The University of Akron
IdeaExchange@UAkron

Williams Honors College, Honors Research Projects

The Dr. Gary B. and Pamela S. Williams Honors College

Spring 2020

QuickCut CNC Waterjet Cutter

Kelly V. Robbins
kvr7@zips.uakron.edu

QuickCut Tabletop CNC WaterJet Cutter

Senior Design Project - Spring 2020

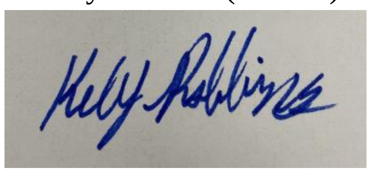
4600:471:001

Project Advisor: Dr. Gopal Nadkarni

Harrison Estes

Noah Hersher

Kelly Robbins (Honors)



Acknowledgements

As a group, we would like to thank Dr. Gopal Nadkarni for affording us the opportunity to work on this project of his that has been in the works since last year. Also, we thank Bryce Allensworth, the previous designer who worked on the project, for providing us with necessary information to continue this project with a common goal in mind. We would not have been able to reach the milestones we did without the provided workspace from The University of Akron along with additional help from shop staff (Steve Gerbetz) and other College of Engineering staff. WardJet was also helpful in giving us insight into how water jet machines work, the process, the industry, as well as helpful tips for our project. WardJet was also generous enough to allow us to use their WardCAM software for programming toolpaths. In addition, we extend our gratitude to Arduino for the free software they have available as well as the community of supportive makers that has been formed over the years.

Table of Contents:

1.) Introduction

Waterjet cutting was introduced to the manufacturing industry in the 1930's as a Paper Metering system. Early applications required a low pressure water stream because the machines were primarily used to cut soft materials. The emergence of high pressure waterjet cutting came after the World War II era and resulted in faster cutting times, higher precision and expanded capabilities. Modern waterjet systems are CNC controlled and use a high pressure stream of water to erode a sample of raw material (foam, wood, aluminum, etc.). In the case of harder materials such as titanium and steel, a garnet abrasive is added to the high pressure water stream to enhance the cutting power. The garnet is simply fed into the water stream from a hopper, making it simple to remove the added feature if necessary. The goal of this project is to complete the design of a tabletop CNC waterjet to cut aluminum tensile test samples for Dr. Gopal Nadkarni of The University of Akron. This design project takes a top-down approach starting from the conceptual design stage to complete the design and layout of the waterjet cutter originally started by a former mechanical engineering student.

The objective of this design project is to improve and make operational the design of the QuickCut Tabletop CNC waterjet cutter. The specific purpose of the machine is to cut 1/16" or 1/8" thick aluminum test specimens to be used by Dr. Gopal Nadkarni for tensile testing. A CNC, or computer numeric control, waterjet cutter offers a way to precisely and consistently cut computer generated designs out of different materials. There are three primary objectives which must be completed in order for the machine to be operational. The first is in regard to the structure of the existing machine. Currently, the frame does not possess enough rigidity to resist the forces that are induced by the 3,000 psi water jet coming out of the nozzle. The instability not only makes the machine unsafe for operation but it also induces error in the making of consistent and precise cuts. The second design objective is to devise a reconfiguration of the machine so that the nozzle remains stationary while the cutting bed moves on a gantry system. The third objective is to design and build an automated control system. The fundamental idea behind a CNC is for the machine to make extremely precise movements via stepper motors under the command of a controller. The control system will consist of an Arduino microcontroller, electric stepper motors, stepper motor drivers and the associated software required to create toolpaths as well as a graphics user interface (GUI) for simple, streamlined operation. Other issues have been noted in the existing design including the abrasive material feed system and the inability to easily move the heavy machine without lifting it. There are many benefits to building a CNC machine of this size and complexity to produce desired shapes such as tensile test specimens. The greatest benefit is the ability to produce consistent and precise cuts, using a computer to tell the machine what to do. In order to achieve the accurate results from a tensile test, it is best to test multiple identical specimens in order to get more data. The cost of the machine is estimated to be under $2000 making it stand out to the maker and hobbyist market.

2.) Conceptual Design

Expanded Design Brief

The general goal for the QuickCut CNC Waterjet Cutter is to make the machine operable and safe. The existing machine was composed of a steel frame, electric motor, high pressure water pump and associated plumbing, high pressure nozzle, 2-axis gantry with stepper motors and the cutting bed. Although the machine was mostly assembled, it was not up to safety standards and it did not work. The primary issue regarding functionality is that there is no control system with a graphics user interface or communication with the stepper motors to drive the motion of the machine. Moving forward, it was critical to implement additional structural supports to make the machine more rigid. The 1/4 inch square tube material used as vertical support is the primary location where additional support is needed. The vertical support holds the abrasive hopper and the high pressure water hose is routed along it using zip ties. Using the existing design without vertical supports creates vibration when the motor is powered. The machine is heavy and currently sits on the ground making a need for portability.

Product Specifications, Customer Needs, and Potential Markets

The QuickCut tabletop CNC waterjet is designed for hobbyists, makers and those who need a waterjet cutter but don't want the expensive and complex ones available on the market today. Our client happens to be a research professor who would like to use the machine to cut dog bone shaped tensile test specimens out of 1/16 inch aluminum. The machine is sized well for our customer needs and it will provide the ability to cut desired shapes at a fraction of the cost of similar machines. Using an arduino based control system will allow for end users to manipulate the open-source programming as needed. Arduino is a rather cheap option because other than the stepper motors, all that is needed is an Arduino UNO microprocessor and associated CNC software, stepper motor drivers, a breadboard, jumper wires and miscellaneous resistors and capacitors. Using GRBL software on an Arduino makes for a high performance controller at a low cost. Additionally, at the courtesy of WARDJet, WardCAM software has been provided for use on this project. WardCAM is computer aided manufacturing software which allows users to import drawing files and create instructions, or g-code, to drive the CNC machine. WardCAM is specifically tailored for waterjet cutting machines and provides a graphics user interface for operators to reach the full potential of their waterjet.

The design process began by developing a solutions list, which held value because it helped weigh the pros and cons of each solution. For example, we need to be able to see the benefits of a design with a stationary versus mobile cutting nozzle. Below is Figure 1 which shows our analysis for solutions including: nozzle, fixturing, cutting operation and garnet hopper. "Y" denotes the best option for each category.

