Design of a Mobile CNC Router

Group members

Marcus Jackson, email: msj18@students.uwf.edu

and

Benjamin Linam, e-mail: bml42@students.uwf.edu

and

John Murphy, email: jgm15@students.uwf.edu

and

Mike Zaia, e-mail: mbz1@students.uwf.edu

Team Leader

John Murphy

Speciality Advisor

Dr. J. Mann

Course Instructor

Dr. J. Piacenza

Capstone Design I

EGN4950

Fall 2018

We certify that this assignment is the result of our own efforts.

Abstract: In an age where convenience is becoming necessity, making a machine that can handle whatever demand its user has for it just seems obvious. So, why not design and build a machine that can take the concept of a router controlled by a computer to its logical extreme? A CNC router that can perform operations on materials of any size. This paper goes over the design of such a machine; though, with the limitations one might expect from a two-term, senior design project. It should also be stated upfront that the machine is still in its design phase, and so some aspects are still subject to change.

Table of Contents

1. Introduction:

CNC stands for Computer Numerical Control—it refers to the automated control of tools utilized in machining by a computer. Thus, a CNC machine is a device such as a plasma cutter, laser cutter, mill, or router that is controlled by a computer such that a tool is moved along a set of axes in order to perform jobs on work materials or workpieces.

For this project, the goal is to design and build a CNC router that can perform operations on a workpiece beyond the basic axis limits of the machine. This will be accomplished by combining the basic 3-axis, CNC router system with an additional movement option that allows the entire CNC machine's frame to move as part of the automated process of routing the workpiece. To be more specific, the Mobile CNC Router will perform routing operations within its base work area determined by the limits of its axes, and if the job area is larger than the machine's base area—the machine will move to the next area, then the machine body will become stationary once more, and the machine will perform routing operations again.

2. Problem Definition:

2.1 Problem/Need:

Normally, a CNC router can only cut within the limits of its axes, and if a job is too large for the CNC router a user has, then the user is forced to work with a handheld device (less accurate), find a larger CNC router that can do the job (potentially leading to having to buy a larger CNC router which can be expensive or having to pay someone to do the job for them who already owns such a device), go through the process of cutting the workpiece in smaller portions (which can be a hassle due to having to reorient the workpiece repeatedly on the machine and having to make sure everything is lined up properly by hand), or the user can give up and decide that the job isn't feasible for them. Therefore, there's a need for a CNC router that can perform routing operations on a large scale while staying reasonably priced for the customer's who would need one.

2.2 Intended user(s) and use(s):

The intended user for the design would be any customer who needed a router to cut a workpiece to realize their designs—however, there will be stipulations in regards to what can be reasonably be accomplished by the end Capstone II. While commercial routers often vary in terms of materials they can cut, the limited amount of time for this project means that only one material will be focused on for our proof of concept, and so the intended use for this project will be to route designs into a sheet of balsa wood, in particular. An example of users who could make use of a CNC router that can cut varying sizes of balsa wood sheets would be customers who require balsa wood for modeling. Planes, buildings, and even bridges can be modeled with balsa wood due to the material being both light and strong.

2.3 Assumptions and limitations:

Assumption 1: Our team will have time to work on the project enough to see it to completion.

Assumption 2: We'll be able to find cheap enough parts and get creative enough to realize the goal of staying within our projected budget.

Assumption 3: The machine can be made stable enough to operate properly; therefore, chatter/vibrations from the secured rotational cutting device will not be so detrimental that the machine cannot perform adequately, and the act of cutting will not push the machine upward to the point where the workpiece is negatively affected.

Assumption 4: The Arduino will suffice for our proof of concept project and a specific, dedicated microcontroller will not need to be used.

Limitation 1: As a negative extension of **Assumption 1**, two of our members work and are taking 14 credit hours' worth of classes this term and will be doing the same thing next term which makes available project time scarcer for them.

Limitation 2: If an alternative source of funding is not secured for our budget, then our team will be paying out of our own pockets. Because of this, we're limited by how much we're willing and able to spend.

Limitation 3: Though we've put in a lot of research into CNC machines by this point, our knowledge is still limited based on what we've gathered in a short time, so we're limited by our own expertise and what expertise we can obtain from faculty, our peers, and consulting the Internet.

Limitation 4: There is a limited amount of time to complete the project. The project only has time allocated for two terms, and most of Capstone I has been planning and design. In response to this limitation and **Limitation 1**—it's vital to simplify the project where possible. While it would be nice to have a project that could go straight to the market as a modern marvel, such an outcome is outside the scope of this senior design project.

Limitation 5: While it would be nice to incorporate features such as a small vacuum into the machine to clean up dust—if time doesn't permit, cost becomes an issue, or it just doesn't appear feasible then extra conveniences like this may have to be rejected; in such a case, tasks like this may fall to the operator cleaning up the dust and chips with a personal vacuum, or these features may be added after Capstone II if our team continues to fine tune the project for a potential future release.

Limitation 6: The machine will not be as portable and as freely mobile as an ideal version would be. For the prototype, the machine will be connected to an external computer, the motor drivers will likely also be external, and the machine will be powered by a power supply connected to a wall outlet. Thus, cutting area will be limited by the length of the shortest cord connected externally to the machine.

Limitation 7: Since the machine's body can move, a vacuum table being included with the router isn't feasible. This means that workpieces will need to be secured before cutting—either using clamps, double-sided tape, or being screwed into a sacrificial board beneath the workpiece. To prevent material pop-up when cutting all the way through a sheet, it may be necessary to leave small sections of the workpiece uncut which would keep the design secured to the material it was cut from—these uncut sections of the workpiece are often referred to as tabs.

Limitation 8: The Arduino is more limited than a microcontroller fine-tuned and setup for our purposes.

2.4 Design objectives:

1) The attached cutting bit will be able to be moved along three axes.

2) Early testing with the axis system may use something like a pen to trace along paper instead of an actual cutting bit—this is to prevent damaging cutting bits unnecessarily.

3) The device will be able to complete a job within its base cutting area.

4) If the device cannot finish its job within its base cutting area—it will cease cutting operations, move to the next location, reposition the cutting bit, and then continue to cut. For the sake of simplifying this project to be more feasible, the body of the machine will only be able to move with one degree of freedom.

5) Like most other CNC machines, the machine should be compatible with g code.

6) The final design will need to be tested near the end of Capstone II, and the most important aspect will be to show the proof of concept—that the machine can perform its cutting operation via the use of its axes and then move itself to its next cutting location. Certainly, because the project goal is to create a router, it's desirable to be able to route through balsa wood as intended. To that end, a good test would be to cut an ellipse due to it requiring both the x and y axes to perform properly. It will also be important to make the ellipse long enough to necessitate the machine frame having to move to the next cutting location to finish the part.

