Multi-Process CNC Build

Preliminary Proposal

Bader Alfadhli

Jessica Collins

Sara Hamadah

Uday Kadhum

Micael Ljungberg

Jason Troxler

2016-17

Project Sponsor: NAU/CEFNS

Faculty Advisor: David Willy

Sponsor Mentor: David Willy

Instructor: Dr. Trevas

DISCLAIMER

Students prepared this report as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

TABLE OF CONTENTS

1 BACKGROUND

1.1 *Introduction*

The purpose of this project was to design and construct a computer numerical control (CNC) table. The CNC table was built with multiple functions in mind that include routing, 3D printer, and a laser cutting. CNC machines currently perform functions and movements, which were traditionally performed by skilled machinists. CNC machines are designed to meet the requirements of high production rates, uniformity and consistent quality of parts. Programmed instructions are converted into output signals, which in turn control machine operations such as spindle speeds, tool selection, tool movement, and cutting fluid flow [1]. CNC Machines play a very important role in manufacturing complex curved geometries in 2D or 3D with reduced cost. The machine components can have high accuracy and are capable of unmanned operations [2]. This project is initiated and sponsored by David Willy, a Mechanical Engineering professor at Northern Arizona University (NAU), located in Flagstaff, Arizona.

1.2 *Project Description*

Following is the original project description provided by Dr. David Willy:

> The Mechanical Engineering Department is looking for a space saving CNC table that can be retrofitted as a routing table, a 3D printer, or even a laser cutter. This year's project will be centered on a routing table design configuration. As such, the client is looking for the following out of the finished product:
>
> - Ability to use both a typical router or dremel tool as the spindle
> - A robust table that has the ability to clamp typical work pieces
> - A robust travel system that limits deflection of tooling during operation
> - Ability for the table, travel system, and controls to convert into future configurations (3D printer or laser cutter) by future capstone teams
> - Travel – approximately 12x12x3 inches
> - Ability to make both aluminum and wooden parts
> - Uses standard 120V 60Hz.
> - Uses commercially available control boards and motors
> - Interfaces with available open source software on a windows operating system
> - Safety shielding around the table and the ability for the operator to still see the work piece.
> - Must have a safety kill switch and appropriate fusing per industry standards.
>
> The finished deliverable to the client will include the following:
>
> - The functional system after a demonstration of the system making aluminum and wooden parts
> - Provide cut depth and width recommendations based on final design.
> - Provide a feeds and speeds chart based on different materials.
> - Provide a user's manual for operation Original System Structure [3].

This project involved the design of a completely new CNC Table. There was no original system when this project began.

2 REQUIREMENTS

This section explains the different parts of the House of Quality, including customer requirements, engineering requirements, testing procedure, and design links.

2.1 *Customer Requirements (CRs)*

Together with the client, David Willy, the requirements were weighted after importance. The assigned weightings add up to 130. These values were normalized to a scale out of 100%. The most important requirements were safety, cutting ability, and cost. The CNC machine needs to perform safely when cutting wood and aluminum. Cost is also a major constraint due to the budget given for the project. Tolerance of the finished part together with the ability to change the spindle to either a laser cutter or a 3D printer pen were also considered to be of high importance. Requirements that were preferable but not necessary are size, portability, and open source software.

Table 1: Weighted customer requirements.

QUALITY/CUSTOMER REQUIREMENT	**WEIGHTINGS**	**MULTIPLIERS**
1.Safety	25.0	25/130*100%=19.2%
2. Cutting Ability (wood/ Al)	25.0	25/130*100%=19.2%
3. Cost	25.0	25/130*100%=19.2%
4. Tolerance	20.0	20/130*100%=15.3%
5. Open Source	10.0	25/130*100%=7.6%
6. Multiple Usage	15.0	15/130*100%=11.5%
7. Size	7.0	25/130*100%=5.3%
8. Portable	3.0	3.0/130*100%=2.3%
Total	130.0	100%

2.2 *Engineering Requirements (ERs)*

By analyzing the customer needs, the engineering requirements (ERs) were generated and engineering attributes were found that could meet these needs. Each of the customer needs was ensured to have a ER associated with it. This process involved investigating what characteristics affected the customer need and then designing a parameter around that characteristic. This ensured that all customer needs will be met in the design process. Specifications and tolerances have been provided below.

- Spindle Power (Watts) 2000 ± 1800.
- Tooling Deflection (mm) 0.0254 ± 0.0127.
- X, Y Dimensions (mm) 300 ± 100.
- Linear Motion Precision (mm) 0.0254 ± 0.0127.
- Z Axis Travel (mm) 127 ± 51.
- Stepper Motor Torque (N/cm) ≥ 13.7.
- Shielding Material Thickness (mm) 5 ± 3.
- G-Code Software: Open Source.
- Controller: Open Source.
- Set up time (min) 10 ± 5.
- Weight (kg) 34 ± 23.
- Voltage (V) 120.

The tolerances on each of the engineering requirements were chosen so that the production of the CNC would not be too tightly constrained by unreachable requirements.

2.3 *Testing Procedures (TPs)*

Test procedures are performed to determine whether machine components conform to the requirements of that activity and whether the system and/or software satisfies its intended use and user needs. The testing procedure for the CNC router table will be performed for each customer requirement. A correlation between customer requirements and testing procedures can be seen in Table 2. The testing procedures are the following:

1. The vendor supplied specifications will be utilized to choose an appropriate range. As of now the team will not test the spindle power.
2. The measurements for the machined parts will be taken to ensure deflection of tooling is not occurring. Measuring the top and bottom edge of cuts to see if there is an appreciable difference can do this. Measurement will be done with a digital micrometer that will be procured from the machine shop in building 98c.
3. The actual travel of the tool head in the XY- direction and the Z-Axis will be measured to ensure compliance with specifications. This will be done with a tape measure that reads to at least 1/8th of an inch. The tape measure will be sourced from the machine shop in building 98c.
4. For the frame and bearing deflection, a force equivalent to the maximum value of the expected cutting force will be applied to the bottom of the spindle using a hanging mass

or pull scale then, a measurement with a dial indicator will be made at the spindle tip of total deflection when force is applied and compared against static values.

5. The stepper motor torque will be tested by a torque test. A lever arm will be attached to the motor. A known weight will be attached to the lever arm. The motor will then be turned on and programed to turn the lever arm a certain degree of a revolution.
6. Taking the measurements using dial calipers will test the shield thickness.
7. The actual time needed to set up the machine on the table to the time when the machine is ready to receive G code will be tested by using a stopwatch application on a cell phone.
8. The weight of the machine will be tested by using a scale which can be obtained from the soils lab in the engineering building.

2.4 *Design Links (DLs)*

1. Spindle (Router) will be selected to fit within desired range. From the HOQ, the spindle power should be 2000 W [Symbol] 1500W. That is the desired range.
2. Feeds and speeds will be adjusted to minimize (eliminate) tooling deflection. The allowable deflection is 0.0254mm [Symbol] 0.0127mm.
3. Work platform will be built around desired 12”x12” work envelope. The allowable measurements for the XY dimensions as specified in the HOQ are 300mm [Symbol] 100mm.
4. Predicted force calculations will be done to ensure that the material and bearing combination will result in the lowest deflection possible within budget/weight constraints. The allowable deflection of the frame and bearings is 0.0254mm [Symbol] 0.0127mm as seen in the HOQ.
5. Designed to have a minimum travel of what is desired. With a max travel of around 2times the minimum travel. The allowed Z-axis travel seen in the HOQ for is anything above 76.2mm.
6. The Stepper motor torque required will be estimated using a force and momentum evaluation of the proposed design. The range of the stepper motor torque considered can be seen in the HOQ as ≥ 17.3 N/cm.
7. Look at what kind of forces the shielding will be subjected to and apply a thickness sufficient to block these forces coming from various kinds of debris. The amount of shielding depends on the customer’s safety concerns. The required shield material thickness specified in the HOQ is 5mm [Symbol] 3mm.
8. Will use an Open source software package to comply with the request.
9. Create mounts that comply with power units that can perform laser cutting, 3D printing and milling.
10. Use materials that will fulfill strength requirements and optimize weight reduction efforts that fit within budget constraints
11. Select spindle assemblies that fit within the desired voltage supply requirements

Table 2: Engineering requirement correlation to design links and testing procedures.

Number	Engineering Requirement	Design Link	Testing Procedure
1	Spindle power	1	1
2	Tooling deflection	2	2
3	XY dimensions	3	3
4	Frame and Bearing Deflection	4	4
5	Z axis travel	5	3
6	Stepper motor torque	6	5
7	Shield thickness	7	6
8	G-code sending	8	1
9	Controller for Motion	8	1
10	Set up time	9	7
11	Weight	10	8
12	Power requirements	11	1

2.5 *House of Quality (HoQ)*

Table 3: Multi-Purpose CNC Teams HOQ

House of Quality (HoQ)															
CNC Router Team A	Weighting		Engineering Requirement												
Customer Requirement	Initial Customer scoring	Weight out of 100%	Spindle power (W)	Tooling deflection (mm)	X Y Dimensions (mm)	Frame and Bearing deflection (mm)	Z Axis Travel (mm)	Stepper Motor Torque (N/cm)	Sheilding material thickness (mm)	G-Code Software	Controller	Set up time (min)	Weight (kg)	Power requirements (V)
1. Safety	25	16%	3	1	1	1	1	1	5	1	1	1	3	1
2. Cutting Ability (wood/ Al)	25	16%	5	3	1	3	1	5	1	1	1	1	3	1
3. Cost	25	16%	5	5	3	5	3	3	1	1	5	1	3	1
4. Tolerance	20	13%	1	5	1	5	1	1	1	1	1	1	3	1
5. Open Source	10	6%	1	1	1	1	1	1	1	5	5	1	1	1
6. Multiple Usage	15	10%	1	1	1	1	1	1	1	1	3	5	1	1
7. Size	7	5%	1	1	5	1	5	1	1	1	1	1	5	1
8. Portable	3	2%	1	1	3	1	3	1	1	1	1	3	3	1
9. Typical house hold elec service	25	16%	3	1	1	1	1	1	1	1	1	1	1	5
Total	155	100%												
Absolute Technical Importance (ATI)			2.45	2.32	1.38	2.32	1.38	1.81	1.48	1.10	1.94	1.26	2.28	0.84
Relative Technical Importance (RTI)			1	2	8	2	8	6	7	11	5	10	4	12
Target(s), with Tolerance(s)			2000 ± 1800	0.0254 ± 0.0127	300 ± 100	0.0254 ± 0.0127	127 ± 51	≥ 13.7	5 ± 3	Open source	Open Source	10 ± 5	34 ± 23	120
Testing Procedure (TP#)														
Design Link (DL#)														

Approval (print name, sign, and date):

Team member 1: Bader Alfadhli

Team member 2: Jessica Collins

Team member 3: Sara Hamadah

Team member 4: Uday Kadhum

Team member 5: Micael Ljungberg

Team member 6: Jason Troxler

Client Approval: David Willy

3 EXISTING DESIGNS

CNC machines come in different sizes and models depending on the application. The following section explains how the team started researching over a wide range of CNC machines and similar machines. The section also includes different alternatives of CNC machines as well as different alternatives for the subsystems of a CNC machine.

3.1 *Design Research*

The purpose of the research was to expand on the team's previous knowledge of CNC machines, and widen the knowledge about machines used for similar applications. The research incorporated CNC machines as well as lathes, drill presses, and milling machines. The research also included machines ranging from machines used in industry to machines used for hobby applications. Web-based sources comprised most of the research because of both the diversity, as well as the amount of information. Without previous knowledge of building a CNC router table, the team conducted extensive research about the CNC router table and its components.

3.2 *System Level*

This section examines commercially available CNC machines. The following designs assisted in generating ideas for meeting the client's needs. Each table uses a router or similar cutting instrument and can mill multiple materials from wax, various plastics, hardwoods and metals. The tables are compared based on cutting area, power, software available, size and cost. Cutting area, power, software, and size are project requirements. Cost is used a benchmarking tool for comparing various capabilities between the different machines.

3.2.1 *Existing Design #1: Carbide 3D Nomad 883 Pro*

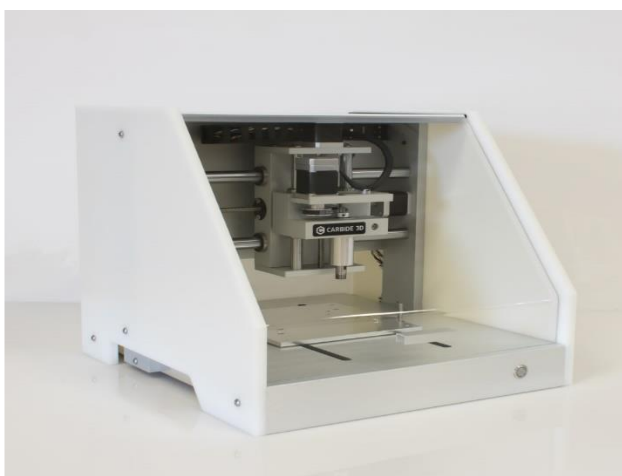


Figure 1: Carbide 3D Nomad 883 [4]

Table 4: Specifications for the Carbide 3D Nomad 883 [4]

Cutting Area	Power	Software	Size & Weight	Cost
8" X 8" X 3"	110V	Carbide Create MeshCAM	20"X20" 65lbs	$2599.00

The Nomad 883 Pro is a 3-axis fully enclosed desktop CNC machine capable of cutting all materials and is Mac and Windows compatible. This design is comprised mainly of aluminum and comes in HDPE (High-Density Polyethylene) or Bamboo housing.

Design #1 is fully enclosed which protects users and bystanders from expelled pieces of milled materials. This project requires a safety shield to ensure expelled milled materials do not harm bystanders. This design shows an option of adding a safety shield to the table without compromising the machine's capabilities and allows for viewability.

3.2.2 *Existing Design #2: Shapeoko Deluxe RB-Spa-1299*

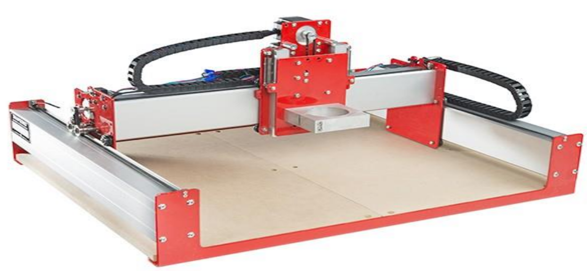


Figure 2: Shapeoko Deluxe RB-Spa-1299 [5]

Table 5: Specifications for the Shapeoko Deluxe RB-Spa-1299 [5]

Cutting Area	Power	Software	Size & Weight	Cost
17" X17" X 3"	24V	Open Source Java	28.5" X 23.6" 55lbs	$999.95

The Shapeoko is a desktop 3-axis milling CNC machine capable of milling non-ferrous metals such as aluminum, hardwoods and plastics. This table is comprised of steel and extruded aluminum, and the spindle head is not included in this package.

Design #2 is not enclosed but offers a larger cutting surface closer to those required. Another of this project's requirements is that the table is capable of using some type of open source software, which this table is capable of.

3.2.3 *Existing Design #3: BoXZY Three-in-one 3D printer, CNC Mill and Laser Engraver*

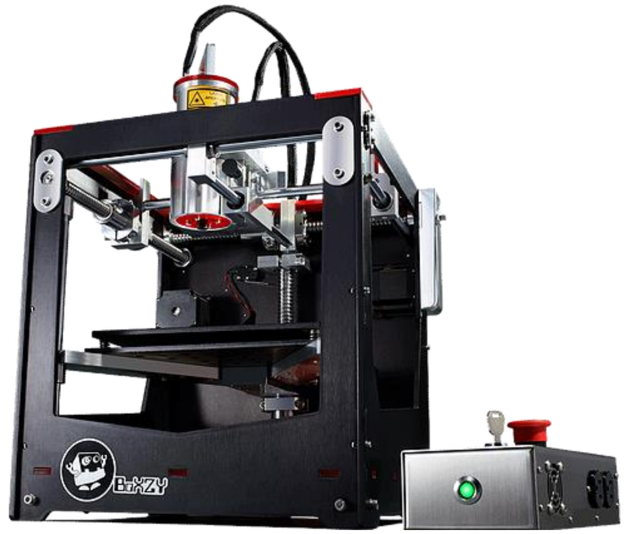


Figure 3: BoXYZ Three in on 3D printer [6]

Table 6: Specifications for the BoXYZ [6]

Cutting Area	Power	Software	Size & Weight	Cost
9.63" X 4.25" X 2.5"	19V	Open Source Google Sketchup	15.5" X 13.35" X 14.06" 40-45lbs	$3599.00

BoXZY is a desktop CNC table that is capable of interchanging milling, laser cutting, and 3D printing. The final goal of the project is to create a desktop table that is able to easily shift between these same three capabilities.

Design #3 is a fully enclosed milling, laser cutting, and 3D printing machine. This project's end desire is to incorporate each of these functions seamlessly which this design has already accomplished.

3.2.4 *Existing Design #4: Pocket NC*

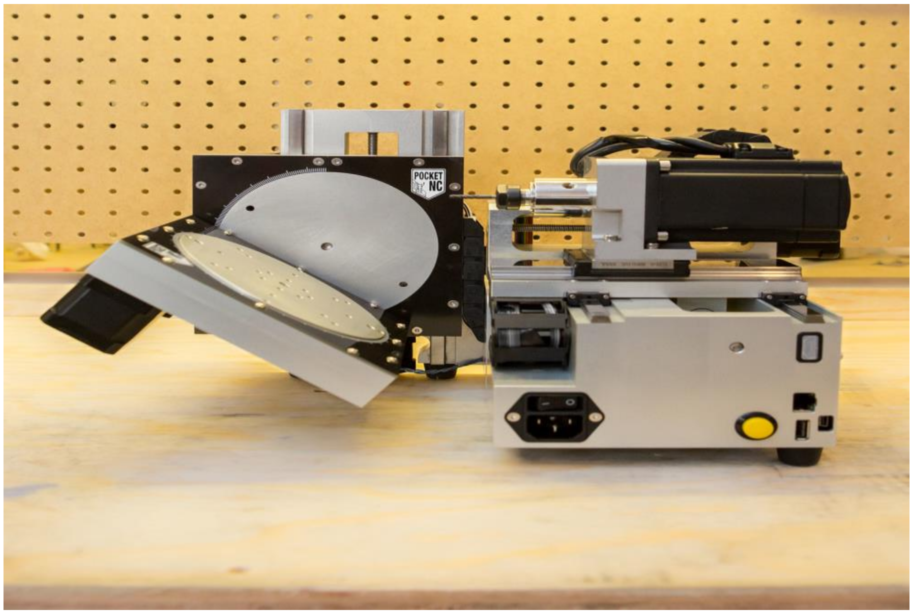


Figure 4: Pocket NC [7]

Table 7: Specifications for the Pocket NC

Cutting Area	Power	Software	Size & Weight	Cost
4” X 5” X 3.55” 100° 360°	90-264VAC 127-370VDC 47-63Hz	Autodesk Fusion360	17.5” X 12.5” X 12.5”	$4000.00

The Pocket NC is a 5 axis desktop CNC machine. Unlike many commercially available CNC tables where the spindle head moves while the cutting surface remains stationary, the PocketNC is capable of moving in the x,y,z,a and b axes and is able to create complicated geometric parts while staying compact.

Design #4 is a desktop CNC milling machine capable of traversing in 5 axes. This project requires 3 axis travel but does not specify if more axes could be added. This design is capable of creating more complex geometries compared to the traditional 2 or 3 axes machines. This design shows an alternative for the project where instead of the spindle head being mobile, the cutting surface is mobile.

3.3 *Subsystem Level*

This section will take a closer look at some of the core subsystems that make a CNC machine function. Each of these subsystems will directly impact the performance and ability of the CNC machine and will be analyzed in the following sections. The subsystems being looked at are the spindle, linear motion, and the bearings and guides. All of these subsystems can make or break a system if an inadequate part is chosen for the application.

3.3.1 *Spindle System*

The spindle system is at the heart of the cutting ability for the CNC machine. The power, run time capability, speed variability, and tooling availability will dictates how efficiently the CNC machine will meet the cutting requirements. There are multiple options available for a CNC machine. Table 6 above shows the three types of spindle systems that are regularly used in desktop CNC machines. Table 6 also compares some of the feature and options for each type.

Table 8: Spindle comparison chart [8] [9] [10]

Spindle System Comparrison	Image	Power available (W)	Capabilities to engrave			Capabilities to Shape/Route/Cut			Cost Range (USD)	Cooling	Variable Speed
			Wood	Metal	Plastics	wood	Metal	Plastics			
Dremel Tool		<192	🟢	🟢	🟢	🟡	🟡	🟡	40-120	🔴	🟡
Router		700-2400	🟢	🟢	🟢	🟢	🟢	🟢	50-400	🔴	🟡
Spindle		275-2200	🟢	🟢	🟢	🟢	🟢	🟢	150-3500	🟡	🟢
🔴 Not Available 🟡 Available or Moderate 🟢 Standard or Yes											

3.3.1.1 *Subsystem #1: DREMEL®*

Dremel rotary tools are often used in small CNC routing and engraving machines. Dremel have capabilities in cutting metal, plastics, fiberglass, and wood. They also have the ability to do small detail work due to the availability of smaller tool sizes. Some of the models offer adjustable speed ranges so that the cutter speed can be changed based on what fits best to the application. Figure 5 shows what the Dremel® rotary tool looks like. This tool if implemented in the CNC project would enable the machine to engrave, and cut aluminum and wood but at a relatively slow speed when compared to the router or spindle options.

Figure 5: Dremel ® rotary tool [8]

3.3.1.2 Subsystem #2: Router

Routers are powered hand tools that are meant to shape and form wood and plastics. Some models are available with adjustable speeds similar to what is offered in the Dremel® tool. Routers generally have a much higher power rating when compared to a Dremel® tool, usually between 0.5-3.5hp. Tooling to cut aluminum is also available for routers and there are commercially available CNC machines with routers as the spindle system. Routers offer relatively inexpensive horsepower when compared to CNC spindles. Drawbacks to using routers are the larger size, when compared to spindles, often have non-variable drives, and typically have a plastic case, which is less rigid than a metal encasement.

Figure 6: Dewalt 2.25hp router [9]

3.3.1.3 Subsystem #3: Spindle

A spindle is rotary tool that is intended to be used in a machine application. Typically spindles come with a variable frequency drive (VFD), and have water cooling as another option. The VFD enables the spindle to work at a wide variety of spindle speeds by rheostat type control that offers infinite adjustability within the capabilities of the spindle. In comparison the router and Dremel tools usually have selectable ranges for speed. Although, top router models do offer an electronic VFD type system built into the assembly. Figure 7 shows what a typical spindle with VFD looks like.

Figure 7: Spindle with VFD unit [10]

3.3.2 *Linear Motion*

Linear motion will look into the systems that transfer the drive motor power to motion in the CNC system. There are several systems available for the desktop CNC machine. These include the pulley and belt system, rack and pinion, and lead screw or ball screw designs.

3.3.2.1 Existing Design #1: Pulley and Timing Belt

The pulley and belts utilize a drive pulley, idler pulley, and a drive belt to transfer motor motion to the CNC assembly. The drive pulley attaches to the drive motor so that all of the motor power can be transferred to the belt. The belt transfers the motion to the part that needs to be moved. For instance; the gantry assembly of a CNC machine. The idler pulleys' purpose is to guide the belt and maintain tension to ensure that power gets transferred to the assembly intended to move. Figure 8 shows what a typical pulley and belt system may look like, and how that would attach to the CNC machine. Advantages for a timing belt with pulley system is that gear ratios can be changed, accurate, and can transfer power perpendicular to the motor location. Some disadvantages include less capable at higher torques, may experience slippage, and can be susceptible to oils and grease [11].

