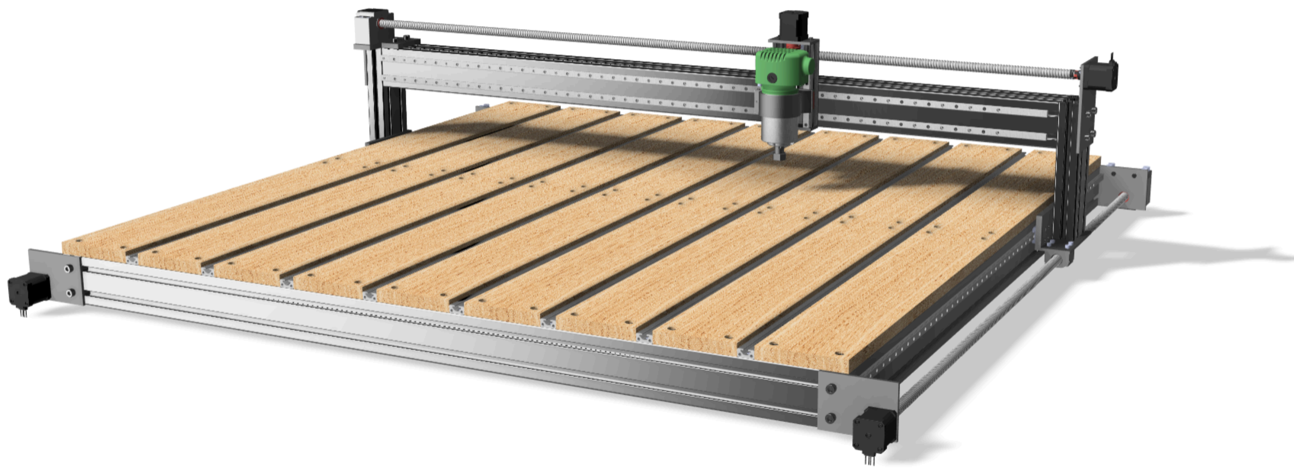


MIE 243
Prof. Mackay
TA: Stephen Yang
Team 02
CNC Router Project

Contributors
Russell Passmore 1010011531
Stephen Kang 1010092178
Kaida Xu 1009271510
Jack Zhang 1009794064

1.0 Introduction

Computer Numerical Controlled (CNC) Machines have become vital in modern manufacturing for their precision, repeatability, and versatility. They empower hobbyists and professionals alike to create intricate parts with low tolerance.

Despite their widespread use, a gap remains for a cost-effective, large scale CNC system that caters to hobbyist and small scale workshops. Commercially available CNC often falls into two categories: compact models with limited cutting capacities, or industrial systems that are prohibitively expensive and impractical for non-professional users. This leaves hobbyists, makers, and small business owners with few viable options for an affordable, easily sourceable, and large format CNC solution capable of handling large workpieces with high precisions

This project aims to bridge that gap by designing a CNC router specifically tailored towards the needs of hobbyist users, focusing on ease of source for the parts, affordability, and performance.

2.0 Research and Scope

To direct the project, the team conducted thorough background research and analysis of the request for proposal (RFP). These initial steps provide guidelines for the capabilities that our team should aim to achieve in the CNC model.

2.1 Background Research

Research was conducted on several CNC options available on the market. We considered various options and sources, including Amazon, Carbide 3D, Robotshop, and some do-it-yourself (DIY) creators. CNC's of various sizes and price points were considered, in order to analyze the tradeoff between capability and cost. The core differences between the CNC machines lay in their respective motion systems, methods of motion support, and quality-of-life features. Appendix A contains a detailed analysis of existing options, highlighting differences in costs and capabilities.

2.1.1 Layouts and Sizes

Every CNC router analyzed during research had a three-axis layout, with motors controlling each of the X-, Y-, and Z-axes. The standard layout typically comprises a gantry resting on two supports, which control the y-direction. The gantry itself moves the router in the X-direction, and contains a Z-assembly which enables vertical position control

The working area of these machines ranges from smaller sizes of 10" by 14" [1] to full sized 48" by 96", enabling support of large sheets [2].

2.1.2 Motion Systems and Support

All the CNC machines analyzed utilized stepper motors as the motion source for all three axes. In addition, there were common components shared between the designs. Four of the six designs analyzed utilized belts in the X and Y direction. The motors driving said belts were fixed onto the carriage itself, instead of the frame, acting similarly to a rack and pinion with the tensioned belt acting as the rack. On a similar note, all designs but one used lead screws to drive the Z-axis. The most expensive design, the AltMill CNC Router, uses ball screws to control all three axes [3]. Primary methods of motion support in the existing designs were v-rollers and linear rails.

2.1.3 Capabilities and Construction

Except for the cheapest CNC router at a value of $600, every machine was capable of cutting aluminum, woods, and plastics [1]. This is likely due to said machine using a DIY all-wood construction of the frame, whereas the rest used stronger materials such as steel and aluminum as the structural support.

2.2 Scope Analysis

An analysis of the RFP is provided in Appendix B. The resulting scope modifications were made:

- Aluminum, wood, and plastics are the primary materials of focus. Materials harder than aluminum will not be considered within the scope.
- Functionality of safety switches and homing will not be covered in this report
- Dust collection systems are not within scope as they vary in forms and sizes

3.0 Engineering Specifications

Using the RFP and background research, the team determined the following engineering specifications for the project, as seen in Table 1. Justification for specifications can be found in Appendix C.

Table 1. Engineering Specifications

Category	**Specification**
Size	• Working area of 4’ by 4’, with a working height of 3” [4][5] • Body of design fits within an area of 5’ by 6’ [6]
Cost	• All components must cost less than $4000 CAD to acquire [7] • Majority of components should be from consumer sources
Capabilities	• 3-D axis motion precision in line with ISO 230-2 [8] • Compatible with aluminum with a safety factor of 4 [9][10][11]
Operation	• The design must be easily assembled by one person with the

	provided instruction manual ● Design components can be connected through standardized means and/or materials

4.0 Candidate Designs

This section outlines the steps taken to generate, refine, and evaluate the candidate designs leading to the selection of the final conceptual design. The process began with brainstorming three initial concepts, followed by the development of three additional designs to expand the design space and explore alternative configurations. Each design was analyzed to balance precision, cost, and ease of assembly while meeting the project goals outlined in Section 3.0.

4.1 Idea Generation and General Component Exploration

In the initial design phase, the team focused on exploring a wide range of components and configurations to identify viable options for the CNC machine. This phase emphasized on balancing precision, cost, scalability, and accessibility while maintaining flexibility for future refinement through calculation. The brainstorming process considered the pros and cons of various motion systems, frame materials and additional features. A summary of the component exploration and analysis can be found in Table 2 below.

Table 2. Component exploration and analysis.

Category	Option	Description
Motion Constraint	Linear rails	Linear rails are easily extendable and mountable to many frame materials. They are sold in customizable sizes with pre-drilled holes [12]. They provide excellent rigidity to constrain motion in all axes. However, as sizes grow, the cost can increase faster than other options due to the more complex geometry [13].
	Linear bearings	Linear bearings are another industry standard approach to motion constraint [13]. The simplified geometry compared to linear rails makes it cheaper for containing larger distances [12][14].
	V-rollers	V-rollers offer a cheaper motion constraint option that sacrifices a bit of rigidity. The mechanism is more prone to wear, which can cause tolerance issues over its lifespan. However, they are still a viable motion constraint option for CNC routers [15].
Motion system	Lead screws	Simple and reliable, commonly used for slower-speed applications like Z-axis motion [16]. Affordable and easy to source but can introduce minor backlash over longer

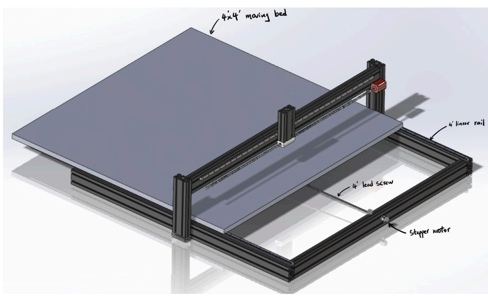
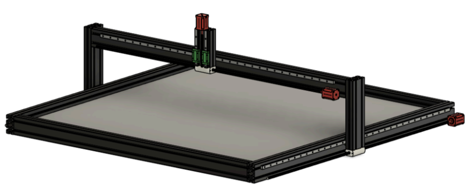
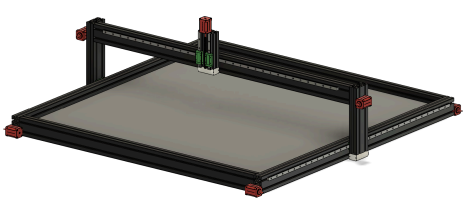
		distances [17]. Do not require a brake when used vertically.
	Ball screws	Precise motion system with minimal backlash, suitable for applications requiring tight tolerances. Higher cost and requires precise alignment during assembly. However, when off, it requires a stopper or brake for applications where a load is present to prevent back driving [16] [18][19].
	Belts	Lightweight and easy to install, offering high-speed motion and scalability for larger work areas [20]. Requires consistent tensioning and regular maintenance, with reduced precision over time [15].
	Rack and Pinion system	Durable and capable of handling long travel distances, often used in larger CNC machines. It may sacrifice some precision and is more complex to integrate compared to other systems [21][22].
Frame Material	Aluminum Extrusions	Modular and easy to assemble, offering a balance of rigidity, weight, and scalability [23]. Less rigid than steel for extremely high-force applications.
	Plywood/MDF	Affordable and simple to fabricate, often used for lightweight, cost-effective designs. Prone to warping under heavy loads and lacks the rigidity required for precision machining [23].
	Steel plates	Extremely rigid and durable, suitable for heavy-duty applications where precision and stability are critical. Heavy, expensive, and difficult to machine or assemble without specialized tools [23].
	Aluminum Plate	Aluminum plates can provide a good middle ground between rigidity and machinability. They require more expensive tooling than aluminum extrusions, but are not as difficult to machine as steel. Holes can be drilled with a drill press, but more intricate shapes must be cut with a CNC mill [23][24].