3. Design Specifications:

- 3-axis CNC router system
- Overall dimensions of 30" by 30" (762 mm by 762 mm)
- Cut with a depth of at least 0.25" through sheet of balsa wood
- Cutting area (without moving entire machine body) of approximately 19" by 21" (482.6 mm by 533.4 mm)
- Cutting area (with moving entire machine body) of approximately 28.5" by 21" (723.9 mm by 533.4 mm)
- 120V wall input
- 30V stepper driver input from power supply
- Max spindle speed of 25000 rpm
- Max feed rate of 5000 mm/min

4. End-Product Description:

We're very excited to introduce our new product—the Mobile CNC Router. After extensive research our team came to the realization that CNC routers would be a lot more convenient for the user if they could get one that was cheap and if it could more easily cut past its conventional limits. For instance, is the sheet of balsa you want to cut too long? Instead of going through the headache of fiddling around with a wooden sheet that's just too big for your router table, just attach your workpiece to a sacrificial board, set the Mobile CNC Router around or on the workpiece, upload your instructions, and then watch it go. Alternatively, you need to engrave a floor? Well, you can't do that with a traditional CNC router, but The Mobile CNC Router's got you covered there too.

5. Design constraints:

5.1 Economical

The economical aim of this project is to keep costs low where possible. Not only are we going to construct the machine ourselves instead of using a kit in order to save on costs, but furthermore, the Mobile CNC Router will be small for what it can accomplish. For instance, a conventional CNC router could easily cost in the thousands of dollars depending on how big it is, but because our machine is smaller we can attempt to keep it within a lower cost. Because we're thinking about the machine as a potential product, keeping costs low to maximize potential future profits makes sense.

5.2 Ethical

A CNC router, in general, can take jobs away from people who cut material sheets by hand with non-automated tools.

If the product were to be successful and we eventually took it to market in some form, even some CNC router manufacturers could lose money. Though, admittedly, the likelihood of our project beating out professional grade CNC routers is unlikely by the end of Capstone II.

5.3 Health and Safety

Fail-safes will need to be designed and implemented to prevent the device from harming users in the event of a machine failure.

Proper safety equipment will need to be worn while working on the device. As a few examples, safety glasses to protect people's' eyes and breathing masks to prevent the inhalation of wood dust would potentially be necessary when working on the project.

Warnings, cautions, and guidelines for safe operation should be provided for the for users.

Dangerous parts such as belts that users could get hair or jewelry stuck in need protective housing/covering to prevent injuries.

5.4 Manufacturability and Sustainability

This project is more of a proof of concept in many ways. If we were making an actual product version of our project, we would likely replace the Arduino Uno with some particular microcontroller. Other than that, it's important to keep costs low where possible while still attempting to attain the best possible product within reason. Not overcomplicating the design will also be good in terms of manufacturability.

In terms of the design using energy and resources efficiently, the project doesn't seem to have too many issues with sustainability. If any batteries end up being used, then it's important to take efforts to make sure they're recycled properly at the end of their lifespan since just throwing those away normally can be bad for the environment. The project doesn't endeavor to tap into any renewable sources of energy. Harvested wood debris from cutting could potentially be harvested for other purposes—there are various ways to reuse wood shavings, dust, and chips. Some places will burn them as renewable energy, for instance—though you would need around a literal ton of them to start seeing much profit, so it would just be something for the environment instead of specifically for ulterior gain.

6. Engineering Standards:

For a CNC machine, one industry standard is being compatible with G-code. It's also important that the machine is safe for users to operate, stable enough to function properly, and can perform routing operations accurately. Further, NEMA 17 motors are currently being looked at for use with the project, and the "17" in NEMA 17 corresponds to the size of the motor—this is a useful standard in that NEMA 17 motors should be close to the same size from manufacturer to manufacturer; although, sizes can vary somewhat between different NEMA 17 motors depending on the manufacturer, so it's still good to not buy motors from alternative manufacturers carelessly.

7. Technical Approach:

7.1 Functional Block diagrams.

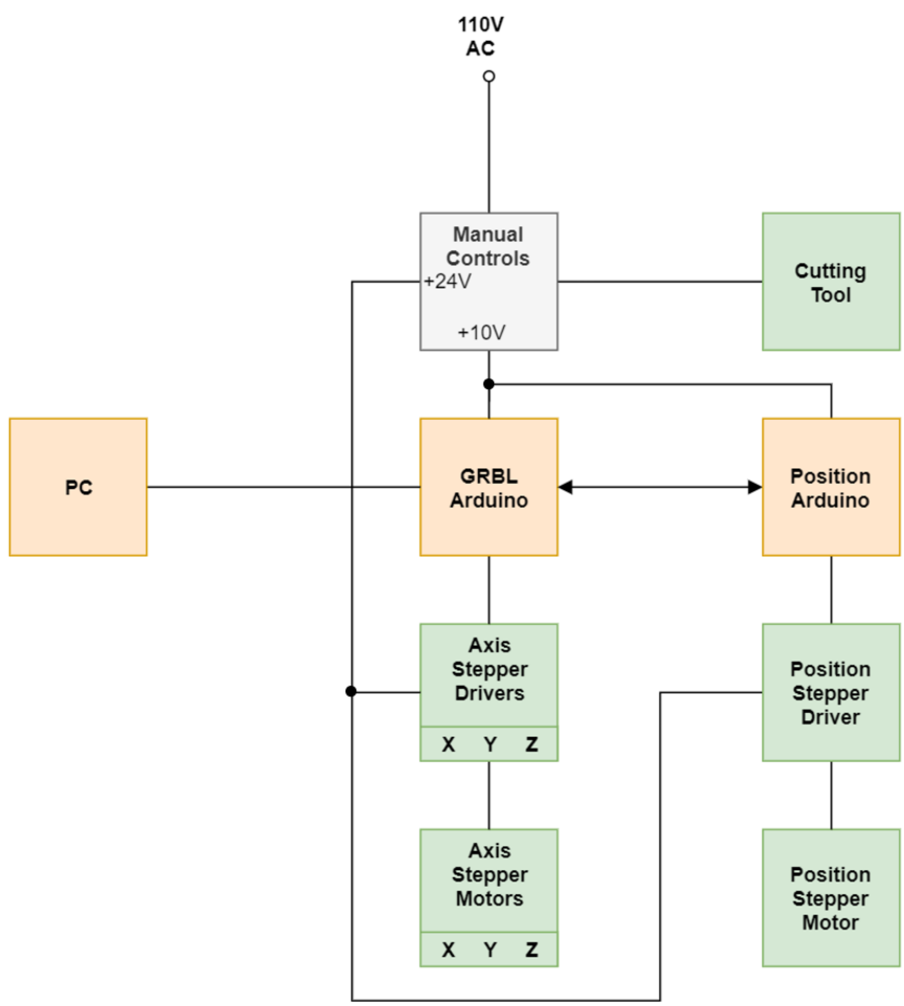

Figure 1. A block diagram of the Mobile CNC Router system. Software components are shown in red, electrical components are shown in green, and the blue-gray Manual Controls block corresponds to Figure 2.

