roller Cam requires little maintenance as opposed to the regular worm gear, and it greatly reduces backlash toward 0 [13], if coupled with high-precision Motor+Gearbox, this design delivers extreme precise position control; It greatly reduces friction between tooth, which make torque delt from the motor to better transfer onto the swinger shaft. This choice does have various drawbacks, in that **1.** Roller Cam Drives are much more expensive than regular worm gear, but since we have compromised on various other parts in the design and given all the benefits delivered, no backlash, no maintenance, little to no noise, this is the part that we are willing to risk utilizing despite the cost limit: Team consider this to be the highlight of our design which can actually add to consumer value and can serve as promotion technique in that it delivers premium / high-end technique and excellent performance at a medium overall price. This, however, is not totally true, what consumers will not know is that the level of precision relies on the limited load being applied. This introduces drawback **2.** since this is a mechanism that faces guaranteed backward torque from the swinger as it is held away from initial θ=0. The choice of roller bearing at a spot used to be solid tooth reduces friction in between and thus make it easier for torque from swinger to affect motor performance, especially for our selection of stepper motor, which adopts open-loop control, which means no Negative feedback exists to justify the output result have the motor suscept overload which causes the step skip.

4.1.6 Justification of **Stepping motor:**

The Team did recognize this problem. In fact, as said in the previous portion of power source selection, the team struggled and spent an excessive amount of time choosing between Stepper and Servo Motor. The team's decision is that knowing the potential detrimental step skip is undetectable by the motor itself, we will compensate using a larger stepper motor that delivers excessive torque because since the motor is mounted vertically, its size does not affect the size of the entire design.

Choosing a large stepper motor does not trade off size and price, since we know, according to Professor Mackay, at roughly identical engineering specification, a single servomotor generally costs 50% more than a Stepper motor, and servo motor, as discussed in Power source selection part above, this is not adding that servo motors also come with their own encoder and other electric control equipment that also counts into the cost of using a servo. This excess equipment also counts as extra size and weight, while Stepper motors are small or less weight, and cost less generally. If we scale the size and power output of the stepper motor, we achieve the relatively same price and volume, and weight of the smaller servo motor, while achieving higher torque and precisely controlled stepping motion.

Stepper motor also benefits the design (there were covered in Power source selection segment) in that it has detent torque that can maintain the position when powered off, and it can achieve the highest torque (also maintain the shaft in a static position), but unlike most other motors, this maintaining highest torque in 0 speed does not cause overheating by nature of how stepper motor is built. Our case scenario features halting the swinger at a particular position and maintaining its position, stepper motor could maintain this ideally by switching off, it also has a natural benefit of exerting maximum torque to counter the load torque when at 0 speed with no heat generation.

4.1.7 Justification of **Bearings and their Shaft attachment method:**

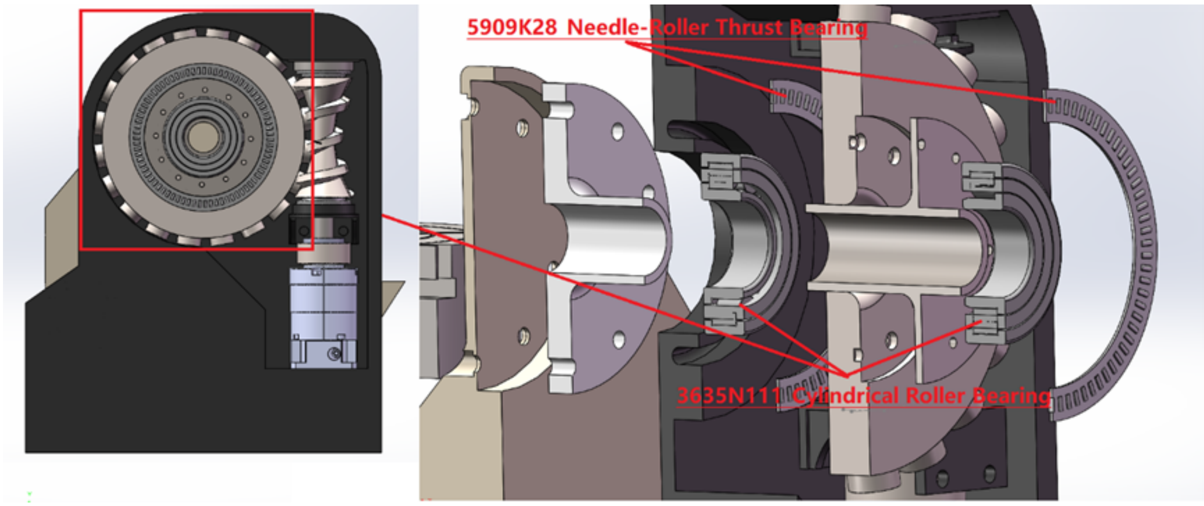


Figure 4.1.13

1. Two Cylindrical Roller bearings (3635N111_Cylindrical Roller Bearing) are mounted on along the holes as seen in Figure 4.1.13, **One** mounted on the other hole in Figure 4.1.13, to allow rotational movement of the swinger, and to sustain very significant downward(occasionally side-ward, along the Z-axis, but **little to no Y-axis force**) pointing load, this load we think is more than the capability of a Ball Bearing, so we use Cylindrical Roller bearing. We did not use an additional Roller Bearing (angled one that resembles a trapezoidal shape from side view) because we are sure there is little to no Y-axis force exerted. This is covered in the Swinger Part justification. Two 3635N111_ are assembled on two sides of the roller cam to make sure bending torque from the swinger will be isolated from the roller cam.

These are attached to the shaft by **the "Square, Rectangular, or Parallel Keys" technique** because these are capable of transferring high torque and are relatively cheap.

2. Two Needle-Roller Thrust Bearing (5909K28_Needle-Roller Thrust Bearing) is mounted on two sides of the Roller Cam Gear, this is because as suggested during the lecture, worm and gear mechanism will generate the internal force on both radial and axial direction, due to how the gears and poles are positioned. Our case is similar to Worm and Gear, so I included a cheap Needle-Roller Thrust bearing. No more robust, expensive bearing because this axial force will not be significant given it is only internal force delt between pole and gear. Any potential axial force due to bending delt by swinger is canceled by the two 3635N111_ mounted on two sides of the roller cam.

These are not rigidly attached to any surface, they are only constrained by internal designed (not drawn in CAD) slots inbuilt on SwingerSupportCase and Roller cam, thus constraining its motion and position, because of how thin it is and it is basically not necessary since they are just there to support axial force and smoothly relative rotational motion between roller cam and case.

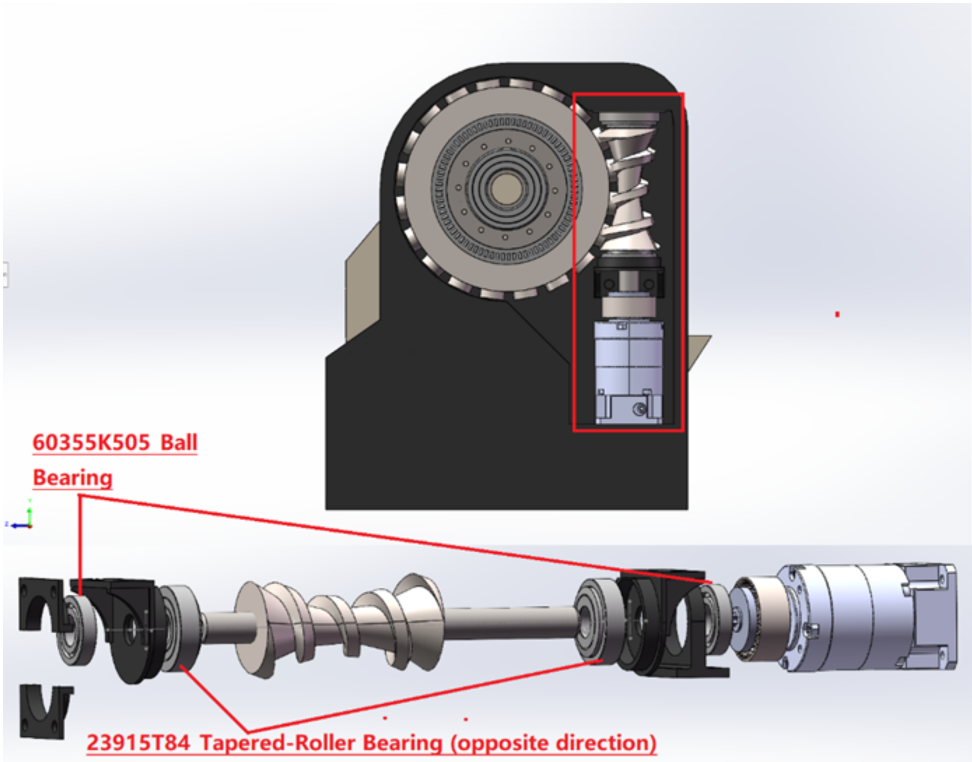


Figure 4.1.14: Exploded View of worm gear and worm pole

3. Two 23915T84_Tapered-Roller Bearing is attached right next to the worm pole(Regard Figure Z13), this is because as suggested during the lecture, the worm and gear mechanism will generate the internal force on both radial and axial direction, due to how the gears and poles are positioned. Our case is similar to Worm and Gear, so I included roller bearings on either side of the worm pole to counter the sure happening axial load in either direction corresponding to CW and CCW roller cam motion.

The 23915T84s are rigidly attached to the shaft via the **“Gib-Head Keys' ' technique**, since this step is easy to do, quite reversible, and can excellently support axial force.

4. Two 60355K505_Ball Bearings are attached to the same shaft that is rigidly connected to the worm gear, but further to the ends of the shaft. As suggested during the lecture, the worm and gear mechanism will generate internal force in both radial and axial directions, due to how the gears and poles are positioned. Our case is like Worm and Gear, so I added these roller bearings to support the Worm pole's radial load exerted by Roller Cam Gear.

This is simply connected to the shaft with the **"Square, Rectangular, or Parallel Keys" technique** because these are capable of transferring high torque and are relatively cheap, AND since any axial load is, hopefully, blocked by the two 23915T84s discussed previously. **It would not help to use the Gib-Head Keys technique** since the ball bearing is weak (extremely weak on one side) toward the axial load. If an axial load is impending anyway, I would rather let it slide past the ball bearing, strike the casing, and let the casing fight against that axial load, instead of male posing a ball bearing resulting in no method against preceding radial load. **Gib-Head Keys technique** is also not that reversible, as well as **"Square, Rectangular, or Parallel Keys" technique.**

All bearings are held in place in space using proper housing I drew myself, regardable in Explosion View at Figure 4.1.12 and Figure 4.1.13, All bearing are directly downloaded from Mcmaster Carr, so they SHOULD all have their McMaster Carr housing counterpart, however, none of them fits under our CAD modeling given non-standardized orientated dimensioning. When our design won the bidding and we considered actual manufacturing, we will reconcile the entire design to incorporate the entire design under industry standards, which means standardizing parts, then, we can use supports well massively available in the market.