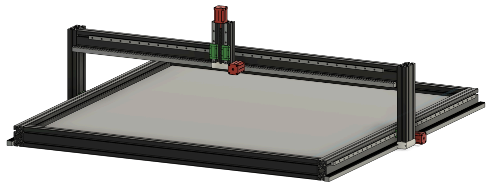
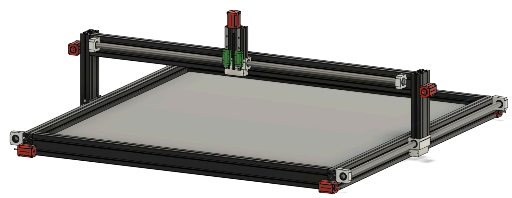
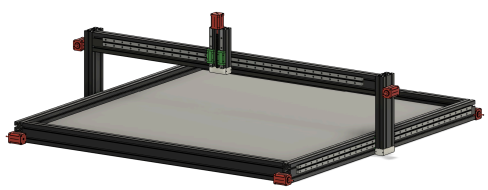
This exploration of the component provided a robust foundation for the candidate design; they were applied to develop six distinct candidate designs.

4.2 Candidate Designs

Building on the insights from the idea generation phase, the team developed six distinct candidate designs, which can be found in Table 3 below, visualized in Figures 1 through 6 respectively. Each design combined the identified components and exploited different configurations of motion system and frame layout to balance trade-offs in performance and cost. To simplify the candidate design phase, the team deferred frame material selection to the final conceptual phase. This is because the main distinguishing feature between CNC designs is the motion constraint and motion transmission system, and not what the frame is made of. Any of the motion constraint and motion transmission components could be used with any of the frame materials.

Table 3. Candidate designs and analysis.

Design No.	Picture	Configuration	Description, Pros and Cons
1	 Figure 1. Candidate 1	Lead Screw Z + Linear Rails, Ball Screw X and Y (Y-Moving Bed).	Combines high-precision ball screws with a moving bed layout. Suitable for compact gantry systems, but has a larger overall footprint.
2	 Figure 2. Candidate 2	Lead Screw Z + Linear Rails, Ball Screw X and Y (Y-Moving Gantry, 1 rail per side).	Features a single-rail moving gantry for workspace efficiency. Compact and lightweight, but requires precise alignment to prevent deflection.
3	 Figure 3. Candidate 3	Lead Screw Z + Linear Rails, Belt X and Y.	Utilizes belts for cost-effective high-speed motion. Lightweight and simple, but may introduce backlash and require regular maintenance.

4	 Figure 4. Candidate 4	Lead Screw Z + Linear Rails, Rack and Pinion X and Y.	Employs a rack-and-pinion system for robust long-distance travel. Durable and scalable, but less precise than ball screws.
5	 Figure 5. Candidate 5	Lead Screw Z + Linear Bearings, Belt X and Y.	Combines linear bearings with belts for a simplified and lightweight motion system. More precision but higher cost compared to linear rails.
6	 Figure 6. Candidate 6	Lead Screw Z + Linear Rails, Ball Screw X and Y (Y-Moving Gantry, 2 rails per side).	A dual-rail moving gantry for maximum stability and precision. Great for heavy-duty machining but increases cost and weight.

4.3 Selection Process

The six designs were evaluated based on their ability to meet the project objectives, including precision, affordability, and scalability. The team used a weighted decisions matrix along with the prior research about CNC components to make decisions about which of the conceptual designs is the best to proceed with.

4.3.1 Weighted Decision Matrix

Objectives regarding cost, tolerance, ease of sourcing, and ease of assembly are pulled directly from the engineering specifications. Additional objectives centring quality of life were added by the team to add additional quality-of-life criteria into the comparison. A complete justification of the added objectives can be found in Appendix D.

The team employed a weighted decision matrix to objectively compare the designs against key criteria. Weights were determined using a pairwise comparison chart (Appendix D), which ranked the importance of each objective. We then distributed percentages based on the order of the pairwise comparison chart.

Using these percentages, the team created a weighted decision matrix to compare each of the six candidate designs, using the weights from Appendix D, Table D2. Conceptual designs were compared against one another in a six-point scoring system, allocating points in descending order from best to worst at a given objective. The complete weighted decision matrix is located below in Table 4.

Table 4. Weighted Decision Matrix

Conceptual Design Number							
Objective	**Weights (%)**	**1**	**2**	**3**	**4**	**5**	**6**
1. Cost	**25**	1	4	6	5	3	2
2. Tolerance	**22.5**	4	5	2	1	3	6
3. Easy to source	**15**	1	4	6	2	5	3
4. Ease of Assembly	**12**	1	6	4	2	3	5
5. Maintenance	**10.5**	1	6	2	4	3	5
6. Scalability	**8**	1	3	5	6	4	2
7. Speed	**4**	1	3	6	2	6	3
8. Noise	**3**	2	3	6	1	6	3
Totals		1.705	4.525	4.36	3.025	3.59	4.295

Note: no ties were permitted for the weighted decision matrix.

5.0 Final Conceptual Design

The conceptual design selected to move forward is characterized by its lead screw Z axis, ball screw XY-axis, and linear rails on all axes; design two. Through the weighted decision matrix, this design had the best balance of meeting our objectives. However, the weighted decision matrix only decides the optimal motion transmission and constraint components. This leaves the bed and frame materials still undecided, requiring iteration in the final conceptual stage.

5.1 Frame Material Selection

All supporting components, including the frame, will be made of aluminum extrusions and plates. When selecting a material for a machine frame, rigidity and damping are critical considerations. Aluminum excels in damping performance, as it does not require stress relief like steel. It also provides a significantly lighter alternative to steel while maintaining a high strength-to-weight ratio. Furthermore, aluminum is relatively cost-effective, making it an ideal choice for our hobby CNC application [25]. Extrusions will be used for the base frame and the gantry. Aluminum plates will be used to affix bearings, motors, ball screws, and aluminum extrusions together. This is to provide more rigidity than other options, like 3-D printed parts, while maintaining relatively easy machining. To keep machining simple, we will only design aluminum plate brackets to have 90º cuts made into them. All plates must be available from online sources to keep them easy to source. Holes are also permitted to be drilled into these brackets. There is more information later in the document on these custom aluminum plate parts (Section 5.3.5). Machining for aluminum extrusions will be kept to: cutting to length if not pre-cut, drilling holes, and tapping holes.

5.2 Design Analysis And Detailed Part Selection

This section provides an in-depth analysis of the CNC machine's design, evaluating key aspects such as structural integrity, cost consideration, and components selection. A complete bill of materials (BOM) for the components listed in this section can be found in Appendix E. Supporting calculations, material justifications and analysis are attached below.

5.2.1 CNC Force Calculation

We selected 4080 aluminum extrusion as the first aluminum profile option to test to see if it could meet the tolerances for our cutting forces.

For most CNC operations, it is easy to estimate the maximum cutting force using the rated power of the spindle motor. The formula is listed below:

$$F_{t,max} = \frac{63025 \times P}{r_{tool} \times n}$$

The formula relates the maximum force a spindle can provide with its horsepower, tool head radius and spindle speed. In the worst case scenario, we are using full power, the lowest spindle speed and smallest radius tool head [26][27].

The Makita spindle we are using has a maximum power of 1.25 HP and the lowest spindle speed of 10,000 RPM [28]. If we are using a ¼" radius tool head, the maximum force will be around 280 N.

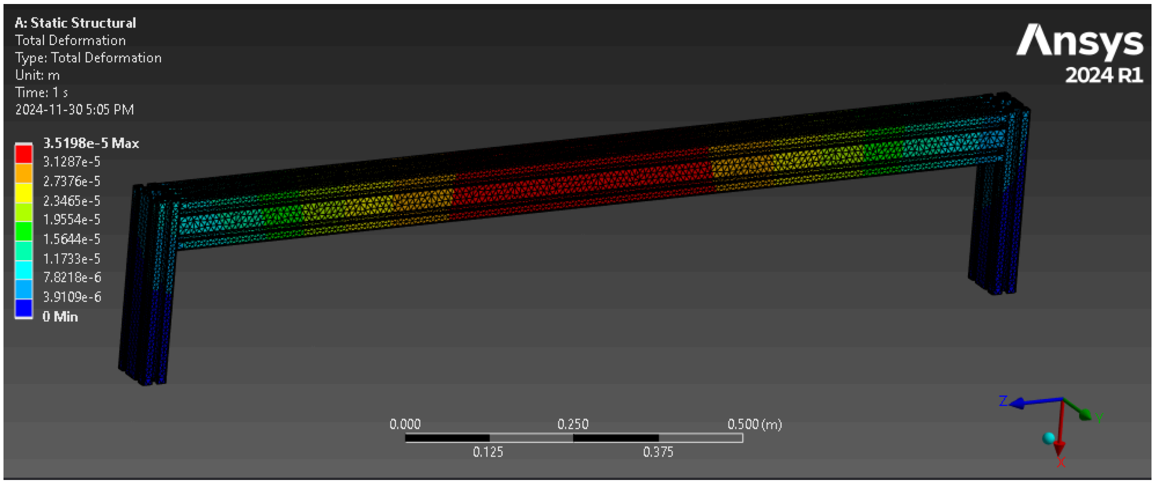


Figure 7. Total gantry deformation from Ansys simulation.

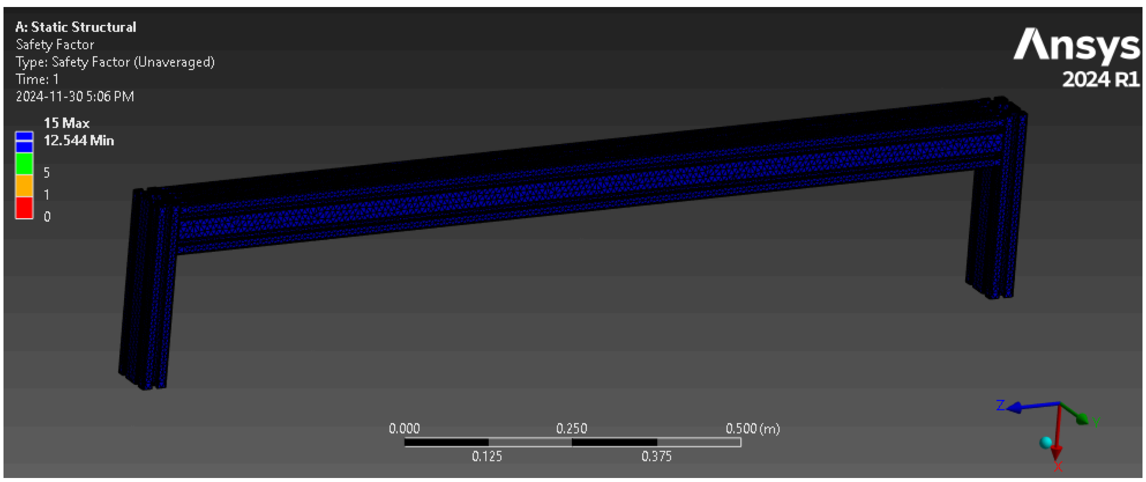


Figure 8. Gantry safety factor based on the Ansys simulation.