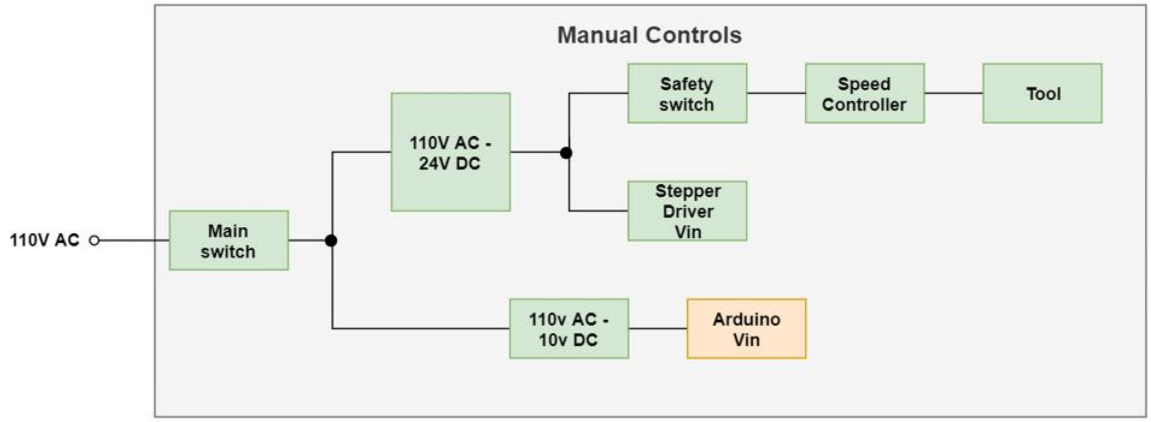

Figure 2. A more detailed view of the Manual Controls block from Figure 1. Software components are shown in red, and electrical components are shown in green.

7.2 Functional Requirements for Blocks

Table 1. Functional requirements and specifications of the Manual Controls block.

Requirements	Specifications
Functional Requirements	Supply power to the stepper drivers (24V) Supply power to the Arduino controllers (10V) Power switches and cutting tool speed controller knob
Performance Requirements	V_{in}: 120V AC V_{out}: 24V DC @100watts V_{out}: 10V DC @10watts
Operator Interaction	Main power switch Cutting tool safety switch Cutting tool speed controller

Table 2. Functional requirements and specifications of the GRBL Arduino block.

Requirements	Specifications
Functional Requirements	G-code interpretation to control axis motion
System Interaction	Connected to 10V supply
Operator Interaction	Stop/Reset button
Hardware/software interface	Axis Stepper Drivers(dp0 - dp7) Position Update Arduino External PC

Table 3. Functional requirements and specifications of the Position Arduino block.

Requirements	Specifications
Functional Requirements	Programed segment locations to control position update
System Interaction	Connected to 10V supply
Operator Interaction	Stop/Reset button
Hardware/software interface	Machine Position Stepper Drivers GRBL Arduino

Table 4. Functional requirements and specifications of the Axis Stepper Drivers block.

Requirements	Specifications
Functional Requirements	Convert the low power digital stepping signal from Arduino to a high power stepping signal to drive the stepper motors. Power output of each stepper driver goes to an individual stepper motor.
Performance Requirements	V_{in}: 24V DC
System Interaction	Drives stepper motors

Table 5. Functional requirements and specifications of the Axis Stepper Motors block.

Requirements	Specifications
Functional Requirements	Convert the high power stepping signal from driver output to rotational motion.
Performance Requirements	NEMA 17 compatibility standards I_{in}: 1.5A
System Interaction	Drive Axis motion

Table 6. Functional requirements and specifications of the Cutting Tool block.

Requirements	Specifications
Functional Requirements	Powered/controlled via speed controller in manual controls
Performance Requirements	V_{in}: 120V AC I_{in}: 5A
Operator Interaction	Powers on with safety switch. Stepper drivers will not get power until the cutting tool is spinning.

7.3 Technical Details of Implementation

7.3.1 Theory and Calculations

Stress:

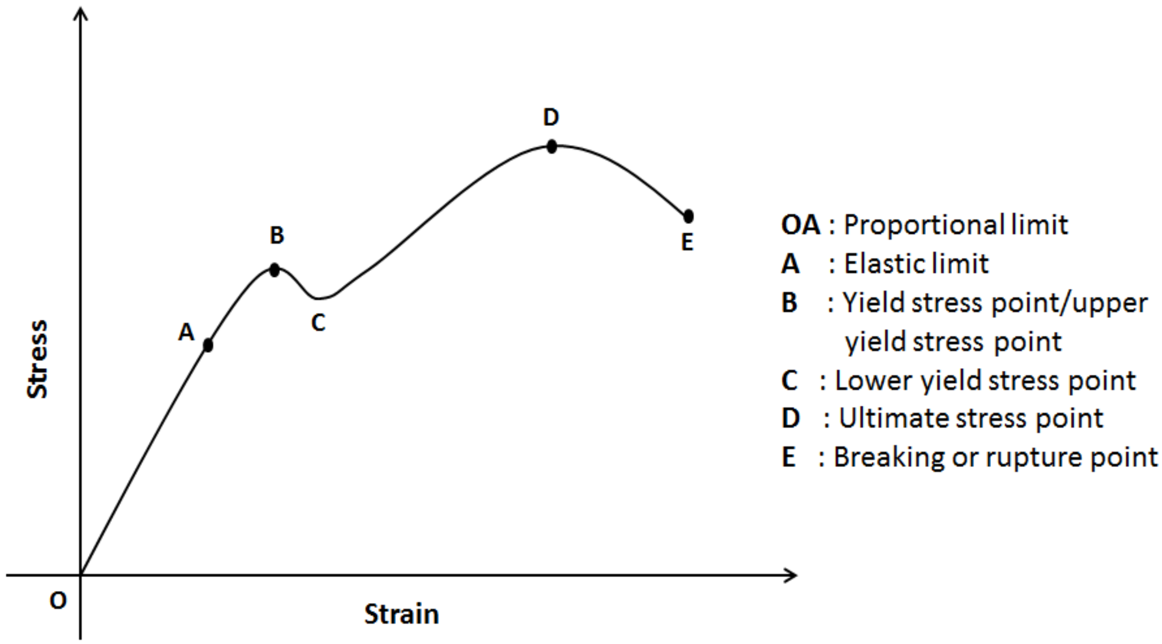

Figure 3. A general stress-strain curve.

This stress-strain curve shows how to make sure the materials that are picked will be rigid enough. The yield strength of the metal plates, members, and fasteners can be easily obtained. All members will be kept well below their elastic limit. To ensure this, the stress equation shown in Equation 1 can be rearranged to find the minimum cross-sectional area needed to support the conditions.

$$\sigma = \frac{F}{A} \tag{1}$$

In conjunction with this, shear stress at all joints and fasteners will be calculated as well. The equation for shear stress is the same in principle, but the force accounted for is the force normal to the joint.

Power Consumption:

$$P = IV \tag{2}$$

$$P_{Total} = P_{Driver} + P_{Arduino} + P_{Tool} - P_{Loss} \tag{3}$$

$$P_{Loss} = P_{Supply-in} - P_{Supply-out} \tag{4}$$

These power consumption equations will be used to calculate the estimated operating power consumption of the machine where P_{Loss} represents the efficiency of the power supply.