4.1.8 Justification of **coupling method and miscellaneous:**

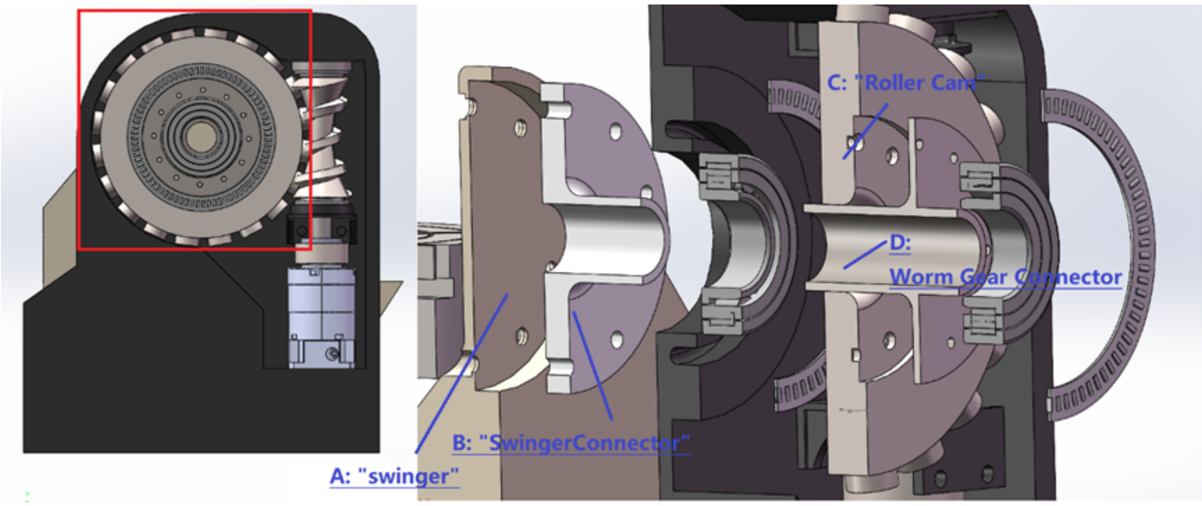


Figure 4.1.15: The coupling used in the worm gear

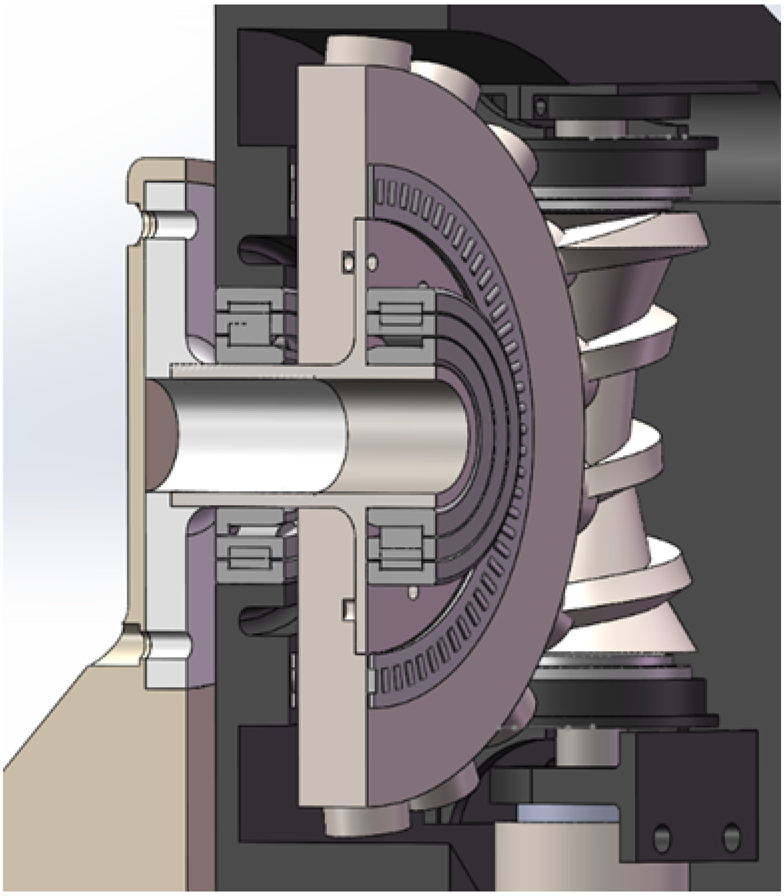


Figure 4.1.16: section view of the worm gear

Figure 4.1.15 marks 4 of the concerned parts in this section by **A, B, C, and D**. Figure 4.1.16 is what it looks like when assembled. Details justification are as below. **Note** that I did not model the attachment method between B and C.

A2B and C2D: Coupling between **A:** “Swinger” and **B: “**SwingerConnector”, Attachment between **C:** “Roller Cam” and **D:** ”Worm Gear Connector”: **“Rigid Coupling”.**

These are connected via Rigid Coupling because this is the part, **in fact throughout this section, all connections: A2B, B2C, C2D, are all high torque, non-miss-alignment tolerance scenarios**, Rigid Coupling is the best choice since 1. I know that the shafts are pre-aligned, so no potential vibration or torque. 2. I wish for a high torque scenario, which is quintessential for this part of the design that involves heavy loads. 3. This coupling technique is relatively cheap than otherwise. One might argue the advantage in simply manufacturing custom parts with A and B, C and D respectively internally built together as one piece since we are already customizing both parts. the reason I did not draw A and B, C and D as respectively 1 piece is:

1. **for A and B**, if it were in one piece, the assembly of this machine will be extremely hard because there will be fundamentally no way for the swinger, then, to find its two outreaching shafts into the holes I drew in the SwingerSupportCase.

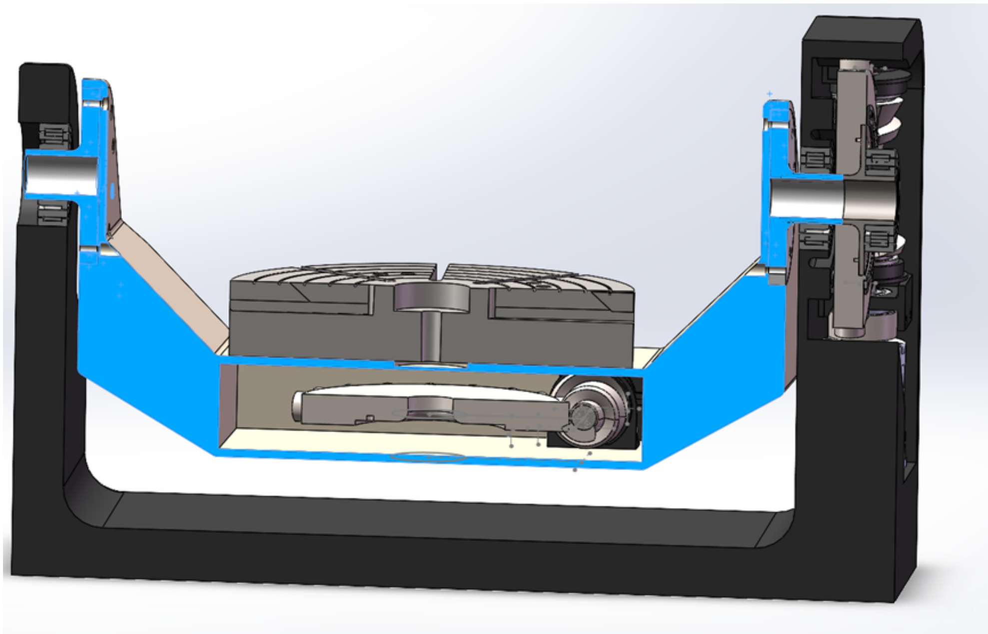


Figure 4.1.17: Sectional view of the entire design, with swinger, marked blue

Hopefully, Figure 4.1.17 can give you a good idea as to why A and B are not welded together. **You cannot assemble this thing if welded together unless you introduce a server in the middle of the dark SwingerSupportCase,** which will drastically limit its life cycle, as well as stiffness as a structure.

2. **for C and D**, this is due to how we acquired the Roller Cam. Our supplier, WDS Precision Machinery INC., **does not offer this roller cam as standardized parts** [12], every piece of Roller Cam is a customized part until perhaps our # if the order goes up and it achieves economy of scale, then one piece of the roller cam goes down. One fact notable is that for the mechanism **driving the swinger and the swinger driving the rotary table**, **they are both Roller Cam Gears and They are identical**. IF we were to ask WDS to customize such that C and D are together, yet this design is not applicable as used in the swinger, we will have to order **two separate orders for two kinds of customized parts from WDS, thus the cost will elevate greatly, so will the market price!**

while attachment D: Worm Gear Connector is a standardized part, even though it is not, since the team drew it and introduced a fillet to fight stress concentration, this kind of part is available on the market. We can tell WDS to manufacture the Roller CAM to fit attachment D and reduce cost, with little to no loss of torque transmission or any other considerations.

Note the **fillet corner** of B: "SwingerConnector" and D:" Worm Gear Connector", these are potential major engineering stress concentrations that WILL undergo large torque derived from swinger and motor, when those connectors are rigidly connected to the swinger and Roller Cam Gear and share the same exact rotary motion thus same torque.

B2C: Attachment between **B: "**SwingerConnector" and **C:** "Roller Cam": **"Oldham Coupling variance".**

This is the difficult one because they meet each other in a constrained space. I cannot simply make B and C into one piece because that will undermine that assembly process. (regard Figure 4.1.15 and Figure 4.1.16) In this constrained space, Regular Rigid Coupling will be hard to perform during assembly.

The team thinks this coupling will resemble most like the "Dog Clutch " coupling when we introduced clutches, there will be mechanical parts physically touching to bring one another into motion, this is an Oldham coupling variance because it looks like one.

Suppliers of parts not customed (drawn by us):

In solidwork Part name	True name + Part specifications	Supplier
WormGear_RSupport_5909K28_Needle-Roller Thrust Bearing	5909K28_Needle-Roller Thrust Bearing Thrust bearing Diameter: 3.0 inch inner 3.75 inch outer	
23915T84_Tapered-Roller Bearing	23915T84_Tapered-Roller Bearing <u>Roller Bearing(angled, trapezoidal, the one with axial force capability)</u> Diameter: 0.5 in inner 1.41 in outer	McMaster Carr
60355K505_Ball Bearing (for motor shaft 0.5 support)	60355K505_Ball Bearing <u>Ball Bearing</u> Diameter:	McMaster Carr

	0.5 in inner 1.13 in outer	
3635N111_Cylindrical Roller Bearing	3635N111_Cylindrical Roller Bearing Cylindrical Roller Bearing Diameter: 0.98 in inner 2.05 in outer	McMaster Carr
GBPS-0401-CS-AA171-197	Stepper”57BYG250C-8” +gearbox “57PX6” Stepper Motor with high precision planetary gearbox. Gear ratio: 100:1 Backlash: 4 arc-min Static torque: 411	PU FEI DE MOTORS CO. LTD
WormGear, WormPole	Roller Cam Drive (worm drive with roller pin as gear tooth) Roller pin number: 20 Pitch circle: 2.7 inch	WDS Precision Machinery Co., Ltd

4.2 Internal Support of the Rotary Table:

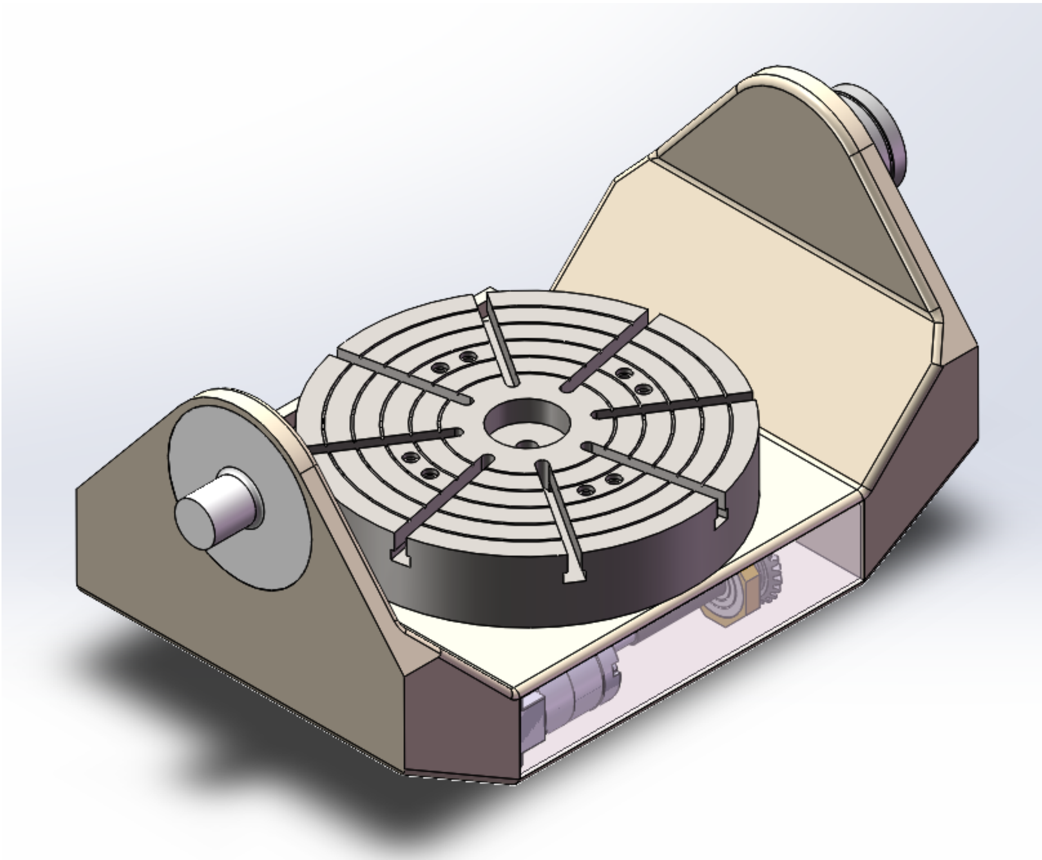


Figure 4.2.1 Isometric view of the rotary table (swinger)

General design idea:

This rotary table mechanism consists of two parts; the rotary table, and the swinger. In the body of the swinger, a motor is connecting an output shaft, and through a pair of two bevel gears, it transforms the circular motion of the shaft to another shaft which is 90 degrees to the motor output, and connected to the worm gear. The worm gear has an output shaft that connects its center to the center of the rotary table. Therefore, the worm gear then goes in circular motion and makes the rotary table which is right above it to go in circular motion, with a speed ratio of 1:1.

4.2.1 Justification of the overall shape

As 4.2 is focused on the SwingerSupportCase, 4.3 is focused on the Swinger itself. As illustrated in figure 4.4.2, the swinger consists of two parts: 1) the supporting casing, which contains the motor, roller cam drive (worm gears), bevel gears, and shafts that connect worm gear to the actual rotary table above; 2) the rotary table itself, which is a thick, short cylinder. The supporting casing of the swinger contains several components, which are a casing, one DC motor, two shafts that connect the output of the motor to the input of the worm gear, two bevel gears that are used as 90 degrees motion transmission, the worm gear itself, and a shaft that connects the worm gear to the rotary table above (connect means they see as one part, rotate in 1:1 ratio), and finally a rectangular glass, that's on the side of the casing, showing all the components inside.