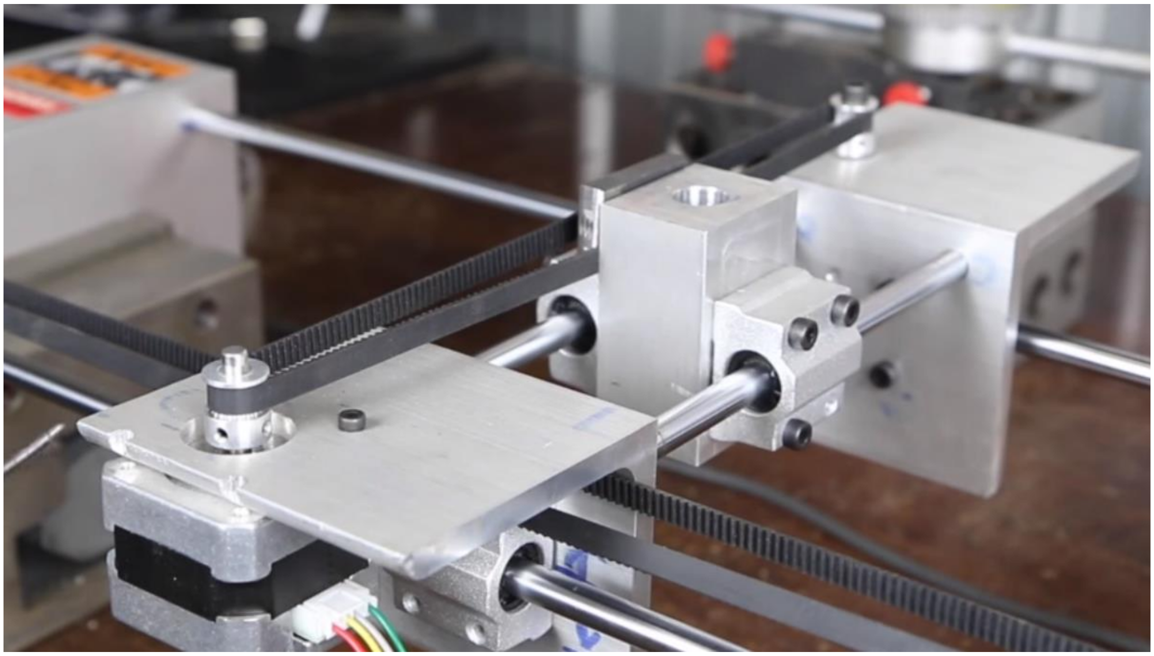


Figure 8: Timing belt and pulley arrangement [12]

3.3.2.2 Existing Design #2: Rack and Pinion

Rack and pinion drive systems use a pinion gear and a drive rack. The pinion gear is either connected directly or indirectly, with a belt, to a drive motor. When the drive motor turns, it drives the pinion gear on the rack. This moves the pinion assembly along the rack, or depending on how it is positioned, the rack across the pinion gear. Figure 9 shows a rack and pinion with a belt driven pinion gear, this is an example of a stationary rack with moving pinion gear.

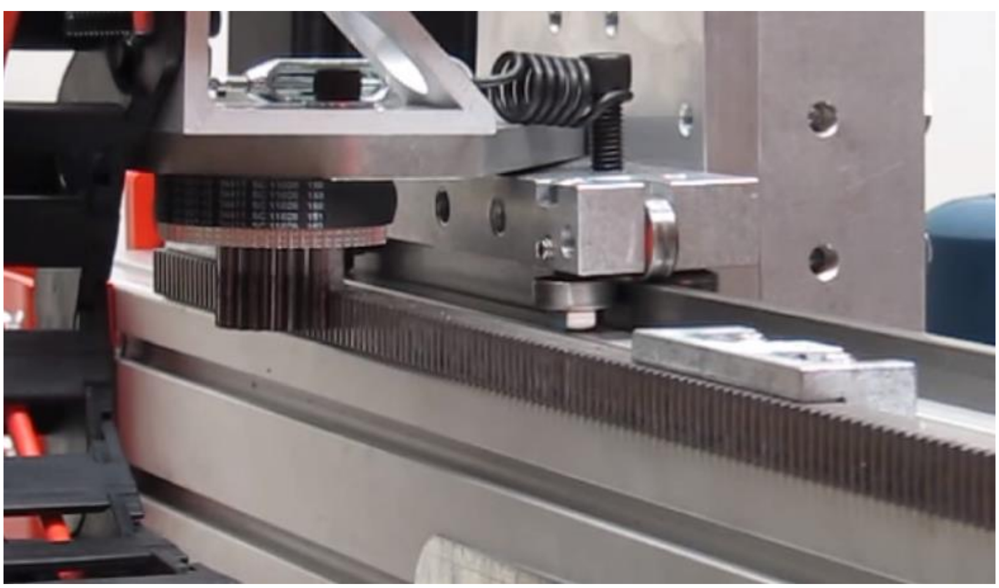


Figure 9:Stationary rack and belt driven pinion assembly [13]

3.3.2.3 Existing Design #3: Lead Screw/ Ball Screws

Lead screws and ball screws use a spirally machined shaft to drive parts back and forth. A typical lead/ball screw assembly will consist of two fixed bearings, screw shaft, and a drive housing. The fixed bearings will support the assembly on either end so that the shaft can freely rotate without translating. The screw shaft can be driven at one end by either attaching a belt, pulley, or directly by a drive motor. The drive housing is where the lead screw and balls screw assemblies differ. Lead screw drive housings have a matching thread pattern to the screw shaft. This enables the drive housing to translate when the screw shaft rotates. The ball screw drive housing contains a system of recirculating balls that move around within the drive housing when the screw shaft is turned, reducing the friction when compared to the lead screw system. Advantage to the lead/ball screw systems is that they can be very precise, accurate, and handle heavy loads. Disadvantages are that they can be expensive when compared to other drive systems and the ball screws can be driven backwards without a braking system [14]. A recirculating ball drive assembly is shown on a screw shaft in Figure 10.

Figure 10: Recirculating ball drive assembly with screw shaft [15]

3.3.3 *Bearings and Guides*

Bearings and guides are important to the efficiency and accuracy of the CNC system. Just as the drive system previously discussed, the bearings and guides have a large impact on the accuracy and repeatability of movement. A poorly designed bearing and guide system will result in twisting of assemblies or unwanted lateral translation.

3.3.3.1 V Wheels and V Guides

The first bearing and guide system that will be looked at is the v wheel and v track systems. V track is similar in concept to how sliding doors work. There is a track the keeps a wheel restrained within the track, usually by the shape and pressure applied to the wheel. Multiple wheels can be used on the top and bottom in v track type systems to “cage” the assembly so that it will not lift off the track when a force is applied. V wheel and track systems are usually the less expensive when compared to other bearing and guide systems, and when properly designed can provide suitable stability in low weight, low torque applications. Figure 11 shows a “caged” v track system on a CNC machine.

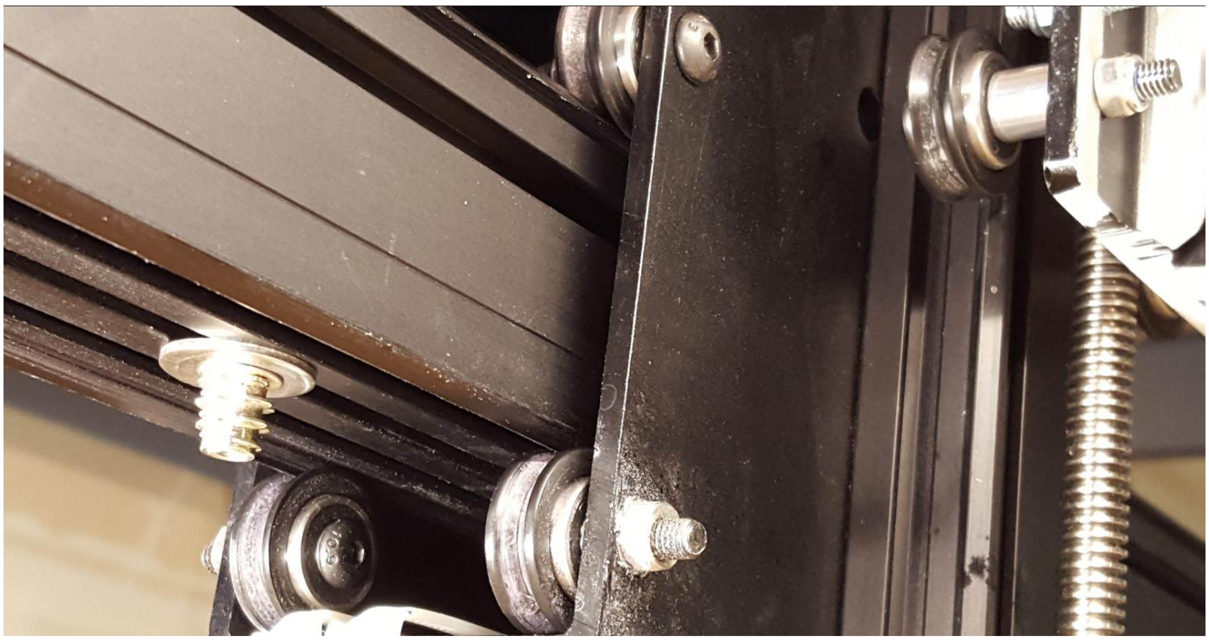


Figure 11: V track wheel system [16]

3.3.3.2 Linear Shafts and Bearings

Linear shafts are the next evolution of stability commonly found in CNC machines. These consist of either fully supported rails or rails with supports on either end. Depending on the type of rail there can be some different bearing options as well. The fully supported rail uses an open bearing design so that it can slide down the rail. The open rail with supports on either end uses a close bearing design. These systems can usually provide less friction and more accuracy than the v track systems. However, they do cost more than the v track systems making them less desirable for some hobbyist level CNC machines. Figure 12 illustrates the open and closed linear rail systems.

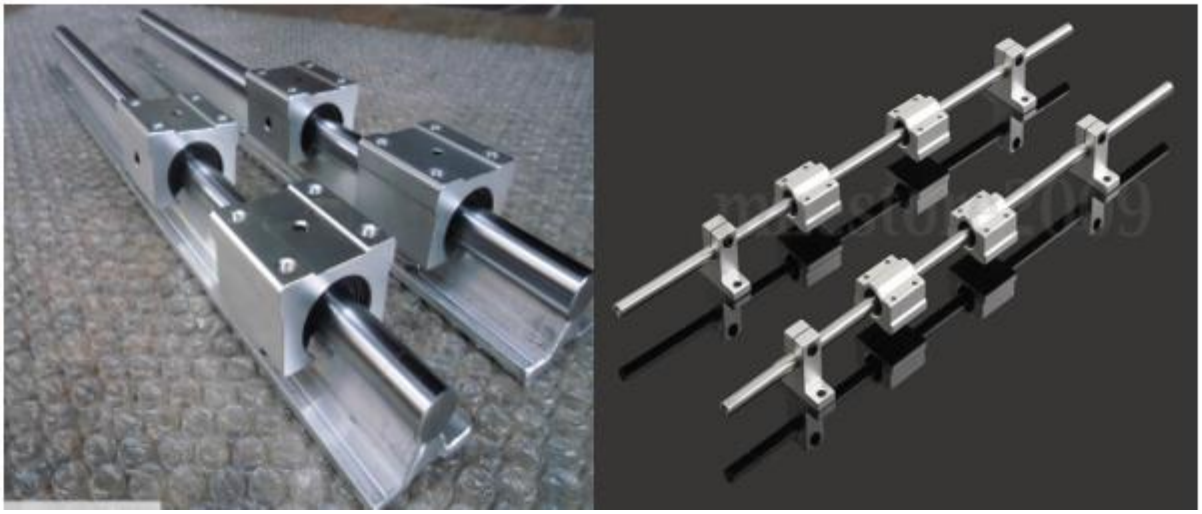


Figure 12: Linear rail systems with open bearings on the left and closed bearing on the right [17] [18]

3.3.3.3 Linear Motion Guides

Linear motion guides offer the best performance available for CNC machines currently. Linear motion guides are capable of having loads in any direction without deflection. The guide bearing works on a recirculating bearing designs that resist motion other than in the direction of the track. These bearing systems offer more rigidity and accuracy than the linear rails and the v track systems discussed in previous sections. However, they are typically twice the price of similarly sized linear rails. A typical linear guide is shown in figure 13. Linear guides are offered in two general types. The recirculating ball bearing type and the recirculating roller bearing. The biggest difference in the bearing types is that the roller bearing resist motion in unintended direction better than the ball bearing design, meaning they can be used in any orientation [19].

Figure 13: Linear motion guides with round bearings (left) and roller bearings (right) [19]

3.4 *Functional Decomposition*

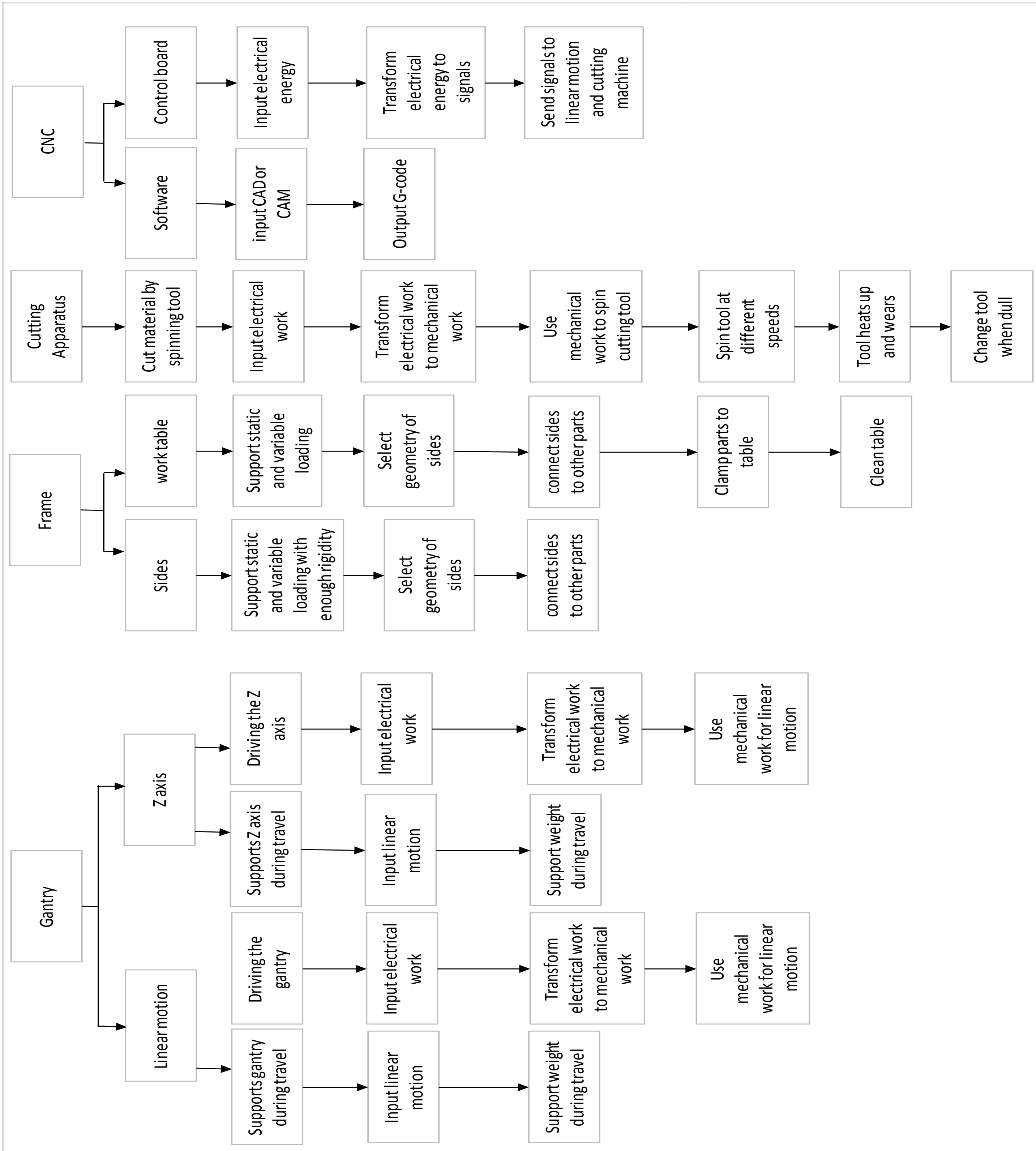


Figure 14: Functional Decomposition

4 DESIGNS CONSIDERED

A combination of techniques was used to generate design options for the CNC Router build. Some of these techniques were researching current models available when performing the benchmarking. Other techniques were brainstorming sessions with the design team. These brainstorming sessions included typical features that were noticed on other machines, bio inspired, as well as Morph matrix design creations. Over twenty-five different design concepts and features were discussed. The following are the top ten ideas based on feasibility and uniqueness.

4.1 *Design #1: High Sided Precision CNC*

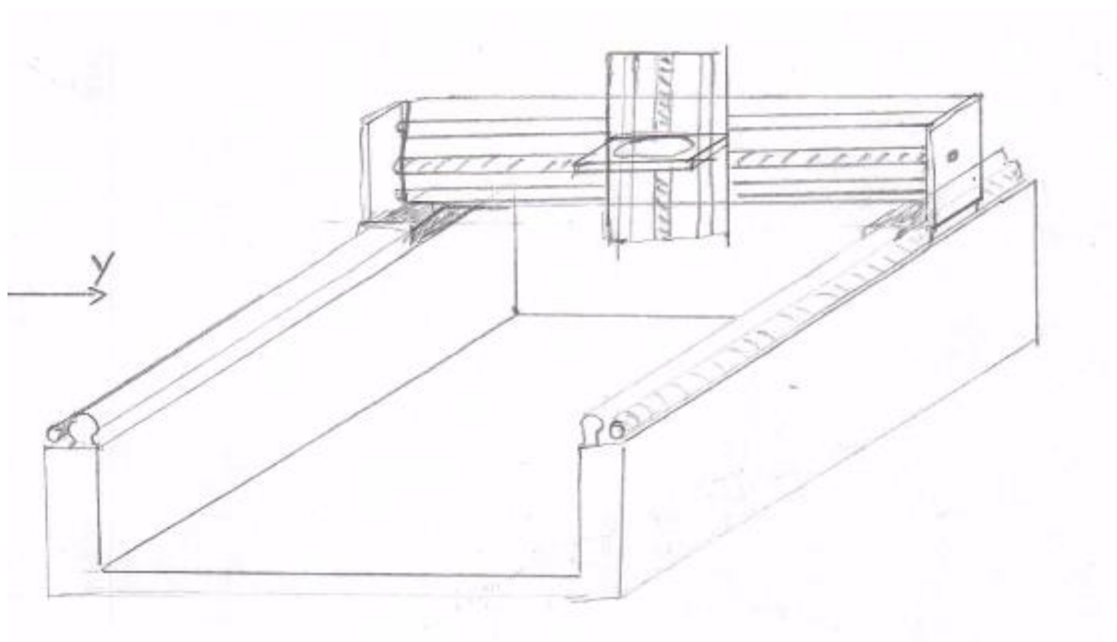


Figure 15: High Sided CNC

Table 9: Specifications for High Sided CNC

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving Gantry	2.25 hp Porter Cable	T-7 supported ball screws	Supported linear Rail and Open Bearings

The first design considered is the High Sided Precision CNC. This design is unique because it has a moving gantry without the typical tall support sides. The high walls of the assembly reduce the deflection that could occur with the typical tall sided gantry. The subsystem features are the 2.25 HP variable speed Porter Cable router used for the spindle. This will provide sufficient power for cutting through hard woods and aluminum, while still using typical household outlet power. The router will be moved by T-7 supported ball screws on supported linear rails with open bearings. T7 ball screws offer accuracy of 0.004 in/ft which can provide the client with dependable and repeatable movements. The XY and Z axis will move on supported rails with open bearings. This design was chosen due to the extra rigidity found in a fully supported rail, when compared to partially supported rail. The open bearings offer preload adjustments in two directions to eliminate any unwanted movement. However, the open bearings will be more susceptible to contamination getting into the bearings without an outer seal to protect the bearings. This may reduce the overall life of the bearings.

4.2 *Design #2: Polar Coordinate Mill*

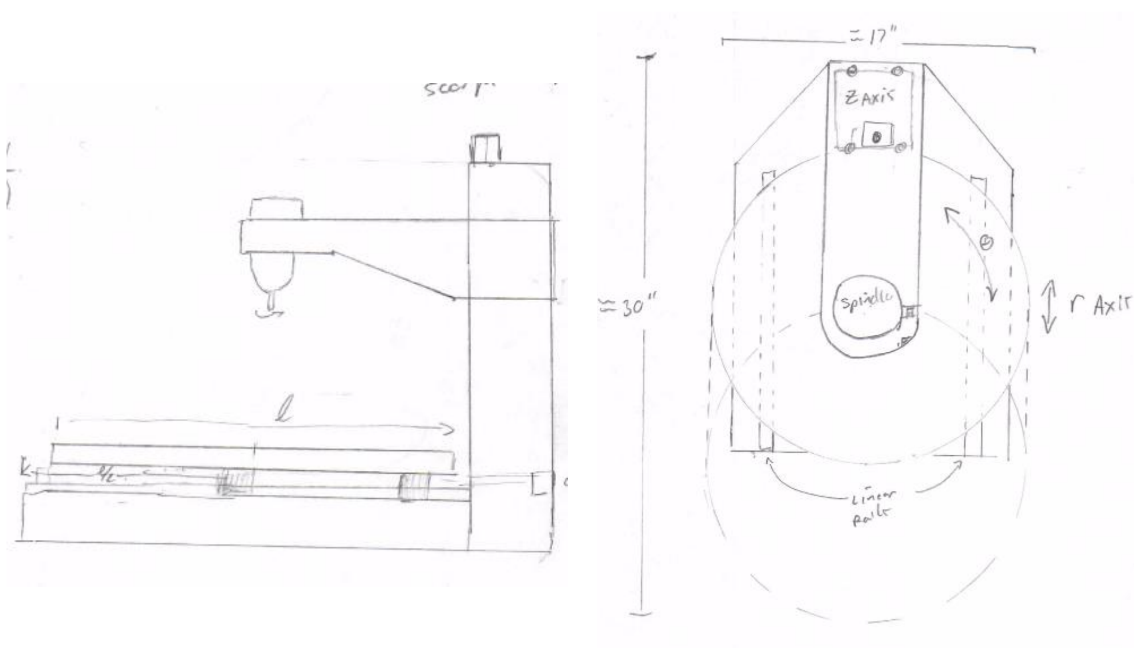


Figure 16: Polar Coordinate Mill side and top view.

Table 10: Polar Coordinate CNC

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Fixed Spindle Rotating/Sliding Bed	2.25 HP Makita Router	T-7 supported ball screws with Ring and Pinion	Linear Motion Guides and Thrust Bearing

The Polar Coordinate Mill came from a bio-inspired brainstorming session. The main design features are the fixed spindle overhanging the workpiece, which resembles a scorpions' stinger. Another bio-inspired feature is the work piece clamping system, which features multiple sliding clamps that will trap a work piece on six different sides. This is similar to how a spider may trap a fly with the exception of two additional legs to work with.

Some of the major features that make this mill unique are the rotating and sliding work piece table. The table will feature a large thrust bearing that will be fixed to a set of linear motion guides. The linear motion guides offer tighter tolerances when compared to the linear rail systems. Linear motion guides were chosen because of the need to have a low profile, precision bearing assembly that would not flex laterally. A T-7 ball screw will move the work platform in the R axis direction. The Theta movements will be handles by a pinion and ring gear under the thrust bearing. Movements in the Z axis direction will be provided by a ball screw drive and supported by two sets of linear motion guides. Spindle power will be a 2.25 HP Makita router.

Benefits of this system are limited motion of the spindle head, ability to easily shape arcs into a design, and uniqueness. The spindle in this design will only move in the Z axis direction, with a rigid tool holding arm. This will result in reduced flex in the other directions by reducing the amount of moving parts in high center of gravity frame sections. Also by utilizing the Theta direction instead of the Y Axis, arcs will be made with less motor cooperation than with the typical XYZ format.