7.3.2 Flow Charts

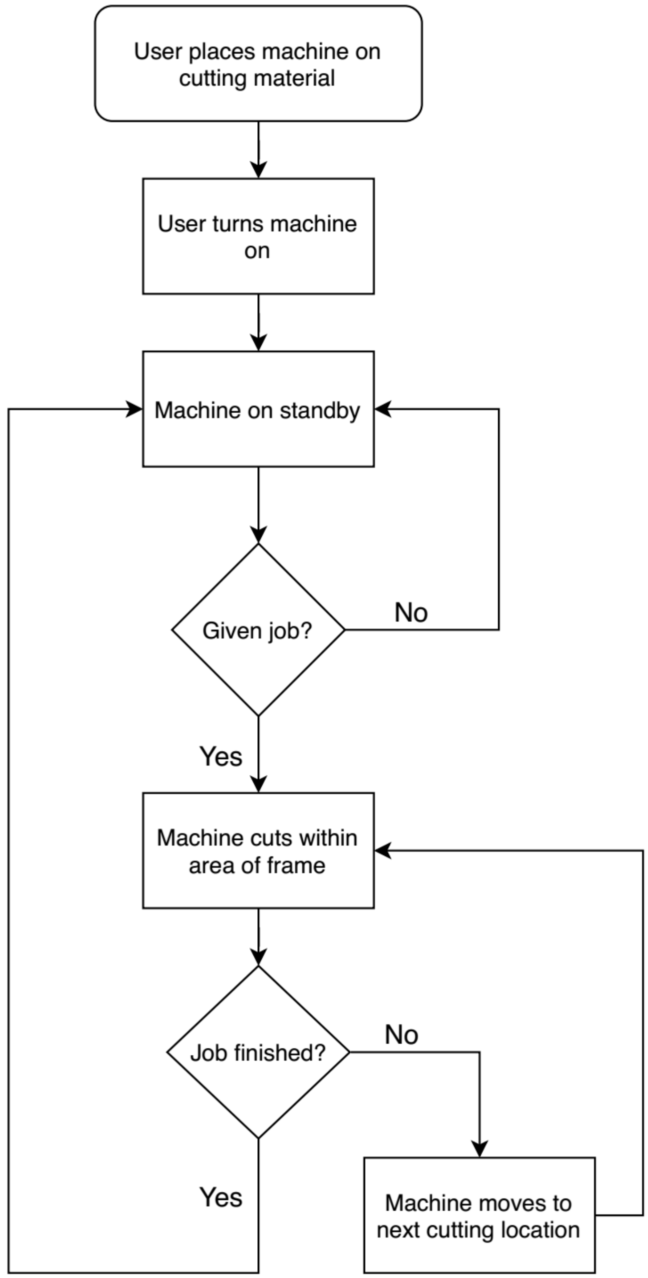

Figure 4. A flow chart showing how the Mobile CNC Router should function.

7.3.3 Schematics

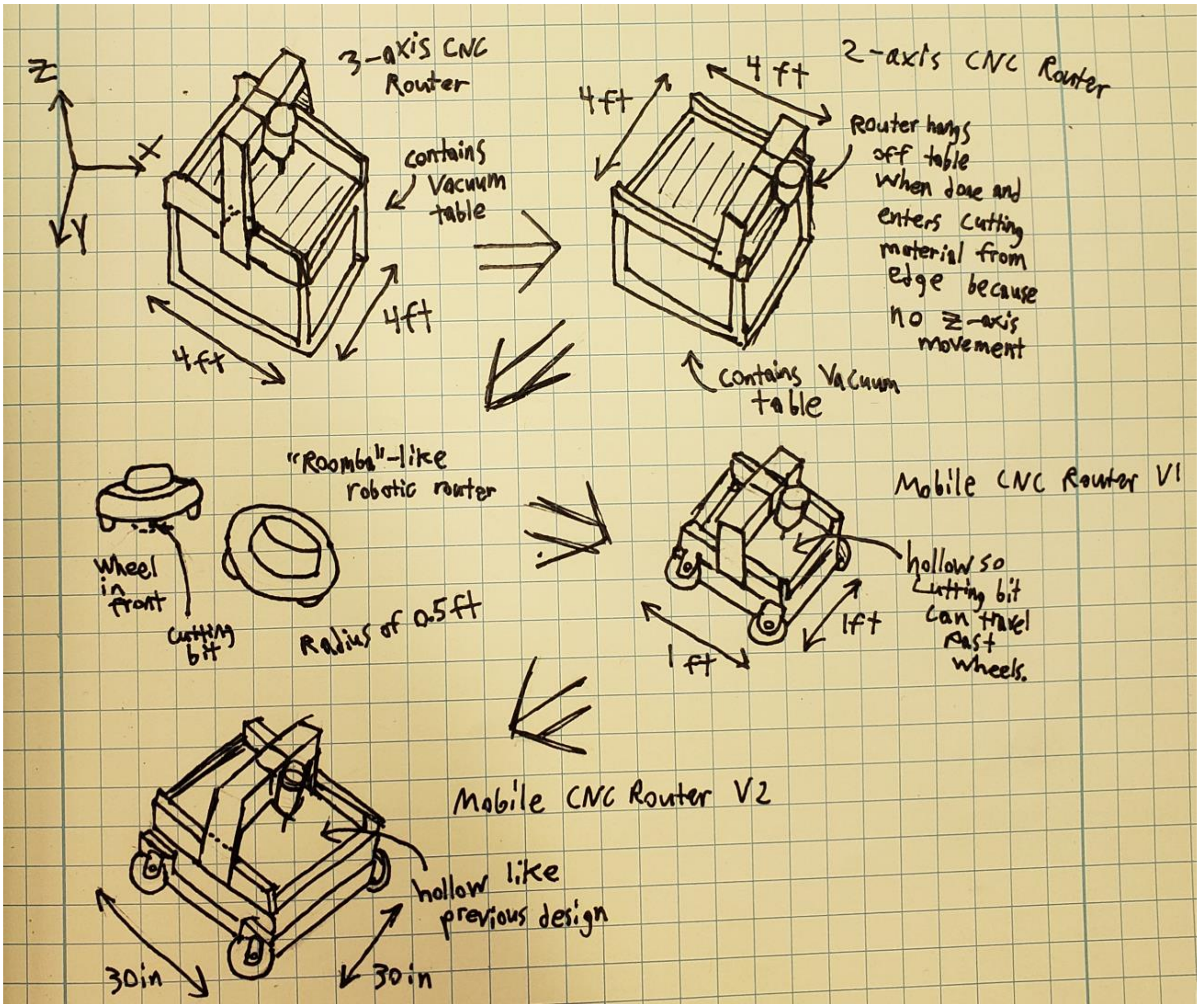

Figure 5. Sketches showing the evolution of our project from the first router design to our current design. There were additional variations of the designs that are not pictured here, but many of those were too derivative of the pictured designs to include.

