# LARGE FORMAT HOME/HOBBY CNC MACHINE
# MIE243 DESIGN PROJECT

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# *Project Requirements*

## Introduction

The aim of this project is to design a large format, beginner/hobby-level CNC milling machine that is ready to enter the detailed design phase. In general, a CNC mill operates by executing pre-programmed commands (usually in the form of G-Code), which dictates the movement of the machine in order to mill a piece to desired specifications.

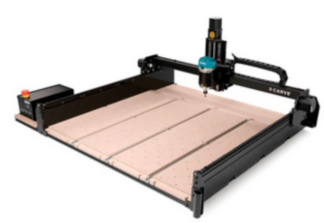
The general design guidelines are outlined in the MIE243 Design Project document. Our design will be solely concerned with the physical components of the machine, not the electronics or circuitry. In general, the document emphasizes that the design should have the appropriate specifications for a beginner or hobbyist environment, be able to work large pieces, and comfortably fit within a small home or garage workshop.

## Preliminary Research and Benchmarking

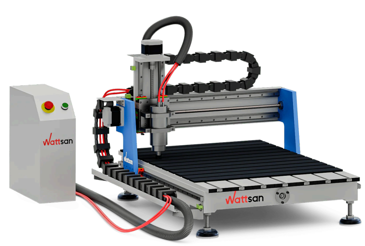
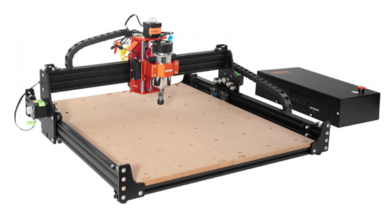
In order to get an initial idea of the general specifications and components that make up a CNC machine, we conducted market research on the types of CNC machines available.

Our group started off brainstorming a general idea/general dimensions of what a CNC machine should look like by analyzing the specifications of different CNC machines we found on the internet. All types of CNC machines were researched so that we did not limit our design space, though particular focus was given to products that were the most relevant to our audience (home/hobby environments). The benchmark designs shown below were chosen such that we had enough information about the types of CNC machines to make informed decisions about our engineering specifications.

Table 1: Benchmark Designs

| | | |
|---|---|---|
| Photo |  |  |

| | | |
|---|---|---|
| Model Name | Shapeoko 4 CNC router (XXL Size) [1][2] | X- Carve CNC machine [3][4] |
| Axis of movement | 3 | 3 |
| Frame Material | Aluminum | Unknown |
| Footprint (x,y,z) [mm] | 1270 x 1067 x 483 | 1250x1000x350 |
| Travel Range (x,y,z) [mm] | 838 x 838 x 102 | 750x750x114mm |
| Accuracy | 0.127mm | 0.127mm |
| Spindle Speed | 12000-30000 RPM [3] | 10000-30000 RPM |
| Spindle Power | 920w | 800w |
| Compatible Materials | Wood, plastics, non ferrous metals (aluminum, brass, copper) | Woods + Composites, Plastics, Non ferrous Metals |
| Weight | 79 Kg | 45 kg |
| Cost [$CAD] | 3488.81 | 1954.74 |

| | | |
|---|---|---|
| Photo |   |  |
| Model Name | Wattsan 6090 MINI [6] | Vevor CNC Router Machine [7] |
| Axis of movement | 3 | 3 |
| Frame Material | Cast Iron, Aluminum | Aluminum |
| Footprint (x,y,z) [mm] | 915x1210x740mm | 710x600x320 |

| | | |
|---|---|---|
| Travel Range (x,y,z) [mm] | 600x900x100 | 400 x 400 x 75 |
| Accuracy | 0.002mm | 0.05mm |
| Spindle Speed | Reaches 24000 RPM | 12400 RPM |
| Spindle Power | 2.2kW | 300w |
| Compatible Materials | Wood, MDF, plastics, aluminum, brass, | Woods, Acrylics/Plastics |
| Weight | 175kg | 13kg |
| Cost [$CAD] | 6651.30 | 529.99 |

From the benchmark designs, we also conducted some preliminary research into individual CNC-related specifications that would help form engineering specifications, as well as some research to synthesize information from the project document.

*Material Compatibility:*
In general, the machines we researched were all able to cut the same sets of materials, which included woods, wood composites (plyboards), plastics, and soft metals(mainly aluminum). Only one design shown above wasn't able to cut aluminum. These materials are generally soft, and are common in a beginner/hobbyist environment. Machines that cut harder materials such as steel exist, but are out of scope for the audience we are targeting.

*Spindle Requirements:*
The CNC machines we researched that were capable of meeting the range of materials encountered in a hobbyist setting (woods, plastics, aluminum) generally had specifications of 800-2200 watts for power, and speeds ranging from 10-30k RPM. Additionally, the spindle should be able to support different types of bits for different purposes. Expanded research related to spindles can be found below.

*Axis:*
In general, most CNC machines we found operate on 3 axes (x,y,z). There are machines capable of machining in up to 5 axes, but those features are out of scope for a hobbyist environment, and would add an extraordinary amount of mechanical complexity and cost [8].

*Large-format/Size and foot print:*

The design document had a particular emphasis on the ability of the router to mill large work pieces. Therefore, we considered the dimensions of common plywood stock, which we found to be mostly 2x2 ft, 4x2 ft, and 4x8 ft [9]. The thickness of the sheets were also generally under 1 inch. However, the emphasis on large format has an impact on cost, and the ability to fit comfortably within a home environment, which we need to consider in forming specifications.

## Engineering Specifications:

From our benchmark designs and preliminary research, we formed a set of engineering specifications for the parameters that we felt were the most relevant. The metrics that we chose were loosely defined in order to ensure our design space was not limited.

In general, the design should consist of a large format CNC machine targeted towards beginners and hobbyists for home usage. The design should balance affordability, user friendly operation, and consistent performance (in terms of rigidity and accuracy), while fitting comfortably within a home workshop. Since the design is targeted towards beginners, low maintenance should be prioritized when selecting parts. Additionally, compatibility with open source kits and upgrades would ideally be supported.

1. Must cost under $3000CAD
2. Must not have a larger footprint than 2000mmx2000mmx500mm
3. Must be under 100kg
4. Must have a minimum working area/travel range of 650x600x75mm (to accommodate 2ft (609.6mm) wide stock sheets, with the rest of the distance passing through)
5. Must be able to cut woods, wood composites(including plywood, MDF, etc), plastics(including HPDE, acrylic, etc), and aluminum
6. Spindle must support different types of bits/end mills
7. Must operate in at least 3 axes of movement(x,y,z)
8. Must not have an accuracy less than 0.13mm

Specifications 1-3 are targeted towards ensuring the design would be catered towards beginners and hobbyists, fitting within a home workshop. Specifications 4-8 are to ensure that the design would be able to perform the expected cutting tasks expected of a hobbyist CNC machine. However, specification 5 is dependent on factors related to spindle specs, which is discussed later

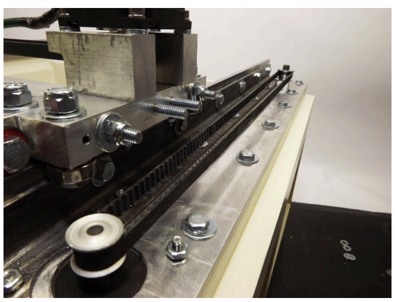
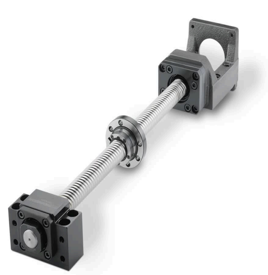
# *Research*

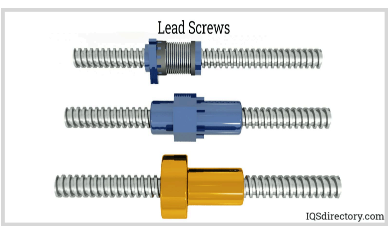
Research was conducted on the individual components within a CNC machine in order to gain more insight into how the components potentially fit or clash within our engineering specifications.

## Linear Transmission:

Linear Motion System is made up of components that create linear motion for the overall CNC Router. Our group analyzed various linear motion components in the current market. Each of these linear motion systems were applied to our candidate designs. The table below illustrates these linear systems.

Table 2: Linear Motion Research

| **Linear Motion System** | **Pros** | **Cons** |
|---|---|---|
| **Timing Belt**<br><br>In a CNC router, a timing belt helps move parts like the cutting head or gantry smoothly and accurately by connecting them to the motor. | - Cost-effective<br>- Requires minimal lubrication and maintenance<br>- Low noise<br>- Allow for fast motion<br>- Easy to replace[10] | - Less accurate compared to other transmission systems [11]<br>- Over time belts may stretch and introduce backlash defeating the minimize noise and backlash objective.<br>- Belts wear out faster than screws.<br>- Not suited for high loads |
| **Ball Screw**<br><br>A ball screw is a mechanical device that converts rotary motion into | - Ball screw is more precise and provides minimal backlash[12]<br>- Lots of durability and resist wear due to their rolling-contact design<br>- High efficiency due to low friction | - Ball screws are more expensive than timing belts and lead screws, impacting affordability objectives.<br>- Maintenance required regular lubrication[13] |

| | | |
|---|---|---|
| precise linear motion. It uses a threaded shaft and ball bearings to reduce friction, allowing smooth and accurate movement, often used in CNC machines. | between components<br><br>- Provide smooth consistent vibration-free linear motions<br><br>- Can handle heavier loads compared to timing belts and lead screws | |
| **Lead Screw**<br><br><br><br><br>A lead screw converts rotary motion into linear motion using a threaded shaft and nut. | - Cheaper than ball screws but most expensive than timing belt<br><br>- Easy to install<br><br>- Provides decent accuracy<br><br>- Can handle moderate loads | - Lower mechanical efficiency compared to ball screws due to higher friction between materials<br><br>- Slower compared to timing belts which may be a drawback for large work area<br><br>- Can produce more noise than timing belts |
| **Rack and Pinion**<br><br><br><br>Rack and pinion convert rotary motion into linear motion using a pinion and a rack | - Cost effective for large areas and replacement is cost-effective as well [14]<br><br>- Durable and resistant to wear in heavy load applications.<br><br>- Easily scalable for very large work areas<br><br>- Unlike timing belts | - Rack and Pinion systems usually have more backlash than ball and lead screws[15]<br><br>- Higher noise and vibration at high speeds<br><br>- Rack and pinion need to have proper alignment for smooth operation. This may complicate the installation of |

| | | |
|---|---|---|
| | there is no risk of elongation over time | rack and pinion<br>- Not a good option for Z-axis movement due to difficulty in maintaining precision and stability against gravity. |

## Spindles:

Spindles refer to the component within a CNC machine that holds and rotates the cutting tool of the CNC machine to remove material.

**Specifications**

To ensure the hobby-level machine would be capable of cutting through woods, wood composites, plastics, and aluminum, several factors must be considered:

- **Torque**
  The spindle should have substantial low end torque of at least 30 Nm to ensure performance is maintained when using larger diameter tools for efficient material removal even with aluminum[16].
- **Power Rating**
  A spindle power rating of 1.5 kW to 3.0 kW (approximately 2 HP to 3 HP) ensures the spindle is capable of handling a variety of materials, including softwoods, hardwoods, plastics, and even metals like aluminum[17].
- **Speed Range (RPM)**
  A spindle with a speed range of 8,000 to 24,000 RPM offers flexibility for the different materials. Higher speeds are optimal for small-diameter tools (up to 3/8” shank) and softer materials, while lower speeds are better suited for larger tools and harder materials, reducing heat buildup and improving tool life [16] [18].
- **Cooling Method**
  Water-cooled or air-cooled systems should be considered if the machine is designed to cut through metals. This helps maintain optimal operating temperatures and prolongs spindle life[19].

**Market Research and Comparison:**

We conducted research on our options with spindle selection and created a pros and cons comparison while putting into consideration the targeted demographic and ideal use cases.

Table 3: Spindle Research

| Feature | Pre-built Water-Cooled Spindles | Pre-built Air-Cooled Spindles | Servo Motors with In-House Designs |
|---|---|---|---|
| **Pros** | - Excellent cooling for extended use<br>- Ensures precision<br>- Quiet operation<br>- Ideal for heavy-duty tasks | - Simple and lightweight<br>- Easy to set up<br>- Affordable<br>- Portable for hobby use | - Highly customizable<br>- Precise control and integration<br>- Higher accuracy and efficiency |
| **Cons** | - Complex setup with water pumps and tubing<br>- Higher maintenance and cost<br>- Bulkier, less portable | - Louder operation<br>- Less efficient cooling<br>- Potential overheating in long or heavy use | - Significant design effort and testing<br>- Higher costs and time investment<br>- May lack proven reliability |
| **Ideal Use Case** | Heavy-duty, high-precision applications | Hobby or light-duty machining | Custom, specialized projects requiring high accuracy |

## Motors

These motors refer to the motors used to power the linear transmission mechanisms within the CNC machine. Several different types of motors were researched and shown below.

**Servo Motors**

Servo motors are precise, closed-loop motors [20] that use feedback from encoders to maintain their position, speed, and torque. They are ideal for applications requiring high precision, variable speed, and dynamic load handling as shown in MIE243 Tutorial slides.

- **Pros**: Servo motors possess high precision due the closed-loop control which ensures accurate positioning and speed. Furthermore it is suited for high torque, variable speeds, minimal heat generation, high energy efficiency, and the encoders in it provide real-time position and velocity data for accuracy. Meaning it is easier to control using G-code.

- **Cons**: Servo Motors are more expensive than stepper motors, they require advanced drivers and encoders which might be hard to integrate into the system.

**Stepper Motors**
Stepper motors are open-loop motors that move in discrete steps, making them ideal for applications where simplicity and moderate precision are sufficient as demonstrated in the MIE243 Slides.

- **Pros:** Stepper Motors are easy to control and integrate with CNC controllers, they are less expensive than servo motors, high torque at low speeds, and efficient in terms of maintenance.

- **Cons:** Limited speed and torque at higher speeds, less precise than servo motors due to no feedback since it is an open-loop system, and it produces more vibration and noise compared to servo motors.

**DC Motors**
Direct Current (DC) motors directly convert direct current into mechanical energy, and are commonly used for simple motion tasks [21]. They can be paired with encoders for feedback.

- **Pros:** DC Motors are cost effective for basic motion applications, available in lots of sizes and power ranges, and it is easier to speed control using voltage regulation.

- **Cons:** DC motors wear over time requiring constant replacement. Additionally, they require some sort of external feedback system for accurate movement, complicating implementation[22]

**Comparison Table Between Motors**
To compare the motors, a table below has been created to assess the applications of each motor.