Drawbacks to this design are the large thrust bearing needed for the work platform, the larger footprint of the machine, and the need to use polar coordinates. The large thrust bearing adds to design cost and/or building complications. The larger footprint of the machine is due to the round work piece holder needing to encapsulate the customers 12" X 12" ideal dimensions. This results in a circular work holder of approximately 17". In addition, the work table will need to move away from the machine at least one radius of the work piece holder, making this machined about twice as long as a typical moving gantry machine with an equivalent working area.

4.3 *Design #3: Box CNC*

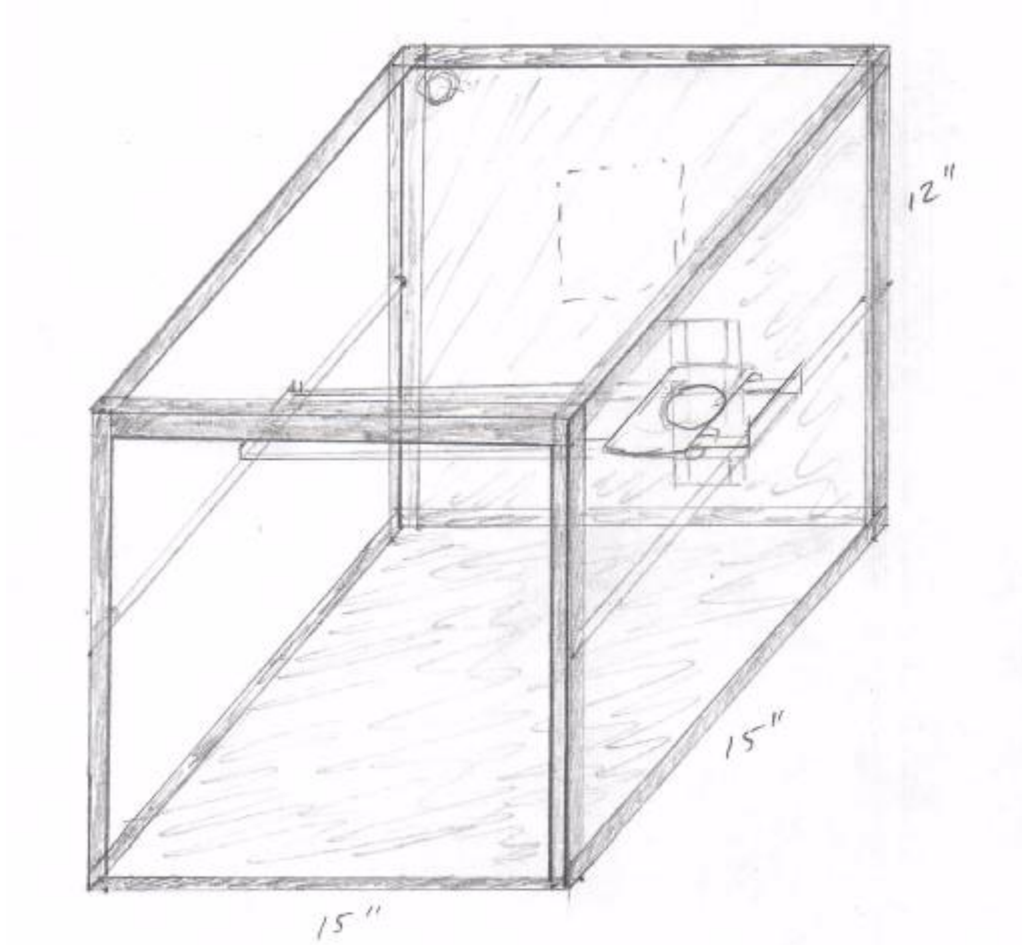


Figure 17: Box CNC

Table 11: Box CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Exoskeleton Frame CNC	1.25 hp Dewalt Router	T-7 supported ball screws	Simply Supported Linear Rails and Full Bearings

The BoXZY machine that was used for benchmarking existing designs inspired the Box CNC. The major difference in the Box CNC is that the gantry will also move in the Z-axis direction, rather than the work platform moving on the BoXZY.

Unique features of the Box CNC are the aluminum exoskeleton and full enclosure for safety. Other features are end supported linear rails with full bearings. These rails and bearings were selected due to the lack of center support offered by the exoskeleton. These rails will be tied into the frame rails and be of a larger diameter to prevent flexing under load. The full bearings have seals that will prevent debris from entering the bearing assembly. This will lead to longer life when compared to open style bearings. The spindle for this design is the 1.25HP Dewalt router. Power was kept around the 1 HP level to reduce the force placed on the end supported rails, in an effort to prevent unwanted deflection.

Benefits of the Box CNC are that in is fully enclosed in a platform that will be easier to handle than other CNC designs. This design will provide the safest working environment due to its full enclosure. This will also provide sufficient power to shape a variety of materials including aluminum. This will also offer an all in one platform, meaning all electronics and wiring are contained within or attached to the assembly.

4.4 *Design #4: V-Rail CNC*

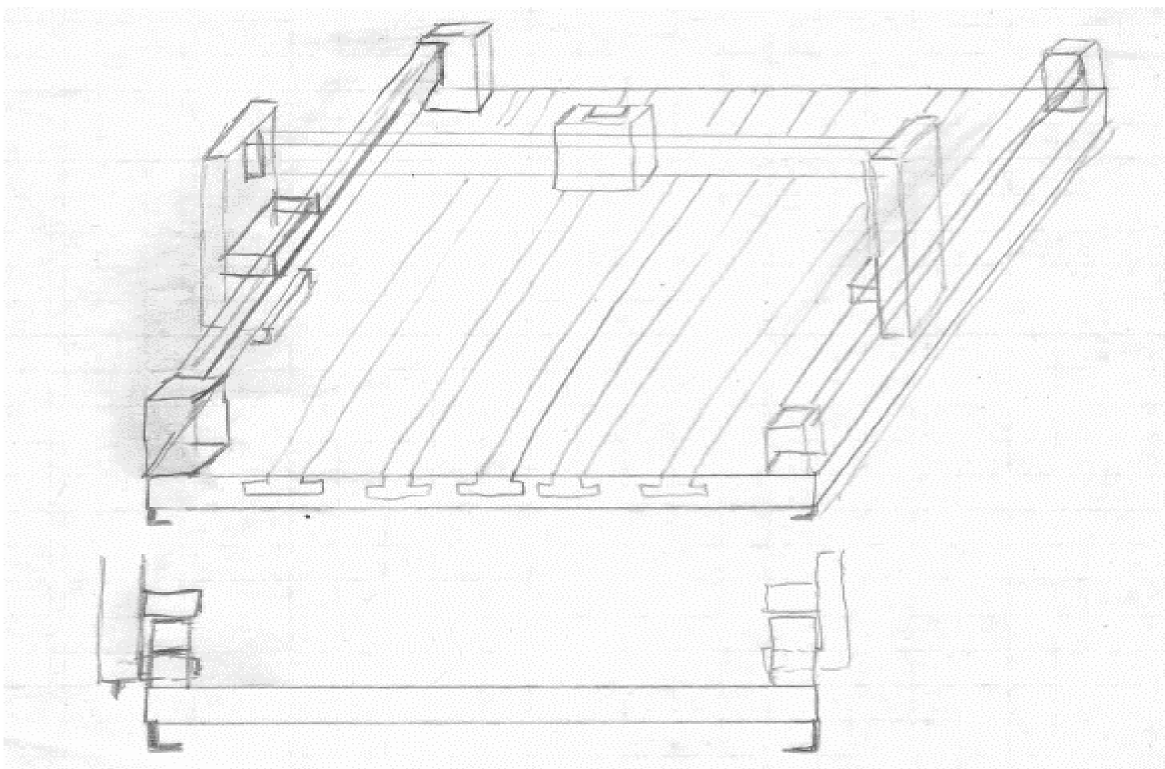


Figure 18:V-Rail CNC

Table 12: V-Rail CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving gantry with hand dolly attachment	1.5kW Water cooled with inverter (VFD)	Belt Drive (XY), Lead Screw (Z)	V Wheels and V Guides

A Shapeoko machine with belt drive and V guides inspired this design. The purpose of the design is to provide a simple and low cost solution while still assessing the customer requirements. The belt drives together with the V guides decrease the cost while it allows for a fast operating machine. The Z axis travel use a lead screw. The machine also includes a hand dolly attachment, which is indicated by the L shapes underneath the table. The hand dolly must be customized for this exact application. Another feature of this machine is that the table (made from aluminum) provides a clamping solution (T-slot). The spindle is a 1.5 kW water-cooled spindle with a VFD inverter.

One drawback of this machine is that the accuracy will go down because of the belt drive and the V guides. The hand dolly also needs to be customized to fit the frame, which will be harder to manufacture.

4.5 *Design # 5: 3030-CNC*

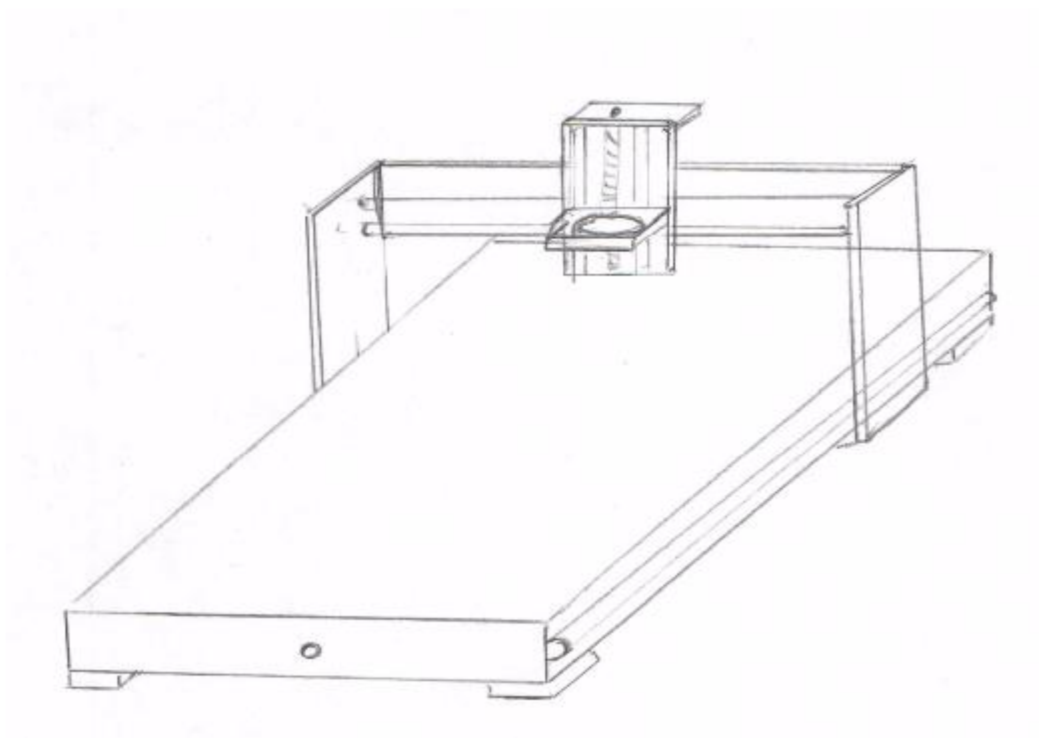


Figure 19: 3030-CNC

Table 13: 3030-CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving Gantry with Undercarriage	1.5kW Water Cooled Spindle with VFD	T-7 Ball Screws (XY) and Lead Screw (Z axis)	Supported Linear rails with open bearings

The 3040 and 6040 style CNC machines that are on the market today inspired the 3030 CNC. The 3030 CNC machine differs in the quality of motion screws used and in the power of the spindle used. The 3030 CNC will provide good quality parts on a moving gantry style machine.

A unique feature on the 3030 CNC is the 1.5 KW water-cooled spindle with variable frequency drive (VFD). This will enable the machine to operate for extended periods of time without overheating concern. A spindle also offers more support bearings and lower run out when compared to routers. This spindle is also able to operate on a typical household outlet.
Other features of the 3030 CNC are the lead screw on the Z-axis. While ball screws have reduced moving friction when compared to lead screws, this can lead to the screws "walking" when mounted in the vertical position. This is not usually too much of an issue when using stepper motors, because the stepper motors will usually have enough holding torque to prevent walking of the ball screw. However, this will aid in preventing any possible position issues of the Z axis.

4.6 *Design #6: Vertical Work Platform*

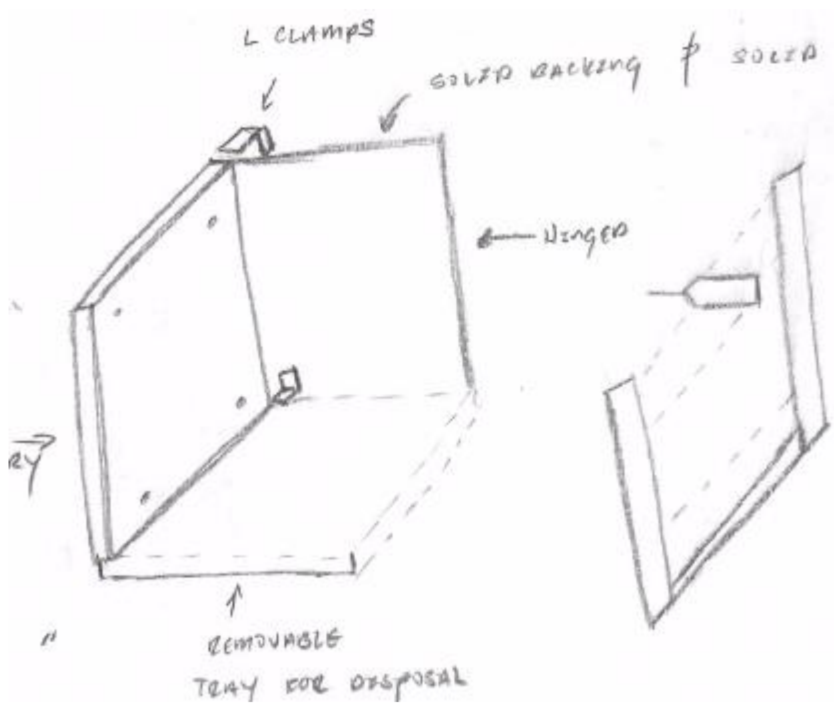


Figure 20. Vertical Work Platform

Table 14: Vertical Work Platform specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Vertical CNC Enclosable box	DeWalt 1.25hp DWP611	Ball screws (X,Y,Z)	Linear rails and closed bearings

Lathes inspired this design. Because lathes cut horizontally it provides a benefit where the cut debris falls away from the tooling head eliminating the need for an attached blower or cleaning apparatus. Only the front face of this machine would be covered by Plexiglas to ensure product view ability and safety from flying debris. The workbench surface would be made of steel and accompanied by L-clamps to secure different work pieces while allowing for maximum surface milling. Ball screws are used for the x and y axes to allow for higher precision and they can handle the stress of higher loads that this particular orientation would provide.

The largest problem with this design is that it would be very difficult to utilize a 3D print head on a vertical work platform. Another problem with this design is that the weight of the machine would be heavily distributed on the side that holds the spindle and a counterweight may be needed to keep the machine steady while in motion.

4.7 *Design # 7: Belt Drive CNC*

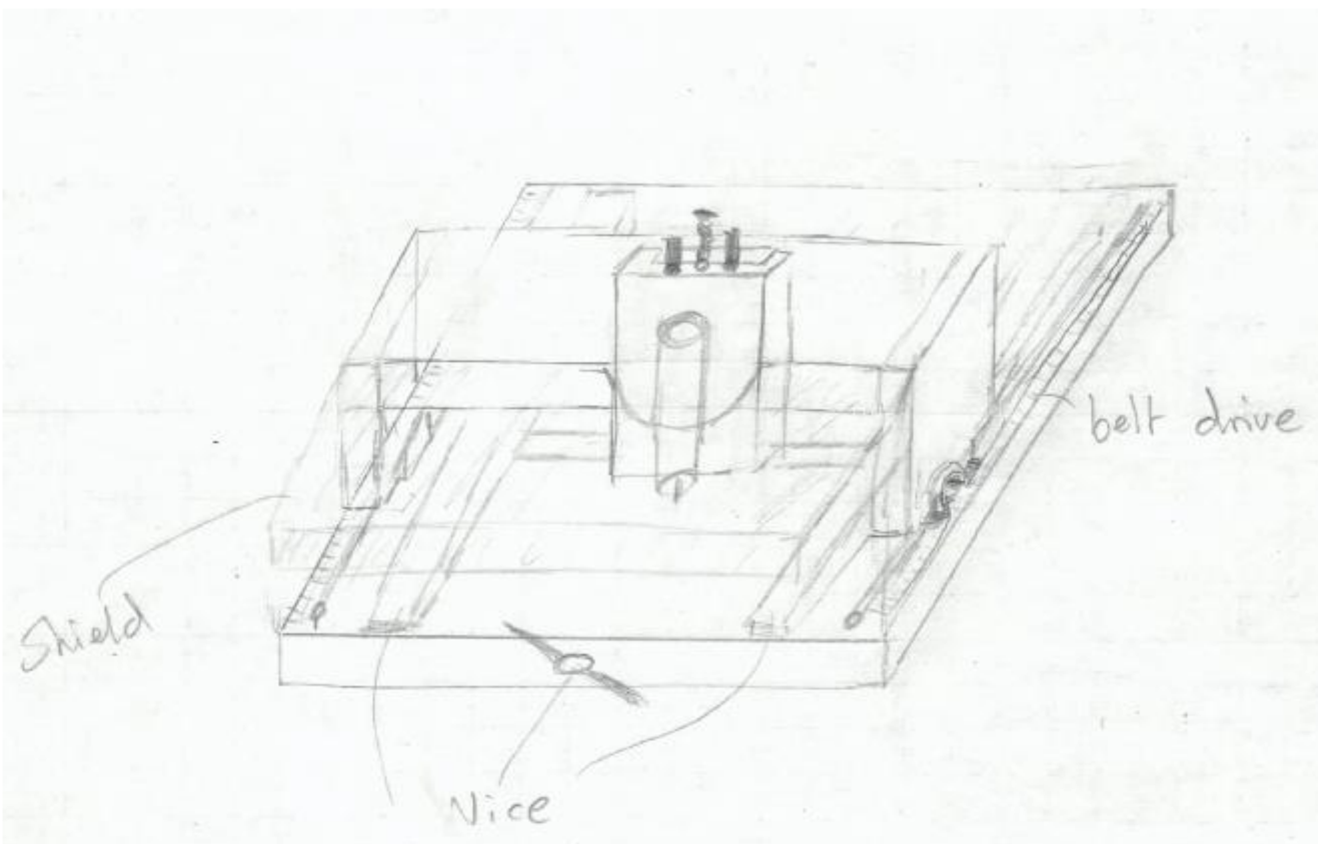


Figure 21: Belt Drive CNC.

Table 15: Belt Drive CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving gantry with partial shielding and built in vice	1.5kW Water cooled with inverter (VFD)	Belt drive (XY), Leadscrew (Z)	Supported linear rails with closed bearings

Design 7 is a standard desktop CNC model, which includes specific features for safety and clamping of the workpiece. The machine includes a hinged partial shield that is meant to redirect the debris away from exposed body parts (the face) during a catastrophic failure. The machine also has a built in vice, which allows for precise and ridged clamping of workpieces. The belt drive allows for fast travel and the supported linear rails allows for an accurate movement.

One problem with this design is that the belt drive limits precision. The belt can extend after multiple usage, which cause precision problems. Another problem is that the partial shielding does not cover the entire machine so it allows for some risks. The vice is also problematic, because it can only clamp in one dimension, if it is required to clamp it in any other dimensions the vice will be insufficient.

4.8 *Design # 8: Moving Table Fixed Gantry*

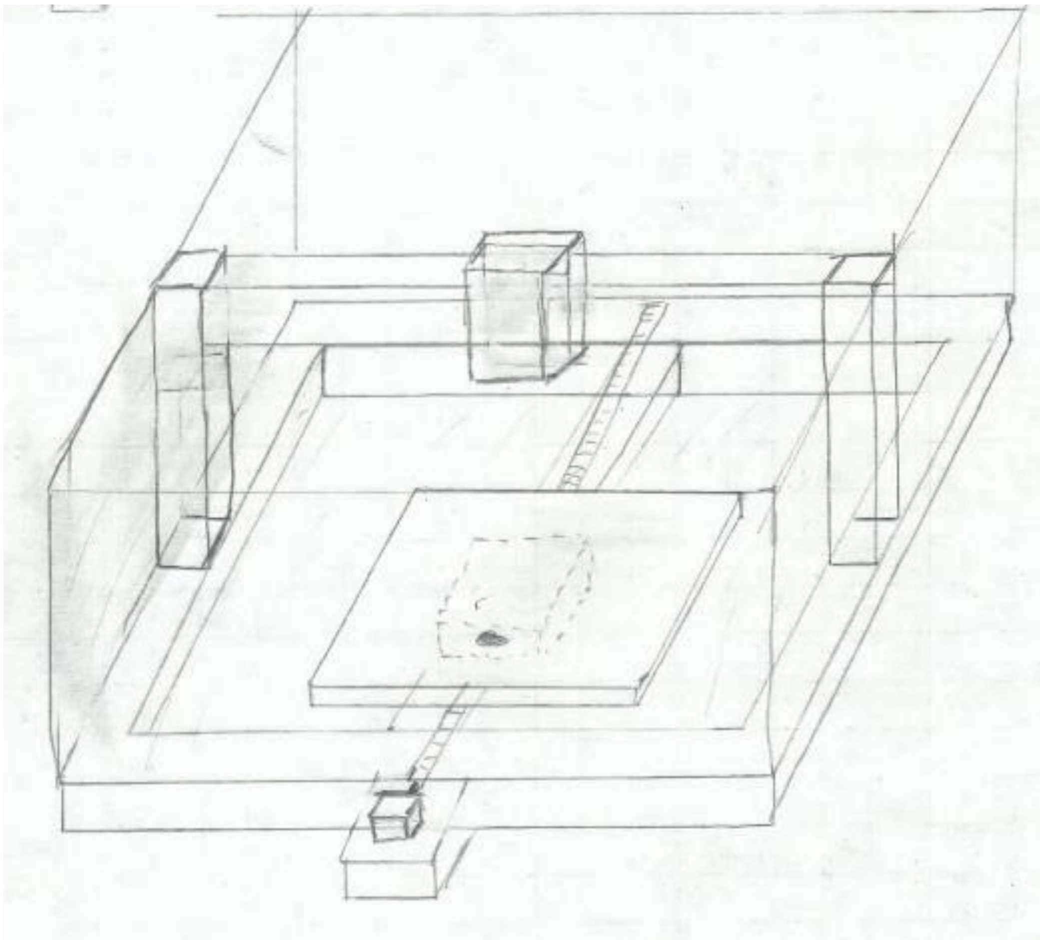


Figure 22: Moving Table Fixed Gantry

Table 16: Moving Table Fixed Gantry specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving table	2.2kW water cooled spindle	Ball screw (XY), Leadscrew (Z)	Supported linear rails with closed bearings

The moving table design was inspired from multiple different designs found online. The main purpose of this design is to make the machine more rigid. The moving table decreases the level of complexity because the table moves independently form the gantry. The table moves in one dimension and the gantry holds and moves the spindle in two dimensions. This design uses ball screws for X and Y travel and a lead screw for the Z travel. The ball screws add precision and can move the table and the workpiece without problem. Supported linear rails guide both the table as well as the spindle assembly.

This design comes with a few other benefits. Because of the added rigidity this design has no problem using a larger more powerful spindle, which is why a 2.2kW spindle was selected. Also the entire machine is fully enclosed in Plexiglas, which makes it safe from eventual debris. The design of the frame also allows for easy cleaning which could increase the lifespan of the machine.