Support casing has the same of mixing between Y-shape and U-shape, and has a generally smaller size compared to the support case, which is the black component,

4.2.2 Justification of Dimension

The dimension of the rotary table is 14 inches × 8 inches × 7.5 inches. The main reason that we chose these dimensions is that the rotary table casing has to fit in the supporting casing, which has a dimension of 20 inches × 20 inches × 20 inches. Also, since we want the rotary table to rotate freely, and in order to avoid collision on the supporting cast, we have to increase the height of the pin which connects the table to the support case. Using the Pathagonal formula, we calculated that the rotary table casing has to be 1.5 inches higher than the Swinger casing support (black component).

For the worm gear itself, since we want to reuse the same worm gear in the supporting casing, there was not much space left for the motor to be in one dimension, connecting the motor and the worm gear. Therefore, we have to use the bevel gears to transfer the transmission by 90 degrees, in order to decrease the space using. It was a very impact design, we used every single space in the supporting casing.

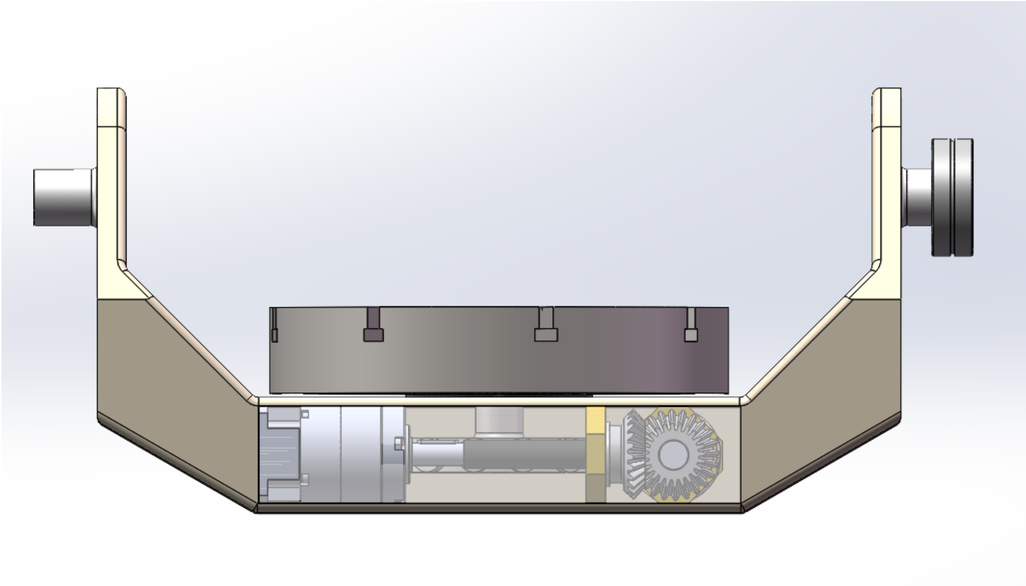


Figure 4.2.2-1 Front View of Rotary Table

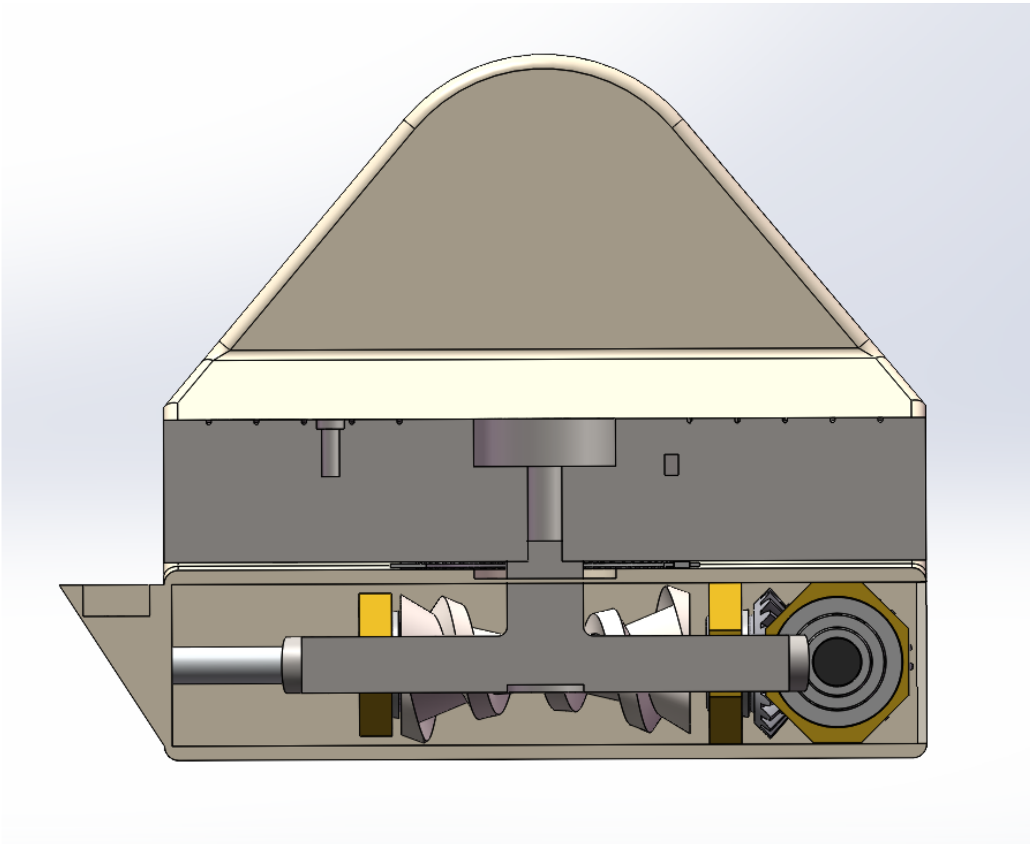


Figure 4.2.2-2: Sectional View (side view)

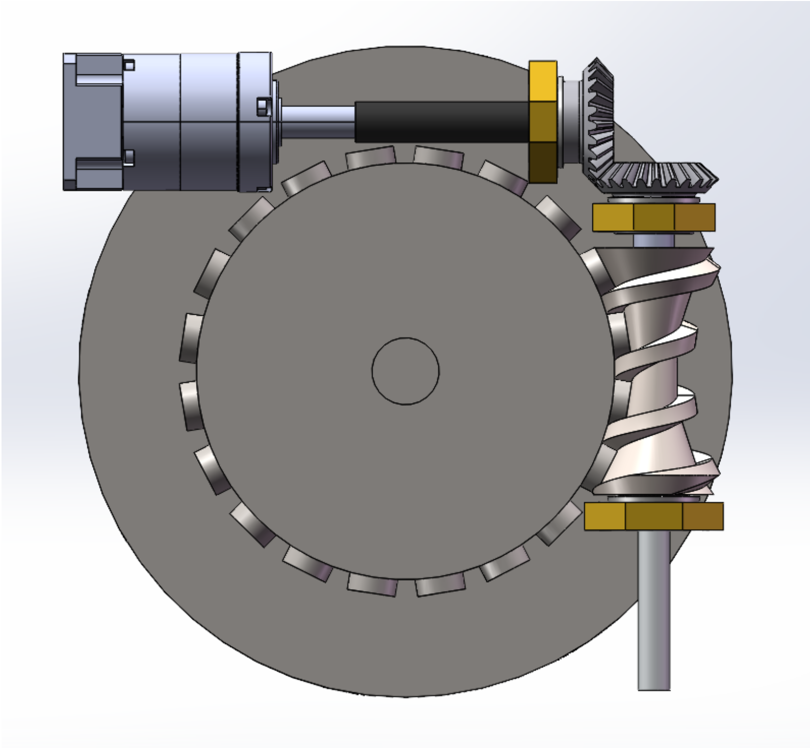


Figure 4.2.2-3: Sectional View (top view)

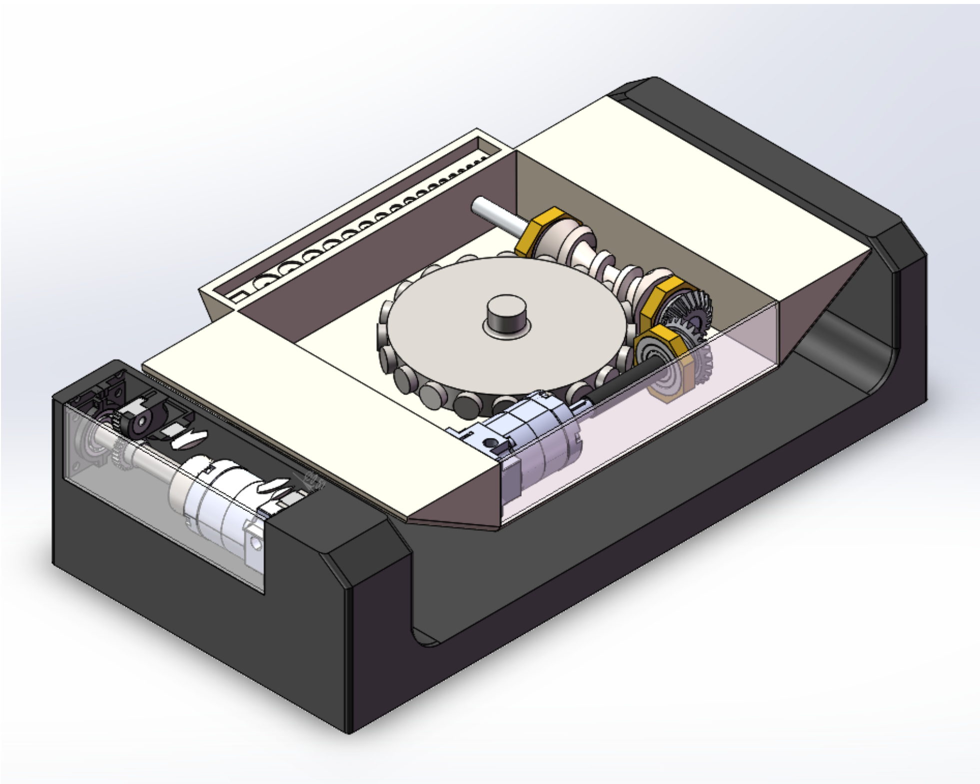


Figure 4.2.2-4 Isometric View of Swinger and its casing

4.2.3 Justification of choosing Stepping Motor:

From section 4.1, choosing between the stepper motor and the brushless servo motor was a struggle, and the decision had to be postponed. After that, we did the justification for all the components on the base part, which consists of a rotary table, rotary table support (swinger), and swinger supporting case. There are two places where we used motors, which are between the swinger and the supporting cast, also between the swinger and the rotary table. Since we are certain that we are using roller cam drive with gearbox, torque is believed to be above the limit where the stepping motors won't have skipping steps. Taking consideration of the comparison in 4.1, a stepping motor is chosen instead of a brushless servo motor.

4.3 Spindle Motor and the Milling Tool

By definition, a spindle is devised of a motor, a taper for holding tools, and a shaft that holds together all the separate components. Spindles rotate on an axis, which receives input on movement from the accompanying CNC controller [14]. In our project, the spindle plays a crucial role in the machining and it determines the quality of the output. Thus, the team has specified the following requirements:

1. The type of motor used: AC Motors or DC Motors
    - The differences between them are as follows:
        - DC spindle is comparatively less expensive than AC spindle [15]
        - The speed of a DC spindle can be controlled by a PWM (Pulse Width Modulation) circuit, which is simpler and less expensive than the driver circuit for AC spindles [14].
2. The rotating speed
    - Generally speaking, for wood and aluminum, the good RPM value is about 24,000 and for steel, the good RPM is between 15,000 and 18,000 [16].
3. The size
    - Consider whether the motor could fit other parts of the design
    - Determines the size of the cutting tools we can use
4. The input power
    - The power determines how fast we can cut material
5. The maximum torque
    - The torque determines the hardness of material we can cut [14]
6. The ways of changing tools
    - According to the original specification, the machine should be able to change the tools themselves without manual input.
7. The coolant associated with the spindle
    - The position of the coolant component
    - Methods of connection between the coolant and the motor

CNC spindles play a crucial role in machining and determine the quality of the output material. The component is fundamental to a fast and efficient process, while also ensuring that produced elements are as precise as possible.

4.3.1 Justification of Selection of Spindle Motor

With the above features identified, we looked for qualified components in the online production website (Banggood Platform) and tried to find the 3D modeling of the part.