Table 4: Comparison Between Motors

| Motor Type | Precision | Cost | Speed | Torque | Maintenance |
|---|---|---|---|---|---|
| **Servo Motors** | High | High | High | High | Moderate |
| **Stepper Motors** | Moderate | Low | Moderate | High at low speeds | Low |

| | | | | | |
|---|---|---|---|---|---|
| **DC Motors** | Low | Low | High | Moderate | Moderate |

**Base Components**

**Frame Material**
Aluminum usually refers to aluminum alloys (such as 6061 and 1060 aluminum), as they are widely used over pure aluminum. Aluminum seems to be the most common material used for CNC machine frames, considering market research. Notable qualities of aluminum include its low density (2.7 g/cm^3), resistance to corrosion, and its strong mechanical properties, handling tensile and compressive stresses well [23]. The low density of aluminum makes it suitable for hobby level machines, as the reduced weight will make it easier to set up. Furthermore, the prevalence of readily available aluminum stock extrusions, could allow the customer to replace frame parts alone if we were to use them within our design. Aluminum is also easier to machine, which makes custom parts easier to make [24]. However, the lower density could be detrimental to the overall rigidity of the machine

Other materials such as steel can also be used in CNC machine frames. Steel exhibits a higher density and rigidity than aluminum. However, those materials often see usage in machines designed for industry rather than a hobby environment where rigidity is emphasized more due to the harder materials being machined [25]. Additionally, steel exhibits almost 3 times the density of aluminum, which impacts the ease of assembly and suitability of the machine for a home setting [26]

## Milling Surface:

For the milling surface(the plate where the workpieces will be fixed during machining), 3 main options were observed in most commercial hobby CNC machines, which were the T-slot table, a MDF spoilboard, and a hybrid table combining the two.

**T slot Tables:**

Figure 1: Milling Surface and T-slot clamping fixture[27][28]

A T slot table generally consists of an aluminum plate that contains t slots running across its length. These t slots are then used to facilitate the usage of clamps and fixtures to hold workpieces down.

- **Pros**
  - T slots follow a standard, easier to integrate clamps [29]
  - Added weight makes machine more rigid
- **Cons**
  - More expensive than other alternatives for tabling.

**MDF Surface Board:**

Another option for the cutting surface that is commonly seen in a CNC machine is using a sheet of MDF board. Typically, the board is filled with a grid of holes made for mounting clamps and workpieces to the board.

Figure 2: MDF Surface table, along with clamp [30] [31]

- **Pros**:
  - Cheaper
  - Highly customizable, can machine mounting holes wherever for easy access
  - Users can easily replace with their own MDF boards
  - Can be replaced when mistakes are made(e.g. Plunging too deep)
- **Cons**
  - Mounting certain types of clamps can be difficult
  - Less rigid, prone to warping [32]

**Hybrid MDF Board:**

The next option that was commonly encountered was a hybrid CNC milling surface. This design features aluminum t-slot extrusions integrated with slabs of MDF board, which allows for the integration of T-slot clamps.

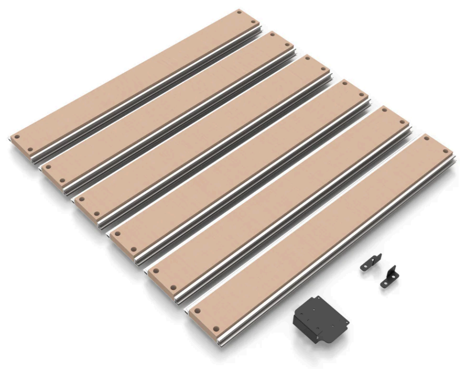


Figure 3: Slabs of hybrid MDF Board [33]

- **Pros**
  - T slots follow a known standard to integrate clamps
  - Modular, so if one piece is damage, can be easily replaced

- **Cons**
  - More expensive than alternatives
  - Compatibility issues when trying to integrate other hybrid boards, as different manufacturers could have different t-slot dimensions

## *Candidate Designs*

Having analyzed the benchmark designs off the internet we created 3 candidate designs in mind that fit within the extremes of our engineering specification . And 1 design that fits into the middle of those two extremes. Below is the table illustrating what the initial specifications for each candidate design we aimed for. Each candidate is expanded on below.

Table 5: Comparison between Candidate Designs

| | **Design 1** | **Design 2** | **Design 3** |
|---|---|---|---|
| **Cost** | Lower-end for hobbyist/beginner focused design | Mid-Higher end hobbyist machine | Higher-end machine for garage/larger workshops |
| **Size (Work Size)** | 650mmx600mm | Up to 700mm x 700mm | Up to 1000mm x 1000mm |
| **What materials it can cut** | Plywood, Plastic, Plexiglass | Plywood, Plastic, Plexiglass, Aluminium | Plywood, Plastic, Plexiglass, Aluminium |
| **Spindle** | 12 KRPM<br>0.5- 1.5 Nm torque | 10-24 KRPM<br>1.5 - 3.5 Nm torque | 24-32 KRPM<br>1.5 - 3.5 Nm torque |

| | | | |
|---|---|---|---|
| | | | |
| **Transmission system (rotational → linear)** | Timing Belt<br><br>Highlighted as an alternative transmission method, possibly more cost-effective but less precise. | Ball Screw for transmission. It will use it to move all 3 of the axes.<br><br>It is more expensive but offers advantages like better spindle rigidity. It mentions the potential issue of backdriving that needs to be considered. | Uses Ball Screw for transmission as well<br><br>More expensive, but higher precision, also lower maintenance<br><br>Moves wasteboard for a more rigid structures larger format enables it |
| **Transmission motors** | Stepper Motors used to keep cost down while maintaining accuracy | Steppers on all axis to maintain a cost-balanced approach | Servo Motors on all axis to ensure best accuracy |
| **What is unique about this design** | Cheapest in terms of parts | High precision hobbyist machine | Very large format, ensures rigidity through axis movement mechanism<br>Higher precision at a large scale |

We noticed that design 2 had a relatively high cost due to the ball screw transmission mechanisms being used, so we decided to form a reiteration of that design using a chapter transmission mechanism(detailed in Candidate 4)

**Candidate Design I**

Since candidate design 1 was designed to be the most-cost effective we used the cheapest and easiest to maintain parts. The figures below highlight the general idea of design 1. This candidate design focuses on cost effective solutions and still prioritizes precision in our design. This design uses one servo motor to control and move the platform using a timing belt along a guide rail to support the overall structure. The Gantry is fixed onto the base which also uses a timing belt to control the overall movement of the spindle. This ensures a cost effective solution while maintaining enough accuracy for operations. The work space is ideally 650x600mm to fit our specification. These specifications are integrated into the design using our engineering specifications, using the appropriate parameters like the general size, weight, cost, etc.

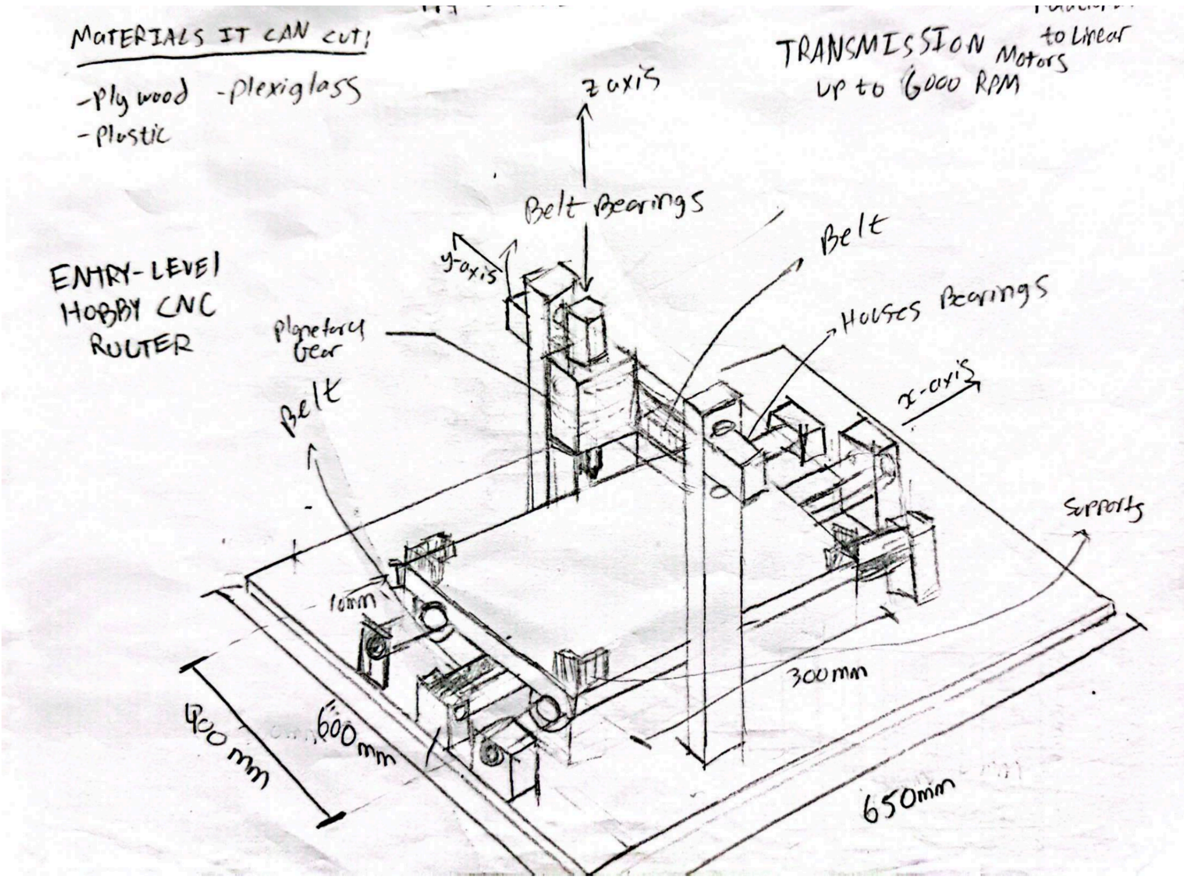



Figure 4: Initial sketches of Candidate Design 1

Table 6: Candidate Design 1 Specs

| **Transmission System** | **Timing Belt** |
|---|---|
| **Type of Motor** | Stepper Motor (x-y-z axis) |
| **Workspace size** | 650mm x 600mm x 75mm |
| **Demographic** | Hobbyist/Entry Level |
| **Pros** | - Fulfills engineering specifications with minimum cost.<br>- Lead screws provide adequate accuracy and durability for milling.<br>- Would be just enough to fit material sheets purchased from chain depot stores.<br>- Will be one of the cheapest models available for |

| | |
|---|---|
| | these specifications, highly competitive price. |
| **Cons** | - Lower quality of components.<br>- Little variation in usage and material.<br>- Little upgradability.<br>- Lead screws may need more frequent repairing and maintenance.<br>- Timing belts may need frequent servicing and maintenance. |

**Candidate Design II**

Candidate two offered a model that looked for a balance between the different facets of the mill, aiming to provide a higher quality of machining capability at a competitive price. This candidate achieves motion in 3 axes through a moving gantry in the x-axis, while the spindle housing moves along the gantry in the y and z axes.

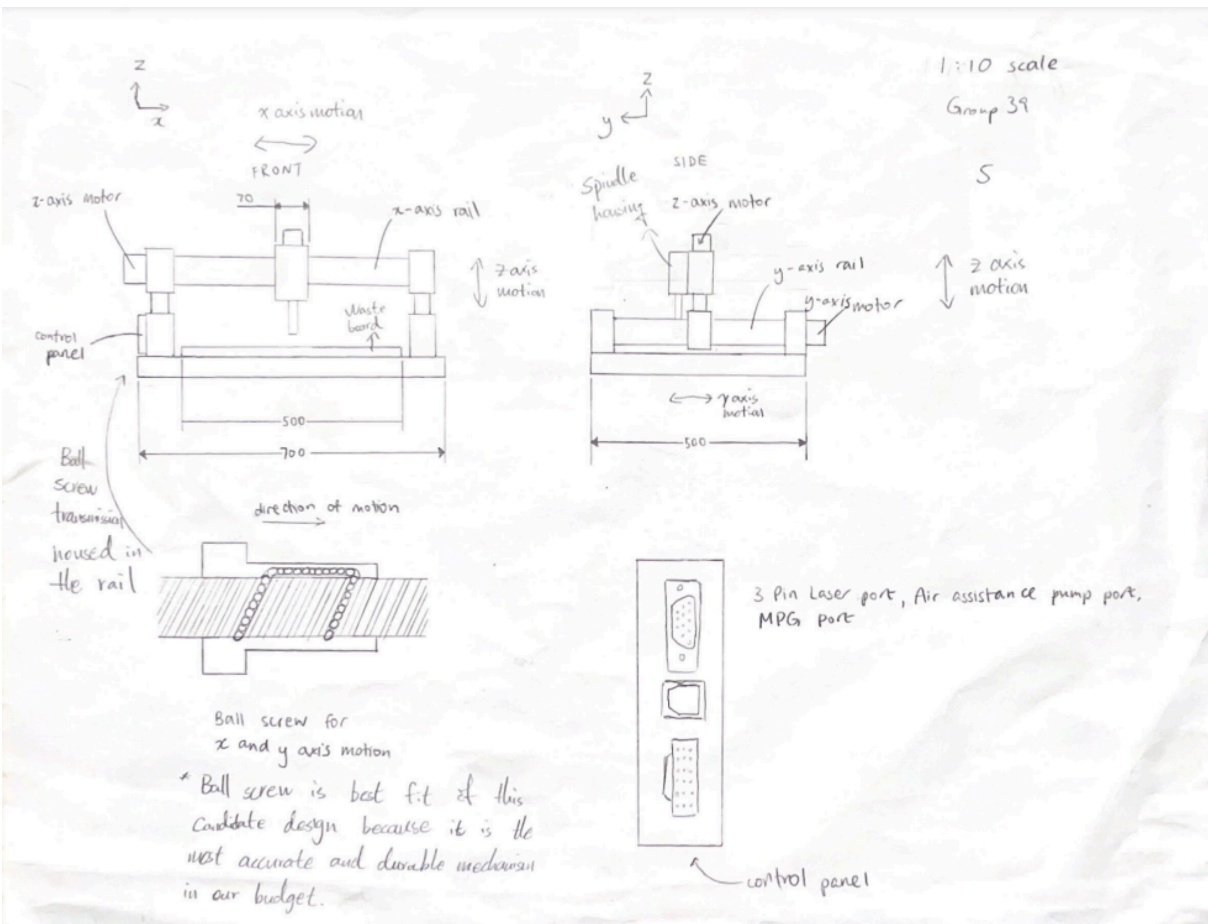



Figure 5: Initial sketches of Candidate Design 2

Table 7 : Candidate Design 2 Specs

| | |
|---|---|
| **Transmission system** | **Ball Screw (x-y-z axis)** |
| **Type of Motor** | Stepper Motor (x-y-z axis) |
| **Workspace Size** | 700mm x 700mm x 80mm |
| **Demographic** | Hobbyists that will look at mid-high price ranges, a bit more experienced |
| **Pros** | - Moving gantry ensures a more compact size while fulfilling the Engineering specifications.<br>- Ball screw provides superior accuracy and durability compared to lead screws and transmission belts.<br>- Comfortable enough to fit material sheets purchased from chain depot stores with a good margin of wiggle room. |
| **Cons** | - Higher prices due to higher quality components.<br>- More complex builds means harder repairs.<br>- Moving gantry system impacts rigidity<br>- Closer in specs and prices to the majority of hobbyist mills on the market, mid range specs and cost may be less competitive on the market. |

**Candidate Design III**

The third candidate design was intended to maximize the rigidity of the machine by using an alternative method to axis movement. The gantry would be fixed in position with aluminum extrusions, and the wasteboard would move instead. However, this would require motion supports to move along with the transmission system, which results in more mechanical complexity. In addition, in order to accommodate for the moving wasteboard the footprint of the machine would be a lot larger than the workspace itself.