Based on the simulation result, a 4080 aluminum extrusion gantry will not exceed a deformation of 3.5e-5 m, and the safety factor is greater than 12.5 times the yield stress. It is more than enough to support the cutting force of the CNC machine. This allows the team to proceed with 4080 extrusion for the design process. Smaller aluminum profiles were not considered to leave available safety factor for forces from accelerating the gantry.

5.2.2 Part Selection and Justification

MGN12H Linear Rail

The MGN12H linear rail was selected for its ability to meet the load requirements with a dynamic load capacity of 3.72 kN, offering a robust safety factor of 13 [29]. Its compact size and geometry make it an ideal choice for seamless integration with the aluminum extrusion frame, as it can be mounted directly using T-slot nuts and standard M3 bolts [30][31]. This compatibility simplifies assembly and ensures precise alignment, contributing to the CNC machine's overall stability and accuracy.

NEMA 17-2004 Stepper Motors
The stepper motors were chosen for their widespread availability, affordability, and compatibility with common control systems. These motors provide sufficient torque to handle the loads and acceleration demands of the CNC machine, particularly when paired with ball screws for the X- and Y-axes, as well as the T8 lead screw for the Z-axis (Appendix F). Their standardized dimensions and mounting interfaces ensure seamless integration with the custom machined plates and other components, simplifying the overall assembly process.

SFU1605 Ball Screw (X- and Y-Axis)
The SFU1605 ball screw was selected for its precision, high efficiency, and excellent load-handling capabilities, making it ideal for the X- and Y-axis of the CNC machine. Its 16 mm diameter and 5 mm lead provide a balance between speed and resolution, ensuring the machine meets the target precision of ±0.005 mm [32].

Ball screws are known for their minimal backlash and high efficiency, typically converting rotary motion to linear motion with 90%–95% efficiency [33]. These characteristics make the SFU1605 well-suited for CNC applications requiring reliable and repeatable motion.

The 5 mm lead on the ball screw provides sufficient resolution for precision tasks, and the ball screw is compatible with the NEMA 17 stepper motors used in the design. Its durability and compatibility with the MGN12H linear rails further enhance the stability and performance of the system. A possible problem with such a long ball screw is that it may sag since it is unsupported, however the team's calculations show this would be kept under 1.7mm Appendix G. This deflection is not a problem since the gantry is supported by the linear rail Detailed calculations supporting the selection, including resolution, load handling, and speed analysis, are provided in Appendix G.

T8*4 P2 Lead Screw (Z-Axis)
The T8*4 P2 lead screw was selected for the Z-axis due to its combination of precision, cost-effectiveness, and self-locking capability. With a lead of 4 mm and a pitch of 2 mm, it provides higher resolution compared to standard lead screws (Appendix G) [34], enabling finer vertical adjustments essential for accurate tool positioning. Its trapezoidal thread profile ensures smooth motion and self-locking when the motor is powered off, eliminating the need for additional braking mechanisms. The T8*4 P2 lead screw is widely available, easy to integrate with standard stepper motors, and compatible with anti-backlash nuts, making it a practical and reliable choice for hobbyist CNC applications.

Makita RT0701c
The team opted for the Makita handheld router due to its consistent cylindrical frame that makes it easy to mount to the frame. There are commercially available mounts for these parts making it an ideal spindle to use for this design. See more on custom spindle mount in 5.3.6.

5.3 Operation and Features

The final conceptual design incorporates several key features that prioritize usability, scalability, and cost-effectiveness. The majority of components used in the design are off the shelf parts, ensuring easy sourcing and simplifying both assembly and maintenance for end users.

5.3.1 X-Axis Motion system

A side view of the X-axis motion system can be found in Figure 9 below.

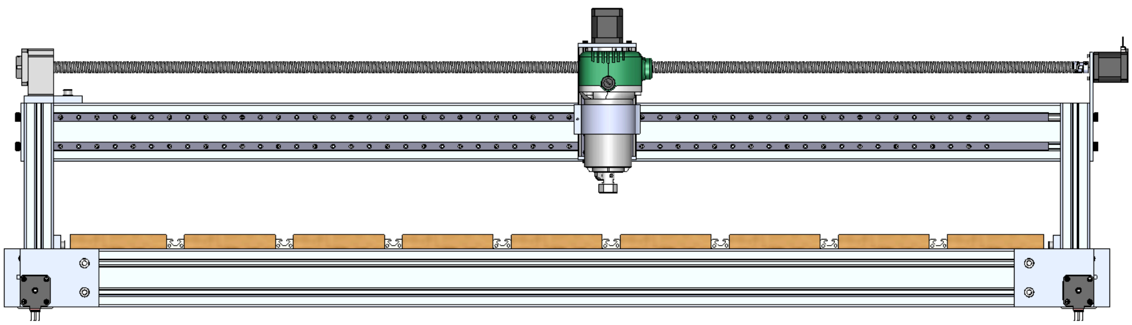


Figure 9: Side view of X-axis motion system.

Motion Transmission:

- **Ball Screw**: The X-axis uses a ball screw to convert the rotary motion of the stepper motor into linear motion. This ensures high precision and minimal backlash, critical for maintaining accurate lateral positioning of the tool head [35].
- **Couplings**: Beam couplings connect the stepper motor to the ball screw, accommodating minor misalignment while providing excellent torsional rigidity for consistent motion [36].

Motion Support:

- **Dual Linear Rails:** The linear rails mounted along the X-axis provide smooth and stable guidance for the tool head's motion. These rails minimize deflection, ensuring repeatable accuracy even during high-speed operation [37].
- **Aluminum Extrusions**: The ball screws and linear rails are securely mounted to 4080 aluminum extrusions, which serve as the primary structural support. T-slot nuts and bolts allow for easy assembly and alignment.
- **Ball bearings:** Ball bearings are used inside the ball screw end supports as a motion support device. Ball bearings reduce friction and ensure smooth rotation, while it can also handle significant axial loads.

5.3.2 Y-Axis Motion System

A side view of the Y-axis motion system can be found in Figure 10 below.

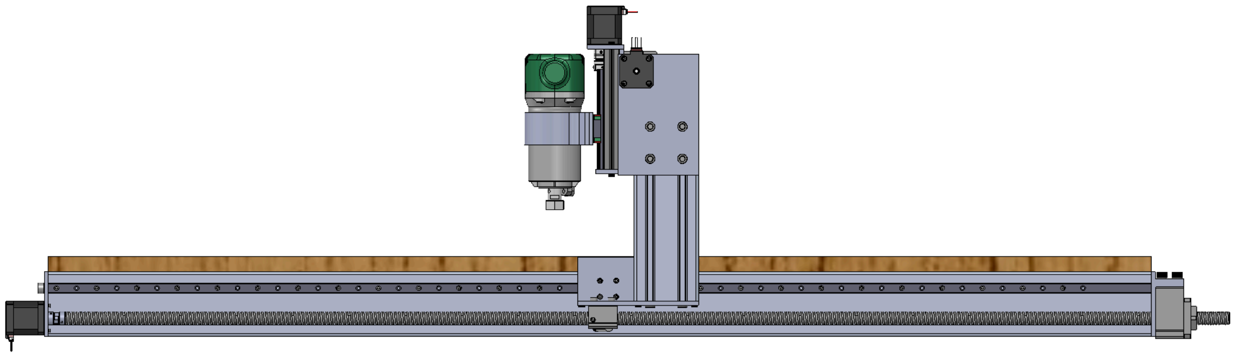


Figure 10: Side view of Y-axis motion system.

Motion Transmission:

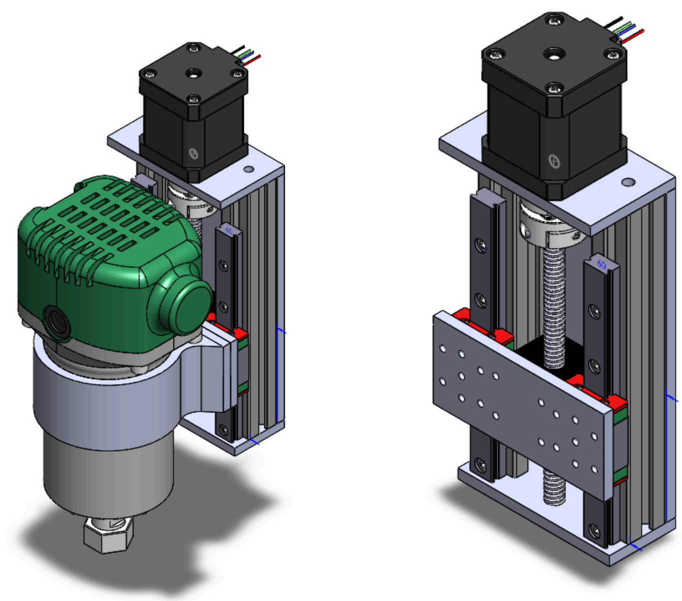
- **Ball Screw**: Similar to the X-axis, the Y-axis employs a ball screw for precise linear motion. Its low-friction design ensures smooth movement along the length of the gantry. [35]
- **Couplings**: Beam couplings are used to connect the stepper motor to the ball screw, ensuring efficient motion transfer with minimal backlash [36].

Motion Support:

- **Linear Rails:** The gantry is supported by two linear rails, with one rail mounted per side on the frame. Each rail includes dual carriages that distribute the load evenly along the axis, therefore increasing the stability. The carriages are then connected to the gantry using custom machined aluminum plates. This configuration prevents sagging or deflection under load, maintaining the machine's precision and stability during operation [37].
- **Aluminum Extrusions:** The ball screws and linear rails are securely mounted to 4080 aluminum extrusions, which serve as the primary structural support. T-slot nuts and bolts allow for easy assembly and alignment [30].

5.3.3 Z-Axis Motion System

An isometric view of the Z-assembly with (left), and without the tool head can be found below in Figures 11 and 12.



Figures 11 and 12: Isometric view of Z-assembly

Motion Type:

The Z-axis is responsible for vertical motion, moving the tool head up and down to adjust the cutting depth or reposition for non-contact travel. This motion is controlled by a lead screw, which provides a simple yet reliable mechanism for vertical movement. See figure 19 below for exploded 2D drawing.