The most critical drawback with having a moving table is that it needs to be larger than a machine using a moving gantry given that the cutting surface is the same size. The moving table needs to move further in order for the spindle to reach the entire cutting surface. Another drawback comes with the fully enclosed shielding. The shield needs to cover the entire table, which is already large because of the moving table. The shielding adds even more size to machine, which might limit where the table can be used.

4.9 *Design #9: Easy Roll CNC*

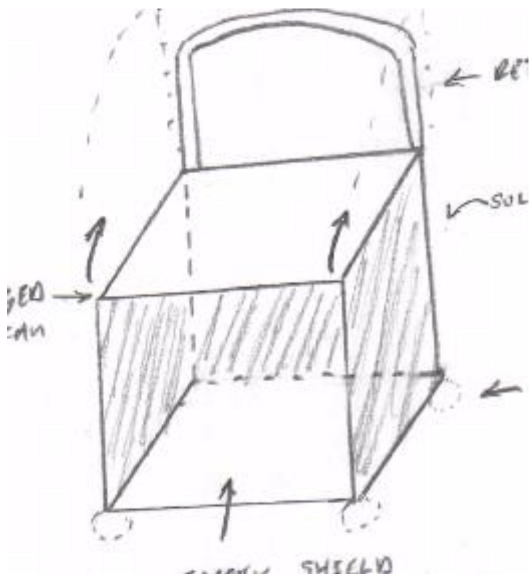


Figure 23: Easy Roll CNC.

Table 17: Easy Roll CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Partially shielded rollable box	1.25 Makita compact Router	Thompson 48" precision ball screw x,y,z	Fully supported linear rails and closed bearings

This design was inspired by a rolling luggage with the telescopic handle. Instead of being a soft carrying case, the sides, the back and the bottom would be made out of high density polyethylene (HDPE), the front and top of the machine would be made of Plexiglas for protection and view ability when the machine is in use. The front and top are capable of swinging open and folding out of the way so that the spindle head can be accessed and changed. The wheels would be either locking castor wheels or removable rubber wheels seen on hand trucks. When the machine is enclosed and the handle is withdrawn, the machine can be tilted back and rolled away, making this model highly portable. When the handle is retracted it would sit flush with the top of the machine.

The interior of the machine works similarly to any typical CNC one would find where the gantry is fixed and the spindle head moves in the x, y, and z coordinates. Fixed and fully supported linear rails would line the left and right sides of the machine and the spindle would be suspended between the two rails. Ball screws are used for the spindle to travel in the y and z axes and would allow for low friction which will require less motor power, and will eliminate backlash commonly seen in rack and pinion linear motion.

The Makita compact router can be plugged directly into a wall outlet and also comes with an optional vacuum attachment, which assists in keeping the workpiece and machine free of debris. It is possible to use this router with aluminum and wood so long as the correct tooling bit and appropriate speed is chosen.

4.10 *Design #10: Rack and Pinion Drive CNC*

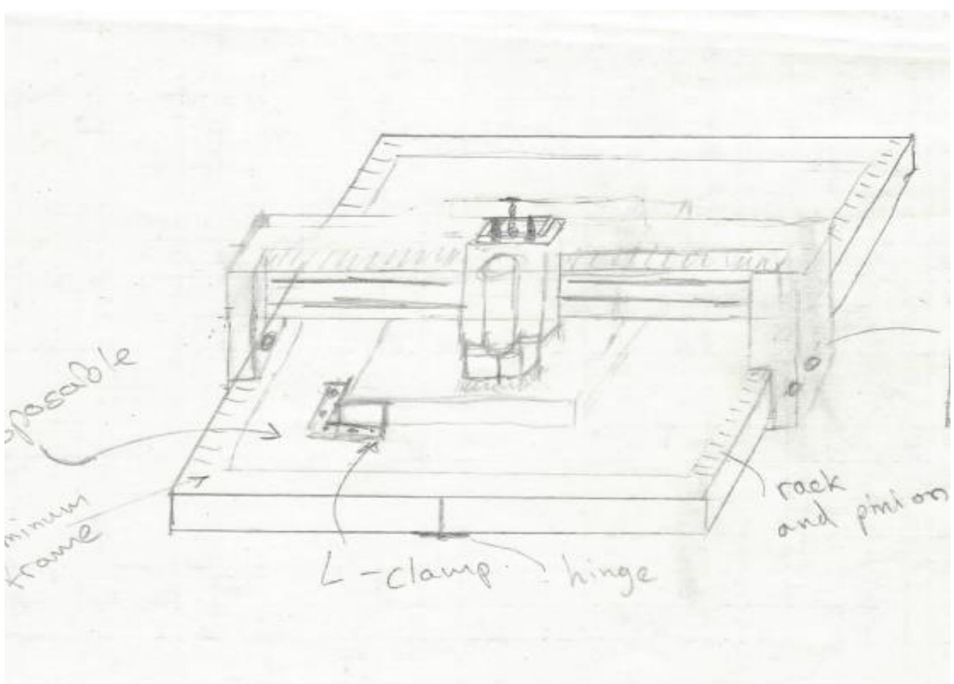


Figure 24: Rack and Pinion CNC.

Table 18: Rack and Pinion CNC specifications

Machine Style	Spindle Type	Linear Motion	Linear Motion Guides
Moving gantry with detachable parts	1.5kW Water cooled with inverter (VFD)	Rack and pinon (XY), Lead screw (Z)	V Wheels and V Guides

Design 10 is a portable design. The purpose is that the gantry can be removed from the table to allow for easy portability. The machine can be disassembled into two parts (gantry and table), which makes it easier to travel over further distances than a standard CNC machine. The table is made of an aluminum frame, which holds the gantry and houses a disposable table. The disposable table can be removed from the frame that can be folded in half. Another benefit of the disposable table is that it can be used to clamp workpieces directly to the table. The design uses a rack and pinion style linear motion because it is unlikely that it will shift during transportation. The V guides were chosen for the same reason. The guides make it easier for transportation, and they are not sensitive to transportation. The design uses a brush shield around the tool head to add safety. A 1.5kW spindle is used.

This design comes with multiple problems. First, because it uses both rack and pinion and V guides, the accuracy decreases. Secondly, the foldable table frame makes it less rigid which also affect the accuracy of cutting process. Thirdly the disposable table needs to fit tightly in the table frame, which might be difficult to achieve in practice. Lastly, even if rack and pinion and V guides are less sensitive to shifting than ball screws and linear guide rails, they still need to be properly aligned. They make it easier to transport the machine, but without careful transportation the frame and gantry might be damage, which will make the machine inoperable.

5 DESIGN SELECTED

5.1 *Rationale for Design Selection*

The selected design solution is the first design described in section 4.1 in this report. The design is called the High Sided Precision CNC. While this design was not the most innovative option that the team had to choose it because of how it scored in both the decision matrix and Pugh charts. This design fulfills all of the customer needs and excelled in the tolerance and cutting ability categories in the decision matrix. Scoring well in the tolerance category was due to several reasons. These reasons include taller side frame sections, shorter gantry sides, and fully supported rails. These three design features will reduce deflection by decreasing the lever arm of the gantry and provide less lateral movement. Which in turn will reduce the deflection seen at the tool head. The cutting ability category scored well due to the 2.25 HP variable speed router used with this design. Having variable speeds combined with the 2.25 HP motor will provide this design with more flexibility when cutting different materials. For the teams Pugh chart this design scored better than average in the manufacturability category. This category had a relatively high weight associated with it due to the lack of manufacturing experience that the team has. The manufacturability is thought to be easier due to the simple base platform assembly design. Safety is a category that can easily be improved in by incorporating some shielding components into the design.

The cons of the high-sided CNC design are in the cleaning and innovation categories. The cleaning aspect of this machine was decided to be more difficult due to the larger sidewalls of the machine. Brushing debris off of the workpiece may prove to be more difficult having only front and back access. Innovation was another category that this design did not score well in. This was mostly due to the variety of creative solutions that the team generated. However, the High Sided Precision CNC will meet all of the customer needs, and with some minor design modifications will improve on some of the current design shortcomings.

5.2 *Design Description*

The following section analyzes each component that is needed for the design. The design consists of:

- A frame that connects the cutting assembly to the worktable.
- Motors that move the gantry.
- Bearings and rails that the gantry travels upon.
- Router/Spindle for cutting workpieces.
- Open source software to generate G-code.
- A Controller Board, which reads data from the open source software.

The final design can be seen in Figure 25.

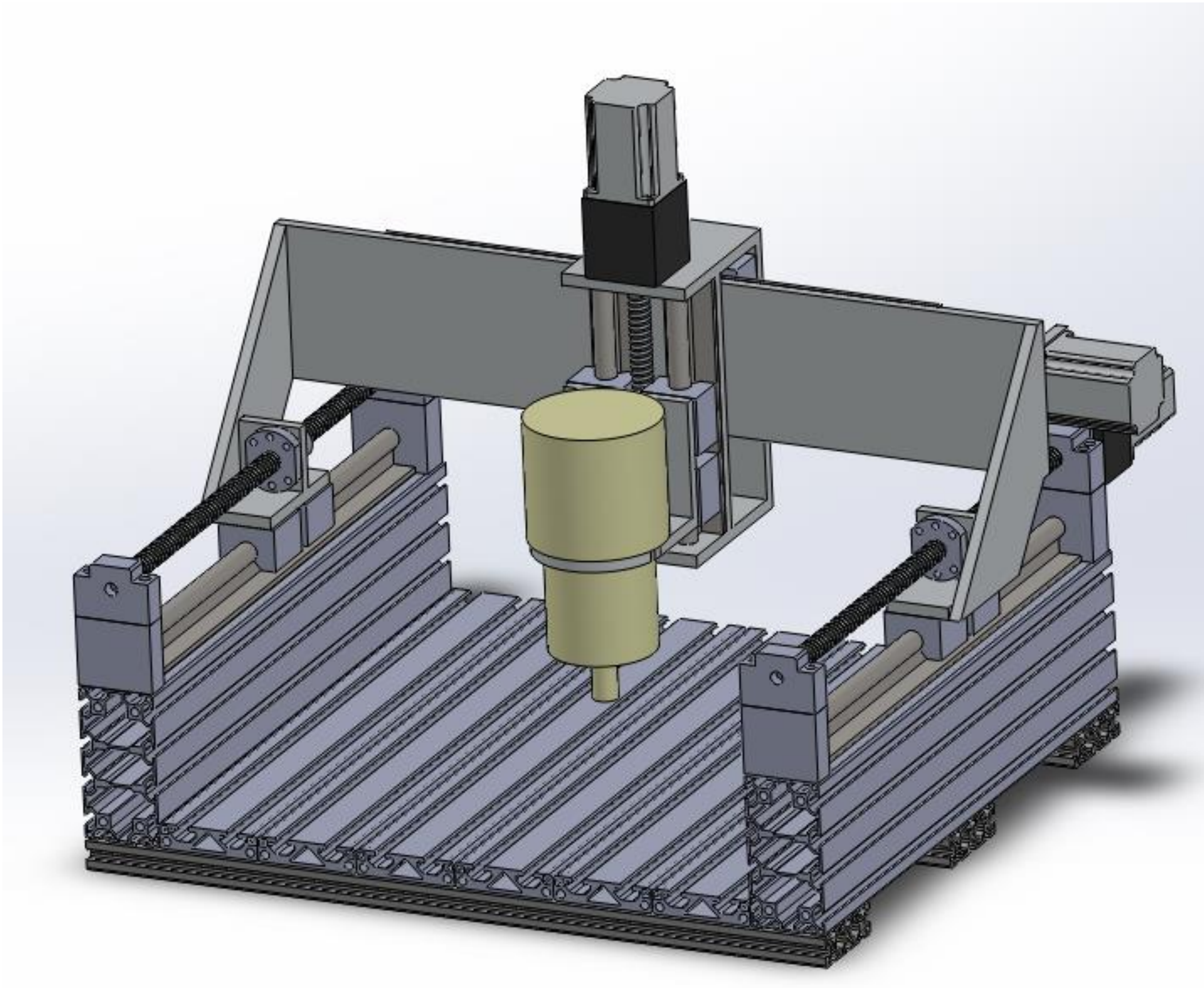


Figure 25: Solidworks sketch of proposed CNC router design

Following are pictures of the prototypes to visualize the size of the final product and to test open source software with g-code to drive stepper motors.

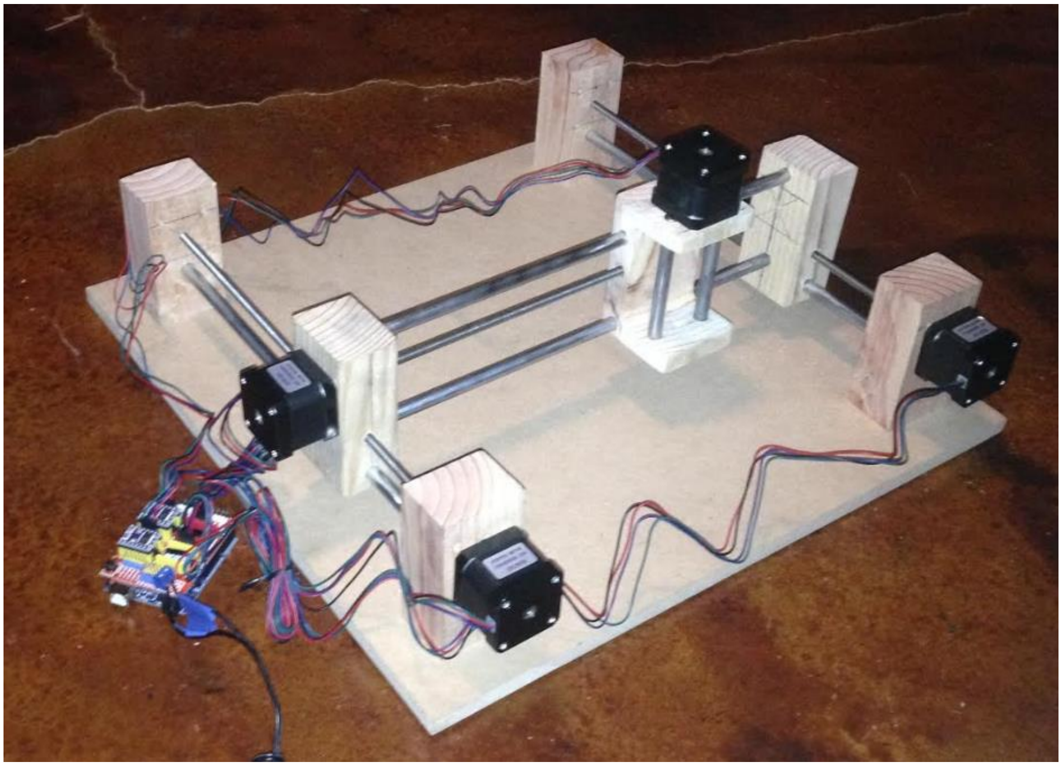


Figure 26: Prototype to test open source software GRBL

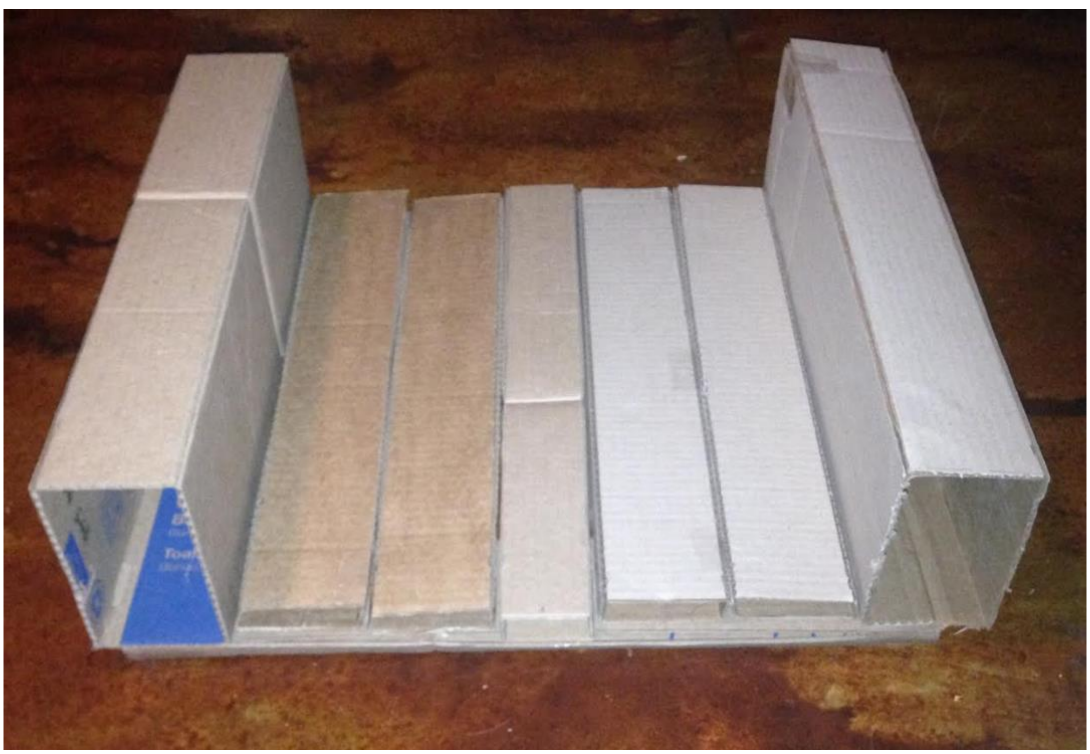


Figure 27: Prototype to model the footprint of the actual CNC Router

5.2.1 *Frame Deflection Analysis*

The deflection of the frame is calculated for basic geometries of the gantry and the sides of the frame. When building the CNC machine it is important that the frame is rigid enough to not allow deflection that will impair the cutting performance. The deflection of the frame is dependent on the cutting force and the frame material and frame geometry. Cutting forces can be adjusted to decrease the frame deflection with the cutback that it will take longer for the machine to perform its tasks (Depth of cut and feed rate will be lower, hence operation time goes up). From the analysis it can be seen that aluminum is going to provide sufficient rigidity at low cutting forces. The purpose of the analysis is to estimate how the frame is going to deflect during operation and that this deflection is much smaller than the wanted cutting tolerance of 0.0254mm (0.001in). The geometries considered are a solid rectangular beam, a rectangular tube, an aluminum extrusion, an I-beam, and a C beam (geometries can be seen Table 22 & Table 23). For all geometries, (except the aluminum extrusion) both steel and aluminum are considered. Figure 30 shows a basic representation of the CNC machine.

Equation 7 is used to find the moment of inertia which is later used to calculate deflection. The polar moment of inertia (Equation 8) is later used to find the angle of twist of the gantry when it is subjected to a torque. [20].

Both the gantry and the frame sides experience some deflection when a force is applied to the cutting tool during operation. In both cases simple enough geometries was used in order to conduct a beam deflection analysis. The gantry was assumed to experience a load in both Z and X (Figure 30) while the frame sides were only assumed to experience a load in the Y (negligible deflection in X was assumed). The gantry was modeled as simply supported and the frame sides were modeled as fixed supported. The equation for a simply supported by is Equation 1. This Equation was used to find the deflection in mm which can be seen in Table 19.

Equations Equation 1Equation 2Equation 3Equation 4Equation 7 andEquation 8 were used to calculate frame deflection and the results can be seen in Table 23: Deflection of the frame sides subjected to a 25N load with all geometries close to the dimension 500x80x160mm.

The aluminum extrusion is the most interesting geometry to consider because of its manufacturability and low weight compared to steel. The two that are the most interesting to compare is the rectangular steel tube against the aluminum extrusion. The rectangular steel tube is outperforming the aluminum extrusion in the deflection analysis. However, it is going to be much harder to manufacture and it is going to be heavier. When comparing the two different products it can be seen that the steel is between 1.76 to 2.45 times heavier and have a difference in price between 0.66 and 1.15 times that of the aluminum extrusion [21] [22]. The deflection of the aluminum extrusion looks sufficient in Y and Z (0.0013mm and 0.0024mm) with 19.5 and 10.6 times smaller than the tolerance goal of a finished part. However, the X deflection (0.0074mm) of 3.4 times smaller than the wanted tolerance seems too close. This analysis is only looking at the frame deflection, and is not considering other sources of deflection like bearings and connections between different parts of the machine (i.e. the spindle attachment connected to the gantry). The team needs to look closely at the deflection in the X direction and it will be necessary to connect all components carefully in order to limit any further deflection.

This analysis is not going to be a perfect model of the real gantry and frame side deflection. The results from this report are meant to highlight areas where the deflection might be critical so the team can address these locations and/or make more accurate models if necessary. By using a simple approach like a beam deflection analysis the team understands more in depth of how the CNC machine will behave during operation. The X axis is going to be the most critical axis to reinforce if using aluminum extrusions as the frame material.

5.2.2 Stepper Motor Analysis

An important component of the machine building process is to select the appropriate drive motors for the system. An appropriate drive motor will be able to satisfy the desired rates of motion under the extremes of the machine design. In addition, there should be a factor of safety built into these specifications that will allow for unforeseen loads being put on the system. For this design analysis, stepper motor sizing will be investigated. Stepper motor sizing will look at several different components to ensure that the motor torque will be sufficient for the application. Driving motors for the CNC will need to move the gantry and spindle at the certain speed in order to meet feed and speed requirements. In addition, the driving motors will also need to accelerate the assembly to this desired speed in an efficient manner. Because of this, two categories will be analyzed to help select the proper motor size. The first category will be forces that can be analyzed statically. The second category will be the inertia associated with all of these moving parts and the acceleration needed to overcome these forces. Finally, the total torque requirements of these categories will be to combined to provide an estimated torque rating for the stepper motors.

Torque of the driving motors can be generated by using the Equation 5 calculates the amount of torque for a given force load and efficiency of screw drive assembly [23].

Typical efficiencies for screw drives [24] [25]:
Ball screws ~90-95%
Lead screws ~30-50%
Trapezoidal lead screws ~20-40%

In order to use Equation 5 it will be important to find the force that will need to be overcome by the motors. This will be the frictional forces associated with the slide assemblies, mass of the gantry, and the cutting force produced by the router in hardest material that it will be designed to cut. The first force to overcome will be the mass of load combined with the frictional coefficient of the slide assemblies. This will use a basic force calculation for friction as shown in Equation 6.

Typical efficiencies of slide types [26] [27]:
Ball slides 0.003-.04
Teflon on steel (non-lubricated) ~0.05-0.2
Bronze on steel (lubricated) ~0.16

The final component for the initial torque calculation is the cutting force that the router will experience. For smaller CNC router tables the estimated torque loads will be approximately 5N for wood and 20N for aluminum [28]. At this point a torque would be able to be calculated using Equation 5. However, this would not include the desired acceleration of the components. This requires factoring in the inertia of the screw drives and gantry assembly.

Next an analysis must be done for the inertial components of the CNC table. The first component to be looked at will be the screw drive. For this the mass and radius must be known so that the inertia can be calculated. Equation 7shows how the inertia for the screw will be calculated.

The following step is to calculate the inertia of the gantry assembly. This is a product of the mass of the gantry assembly and the pithc of the screw drive Equation 8 shows the relationship.

The final component of inertia is the motor inertia which is provided by the motor manufacturer. The total inertia is shown in Equation 11

Determining the maximum speed under load. For cutting aluminum with 0.25" single flute mills, with cutting rpms between 8000-30000, the ideal max feed speed is between 1000-3500mm/min. This was determined using an online milling speed and feed calculator [29]. A large range was selected so that several different scenarios could be run with the calculations to ensure the speed range would be sufficient. To find the max rpm of the stepper motor for the given motor parameters, Equation 12 was used. Equation 13 was then used to find the rate at which the motor would move the screw at that rpm.

Angular velocity of the screw when then be calculated using Equation 14.

Desired acceleration of the motors was not calculated and a standard value was not readily apparent for CNC mills. Research indicated that this is usually found by "tuning" the motors after the machine is built. Instead, a value for acceleration was used based on claimed average acceleration values for hobby CNC machines. This value for motors running approximately 1000mm/min, an acceleration of 2300 rad/sec^2 was chosen. The torque required to achieve this acceleration value is shown in Equation 15. The total torque from the motors is shown in Equation 16.