Solutions List		
Solution	**Benefits**	**Y/N**
1. Stationary Nozzle	Less vibrations. Movable cutting bed. Constant cutting pressure through hose. Larger range of motion.	Y
2. Mobile Nozzle	Less wear and tear on stepper motors. Simpler construction.	N
3. Stationary Machine	Vibration reduction. Stronger design. Simpler setup.	N
4. Mobile Machine	Relocation. Larger range of applications. Lighter weight design.	Y
5. Manual Operation	Ability to make small adjustments. No computer required.	N
6. CNC Operation	Much higher cutting accuracy. Easy operation. Larger range of parts can be manufactured. Remote Operation.	Y
7. Additional Supports	More precise cuts. Vibration reduction. Solid construction.	Y
8. Static Hopper	No extra motors or power source required. Gravity fed.	N
9. Dynamic Hopper	Better abrasive feeding method. More reliable. Rotating unit inside.	Y
10. Emergency Stop	Safety is the #1 priority. Less chance of injury during operation. Kill switch if water contacts electronics.	Y

Figure 2: Solutions List

The Function Structure Diagram is an important part of the design process because it allows the designer to see how materials, energy and information flow through a mechanical system. We created both an Overall and Detailed Function Structure Diagram (Refer to Figures 2 and 3). This helped lay out where energy input, control systems and material needs to be in order to create an effective and efficient process.

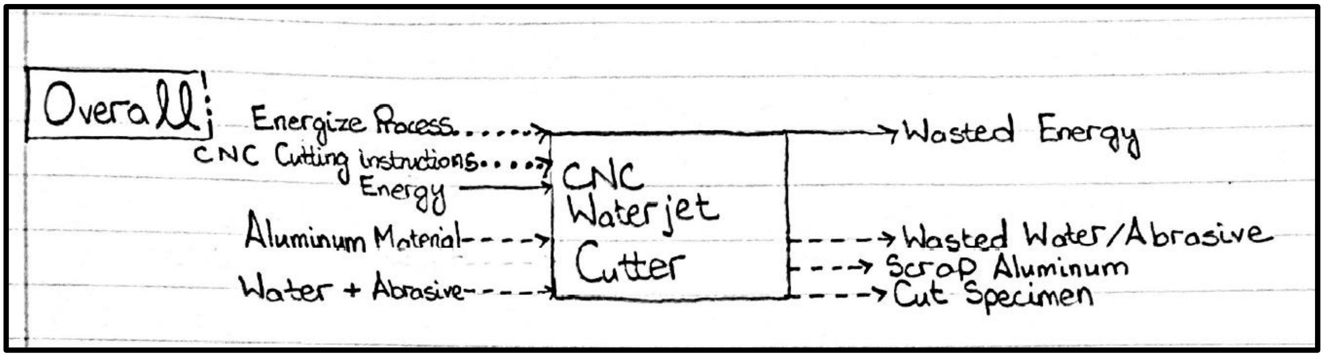


Figure 2: Overall Function Structure Diagram

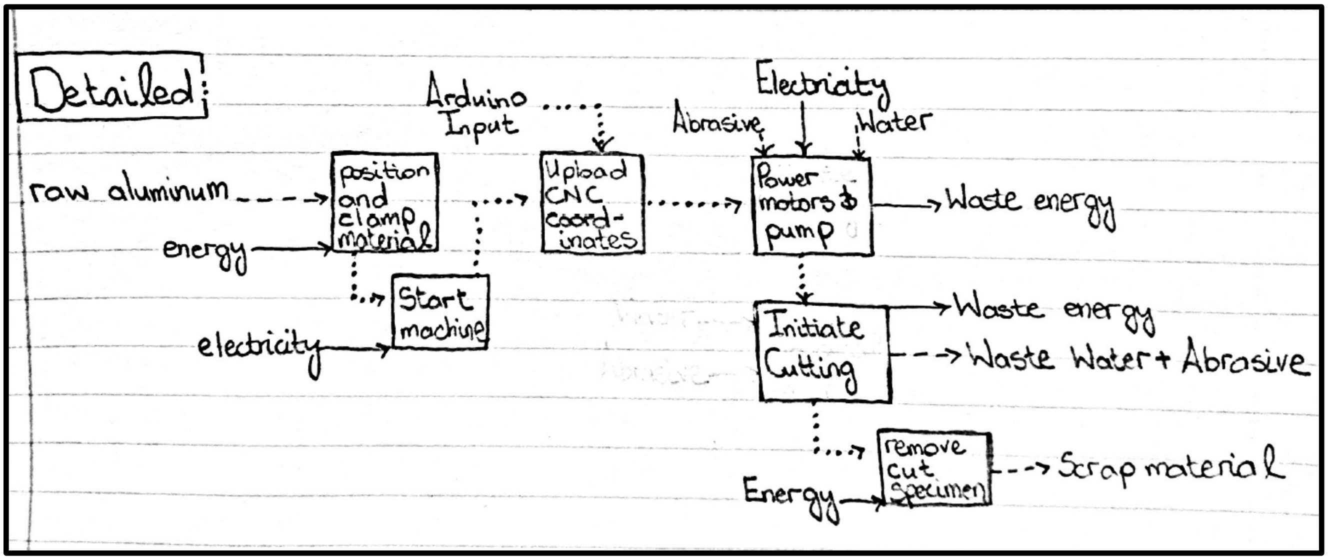


Figure 3: Detailed Function Structure Diagram

The objective tree shows what was considered to be important to each proposed configuration of the waterjet cutter. Each criteria is weighted differently based on importance. The scores of these five different criteria, when added up, equal one. Note that two criteria have two sub categories. These are scored, and the sum of them should equal the original score of the main criteria it falls under. The weighted design matrix is used to envision what is most important to incorporate into the machine and to establish embodiment principles.