Supporting Components:

- **Lead Screw**: The lead screw is selected for its cost-effectiveness and ability to handle vertical loads. Unlike the X and Y axes, the Z-axis does not require high-speed motion, making the lead screw an ideal choice. In addition to this, a lead screw does not require a brake when the machine is powered off [16] [18].
- **Dual Linear Rails**: Dual linear rails guide the Z-axis, minimizing wobble and ensuring stable motion during vertical adjustments. This is particularly important for maintaining accuracy when transitioning between cutting depths. [36]

Calibration:

The Z-axis employs a touch-off mechanism for precise calibration of the tool head. This system allows users to accurately set the cutting depth by referencing the tool against the workpiece surface, ensuring repeatable precision across multiple workpieces [25].

5.3.4 Workpiece Holding and Bed Assembly

Figure 13: Bed Assembly

The bed system (see Figure 13 above) of the CNC machine is stationary and does not incorporate active components such as elevation or tilting. Its primary function is to provide a stable and durable surface for securing workpieces during machining operations [38]. The design aims to emphasize reliability, adaptability, and ease of maintenance.

Workpiece Securing Method

The workpiece is secured to the bed using T-slot channels and clamps, a system designed for flexibility and ease of use:

- T-Nut Integration: T-nuts slide into the grooves of the bed's slats, allowing users to adjust the clamp position to accommodate various workpiece sizes and shapes [39].
- Clamping Process:
    1. Position the workpiece on the table.
    2. Slide T-nuts into the T-slots near the edges of the workpiece.
    3. Place clamps over the workpiece and secure them by tightening bolts into the T-nuts.

This method ensures that the workpiece remains stable during machining, reducing the risk of movement or misalignment.

Levelling System

To achieve a flat working surface, a spoil board (also known as a sacrificial MDF board) is used [40]:

- The MDF spoil board is secured on top of the bed assembly, covering the oak slats and T-slot grooves.
- The spoil board surface is levelled through a milling operation, ensuring that the bed is perfectly flat relative to the CNC's gantry.
- The spoil board protects the underlying bed slats from damage during machining and can be replaced as needed, making it a cost-effective addition to the system.

Material Composition

The bed combines two key materials for optimal performance:

- ¾" Spruce Plywood Slats:
    - Selected for their strength, rigidity, and resistance to deformation, plywood slats are ideal for withstanding prolonged exposure to machining forces [41].
    - As a hardwood, plywood provides durability and stability, ensuring the bed remains reliable over time.
- 4080 Aluminum Extrusion Framework:
    - The oak slats are mounted onto an aluminum extrusion framework, which adds rigidity to the bed while keeping the overall weight manageable.
    - Aluminum's modular nature simplifies assembly and allows for adjustments or scaling if needed.

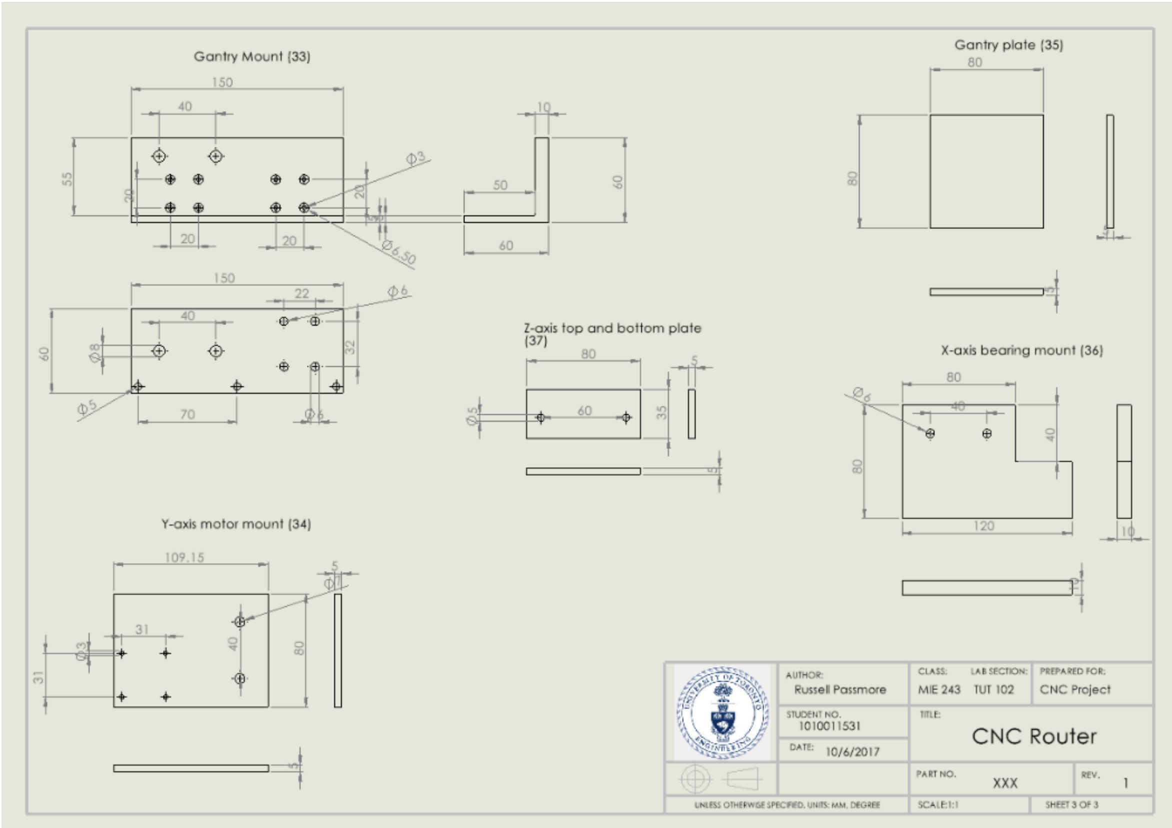
Replaceability

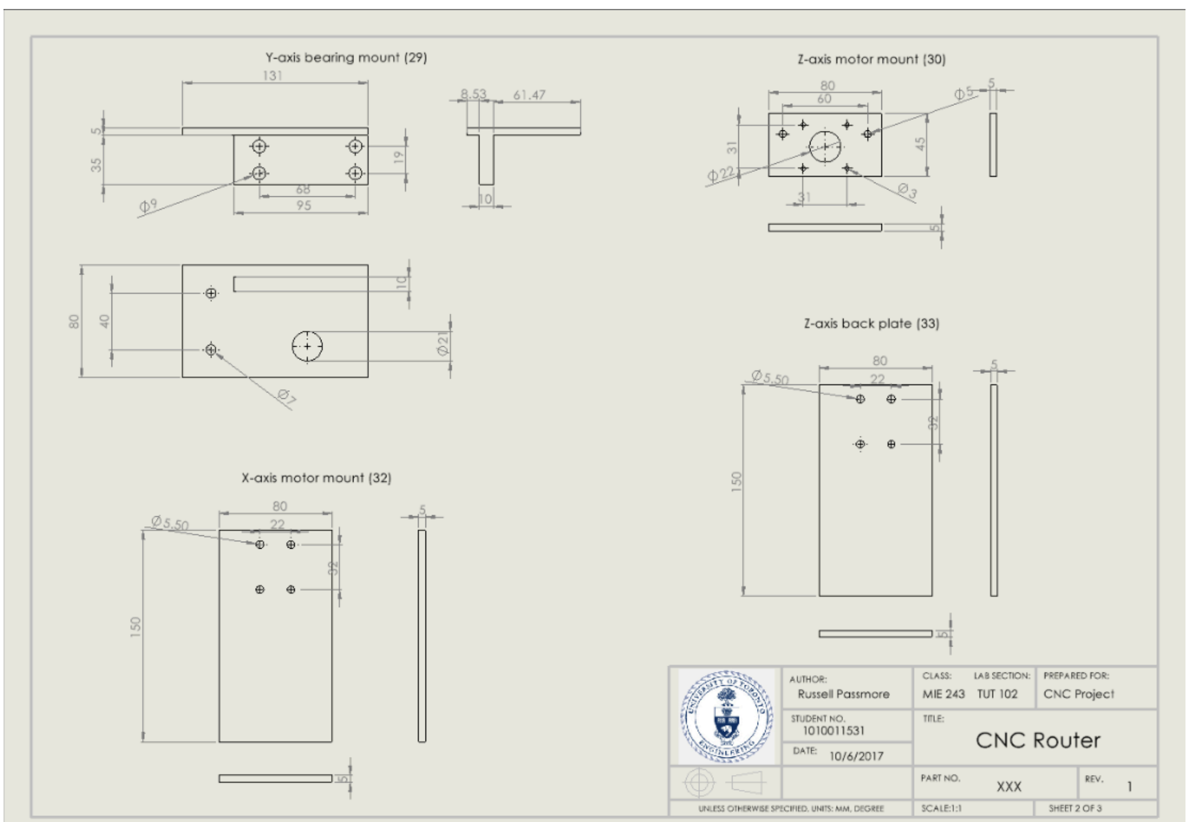
The bed system is designed with replaceability in mind:

- The spruce plywood slats, being wear-out components, can be easily removed and replaced with new ones sourced from local hardware stores.
- This modular approach ensures minimal downtime and maintenance effort while keeping costs low for the user.
- The aluminum extrusion framework remains intact, serving as a durable foundation for future replacements.

5.3.5 Custom pieces:

The CNC design incorporates 9 custom pieces, all of which serve as mounting plates to support components such as stepper motors, the gantry, and others. To ensure accessibility for hobbyist users, all pieces are designed to be machinable using common workshop tools, such as drill presses and circular saw [42], for cutting shapes and drilling holes. Additionally, the required aluminum plates for these parts are easily sourceable from local hardware stores, further simplifying the manufacturing process. See figure 14 and 15 below for engineering drawings of all custom pieces.





Figures 14 and 15: Engineering drawings of custom pieces.

5.3.6 Additional Parts:

The CNC design prioritizes user accessibility by ensuring that nearly every component is either commercially available or easily manufactured at home. However, there is one exception: the spindle mount. Due to its specialized geometry and precision requirements, the spindle mount must be sourced from a third-party supplier [43]. Spindle mounts are critical for securely holding the router or spindle during operation, and their compatibility depends on the specific router model chosen by the user.

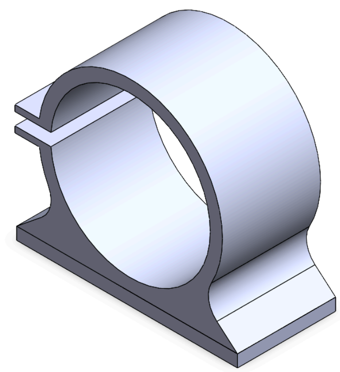


Figure 16 and 17. Placeholder Mount CAD model (left) 3rd Party Mount (right) [43]

To accommodate this, the CAD models provided in the design include a placeholder mount with custom mounting points. The Z-axis carriage plate is designed with adaptable mounting holes, allowing users to modify or adjust the hole positions based on the specific router mount they elect to purchase.