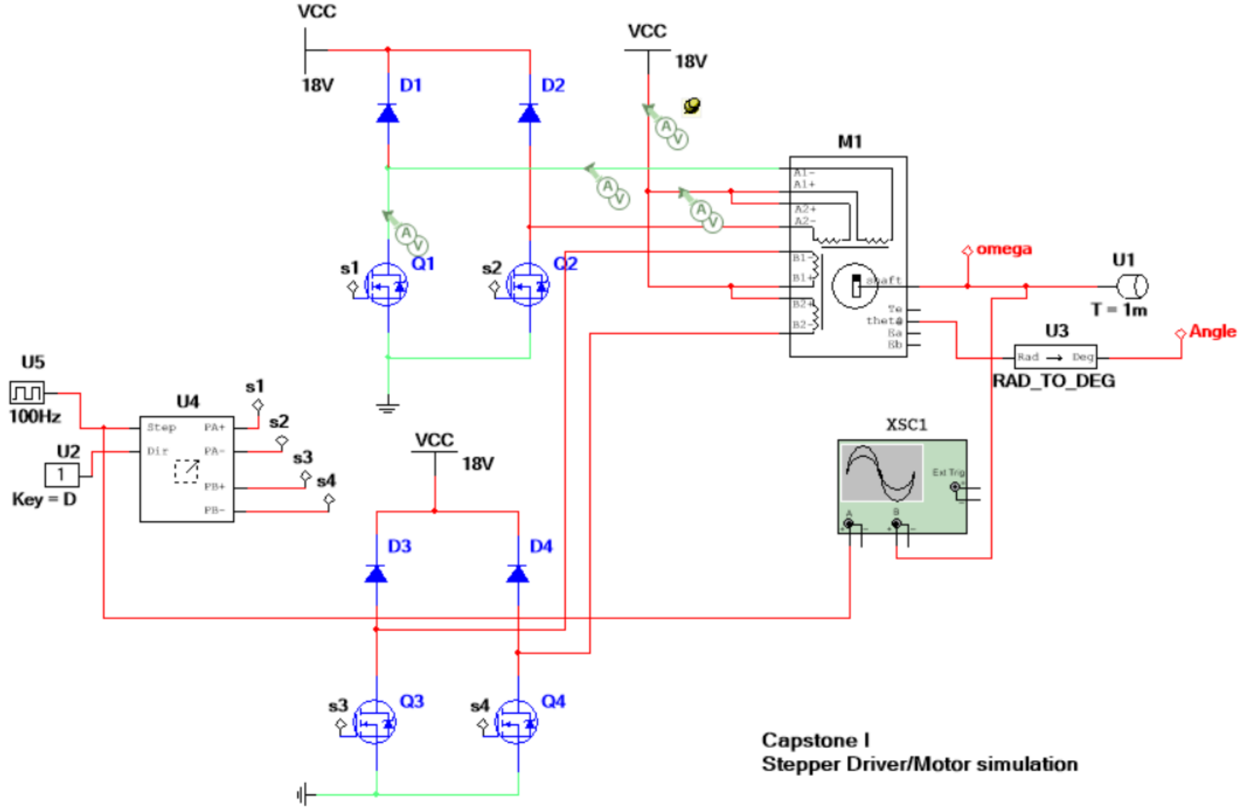

Figure 6. A Multisim circuit schematic detailing wiring from a stepper driver (U4) to a motor (M1) that was created for simulation purposes.

7.3.4 Simulations

Stepper Driver/Motor Simulation:

The following Multisim simulations were performed using Figure 6 from the **7.3.3 Schematics** section. Figure 7 shows the digital input and the stepper motor output for forward motion when tested on a virtual oscilloscope.

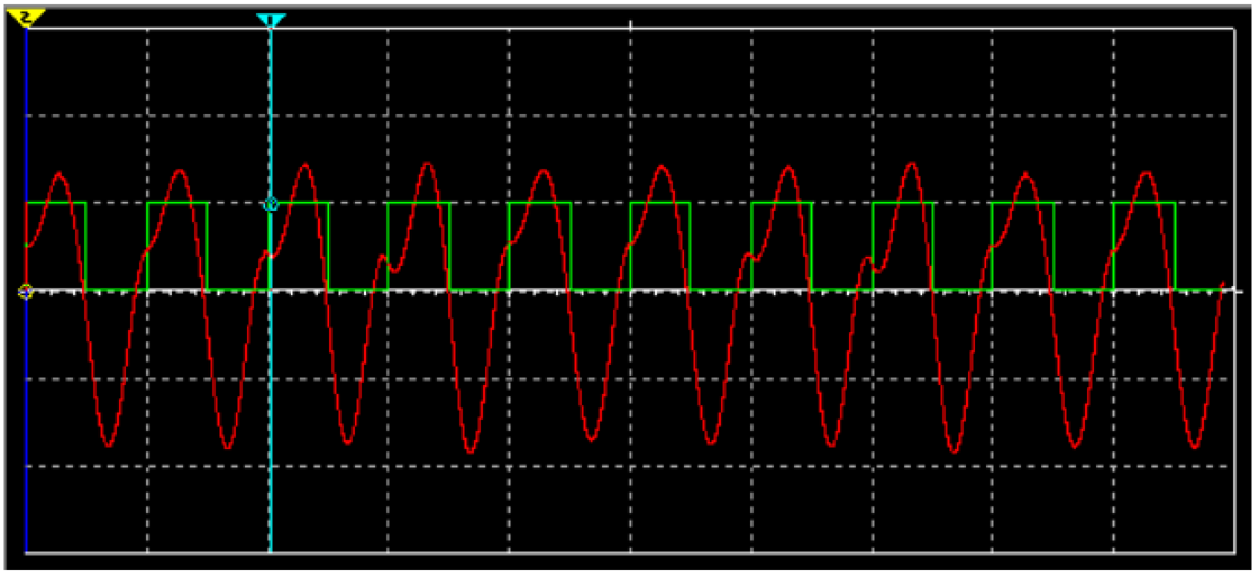

Figure 7. A Multisim simulation of the stepper driver digital input (green) versus the stepper motor shaft forward motion (red) as obtained by a virtual oscilloscope. The digital bitstream input was chosen to be 100 Hz.

Figure 7 represents forward motion. The Arduino controller outputs a logic 1 value to the stepper driver in order to drive the stepper motor forward. A phase shift on the rising edge of the stepper motor output verifies forward rotational motion. This phase shift is triggered on the rising edge of the digital bitstream input.

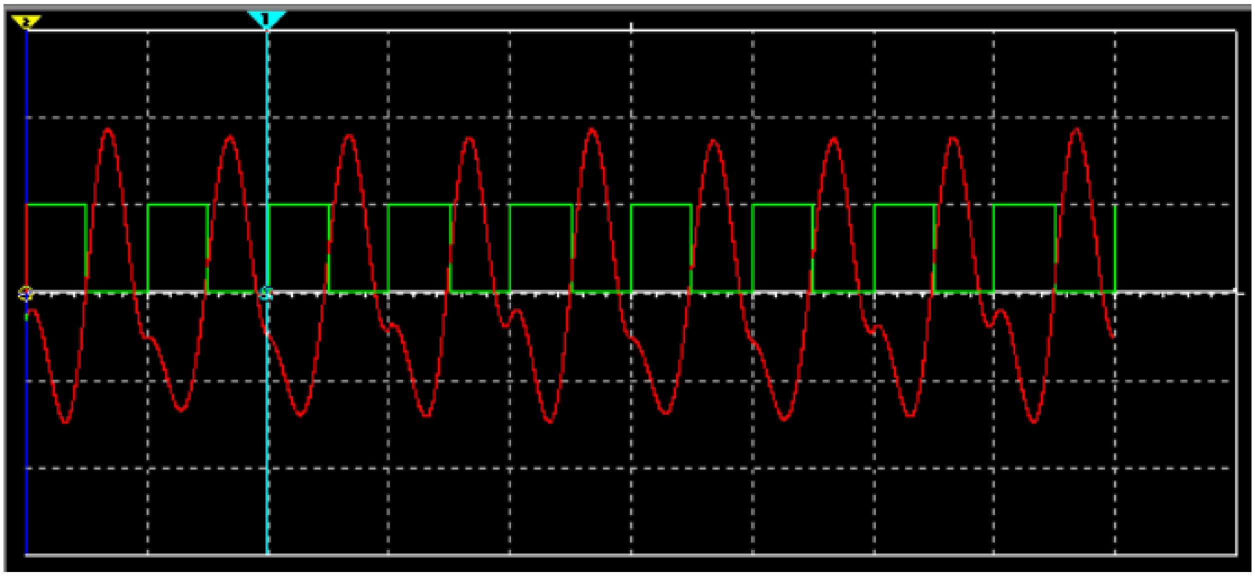

Figure 8. A Multisim simulation of the stepper driver digital input (green) versus the stepper motor shaft reverse motion (red) as obtained by a virtual oscilloscope. The digital bitstream input was chosen to be 100 Hz.