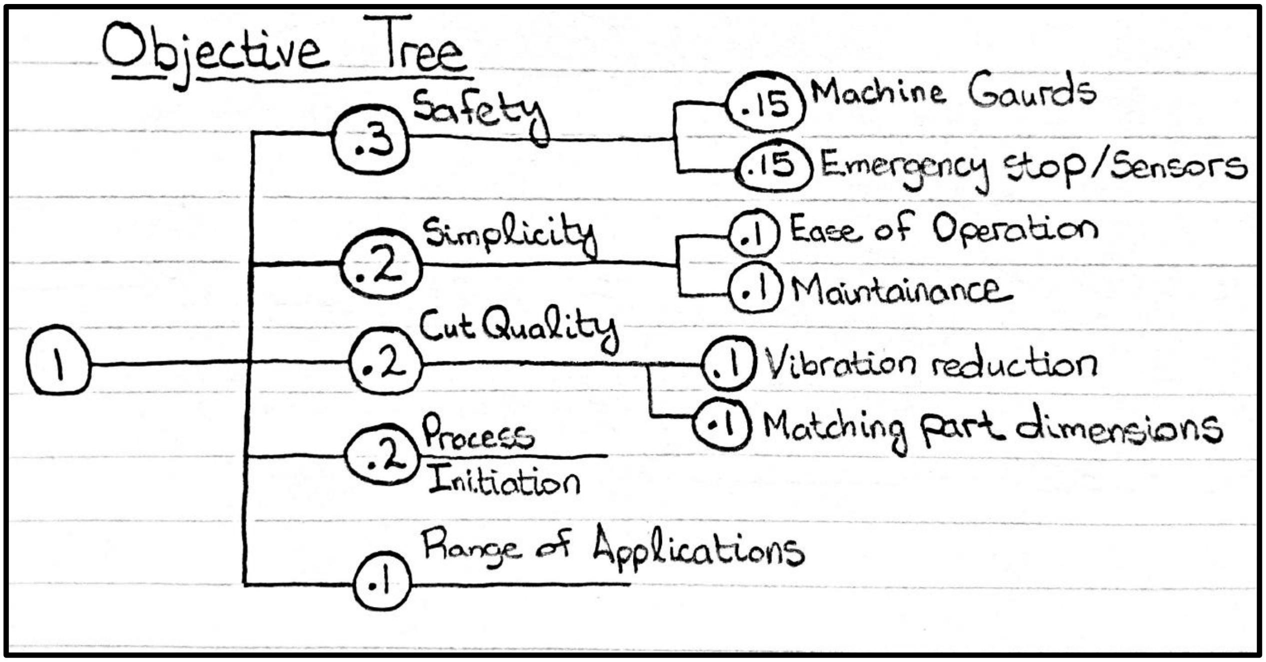


Figure 4: Objective Tree

Several different methods were utilized when coming to a decision on the final design configuration. A solutions list aided in solving some of the main problems faced in this specific application (Refer to Figure 1). The solutions list was a simple way of weighing the pros and cons of every category, leading into the morphological chart. Using a morphological chart, we were able to sort each component category that goes into a waterjet cutter. These categories were chosen based on original ideas as well as research done by each group member. Collectively, this chart allowed us to come up with the six best machine configurations for our given options. Each configuration is evaluated in our weighted decision matrix, which assigns point values to identify which design will best fit our criteria.