This flexible design ensures that the CNC can support a wide variety of routers or spindles, catering to different user preferences and budgets. By integrating this adaptability, the CNC design maintains its modular and user-friendly nature, ensuring that even the inclusion of a third-party part does not limit its accessibility or functionality.

5.4 Price Analysis

As detailed in the Bill of Materials (Appendix E), the total cost of the CNC machine is $3717 CAD, remaining well within the project budget of $4000. To meet the rigidity requirement necessary for machining aluminum, the team selected high quality 4080 aluminum extrusions form Misumi, which, although more expensive than initially anticipated, provided the structural stability needed for precision machining. A significant portion was allocated to the Hiwin linear rails, known for their exceptional quality and precision, as well as having the option to do custom ordered rail lengths. This investment ensures accuracy, durability and reliability, outweighing the potential cost saving from using lower quality alternatives.

While this design is not the least expensive CNC option for hobbyists compared to commercially available CNCs listed in Appendix A, as evidenced by the $600 USD DIY CNC machine from Autodesk Instructables – featuring an all-wood frame, but limited in cutting capability plywood and foams – it provides significantly greater capabilities. A more comparable alternative is the AltMill CNC Router, priced at over $4,600 USD, with optional accessories such as dust collection kits. This proposed design delivers comparable quality at a significantly lower cost. By prioritizing precision, durability and affordability, this CNC machine achieves a superior performance to price ratio, making it an ideal solution for the hobbyist seeking advanced capabilities within a reasonable budget.

5.5 CAD Drawings

Figures 18 and 19 below contain an engineering drawing of the complete assembly.

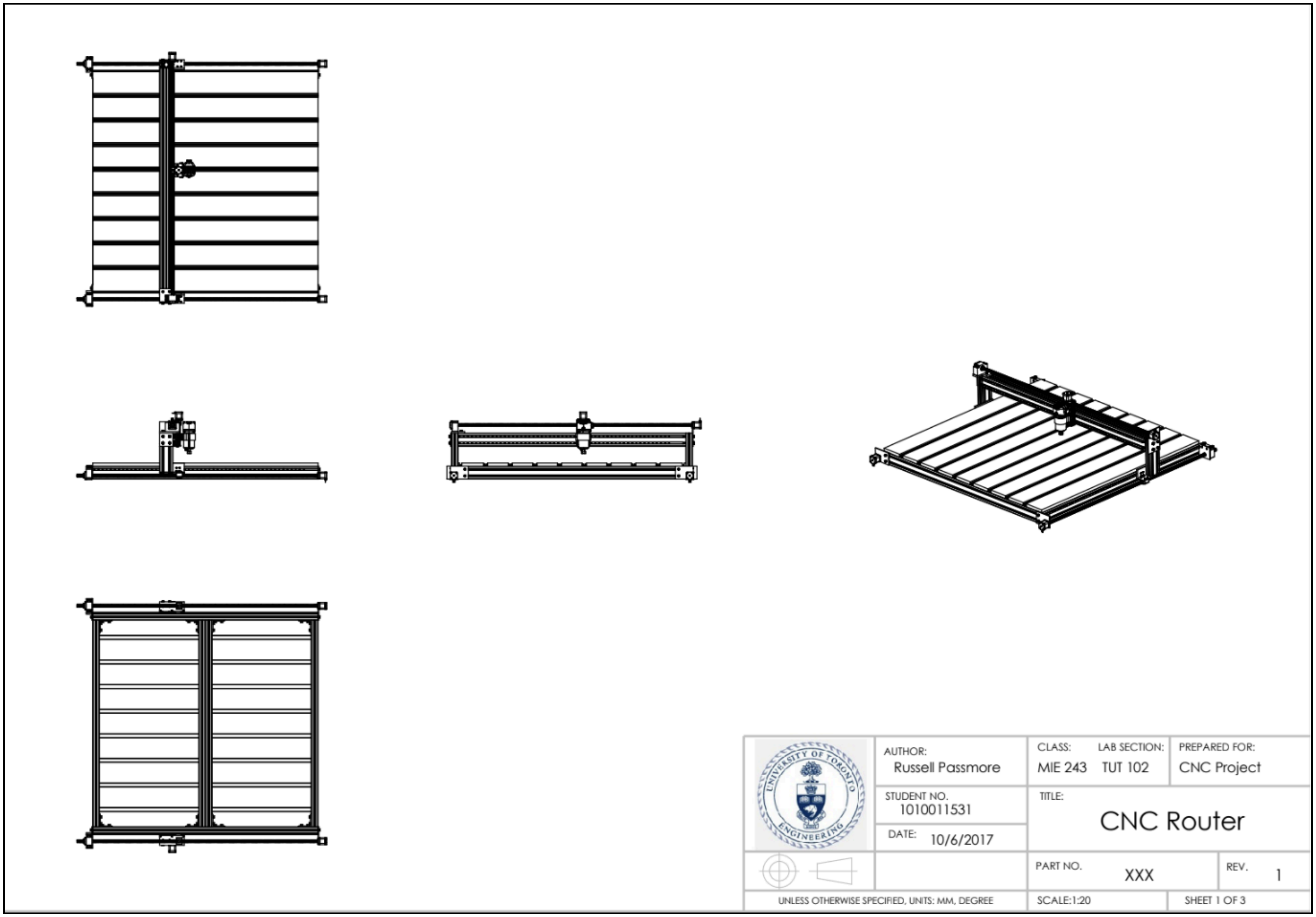
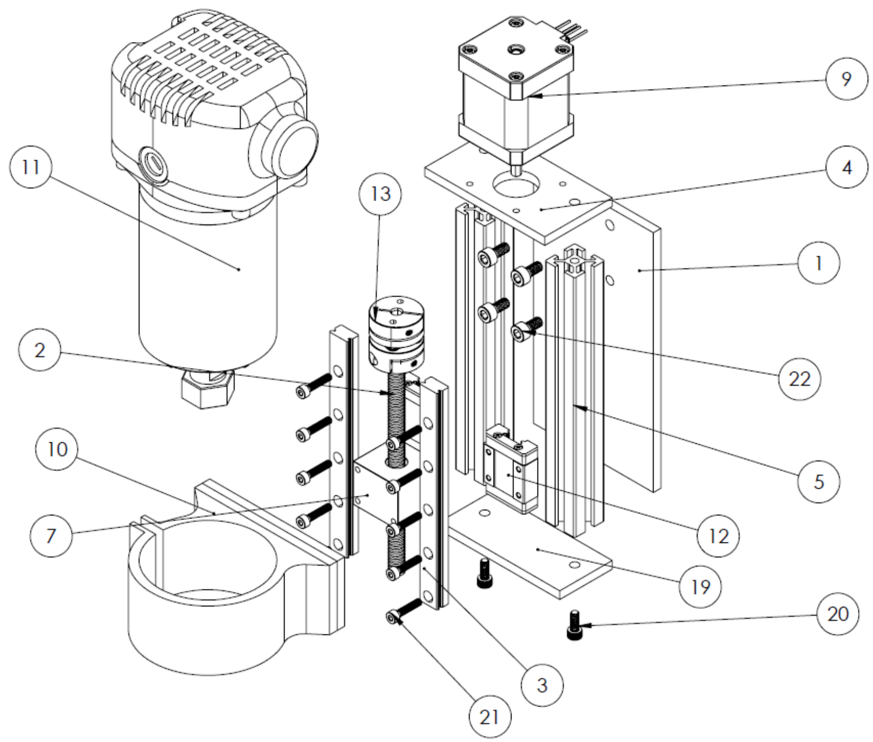


Figure 18. Complete assembly drawing.

ITEM NO.	PART NUMBER	QTY.
1	CARRIAGE PLATE	1
2	LEADSCREW 8mm X 2MMPITCH	1
3	LINEAR_RAIL	2
4	MOTOR MOUNT	1
5	EXTRUSION-2020-150.STP	2
6	MOUNTING PLATE	1
7	LEAD SCREW NUT HOUSING	1
8	LEADSCREW NUT 8mm X 2MMPITCH.STEP	1
9	STEPPER MOTOR.STEP	1
10	TOOL HEAD MOUNT	1
11	RT0700C - MAKITA - ROUTER.STP	1
12	MGN12C1R1 CARRIAGE	2
13	BEAM COUPLING	1
14	WASHER	8
15	19DIAPHRAGM.STEP	3
16	MP2626-8.STEP	1
17	M3-12.STEP	2
18	M3-6.STEP	4
19	Z BOTTOM PLATE	1
20	91274A117 SCREWS	2
21	91290A305 SCREWS	10
22	91290A224 SCREWS	4



AUTHOR: Russell Passmore

CLASS: MIE 243 LAB SECTION: TUT 102

PREPARED FOR: CNC Project

STUDENT NO. 1010011531

DATE: 10/6/2017

TITLE: CNC Router

PART NO. XXX

REV. 1

UNLESS OTHERWISE SPECIFIED, UNITS: MM, DEGREE

SCALE:1:2

SHEET 4 OF 4

Figure 19. Exploded Z-assembly

6.0 Conclusion

There is a key gap in the market for a hobby level CNC Router that is large format and precise. Through research of existing options, the team developed a solution that is a good balance of precision, affordability and easily attainable.

The team used a very structured evaluation system, including a weighted decision matrix, to select the optimal motion configuration. The final design is based upon modular aluminum extrusions for the frame, ball screws, lead screws, and linear rails for precise motion. These motion components are all off-the-shelf parts to ensure user accessibility and ease of assembly. Key features such as sensorless homing, a robust bed assembly, and a modular design framework make this CNC router both functional and adaptable to various user needs.

Detailed analyses, including force calculations and simulations, confirmed that the structural and motion systems meet the project's engineering specifications, including a tolerance of 0.1 mm and the ability to handle forces up to 300 N.

The project not only delivers a functional and reliable design but also delivers hobbyists an open-source solution. This CNC router is positioned to fill a unique niche, although not the least expensive on the market, our design offers a high level of precision that is usually only found on more expensive machines.