Figure 8 represents reverse motion. The Arduino controller outputs a logic 0 value to the stepper driver in order to drive the stepper motor backwards. A phase shift on the falling edge of the stepper motor output verifies reverse rotational motion. This phase shift is triggered on the rising edge of the digital bitstream input.

Axis Movement Simulation (x and y axes only):

Simulation of the x and y axes moving for 11-30-18 build (may need to download to view)

Stress and Displacement Simulation on Slide Rail Joints:

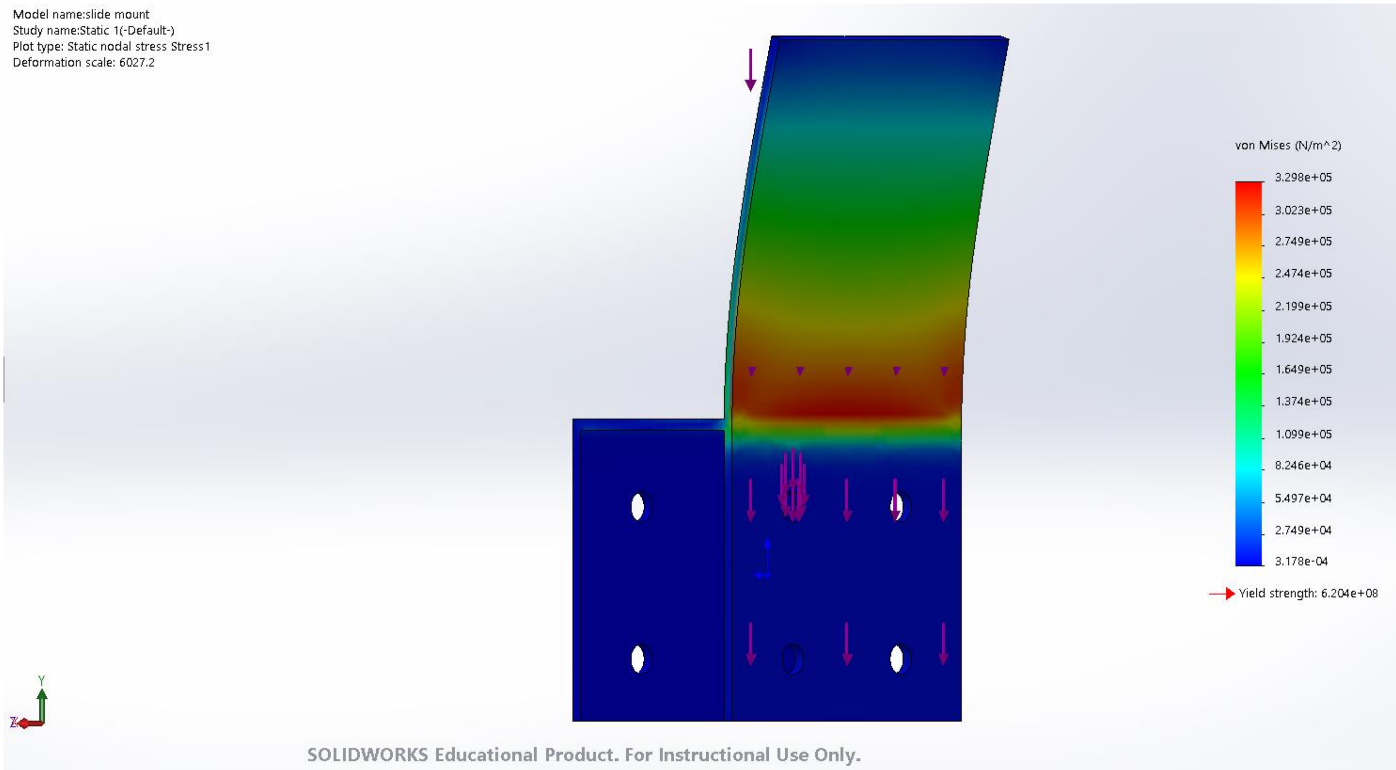

Figure 9. Solidworks study showing estimated stress in the slide rail joints.

Figure 9 shows the estimated stress in the slide rail joints—these are a concern because the router tool itself is suspended between these. For this test, the material specified was Solidworks alloy steel. The thickness of the plate in this test was 3 mm, but this could be increased later on. The input force on the joint was 40 N. This came from the force of gravity on the members as well as the approximate router weight. No fasteners or hardware were accounted for in this calculation because they haven't been decided on yet, but they aren't expected to drastically increase the force. Another thing to note is that two slide mounts will be utilized in the design which effectively means that the force will be half of what was projected.

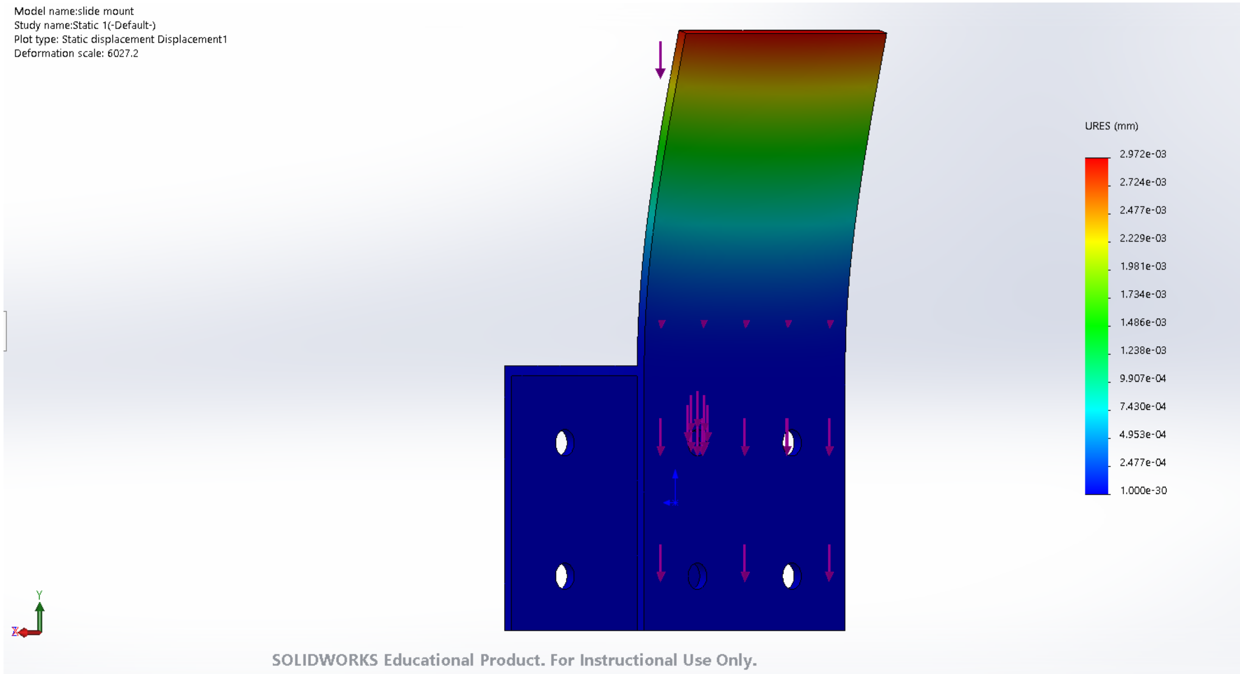

Figure 10. Solidworks study showing estimated displacement of the slide rail joints.