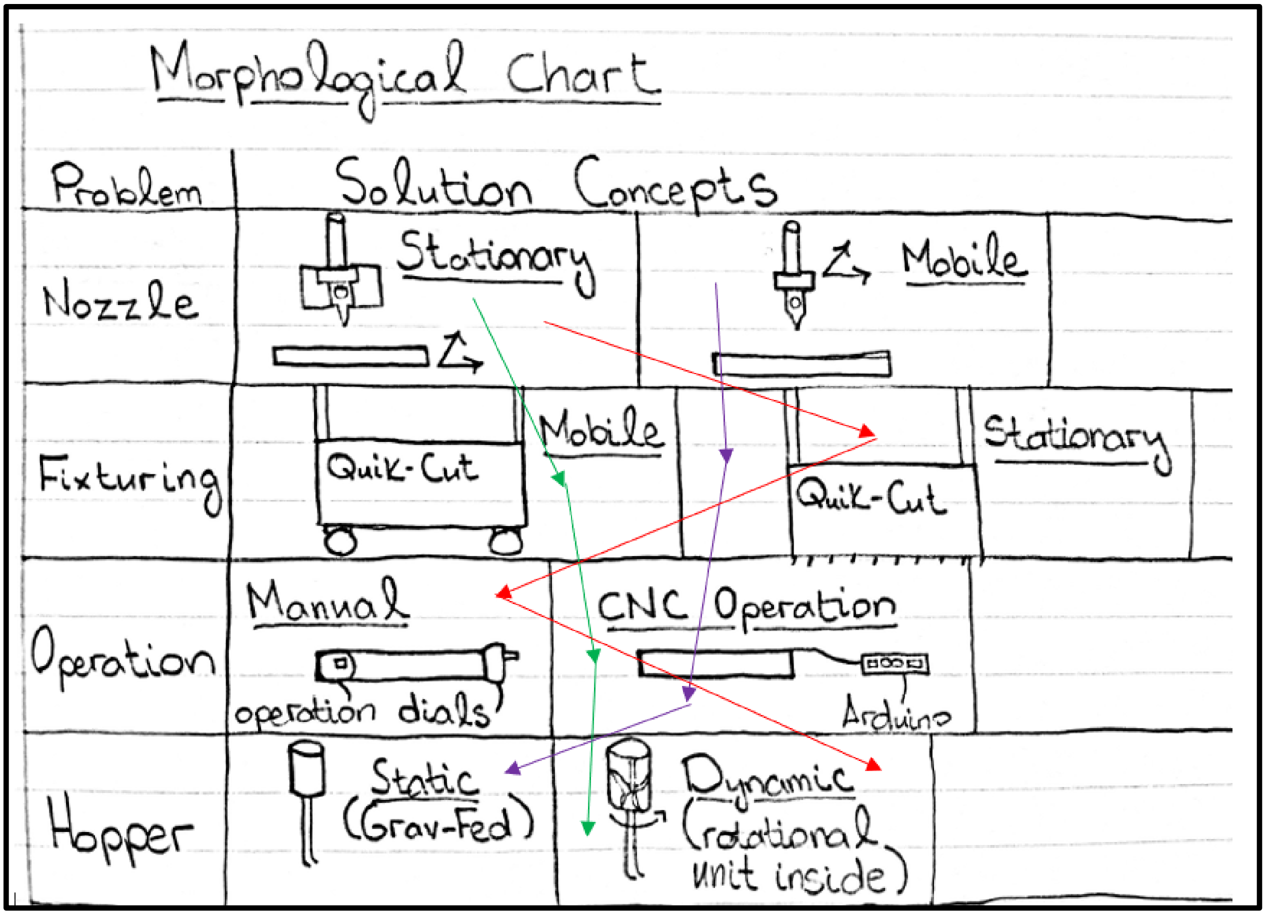


Figure 5: Morphological Chart with Configurations in Figures 6, 7, and 8

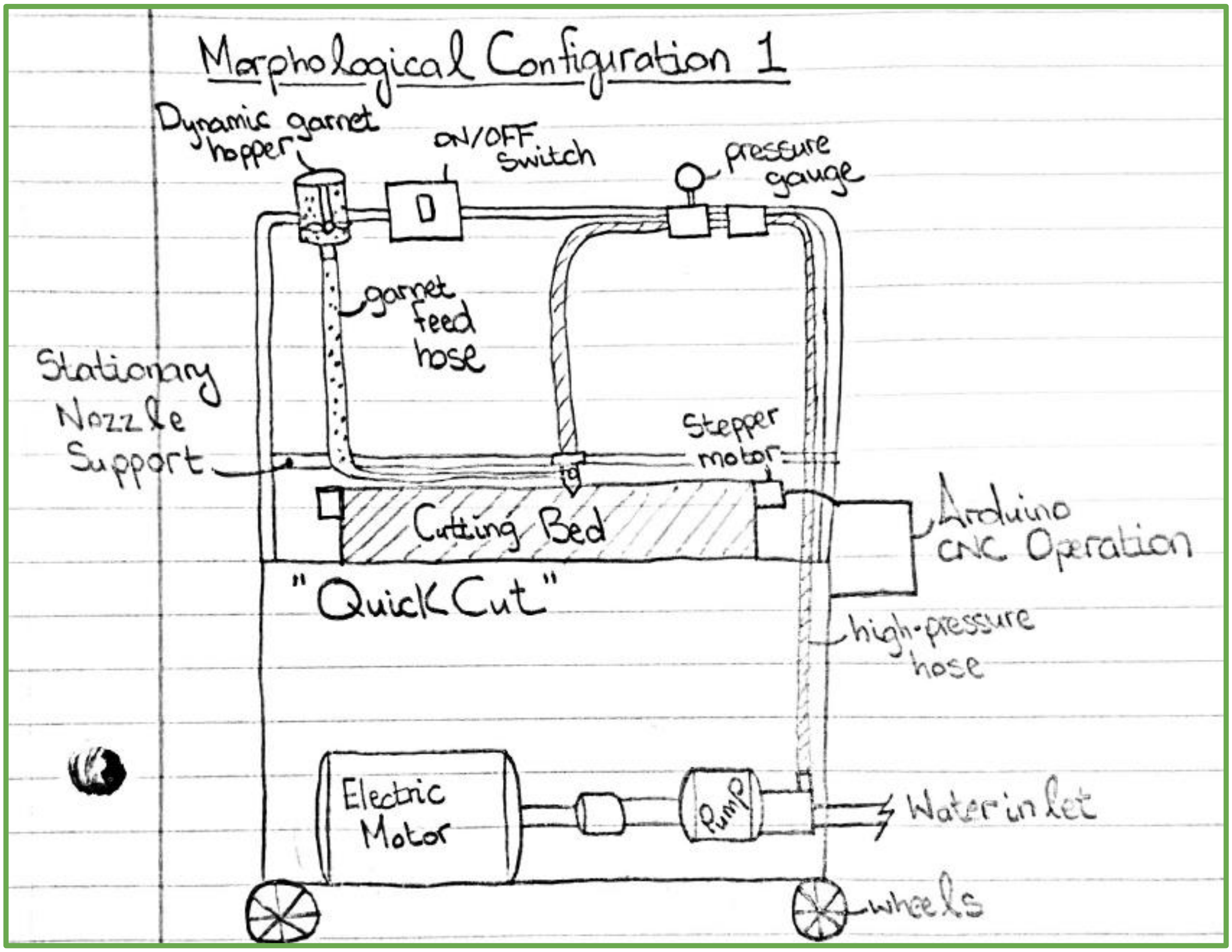


Figure 6: 1st Morphological Configuration

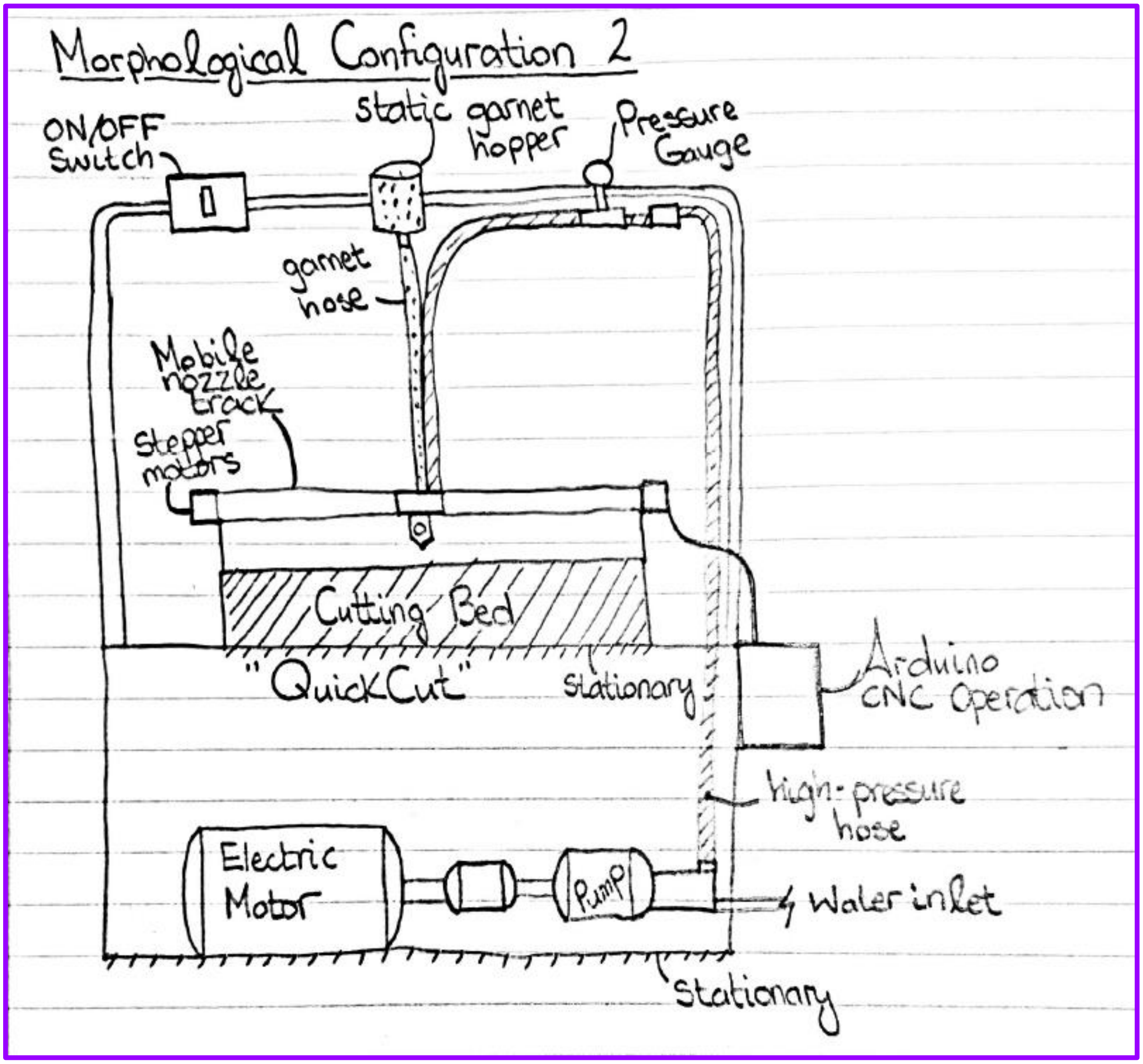


Figure 7: 2nd Morphological Configuration

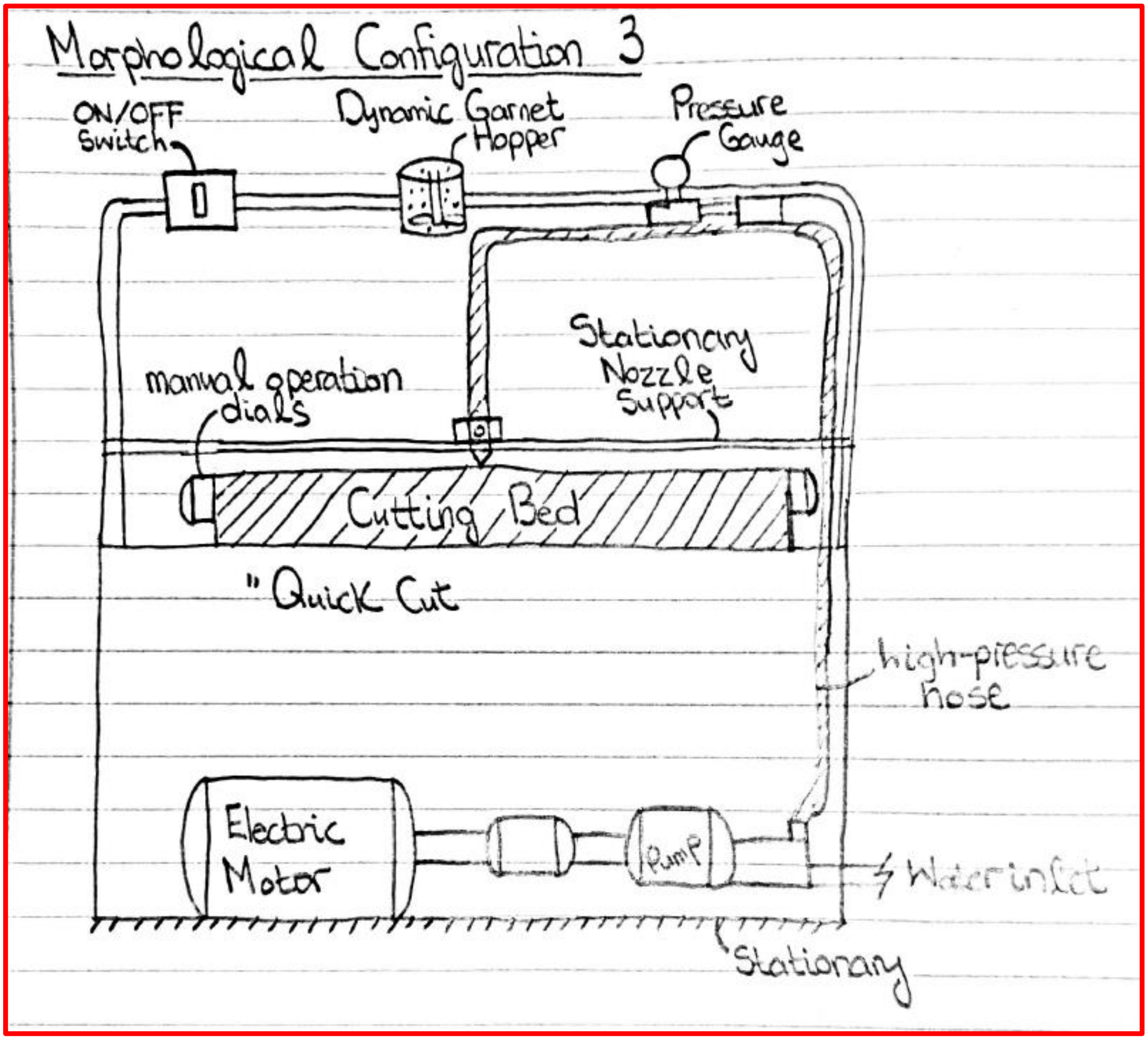


Figure 8: 3rd Morphological Configuration

The evaluation criteria were then used in the weighted decision matrix to determine the best concept solution as shown below in Figure 9. In the weighted decision matrix, the six solution concepts were rated by how well they satisfy the evaluation criteria on a score from one to five, with five being the best. As you can see, waterjet configuration 1 scored the best. In order to satisfy the goal of safety, it was made the main priority when making a decision on the machine configuration. We want to make sure those operating the QuickCut are able to use the machine without injury or damage to themselves, the machine or workpieces. Our next three equally weighted concepts were simplicity, cut quality and process initiation. Cutting time needs to be considered because the machine will be used on an as-needed basis and it is inconvenient for end users if the machine takes a long time to use. Simplicity is important because this machine is designed for the hobbyist and maker market. The machine, while simple in design, should be able to be used properly with minimal training. Ease of maintenance is important because the waterjet cutting process can be quite dirty and it is desired to be a simple machine to maintain. The waterjet will require routine cleaning procedures to limit the probability of aggregate damaging the motor, pump or gantry system.

Evaluation Criteria		Weighing Factor	CNC WaterJet Configuration 1		CNC WaterJet Configuration 2		CNC WaterJet Configuration 3	
			Rating	Score	Rating	Score	Rating	Score
1	Safety	0.15	5	0.75	5	0.75	5	0.75
		0.15	5	0.75	5	0.75	5	0.75
2	Simplicity	0.1	5	0.5	5	0.5	3	0.3
		0.1	3	0.3	3	0.3	4	0.4
3	Cut Quality	0.1	5	0.5	3	0.3	5	0.5
		0.1	5	0.5	5	0.5	3	0.3
4	Process Initiation	0.2	3	0.6	3	0.6	4	0.8
5	Range of Applications	0.1	5	0.5	4	0.4	4	0.4
Total		1	4.4		4.1		4.2	

Figure 9: Weighted Decision Matrix

3.) Embodiment Design

Our three main embodiment design rules are safety, reliability and simplicity. Safety is most important to minimize any risk of injury that could occur while operating the waterjet machine. Fail-safe principles have been implemented into the design of the QuickCut. If any part of the waterjet is not functioning as intended, the emergency stop can be pressed. Pressing the E-stop will shut down all power to the machine and allow the operator to find the source of error. It also uses the indirect safety principle, as there will be clear plexiglass safety shields around the cutting bed. A hinged door will allow an operator to move parts into and out of the