7.0 Citations

[1] Instructables, "How to Make a Three Axis CNC Machine (Cheaply and Easily)," *Instructables*, Jun. 29, 2007. https://www.instructables.com/How-to-Make-a-Three-Axis-CNC-Machine-Cheaply-and-/

[2] "LowRider CNC V4 - V1 Engineering Documentation," *V1e.com*, 2024. https://docs.v1e.com/lowrider/

[3] "AltMill 48×48 | Sienci Labs," *Sienci.com*, Dec. 03, 2024. https://sienci.com/product/altmill/

[4] "Types of Plywood," *The Home Depot*. https://www.homedepot.com/c/ab/types-of-plywood/9ba683603be9fa5395fab909d37f448

[5] "Wood Slab Characteristics | Wood-Ideas," *Wood-Ideas*, 2024. https://www.wood-ideas.com/woodslabcharacteristics

[6] A. B. Jr, "What Is the Standard Garage Size? 1-, 2-, 3-, 4-Car Garage Dimensions + Diagrams," *Alan's Factory Outlet*, Sep. 14, 2022. https://alansfactoryoutlet.com/blog/standard-garage-size/

[7] S. East, "Cost of CNC Machines: A Comprehensive Guide to Their Prices," *SendCutSend*, May 04, 2023. https://sendcutsend.com/blog/cnc-machine-costs/

[8] "ISO 230-2:2014," *ISO*, 2014. https://www.iso.org/standard/55295.html

[9] C. Heintz, "Wood, Aluminum, Steel & Composite Construction," *www.zenithair.com*, Dec. 1985. http://www.zenithair.com/kit-data/ht-85-12.html

[10] American Chemical Society, "Lesson 3.1: What is Density?," *American Chemical Society*, Dec. 08, 2023. https://www.acs.org/middleschoolchemistry/lessonplans/chapter3/lesson1.html

[11] Engineering Toolbox, "Factors of Safety," *Engineeringtoolbox.com*, 2010. https://www.engineeringtoolbox.com/factors-safety-fos-d_1624.html

[12] "Linear Guideways | HIWIN," *Hiwin Corporation*, Nov. 25, 2024. https://hiwin.com/products/linear-guideways/

[13] A. Shearer, "Linear Rails vs Linear Rods: Which is best for your application?," *Kiwi Motion*, Mar. 04, 2024. https://kiwimotion.co.uk/technical-articles/linear-rail/linear-rails-vs-linear-rods/?srsltid=AfmBOooXNUayjUP5d8v5sW-6Dat9ZM7apR2IMntMQti1RKa1-1FEThjp

[14] Misumi, “Linear Shafts,” *Misumi*. https://us.misumi-ec.com/vona2/mech/M0100000000/M0101000000/

[15] J. Madison, “What is Better-Linear Bearings vs. V Wheels for 3D Printers?,” *Kingroon 3D*, 2024. https://kingroon.com/blogs/3d-print-101/better-linear-bearings-vs-v-wheels

[16] “Z axis: ball screws vs belts,” *Duet3D*, Apr. 03, 2021. https://forum.duet3d.com/topic/22546/z-axis-ball-screws-vs-belts

[17] R. M. Mottola, “Liutaio Mottola Lutherie Information Website,” *Liutaio Mottola Lutherie Information Website*. https://www.liutaiomottola.com/Tools/Backlash.htm

[18] “Ballscrews or ACME for Z-axis?,” *Cnczone.com*, 2019. https://www.cnczone.com/forums/linear-and-rotary-motion/28032-ballscrews-acme-z-axis.html

[19] “Ball Screw or Lead Screw - Which Is Best? - Guides - Rowse,” *www.rowse.co.uk*. https://www.rowse.co.uk/blog/post/ball-screw-or-lead-screw

[20] “Belts vs Leadscrews and Ballscrews for CNC Design,” *Blanch Woodwork*, Dec. 04, 2023. https://blanch.org/belts-vs-screws-in-cnc-design/

[21] J. Entwistle, “Separating rack and pinion myths from reality,” *Machinedesign.com*, Nov. 2011. https://www.machinedesign.com/motors-drives/article/21833478/separating-rack-and-pinion-myths-from-reality

[22] J. Tang, “Benefits of an Absolute Rack and Pinion System,” *blog.orientalmotor.com*, Jul. 02, 2019. https://blog.orientalmotor.com/benefits-of-an-absolute-rack-and-pinion-system

[23] Jake, “Guide to CNC Frame Materials,” *Canned Cycle*, Sep. 05, 2023. https://www.cannedcycle.com/guide-to-cnc-frame-materials/

[24] G. Yi, “How To Mill Aluminum: The Ultimate Guide with Chart,” *Yijin Hardware*, Nov. 21, 2022. https://yijinsolution.com/news-blog/how-to-machine-aluminum/

[25] “CNC Milling Machine Frame [Complete DIY Guide],” *Cnccookbook.com*, Jun. 21, 2024. https://www.cnccookbook.com/cnc-milling-machine-frame-complete-diy-guide/

[26] “Touch Off - PyCAM,” *Sourceforge.net*, 2024. https://pycam.sourceforge.net/touch-off/

[27] Dr. J. Ziegert, “Cutting Forces in Milling: The Formula for Successful Workholding,” *www.ame.com*, Mar. 01, 2021. https://www.ame.com/workholding-wisdom-posts/2021/03/01/cutting-forces-in-milling/

[28] "MAKITA 1-1/4 HP (6.5-Amp) Compact Router with Variable Speed Control and Fine Depth Adjustment (120V)," *Home Depot*. https://www.homedepot.ca/product/makita-1-14-hp-65-amp-compact-router-with-variable-speed-control-and-fine-depth-adjustment-120v/1000848739?eid=PS_GO_140203__ALL_PLA-526641&eid=PS_GOOGLE_D00_Corporate_GGL_Shopping_All-Products_All%20Products__PRODUCT_GROUP_pla-298495632901&pid=1000848739&store=7080&gad_source=1&gclid=CjwKCAiAudG5BhAREiwAWMlSjC0rOrAJN2RBF7WKJkLWrjX-t9Dclpy0NfcZHNVuT-1HFlirIryplRoCLfwQAvD_BwE&gclsrc=aw.ds

[29] "Dashboard," *Hiwin.com*, 2024. https://configure.hiwin.com/run.html

[30] "Mounting linear rails on aluminum t-slot extrusions?," *Cnczone.com*, 2017. https://www.cnczone.com/forums/diy-cnc-router-table-machines/346016-mounting-linear-rails-aluminum-t-slot-extrusions.html

[31] "RepRap Forums :: CoreXY Machines," *reprap.org*. https://reprap.org/forum/read.php?397

[32] "SFU1605 Ball Screw - Maker Store USA," *Maker Store USA*, Nov. 28, 2024. https://makerstore.cc/product/tr-bs-sfu1605/

[33] D. Carpenter, "Miniature Ball Screws | Turn rotary motion into linear," *Tpamotion.com*, 2015. https://www.tpamotion.com/miniature-ball-screws.html

[34] R. Campbell, "Accuracy, Repeatability, and Resolution in Precision Machines and Instruments," *Practical Precision*, Apr. 26, 2017. https://practicalprecision.com/accuracy-repeatability-resolution-precision-machines-instruments/

[35] "Lead Screw or Ball Screw," *OpenBuilds*, 2019. https://builds.openbuilds.com/threads/lead-screw-or-ball-screw.13625/

[36] "How to Select a Beam Coupling," *Ruland Manufacturing*. https://www.ruland.com/technical-article-beam-coupling

[37] D. Collins, "When should you use dual guide rails?," *Linear Motion Tips*, Mar. 25, 2016. https://www.linearmotiontips.com/use-dual-guide-rails/

[38] "CNC Machine Beds: The Foundation of Precision - Machining Concepts – Erie, PA," *Machining Concepts – Erie, PA*, Nov. 15, 2024. https://machiningconceptserie.com/cnc-machine-beds-the-foundation-of-precision/

[39] B. Warfield, "Total Guide to CNC Jigs, Fixtures, and Workholding Solutions for...," *CNCCookbook: Be A Better CNC'er*, Aug. 21, 2017. https://www.cnccookbook.com/cnc-jigs-fixtures-workholding-solutions-milling/

[40] G. Fromme, “WHAT IS A CNC ROUTER SPOILBOARD, WHY IT’S IMPORTANT,” *Idcwoodcraft.com*, Sep. 17, 2023. https://idcwoodcraft.com/blogs/news/what-is-a-cnc-router-spoilboard-why-its-important

[41] “Plywood for CNC Work,” *Sawmillcreek.org*, 2016. https://sawmillcreek.org/showthread.php?245934-Plywood-for-CNC-Work

[42] digichefs, “How To Properly Cut Aluminium Sheets and Plates,” *Phillips Machine Tools India*, Jul. 12, 2023. https://phillipscorp.com/india/how-to-properly-cut-aluminium-sheets-and-plates/

[43] “CNC Router/Spindle Mount Clamp Holder Kit for Makita RT0701C 1.25HP - DIY,” *Vbottech.com*, 2024. https://vbottech.com/product/router-mount-makita-rt0701c/

[44] “Amazon.ca,” *Amazon.ca*, 2015. https://www.amazon.ca/FoxAlien-Masuter-Pro-All-Metal-Engraving/dp/B09ZTYGGTJ?source=ps-sl-shoppingads-lpcontext&psc=1&smid=A3JZGB4TAKCL7H

[45] “OpenBuilds LEAD CNC Machine 1515 (60 x 60 in) Black,” *RobotShop Canada*, 2023. https://ca.robotshop.com/products/openbuilds-lead-cnc-machine-1515-60-x-60-in-black

[46] Carbide 3D, “Shapeoko 4 CNC Router,” *Carbide 3D*, 2021. https://shop.carbide3d.com/collections/cnc-routers/products/shapeoko4?variant=33051555921981

[47] “Motor Sizing Calculations,” *Oriental Motor U.S.A. Corp.* https://www.orientalmotor.com/technology/motor-sizing-calculations.html

[48] “Microstepping for Stepper Motors,” *Linear Motion Tips*, Nov. 21, 2017. https://www.linearmotiontips.com/microstepping-basics/

[49] “Roton Products Inc.,” *Roton Products, Inc.*, Sep. 19, 2018. https://www.roton.com/products/ballscrews-and-ballnuts/general-information/

[50] “ Overview of materials for Chrome-moly Steel,” *MatWeb Material Property Data*. https://www.matweb.com/search/datasheettext.aspx?matguid=6d63108ce26941c2935af2e1641c818b

[51] “Beam Deflection Calculator,” *www.omnicalculator.com*. https://www.omnicalculator.com/construction/beam-deflection

[52] “Lead Angle Calculator | Evolvent Design,” *Evolvent Design*, 2024. https://evolventdesign.com/pages/thread-lead-angle-calculator?srsltid=AfmBOooy60KNwRz8LTHtaQebGgeFbbhzhaXCky45MCmApypQd9zPEmJl

Appendix A: Background Research Summary

An analysis of six existing CNC routers is contained below in Tables A1 to A6.