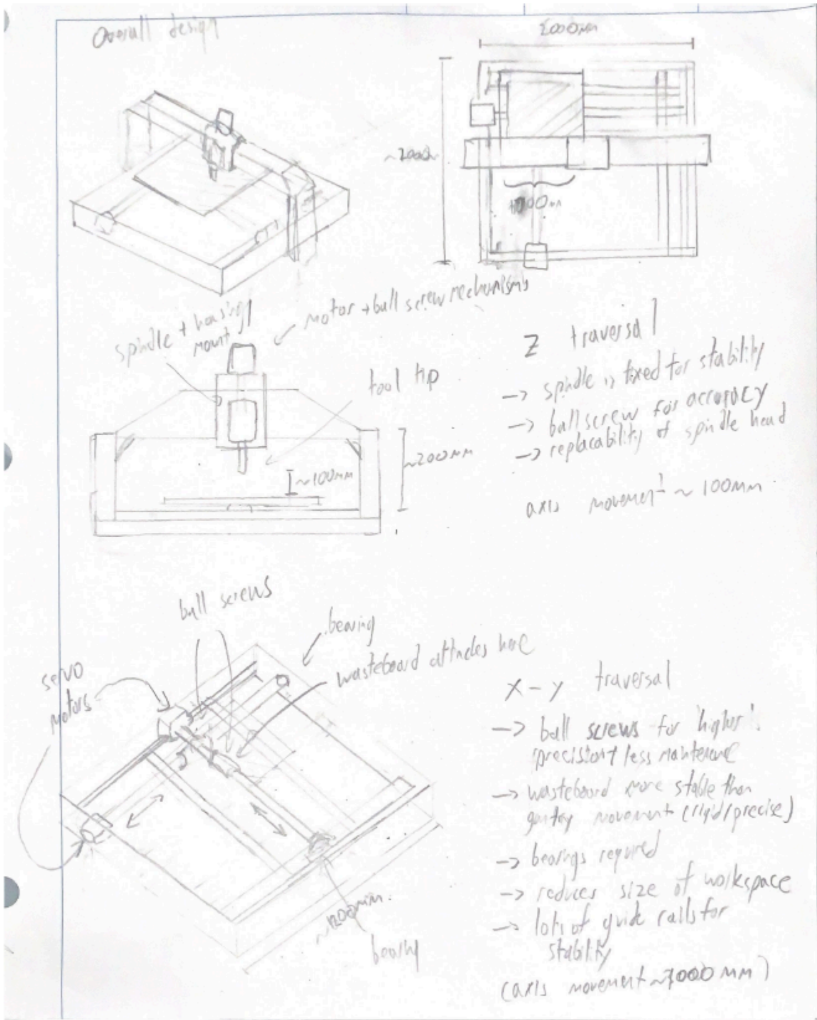



Figure 6: Initial sketches of Candidate Design 3

Table 8: Candidate Design 3 Specifications

| | |
|---|---|
| **Transmission System** | Ball screw |
| **Type of Motor** | Servos motors (x, y, z) axis |
| **Workspace size** | 1000mm x 1000mm |
| **Pros** | - Emphasizes rigidity through wasteboard movement and fixed gantry<br>- Good accuracy due to usage of servo motors and ball screws<br>- Would be able to fit large workpieces comfortably |

| | |
|---|---|
| | - Steel frame ensures rigidity |
| **Cons** | - Expensive due to higher material costs to accommodate frame<br>- Large format impacts ability to fit within a home environment<br>- Servo motors require expensive electrical components<br>- Complex design due to needing to accommodate movement of guide rails along |

**Candidate Design IV**

This candidate design essentially uses all the parameters from candidate design 2 but with one major difference in the transmission system. This design hopes to improve cost solutions even further to satisfy our engineering specifications

**Transmission System:** Utilizes a timing belt transmission system instead of the ball screw mechanism used in Candidate Design II.

**Motor Selection:** Equipped with Nema-23 stepper motors. These motors are chosen for their cost-effectiveness and sufficient torque for hobbyist applications.

**Work Space Area:** Provides a work area of approximately 700x700mm same as design 2, sufficient for most hobbyist projects.

Design 4 targets users seeking a cost-effective yet reliable CNC router for entry-level and intermediate applications. While it does not achieve the same precision as Candidate Design II, it fulfills the essential needs of hobbyist environments and aligns with budget constraints

Table.9 Candidate 4 Specifications

| | |
|---|---|
| **Transmission System** | Belt system |
| **Type of Motor** | Nema-23 stepper motors (x, y, z) axis |
| **Workspace size** | 700mm × 700mm |
| **Pros** | - Cost-effective and reliable for entry-level/intermediate applications<br>- Stepper motors are affordable and provide sufficient torque for hobbyists<br>- Suitable for hobbyist projects due to workspace size |
| **Cons** | - Belt systems may have lower accuracy compared to ball screws<br>- Not as rigid as steel frames with ball screws |

| | |
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| | - Limited to smaller workpiece sizes compared to larger designs |

**Final Design Feature Selection**

We chose the final design based on iterating through a decision matrix where we weighed metrics like precision against each other. This process was done so by assessing a weight to each metric from most important to least important metric based on our engineering specification. Precision being rated 0.9 and noise being 0.1. Then we assessed each candidate design relative to Design 1 if they score better than design 1 or less. We found out Design 2 had the best overall Score as shown below in the table. Justifications for each score can be found below the table, which was based on our research.

Table 10: Decision Matrix

| Metrics | Weight | DESIGN 1 | DESIGN 2 | DESIGN 3 | DESIGN 4 |
|---|---|---|---|---|---|
| **COST**<br>Cheaper is better, $ 3000 limit | 0.9 | 0 | -1 | -2 | 0 |
| **Spindle Capabilities**<br>Ability for spindle to hit required rpm/torque for materials | 0.8 | 0 | 1 | 1 | 1 |
| **PRECISION**<br>Mainly dependent on the transmission system. | 0.7 | 0 | 2 | 2 | 0 |
| **SIZE OVERALL**<br>Aiming for large format workspace while fitting in home workshop | 0.6 | 0 | 1 | -1 | 1 |
| **Durability Overall**<br>Dependent on material and frame design | 0.5 | 0 | 1 | 2 | 0 |
| **Maintenance**<br>How easy is it to clean | 0.3 | 0 | -1 | -1 | 0 |
| **Energy Consumption** | 0.2 | 0 | -1 | -1 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Energy efficiency of machine | | | | | |
| **Noise Level** From transmission system/spindle, lower is better | 0.1 | 0 | -1 | -1 | 0 |
| **TOTAL** | | 0 | 1.8 | 0.2 | 1.4 |

**Decision Matrix Score Justifications:**

**Cost**

- **Design 1:** Lowest cost due to the use of timing belts and minimal components.

  **Reason:** Simplistic design reduces material and component expenses.

- **Design 2:** Balances cost and quality, offering enhanced durability and performance.

  **Reason:** Ball screws add expense but justify the cost with improved accuracy and lifespan.

- **Design 3:** Highest cost due to advanced components and larger size**.**

  **Reason:** Incorporates industrial level features, increasing material and production costs.

- **Design 4:** Optimized for affordability with timing belts, achieving cost savings while maintaining quality.

  **Reason:** Cost-effective components reduce overall expenses without sacrificing key functionality.

**Spindle Capabilities**

- **Design 1:** Limited spindle speed and torque, restricting it to softer materials

  **Reason:** Low RPM spindles struggle with harder materials like aluminum

- **Design 2**: Mid-range spindle with speeds up to 30,000 RPM, handling various materials including light metals

**Reason:** Provides sufficient power for hobbyist needs without unnecessary complexity

- **Design 3**: Same spindle as Design 2, offering similar capabilities

  **Reason:** Shares spindle specifications but supports larger workspaces.

- **Design 4**: Similar spindle specifications to Design 2, providing versatile material handling at a lower cost

  **Reason:** Retains adequate performance while optimizing cost

**Precision**

- **Design 1**: Basic Precision using timing belts, sufficient for simple tasks but lacks precision required for advanced applications

  **Reason:** Timing belts are susceptible to stretching and backpack, which reduces accuracy.

- **Design 2**: Improved precision with ball screw transmission, ideal for hobbyists who need more accurate results

  **Reason:** Ball Screws provide minimal backlash and consistent accuracy.

- **Design 3**: High Precision due to advanced components, which leans towards professional level requirements

  **Reason:** Utilizes high quality ball screws across all axes for industrial level precision

- **Design 4**: Decent precision using timing belts, adequate for most hobbyist projects but inferior to ball screw setups.

  **Reason:** Similar transmission limitations as Design 1.

**Size**

- **Design 1**: Compact, desktop friendly, suitable for limited spaces.

  **Reason**: Small features ensure accessibility and hobbyist specs but restricts project sizes.

- **Design 2**: Moderately sized workspace 700mm x 700mm for medium sized projects.

  **Reason**: Optimal size for most hobbyists, balancing usability and compactness.

- **Design 3**: Largest workspace 1000mm x 1000mm, suitable for professional grade tasks.

  **Reason**: Larger dimensions allow for diverse projects but require more space in terms of footprint due to moving wasteboard mechanism, leaving the scope of hobbyist level cnc router specs.

- **Design 4**: Similar size to Design 2, providing flexibility for typical hobbyist setups.

  **Reason**: Balances workspace size and compactness.

**Durability**

- **Design 1:** Lightweight frame suitable for light tasks, but less durable under heavy usage.

  **Reason:** Aluminum frame prioritizes affordability over rigidity.

- **Design 2:** Sturdy frame, ensuring consistent performance and longevity.

  **Reason:** Ball Screws provide additional durability

- **Design 3:** Most durable due to industrial grade frame and components hard steel.

  **Reason:** Designed for relatively heavy-duty tasks, offering exceptional strength and longevity.

- **Design 4:** Bit lower durability than Design 2, ensuring reliable performance for hobbyist needs.

  **Reason:** Frame materials and design strike a balance between cost and durability, though it loses out on the durability of ball screws

**Maintenance**

- **Design 1:** Minimal maintenance due to simple construction, though adjustments may be required over time.

  **Reason:** Timing belts are easy to replace but require occasional realignment.

- **Design 2:** Moderate maintenance with regular lubrication for ball screws

  **Reason:** Ball screws demand more upkeep but offer superior performance.

- **Design 3:** Similar maintenance requirements as Design 2, scaled for larger components.

  **Reason:** Larger setup increases lubrication and cleaning needs.

- **Design 4:** Low maintenance similar to Design 1, benefiting from simpler timing belt mechanisms.

  **Reason:** Retains Design 1's maintenance requirements

**Energy Consumption**

- **Design 1:** Lowest energy use, ideal for casual and to save power.

**Reason:** Simple transmission and lightweight components reduce power demands for the motors.

- **Design 2:** Moderate energy needs, suited for regular hobbyist tasks.

**Reason:** Ball screw systems increase efficiency but consume slightly more energy.

- **Design 3:** Highest energy consumption due to industrial grade components.

  **Reason:** Larger motors and transmission systems require more power.

- **Design 4:** Energy-efficient design optimized for hobbyist use.

  **Reason:** Combines cost-effective components with low power demands.

**Noise Level**

- **Design 1**: Quietest operation, suitable for home use.

  **Reason**: Timing belts produce minimal noise compared to ball screws.

- **Design 2**: Moderate noise levels, manageable for small workshops.

  **Reason**: Ball screws generate more noise but are not disruptive for hobby environments.

- **Design 3**: Loudest operation, best for industrial or isolated settings.

  **Reason**: Larger motors and robust transmission systems contribute to increased noise.

- **Design 4**: Quiet operation similar to Design 1, suitable for shared spaces.

  **Reason**: Retains the quiet benefits of timing belt systems.

## *Final Design*

### General Summary

The final design of our CNC Router machine is a high quality, hobbyist focused solution that balances precision, affordability, and usability. After evaluating multiple candidate designs using a decision matrix and following closely with our engineering specifications, we decided to follow through and refine our second candidate design through further research into the required parts, which incorporates a ball screw transmission system and NEMA-23 stepper motors. This combination ensures reliable and precise linear motion while maintaining cost-effectiveness for a home or small workshop environment to abide by our engineering specifications.