cutting bed. Efficiency was considered so that the machine can execute the cutting of material in a timely manner. It is desired for the part(s) (tensile test sample) to be cut in one, short cycle in order to maximize output and to save energy, water and garnet. Reiterating what was stated above, the machine is not going to routinely run therefore quick startup and run times are highly preferred. Reliability is an important factor of the design so that it is ready to be used whenever it is needed. Reliability is achieved by creating a simple and rigid design, constructing the machine to design and practicing proper operation and maintenance. Finally, the last embodiment principle is simplicity. We believe that a complex design is not necessary in order to meet the requirements of the machine. Also, the simplicity of the machine means extensive training is not required and it will decrease maintenance and repair times. The QuickCut will have the ability to cut any size specimen up to ⅛ inch thick that will fit within the cutting bed.

Stepper motor connections and calculations must be evaluated/conducted in order to ensure the machine will operate within all of our embodiment principles. The stepper motors for the dynamic garnet hopper and the CNC cutting bed need to be sized based on the load they're carrying and the transmission of force. The dynamic garnet hopper is a rotary device that spins in order to ensure the garnet is being constantly fed into the nozzle at a proper rate. Had we been able to test the machine, we would have run tests to determine the most optimal speed of the garnet hopper motor. Refer to Figure 10 below for a diagram of the force transmission. After entering all parameters of the force transmission such as: table diameter (1in), table thickness (4in.), table material (Nylon), shaft length (1in), shaft diameter (0.5in), shaft material (Nylon), stopping accuracy (30deg), horizontal operation and operating speed (10 rev/min) the computer program selected a stepper motor with a required torque of 2.4 lb*in. See Figure 20 in Appendix for full Dynamic Garnet Hopper Stepper Motor Requirements. The CNC cutting bed utilizes a different form of force transmission referred to as belt actuator (Figure 11). The force transmission parameters for the cutting bed are as follows: weight of load and conveyor belt (3lbs), drive pulley diameter (0.5in), drive pulley weight (1oz), number of drive pulleys (2), mechanism angle (0deg), and operating speed (1in/s). These input parameters provided an output torque of 20.83 lb*ft. However, our stepper motors will not have to meet this exact requirement, because we plan on implementing multiple motors to move in the x and y directions. This will allow for easier force transmission, more precise movements, and less strain on the individual motors. For full CNC Cutting Bed Stepper Motor Requirements see Figure X in Appendix.