After compiling the equations, several different scenarios were run in order to estimate a range of motors that will work for the CNC application. The first step is to estimate the total weight of the gantry assembly. This estimate is based on preliminary design dimensions and materials. The gantry assembly is broken down into the core components as shown in Table 24.

Scenario 1
1. 50kg Gantry
2. Ball slide rails and bearing
3. 16mm ball screws with 5mm lead
4. Cutting aluminum with 20N of cutting force
5. Running at a maximum of 3800 mm/min

This scenario produced an estimated total torque required of 0.327 Nm of torque. Adding a factor of safety of 1.7 to 2 would require a motor of at least 0.55Nm to 0.654 Nm of torque. This data was used to with information on stepperonline.com to find acceptable matches without being excessively large [8]. The range selected was 0.55Nm to 0.7Nm of holding torque. Table 25 shows the results of this search.

Scenario 2
For the next scenario the same weights were used but different screw and linear motion types were chosen.
1. 50 kg gantry weight
2. Bronze on steel bushing slides
3. 8 mm Trapezoidal lead screws with 4 starts and a pitch of 4mm [30]
4. Cutting aluminum with 20N of force
5. Running at 3800mm/min

Scenario 2 generated a required estimated motor torque of 0.594Nm. Using a similar factor of safety range of 1.7-2 a torque range of 1.01Nm – 1.19Nm was selected. Referencing motors within this range from stepperonline.com generated the list shown in Table 26.

The two scenarios presented represent two frictional extremes of the CNC design in question. Scenario 1 utilized all low friction, high quality components. Scenario 2 used higher friction yet still quality components for the build. The required torque values for the second scenario were nearly double that required by the first scenario. Prices for the stepper motors ranged from ~$11-$13.5 for Scenario 1 and $17-$53 for Scenario 2. This particular CNC design will utilize 4 stepper motors for the entire machine. This would give an average difference of ~$22 for motor cost between Scenario 1 and Scenario 2. This will allow cost analysis to be done to see if it is more effective to run larger motors with higher friction components or smaller motors with low friction components.

5.2.3 Feeds and Speeds Analysis

The proposed project is a multi-use CNC Table capable of routing, 3D printing and laser cutting. CNC stands for Computer Numeric Control, and these machines use computers to cut away material to create a part [23], essentially a CNC machine is an automated milling machine. This CNC machine needs to be able to cut through a maximum of three inches of wood or Aluminum. It is unclear if the client wishes to cut through hard woods, soft woods and which grades of Aluminum the table will be subjected to Table 30 and
Table 31 contain a list of various hard/soft woods and common machined Aluminum grades. This analysis will focus on feed rates and speeds for hard/soft woods and machinable grades of Aluminum.

CNC machines can curb the issue of outsourcing manufactured projects to other countries. A CNC machine can create complex parts that cannot be recreated manually by an individual [24]. China does a large portion of manufacturing for the US and this detracts from the jobs that Americans can fill [25]. Thus a CNC machine can keep machining in the US because many different, unique and complex parts can be created using CNC machines.

1. The system is rigid. There is no deflection from the gantry, railings, workpiece or table assembly.
2. Spindle speed is assumed to be between 8krpm and 27krmp. From benchmarking; these speeds are related to spindles that are capable of plugging into a wall outlet, which is a requirement from the client.
3. Conventional face milling where the tool head starts at a depth before cutting into the work piece.
4. Face milling where the tool head starts on the face of the work piece then mills into the material.
5. To minimize calculations for feed rates, the average chip loads are used for the calculations.

The spindle speed that is being targeted is between 8kRPM and 27kRPM. Cutting Speed is also seen as SFM (Surface Feet per Minute) and the tool diameters assumed were common bit diameters of[Equation], [Equation], and [Equation] inches.

Equation 17 can be rearranged to solve for the SFM, which can be seen in Equation 18. There are SFM charts available for various materials, the SFM's for the three materials chosen can be found in Table 32.

The difference between High Speed Steel (HHS) and Carbide end mills depend on rigidity and cost. HHS tools are inexpensive and common but run at slower speeds and have less tool life. Carbide end mills cost more than HHS tools, are more rigid, can run at faster speeds, and are best suited for newer milling machines [26].

Feed rate is the velocity that the tool head moves through the material being cut. Spindle Speed is the rotational velocity of the tool [26]. Chip Load is the material that flies away from the tooling head while the tool is cutting. Chip Load is important since chips carry heat away from the tool head, too low a chip load and the tool head dulls prematurely, too high a chip load and there is potential for tool deflection [27]. Chip loads are different for every material and are measured in inches. There are many charts already calculated for Chip Loads of multiple materials, the chip loads found in Table 32 will be used to calculate the feeds needed for the tools used. Chip Loads used for calculations are the average of the values found in Table 33.

A feed rate can be calculated from Equation 19. Number of teeth is the last variable needed to calculate feeds and speeds. Flutes are the grooves on an end mill or drill bit, and the number of teeth is the same as the number of flutes [https://en.wikipedia.org/wiki/Milling_cutter]. Flute numbers vary from one to multiple flutes. Descriptions of what numbers of flutes are used for what applications can be found in Table 34.

With the previous information a general feed and speed chart can be created for the two materials analyzed. Any speed under or over the 8kRPM and 27kRPM range will not be included because the chosen spindle head will have a range between those RPM's.

.

Depth of cut is important to preserve tools from wearing early and to keep deflection at a minimum. The standard depth of cut approximately 60% of the tool diameter [23]. The depth of cut was calculated by using Equation 20.

The maximum calculated RPM's for Aluminum and Wood with common sized bit/ mill diameters. The numbers are rounded to whole numbers since it is difficult to obtain a percentage of a revolution. Since the RPM's are slower than the RPM range initially given (8k – 27k), a different spindle may have to be chosen to reach these given RPM's. RPM's were checked with Greene Tool System's website calculator [29].

These particular RPM values (Table 35, Table 36) are outside of the RPM range that was specified. A different spindle may need to be purchased in order to use these specific RPM's and consequent feed rates.

Table 37Table 38Table 39 show feed rates for Aluminum, hard/ soft woods for different fluted HHS and Carbide end mills at common tooling diameters.

Feed rates that were calculated to be above 200 inches per minute were neglected for safety and probability of being executed by the CNC design. Also values calculated were seldom slightly above 200 IPM and jumped drastically to larger values. Calculations were checked using Valley Tool Speeds and Feeds Calculator [30].

Table 40 shows a comparison of depth of cuts allowable for tool life and minimal deflection of various tool diameters. For safety and longevity of the tools to be purchased and minimal deflection the values found by using the equation will be used in execution of any cuts.

Feeds will need to be calculated with Equation 19 based upon the RPM range if a slower spindle cannot be found.

For the current analysis HSS tools will be the ideal choice. But if a slower spindle cannot be found carbide tools will be the best choice for the higher speeds that the CNC table will be used at.

Feed rates shall be kept at or under the calculated values found in Table 37Table 38Table 39 to prevent tool deflection and eliminate safety risks with tool breakage. More calculations will be needed once the table is built to ensure safety of the users and CNC table.

Cutting depths will be kept under the calculated values found in Table 40 to preserve tools used and minimize deflection.

5.2.4 Bearing and Rail Design

The router will be moved by T-7 supported ball screws on supported linear rails with open bearings. which can provide the client with dependable and repeatable movements. The X, Y and Z axis will move on supported rails with open bearings. The key point of designing the CNC router is to have a stable and balanced design that will withstand the forces that will be encountered by the spindle due to cutting and moving. This will prevent bearings, and lead screw failure resulting from excess stress and strain. **Error! Reference source not found.** illustrates a side view of a gantry with acting forces and moments.

From **Error! Reference source not found.**, the distances are identified as below:

- D1 is the distance between the cutting tool tip and the center between the two Y-axis linear bearing D3.
- D2 is the distance between lead screw/ linear bearings and the bottom Y-axis linear bearing.
- D3 is the distance between the lower and upper Y-axis linear bearing.
- D4 is the distance between the two linear bearings on the X-axis.

The cutting force will vary depending on factors such as the gantry acceleration, spindle RPM, and the chip load that is the measurement of the thickness of material removed by each cutting edge during a cut. The moment A can be calculated by multiplying the cutting force by the distance D1. The force A at the Y- Axis linear bearing rod 1 is equal to force B at the Y-axis linear bearing rod 2. The value of force A and B can be calculated as follows:

$$Force\ A = Force\ B = Moment\ A\ /\ D3$$

Moment B is equal to force A multiplied by Distance D2. Increased values of moment B will cause the entire gantry to vibrate more than required which cause more deformation on the rails and failure due to fatigue. The best outcome is to reduce the value of moment B to avoid these effects. This can be achieved by designing the linear bearings to have equal amount of force which can be done by reducing the force A or the distance D3. Force C and D are the sum of the weight of the machine and resulting forces that occur as a result of moment B. Table 1 below show the values of moment A with cutting force range of (5-20) N.

Table 19: The values of moment A with cutting force range of (5-20) N.

Cutting Force (N)	Distance D1 (m)	Moment (Nm)	D3 (m)	Force A = Force B (N)	D2(m)	Moment B(Nm)
5	0.2	1	0.12	8.3	0.22	1.8
10	0.2	2	0.12	16.7	0.22	3.7
15	0.2	3	0.12	25.0	0.22	5.5
20	0.2	4	0.12	33.3	0.22	7.3

Figure 32 through Figure 35 is a finite element analysis on 450mm Aluminum rail with maximum force of 35N. the bottom of the rail is fixed. Figure 2 shows the maximum value for directional deformation in Y-axis, and the total deformation. The maximum value of deflection is 9.5665e-5 mm. The chosen rails bearings and their specs can be found in Figure 36, Figure 37 & Table 28, Table 29.

5.2.5 *Software Analysis*

The biggest challenge is coming up with software that can take the algorithm and translate it so as it performs a movement command. The reason behind the challenge is that various motor types and driver types are complex and even it makes it even more difficult if the number of axes exceeds 2. For the CNC routing table with the given engineering requirements, Speed is a critical determinant of the overall performance of the machine. Hence, it is desirable to have a software that takes in the designated codes for execution and processes the commands to be able to carry out the various tasks that are required of the machine.

For milling and lathing, Operations Master cam is excellent software for the computer aided manufacturing operations. The advantage with Master Cam is that it is based on highly dynamic and efficient logic and is therefore able to translate any input given to it either in 2D or 3D fed in real time into an execution instruction. It is quite powerful software and handles a variety of tasks besides giving the user an opportunity to tweak the g code to fit the instructions that they need. The command is then passed to the machine synchronization software: Mach3 or Mach 4. The two depend on voltage and current signals for the commands and generates a g-code as well. The code is excellent for motor drivers. It gives the instruction that makes the engine movement signal control to every axel. However, Master Cam is quite expensive going for around $4000 -$40000. For that reason, it may not be viable for this project. Other CAM software's available for use is PyCAM or sprutCAM. Such software comes in a much more affordable price, approximately around $1500.

Mach 3 happens to be excellent machine interface software that can carry out the various tasks and has high flexibility regarding the no of axes operated. It can also accommodate a wide range and variety of motor types such as the stepper motors, which are applicable for the proposed CNC project, as well as the engine driver type which could be able to operate even DC servo drivers that are voltage controlled. On the same note, to boost the machine's precision Dc servomotors are desirable as they are very fast and active besides their precision in stopping. While the overall budget of this project was supposed to be low to make it affordable to people and industries to purchase, The AC servo drivers could be used or instead of the stepper motors as they are less expensive and less complex. Consequently, they would require much-complicated geometry programming language knowledge to change the code when the need arises.

The other option was using the advanced version of MACH 3 which is MACH 4. MACH 4 has a number of advantages that include a G-code editor making it possible for the user to customize instructions to fit exactly what they need though the inbuilt settings provide for a broad range of applications that are normal for the day to day tasks executions. However, as a matter of cutting cost and for ease of operation, Mach 3 is preferable. Besides, due to its simplicity, it is easy to maintain as well.

5.2.6 Controller Boards

There are controller boards that can be bought that already have instructions, though they may not be completely customized for the CNC router. A good controller board that will be functional can come with a 5-axis CNC kit. The reason the CNC kit is recommended is because, it comes with the power and the controller boards that are open ended for customization and integration into other systems.

Basic components of controller boards

The circuit boards kit should be able to control a motor that is at least 290oz. The majority of circuit boards operate on a DC power supply and therefore there will need to be a conversion if the power that will be used is an AC current. These circuit boards should have a USB inter-phase. The USB inter-phase is the one that will be plugged into the computer where the software will run. An Ethernet cable is plugged in this point to act as the link between the PC and the machine.

There are some adjustments on the multi-capability CNC router table that will need to be done manually. The controller board will therefore need to have an optional manual pulse generator. (MPG)

A processor that is called the IO Expansion system does the brainwork of the controller board. This receives the configuration instructions that are from the computer software and then passes them as impulse instructions to the cutting Torque bit. On average, it should accept 16 different kinds of input instructions that are used by the Toque bit. The 16 instructions are also output as 16 instructions. The other processor that the control board should have is Optional Auto Tool set and the optional Touch Probes Software. The software that runs on the computer to control the multi-capability CNC router table is not a blank slate. There is some set of instructions that it can execute without having to be configured and told to do with every single instruction. This processor performs this function. The other part that needs to be on the controller board is the Encoder Scales. The encoder scales are the ones that determine the sizes of the measurements that the sent instructions are going to yield. These include the sizes of the letters, the styles, the depth and so on. Finally, the processor must have an Optional Operators Control Panel processor. This part of the control board is the one that links up with the software in the computer and enables the customization of the instructions before they are relayed to the circuit board. It acts as the door into the controller board that receives the instructions.

It may be astronomical for a student class to try to print the above set of instructions on a circuit board as it is beyond the scope of our learning. However, when looking for a circuit board, the above considerations should be ensured that they are there. If the above are there, there may be some of the of the more finer and complimentary minor role functions that many come with it.

6 Proposed Design

This section explains how the team expects to implement the proposed design. The implementation plan is described together with the bill of materials and the expected budget for the proposed design. The design and the budget are subjected to change during the entire implementation process.

6.1 *Implementation Plan*

The first step of implementing the proposed design is to buy the parts found in the bill of materials (Table 41). The bill of material includes almost everything needed to build the machine. Some of the parts like reinforcement material; the amount of fasteners, and other smaller parts might be adjusted later during the implementation phase. The proposed design is currently deemed to operate according to the customer's requirements, but the team anticipates issues arising during the implementation phase. However, these issues will most likely not be realized until the testing of the machine. After buying the parts a thorough inspection of these will be conducted. The inspection will include checking if the correct parts arrived and if so, without defects. Once confirmed that all parts are correct and intact, the team will start machining the parts before the assembly can start.

Machining parts will be necessary in order to connect the parts together during the assembly. It is assumed that the team will perform the machining, but there is a possibility of sourcing out work if it is deemed necessary. The team expects to machine the frame, which includes the gantry, the frame sides and the work table. Another part that requires machining is spindle assembly (the component that holds and moves the spindle) and its components. An inspection of each of the machined parts will be conducted to verify that the parts meet the tolerances set before the machining.

The assembly of the machine starts when all the machined parts are cleared. Each of the components in the machine will be connected with various kinds of fasteners. It is critical that all connections are rigid enough to operate properly. This phase also includes setting up the control board and getting familiar with the software that will run the machine. At the end of this process, the machine is operational.

The next phase involves the testing of the machine. At this time G-code is feed to the machine and the team will start with testing different G-codes involving acceleration, start and stop, and different movement patterns. The team will go through the Testing Procedures (TPs) to evaluate if the machine is working properly. If the machine fails one or more of the testing procedures the team will address these issues and redo the testing procedures. When the machine has passed the testing it is ready to perform milling operations. The team will start cutting soft materials like different plastics, and from there advance to wood and then finally aluminum.

The last step that will be a continuous process throughout the entire implementation process is to finish the manual for the machine. The manual will include sections for multiple areas where the team feels like information is necessary for safely running the machine. These sections include but are not limited to, proper set up, clamping of work piece, safety recommendations, and recommended milling operation. The manual should be comprehensive enough so that anyone can operate the machine safely.

During this implementation plan, the team will need the following resources:

- Expertise from personal at the machine shop
- Expertise from staff
- Machines and tools at the machine shop
- Various vendors (i.e. eBay and Homeco) that can supply the machine components
- Client feedback
- Computer to create G-code for the machine
- Testing equipment to test the machine
- Raw material for the machine to mill (wood, plastic, and aluminum)
- Area where the machine can be assembled

6.2 *Bill of materials and budget*

6.2.1 *Complete bill of materials*

The bill of materials (BoM) for the CNC router was developed off of the original design concept mixed with results from the individual analysis assignments. The BoM includes pricing on parts so that a budget could be formed off of the parts. Certain line items in the BoM include just a raw material. For example, line 14 in Appendix D – Preliminary Budget shows aluminum 6061 plate .375" 12"x 24". This plate will be cut into approximately 12 different pieces and machined into parts for the CNC router. Machining is not expected to be an expense, as the team will perform it, so it was kept as one line item on the BoM. Line 10 in the BoM has a generalized listing of "Hardware Package". This was done in an effort to streamline the BoM so that it would be more easily understood. The hardware is broken down in a separate table, which is also located in Appendix D.

6.2.2 Budget comparison

Modeling the team's design in solid works enabled more accurate costing analysis to be done. The Initial design choices included several features that are large portions of the design budget. These were the ball screws, linear ball slides, and a 2 1/4 HP router for the spindle. With these items included, the total cost to build the machine is estimated to be around $1550. Appendix E contains a full breakdown of these costs. This initial cost estimate exceeds the budget of the CNC router by $50 without adding in a contingency budget amount. This is including discounts and package deals offered by several vendors that the router team has approached. Without these discounts there would be an additional $200 of material costs added to this budget.

Based on this overage, several design alterations were calculated using slightly different components. Components that were considered as alternatives were as follows. Acme lead screw instead of ball screws, and a 1 ¼ HP router instead of the 2 ¼ HP router. Although these components offer less performance than their counterparts, they will still meet the customer requirements in precision and cutting ability. With these components exchanged the build price drops to approximately $1304, which is under the initial budget for the team. In order to use these components there would need to be some minor design modifications done to the screw mounting locations and size of the bearing mounts. These would also have an additional frictional drag that would need to be compensated for in the drive motor selection for the machine.

The CNC Router team will continue to pursue other discounts and design combinations in order to secure the best design possible while staying close to the initial budget amount allocated for the project.

6.3 *Schedule of the Implementation Plan*

Task #	**Work to be done**	**Time**
1	Make CAD drawing of the whole assembly with all the parts present using the proposed CAD software.	Nov 8 – Nov 15
2	Make prototypes to check if the machine will be functional only considering where parts are located and that they do not interfere with other parts.	Nov 8 – Nov 9
3	Choose a method to fasten parts together.	Nov 15- Nov 16
4	Create an engineering drawing with all the parts available and create the bill of materials.	Nov 20 – Nov 22
5	Buy the parts seen in the bill of materials.	Dec 19 – Dec 26
6	Conduct the inspection of these parts. The inspection will include checking if the correct parts arrived and if so, they are without defects.	Jan 17 – Jan 20
7	Send back parts if they are either wrong or defective	Jan 21 – Jan 24
8	Machining of parts	Jan 25 – Feb 22
9	Assembly of the machine.	Feb 23 – Feb 28
10	All the electrical wires should then be shielded and bundled together to get them out of the way of moving parts.	Mar 1 – Mar 3
11	Testing procedures	Mar 3 – Mar 10
12	Eventual trouble shooting (repeat steps 11 and 12 as needed)	Mar 10 – Mar 13
13	Start cutting materials	Mar 14 – Mar 17
14	Finish the user manual (continuously over the entire implementation phase)	Mar 18 – Mar 31
15	Present the machine	Apr 1

6.4 Assembly and exploded view

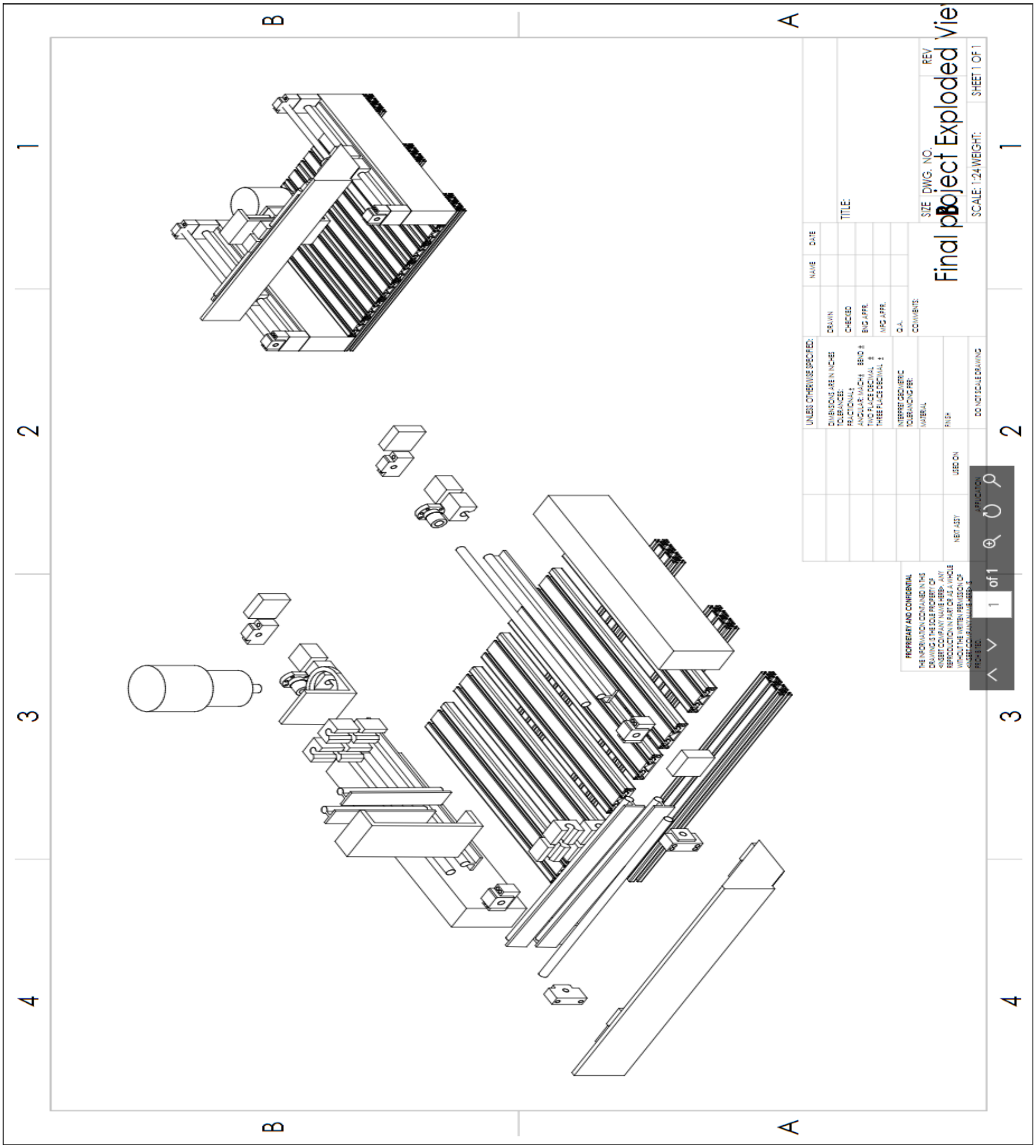


Figure 28: Assembly and exploded view of the CAD drawing

7 Implementation

In this section the implementation of the CNC router table is explained. The implementation can be divided up into 4 phases; the preparation, manufacturing, assembly, and operation phase. A certain amount of overlap occurred between the phases as components were redesigned or assembled early to test tolerances.