Table A1. Analysis of FoxAlien Masuter Pro CNC Router [44]

Price:	$663.20	**Design Notes:**
Dimensions:	15.75” by 15.75” by 2.35”	● Uses V-Rollers as XY motion support ● 0.1 mm tolerance ● MDF grid set up for the bed ● Fully aluminum construction ● Has z-probe and working lamp ● Model can be extended using 4080, has a different bed layout than standard model
Motion System Layout:	X: Belt drive	
	Y: Belt drive	
	Z: Lead screw	
Supported Materials:	Aluminum, wood, acrylic	

Table A2. Analysis of OpenBuilds LEAD CNC Machine [45]

Price:	$3219.68	**Design Notes:**
Dimensions:	48” by 48” by 2.5”	● V-rollers are used on the X-axis for motion support ● 0.05 mm tolerances ● Utilizes NEMA 23 motors ● Aluminum extrusions are C-beam ● Gantry has two parallel extrusions for rigidity ● Tensioning system
Motion System Layout:	X: Lead screw	
	Y: Lead screw	
	Z: Lead screw	
Supported Materials:	Aluminum, wood, plastic	

Table A3. Analysis of Shakeopo 4 XXL CNC Router [46]

Price:	$2300.00	**Design Notes:**
Dimensions:	33” by 33” by 4”	● T-slot table, with T-slot clamps to go with it ● Homing switches ● V-rollers as motion support ● Features a bit setter, enabling fast tool head changes ● Can be assembled in around two hours ● Contains a dust boot attachment for shop vac ● Gantry can be overhung to do wood joinery such as dovetails
Motion System Layout:	X: Belt drive	
	Y: Belt drive	
	Z: Lead screw	
Supported Materials:	Aluminum, wood, plastic	

Table A4. Analysis of DIY Three-Axis CNC Machine [1]

Price:	$600		**Design Notes:**
Dimensions:	14” by 10” by 4”		• All wood construction • Can be constructed with simple tools • No apparent attachment mounts on the bed • Less than 30 unique parts
Motion System Layout:	X: Belt drive		
	Y: Belt drive		
	Z: Lead screw		
Supported Materials:	Plywood and foam		

Table A5. Analysis of Lowrider CNC [2]

Price:	$800	**Design Notes:**
Dimensions:	96” by 48” by 4”	• Mostly 3-D printed parts • Utilizes steel bars for reinforcement • Supported by linear rails • Attaches to an existing table, with a recommended spoiler board on top • Only a singular Y-axis to allow for easy removal
Motion System Layout:	X: Belt drive	
	Y: Belt drive	
	Z: Lead screw	
Supported Materials:	Aluminum (experienced user), wood, plastic	

Table A6. Analysis of AltMill CNC Router [3]

Price:	$4680.00	**Design Notes:**
Dimensions:	49” by 49” by 5.5”	• Aluminum extrusion construction • Shelves available underneath • Horizontal extrusions, no provided bed • Dust boot expansion kit available
Motion System Layout:	X: Ball screw	
	Y: Ball screw	
	Z: Ball screw with brake	
Supported Materials:	Aluminum, wood, plastic	

Appendix B: Scope Analysis

A brief summary of the request for proposal (RFP) underscores the need for a large-format, hobbyist CNC router with a focus on reliability, ease of assembly, and low cost. It is stated that the hobbyist users of the product are looking for the ability to cut materials such as wood, plastics, and aluminum. Therefore, materials harder than aluminum will not be considered in the scope. In addition, it is stated that the design need not detail the electronics side of the CNC. Therefore, design capabilities such as homing the gantry, safety switch are also out of scope.

The RFP also presents three potential construction options for the product: fully-assembled, partially-assembled, or an open source kit. For the purposes of this project, our design team has elected to produce an entirely open source design, due to the upside of upgradability and customization over the lifetime of the product. A manual detailing construction instructions and required parts is included with the submission of this document.

Dust collection and bed levelling are two important components of CNC routers. The team has decided that dust collection should be up to the user, and thus will not be included in the cost analysis. On the other hand, bed levelling is necessary for the proper functioning of the CNC, and thus will be in scope.

Appendix C: Justifications for Engineering Specifications

The engineering specifications are justified below in categories of size, cost, capabilities, and operation.

Size

Because the target audience is hobbyists, who may not have access to large industrial spaces, the team has deduced that a given design should be able to fit within a small garage, with space for a vehicle to fit inside. The standard size of a one-car garage is 12’ wide by 20’ long, while the average car is about 6’ wide by 15’ long [6]. The ability to open the vehicle doors should not be impeded, leaving a working area of approximately 6’ wide by 5’ long as seen in Figure A1.

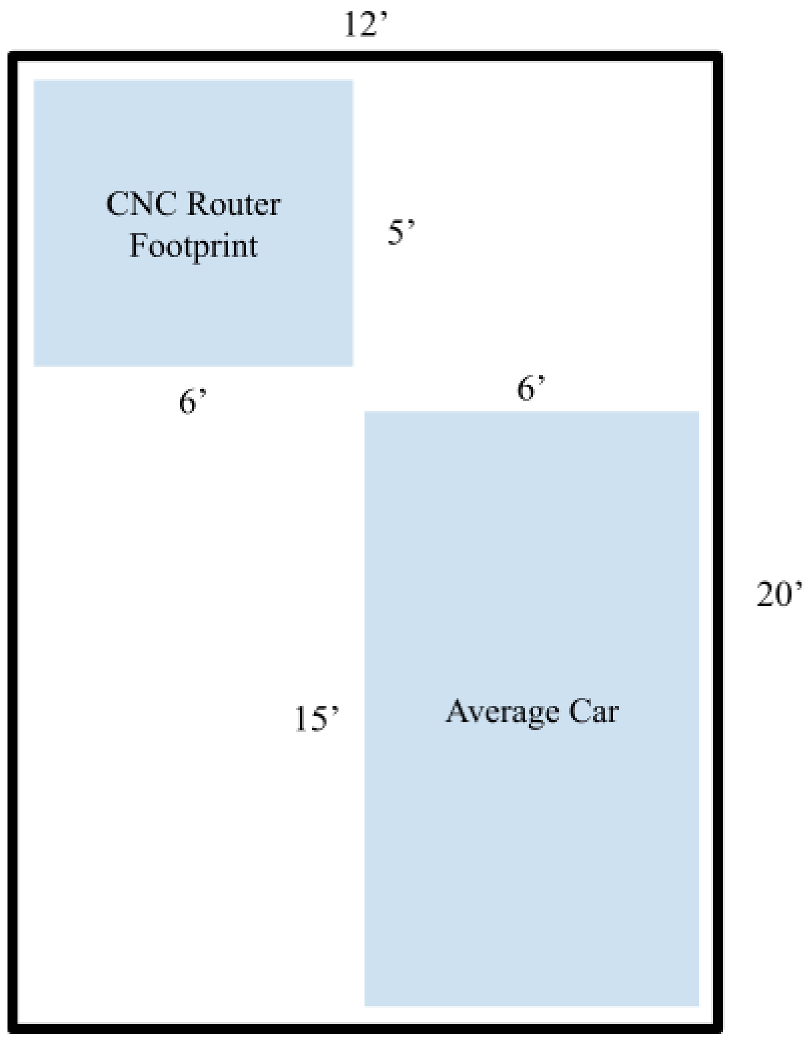


Figure A1. Garage door spacing dimensions.

Furthermore, the criteria of a “large-format” CNC machine implies that large workpieces should be supported, and large wood sheets typically come in 4’ by 8’ [4]. Besides, wood slats typically come in thicknesses up to 80 mm, or about 3’’ [5]. Because of the dimensional limitations of the garage, it becomes feasible to halve this dimension. In addition, the gantry will require extra dimensions to access the full 4' length and width.

The resulting *size specifications* are as follows:

- Working area of 4' by 4', with a working height of 3"
- Body of design fits within an area of 5' by 6'

Cost Analysis

The cost-range for a hobbyist level CNC router typically falls between 1,000 and 3,000 United States Dollars (USD) [7]. In Canadian Dollars (CAD), the upper bound is approximately $4,000. To not constrain the design space, the team takes $4000 as the upper limit for the design budget. Still, component selection will be guided with the goal to make low-cost, yet feasible tradeoffs.

On a similar note, a large portion of custom parts for the design will drive costs up. Therefore, hobbyists should be able to source a majority of the parts from consumer sources.

The resulting *cost specification*:

- The design components must not cost more than $4000 CAD for a hobbyist to acquire
- Most components should be sourced from consumer sources

Capabilities

The use cases of a CNC machine require manipulation of the router head in three-dimensional (3-D) space. Although this requirement is relatively broad, since the motion source must be motors, the input is thus rotational. The RFP states that reliability and consistency are more valuable than precision, and thus the aim is to provide users with a design that meets 3-D axis motion repeatability standard ISO 230-2 [8]. Tolerances, although not a focus, will be a feature of the robustness and rigidity of the design. As a result, the team must consider the tradeoffs between the rigidity of the frame versus cost in the candidate designs.

Because almost all the existing designs analyzed are capable of cutting aluminum, woods, and plastics, the project design too, must be capable of cutting these materials. Because aluminum is approximately three times harder than wood [9] and is denser than plastics [10], ability to cut aluminum will be assumed as the threshold for cutting all three material types. This threshold will be reinforced by a minimum safety factor of 4, as recommended for dynamic loading [11]

The resulting *design capability specifications:*

- 3-D axis motion precision in line with ISO 230-2
- Design is compatible with aluminum with a safety factor of 4

Operation

Because the team has chosen the open-source path, the design must be easily assembled according to the provided instruction pamphlet. This means that the assembly procedure can be completed by a single person, with commonly-available workshop tools.

The resulting *operation specification*:

- The design must be easily assembled by one person with the provided instruction manual
- Design components can be connected through standardized means and/or materials

Appendix D: Idea Selection

The following pairwise comparison chart (Table D1) was used to sort objectives from most important to least important. The larger the total score, the more important the objective is. The objectives used in this chart were extracted from the engineering specifications, and interpreted for user quality-of-life.

An ease of maintenance objective is added as a benefit to the user, aligning with preferred engineering practice. The objective of scalability is inferred from the hobbyist centred market, aiming to provide more layout flexibility to users. Further, the added speed objective is not a primary focus of the design, assuming that a hobbyist consumer is not mass-producing pieces, but will be included as a quality-of-life feature for faster work. Similar justification is used for noise, as quieter machines are preferred in a home setting but not necessary.