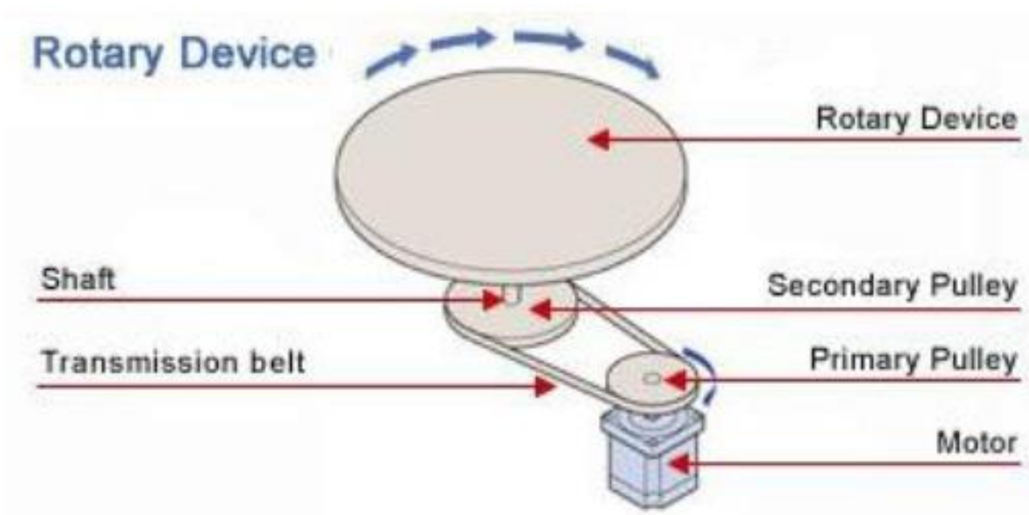


Figure 10: Stepper Motor Rotary Force Transmission Diagram

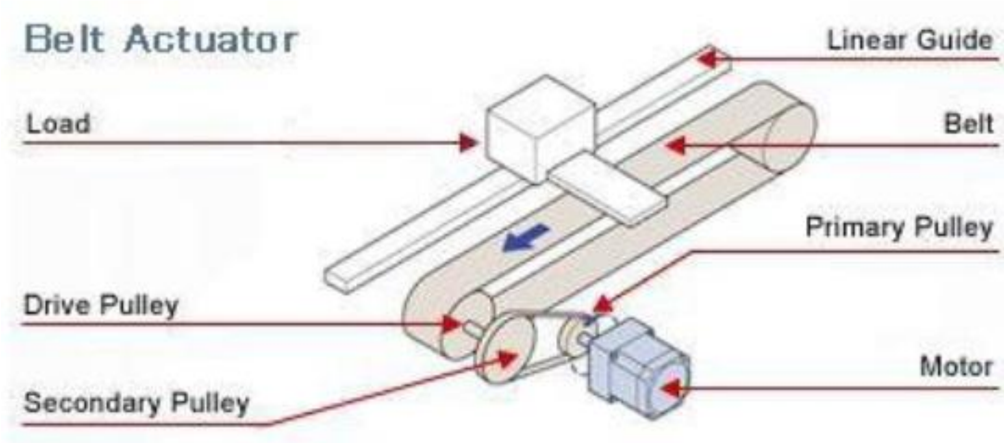


Figure 11: Stepper Motor Belt Actuator Force Transmission Diagram

4.) Machine Improvements

The CNC WaterJet Cutter project was adopted from a former student that designed and fabricated his vision of the machine. The initial design can be found in Figure 12 below. While the design was proven to be a functional waterjet cutter, our group was tasked with adding components that would make the machine fully operational and usable. Some of our major areas of machine improvement focus include mobility, structural stability, safety mechanisms, garnet feeding mechanism and the controls. These areas of focus were evaluated in the conceptual design section above. Due to COVID-19, we were not able to fully implement and test all these improvements. However, this section will provide an outline including what was planned to be implemented and the required parts. Table 1 shows all of the components we acquired and/or purchased that need to be implemented into the final assembly.