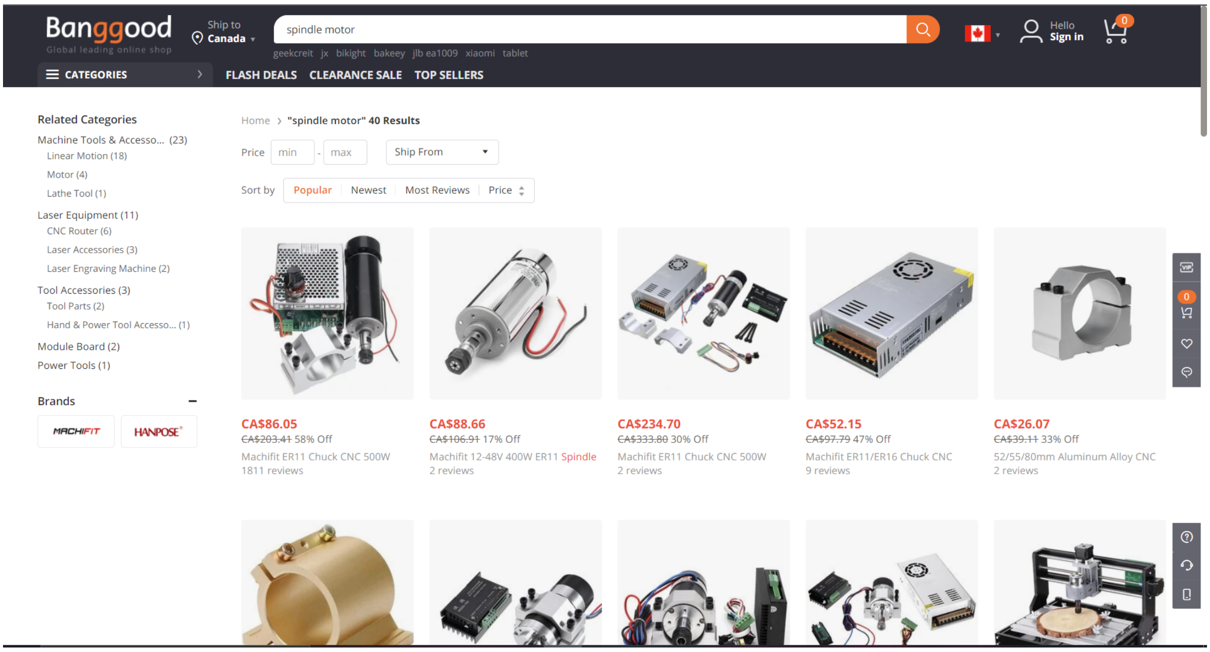


Figure 4.3.1. Screenshot of the Component Searching Process[17]

Thus, we have selected our final choice: Machifit ER11 Chuck CNC 500W Spindle Motor with 52mm Clamps and Power Supply Speed Governor [18].

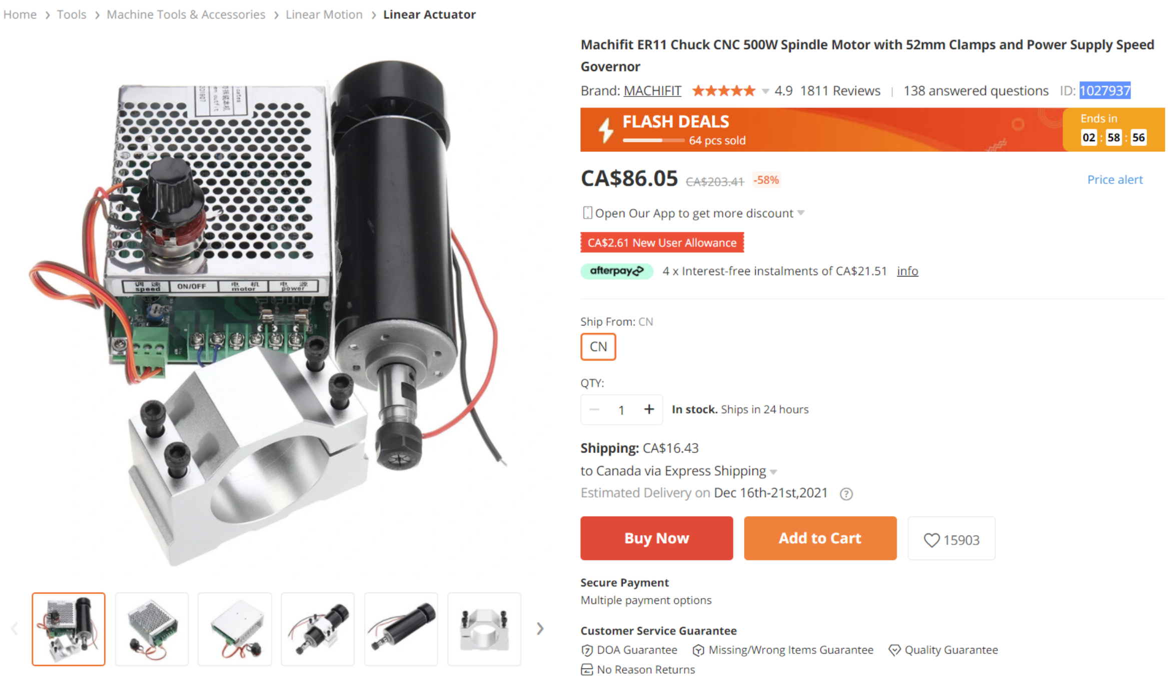


Figure 4.3.2. Selected Spindle Motor [18]

The details of the product are listed as follows:

Specification:
Brand: Machifit

Dimension	130mm×100mm×50mm (L*W*H)
Input	AC110-220V±10% 50/60Hz
Spindle Motor	500w
Spindle Speed	3000-12000r/min
Motor Diameter	52mm
Motor Length	208mm
Operating Voltage (Output Voltage)	100V DC
Current	6A
Speed	Up to idle up to 15,000 rev / min
Torque	5000G/CM
Insulation Resistance	> 2 megohms
Dielectric Strength	400V
High precision spindle runout 0.01-0.03	

Chuck size:
Style: ER11
Chuck Size: 1/8"
Material: High Grade 45 Carbon Steel
Total height: 18mm
Outer diameter(Max.): 11.5mm
Gripping Range: 3mm
Small diameter: 7.8mm
Fits metric shank size(s): 3mm metric shank

Nut Size:
Inner Diameter: 8.7mm
Height: 13mm
Diameter: 17mm
Outer Diameter:19mm

Package Included:
1 x 500W Spindle Motor
1 x Power Supply
1 x 52MM Mount Bracket
1 X ER11 Collect
4 x Screws

Figure 4.3.3. Specification of the Spindle Motor [18]

Since the rotating speed is between 3000 to 12000 rpm, the spindle could modify parts made of steel and wood, possibly coarse aluminum. Also, the motor length of 208 mm could fit well to the desktop outer case.

Then, the team decided to build a 3D model according to the actual size. It turned out that MakerSpaceTgz·Robotics Company [20] has purchased the part and disassembled it for commercial use. The team reached out to the company and got the model measured from the actual dimension as follows:

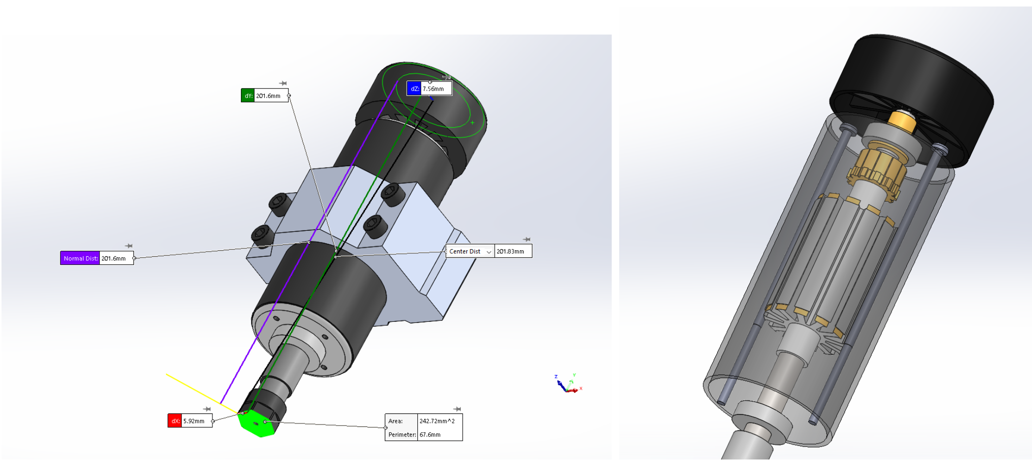


Figure 4.3.4. Screenshot of Assembled Components

4.3.2 Justification of the Milling Tool and Chuck Size:

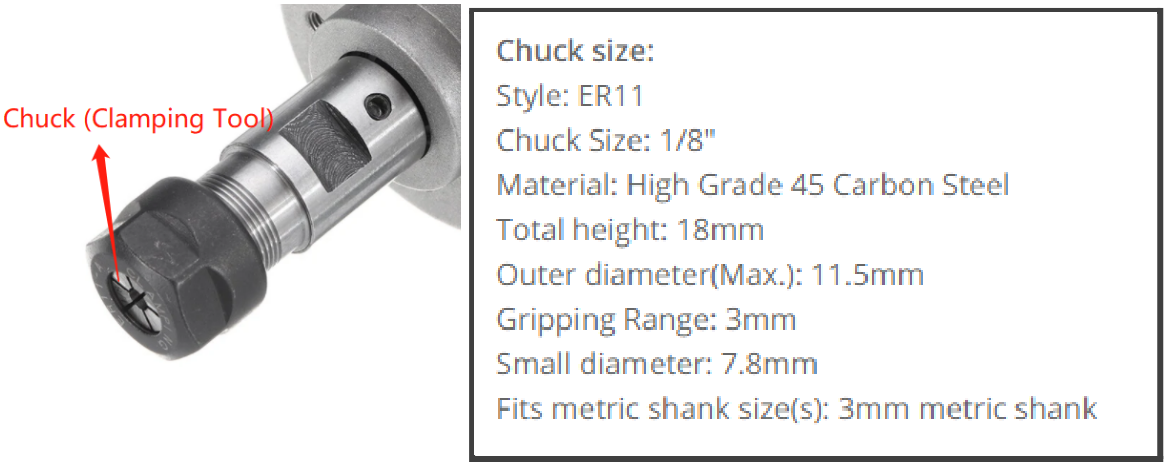


Figure 4.3.5. Specification for Chuck Size

Based on the actual dimension of the chuck size, we searched for the cutting tool components on McMaster Carr and looked for cutting tools with a shank diameter of approximately 3mm (⅛”).

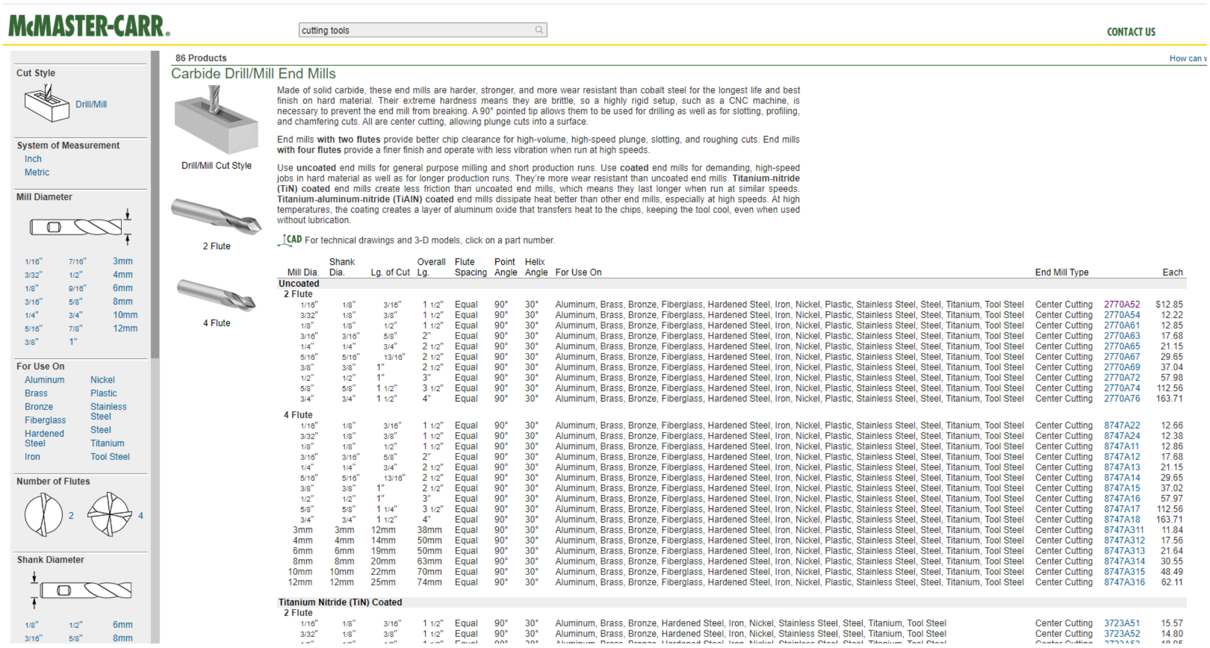
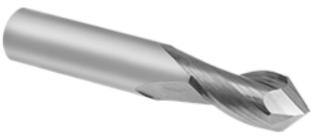


Figure 4.3.6. Search of Suitable Cutting Tools

The specified cutting tool is as follows (dimension and shape are shown in Appendix A):

System of Measurement	Inch
Finish	Uncoated
Material	Carbide
Mill Diameter	1/16"
Mill Diameter Tolerance	-0.003" to 0.000"
Shank Type	Straight
Shank Diameter	1/8"
Length of Cut	3/16"
Overall Length	1 1/2"
Flute Type	Spiral
Number of Flutes	2
Flute Spacing	Equal
Point Angle	90°
Helix Angle	30°
Cut Style	Drill/Mill
Number of Milling Ends	1
For Use On	Aluminum, Brass, Bronze, Fiberglass, Hardened Steel, Iron, Nickel, Plastic, Stainless Steel, Steel, Titanium, Tool Steel
End Mill Type	Center Cutting
Individual/Set	Individual
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	820770.5000
ECCN	EAR99



2 Flute

Figure 4.3.7. Carbide 2 Flute End Mill [20]

Using the Assembly mode, the cutting tool could fit well with the spindle clamp.