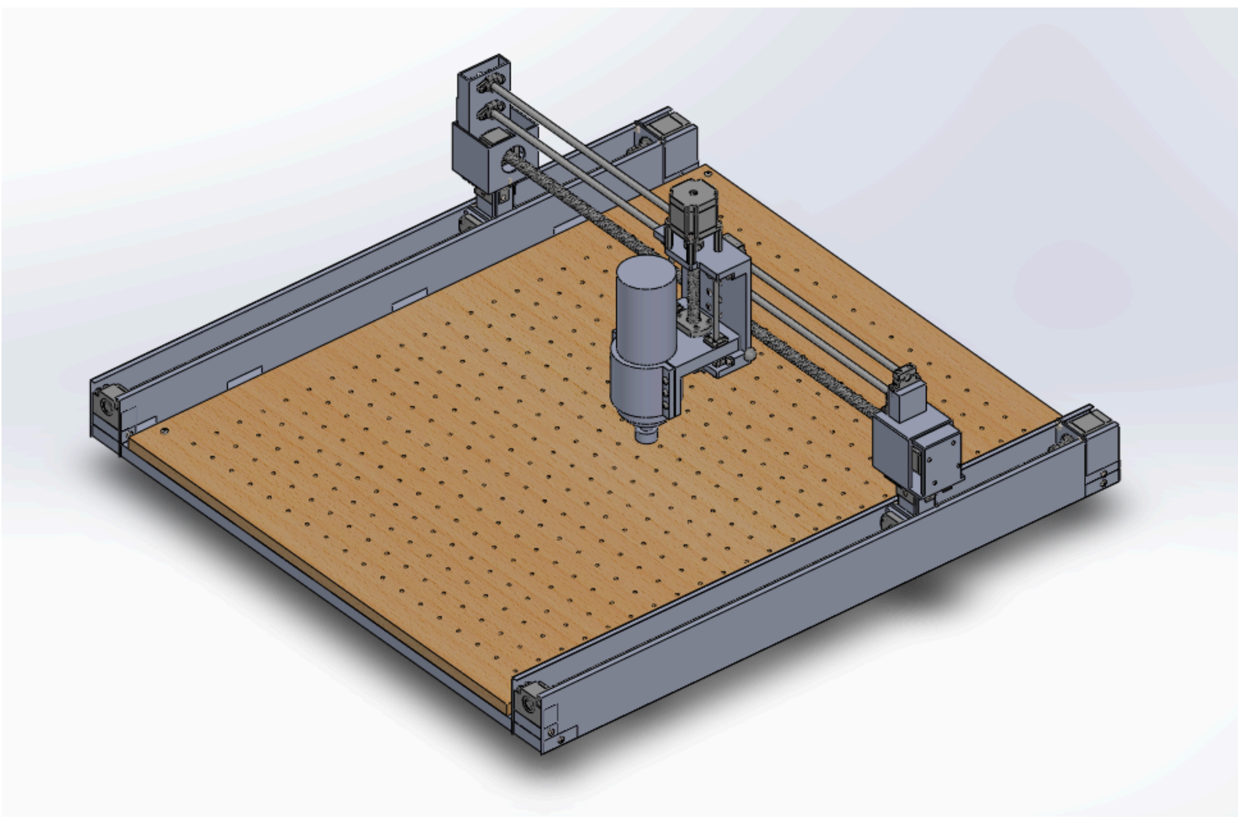


Figure 7: Rendering of Full Assembly of CNC router

### General Specifications

Table 11: Final Design Specs

| | |
|---|---|
| Cost (obtained in Costs section) | $2981.19 CAD |
| Footprint (obtained through CAD) | 999mm x 953mm x 414.3mm |

| | |
|---|---|
| Working Area (obtained through CAD) | 700mm x 670mm x 100mm |
| Spindle Specs (from component analysis) | 2.2 kW, 3 phase, 24000 rpm, 3-phase 220V±10% AC, 8.0A, 400Hz, 0.85 Nm |
| Weight (obtained through CAD) | 42.5 Kg approx |

**Key Features:**

- **Transmission System:** Ball Screws were chosen over timing belts and other systems for their superior accuracy and reduced maintenance which align with our metrics in engineering specifications. Their high cost will be addressed in trade-offs. Motion in all 3 axes is facilitated through a moving gantry (with the spindle attached) in the x direction. Meanwhile, the gantry contains the spindle housing which moves in the y-axis along the gantry, and finally the spindle housing moves the spindle up or down in the z-axis.

- **Motors:** Nema-23 stepper motors provide sufficient torque and control making them suitable for tasks common in hobbyist CNC Machining.

- **Material:** Aluminum was selected as the material for the frame and custom parts due to its lightweight properties, enabling easy assembly of the CNC machine. In addition, the strength and corrosion-resistant properties of aluminum provide adequate rigidity and structural integrity for our design, ensuring that the machine has a long lifespan.

- **Spindle:** A 2.2 kW Air-cooled CNC spindle capable of speeds up to 24000 RPM ensures compatibility with materials like plywood, plastics, and aluminium.

- **Structure:** An aluminium frame offers a lightweight yet sturdy construction, ensuring ease of assembly and resistance to corrosion, suitable for indoor use.

- **Work area:** The machine's dimensions and travel range accommodate a variety of workpieces sizing up to 700x670x100mm. More importantly, 2ft wide extrusions would fit through the machine, enabling large format work. The size of the workspace

**NOTE:** CAD files for parts were pulled often from McMaster Carr, but a separate website was used to determine the prices and specifications for those parts. In general, the dimensions and specifications on the website where the part is from are aligned with the part file from McMaster-Carr, enabling its use in the CAD assembly. Part numbers can be found in the references at the end of the URL. Additionally custom parts were priced according to the cost of aluminum combined with the material, along with the machining costs, which will be expanded in the cost analysis.

## Component List by Section:

Components of the machine are listed below, separated into the subassembly they are in. Important components were provided with additional justification.

**Side Rail Transmission (x-axis transmission components)**

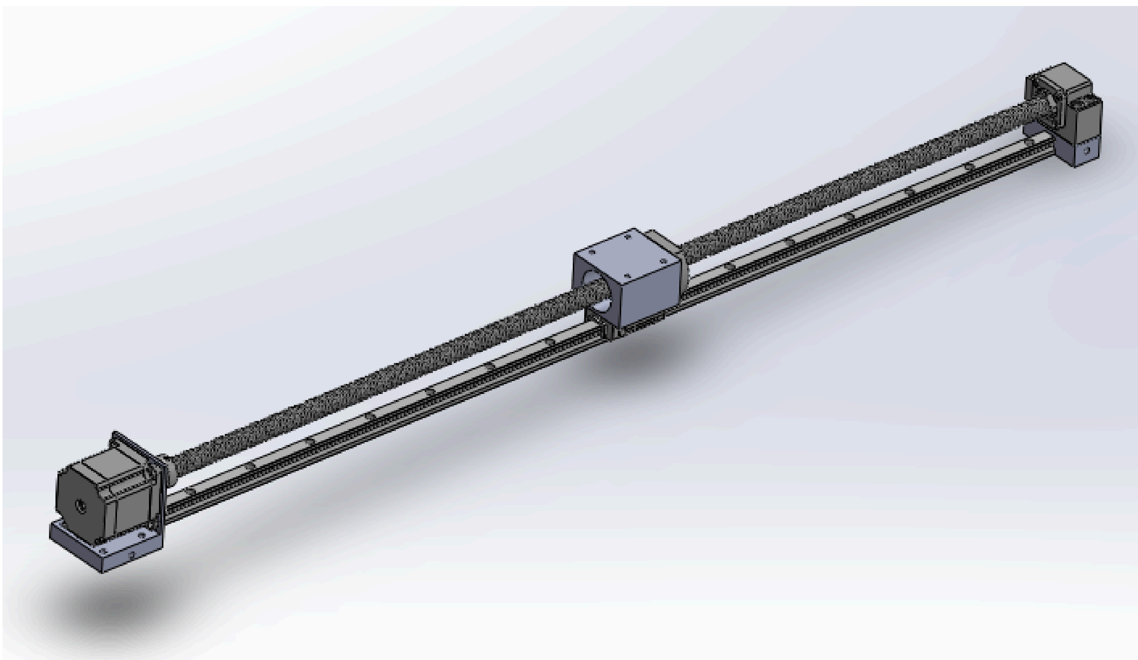
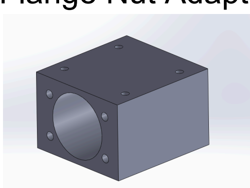
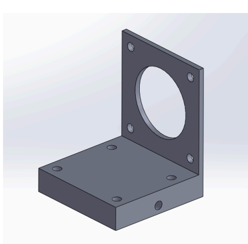


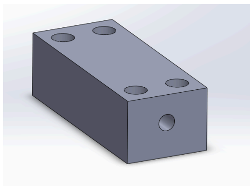
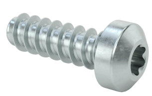
Figure 8: Rendering of x-axis transmission

Note that two of these are used, one on each side of the machine.

Table 12: X-Axis Components

| **Part Name** | **Quantity** | **Price/Unit [CAD]** | **Function** | **Source for CAD** |
|---|---|---|---|---|
| Nema 23 Stepper Motor Bipolar 1.8 Deg 1.9Nm [34]  | 2 | $38.03 | Used to power rotational motion to the ball screw, enabling linear transmission | Adapted from McMaster-Carr, Nema 23 Stepper Motor [35] |
| 6.35mm Flexible Shaft Coupling [36]  | 2 | $3.62 | Used for misalignment between ball screw and motor. Couples motor and ball screw shaft together | Adapted from McMaster-Carr, Set Screw Precision Flexible Shaft Coupling, [37] |
| SFU1605 Ball Screw and Flange Nut, 1000mm [38]  | 2 | $45.29 (Included in SFU1605 Ball Screw Kit) | Converts rotational motion from motor to linear motion to enable x axis travel | Adapted from McMaster-Carr, M16 Ball Screw, 1000mm [39] and M16 Flange Ball Nut [40] |
| BK12 End Support for Ball Screw [38]  | 2 | Included in SFU1605 Ball Screw Kit | Supports the end of the ball screw<br><br>Resists axial and thrust forces in ball screw | Adapted from McMaster-Carr, End Support for Lead/Ball Screws [41] |

| | | | | |
|---|---|---|---|---|
| HGR15R 15mm Linear Guide Rail, 1000mm [42]<br> | 2 | $14.49 | Provides motion support for ball screw transmission mechanism | Adapted from McMaster-Carr, 15mm wide Guide Rail [43] |
| HGW15 Linear Carriage Bearing Block [42]<br> | 2 | $4.59 | Provides motion support for ball screw transmission mechanism | Adapted from McMaster-Carr, Ball Bearing Carriage with Flange [44] |
| Flange Nut Adapter<br> | 2 | $0.70 + 35.18 (machining cost) | Holds SFU1605 Flange Nut to the Linear Guide Rail Carriage<br><br>Connects gantry to x-axis transmission system | Custom Made |
| Custom NEMA23 Motor Bracket<br> | 2 | $0.56 + 35.18 (machining cost) | Attaches NEMA23 Stepper Motor to the frame | Custom Made |

| | | | | |
|---|---|---|---|---|
| Base Adapter for end support  | 2 | $2.25 + 35.18 (machining cost) | Fixes Ball Screw End Support to base with proper height | Custom Made |
| Socket Head Screw 1/4"-20 Thread Size, 2-1/4" Long [45]  | 8 | $0.77 | Attaching the ball screw end support to base | From McMaster-Carr, Socket Head Screws [46] |
| M4.5, 14mm Long Screws [47]  | 24 | $16.73 for 25 | Attaching flange nut to flange housing Attaching linear rails to the frame base | From McMaster Carr, Thread Forming Screws [47] |
| M5 x 0.8, 8mm length screws [48] | 8 | $5.39 for 10 | Attaching Guide Rail Carriage to flange nut adapter | SolidWorks Toolbox |
| M5 x 0.8, 6mm length screws [48] | 8 | $5.25 for 10 | Attaching NEMA23 motor to bracket | SolidWorks Toolbox |
| M5 20mm long pan head [48] | 8 | $5.81 for 10 | Attaching custom motor bracket to base | SolidWorks Toolbox |

**Component Analysis and Justification**

- **Nema-23 Stepper Motor**
  This Stepper Motor was used after closely analyzing our engineering specifications and looking at the needs of the CNC Router in the scope of our range. The 1.8 step angle provides the necessary accuracy for our design, and the lower cost compared to servos made it more suitable for our design.This stepper motor aligned with the required torque and RPM for the practical applications in this project.  The holding torque of this motor is around 190 Ncm which is closely aligned with standard motors used for CNC routers on the

market [49]. However, the exact torque and motor requirements depends on a lot more variables involving forces and weights which could not be feasibly determined.

- **SFU1605 Ball Screw with Flange Nut**
  From our research, we decided to use ball screws for our linear transmission mechanism. While ball screws do have a higher cost associated with them, we felt that the higher accuracy was worth it to ensure we would reliably meet our desired accuracy. Additionally, the higher efficiency of this system would lessen the torque required, lessening the load on the NEMA 23 Stepper motors. The design of ball screws also allows it to be durable, which aligns with our engineering specification for a rigid, reliable design.

- **BK12 Ball Screw End Bearing Support**
  This support secures the ball screws at the end, preventing vibration and misalignment during operation. Additionally, the end supports ensure that the machine can handle the axial and thrust loads during operation, making the machine more rigid.

- **15mm Linear guideway rails + HGW15 Ball bearing Carriage**
  A linear rail and carriage system was chosen for x axis transmission in order to provide motion support and constrain the motion in one axis. Linear rails were easy to integrate into the design, as they simply laid on the frame of the machine. The carriage would slot into the rail, and be attached to the ball screw to facilitate motion support. This also meant that the weight of the gantry would be distributed evenly along the ball bearing carriage, instead of being supported by the ball screw, making the design more rigid and reliable. The linear rails were confirmed to be compatible with the carriage with the specifications off the websites where they are bought from.

- **Flange Nut Adapter**
  This custom piece was made to attach the flange ball nut and the linear rail carriage together. This allows the ball screw mechanism to be supported and constrained by the linear rail system.

- **Custom Nema23 Bracket**
  To accommodate for the height of the linear rails, a custom motor bracket was made to fit the motor we used into the assembly. However, this custom bracket

was made to the NEMA23 standard, which means it facilitates upgrading motors as long as its NEMA23.

- **Ball Screw End Support Adapter**
  This custom piece was made to accommodate for the extra height added to the assembly from the linear rail. This connects the ball screw end support to the base so the ball screw is level.

**Gantry Components:**

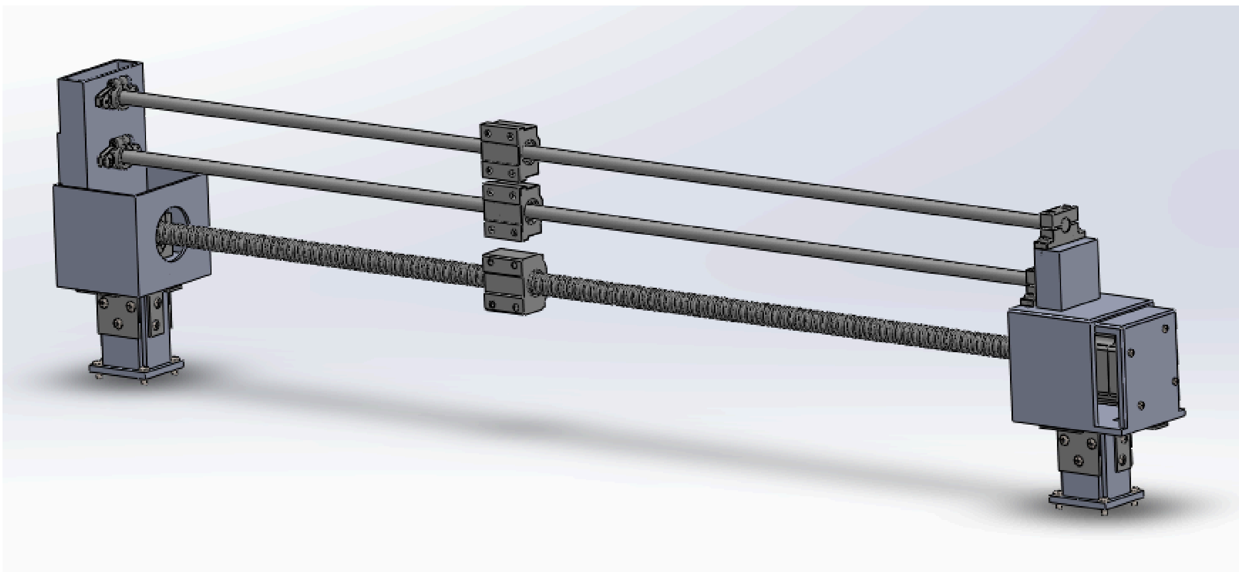
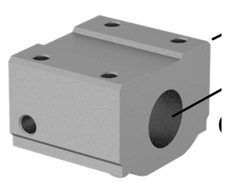
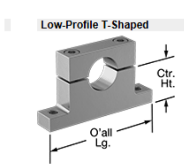