Phase 1: Preparation

In this phase the building plan was created. From the CAD model, the machine consisted of 40 different parts that needed to be manufactured. The team had to carefully plan the approach to finish the machine within the deadline. It was decided to outsource some of the manufacturing to a water jet company (Southwest Waterjet and Laser) to save time during the manufacturing phase. This decision also relieved the team of manufacturing parts that would have been difficult to manufacture in the NAU machine shop. The Southwest Waterjet cut the parts to dimensions and added pilot holes. All other features were created by the team such as drilling and tapping the holes, pocketing, and edge holes. A detailed building plan is shown in table 20. In this figure one can follow the parts that were made by the team and the parts that were outsourced to the machine shop crew. Each team member had a corresponding color, light blue for Micael, light green for Jason, and red for Jessica. The shop crew was neon blue and the yellow column marked the date where hardware review 1 occurred.

Table 20: Build plan for parts. Each part needed to be completed on the left, date on the top.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1			Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
2		Completed	1/22/17	1/23/17	1/24/17	1/25/17	1/26/17	1/27/17	1/28/17	1/29/17	1/30/17	1/31/17	2/1/17	2/2/17	2/3/17	2/4/17	2/5/17	2/6/17	2/7/17	2/8/17	2/9/17	2/10/17	2/11/17	2/12/17	2/13/17	2/14/17	2/15/17	2/16/17	2/17/17	2/18/17	2/19/17	2/20/17	2/21/17	2/22/17	2/23/17	2/24/17	2/25/17	2/26/17	2/27/17	2/28/17	3/1/17
3	Left front L bracket	C																											T												
4	Right Front L bracket	C																											T												
5	Right Rear L bracket	C																											T												
6	left Rear L bracket	C																											T												
7	Y axis bearing pad left	C																				T																			
8	Y axis bearing pad Right	C																				T																			
9	Y axis ball nut mounting plate left	C																							T																
10	Y axis ball nut mounting plate right	C																							T																
11	Gantry sides left outer	C																											T												
12	Gantry sides right outer	C																											T												
13	Gantry sides left inner	C																													T										
14	Gantry sides right inner	C																																			T				
15	fixed bearing spacer 5mm	C																							T																
16	floated bearing spacer 5mm	C																							T																
17	x axis motor mount	C																							T																
18	z axis back panel	C																													T										
19	z axis top panel	C																									T														
20	z axis bottom panel	C																													T										
21	z axis front panel	C																									T														
22	Z axis ball nut mount																															T									
23	tool plate	C																									T														
24	caps for extrusion left	C																							T																
25	caps for extrusion right	C																							T																
26	x ballnut mount																																	T							
27	floated y axis ballscrew mount left																														S										
28	floated y axis ballscrew mount right																														S										
29	Y axis motor mount right	C														T																									
30	Y axis motor mount left	C																				T																			
31	Y axis floated bearing spacer	C									T																														
32	Y axis floated bearing spacer	C																T																							
33	Y axis fixed bearing spacer	C																	T																						
34	Y axis fixed bearing spacer	C																	T																						
35	Back gantry panel	C																			S																				
36	z axis fixed bearing assembly	C																												T											
37	Z axis floated bearing assembly	C													T																										
38	Z axis motor mount	C											T																												
39	base extrusion holes front	C						T																																	
40	base extrusion holes middle	C						T																																	
41	base extrusion holes back	C						T																																	
42	router holder??																																				T				
43																																			HR1						

Phase 2: Manufacturing

Figure 29: Bridgeport manual mill located in NAU's machine shop

The manufacturing phase was the most time consuming. The manufacturing was performed by three team members, with milling and lathe training. Most of the parts were manufactured using a manual 3-axis mill in the NAU machine shop shown in figure 29 in, but the lathe, drill press, belt sander, and horizontal band saw were also used. The band saw was used to cut Aluminum bar stock to size before the pieces were milled down to the correct size. The lathe was used to cut out non standard dimensions of holes or round pieces that could not be done on the mill. Pieces like bearing blocks, and ballscrew nuts needed to be lathed out. The drill press was used to drill standard holes on large pieces such as the Aluminum extrusions. The belt sander was used to sand down corners, faces and edges of the parts so that they could be safer and could be given a brushed Aluminum finish.

The time to manufacture parts took anywhere in between 2-16 hours. The water jetted parts saved an estimate of 250-300 hours of machining. In total the team spent 31 days manufacturing parts or about 200 hours. Without much previous knowledge about operating a manual 3-axis mill and with limited knowledge about the transition between CAD parts to finished parts, numerous mistakes were made. Mistakes made included CAD drawing tolerances, removing material (either too much or too little), tapping holes (wrong size tap) , drilling holes (too large of a bit for tap), design issues, and unforeseen accidents (breaking taps, countersinking wrong sides of pieces). The severity of the mistakes were divided up into two sections; critical and non-critical mistakes. Two parts had to be remade because they were made incorrectly or could not be finished due to restrictions in tooling at the machine shop. 10 parts had to be redesigned because they did not match with the parts purchased for the machine. Most of the mistakes were non-critical and could either be fixed or left unmodified. For the complete bill of materials see Table 39 in appendix E.

The manufacturing was divided up into 3 subsystems; the gantry, table, and the z axis. Beyond these three subsystems a dust shoe, leveling feet and a control box was also manufactured. In following sections each of the subsystem and additional components are explained.

Gantry:
The gantry is the subsystem that is connected to the table and moves the tool in the both X and Y direction. All components are fastened by either M5 or M6 screws into tapped holes. The gantry consists of 17 manufactured parts. The parts can be seen in appendix D under "tall gantry". In this figure all visible parts were water jetted, totaling in 23 parts. Beyond these parts, two linear rails and one ball screw with two bearing mounts were manufactured. The linear rails were bought off the shelf. The base of the linear rails was modified to allow for screw holes. The bearing mounts were manufactured from blocks of 6061 aluminum using a manual mill. The bearing mounts were used in all subsystems and required close tolerances and relationship in order to operate the ball screw accurately. The back gantry plate (the long thick plate) in the tall gantry picture was also a critical part to make accurate because multiple parts connect to it.

Table:
The table is the stationary part of the machine. The table consists of 15 manufactured parts. The parts can be seen in appendix D. The pictures labeled "extrusion", "bracket", "spacer"," fixed ball screw support"," floated ball screw support" and "linear rails" constitutes the table parts. The linear rails were bought off the shelf and left unmodified. The four spacers, 2 ball screw supports were made from blocks of aluminum on the manual mill. The holes for the bearings on the ball screw supports were manufactured using both a CNC mill and manual lathe. The three bottom extrusions were drilled through and counterbored so it could be fastened to the extrusions creating the work table surface.

Z axis:
The Z-axis is the subsystem that moves the tool in the Y and Z direction. The Z-axis subsystem has to connect to the gantry and be able to support the weight of the router/spindle while minimizing any deflection. The Z-axis consists of 8 manufactured parts. The parts can be seen in appendix D. The parts labeled "z-axis spacer", "Z-axis plate", "linear rails", "ball screw", "bearing mounts", "Z motor spacer" and "ball screw nut". The parts in the "Z axis plate" were water jetted. The two linear rails, and one ball screw were bought off the shelf and left unmodified. The rest of the parts were made from blocks of aluminum. The router holder has not been machined because the final decision has not been made on whether the team will use a spindle or router. The design has been constructed and can be modified in Solidworks before the dimensions are finalized and the final product produced.

At this point the following components have not been manufactured yet:
Leveling feet
Control box

Spindle/Router holder

Phase 3: Assembly
In the early stage of the assembly phase parts were fastened together and modified to resolve design issues and interferences. Each of the subsystems was first assembled individually. When the subsystems were assembled, modifications were made to resolve any alignment issues encountered. The next step is to disassemble the subsystems and reassemble the full machine. It is expected that more issues will arise when the subsystems are combined into the full machine. Extra machining might be necessary. When the machine is fully assembled the last step is to use cable chains to manage the wires and guide them to the control box.

7.1 *Design of Experiments*

The DOE is not completed at this time. The DOE will be performed on the control box for the machine. The control box will house the smoothieboard, the power supply, and the power strip. The control box is the brain of the CNC machine and it will be necessary to keep temperatures low in the box at all times so that overheating will not occur. Table 1 shows the variables that will be considered. There will be two alternatives for each variable giving a total of 8 tests. The orientation of internal components refers to the smoothieboard and if it will be elevated or fixed to the bottom of the control box. The ventilation holes variable refers to either to use holes or to not.

Table 21: Variables for the control box DOE.

Variable	Test 1 to 8
Fan size	Alt 1 and Alt 2
Ventilation holes	Alt 1 and Alt 2
Orientation of internal components	Alt 1 and Alt 2

7.2 *Design Changes*

As of 3/3/17 there have not been any design changes.

References

[1] H. M. Rizwan, "CNC Machines," [Online]. Available: http://physlab.org/wp-content/uploads/2016/04/CNCPRESENTATION. [Accessed 30 September 2016].

[2] R. Johnstone, "What is a CNC Router," Woodworkers Journal, 12 September 2014. [Online]. Available: http://www.woodworkersjournal.com/cnc-router/. [Accessed 30 September 2016].

[3] D. Willy, "CNC Table for Routing, Printing, and Laser Cutting," 2016. [Online]. Available: https://bblearn.nau.edu/bbcswebdav/pid-4686009-dt-content-rid-37760908_1/courses/1167-NAU00-ME-476C-SEC001-2176.CONTENT/J-%20ME%20dept%20Competition%20-%20CNC%20Table%20for%20Routing.pdf. [Accessed 30 September 2016].

[4] "The Nomad 883 Pro," Carbide 3D, 2016. [Online]. Available: http://carbide3d.com/nomad/. [Accessed 26 September 2016].

[5] "Shapeoko Deluxe 3-Axis CNC Desktop Kit," RobotShop, 2016. [Online]. Available: http://www.robotshop.com/en/shapeoko-deluxe-3-axis-cnc-desktop-kit.html. [Accessed 26 September 2016].

[6] "BoXYZ," BoXYZ, 2016. [Online]. Available: http://www.boxzy.com/tech-specs-1. [Accessed 26 September 2016].

[7] "Pocket NC," Pocket NC, 2016. [Online]. Available: http://www.pocketnc.com/pocketnc/pocket-nc. [Accessed 26 September 2016].

[8] "4200 High-Performance Rotary Tool," DREMEL, 2016. [Online]. Available: https://www.dremel.com/en_US/products/-/show-product/tools/4200-high-performance-rotary-tool#.V-bB3CgrKUl. [Accessed 24 September 2016].

[9] "DEWALT 2-1/4 HP Elctronic Variable Speed Router with Soft Start," The Home Depot, 2016. [Online]. Available: http://www.homedepot.com/p/DEWALT-2-1-4-HP-Electronic-Variable-Speed-Router-Motor-with-Soft-Start-DW618M/203164064?cm_mmc=SEM%7CTHD%7Cgoogle%7C&mid=sbDUziBU7%7Cdc_mtid_8903tb925190_pcrid_50250225699_pkw__pmt__product_203164064_slid_&gclid=COWQgufjqM8CFcEd. [Accessed 24 September 2016].

[10] technical.jrs, "2.2KW Water Cooled Spindle Motor ER20& VFD Inverter Drive 80mm Diamter CNC," ebay, 19 August 2016. [Online]. Available: http://www.ebay.com/itm/2-2KW-WATER-COOLED-SPINDLE-MOTOR-ER20-VFD-INVERTER-DRIVE-80MM-DIAMETER-CNC-/252029788256. [Accessed 24 September 2016].

[11] "Timing Belt Advantages and Disadvantages," Ecreativeworks, 2016. [Online]. Available: http://www.pfeiferindustries.com/timing-belt-advantages-disadvantages-i-15-l-en.html. [Accessed 24 September 2016].

[12] J. Saunders, "DIY Cheap Arduino CNC Machine - Machine is Complete and Accurate!," Weebly, 5 January 2015. [Online]. Available: http://www.nyccnc.com/wednesday-widget/diy-cheap-arduino-cnc-machine-machine-is-complete-and-accurate. [Accessed 24 September 2016].

[13] "Standard Rand and Pinion Drive, NEMA 23," CNCRouterParts, 2016. [Online]. Available: http://www.cncrouterparts.com/standard-rack-and-pinion-drive-nema-23-p-50.html?osCsid=3g4t8fu77c7bonr6vck89ej3v1. [Accessed 24 September 2016].

[14] "The Engineer's Guide: Lead Screws VS. Ball Screws," 2016. [Online]. Available: http://www.engr.uvic.ca/~mech464/lead_screw_vs_ball_screw.pdf. [Accessed 24 September 2016].

[15] "Our Ball Screw repair process," American Ball and Screw, 2016. [Online]. Available: http://www.americanballscrewrepair.com/ball-screw-repair-process/. [Accessed 24 September

2016].

[16] MattWheeler, "A 30 minute x-axis mod to reduce chatter," Inventables, 2 November 2015. [Online]. Available: https://discuss.inventables.com/t/a-30-minute-x-axis-mod-to-reduce-chatter/15775. [Accessed 24 September 2016].

[17] econvenience1986, "2 Set SBR20-1500mm 20mm Fully Supported Linear Rail Shaft Rod with 4 SBR20UU," ebay, 4 August 2016. [Online]. Available: http://www.ebay.com/itm/2-Set-SBR20-1500mm-20-MM-FULLY-SUPPORTED-LINEAR-RAIL-SHAFT-ROD-with-4-SBR20UU-/251022549100. [Accessed 24 September 2016].

[18] mhestore2009, "2Pcs 8mm 400mm Linear Shaft Rod Rail Kit W/ Bearing Block for 3D Printer CNC," ebay, 26 September 2016. [Online]. Available: http://www.ebay.com/itm/2Pcs-8mm-400mm-Linear-Shaft-Rod-Rail-Kit-W-Bearing-Block-For-3D-Printer-CNC-/371697485067. [Accessed 26 September 2016].

[19] "Linear Motion Guides," DC Auto-Motion, 2016. [Online]. Available: http://www.dcauto-motion.co.za/thk/linear-motion-guides/. [Accessed 24 September 2016].

[20] "Physics tutorvista," 2016. [Online]. Available: http://physics.tutorvista.com/rotational-dynamics/moment-of-inertia.html. [Accessed 18 November 2016].

[21] "Engineers Edge," 2016. [Online]. Available: http://www.engineersedge.com/beam_calc_menu.shtml. [Accessed 18 November 2016].

[22] M. P. Grover, "Materials, Processes, and Systems," in *Fundamentals of Modern Manufacturing 5th Edition*, Wiley, 2012, pp. 526-542.

[23] "8020," 2016. [Online]. Available: https://8020.net. [Accessed 18 November 2016].

[24] "Efunda," 2016. [Online]. Available: http://www.efunda.com/designstandards/beams/SquareIBeam.cfm. [Accessed 18 November 2016].

[25] "compare stepper motor," [Online]. Available: http://www.omc-stepperonline.com/compare_stepper_motor.html. [Accessed 18 November 2016].

[26] McMaster-Carr, "Support-Rail Shaft for Harsh Enviornments," 1 Jan 2016. [Online]. Available: https://www.mcmaster.com/#1049k14/=153kg09. [Accessed 18 Nov 2016].

[27] McMaster-Carr, "Mounted Linear Ball Bearing," 1 Jan 2016. [Online]. Available: https://www.mcmaster.com/#1049k14/=153kg09. [Accessed 18 Nov 2016].

[28] Diffen LLC, n.d., "Hardwood vs. Softwood," 1 Jan 2016. [Online]. Available: http://www.diffen.com/difference/Hardwood_vs_Softwood. [Accessed 16 Nov 2016].

[29] Irwin Industrial Tools, "Metal Drilling Reference Guide," 1 Jan 2004. [Online]. Available: http://www.irwin.com/uploads/documents/11_Decimal_Equivalents_Guide.pdf. [Accessed 16 Nov 2016].

[30] Tink & Tinker, Ltd. , "Matching Speeds and Feeds," 10 Oct 2016. [Online]. Available: file:///C:/Users/jc2555/AppData/Local/Downloads/Machining-Speeds-and-Feeds%20(1).pdf. [Accessed 16 Nov 2016].

[31] Drill Service (Horley) Ltd., "Recommended Cutting Speeds and Feeds for Carbide Tools," 1 Jan 2016. [Online]. Available: http://www.drill-service.co.uk/images_Technical/Speeds-and-Feeds.pdf. [Accessed 16 Nov 2016].

[32] PDS: Precision Drive Systems, "Spindle RPM and Feed Rate Calculations: Chip Load Formula," 1 Jan 2016. [Online]. Available: http://www.pdsspindles.com/engineering-speeds. [Accessed 16 Nov 2016].

[33] CNC Cookbook, "Tool Deflection Conbtrol: Critical to Your Success," 1 Jan 2016. [Online]. Available: http://www.cnccookbook.com/CCCNCMillFeedsSpeedsDeflect.htm. [Accessed 16 Nov 2016].

[34] "MetalsDepot," 2016. [Online]. Available: http://www.metalsdepot.com. [Accessed 18 November 2016].

[35] "Trapezoidal Lead Screws," ROTON, [Online]. Available: http://www.roton.com/page.aspx?id=22. [Accessed 7 November 2016].

[36] "Friction and Friction Coefficients," The Engineering Toolbox, [Online]. Available: http://www.engineeringtoolbox.com/friction-coefficients-d_778.html. [Accessed 7 November 2016].

[37] irving2008, "What size steeper motor do I-need," mycncuk, 24 December 2009. [Online]. Available: http://www.mycncuk.com/threads/1524-What-size-stepper-motor-do-I-need. [Accessed 5 November 2016].

[38] "Milling Speed and Feed Calculator," custompartnet, 2009. [Online]. Available: http://www.custompartnet.com/calculator/milling-speed-and-feed. [Accessed 14 November 2016].

[39] Shop Bot Tools, "What is CNC Anyway," 1 Jan 2016. [Online]. Available: http://www.shopbottools.com/mproducts/WhatsCNC.htm. [Accessed 16 Nov 2016].

[40] Metal Supermarkets, "7 Things to Consider when Choosing an Aluminum Grade," 19 Jan 2016. [Online]. Available: https://www.metalsupermarkets.com/7-things-consider-choosing-aluminum-grade/. [Accessed 16 Nov 2016].

[41] Machinist.org, "The Invention of CNC Machining," 1 Jan` 2016. [Online]. Available: http://machinist.org/cnc-computer-numerical-control/the-invention-of-cnc-machining/. [Accessed 16 Nov 2016].

[42] K. Amadeo, "How Outsourcing Jobs Affects the U.S. Economy," U.S. Economy, 25 Jun 2016. [Online]. Available: https://www.thebalance.com/how-outsourcing-jobs-affects-the-u-s-economy-3306279. [Accessed 16 Nov 2016].

[43] Quaker, "Feeds, Speeds and Depth of Cut," 1 Jan 2013. [Online]. Available: https://www.quakerchem.com/wp-content/uploads/pdf/skill_builders/no12_feeds_speeds_depth_cut.pdf. [Accessed 16 Nov 2016].

[44] Shapeoko, "Endmills," 15 Nov 2016. [Online]. Available: http://www.shapeoko.com/wiki/index.php/Endmills. [Accessed 16 Nov 2016].

[45] Green Tool Systems, Inc., "Speeds and Feeds Calculator," 1 Jan 2015. [Online]. Available: http://greenetool.com/calculator/. [Accessed 16 Nov 2016].

[46] Virtualtech Website Design and Promotion, Inc., "Speeds and Feeds Calculator," 1 Jan 2016. [Online]. Available: http://www.valleytool.net/calculator.php. [Accessed 1 Nov 2016].

[47] "8mm Acme Lead Screw," Openbuild partstor, 2016. [Online]. Available: http://openbuildspartstore.com/8mm-metric-acme-lead-screw/. [Accessed 18 November 2016].

[48] "Ball & Acme Lead screw technical information," SDP/SI. [Online]. Available: https://www.sdp-si.com/D810/PDFS/Ball%20And%20Acme%20Lead%20Screw%20Technical%20Info.pdf. [Accessed 7 November 2016].

[49] "Ball Screw Torque Calculations," NOOK, [Online]. Available: http://www.nookindustries.com/LinearLibraryItem/Ballscrew_Torque_Calculations. [Accessed 7 November 2016].

[50] LMT Onsrud, "Chiploads," 1 Jan 2010. [Online]. Available: https://www.onsrud.com/xdoc/feedspeeds. [Accessed 16 Nov 2016].

[51] "Coefficient of friction, Rolling resistance and Aerodynamics," Tribology-abc, [Online]. Available: http://www.tribology-abc.com/abc/cof.htm. [Accessed 7 November 2016].

[52] Melin Tool Company, "End Mill Training - Types and Characteristics of End Mills," 1 Jan 2016. [Online]. Available: http://www.endmill.com/pages/training/types.html. [Accessed 16 Nov 2016].

Appendix A - Equations

Deflection

Equation 1

$$\delta = \frac{Pl^3}{48EI} \text{ [21]}$$

Where:
δ: Simply Supported Beam Deflection [mm]
P: Load [N]
l: Length of the beam [mm]
E: Modulus of Elasticity [MPa]
I: Moment of inertia [mm^4]

Equation 2

$$\theta = \frac{Tl}{GJ} \text{ [21]}$$

Where:
θ: Torsional Deflection [radians]
T: Torque experienced from the force of the cutting force and the lever arm of the spindle [Nm].
G: Modulus of Rigidity [MPa]
J: Polar Second Moment of Area [kgm^2]

Equation 3

$$\delta = L\frac{Tl}{GJ} \text{ [21]}$$

Where:
δ: Angle of Deflection [radians]
L: is the length of the lever arm [mm]
T: Torque [Nmm]
l: Length of the beam [mm]
G: Modulus of Rigidity [MPa]
J: Polar second moment of area [mm^4]

Equation 4

$$\delta = \frac{Pl^3}{3EI} \text{ [21]}$$

Where:
δ: Cantilever Deflection [mm]
P: Load [N]
l: Length of the beam [mm]
E: Modulus of Elasticity [MPa]
I: Moment of inertia [mm^4]

Static Forces

Equation 5

$$T = \frac{FP_h}{2\pi\eta}$$

T: Torque [Nm]
F: Axial Load [N]
P_h: Pitch/Lead [mm]
η: Normal efficiency [%]

Equation 6

$$F = Mg\mu$$

M: Mass of Gantry Assembly [kg]
g: Acceleration due to gravity [m/s^2]
μ: Coefficient of Friction [Unit less]

Inertial Forces

Equation 7

$$I = \frac{1}{12}bb^3$$

Where:
I : Moment of Inertia [mm^4]
b: Width [mm]
h : Height depending on about which axis the moment of inertia is required [mm].