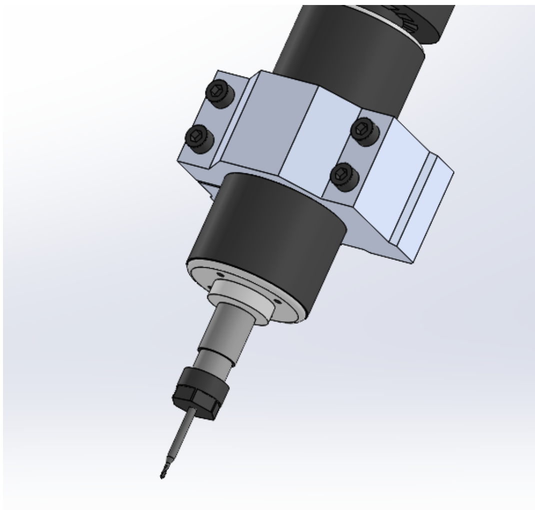


Figure 4.3.8. Milling Tool attaching to the Spindle Motor

4.4 Overall Assembly Mechanism of the Design

The final assembly of the design combines every sub-assemblies together and represents the group's critical thinking about the overall design. The initial assembly design was shown as follows:

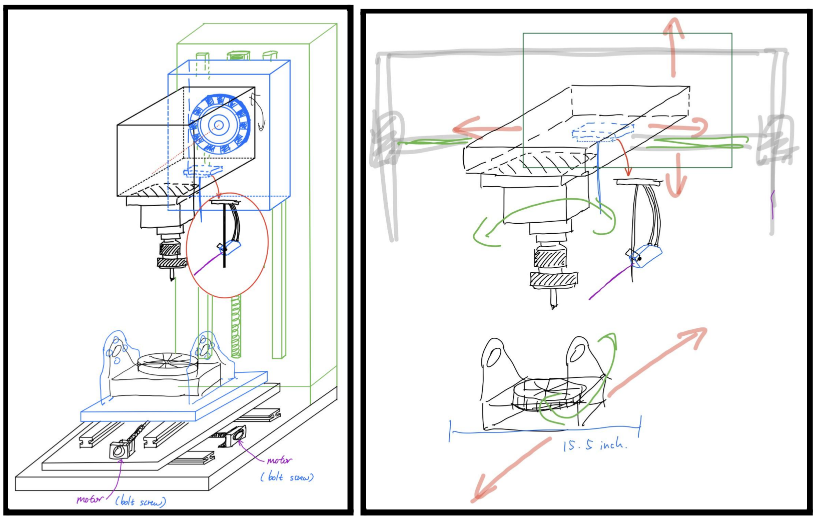


Figure 4.3.9. Initial Rough Designs of the Assembly

The basic ideas and design goals are as follows:

- The linear movement in the x, y, z-axis is controlled by the ball screws and linear stages (standardized parts could be found on McMaster Carr).
- Since three linear axes are involved, we need to generate three pairs of guide rails and three motors as the power input.
- The coolant is located on the same plane with the spindle or the positions are close to each other (save the traveling distance of the cooling fluid).
- The backplate of the spindle is perpendicular to the backplate of the rotary table to save the supporting material and space utilization.

This part will introduce the explanation and justification of the following two aspects: the mechanism of linear movement and the final casing design.

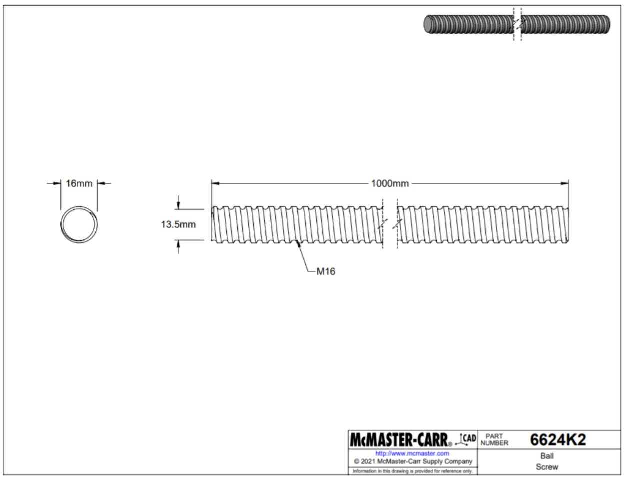
4.4.1 Justification of Movement in x, y and z axis Using Linear Stages

As identified in lectures, the linear stages will create controlled, 1D motion along a certain axis [21]. Typically, the power source is provided by a DC motor (with an extended shaft),

which is connected concentrically to a ball screw. A ball nut is connected to the screw, and the rotation of the DC motor will lead to rotation of the ball screw so generated linear motion of the ball nut. This is a motion conversion mechanism in which rotational input from the DC motor is converted to the linear motion of the ball nut.
In addition, the mechanism needs extra guide rails and their corresponding bearing carriages to ensure the plate is moving on one plane and reduce vibration. One significant factor to consider is that screws should mesh with all the other components, which means the thread size should be the same. For this case, the team has set the thread size to be M16.

According to the specification at the beginning of the design process, the team has set the rough dimension of 20 * 20 * 20 inch. During the distribution of work, every team member tried to find standardized parts that are approaching those lengths. With the above operating functions identified, the team has selected the following components (with the same M16 thread size) for the final assembly of the design:

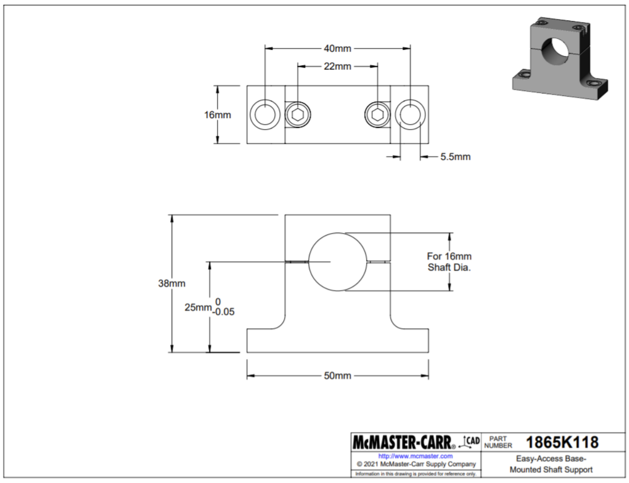
<u>Ball Screw [ID - 6624K2]:</u>



Component	Ball Screw
Thread Type	Metric Ball
Threading	Fully Threaded
Thread Direction	Right Hand
Thread Fabrication	Rolled
Material	Carbon Steel
Thread Size	M16
Length	1,000 mm
Number of Thread Starts	1
Travel Distance per Turn	5 mm
Accuracy for Travel Distance per Turn	±0.210 mm per 300 mm
Root Diameter	13.5 mm
Hardness	Rockwell C58
Tensile Strength	21,000 psi
Temperature Range	5° to 175° F
System of Measurement	Metric
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	Japan
Schedule B	848390.9500
ECCN	EAR99

Figure 4.4.1. Ball Screw 6624K2 [22]

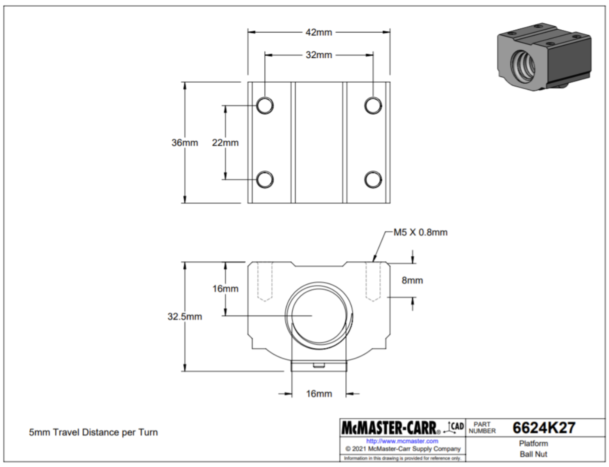
Easy-Access Base-Mounted Shaft Support [ID - 1865K118]:



Material	Black Anodized 6061 Aluminum
For Shaft Diameter	16mm
Overall	
Length	50mm
Width	16mm
Height	38mm
Center Height	25mm
Center Height Tolerance	-0.05mm to 0mm
Mounting Hole	
Number of	2
Center -to-Center	40mm
Diameter	5.5mm
Clamping Screw Thread Size	M4
Construction	Two Piece
Shaft Support Type	Base Mount
System of Measurement	Metric
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	848790.0080
ECCN	EAR99

Figure 4.4.2. Easy-Access Base-Mounted Shaft Support 1865K118 [23]

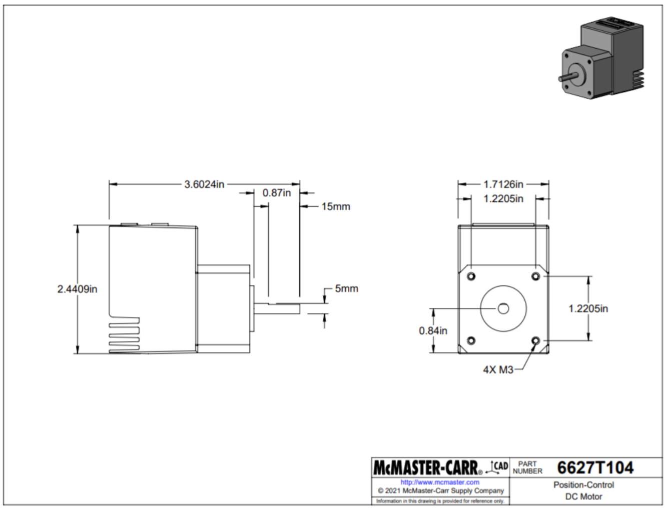
Platform Ball Nut, M16 Thread Size [ID - 6624k27]:



Component	Ball Nut
Nut Type	Platform
Thread Type	Metric Ball
Thread Direction	Right Hand
Material	Alloy Steel
Thread Size	M16
Length	36 mm
Width	42 mm
Height	32.5 mm
Center Height	16 mm
Number of Thread Starts	1
Travel Distance per Turn	5 mm
Mounting Hole	
Number of	4
Thread Size	M5
Thread Pitch	0.8 mm
Depth	8 mm
Center-to-Center Length	22 mm
Center-to-Center Width	32 mm
Hardness	Rockwell C58
Dynamic Thrust Load Capacity	1,200 lbs.
Maximum Backlash	0.1 mm
Temperature Range	5° to 175° F
System of Measurement	Metric
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Figure 4.4.3. Platform Ball Nut 6624k27 [24]

Position-Control DC Motor [ID - 6627T104]:



Power Source	Electric
Mounting Style	Face
Face Shape	Square
Motor Frame Size	NEMA 17
Power	0.0708 hp
Maximum Speed	3,000 rpm
Continuous Operating Torque	12.5 in.-oz.
Starting Torque	31 in.-oz.
Motor Enclosure Type	Closed
Electrical Connection Type	Hardwire
Wire Connection Type	Wire Leads
Duty Cycle	Continuous
Motor Type	Brushless, Permanent Magnet
Motor Design	Integrated Driver, Motion Controller
Full Step	
Increment	1.8°
Steps per Second	10,000
Smallest Step Increment	0.007°
DC Voltage	12-48
Full Load Current	1.1 A
Overall	
Length	3 5/8"
Width	1 3/4"
Height	2 7/16"
Mounting Orientation	Any Angle, Horizontal, Vertical
Enclosure Material	Aluminum and Steel
Bearing Type	Ball
Overload Protection Type	Automatic
Number of Input Data Ports	3
Number of Output Data Ports	1

Figure 4.4.4. Position-Control DC Motor 6627T104 [25]

With a similar approach, the suitable selections for guide rails and bearing carriages are 6725K532 Long Rail for Ball Bearing and 8438K4 Corrosion Resistant Ball Bearing Carriage. One complete assembly for linear movement in one direction is shown in Figure 4.4.5.