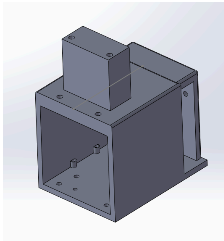
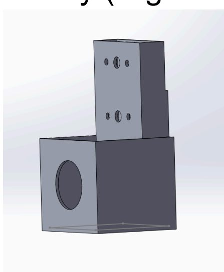
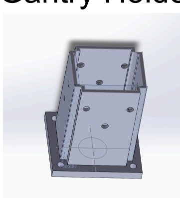
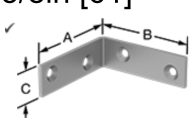
Figure 9: Rendering of Gantry

Table 13: Gantry Transmission (y-axis)

| **Part Name** | **Quantity** | **Price/Unit [CAD]** | **Function** | **Source for CAD** |
|---|---|---|---|---|
| Nema 23 Stepper Motor Bipolar 1.8 Deg 1.9Nm [34]  | 1 | $38.03 | Used to power rotational motion to the ball screw, enabling linear transmission | Adapted from McMaster-Carr , Nema 23 Stepper Motor [35] |

| | | | | |
|---|---|---|---|---|
| 6.35mm Flexible Shaft Coupling [36]<br> | 1 | $3.62 | Appropriate Couplings to pair with the motor sizes. | Adapted from McMaster-Carr , Set Screw Precision Flexible Shaft Coupling,[37] |
| SFU1605 Ball Screw 1000mm[50]<br> | 1 | $16.99 | Converts rotational motion from motor to linear motion to enable y axis travel<br>(The flange nut that is bundled is not needed) | Adapted from McMaster-Carr , M16 Ball Screw, 1000mm [39] |
| Platform Ball Nut, M16 Thread Size, 36 mm Long [51]<br> | 1 | $386.46 | Converts rotational motion to linear motion<br><br>Attaches to have a platform on top to put flat components. | Adapted from McMaster-Carr , Platform Ball Nut<br>[51] |
| BK12 and BF12 Ball Screw End Bearing Supports for SFU1605 [52]<br> | 1 | $10.89 | Supports the end of the ball screw,<br><br>Resists axial and thrust forces in ball screw | Adapted from McMaster-Carr ,<br>End Support for Lead/Ball Screws [41] |

| | | | | |
|---|---|---|---|---|
| Linear, Guide Rail Shafts 10mm diameter, 1000mm length [53]  | 2 | $7.19 | The guide rail shaft is used as a support to align and provide structural integrity to the ball screw platform nut. | Adapted from McMaster-Carr , Linear Motion Shaft 10mm diameter [54] |
| Mounted Linear Ball Bearing block, 10mm diameter[55]  | 2 | $24.99 for 4 | Used to attach the backplate which is what attaches the spindle to that Gantry. | Adapted from McMaster-Carr , Mounted Linear Ball Bearing [56] |
| Flange-Mounted Shaft Support for 10mm Shaft [57]  | 2 | $0.69 | To stabilize and hold the guide rail shafts of one end | Adapted from McMaster-Carr .Flange-Mounted Shaft Supports [58] |
| Aluminum Easy-Access Base-Mounted Shaft Support, Anodized, Low-Profile T-Shaped, for 10 mm Shaft Diameter   [59] | 2 | $40.23 | To stabilize and hold the guide rail shafts of other end | From McMaster-Carr ,Aluminum Easy-Access Base-Mounted Shaft Support [59] |

| | | | | |
|---|---|---|---|---|
| Gantry (Left Side)<br> | 1 | $5.63 + 140.70 | Custom Part to hold all the end supports and to provide structural integrity to overall structure | Custom |
| Gantry (Right Side)<br> | 1 | $5.63 + 140.70 | Custom Part to hold all the end supports and to provide structural integrity to overall structure | Custom |
| Gantry Holder<br> | 2 | $0.28 + 70.35 | Custom Part to hold the Gantry and attach to the platform nut in the linear transmission system | Custom |
| Threaded-Stud Bumper [60]<br> | 2 | $13.01 for 10 | Used to prevent damage if spindle housing accidentally collides with gantry | From McMaster-Carr, Threaded-Stud Bumper [60] |
| Zinc-Plated Steel Corner Bracket, 1.5 in x 1.5in x 5/8in [61]<br> | 6 | $1.14 | Used to stabilize and position motors and gantry and make sure they stay in place during the practical application of the router | Adapted from McMaster-Carr Zinc-Plated Steel Corner Bracket [61] |
| M4 10mm screws [62] | 8 | $4.20 for 10 | Attaches gantry holder to flange nut adapter/ x-axis transmission | SolidWorks Toolbox |

| | | | | |
|---|---|---|---|---|
| ¼ in, 2in length screws [63] | 4 | $6.99 for 40 | Attaches the ball screw end support to the gantry | SolidWorks Toolbox |
| M2.5 16mm length screws [64] | 8 | $3.64 for 10 | Attaches NEMA23 motor directly to the gantry | SolidWorks Toolbox |
| M5 6mm length screws [48] | 6 | $5.25 for 10 | Attaches motor bracket with NEMA23 Motor and Gantry | SolidWorks Toolbox |
| M4.5 10mm screws [65] | 4 | $13.01 for 25 | Screws down Easy-Access Base-Mounted Shaft Supports onto the Left Gantry | From McMaster Carr, Thread Forming Screws, [65] |
| M3 10mm screws [66] | 12 | $3.64 for 10 | Used to attach gantry holder and gantry parts to the brackets, securing them together | SolidWorks Toolbox |
| Hex-nut for M4 Screws [67] | 12 | $0.18 | Used to stabilize screws within the Gantry and are flushed against a surface to constrain additional movement | SolidWorks Toolbox |
| Hex-nut for M3 Screws [68] | 9 | $1.25 for 2 | Used to stabilize screws within the Gantry and are flushed against a surface to constrain additional movement | SolidWorks Toolbox |
| M4 10mm screw [62] | 28 | $4.20 for 10 | Used to attach gantry holder and gantry parts to the brackets, securing them together | SolidWorks Toolbox |

| | | | | |
|---|---|---|---|---|
| Phillips Rounded Head Screws for Sheet Metal 18-8 Stainless Steel, M5.5 Screw Size, 13 mm Long [69] | 4 | $10.30 for 10 | Used to Hold and Flush Flange Mounted Shaft Support onto the Upper Gantry | From McMaster-Carr, Phillips Rounded Head Screws for Sheet Metal [69] |

**Component Analysis and Justification**

- **Nema-23 Stepper Motor**
  This is the same stepper motor that was used in the x-axis transmission system, where we justified its use in our design in relation to our engineering specification. Naturally, this also means that this motor would be sufficient for our y-axis transmission, since the qualities that justified its use in other parts of the design(low cost, sufficient torque/accuracy) would apply here. In addition, the motor used here would only need to provide torque to move the spindle housing, which is much lighter than the entire gantry (which is moved by the same motor).

- **SFU1605 Ball Screw 1000mm**
  Ball screws were chosen for our y-axis transmission as well for the same reasons they were chosen for our x-axis transmission (higher accuracy, efficiency, and durability)

- **Platform Ball Nut, M16 Thread Size, 36 mm Long**
  Compatible with the ball screw, since this nut was designed for a 5mm pitch and an M16 thread size, which matches up with 1605 dimensions [70]. The platform nut provides a low-friction, stable base for motion while . Their design ensures that the load is distributed evenly, improving the durability of the system.

- **BK12 Ball Screw End Bearing Support**
  This support secures the ball screws at both ends, preventing vibration and misalignment during operation. Proper support enhances the system's rigidity and accuracy.

- **Guide rail shafts, mounted linear ball bearings, and Flange-mounted/Base mounted shaft supports**
  These parts form a guide rail system in order to support motion in the y-axis within the gantry. To constrain motion in the y-axis, two sets of guide rails and linear bearings were integrated into the gantry. Having two sets of guide rails

ensures that motion is properly supported for the entire length of the gantry, especially considering the length of the y-axis transmission.

- **Gantry Custom Parts** (Includes left side, right side, gantry holders)
  We chose to custom build our gantry due to the custom structure that was needed to be compatible with the overall assembly.

- **Threaded-Stud Bumper**
  The threaded bumpers were implemented to avoid wear and damage to surfaces the spindle comes in contact with.

**Spindle/Z-axis Transmission Components:**

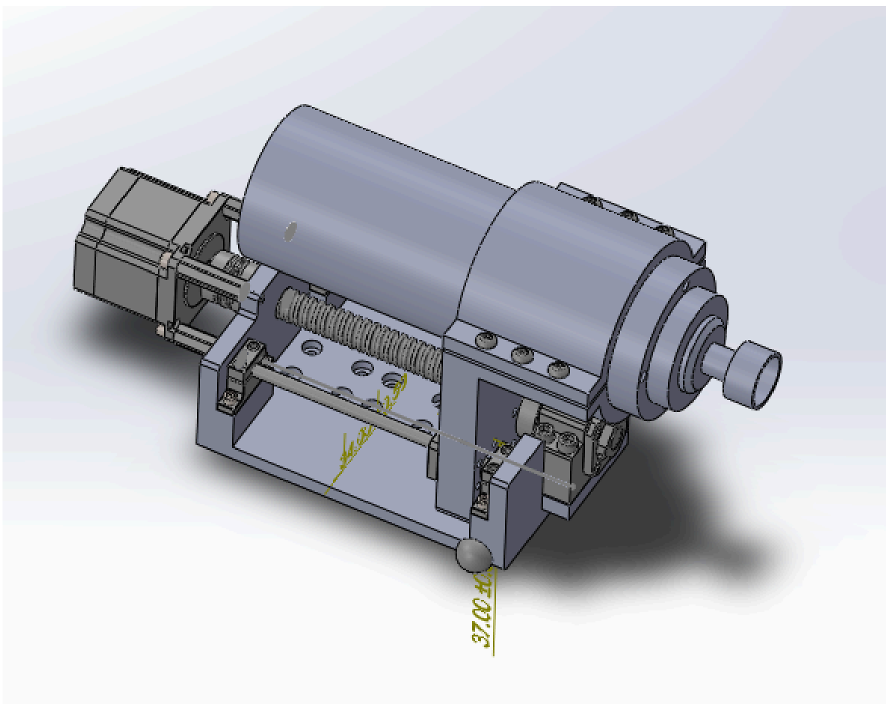
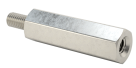
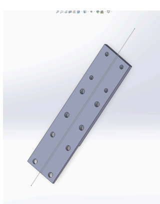
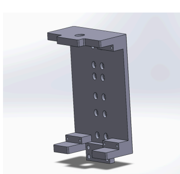
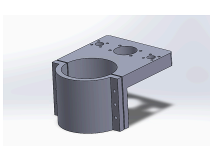


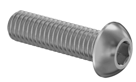
Figure 10: Rendering of Spindle and Z-axis transmission subassembly

Table 14: Spindle and Z-axis Transmission

| **Part Name** | **Quantity** | **Price/Unit** | **Function** | **Source for CAD** |
| --- | --- | --- | --- | --- |
| 2.2 kW Air Cooled CNC Spindle Motor, 24000 rpm, ER20 [71]  | 1 | $219 | The spindle motor provides the mill with its primary function to subtract material. | Simplified model based off of official dimensions off site. |
| MC40A, 1/8" Shank, CNC Cutter Milling Carving Bit Set, 40-PCS [72]  | 1 set | $35 | The various types of drill heads allow for the spindle to subtract material according to what the user desires. | Not shown in CAD |
| Nema 23 Stepper Motor Bipolar 1.8 Deg 1.9Nm [34]  | 1 | $38.03 | Used to power rotational motion to the ball screw, enabling linear transmission | Adapted from McMaster-Carr, 6627T61 Nema 23 Stepper Motor [35] |

| | | | | |
|---|---|---|---|---|
| Male-Female Threaded Hex Standoff, 10mm Hex size M5 45mm Long[73]<br> | 4 | $8.47 | Attaches NEMA23 motor to Z-axis bracket | Adapted from McMaster-Carr, Male-Female Threaded Hex Standoff [73] |
| 6.35mm Flexible Shaft Coupling [36]<br> | 2 | $3.62 | Used for misalignment between ball screw and motor. Couples motor and ball screw shaft together | Adapted from McMaster-Carr, Set Screw Precision Flexible Shaft Coupling, [37] |
| SFU1605 Ball Screw and Flange Nut, 300mm [38]<br> | 1 | $36.09 (Included in SFU1605 Ball Screw Kit) | Converts rotational motion from motor to linear motion to enable x axis travel | Adapted from McMaster-Carr, M16 Ball Screw, 1000mm [39]<br>And<br><br>M16 Flange Ball Nut [40] |
| BK12 End Support for Ball Screw [38]<br> | 1 | Included in SFU1605 Ball Screw Kit | Supports the end of the ball screw<br><br>Resists axial and thrust forces in ball screw | Adapted from McMaster-Carr, End Support for Lead/Ball Screws [41] |
| Guide Rail Shaft, ¼” diameter. 6” length [74]<br> | 2 | $9.03 | Supports Z-axis motion of the spindle bracket | Adapted from McMaster-Carr, Linear Motion Shaft [74] |

| | | | | |
|---|---|---|---|---|
| Aluminum Easy-Access Base-Mounted Shaft Support [75]  | 4 | $26.17 | Holds and stabilizes guide rails | Adapted from McMaster-Carr, Base Mounted Shaft Support [75] |
| Flange-Mounted Linear Ball Bearing Square Flanged Housing [76]  | 2 | $39.89 | Allows the bracket carrying the spindle to move along the guide rails on the Z axis, providing motion support | Adapted from McMaster-Carr Flange-Mounted Linear Ball Bearing [76] |
| Spindle Backplate  | 1 | $3.75 + 36.16 | Used as a way to attach the overall spindle assembly onto the gantry platform nuts | Custom Made |
| Custom Z-axis Bracket/Spindle Housing  | 1 | $3.76 + $140.77 | This custom bracket carries the spindle and spindle clamp while housing the ball screw and Z axis motor. It is attached to the gantry of the machine. | Custom |
| Custom Spindle Bracket  | 1 | $4.13 + $70.33 | This custom bracket and clamp secures the spindle to the Z-axis bracket. In addition, the bracket houses the linear bearings and flange nut for the ball screw | Custom |

| | | | | |
|---|---|---|---|---|
| 22mm Long M6 x 1mm Button Head Hex Drive Screw [77]<br> | 6 | $10.41 per pack of 25 | Clamps spindle into spindle bracket | Adapted from McMaster-Carr Button Head Hex Drive Screws [77] |
| 1/4-20 x 1-1/2" Socket Head Cap Screws [78] | 4 | $24.71 for 50 | Attaches BK12 ball screw end support to Z-axis bracket | Adapted from McMaster-Carr, Alloy Steel Socket Head Screws [79] |
| M5, 16mm Hex Socket Head Cap Screw [80] | 4 | $4.55 for 10 | Attaches motor to hex standoffs | SolidWorks Toolbox |
| M5, 30mm Socket head cap screws [81] | 4 | $16.99 for 50 | Attaches z axis bracket to backplate and gantry platform ball screw nut | SolidWorks Toolbox |
| M4, 16mm Socket head cap screws[82] | 8 | $2.87 for 10 | Attaches z axis bracket to backplate and gantry platform nuts | SolidWorks Toolbox |
| #8-32 , 1/2 Socket Head Cap Screw [83] | 16 | $9.99 for 25 | Attaches Linear Rail shaft supports to z axis bracket<br><br>Attaches Linear ball bearings to spindle bracket | SolidWorks Toolbox |
| M4.5 14mm Screws [47] | 4 | $16.73 per pack of 25 | Attaches Flange Nut to Spindle Bracket | From McMaster Carr, Thread Forming Screws [47] |

**Component Analysis and Justification**

- **2.2 kW Air Cooled CNC Spindle Motor, 24000 rpm, ER20**
  The air cooled spindle motor allows for physical capabilities that fulfill the CNC machine's specifications needed for mill work on materials like plywood and aluminum. Unlike the water cooled variant that requires a complex set up or the inhouse design which involves a difficult design process, a risk of failure and complex repair or replacement process the air cooled pre built model provides an easy set up with simple procedures to replacement and upgrades. Additionally, the ER20 collet ensures that multiple types of end mills can be used, fulfilling a part of our engineering specifications.