Equation 8

$$J = I_{xx} + I_{yy} \quad [20]$$

Where:

J: Polar Moment of Inertia. Perpendicular to both I_{xx} and I_{yy} [kgm^2]
I_{xx}: [mm^4]
I_{yy}: [mm^4]

Equation 9

$$J_s = \frac{M_s R^2}{2}$$

Where:
J_s: Inertia of Screw Assembly [kgm^2]
M_s: Mass of Screw Assembly [kg]
R: Radius of Screw Assembly [m]

Equation 10

$$J_g = \frac{M P_h^2}{2\pi^2}$$

Where:
J_g: Inertia from Gantry Assembly [kgm^2]
M: Mass of Gantry Assembly [kg]
P_h: Pitch/Lead [mm]

Equation 11

$$J_{total} = J_m + J_g + J_s$$

Where:
J_m: Motor Inertia [kgm^2]
J_T: Total Inertia of the System [kgm^2]

Equation 12

$$rpm = \left[\frac{V}{2 * I_{max} * L}\right]^{-1} * 60$$

Where:
rpm: Revolutions Per Minute
V: Voltage [v]

I_{max}: Maximum Current of the Motor [A]
L: Inductance [mH]

Equation 13

$$S_{max} = RPS * P_h$$

Where:
S_{max}: Maximum Cutting Speed [mm/min]
RPS: Revolutions Per Second
P_h: Pitch/Lead [mm]

Equation 14

$$\omega = 2\pi(\frac{rpm}{60})$$

Where:
ω: Angular Velocity [rad/sec]
rpm: Revolutions Per Minute

Equation 15

$$T = J_{total} * A$$

Where:
T_j: Torque to Overcome Inertia [Nm]
J_{total}: Total Moment of Inertia [kgm^2]
A: Acceleration [m/s^2]

Equation 16

$$T_{Total} = T_j + T$$

Where:
T_{Total}: Total Torque Required [Nm]
T_j: Torque to Overcome Inertia [Nm]
T: Torque [Nm]

RPM

Equation 17

$$N = \frac{v}{\pi D} \text{ [22]}$$

Where:
N: Spindle speed [rev/min]
v: Cutting Speed/ Surface Feet per Minute [m/s (ft/min)]
D: Tool Diameter [mm (in)]

Cutting Speed/ Surface Feet per Minute (SFM)

Equation 18

$$v = N * .2618D \text{ [22]}$$

Where:
v: Cutting Speed/ Surface Feet per Minute [m/s (ft/min)]
N: Spindle speed [rev/min]
D: Tool Diameter [mm (in)]

Feed Rate

Equation 19

$$f_r = Nn_tf \text{ [22]}$$

Where:
f_r: Feed Rate [mm/min (in/min)]
N: Spindle speed [rev/min]
n_t: Number of teeth on cutter
f: Chip Load [mm /tooth (in/tooth)]

Depth of Cut

Equation 20

$$d = \frac{-\left(\sqrt{D^2-4A^2}+D\right)}{2} \text{ [22]}$$

Where:
A : Distance from center of tool to the cutting edge [mm (in)].
D : Tool Diameter [mm (in)].
d : Depth of Cut [mm (in)].

Appendix B – Tables of Calculations

Table 22: Deflection of the gantry subjected to a 25N load with all geometries close to the dimension 500x40x80mm.

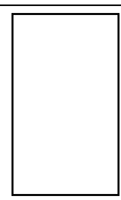
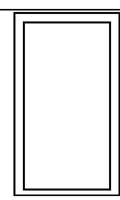
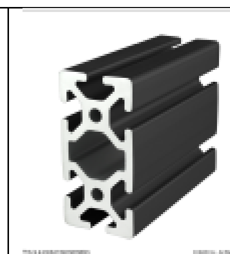
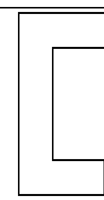
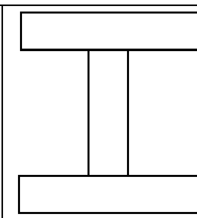
Gantry Geometry (cross-section)					
Moment of inertia Ixx	1706666 mm^4	849166 mm^4	252640 [23] mm^4	635833 mm^4	849167 [24] mm^4
Moment of inertia Iyy	426666 mm^4	269166mm^4	972720 [23] mm^4	128333mm^4	59167 [24]mm^4
Polar Moment of inertia J	2133333 mm^4	1118333 mm^4	1225360mm^4	764166mm^4	908333mm^4
Total deflection of a cutting force of 25N (Aluminum)	0.00055mm (Z) 0.0063mm (X)	0.0011mm (Z) 0.011mm (X)	0.0013mm (Z) 0.0075mm (X)	0.00051mm (Z) 0.014mm (X)	0.00031mm (Z) 0.0050mm (X)
Total deflection of a cutting force of 25N (Steel)	0.00019mm (Z) 0.0023mm (X)	0.00038mm (Z) 0.0041mm (X)	0.0013mm (Z) 0.0029mm (X)	0.00051mm (Z) 0.0067mm (X)	0.00011mm (Z) 0.0018mm (X)

Table 23: Deflection of the frame sides subjected to a 25N load with all geometries close to the dimension 500x80x160mm.

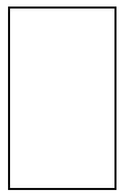
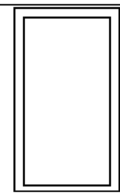
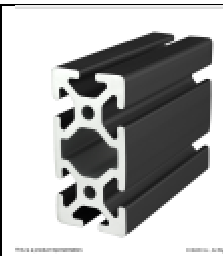
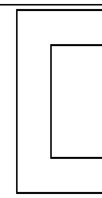
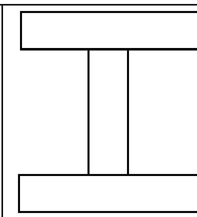
Frame side Geometry (cross-section)					
Moment of inertia Izz	6826666 mm^4	2638300 mm^4	3200280 [23] mm^4	366667 mm^4	393339 [24] mm^4
Total deflection of a cutting force of 25N (Aluminum)	0.0011mm (Y)	0.0029mm (Y)	0.0024mm (Y)	0.012mm (Y)	0.019mm (Y)
Total deflection of a cutting force of 25N (Steel)	0.00038mm (Y)	0.00099mm (Y)	0.00081mm (Y)	0.0041mm (Y)	0.0066mm (Y)

Table 24: Gantry assembly total weight.

Gantry Assembly					
Aluminum					
Width (m)	Depth (m)	Length (m)	Volume m^3	Density (kg/m^3)	Weight (N)
0.6	9.53E-03	0.1	5.72E-04	2700	15.14
0.3	9.53E-03	0.1	2.86E-04	2700	7.57
0.1	9.53E-03	0.1	9.53E-05	2700	2.52
Spindle					
		lbs	slugs ($lf*s^2/ft$)	kg	weight (N)
		5.6	0.2	2.5	24.9
				Total	50.13

Table 25: Stepper motors compatible with scenario 1 [25].

Model	Step Angle	Bi/Unipolar	Size		Holding Torque		Current	Resistance	Shaft Type	Inductance	Weight
P/N	Degree	No of Leads	Nema	[mm]	[N.cm]	[Oz.in]	[A]	[Ohm]	[S/D]	[mH]	[Kg]
23HM22-2804S	0.9	Bi (4)	NEMA 23	57x57x56	126	178.43	2.8	0.9	S	4.5	0.7
23HR20-2804S	1.8	Bi (4)	NEMA 23	57x57x52	70	99.13	2.8	0.65	S	1.6	0.6
23HS20-2004S	1.8	Bi (4)	NEMA 23	57x57x56	90	127.45	2	1.8	S	5	0.65
23HS22-1504S	1.8	Bi (4)	NEMA 23	57x57x56	116	164.27	1.5	3.6	S	13	0.7
23HS22-2804S	1.8	Bi (4)	NEMA 23	57x57x56	126	178.43	2.8	0.9	S	2.5	0.7

Table 26: Stepper motors fitting scenario 2 torque requirements [25].

Model	Step Angle	Bi/Unipolar	Size		Holding Torque		Current	Resistance	Shaft Type	Inductance	Weight
P/N	Degree	No of Leads	Nema	[mm]	[N.cm]	[Oz.in]	[A]	[Ohm]	[S/D]	[mH]	[Kg]
23HS22-1006D	1.8	Uni (6)/Bi (4)	NEMA 23	57x57x56	128	181.26	1	14.8	D	40	0.7
23HS22-1504S	1.8	Bi (4)	NEMA 23	57x57x56	116	164.27	1.5	3.6	S	13	0.7
23HS22-2804S	1.8	Bi (4)	NEMA 23	57x57x56	126	178.43	2.8	0.9	S	2.5	0.7
23HT31-5206D	1.2	Uni (6)	NEMA 23	57x57x79	120	169.93	5.2	0.8	D	1.5	1.1

Table 27: The values of moment A with cutting force range of (5-20) N.

Cutting Force (N)	**Distance D1 (m)**	**Moment (Nm)**	**D3 (m)**	**Force A = Force B (N)**	**D2(m)**	**Moment B(Nm)**
5	0.2	1	0.12	8.3	0.22	1.8
10	0.2	2	0.12	16.7	0.22	3.7
15	0.2	3	0.12	25.0	0.22	5.5
20	0.2	4	0.12	33.3	0.22	7.3

Table 28: Specification of 6063 Aluminum, 1/2" Diameter rail [26].

Material	Ceramic-Coated 6063 Aluminum
Temper	T6
Diameter	1/2"
Length	18"
Center Height	1 1/8"
Overall Width	1 1/2"
End-to-Mounting Hole Length	1"
Mounting Hole	
Center-to-Center Length	4"
Center-to-Center Width	1"
Diameter	5/32"
Mounting Fasteners Included	No
Diameter Tolerance	-0.0012" to -0.0004"
Straightness Tolerance	0.001" per ft.
Length Tolerance	-0.03" to 0.03"
Finish Thickness	0.002"
Surface Smoothness (RMS)	20 microns
End Shape	Chamfered
Hardness Rating	Ultra Hard
Hardness	Rockwell C70
Yield Strength	31,000 psi
Surface Yield Strength	31,000 psi
For Motion Type	Linear
For Linear Bearing Type	Plain
Shaft Type	Round with Support Rail
End Type	Straight
Specifications Met	MIL-A-8625
RoHS	Compliant

Table 29: Specification of Mounted Linear Ball Bearing [27].

Misalignment Capability	1°
Housing Type	Base Mount
With End Seals	Yes
For Shaft Diameter	1/2"
ID	0.500"
ID Tolerance	Not Rated
Overall	
Length	1 1/2"
Width	2"
Height	1 3/32"
Center Height	11/16"
Center Height Tolerance	-0.001" to 0.001"
Base Thickness	1/4"
Width	1/4"
Material	
Bearing	Acetal
Housing	6061 Aluminum
Ball	Steel
Load Capacity, lbs.	
Dynamic	230
Static	290
Lubrication	Required
Replaceable Insert Bearing	Yes
Temperature Range	-4° to 176° F
For Shaft Material	Steel, Stainless Steel
For Minimum Shaft Hardness	
Steel	Rockwell C50
Stainless Steel	Rockwell C50
Mounting Holes	
Number of	4
Diameter	5/32"
Center-to-Center, Length	1"
Center-to-Center	1.688" width
RoHS	Compliant

Table 30: List of various hard and soft woods [28].

Hardwoods	Softwoods
Alder	Cedar
Aspen	Douglas Fir
Balsa	Juniper
Beech	Pine
Hickory	Redwood
Magnolia	Spruce
Mahogany	Yew
Maple	
Oak	
Poplar	
Teak	
Walnut	

Table 31: Aluminum grades typically used in machining [46].

Aluminum Grade	Machinability
1100	Good (Best if Hard Tempered)
2011	Excellent
2024	Fair (Best in annealed condition)
3003	Good
5052	Fair (Better if Hard Tempered)
6061	Good (T4 and T6 Tempers)
6063	Fair
7075	Fair (Best in Annealed Condition)

Table 32: Low and High SFM's for Wood and Aluminum cut with High Speed Steel (HSS) or Carbide end mills.

End Mill Material	Wood	Aluminum
HSS	300 – 400 [29]	200 - 300 [29]
Carbide	3000 – 5000 [30]	250 – 450 [31]

Table 33: Chip Loads for common bit sizes for project materials [32].

Material	Bit Diameters [in]		
	$1/4$	$3/8$	$1/2+$
Aluminum	.005-.007 in	.006-.008 in	.019-.021
Hardwood	.009-.011 in	.015-.018 in	.019-.021 in
Softwood	.011-.013 in	.017-.020 in	.021-.023 in

Table 34: The amount of Flutes and their applications for milling [51].

Number of flutes	Application
Single	Aluminum/ Plastics
Two	Slotting and pocketing of non-ferrous materials.
Three	Similar to two Flutes, but greater rigidity.
Four/ Multiple	Provides finer surface finish.

Table 35: RPM's for Aluminum at different tool diameters.

Aluminum	$^1/_4$	$^3/_8$	$^1/_2$
HSS	3056 – 4584	2037 – 3056	1528 – 2292
Carbide	3820 – 6876	2546 – 4584	1091– 3438

Table 36: RPM's for Wood at different tool diameters.

Wood	$^1/_4$	$^3/_8$	$^1/_2$
HSS	4584 – 6112	3055 – 4074	2292 – 3056
Carbide	45837 – 76394	30558 – 50930	22918 – 38197

Table 37: Feed rate (in/min) for Aluminum cut with different diameters using a HSS and Carbide end mill at low and high SFM's respectively.

Number of Teeth	¼ HSS/Carbide		3/8 HSS/ Carbide		½ HSS/ Carbide	
1	18	23	14	18	31	38
	28	41	21	32	46	69
2	37	46	29	36	61	76
	55	83	43	64	92	138
3	55	69	43	53	92	115
	83	124	66	96	138	-
4	73	92	57	71	122	153
	110	165	86	128	183	-

Table 38: Feed rate (in/min) for Hard Woods cut with different diameters using a HSS and Carbide end mill at low and high SFM's respectively.

Number of Teeth	¼ HSS/ Carbide		3/8 HSS/Carbide		½ HSS/Carbide	
1	5	46	50	-	46	-
	6	76	67	-	61	-
2	9	92	101	-	92	-
	12	153	135	-	122	-
3	14	136	151	-	138	-
	18	-	-	-	183	-

4	18	183	-	-	183	-
	24	-	-	-	-	-

Table 39: Feed rate (in/min) for Soft Woods cut with different diameters using a HSS and Carbide end mill at low and high SFM's respectively.

Number of Teeth	**¼ HSS/ Carbide**		**3/8 HSS/Carbide**		**½ HSS/Carbide**	
1	50	-	57	-	50	-
	67	-	75	-	67	-
2	101	-	113	-	101	-
	135	-	151	-	135	-
3	151	-	170	-	151	-
	-	-	-	-	-	-
4	-	-	-	-	-	-
	-	-	-	-	-	-

Table 40: Comparison of depth of cuts (in) allowable for .001 tool deflection [33].

Tool Diameter	**Equation**	**60% Tool Diameter**
$1/4$	0.0625	0.15
$3/8$	0.09375	0.225
$1/2$	0.125	0.3

Appendix C – Figures

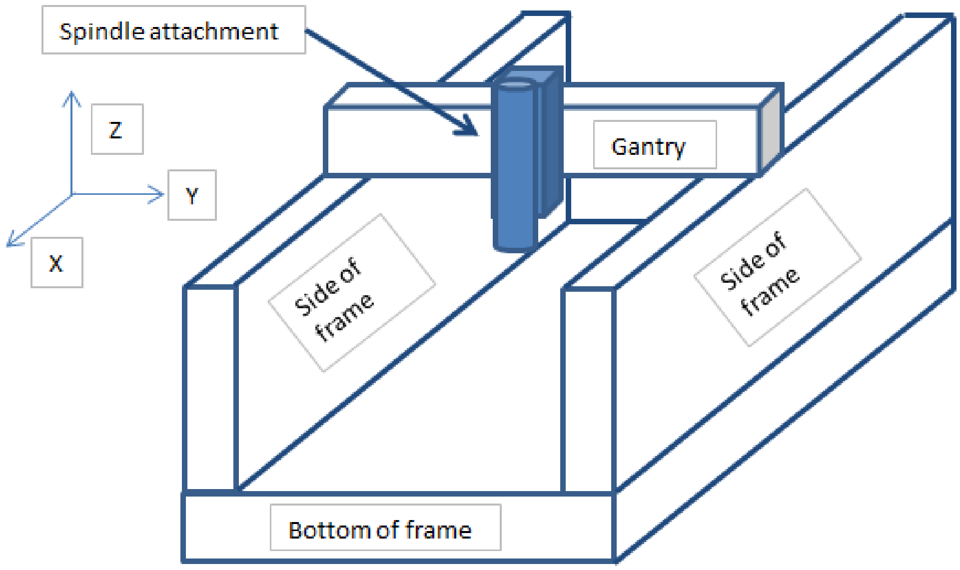


Figure 30: Basic representation of the CNC milling machine (gantry is simply supported and the frame sides are cantilever beams).

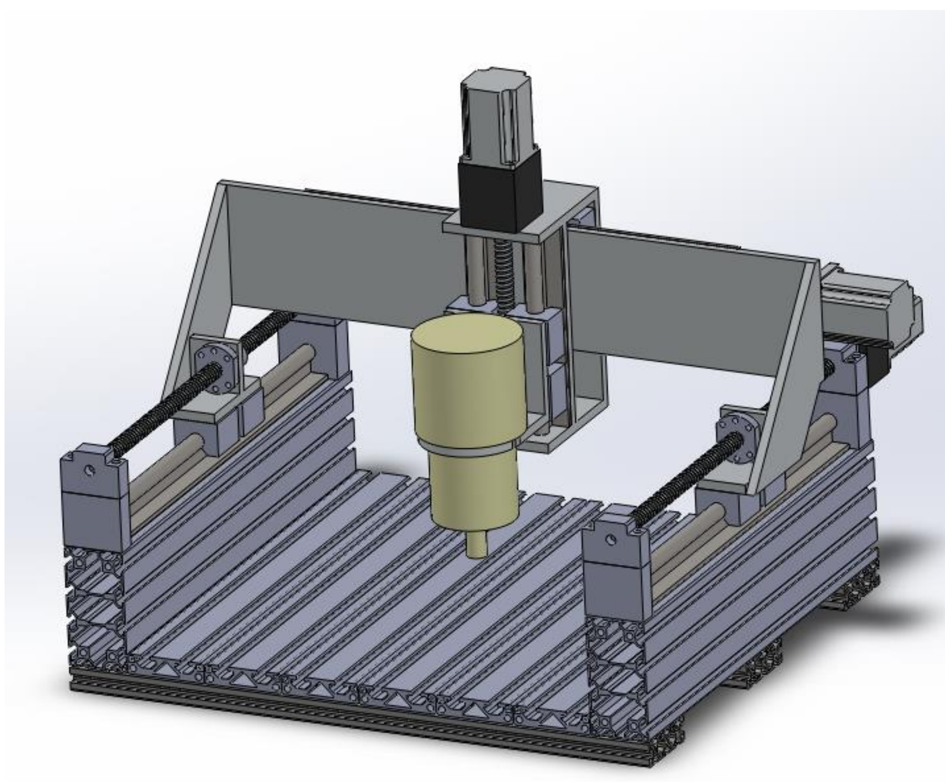


Figure 31: A 3D model for the CNC router system.

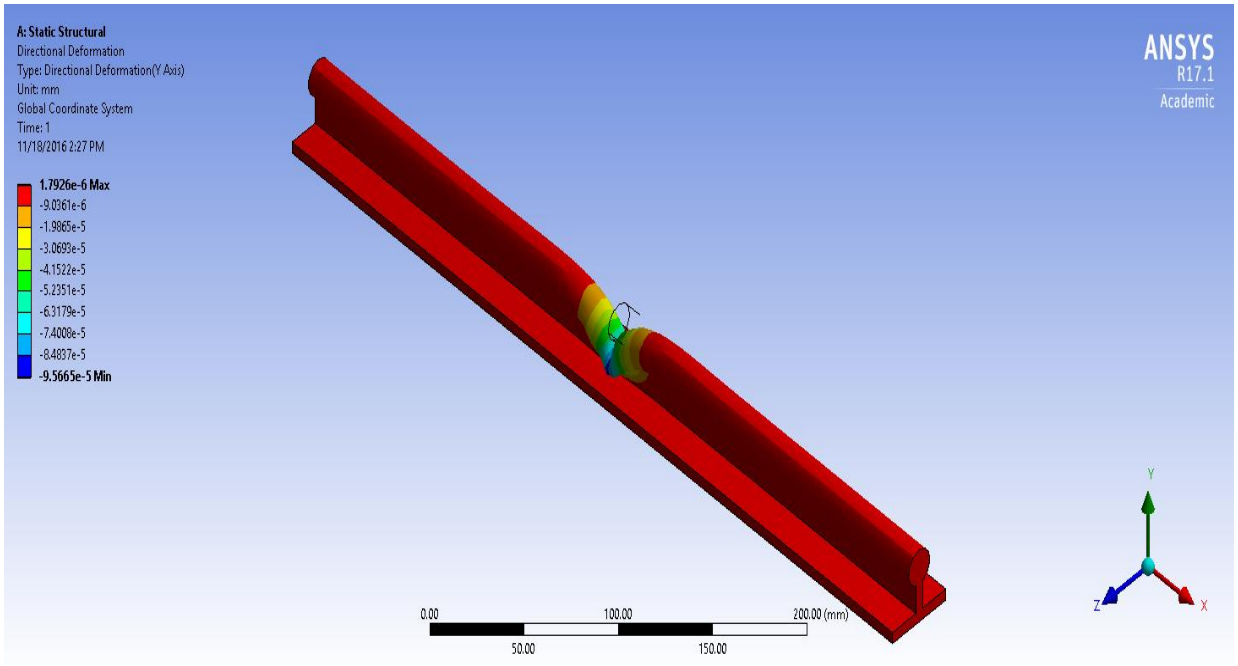


Figure 32: the total deformation for a 450 mm Aluminum rail.

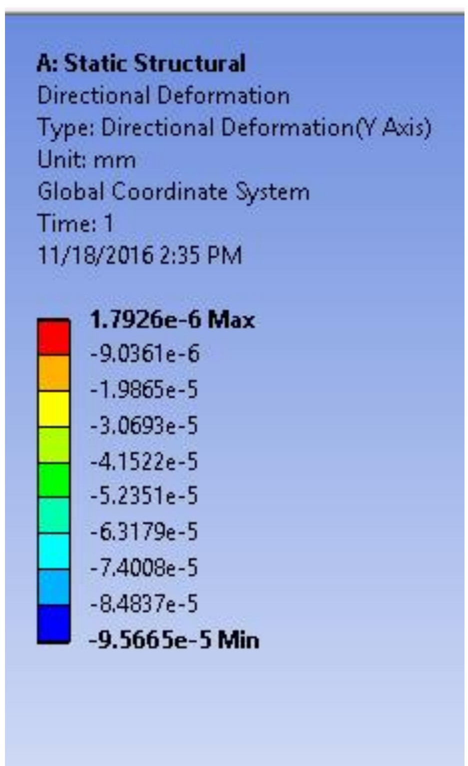


Figure 33: The values of maximum and minimum deflections on the rail.

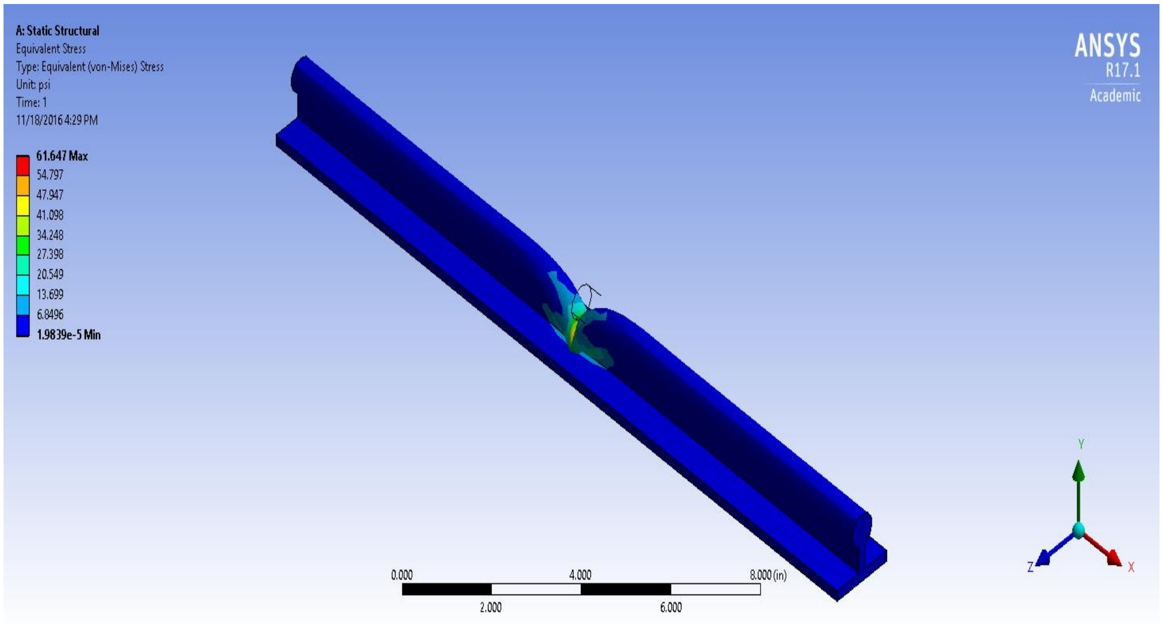


Figure 34: The maximum and minimum equivalent stress values for Aluminum 450 mm rail.