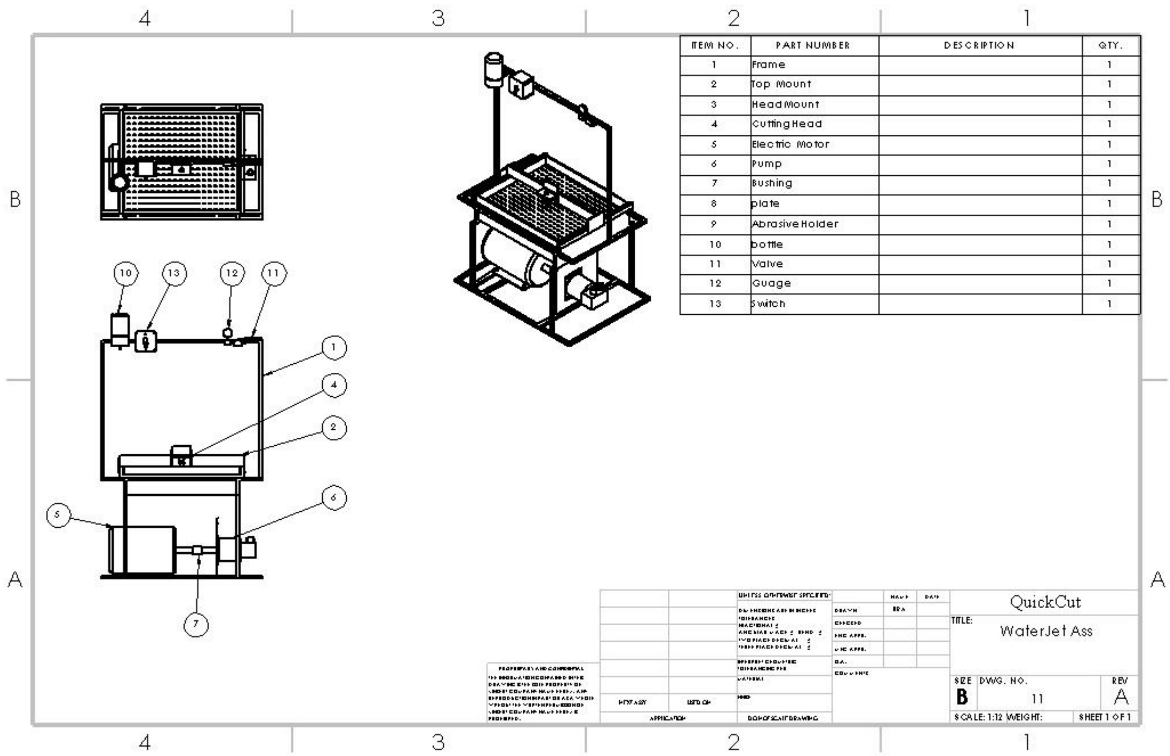


Figure 12: The Initial State of the waterjet cutter

When the waterjet Cutter was initially being evaluated, the first point of emphasis came from the amount of vibration created by the motor during operation. The top bracket of the machine was vigorously wobbling back and forth causing the final workpiece to greatly deviate from the desired geometry. This was combated by welding additional vertical supports so the top bracket of the machine would no longer have the ability to wobble (total of 4 added). This machine upgrade can be seen in Figures 13 and 19. A safe design also limits the possibility of operator injury. After considering different options, it was decided this could be best accomplished by adding clear machine safety guards around the cutting area and an emergency stop button. The machine guards would be made from rated clear plexiglass. These solutions should prove effective given our machine does not have the high water pressure of an industrial waterjet cutter. An emergency stop button can be easily sourced and is a necessary component to any machine design with moving components. Refer to Figure 22, in the Appendix, for the sourced emergency stop button.

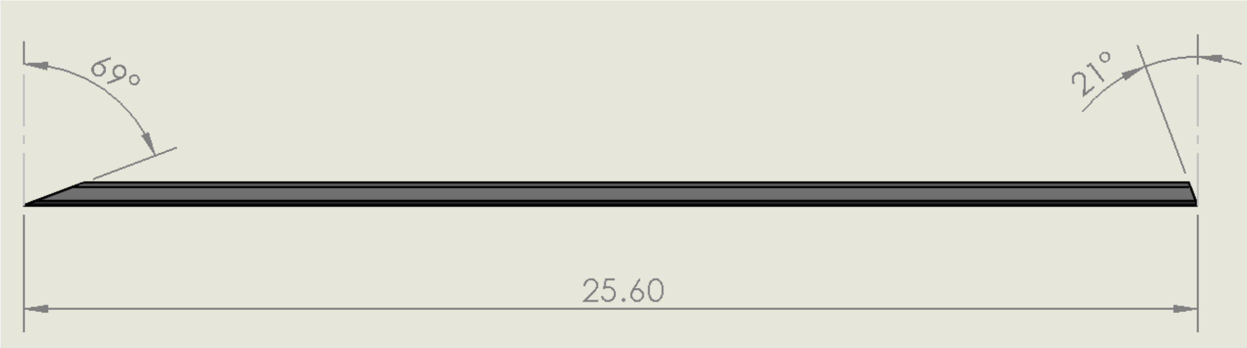


Figure 13: Drawing for the Vertical Vibration Reducing Supports

A CNC machine, or computer numerical control machine, is able to move the cutting head or the bed by command of a computer, allowing fast paced, precision cutting. Almost all water jet cutters on the market today are CNC and there are a wide variety of control systems used. For this application, an Arduino-based system is the ideal solution. Arduino allows an open source platform for end users to program their controller to do almost anything through the control of inputs and outputs. In order to control 2 axes and cut the proper geometry, a g-code must be developed to send to the Arduino UNO, and the Arduino needs GRBL software to process the g-code and output signals to the stepper motors. GRBL is a free, open source, high performance software for controlling the motion of machines that move, that make things, or that make things move, and will run on a straight Arduino. Once the GRBL is flashed to the Arduino, it is able to process g-code and send commands to the stepper motor drivers. A free, universal g-code sender (UGS) can be used as a graphics user interface on a PC. WardCAM software, provided to our group by WARDJet, allows users to take a drawing file or pdf and create proper toolpaths and generate g-code for the Arduino. Although we were not able to get all the software bugs worked out and perform test cuts, the control system is rather straightforward. The Arduino was wired to the stepper motor drivers using a breadboard and jumper wires per the wiring diagram shown below.

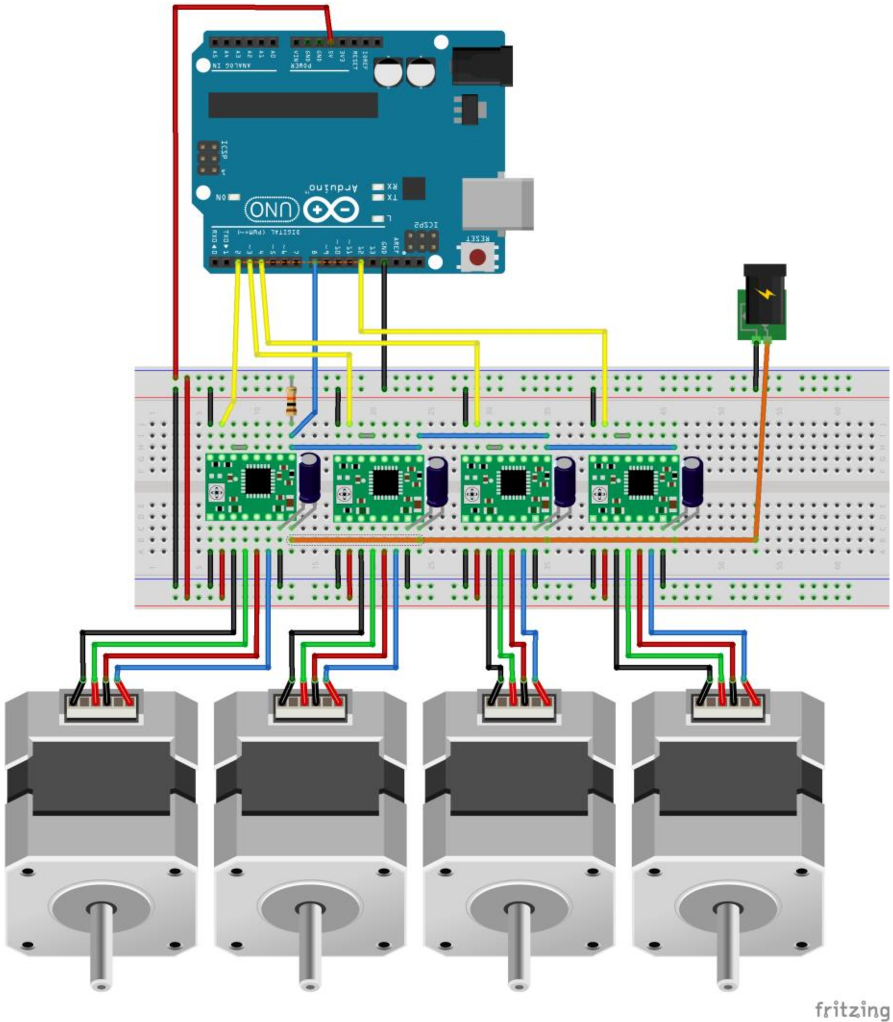


Figure 14: Arduino, stepper motor driver and stepper motor wiring diagram

WaterJet Components List	
Component	**Purpose**
Wooden/Metal Cart	Allows the machine to be easily relocated.
Dyn. Garnet Hopper Unit	Constant feed of abrasive material
Servomotor	Rotates the Garnet Hopper Unit
1" Tube Steel	Vibration Reducing Supports
	Bracket for the Stationary Nozzle
Arduino UNO Microprocessor	Provides input to the CNC Cutting Bed
A4988 Stepper Motor Driver	
4 Pin Stepper Motor Wire	
BreadBoard	
9v Battery Adapter	