- **MC40A, 1/8" Shank, CNC Cutter Milling Carving Bit Set, 40-PCS**
  This is a complete set of high quality drill tips that allow the spindle to work various types of tasks on a selection of materials. The complete set does not need to be purchased for basic work environments.

- **Nema-23 Stepper Motor**
  This is the same stepper motor that was used in the x-axis transmission system, where we justified its use in our design in relation to our engineering specification. Naturally, this also means that this motor would be sufficient for our z-axis transmission, since the qualities that justified its use in other parts of the design(low cost, sufficient torque/accuracy) would apply here. In addition, the motor used here would only need to provide torque to move and hold the spindle, which is much lighter than the entire gantry (which is moved by the same motor).

- **SFU1605 Ball Screw and Flange Nut, 300mm**
  Ball screws were chosen for our y-axis transmission as well for the same reasons they were chosen for our x-axis transmission (higher accuracy, efficiency, and durability).

- **BK12 Ball Screw End Bearing Supports**
  End support for the ball screw to constrain motion only to angular motion and help support the screw

- **Guide Rail shafts, Base Mounted Shaft Supports, Flange-Mounted Linear Ball Bearing)**
  These parts form a guide rail system in order to support motion in the z-axis. Two sets of guide rails and linear bearings were integrated into the custom Z-axis and Spindle Brackets. Having two sets of guide rails ensures that motion is properly supported on both sides of the spindle, which helps prevent misalignment and loss of accuracy, as well as proper motion support for the spindle.

- **Custom Z-axis Bracket**
  This in house design can accommodate the attachment of a spindle as it moves

around the ball screw along the Z axis. The back plate of which is screwed into the gantry of the mill.

- **Custom Spindle Bracket**
  This in house design allows for a stable and snug fit holding down the spindle as it works on its milling tasks. The design also allows for users to interchange and upgrade spindles easily(that are 80mm in diameter) without dismounting the spindle or taking apart other components. The user can uninstall and reinstall the motor with ease through this bracket. The bracket also allows the user to adjust the height of the spindle to accommodate different heights of end mills.
  This bracket also contains the mounting holes for the flange nut and flange mounted linear bearings to facilitate and support z-axis movement.

**Frame and Base Components:**

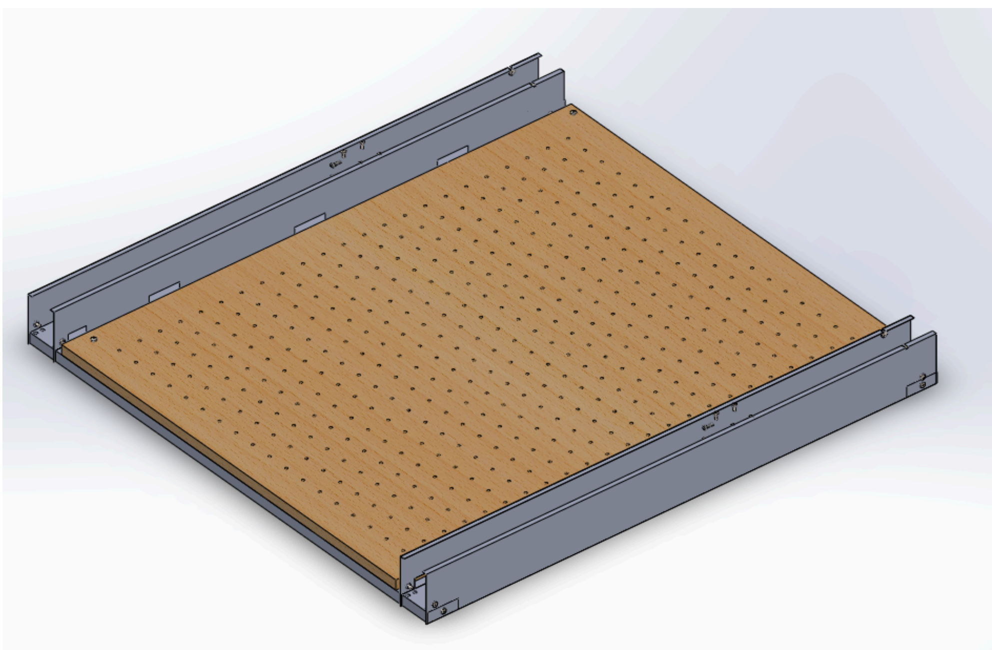
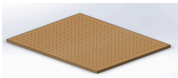
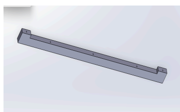
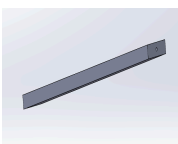
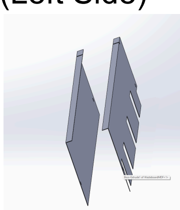
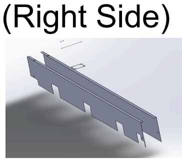


Figure 11: Rendering of Frame and Base Components

Table 15: Base and Wasteboard components

| **Part Name** | **Quantity** | **Price/Unit [CAD]** | **Justification/Function** | **Source for CAD** |
|---|---|---|---|---|
| MDF Wasteboard, 800x1000mm, formed from | 1 | $49.98 | Surface for which workpieces will be mounted onto for machining | Custom Made |

| | | | | |
|---|---|---|---|---|
| stock MDF board [84]  | | | | |
| Linear transmission base bars  | 2 | $6.28+ 35.18 (machining cost) | Part of the frame that functions as a way to hold the overall base together | Custom Made |
| Frame support base bars  | 5 | $9.85+35.18 (machining cost) | Part of the frame that functions as a way to hold the overall base together | Custom Made |
| Dust Guards (Left Side)  | 1 | $17.49+70.35 (machining cost) | Protects ball screw from dust/material particles so that the ball screw doesn't corrode or damage | Custom Made |
| Dust Guards (Right Side)  | 1 | $17.49+70.35 (machining cost) | Protects ball screw from dust/material particles so that the ball screw doesn't corrode or damage | Custom Made |
| Pan Head M5 8mm screws [48] | 8 | $5.39 for 10 | Attaching dust guards to linear transmission base | SolidWorks Toolbox |

| | | | | |
|---|---|---|---|---|
| Pan Head M5 50mm screws [48] | 10 | $6.37 for 10 | Attaching linear transmission base to support bars | SolidWorks Toolbox |
| Pan Head M5 25mm screws [48] | 4 | $5.95 for 10 | Attaching wasteboard to frame | SolidWorks Toolbox |

**Component Analysis and Justification**

- **MDF Wasteboard**
  MDF was chosen for our cutting surface due to its much lower price compared to the alternatives, making it suitable for beginners. Additionally, its ability to be replaced with other MDF spoil boards that the user may have enables compatibility. Replaceability is also an asset for when mistakes are made and the spindle cuts into the cutting surface, as it can just be replaced. The customizability of the MDF board was also an asset, as users could drill their own mounting holes compared to T-slots, where the user had to use clamps specifically designed for those.

- **Dust Guards**
  Dust guards are essential in providing adequate protection for the transmission system so that the ball screws are not susceptible to corrosion and damage from the materials being cut. The price was acquired from finding the total volume they take up and multiplying by the density found in the market for that material(Aluminum).

# *Cost*

**Forming Cost Estimate:**
We first summed up the costs for the components we got online. For screws, we found and divided the prices of bundled packages accordingly to get a per piece estimate. Our costs for our custom parts were calculated by finding out how much our material costs per cubic millimeter and then multiplied by the overall volume for the individual part (which was found with SolidWorks). For instance, for aluminium 1060 we found the price to be 2.60 USD per kilogram( which translates to 0.00000702USD per cubic millimeter) [85]. We then included machining costs, assuming $50USD ($70.35 CAD)/hour [86] and then factored the amount of time we saw fit for machining the part to get the total cost for the custom part. Below shows the summation of the costs of all the parts

Table 16: Final Cost

| Part Name | # of parts | Price/Unit [CAD] |
|---|---|---|
| **Side Rail(x axis transmission) Parts** | | |
| Nema 23 Stepper Motor Bipolar 1.8 Deg 1.9Nm | 2 | $38.03 |
| 6.35mm Flexible Shaft Coupling | 2 | $3.62 |
| SFU1605 Ball Screw and Flange Nut, 1000mm | 2 | $45.29 |
| BK12 End Support for Ball Screw | 2 | (included above) |
| HGR15R 15mm Linear Guide Rail, 1000mm | 2 | $14.49 |
| HGW15 Linear Carriage Bearing Block | 2 | $4.59 |
| Flange Nut Adapter | 2 | $35.88 |
| Custom NEMA23 Motor Bracket | 2 | $35.74 |
| Base Adapter for end support | 2 | $37.43 |
| Socket Head Screw<br>1/4"-20 Thread Size, 2-1/4" Long, | 8 | $0.77 |
| M4.5, 14mm Long Screws | 24 | $0.67 |
| M5 x 0.8, 8mm length screws | 8 | $0.54 |
| M5 x 0.8, 6mm length screws | 8 | $0.53 |
| M5 20mm long pan head | 8 | $0.58 |
| **Gantry Parts** | | |

| | | |
|---|---|---|
| Nema-23 Stepper Motor | 1 | $38.03 |
| 6.35mm Flexible Shaft Coupling | 1 | $3.62 |
| SFU1605 Ball Screw 1000mm | 1 | $16.99 |
| Platform Ball Nut, M16 Thread Size, 36 mm Long | 1 | $386.46 |
| BK12 and BF12 Ball Screw End Bearing Supports for SFU1605 | 1 | $10.89 |
| Linear, Guide Rail Shafts 10mm diameter, 1000mm length | 2 | $7.19 |
| Mounted Linear Ball Bearing | 2 | $6.25 |
| Flange-Mounted Shaft Support for 10mm Shaft | 2 | $0.69 |
| Aluminum Easy-Access Base-Mounted Shaft Support, Anodized, Low-Profile T-Shaped, for 10 mm Shaft Diameter | 2 | $40.23 |
| Gantry (Left Side) | 1 | $146.33 |
| Gantry (Right Side) | 1 | $146.33 |
| Gantry Holder | 2 | $70.63 |
| Threaded-Stud Bumper | 2 | $1.30 |
| Zinc-Plated Steel Corner Bracket, 1.5 in x 1.5in x 5/8in | 6 | $1.14 |
| M4 10mm screws https://canadabolts.ca/products/metric-machine-screws-phillips-pan-head-stainless-steel-m4?variant=44785615536352 | 8 | $0.42 |
| ¼ in, 2in length screws | 4 | $0.17 |
| M2.5 16mm length screws | 8 | $0.36 |
| M5 6mm screw for brackets | 6 | $0.52 |
| M4.5 10mm screws | 4 | $0.52 |
| M3 10mm screws | 12 | $0.36 |
| Hex-nut for M4 Screws | 12 | $0.18 |
| Hex-nut for M3 Screws | 9 | $0.63 |
| M4 10mm screw | 28 | $0.42 |
| Phillips Rounded Head Screws for Sheet Metal 18-8 Stainless Steel, M5.5 Screw Size, 13 mm Long | 4 | $1.03 |

| | | |
|---|---|---|
| **Spindle + Spindle Housing Parts** | | |
| 2.2 kW Air Cooled CNC Spindle Motor, 24000 rpm, ER20 | 1 | $219 |
| MC40A, 1/8" Shank, CNC Cutter Milling Carving Bit Set, 40-PCS | 1 | $35 |
| Nema-23 Stepper Motor | 1 | $38.03 |
| Male-Female Threaded Hex Standoff | 4 | $8.47 |
| 6.35mm Flexible Shaft Coupling | 1 | $3.62 |
| SFU1605 Ball Screw and Flange Nut, 300mm | 1 | $36.09 |
| BK12 End Support for Ball Screw | 1 | Included above |
| Guide Rail Shafts | 2 | $9.03 |
| Aluminum Easy-Access Base-Mounted Shaft Support | 4 | $26.17 |
| Flange-Mounted Linear Ball Bearing Square Flanged Housing | 2 | $39.89 |
| Spindle Backplate | 1 | $39.91 |
| Custom Z-axis Bracket | 1 | $144.53 |
| Custom Spindle Bracket | 1 | $78.59 |
| 22mm Long M6 x 1mm Button Head Hex Drive Screw | 6 | $0.41 |
| 1/4-20 x 1-1/2" Socket Head Cap Screws | 4 | $0.49 |
| M5, 16mm Hex Socket Head Cap Screw | 4 | $0.46 |
| M5, 30mm Socket head cap screws | 4 | $0.34 |
| M4, 16mm Socket head cap screws | 8 | $0.29 |
| #8-32 , ½ Socket Head Cap Screw | 16 | $0.40 |
| M4.5 14mm Long Thread-Forming Screws for Thin Plastic | 4 | $0.67 |
| **Frame Parts** | | |
| MDF Wasteboard, 800x1000mm | 1 | $49.98 |
| Linear transmission base bars | 2 | $41.46 |
| Frame support base bars | 5 | $45.03 |
| Dust Guards (Left Side) | 1 | $87.84 |
| Dust Guards (Right Side) | 1 | $87.84 |

| | | |
|---|---|---|
| M5 8mm screws | 8 | $0.54 |
| M5 50mm screws | 10 | $0.64 |
| M5 25mm screws | 4 | $0.60 |

An additional hour of machining was added for machining the ends of the ball screws to fit with the couplings ($70.35).