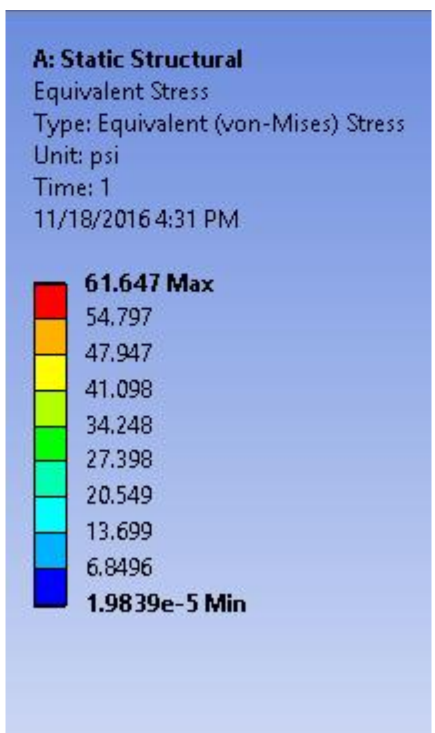


Figure 35: The maximum and minimum equivalent stress values for Aluminum 450 mm rail.

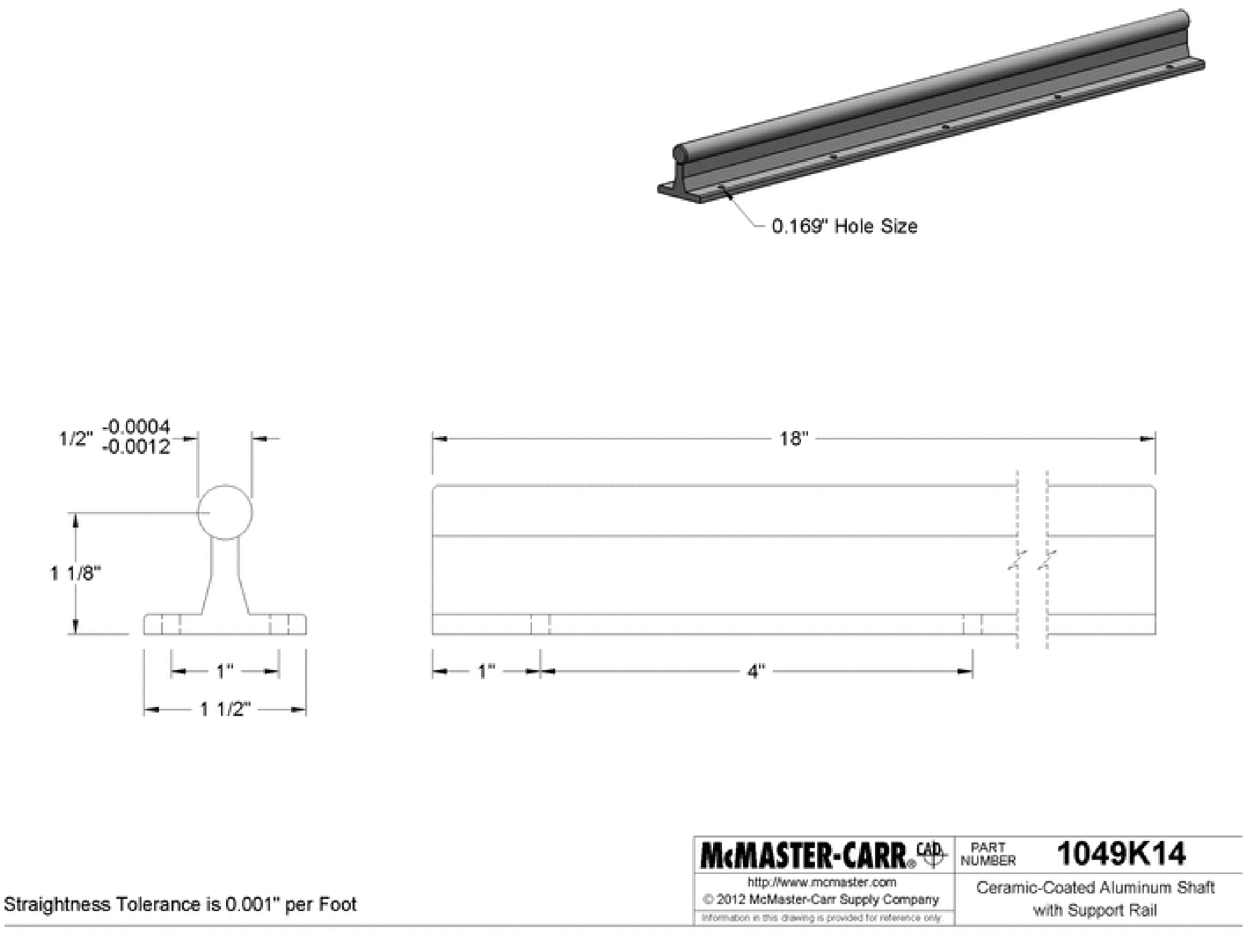


Figure 36: 6063 Aluminum, 1/2" Diameter rail [26].

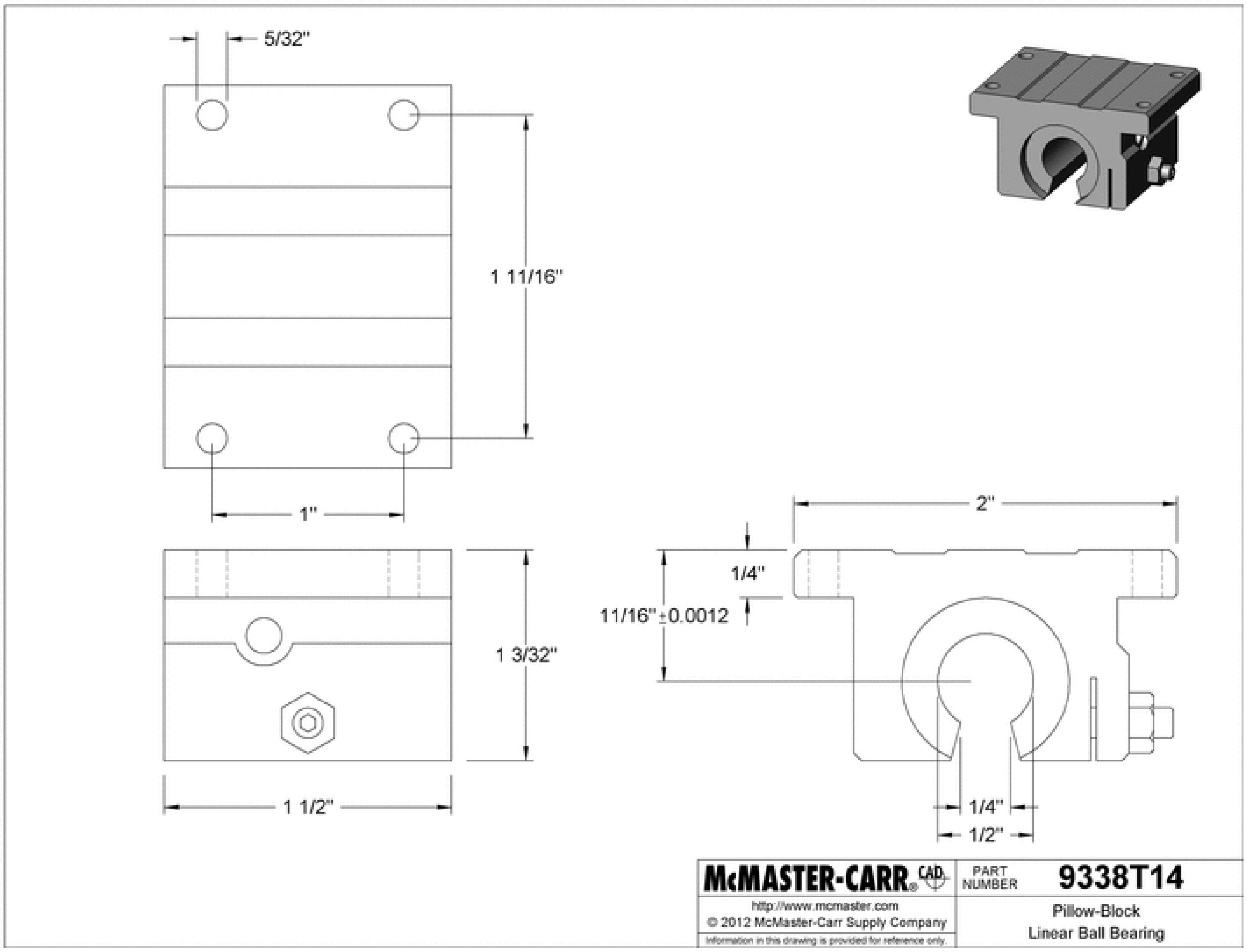
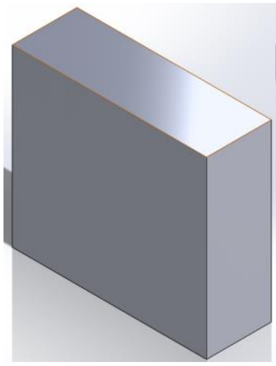
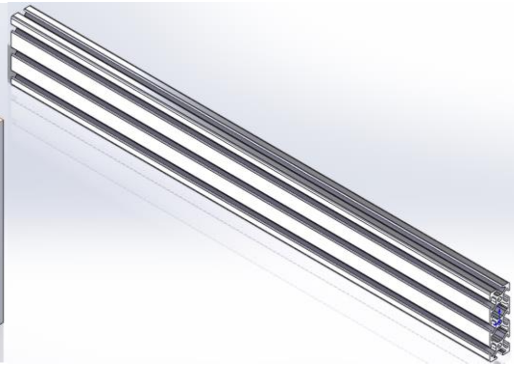
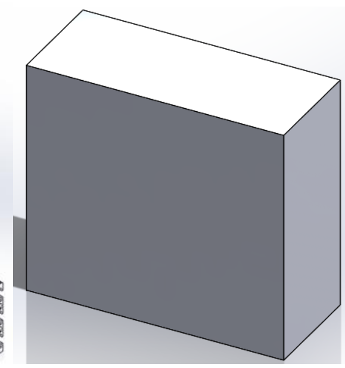
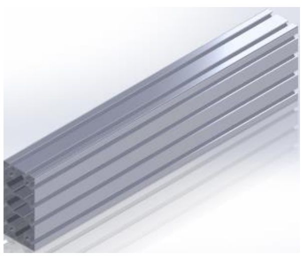
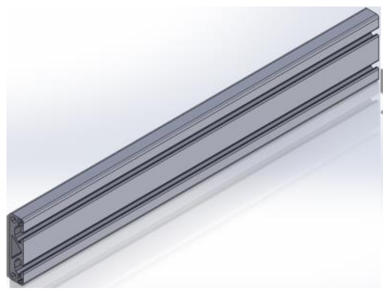
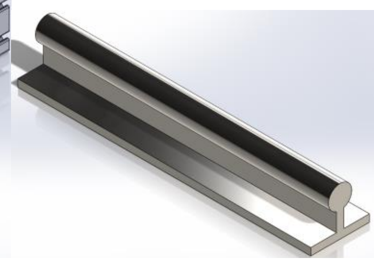


Figure 37: Mounted Linear Ball Bearing for Support Rail Shafts, 1-1/2" Length, 2" Width, 1-3/32" Height [27].

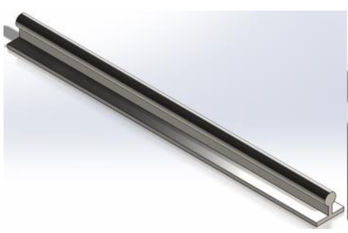
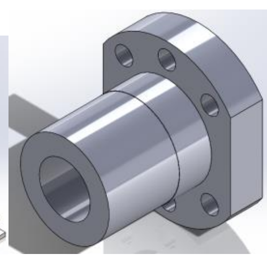
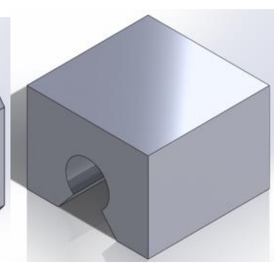
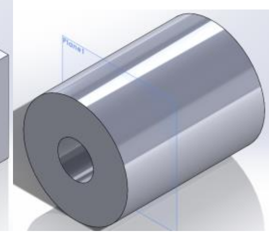
Appendix D – CAD Package

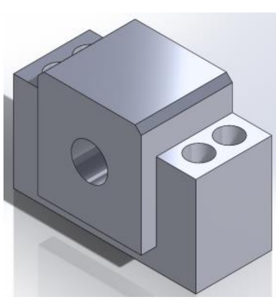
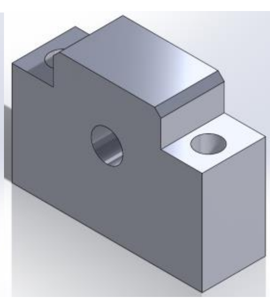
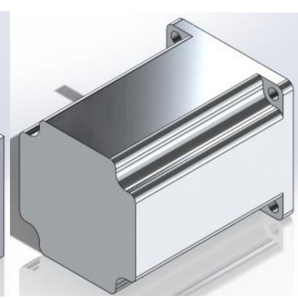
20 spacer mm 25 2576 600 CL 25mm spacer

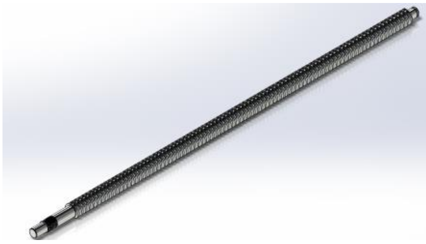
60x120 misumi extrusion 80x20 base extrusion 150mm linear rail

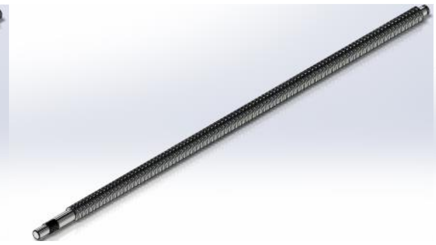
450mm rail ballscrew nut bearing block coupler for nema 23

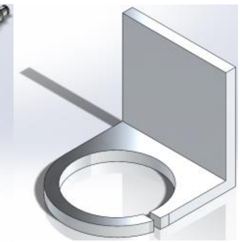

Fixed ballscrew support Floated ballscrew support Nema 23 280ozin RM1605-C7 L200



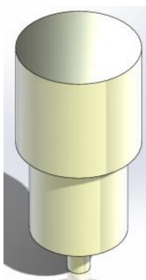
RM1605-C7 L450



RM1605-C7 L500

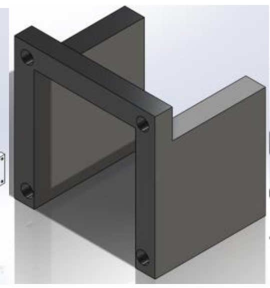


Router Mount

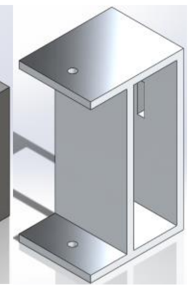


Router

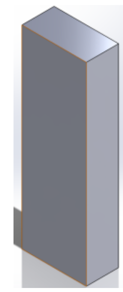
tall gantry



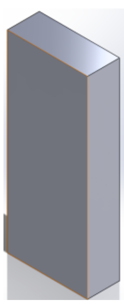
x motor spacer



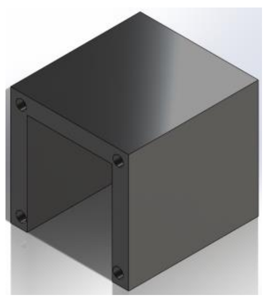
z axis plate



z axis spacer 20mm



z axis spacer 25mm



z motor spacer

Appendix E – Preliminary Budget

Table 41: Preliminary budget proposal for CNC Router Team A.

BoM for CNC Router Team A						
Item	**Qty**	**Price Each**	**Total**	**description**	**location**	**link**
1	1	$ 400.00	$ 400.00	Package discount for 3-450mm rail and 3-500mmball screw. 1 250mm ballscrew and 1 200mm linear rail set. Motor couplers and bearings.	ebay	http://www.ebay.com/itm/2-x-SBR20-500mm-linear-rail-1-ballscrew-RM1605-500mm-1-set-BK-BF12-1-couplers-/152209291431
2	1	$ 144.99	$ 144.99	Dewalt 2.25HP Router	amazon	https://www.amazon.com/Dewalt-DW618M-Maximum-motor-Router/dp/B0009E6JHK/ref=sr_1_21?s=hi&ie=UTF8&qid=1479661881&sr=1-21&keywords=dewalt+router
3	1	$ 245.00	$ 245.00	TinyG 3 axis kit	Automation Tech	http://www.automationtechnologiesinc.com/products-page/tinyg-kit/tinyg-3-axis
4	1	$ 26.00	$ 26.00	4th Axis for TinyG	Automation Tech	http://www.automationtechnologiesinc.com/products-page/nema-23/nema-23-quarter-inch-dual-shaft-with-flat
5	2	$ 27.75	$ 55.50	60x120 extrusion for sides	Misumi	https://us.misumi-ec.com/vona2/detail/110302688030/?Inch=0&CategorySpec=00000042730%3A%3Ax
6	6	$ 14.46	$ 86.76	80x20 extrusion for bed	8020.net	https://8020.net/shop/40-8020.html
7	1	$ 36.90	$ 36.90	Raspberry pi	amazon	https://www.amazon.com/Raspberry-Pi-RASP-PI-3-Model-Motherboard/dp/B01CD5VC92/ref=sr_1_3?s=pc&ie=UTF8&qid=1479090273&sr=1-3&keywords=raspberry+pi
8	1	$ 9.69	$ 9.69	Cable Chain 10x10mm x1000mm	Automation Tech	http://www.automationtechnologiesinc.com/products-page/cnc-parts/cable-drag-chain-wire-carrier-1020mm-r28-1000mm-40
9	3	$ 14.23	$ 42.69	25x75x600mm extrusion for base	8020.net	https://8020.net/shop/25-2576.html#product_tabs_cad
10	1	$ 109.68	$ 109.68	Hardware package (see hardware breakdown)	Openbuilds	http://openbuildspartstore.com/low-profile-screws-m5/
11	1	$ 49.95	$ 49.95	Clamping kit 6mm 36pc	Litlle Machine shop	http://littlemachineshop.com/products/product_view.php?ProductID=2718&category=11
12	1	$ 15.45	$ 15.45	18x18" 0.025" 4130 alloy sheet	Online metals	https://www.onlinemetals.com/merchant.cfm?pid=9659&step=4&showunits=inches&id=814&top_cat=197
13	60	$ 1.20	$ 72.00	Spring loaded T nuts	Openbuilds	http://openbuildspartstore.com/spring-loaded-tee-nuts/
14	1	$ 80.14	$ 80.14	Aluminum 6061 plate. 12x24" .375	online metals	https://www.onlinemetals.com/merchant.cfm?pid=1249&step=4&showunits=inches&id=76&top_cat=60
15	1	$ 15.90	$ 15.90	Aluminum 6061 bar 1x2.5x12"	online metals	https://www.onlinemetals.com/merchant.cfm?pid=13491&step=4&showunits=inches&id=997&top_cat=60
16	1	$ 28.00	$ 28.00	Aluminum 6061 plate .375x2.5x40	online metals	https://www.onlinemetals.com/merchant.cfm?pid=1249&step=4&showunits=inches&id=76&top_cat=60
17	4	$ 4.95	$ 19.80	Jog knobs	Openbuilds	http://openbuildspartstore.com/jog-knob/
18	5	$ 4.50	$ 22.50	Limit switches	Openbuilds	http://openbuildspartstore.com/micro-limit-switch-kit-with-mounting-plate/
19	20	$ 2.00	$ 40.00	3 wire cable by the foot	Openbuilds	http://openbuildspartstore.com/wire-cable-by-the-foot/
20	20	$ 2.50	$ 50.00	4 wire cable by the foot	Openbuilds	http://openbuildspartstore.com/wire-cable-by-the-foot/
		Total	$ 1,550.95			

Table 42: Hardware Breakdown for CNC Router Team A

Hardware summary for CNC Router				
Work Platform				
Qty	Size	Location being used	cost	total cost
36	M5 x 10mm	Attach work platform to baseplate	0.128	4.608
36	Spring loaded t-nuts	Slide in baseplate frame	1.2	43.2
Side Extrusion Attachment				
14	Double L bracket	Attaching sides to base and work platform	1.25	17.5
56	M5 x 8mm	for use in L brackets	0.12	6.72
56	T-nuts	Insert in extrusion tracks for to use with L brackets	0.198	11.088
Plates on top of side extrusions				
12	M5 x 10mm	Attaching Plate to side extrusions	0.128	1.536
12	Spring loaded t-nuts	Sliding into side extrusions for plate attachment	1.2	14.4
Linear Rails for X axis				
12	M5 x 8mm	Attach linear rails to Plate on side extrusion	0.12	1.44
Bearing Blocks				
16	M5 x 30mm	Bolt from Plates on extrusion sides into Bearing spacers	0.16	2.56
8	M6 x 60mm	Bolts through bearing block to spacer	0.2432	1.9456
Bearing to Gantry Attachment				
16	M5 x 10mm	Attach gantry to x axis bearings	0.128	2.048
Ball Screw nut to Gantry attachment				
8	Nylon hex nut	secure ballscrew to gantry	0.15	1.2
8	M5 x 25mm	Bolt through ballscrew nut and gantry plate	0.15	1.2
X axis motor mounts				
4	M5 x 65mm	Bolt through motor flange and bracket into the bearing mount	0.206	0.824
8	M5 x 10mm	Attach motor to spacer or spacer to bearing block	0.128	1.024
4	Nylon hex nut	hold bolt that go through motor into spacer	0.15	0.6
Ball nut mount plate to gantry attachment				
8	M5 x 20mm	Ball nut mounting plate attachment to gantry	0.136	1.088
Gantry Bearing mount plate to gantry assembly				
8	M5 x 20mm	Attaches x axis bearings mount to gantry	0.136	1.088
Ganty Back Plate to gantry side attachment				
18	M5 x 20mm	This will use corner block in gantry with 3 screws from each direction	0.136	2.448
Ganty motor mount for y axis				
2	M5 x 30mm	Attach motor mount to gantry	0.16	0.32
4	M5 x 20mm	Attach motor to motor mount	0.136	0.544
4	Nylon hex nut	Secures through bolts	0.15	0.6
Y axis ballscrews				
4	M6 x 60mm	Attach bearing block to gantry for y axis	0.2432	0.9728
Y axis linear rails to gantry				
12	M5 x 10mm	Attach linear rails to back of gantry	0.128	1.536
Y axis bearing blocks attached to z axis				
16	M5 x 20mm	Attach bearing blocks to the z axis	0.136	2.176
Z axis frame assembly				
12	M5 x 20mm	Attaches all z axis frame panels to each other	0.136	1.632
Z axis linear rail attachment				
8	M5 x 10mm	Attaches linear rails to the z axis frame	0.128	1.024
Z axis bearing blocks to router mount				
16	M5 x 20mm	Attach bearing blocks of z axis to router mount	0.136	2.176
Router Mount				
2	M5 x 30mm	Mount router to router mount	0.16	0.32
2	M6 x 30mm	Mount router mount to back plate	0.1962	0.3924
Z axis motor mounts				
4	M5 x 65mm	Through z axis motor, through the spacer into z axis	0.206	0.824
			Total Hardware cost	$ 129.03
			Total cost with Openbuilds discount	$ 109.68