Table D1. Engineering objectives pairwise comparison.

Objectives	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
1. Cost	x	1	1	1	1	1	1	1	**7**
2. Assembly	0	x	0	0	1	1	1	1	**4**
3. Source	0	1	x	0	1	1	1	1	**5**
4. Tolerance	0	1	1	x	1	1	1	1	**6**
5. Noise	0	0	0	0	x	0	0	0	**0**
6. Speed	0	0	0	0	1	x	0	0	**1**
7. Maintenance	0	0	0	0	1	1	x	1	**3**
8. Scalability	0	0	0	0	1	1	0	x	**2**

The resulting objective rankings:

1. Cost
2. Tolerance
3. Source
4. Assembly
5. Maintenance
6. Scalability
7. Speed
8. Noise

After ranking the objectives through pairwise comparison, the team discussed the importance of each objective to the CNC design.

Table D2. Weights for Weighted Decision Matrix

Objective	Weight (%)
1. Cost	25
2. Tolerance	22.5
3. Source	15
4. Assembly	12
5. Maintenance	10.5
6. Scalability	8
7. Speed	4
8. Noise	3

Appendix E: Bill of Materials

Table E1. Bill of materials.

Category	Component	Qty	Size	Recommended	Alternative Source	Price Per Unit (CAD)	Price Total (CAD)
Electronics	Nema 17 Motor	4	N/a	Stepper Online		$9.75	$39.00
Frame	Misumi HFSB5-2020	2	150mm	Misumi		$6.53	$13.06
Frame	Misumi HFSB5-4080	2	1370mm	Misumi		$106.95	$213.90
Frame	Misumi HFSB5-4080	2	1260mm	Misumi		$98.37	$196.74
Frame	Misumi HFSB5-4080	2	240mm	Misumi		$23.34	$46.68
Frame	Misumi HFSB5-8080	1	1260mm	Misumi		$240.47	$240.47
Frame	Misumi HFSB5-8080	1	1386mm	Misumi		$264.51	$264.51
Motion	Ball Screw & Nut	3	1500mm	Maker Store		$105.02	$315.06
Motion	Ball Screw Nut Holder	3	N/A	Maker Store		$10.50	$31.50
Motion	Ball Screw Coupling	3	5mm - 16mm EKL_Size2	Misumi	Amazon	$36.25	$108.75
Motion	Lead Screw	1	T8*4 P2 @ 125mm	Spool 3D		$8.00	$8.00
Motion	Lead Screw Nut	1	T8*4 P2	Spool 3D		$5.00	$5.00
Motion	Lead Screw Nut Holder	1	N/A	Spool 3D		$10.00	$10.00
Motion	Lead Screw Coupling	1	5mm - 8mm	Stepper Online		$6.96	$6.96
Motion	Ball Screw End Support	3	N/A	Maker Store		$44.87	$134.61
Motion	MGN12 Linear Rail (X&Y)	4	1370mm	Hiwin		$250.00	$1,000.00
Motion	MGN12 Linea Rail (Z)	2	125mm	Hiwin		$30.00	$60.00
Fasteners	M6 Socket Bolt	8	40mm	Mcmaster Carr		$14.60	$116.80
Fasteners	M6 Socket Bolt	100	16mm	Mcmaster Carr		$0.23	$23.00
Fasteners	M5 Socket Bolt	100	10mm	Mcmaster Carr		$0.19	$19.00
Fasteners	M5 Flat Head Bolt	10	14mm	Mcmaster Carr		$4.87	$48.70
Fasteners	M4 Socket Bolt (Z assembly)	4	10mm	Mcmaster Carr		$5.28	$21.12

Fasteners	M3.5 Socket Bolt	16	16mm	Mcmaster Carr		$3.90	$62.40
Fasteners	M3 Socket Bolt	200	15mm	Mcmaster Carr		$0.17	$34.00
Fasteners	M3 Flat Head Bolt	100	10mm	Mcmaster Carr		$0.89	$89.00
Fasteners	M6 Slide-in T-Nut	20	N/A	Spool 3D	80/20	$0.40	$8.00
Fasteners	M4 Slide-in T-Nut	200	N/A	Spool 3D		$0.30	$60.00
Fasteners	Angle bracket	8	N/A	8020		$13.72	$109.76
Bed Assembly	Single Open T-Slot	8	1370mm	8020		$21.00	$168.00
Bed Assembly	Plywood Sheet - Spruce	1	4'x8'x3/4'	Home Depot		$33.15	$33.15
Router	Makita RT0701C	1	N/A	Amazon		$130.00	$130.00
Custom Mounts	Y-axis bearing mount	2		Mcmaster Carr			
Custom Mounts	Z-axis motor mount	1		Mcmaster Carr			
Custom Mounts	X-axis motor mount	1		Mcmaster Carr			
Custom Mounts	Z-axis back plate	1		Mcmaster Carr			
Custom Mounts	Gantry mount	2		Mcmaster Carr			
Custom Mounts	Y-axis motor mount	2		Mcmaster Carr			
Custom Mounts	Gantry plate	2		Mcmaster Carr			
Custom Mounts	X-axis bearing mount	1		Mcmaster Carr			
Custom Mounts	Z-axis top and bottom plate	2		Mcmaster Carr		$100	$100
							$3,717.17

Appendix F: Motor Calculations
These calculations are used to find the required torque for the stepper motor in our design. The force used is from a force calculation done assuming aluminum as the cutting material (Section 5.2).

P (pitch distance) = 5 mm
D (diameter) = 16 mm
r (radius) = 8 mm
M_a (mechanical advantage)
T = torque
Pitch angle = 5.68 [47]

$$F = F_A + mg(sin\theta + \mu cos\theta)$$
$$F = 300N + (16kg)g(sin(5.68) + (0.05)cos(5.68))$$
$$F = 323.34N$$

This section uses the mechanical advantage that the ball screw gives from the pitch. One revolution of the ball screw gives 10 mm of travel. Since circumference is greater than 10 mm we get a mechanical advantage.

$$M_a = \frac{F\ out}{F\ in} = \frac{16\pi}{5}$$
$$F_{in} = 32.16N$$

Torque can be calculated by the distance the force is going to act from the centre of the ball screw [47].

$$\tau = F_{in} \bullet r$$
$$\tau = 32.2 \bullet 0.008m$$
$$\tau = 25.76N \bullet cm$$

Appendix G: Resolution Calculations

Deflection:

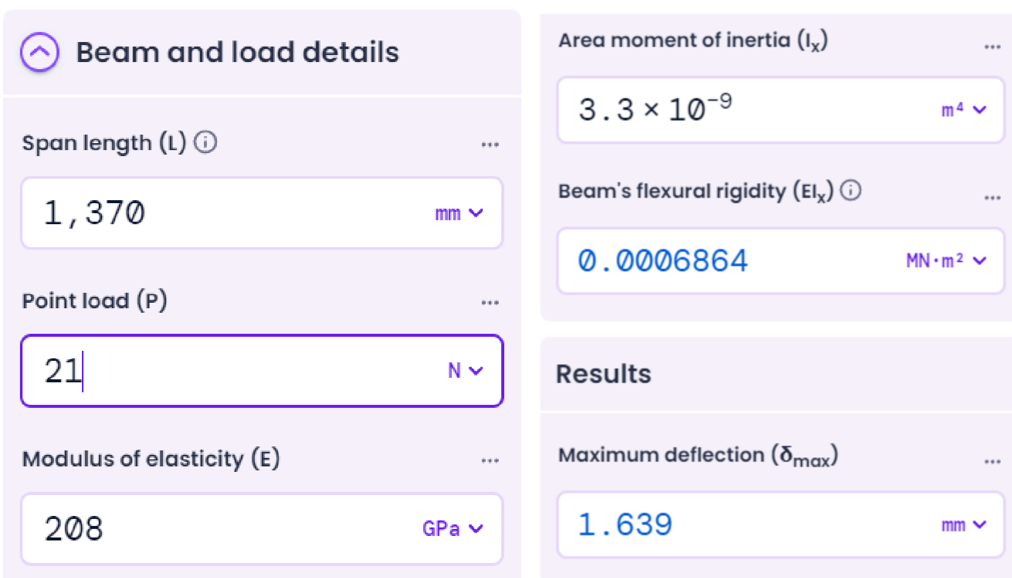
Type of steel: chrome steel [49]
Chrome steel E: 208GPa [50]
Chrome steel density: 7.94 g/cc [50]
Ball screw mass:

$$\pi r^2 h\rho = \pi(0.008m)^2(1.37m)(7940\ kg/m^3) = 2.187\ \text{kg}$$

Ball screw:

$$I_x = \frac{\pi}{4}r^4 = \frac{\pi}{4}(0.008)^4 = 3.216 \times 10^{-9} m^4$$

Deflection using weight of ball screw using calculator shown in Figures G1 and G2:



Figures G1 and G2. Deflection calculator results [51]

Ball Screw:

The ball screw has a 5 mm lead (distance travelled per revolution) and a 2 mm pitch (thread spacing), the resolution of the XY-axis motion system can be determined by the step size of the stepper motor and the lead of the screw:

1. **Stepper Motor Step Size:**
   - The chosen NEMA 17 stepper motor has 200 steps per revolution (1.8° per step).

- With microstepping (e.g., 1/16th microstepping) [48], the effective steps per revolution increase to:

$$200 \times 16 = 3200\, steps/revolution$$

2. **Distance per step (DPS)**
   - The ball screw has a 5 mm lead, meaning it moves 5 mm per revolution [**52**].

$$DPS = \frac{Lead}{Steps\ per\ revolution} = 0.0015625 mm/step.$$

This translates to a resolution of **1.56 microns per microstep**, which is sufficient for achieving the desired precision in the XY-axis.

Lead Screw:

The lead screw has a 4 mm lead (distance travelled per revolution) and a 2 mm pitch (thread spacing). The resolution of the Z-axis motion system can be determined by the step size of the stepper motor and the lead of the screw:

3. **Stepper motor step size:**
   - The chosen NEMA 17 stepper motor has 200 steps per revolution (1.8° per step).
   - With microstepping (e.g., 1/16th microstepping) [48], the effective steps per revolution increase to:

$$200 \times 16 = 3200\, steps/revolution$$

4. **Distance per step:**
   - The lead screw has a 4 mm lead, meaning it moves 4 mm per revolution [52].

$$DPS = \frac{Lead}{Steps\ per\ revolution} = 0.00125 mm\ per\ step$$

This translates to a resolution of **1.25 microns per microstep**, which is sufficient for achieving the desired precision in the Z-axis.