**Cost/Performance Analysis:**

The total cost of the design remains within our group's targeted budget of $3000, with a cost of  $2981.19 CAD. This aligns with our affordability specs for hobbyist users, though it is on the very upper end of that spectrum. This section details the reason for that high cost, and the trade-offs between cost and performance we made in certain parts.

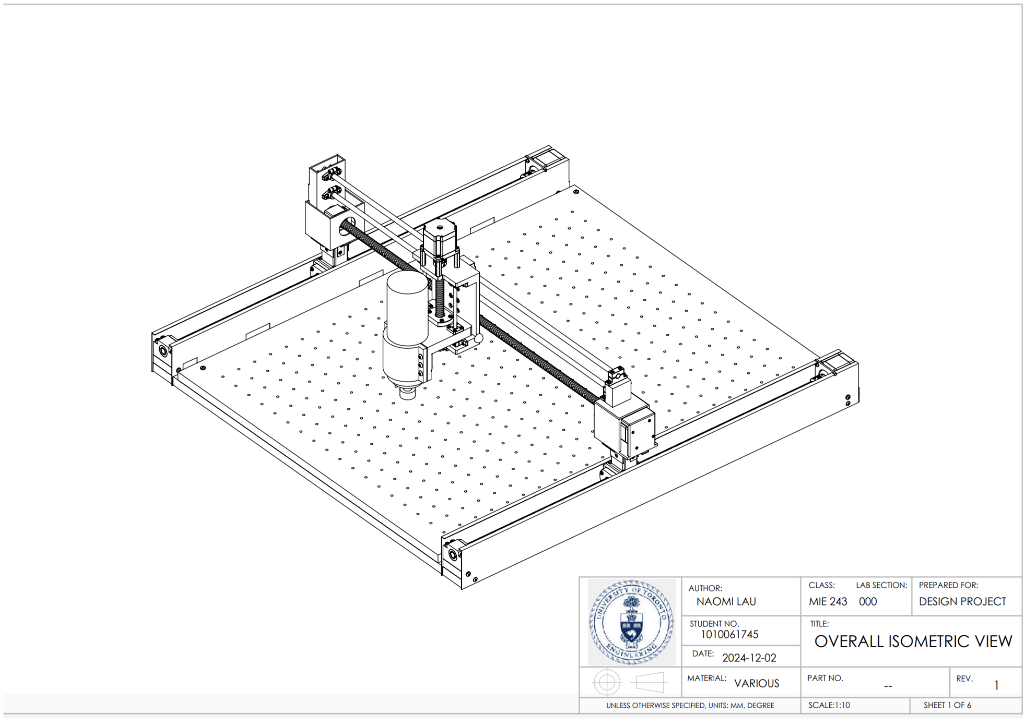
In terms of our transmission system, our group chose the most expensive transmission system, which was the ball screw. Our justification for that is in the component analysis section(under x-axis transmission), but we believed the benefits of higher accuracy, efficiency, and durability would align more with our engineering specifications, and that we could make the design more affordable through other means. The transmission mechanism is also something that isn't very upgradable within the CNC machine, so if there was a component we should invest more into it would be this part. Additionally, we were able to find a very cheap source for ball screws.

In contrast, a section where we decided to save money was on the motor selection. Stepper motors, with their built in discrete steps and torque/RPM capabilities were sufficient enough to satisfy our engineering specification , but they lack the accuracy of servo motors. We do believe that the superior accuracy of the ball screw will allow us to hit that metric, though it is difficult to calculate that ourselves. Also, as long as the new motor fits within the NEMA23 standard, the motor can be upgraded.
Linear motion supports were also a large contributor to the cost of the machine, though they provided the necessary rigidity to the linear transmission systems. This is because the mechanism of having a moving gantry with a moving spindle housing is a bit more unstable than having a fully or partially fixed gantry.

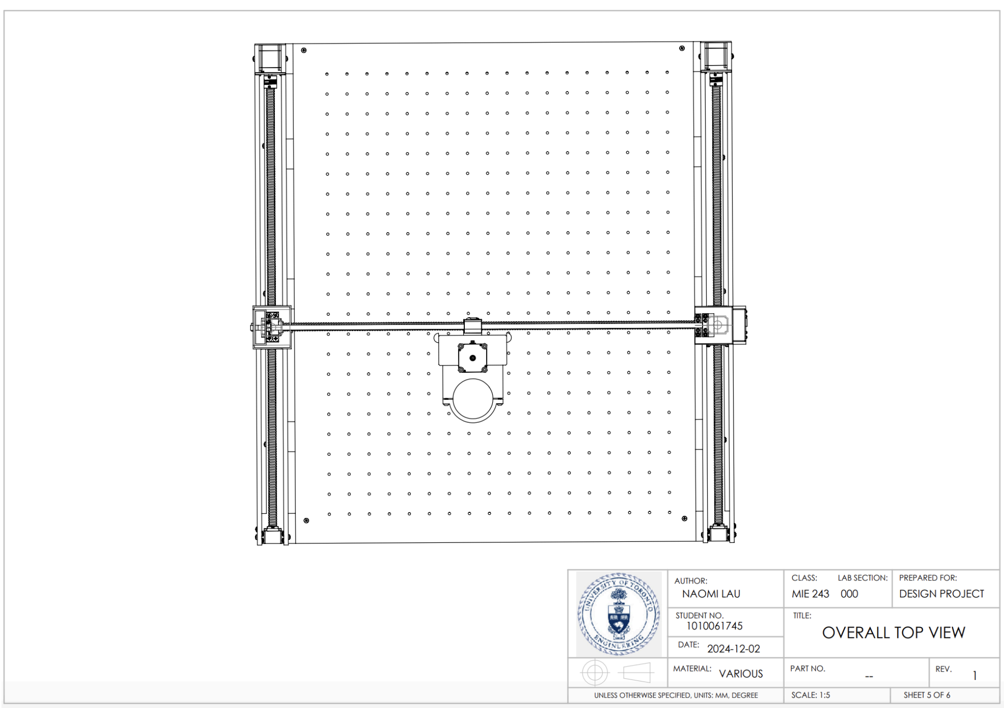
In terms of the overall axis movement mechanisms, having a moving gantry and a stationary milling surface allowed the machine to maximize its cutting area, while having a minimal footprint. In addition, this design lets us comfortably fit 2 foot wide workpieces through the design, which means the machine can support workpieces that are longer than it.

# *Drawings*

## Overall Isometric View

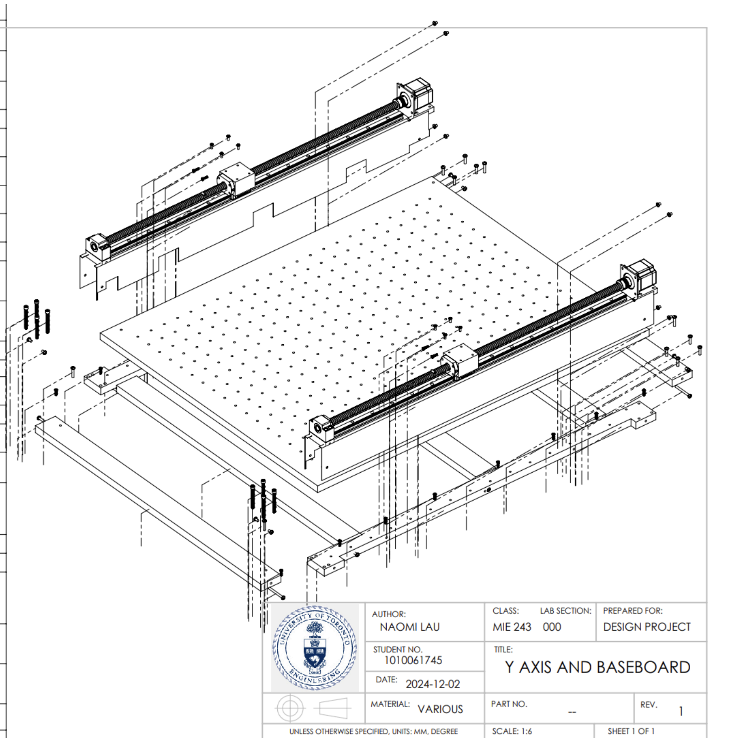



## Top view



## X-axis Transmission and Base Subassembly

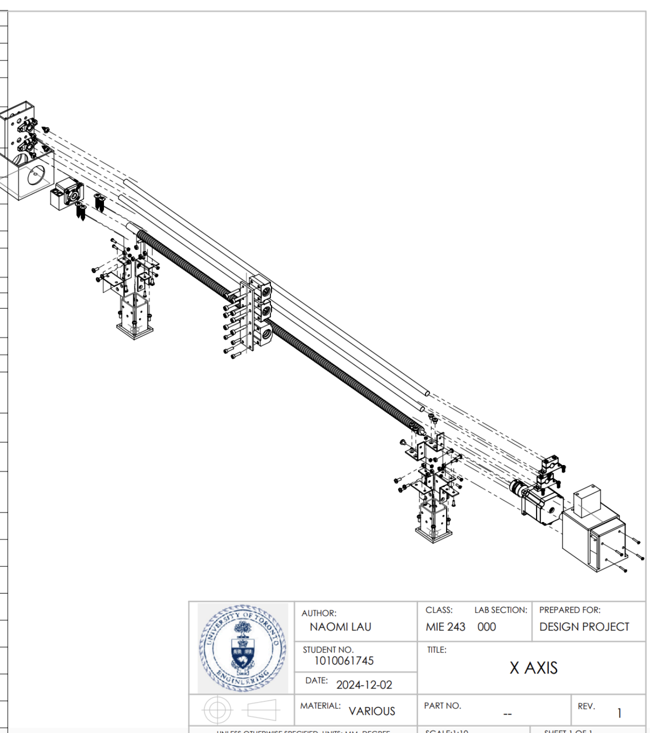
| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Linear transmission base bar (Right) | | 1 |
| 2 | Linear transmission base bar (Left) | | 1 |
| 3 | Frame support base bar 1 | | 1 |
| 4 | MDF Wasteboard | | 1 |
| 5 | Frame support base bar 2 | | 1 |
| 6 | Frame support base bar 3 | | 1 |
| 7 | Frame support base bar 4 | | 1 |
| 8 | Frame support base bar 5 | | 1 |
| 9 | 6627T621 | Stepper Motor | 2 |
| 10 | 9861T614 | Set Screw Precision Flexible Shaft Coupling | 2 |
| 11 | 6624K56_End Support for Lead and Ball Screws | End Support for Lead and Ball Screws | 2 |
| 12 | 6624K2 | Ball Screw | 2 |
| 13 | 6624K41 | Flange Ball Nut | 2 |
| 14 | 6709K11 | Ball Bearing Carriage | 2 |
| 15 | Flange Nut Adapter | | 2 |
| 16 | Base Adapter for end support | | 2 |
| 17 | NEMA23 Motor Bracket | | 2 |
| 18 | 6709K332 | 15 mm Wide x 1600 mm Long Guide Rail for Ball Bearing Carriage | 2 |
| 19 | Left Dust Cover | | 1 |
| 20 | Right Dust Cover | | 1 |
| 21 | B18.6.7M - M5 x 0.8 x 20 Type I Cross Recessed PHMS --20N | | 46 |
| 22 | 96817A552 | Thread-Forming Screws for Thin Plastic | 16 |
| 23 | 96817A552 | Thread-Forming Screws for Thin Plastic | 8 |
| 24 | SSCUPSKT 0.19-24x0.5-HX-N | | 2 |
| 25 | 90044A126 | Black-Oxide Alloy Steel Socket Head Screw | 8 |





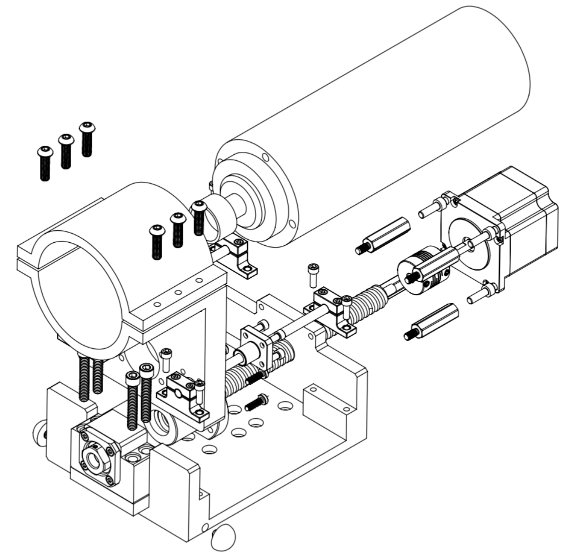

## Gantry (Y-axis Transmission) Subassembly

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Gantry Holder | | 1 |
| 2 | Gantry (Left Side) | | 1 |
| 3 | 6627T621 | Stepper Motor | 1 |
| 4 | 62645K41 | Flange-Mounted Shaft Support | 2 |
| 5 | 1865K22 | Aluminum Easy-Access Base-Mounted Shaft Support | 2 |
| 6 | 9338T52 | Mounted Linear Ball Bearing | 2 |
| 7 | 6624K27_Platform Ball Nut | Platform Ball Nut | 1 |
| 8 | 1556A63 | Zinc-Plated Steel Corner Bracket | 3 |
| 9 | Spindle Backplate | | 1 |
| 10 | 6624K56 | End Support for Lead and Ball Screws | 1 |
| 11 | 6112K16 | Linear Motion Shaft | 2 |
| 12 | 6624K2 | Ball Screw | 1 |
| 13 | 9861T614 | Set Screw Precision Flexible Shaft Coupling | 1 |
| 14 | Gantry (Right Side) | | 1 |
| 15 | Gantry Holder | | 1 |
| 16 | B18.6.7M - M4 x 0.7 x 10 Type I Cross Recessed PHMS --10N | | 49 |
| 17 | 96817A544 | Thread-Forming Screws for Thin Plastic | 4 |
| 18 | 92470A382 | Phillips Rounded Head Screws for Sheet Metal | 4 |
| 19 | 97503A176 | Stainless Steel Phillips Oval Head Thread-Cutting Screws | 4 |
| 20 | B18.3.1M - 5 x 0.8 x 30 Hex SHCS -- 22NHX | | 12 |
| 21 | 17715A43 | Zinc-Plated Steel Corner Bracket | 1 |
| 22 | 17715A43 | Zinc-Plated Steel Corner Bracket | 1 |
| 23 | 1556A63 | Zinc-Plated Steel Corner Bracket | 1 |
| 24 | 17715A43 | Zinc-Plated Steel Corner Bracket | 1 |
| 25 | 17715A43 | Zinc-Plated Steel Corner Bracket | 1 |
| 26 | 1556A63 | Zinc-Plated Steel Corner Bracket | 1 |
| 27 | 1556A63 | Zinc-Plated Steel Corner Bracket | 1 |
| 28 | B18.2.4.1M - Hex nut, Style 1, M4 x 0.7 --D-N | | 21 |