Figure 10 above shows the displacement of the part with the 40 N load applied. One thing to note is that if the simulation results are exaggerated to show the values more clearly, the maximum displacement of this bracket at the very tip is only 2.97 microns. The design phase is still in progress, but the next step would be to verify that the value obtained for deflection is acceptable; in order to determine this, tolerances will have to be evaluated. The 40 N load is applied in the negative y direction along the entire face of the bracket. In the actual machine, this wouldn't be the case. If it is determined that the deflection is unacceptable, the plate can be made thicker, and the height of the bracket can be decreased while the width is increased.

7.4 Brief Discussion of Other Technical Approaches Considered

The current design is believed to be the best of multiple iterations. Originally there were many different concepts considered—one of the first ideas for a mobile CNC router was essentially a small "Roomba" type machine with a router attached instead of a vacuum. The vacuum could still be utilized later but only for clearing chips. This idea was possible but wasn't considered optimal. Another proposed idea was a robotic machine that could drive in any desired direction and would utilize a very intricate control system to to maintain the accuracy of cutting toolpaths. In terms of feasibility, this idea wasn't bad, but other designs could complete the same objective more efficiently.

When it comes to the current design, not everything is finalized, but the general idea for the main structural components is as follows—the anticipated rails systems that will be used are comprised of 80/20 T-slots; however, alternative designs have been considered utilizing angle iron and bearings. The angle iron idea isn't as universal, sustainable, or rigid; Although, it would save a significant amount in terms of cost.

The axes were initially going to use lead screws; however, upon further investigation, it was decided that a belt drive system would be a better choice for the x and y axes, but the z axis would be fine as a ball screw. Utilizing belts where possible is primarily to reduce design costs.

As far as the mobility system for the machine's frame is concerned—multiple different systems have been considered, and alternatives are still being considered as a part of an ongoing process throughout our design phase. One of the earliest proposed ideas was a rail system for the machine to slide back and forth on. While such a means of mobility is feasible, this was dismissed since it would essentially be too similar to a conventional CNC machine—a machine that moves a router across rails, but the machine, itself, is also moving on rails. Another idea was to use omnidirectional wheels and allow the machine to move in several directions, but later it was determined that it would be best to limit our machine to one degree of freedom to simplify the design and increase the feasibility of the project given our limited time to complete it. It will likely prove challenging just to fine-tune the accuracy of the machine's output when the machine's frame can only move in one direction. For the design, having four, single, skinny wheels that are always suspending the machine off the ground is no longer being considered. There is a large concern that the cutting forces will cause the machine to slide back and forth and increased chatter will be detrimental to the machine's performance, overall—utilizing wheels in this conventional way may lead to undesirable behavior.

Other methods were discussed such as having a wireless connection between the user PC and the microcontroller itself to prevent restrictions caused by the length or weight of the communication line. It was decided that there should instead be a hardwire connection as it would prove more beneficial to cut down on the complexity of the design for the purpose of having a functioning prototype to present in Capstone II. There was also a point in time where the design included the potential for the primary or a secondary microcontroller to store the G-code required to control the axes of the machine as opposed to having a direct link with the user PC. This was decided against in order to maintain a simple design for the machine.

8. Part List and Budget

Cost-effectiveness is a priority for our project. This is to ensure that if the machine was marketed, it would remain competitively priced and still meet our design specifications. Because low-priced components can sometimes reflect the quality of the product, higher rated components have been chosen where necessary in order to ensure the functionality of our design. It should be noted that some parts have yet to be determined because we're still only midway through our design phase.

A 24V DC power supply is going to be utilized because stepper motor drivers have an operating voltage range of around 12-30V. Using a 24V supply will draw less current than using 12V, and this will yield less power loss through heat and will require less demanding electrical components.

The T-slots have currently been selected for the frame because they are versatile and cost effective for the level of precision that is being sought. One of the main focuses of this machine design is cost effectiveness. The size of the machine was determined so that the cutting areas would be sufficiently large after all mounts and drive components were fully specified. Also, the larger the area, the less the machine would have to update its position which could speed up cutting jobs.

In order to obtain the projected overall price for any item in the part list/budget shown in Table 7, Equation 5 is utilized.

$$Projected\ Overall\ Prince = Quantity\ \times Projected\ Individual\ Price \qquad (5)$$

Table 7. Part and price list.

Parts	Manufacturers	Quantity	Projected Individual Price	Projected Overall Price
24V DC Power Supply	Supernight	1	$25.00	$25.00
Arduino Uno Rev3	Arduino	2	$25.00	$50.00
Arduino Gshield (incl. Stepper Drivers)	Protoneer	1	$50.00	$50.00
Stepper Motor	Yosoo	5	$15.00	$75.00
2’ 40mm T-Slot	To Be Determined	2	$20.00	$40.00
2’ 80mm T-Slot	To Be Determined	3	$35.00	$105.00
3-way Corner	To Be Determined	4	$12.00	$48.00
Bearing Carriage Pad	To Be Determined	8	$3.00	$24.00
Drive Components	To Be Determined	To Be Determined	$100.00	$100.00
Contingency			$300.00	$300.00
Total				$817.00

9. Project Timeline

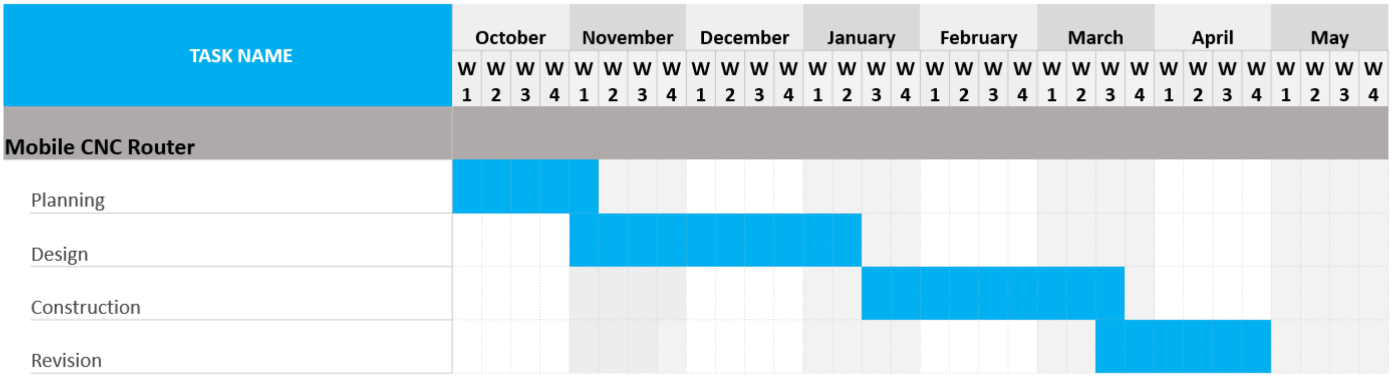

Figure 11. The simple project timeline.