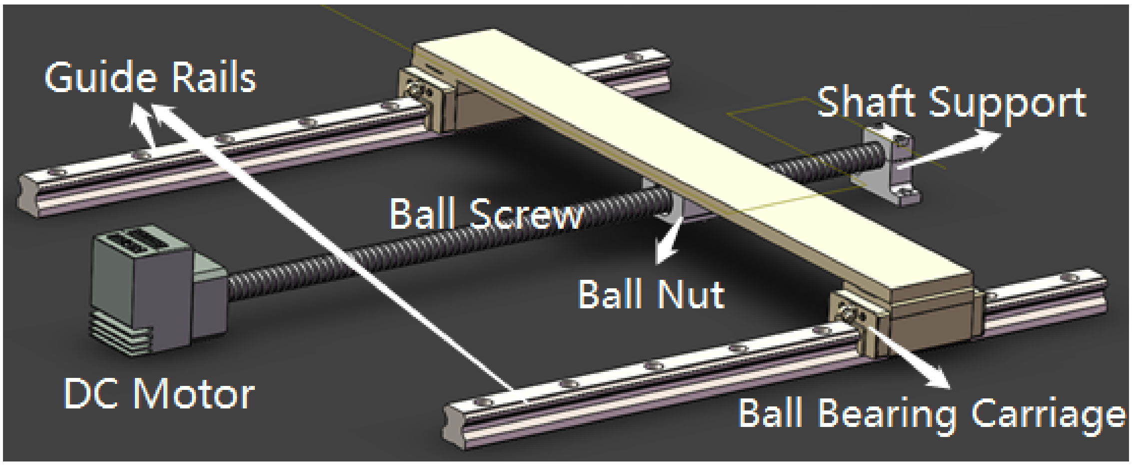


Figure 4.4.5. Assembly of Linear Motion for One Axis

The Travel Distance for the rails is 18 inch so the three axes could fit well into the casing. Also, this mechanism ensures the top plate (shown in pale yellow) in figure 4.4.5 could translate linearly on the bottom plane.

4.4.2 Justification of Overall Casing of the Design

The casing of the design assembles previous sub-parts together and provides additional support to floating elements (if needed). It determines the overall footstep of the machine and represents the team's design goal and design outcome. Thus, careful justification and explanation are needed.

In the design process of the spindle support plate, the team has identified that the support should allow the spindle to translate freely in x-direction (on the linear stages) and enable the spindle to move to the right top of the rotary table. To achieve this goal, the team has made several iterations. In the first version (shown in figure 4.4.6), the supporting plate is designed to be a rectangular shape, perpendicular to the bottom plane.

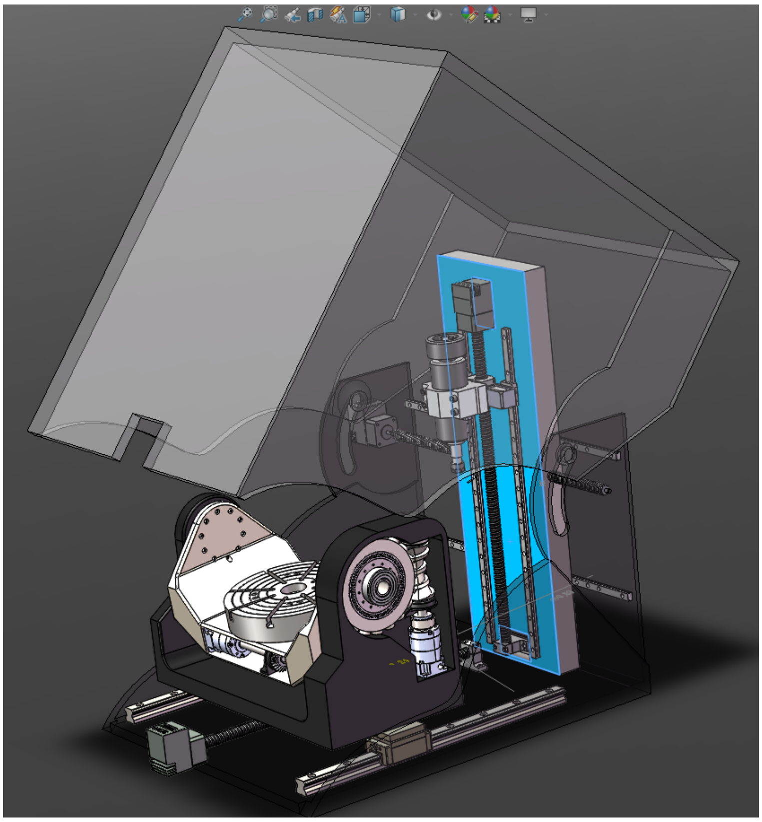


Figure 4.4.6 First Version of the Design - Rectangular Supporting Plate (shown blue)

However, from the top view, we realized that the spindle could not move to the right top of the rotary table even in the nearest position so the center of the material cannot be cut.

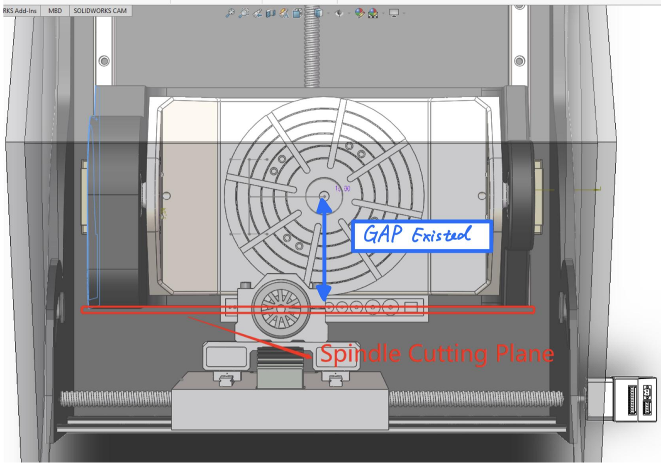


Figure 4.4.7 Top View of the Machine when Rotary Table is in the Nearest Position

In the next iteration, the team has designed an “S-shaped” backplate which could translate on the guide rails at the back. Also, compared to the last version it extends the spindle outward by a distance of 10.4 inches (see Figure 4.4.7), so decreasing the minimum normal distance between the Milling tool and the cutting material (the spindle could move to the top of the cutting tool without collision between the rotary table and the spindle supporting plate).

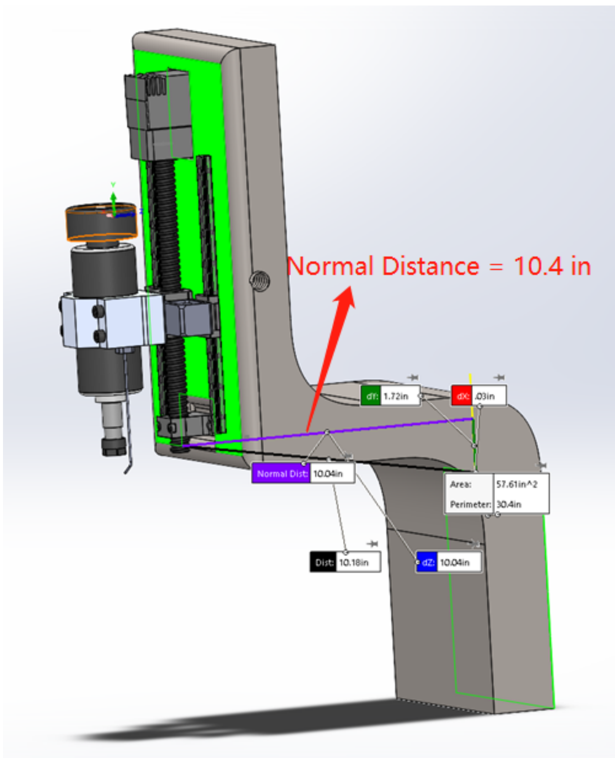


Figure 4.4.8. 2nd Version of Spindle Support Plate

Then, from the top view, we could see now the spindle could move to the top of the whole rotary table and be able to cut the entire surface of the material (see Figure 4.4.9).

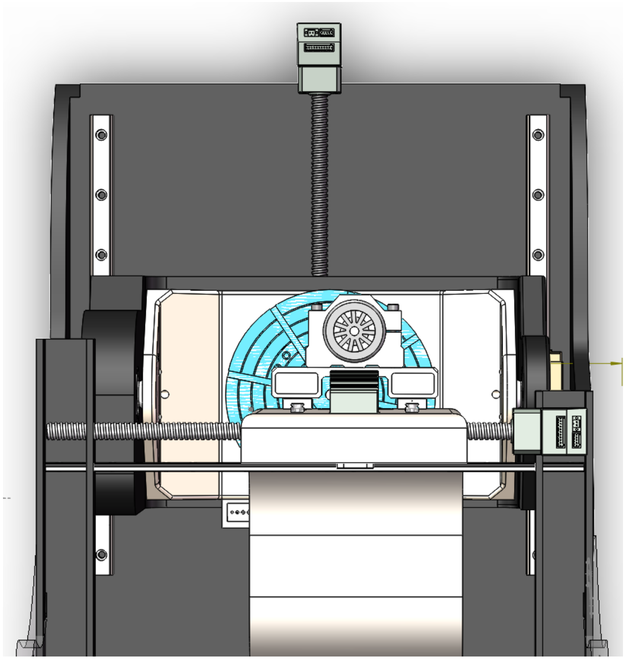


Figure 4.4.9. Top View of 2nd Version of Design

The case has also designed supporting frames for two DC motors. For the motor in the y-direction, we have extruded a hole on the upper cover. For the motor in the x-direction, we have extended the upper part of the bottom case and designed a fixing position to mount the motor (see Figure 4.4.10).

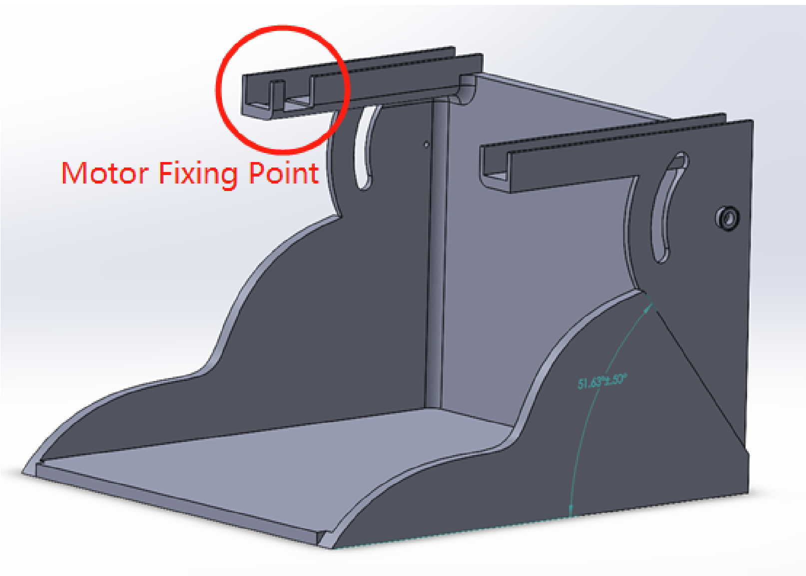


Figure 4.4.10. Bottom Case

With the above support problems solved, the Overall Outer Assembly is shown in Figure 4.4.11 as below:

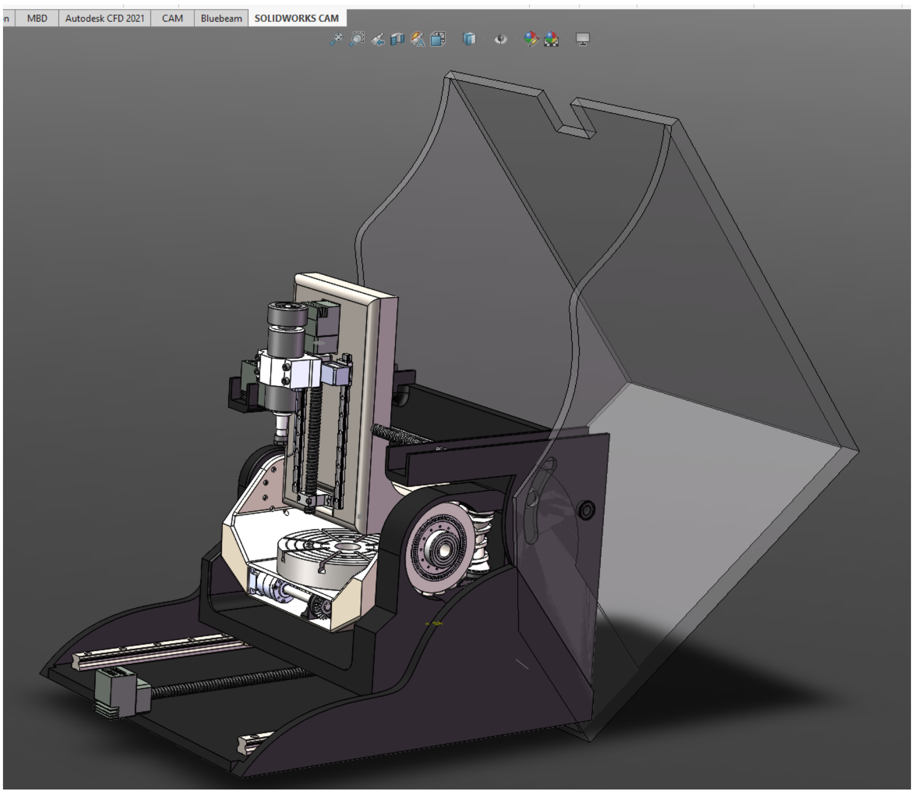


Figure 4.4.11. Overall Outer Assembly of the Design (with Case Opened)

The outer case is in cubic shape with dimension 19 * 24 * 25.88 inches and has two separated parts: a bottom case (shown in dark purple in figure 4.4.11) and an upper cover which could rotate about an axis in the back (represented by the circular pin near the back wall in Figure X).