## Z axis Transmission and Spindle Subassembly

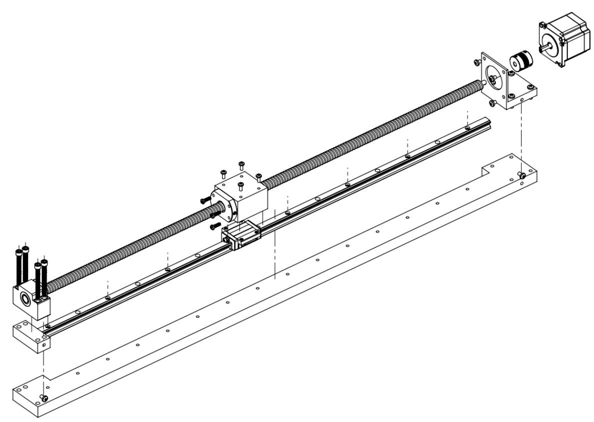
| TEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Spindle Bracket | | 1 |
| 2 | Z-axis Bracket | | 1 |
| 3 | 6061K411 | Linear Motion Shaft | 2 |
| 4 | 6624K2 | Ball Screw | 1 |
| 5 | 6624K56_End Support for Lead and Ball Screws | End Support for Lead and Ball Screws | 1 |
| 6 | 6627T621 | Stepper Motor | 1 |
| 7 | new 6624K41_Flange Ball Nut | Flange Ball Nut | 1 |
| 8 | 6483K61 | Flange-Mounted Linear Ball Bearing | 2 |
| 9 | 2.2 kW Air Cooled CNC Spindle Motor | | 1 |
| 10 | 92095A488 | Button Head Hex Drive Screw | 6 |
| 11 | 93655A246 | Male-Female Threaded Hex Standoff | 4 |
| 12 | 9861T614 | Set Screw Precision Flexible Shaft Coupling | 1 |
| 13 | 1865K1 | Aluminum Easy-Access Base-Mounted Shaft Support | 4 |
| 14 | 96817A552 | Thread-Forming Screws for Thin Plastic | 4 |
| 15 | B18.3.1M - 5 x 0.8 x 16 Hex SHCS -- 16NHX | | 4 |
| 16 | HX-SHCS 0.164-32x0.5x0.5-N | | 16 |
| 17 | 90044A123 | Black-Oxide Alloy Steel Socket Head Screw | 4 |
| 18 | 9541K82 | Threaded-Stud Bumper | 2 |



| AUTHOR: NAOMI LAU | CLASS: MIE 243 | LAB SECTION: 000 | PREPARED FOR: DESIGN PROJECT |
|---|---|---|---|
| STUDENT NO. 1010061745<br>DATE: 2024-12-02 | TITLE: SPINDLE AND Z AXIS | | |
| MATERIAL: VARIOUS | PART NO. -- | | REV. 1 |
| UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE | SCALE: 1:2 | | SHEET 1 OF 1 |

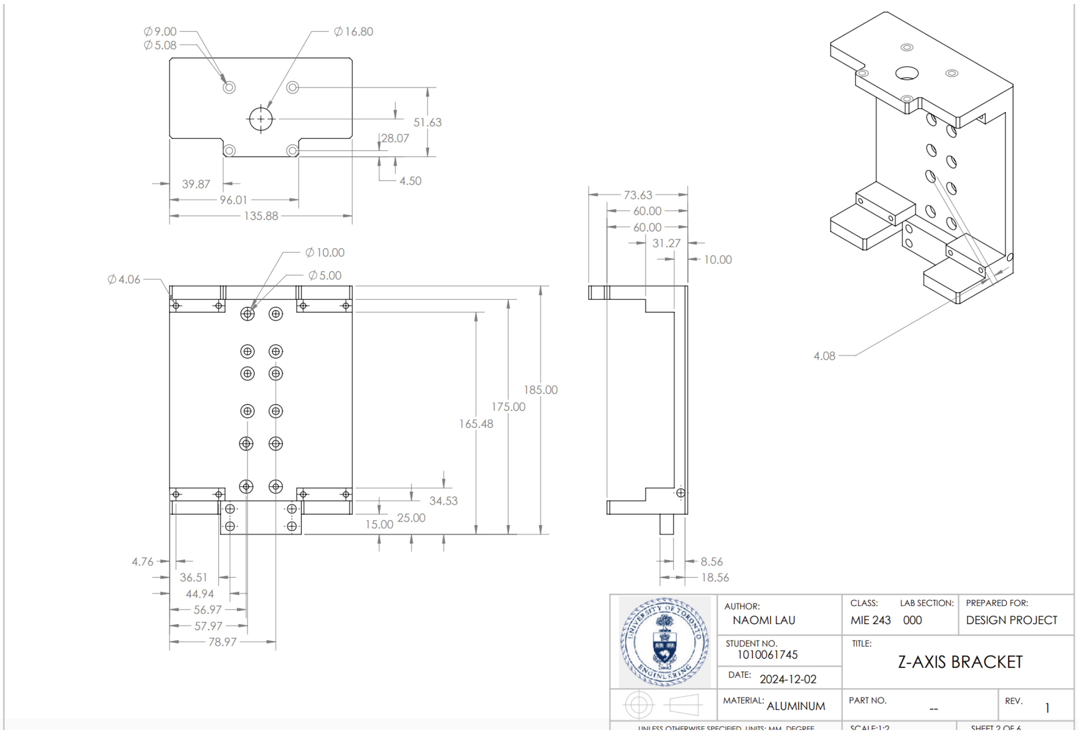
## X-axis Transmission Subassembly

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Linear transmision base bar | | 1 |
| 2 | 6627T621 | Stepper Motor | 1 |
| 3 | 9861T614 | Set Screw Precision Flexible Shaft Coupling | 1 |
| 4 | 6624K56 | End Support for Lead and Ball Screws | 1 |
| 5 | 6624K2 | Ball Screw | 1 |
| 6 | 6624K41 | Flange Ball Nut | 1 |
| 7 | 6709K11 | Ball Bearing Carriage | 1 |
| 8 | Flange Nut Adapter | | 1 |
| 9 | Base Adapter for end support | | 1 |
| 10 | NEMA23 Motor Bracket | | 1 |
| 11 | 6709K332 | 15 mm Wide x 1600 mm Long Guide Rail for Ball Bearing Carriage | 1 |
| 12 | B18.6.7M - M5 x 0.8 x 20 Type I Cross Recessed PHMS -- 20N | | 14 |
| 13 | 96817A552 | Thread-Forming Screws for Thin Plastic | 8 |
| 14 | 96817A552 | Thread-Forming Screws for Thin Plastic | 4 |
| 15 | SSCUPSKT 0.19-24x0.5-HX-N | | 1 |
| 16 | 90044A126 | Black-Oxide Alloy Steel Socket Head Screw | 4 |

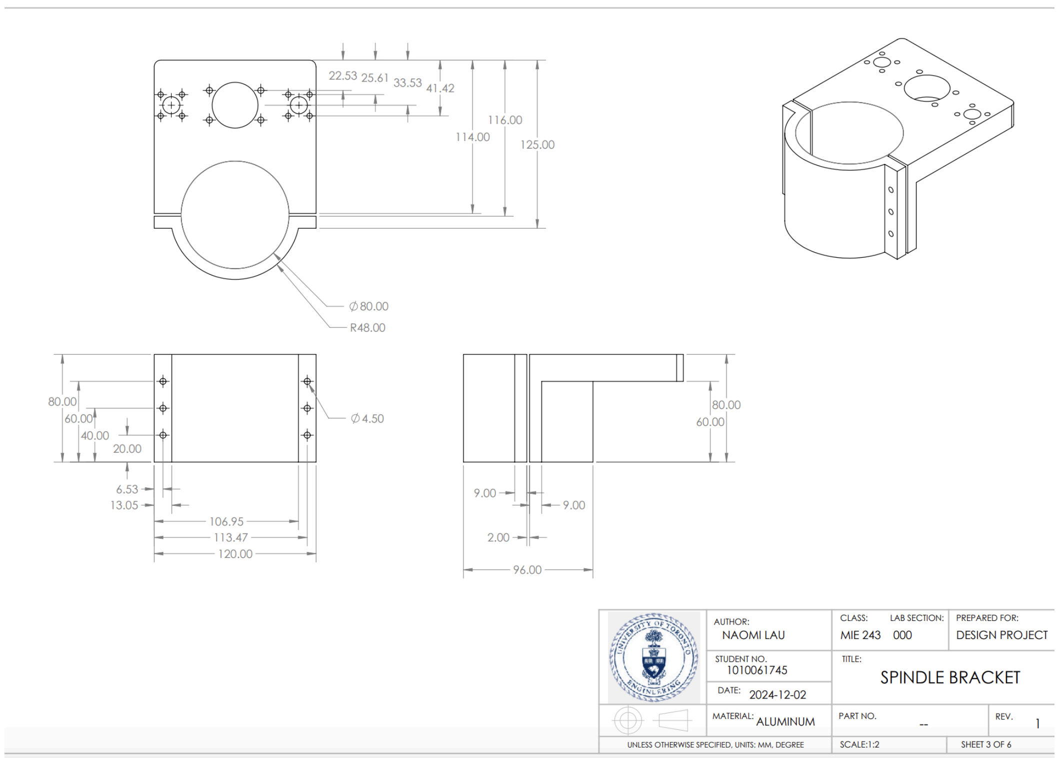


| AUTHOR: NAOMI LAU | CLASS: MIE 243 | LAB SECTION: 000 | PREPARED FOR: DESIGN PROJECT |
|---|---|---|---|
| STUDENT NO. 1010061745<br>DATE: 2024-12-04 | TITLE: SIDE RAIL ASSEMBLY | | |
| MATERIAL: VARIOUS | PART NO. -- | | REV. 1 |
| UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE | SCALE: 1:4 | | SHEET 1 OF 1 |

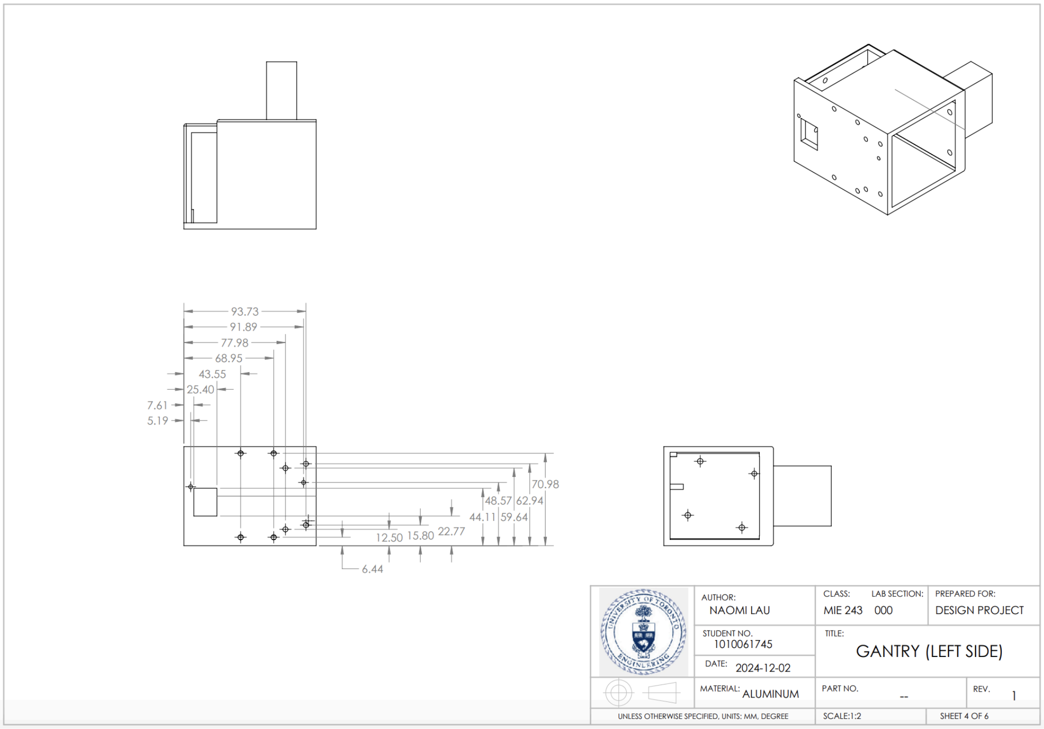
## Z-axis Bracket



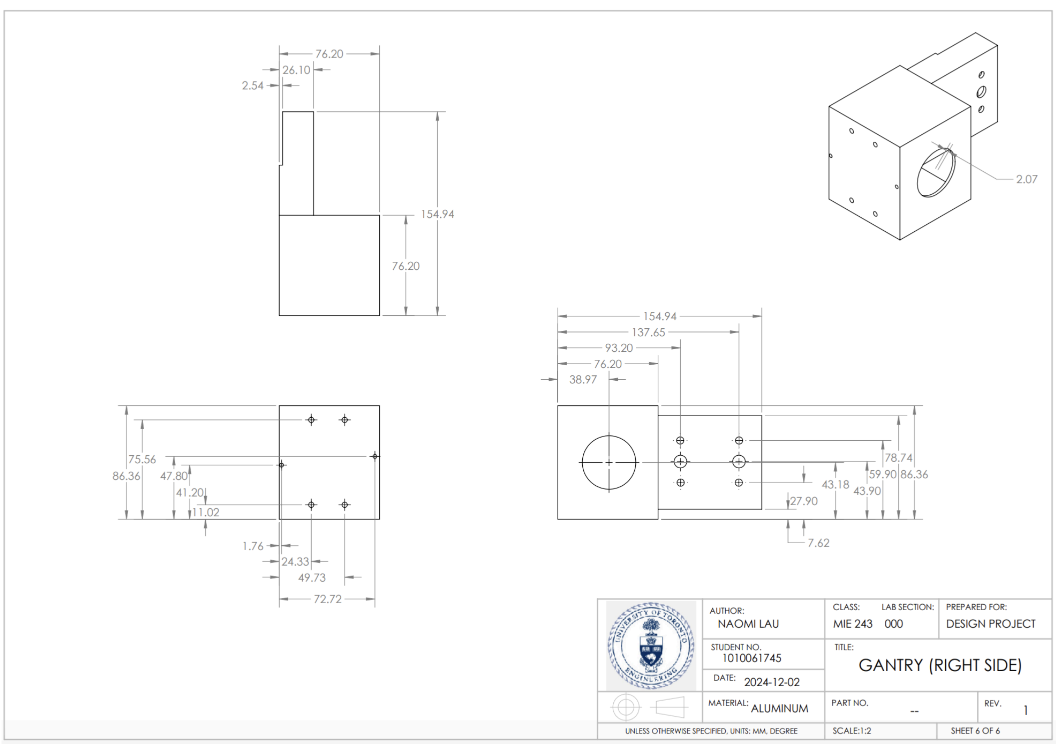

## Spindle Bracket



## Gantry (Left Side)




## Gantry (Right side)



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