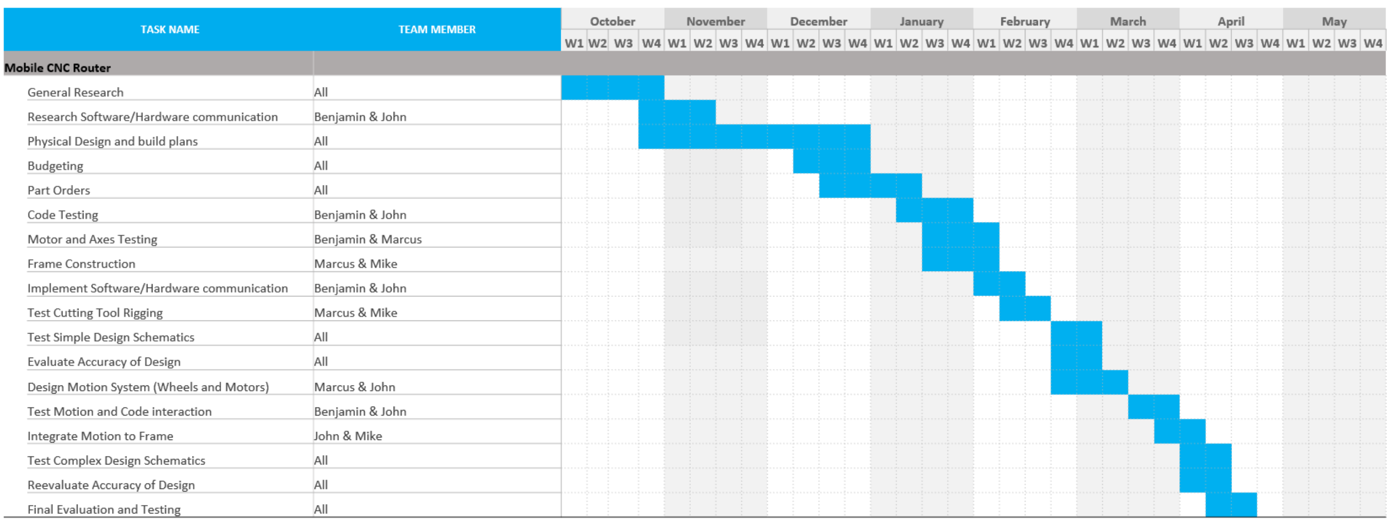

Figure 12. The in-depth project timeline.

(Report does not go beyond this point for Capstone I)

10. *Testing Approach:* This section should describe in details how you designed and set up your testing strategy/experiment to verify the correct operation of your project.

11. *Final Product/Project Results:* This section should describe the final design or product achieved. It should document the product/design performance in comparison to the design specifications. Photographs of the final product (if any) may be included in this section.

12. *Flow Chart of Design Process*: Describe the design process with a flow chart.

13. Conclusion: This section should summarize your project and the main results. You may also discuss areas or ideas for future improvement and issues to be addressed.

14. Assessment of Math, Science and Engineering Topics: Indicate by a numeric value (1-4, 1 meaning not at all, 4 meaning high usage) what amount of knowledge and skills your capstone team used in the capstone project from the following courses.

Table 8. Assessment of Math, Science and Engineering Topics

Topics	Team member 1	Team member 2	Team member 3	Team member 4
CAD/modelling/simulations				
Chemistry courses				
Circuits				
Communications				
Computer Architecture				
Control Systems				
Digital Design				
Electromagnetic				
Electronics				
Engineering Software tools				
Fluid/Thermodynamic systems				
Image Processing				
Industrial/Manufacturing Engineering				
Material Science				
Math courses				
Mechanical Engineering				
Microprocessors/Interfacing/Embedded Systems				
PC Board				
Project Management				
Physics courses				
Power Engineering				
Programming				
Signal and Systems				
Soldering/welding				
Statics and Dynamics Course				
Statistics				
System integration				
Very Large Scale Integration (VLSI)				
Others: List				

15. Team Activity Report. This section should summarize the contributions of each member – who contributed to what sections of the project and the report.

Table 9. Team Activity Report – Summary of Contributions by Team Members

	Team Members		
Sections	Name 1	Name 2	Name 3
Abstract			
1.0 Introduction			
2.0 Problem Definition			

2.1 Problem/Need			
2.2 Intended user(s) and use(s)			
2.3 Assumptions and limitations			
3.0 Design Objectives			
4.0 End-Product Description			
5.0 Design constraints			
5.1 Economical			
5.2 Environmental			
5.3 Social and Political			
5.4 Ethical			
5.5 Health and Safety			
5.6 Manufacturability and Sustainability			
6.0 Engineering Standards			
7.0 Technical Approach			
7.1 Functional Block diagrams			
7.2 Functional Requirements for Blocks			
7.3 Technical Details			
7.3.1 Theory and Calculations			
7.3.2 Flow Charts			
7.3.3 Schematics			
7.3.4 Simulations			
7.4 Other Approaches			
Change the list as appropriate for the project			
8 Part List and Budget			
9 Gantt Chart			
10. Testing Approach			
11. Final Product/Project Results			
12. Flow Chart of Design Process			
13. Conclusion			
References			

Appendix A should be the resumes for each of your team members and the team member profile forms you filled out last semester.

Other Appendices as needed. Eg: Data sheets for specialized equipment, software, etc.

References

1. Arduino, "Arduino Uno Rev 3," *Arduino Uno Rev3*, 2018. [Online]. Available: https://store.arduino.cc/usa/arduino-uno-rev3. [Accessed: 07-Dec-2018].
2. DIYMACHINING, "Best Arduino CNC Shield – How to Select the Right One," *diymachining.com*, 2018. [Online]. Available: http://www.diymachining.com/best-arduino-cnc-shield/. [Accessed: 07-Dec-2018].
3. Amazon, "Yosoo 57oz-in 1Nm Nema 17 Stepper Motor 1.3A 40mm for CNC Router or Mill," *Amazon*, 2018. [Online]. Available: https://www.amazon.com/gp/product/B00C4P382G/ref=as_li_tl?ie=UTF8&camp=1789&creative=390957&creativeASIN=B00C4P382G&linkCode=as2&tag=nc07d-20&linkId=DO3KRRKUQCUZUVMV. [Accessed: 07-Dec-2018].
4. "Assem2 40mm design.avi," *Google Drive*, 30-Nov-2018. [Online]. Available: https://drive.google.com/file/d/1awE1ehWWrj-TE6PbeTva2kZva_wal3SB/view?usp=sharing. [Accessed: 07-Dec-2018].

Appendices

Table of Figures:

Table 10. A table noting all the figures used in the report.

Table of Tables

Table 11. A table noting all the tables used in the report.