In terms of the material selection, because the bottom case needs to withstand a large weight and possibly intense vibration, the material should have high tensile strength, fracture toughness, and hardness. Using the Cambridge Engineering Selector (CES) software, we have identified some suitable materials for this application (see Figure 4.4.12).

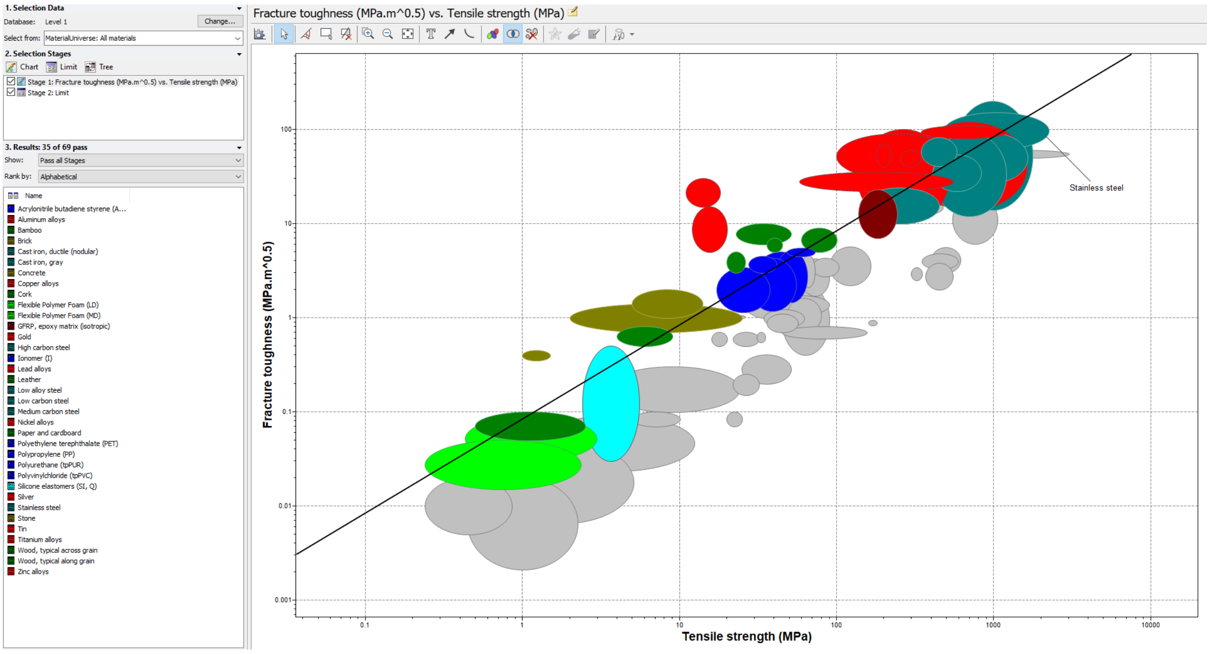


Figure 4.4.12. Material Selection Using CES

For simplicity, we have selected Stainless Steel because of its high performance and relatively low cost.

For the upper cover, we need it to be transparent and also have high toughness. Comparing all the transparent polymers, we have selected the acrylic plate because of a similar reason.

Acrylonitrile butadiene styrene (ABS)

Datasheet view: All properties   Show/Hide

enough to survive the worst that children can do to it. © Gettyimages

The material

ABS (Acrylonitrile-butadiene-styrene) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Composition (summary)

Block terpolymer of acrylonitrile (15-35%), butadiene (5-30%), and styrene (40-60%).

General properties			
Density	1.01e3	1.21e3	kg/m^3
Price	* 2.92	2.97	USD/kg
Mechanical properties			
Young's modulus	1.1	2.9	GPa
Yield strength (elastic limit)	18.5	51	MPa
Tensile strength	27.6	55.2	MPa
Elongation	1.5	100	% strain
Hardness - Vickers	5.6	15.3	HV
Fatigue strength at 10^7 cycles	11	22.1	MPa
Fracture toughness	1.19	4.29	MPa.m^0.5
Thermal properties			
Maximum service temperature	61.9	76.9	°C
Thermal conductor or insulator?	Good insulator		
Thermal conductivity	0.188	0.335	W/m.°C
Specific heat capacity	1.39e3	1.92e3	J/kg.°C
Thermal expansion coefficient	84.6	234	µstrain/°C
Electrical properties			
Electrical conductor or insulator?	Good insulator		

Figure 4.4.13. Properties of Acrylic Materials

The cover has two degrees of freedom, which means it could move linearly as well as a free rotation about the pin. Note that the cover is connected to a slot on the bottom case (shown blue in Figure 4.4.14) and the slot itself could translate in the arc-shaped trail.

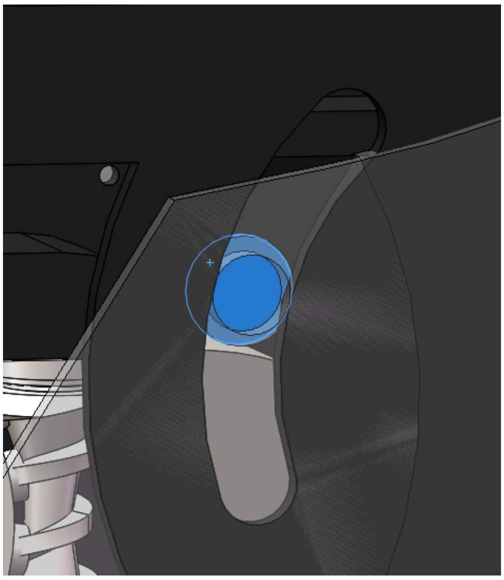


Figure 4.4.14. Slot and the Arc Trail

Thus, the machine has two limiting positions:

a. the slot is at the bottom of the arc trail and the cover is completely closed
b. the slot is at the top of the arc trail and the backplane of the cover forms an angle with the backplate of the bottom case

When the case is fully closed, the machine looks as follows:

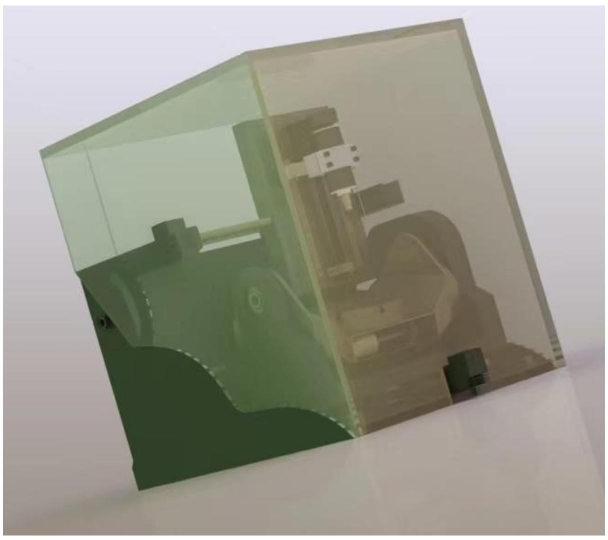


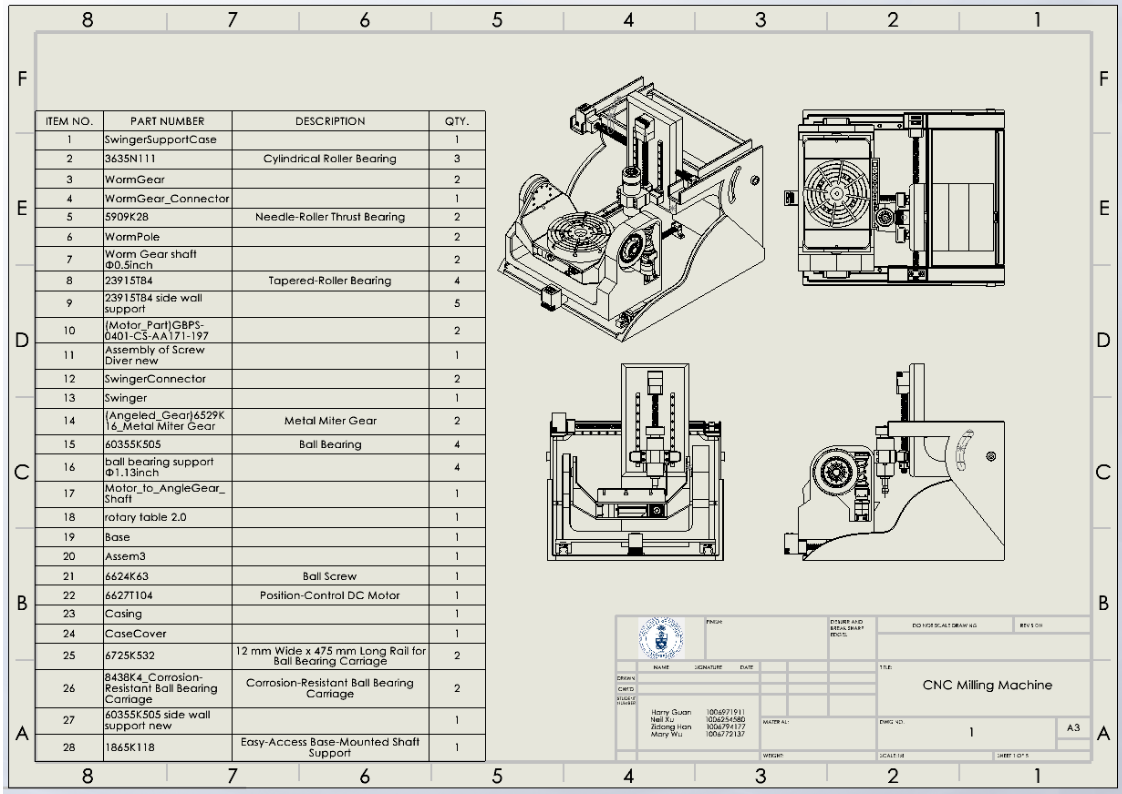
Figure 4.4.15. Situation when Case Fully Closed

4.5 Cost Estimation

Estimating Cost of the Milling Machine based on Standardized Parts:

part name	cost per item ($)	# of items	total cost($)
5909K28 Needle-Roller Thrust Bearing	13.38	3	40.14
3635N111_Cylindrical Roller Bearing	70.31	3	210.93
23915T84_Tapered-Roller Bearing	64.00	4	256
(Motor)GBPS-0401-CS-AA171-197	74.00	2	148
60355K505_Ball Bearing	6.65	4	26.6
1865K118 Easy access base mounted shaft	26.07	3	78.21
6624K27 Platform Ball Nut	286.27	2	572.34
6624K63 ball screw	105.88	2	211.76
6627T104 Position control DC motor	282.14	3	846.42
6709K16 bearing carriage	153.45	2	306.9
6709K531 Long guide rail for ball bearing carriage	118.97	1	118.97
6709K532 Long rail for ball bearing carriage	168.97	1	168.97
8438K4_Corrosion-Resistant Ball Bearing Carriage	86.91	4	347.64
60355K505_Ball Bearing (for motor shaft 0.5 support)	6.65	4	26.6
Machifit ER11 Chuck CNC 500W Spindle Motor	86.05	1	86.05
Total Cost:			$3445.53

5. The Assembly Drawings of the Milling Machine



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SwingerSupportCase		1
2	3635N111	Cylindrical Roller Bearing	3
3	WormGear		2
4	WormGear_Connector		1
5	5909K28	Needle-Roller Thrust Bearing	2
6	WormPole		2
7	Worm Gear shaft Φ0.5inch		2
8	23915T84	Tapered-Roller Bearing	4
9	23915T84 side wall support		5
10	(Motor_Part)GBPS-0401-CS-AA171-197		2
11	Assembly of Screw Diver new		1
12	SwingerConnector		2
13	Swinger		1
14	(Angeled_Gear)6529K16_Metal Miter Gear	Metal Miter Gear	2
15	60355K505	Ball Bearing	4
16	ball bearing support Φ1.13inch		4
17	Motor_to_AngleGear_Shaft		1
18	rotary table 2.0		1
19	Base		1
20	Assem3		1
21	6624K63	Ball Screw	1
22	6627T104	Position-Control DC Motor	1
23	Casing		1
24	CaseCover		1
25	6725K532	12 mm Wide x 475 mm Long Rail for Ball Bearing Carriage	2
26	8438K4_Corrosion-Resistant Ball Bearing Carriage	Corrosion-Resistant Ball Bearing Carriage	2
27	60355K505 side wall support new		1
28	1865K118	Easy-Access Base-Mounted Shaft Support	1

Figure 5.1 Assembly drawing 1

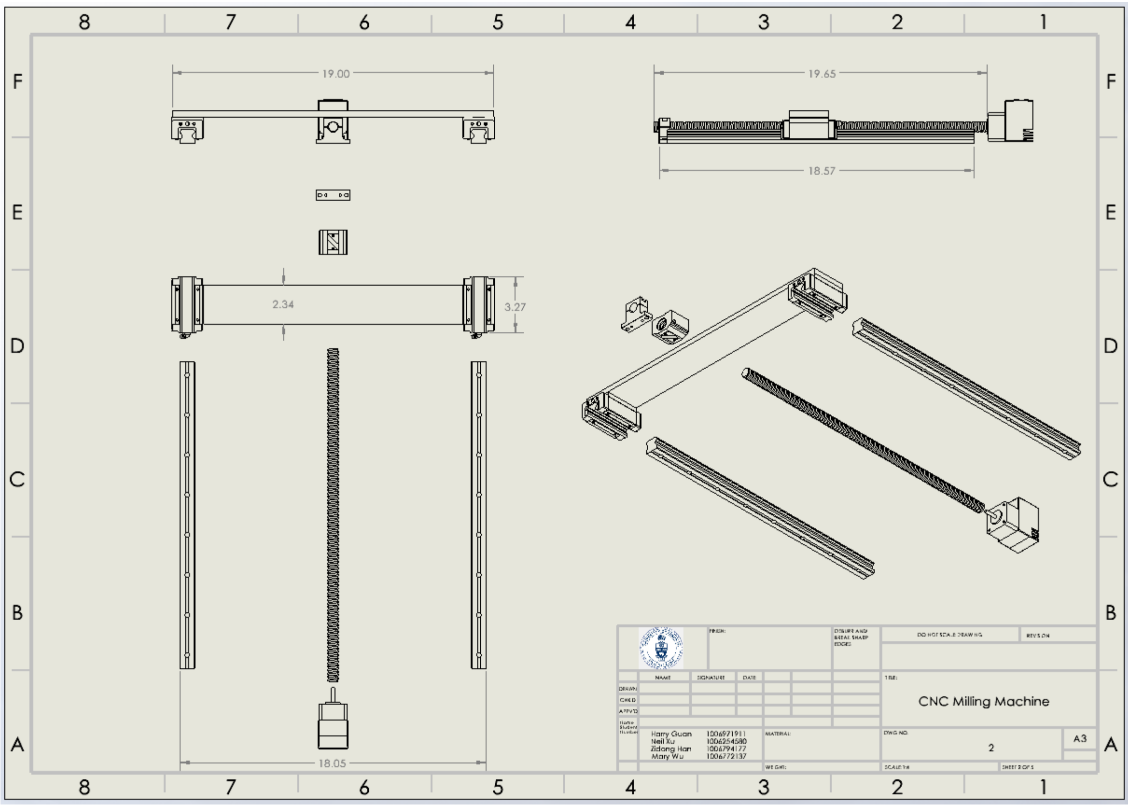


Figure 5.2: Assembly drawing 2

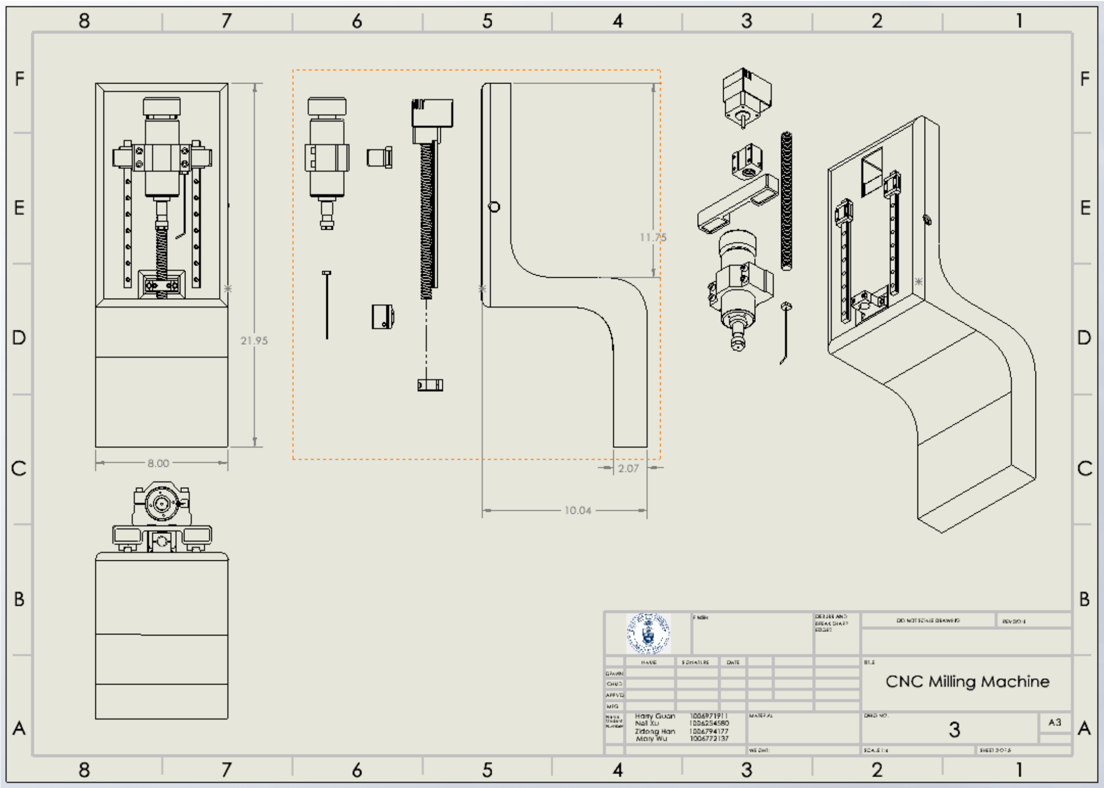


Figure 5.3: Assembly drawing 3

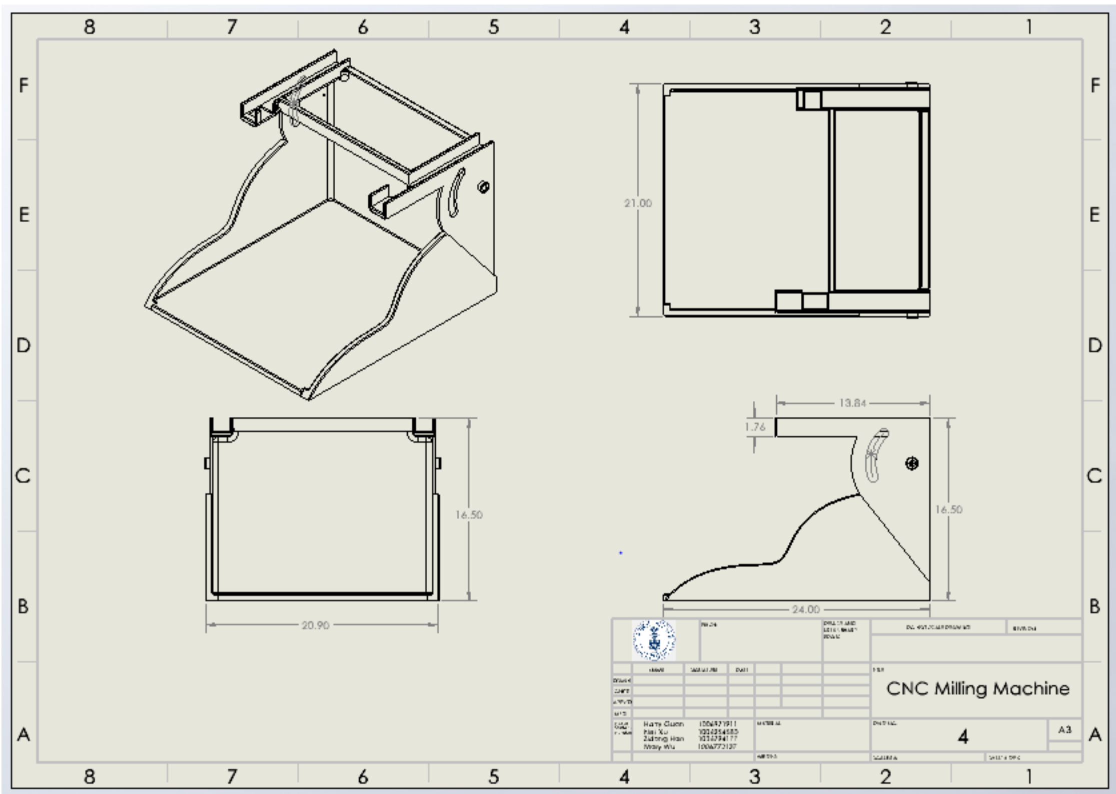


Figure 5.4: Assembly drawing 4

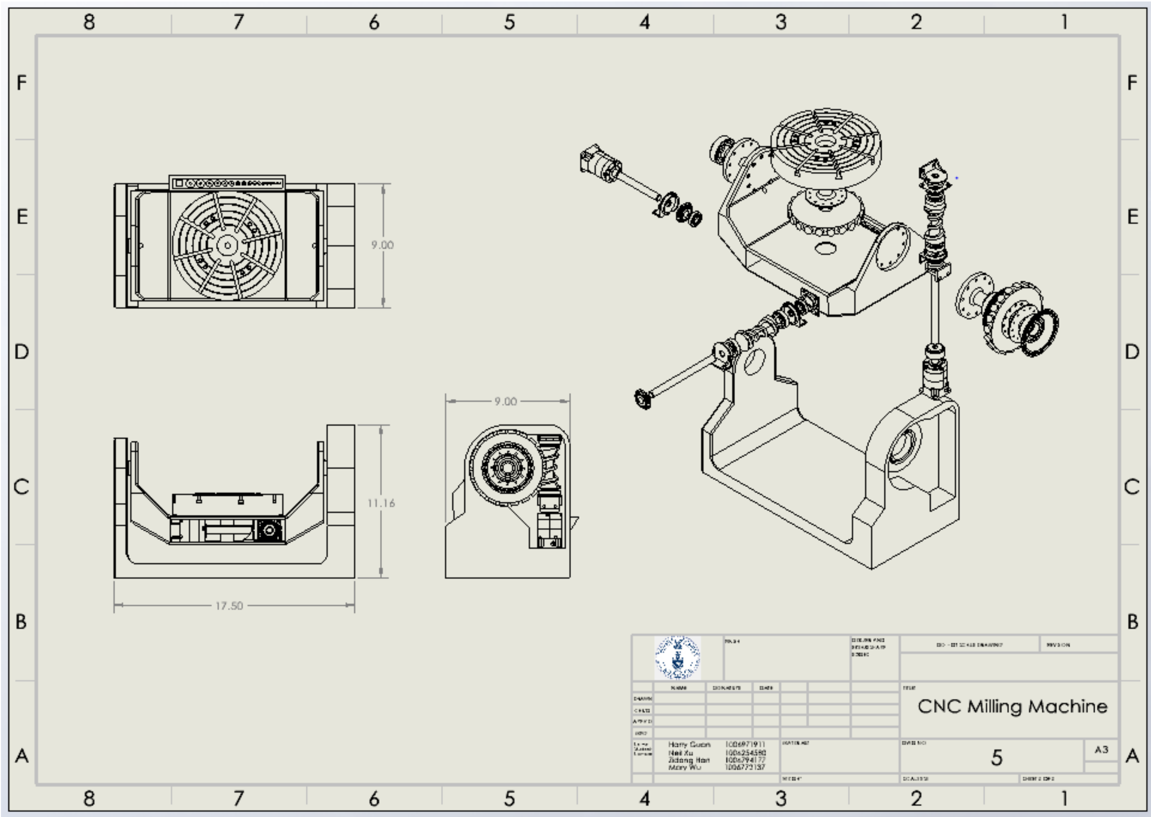


Figure 5.5: Assembly drawing 5

6. Conclusion

The team has analyzed the problem statements, developed the need from the potential target audience (the professional design companies such as the small engineering firms), and completed a thorough design process.

Starting with the market research about the existing products, the team has identified the milling machine design's functions, objectives, and constraints. After the candidate designs, selected the top candidate and made modifications on different components. The major mechanisms are identified, explained, and modeled in detail, reaching maximum precision.

Thus, the output of the overall design process is a desktop 19' * 24' * 25.88' milling machine with 5 axes of movement. The Machifit ER11 Chuck 500 W Spindle Motor could cut wooden, aluminum, and stainless steel materials at a maximum rotation speed of 12,000 rpm and move in x and z-direction. The maximum diameter of the cutting material is 8 inches, and it could translate in the y-axis as well as rotate about a horizontal axis.

Referring to section 4.5, we have added up the parts from McMaster Carr and considered the price of other custom parts with a cost tolerance of 1500$ (including but not limited to roller CAM drive). Also, the casing's material and cutting cost is included inside the tolerance. Thus, the total cost of this specific five-axis milling machine is around $5000.

The milling machine is compact, with all sub-components translated freely on the desired axis, and the precise cutting output will be reached. It is user-friendly, could change the milling tool automatically, and is environmentally friendly since the dust, the cooling fluid, and metal scrap are recycled in a closed environment. The design meets all the problem requirements, adds additional functionality, and the team hopes that the proposed conceptual design will be manufactured and produce a satisfying output.

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8. Appendix A

[1] 2 Flute Carbide End Drill/Mill