Table 1: List of Components to-be Implemented

5.) Discussion

The goal of the design project was to utilize the engineering design process to improve the design of the QuickCut CNC Waterjet Cutter and make the machine fully operational. Starting with the existing design, the machine was broken down into different components and each was studied on how they contribute to the overall function of the machine. It was also critical to determine everything that was good with the existing design, what needed changed moving forward and what needed added to make the machine safe and operational. A study of the waterjet cutter market showed that these machines are useful in many different applications, proof of a need beyond our client, Dr. Gopal Nadkarni. As a group, we came up with different ideas as to where we could take the waterjet cutter including what would make it better and the most effective ways we could reach the goal of the project. After writing an expanded design brief, the conceptual design was developed and a solutions list was created to determine the best __________. A detailed function structure diagram was used to highlight the function of each part of the machine and to better understand the inputs and outputs of each component. An objective tree was used to create a hierarchy or weighted matrix of design considerations. A weighted matrix served as a guide when selecting a path toward each design goal. Once the design was selected, we were able to move forward with mode

6.) Conclusion

The QuickCut CNC Waterjet Cutter was started by a mechanical engineering student at The University of Akron in 2018 as a senior design project. For our Spring 2020 senior design project, we took up the task of improving the design and attempting to make the machine fully operational. Due to time constraints as well as COVID-19 interruptions with accessing the machine, we were unable to reach our desired goal. Using the engineering design process we were able to develop a design that we feel is perfectly suitable for Dr. Professor Nadkarni to cut tensile test strips out of 1/16 inch aluminum. After carefully analyzing the frame of the machine, a layout was determined that would greatly reduce machine vibration and improve structural stability. The Arduino based control system was set up to control the stepper motors which move the bed of the machine. Integrated with the Arduino UNO is GRBL software to process g-code and WardCAM was provided for creating toolpaths and writing g-code. To our team's fortune, the University surplus store had a cart available to make the machine mobile. With a small amount of trimming, the cart is a perfect fit for the machine. The addition of an auger for the garnet hopper will ensure that the garnet is continuously fed at the proper rate. With more time and access to the machine, the end goal could be achieved. While it is unfortunate we could not finish and test the machine, we each learned a great deal and became equally infatuated by the capabilities of waterjet cutting machines.

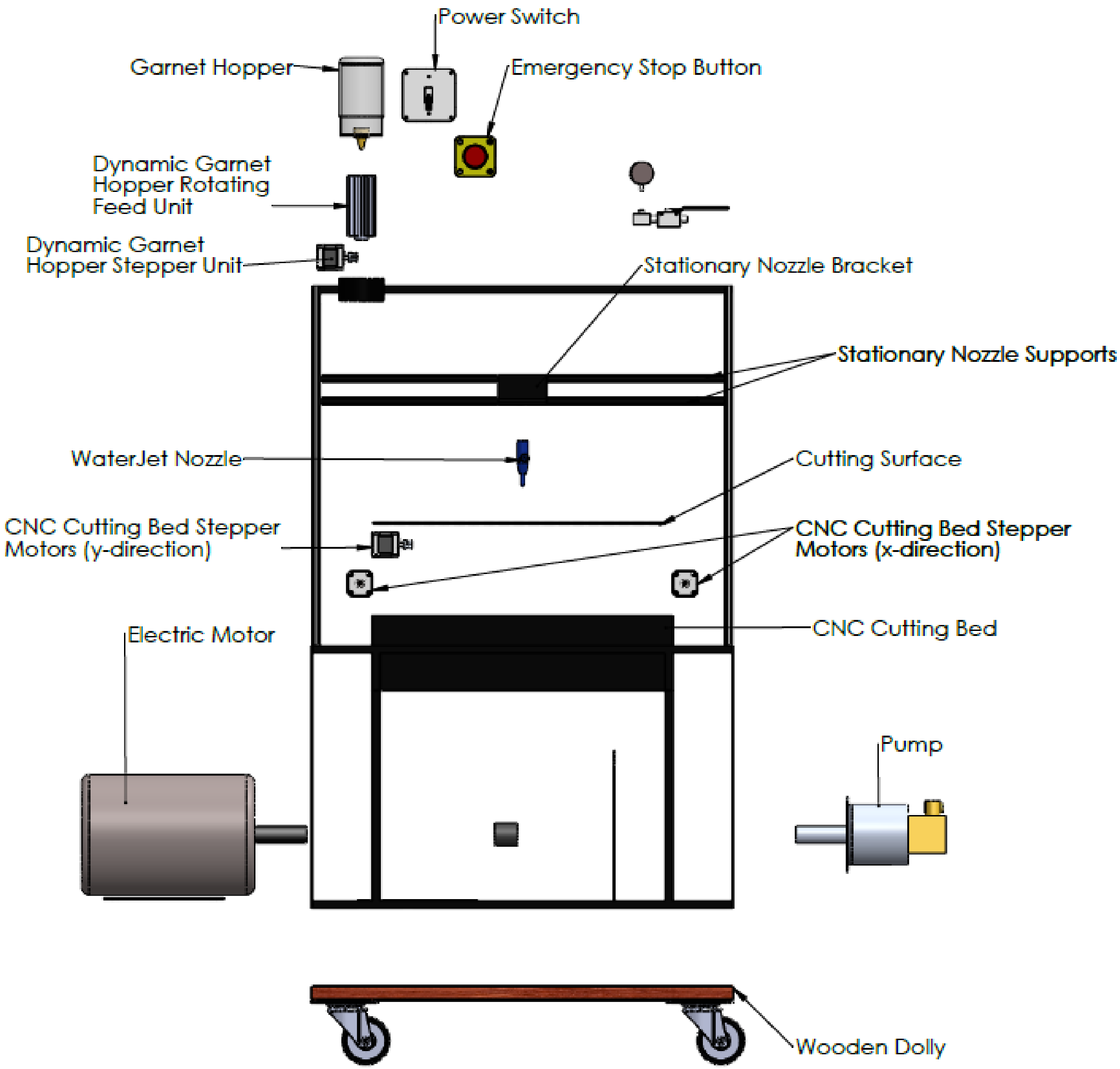


Figure 15: Exploded Component View of Final WaterJet Cutter (Front View)

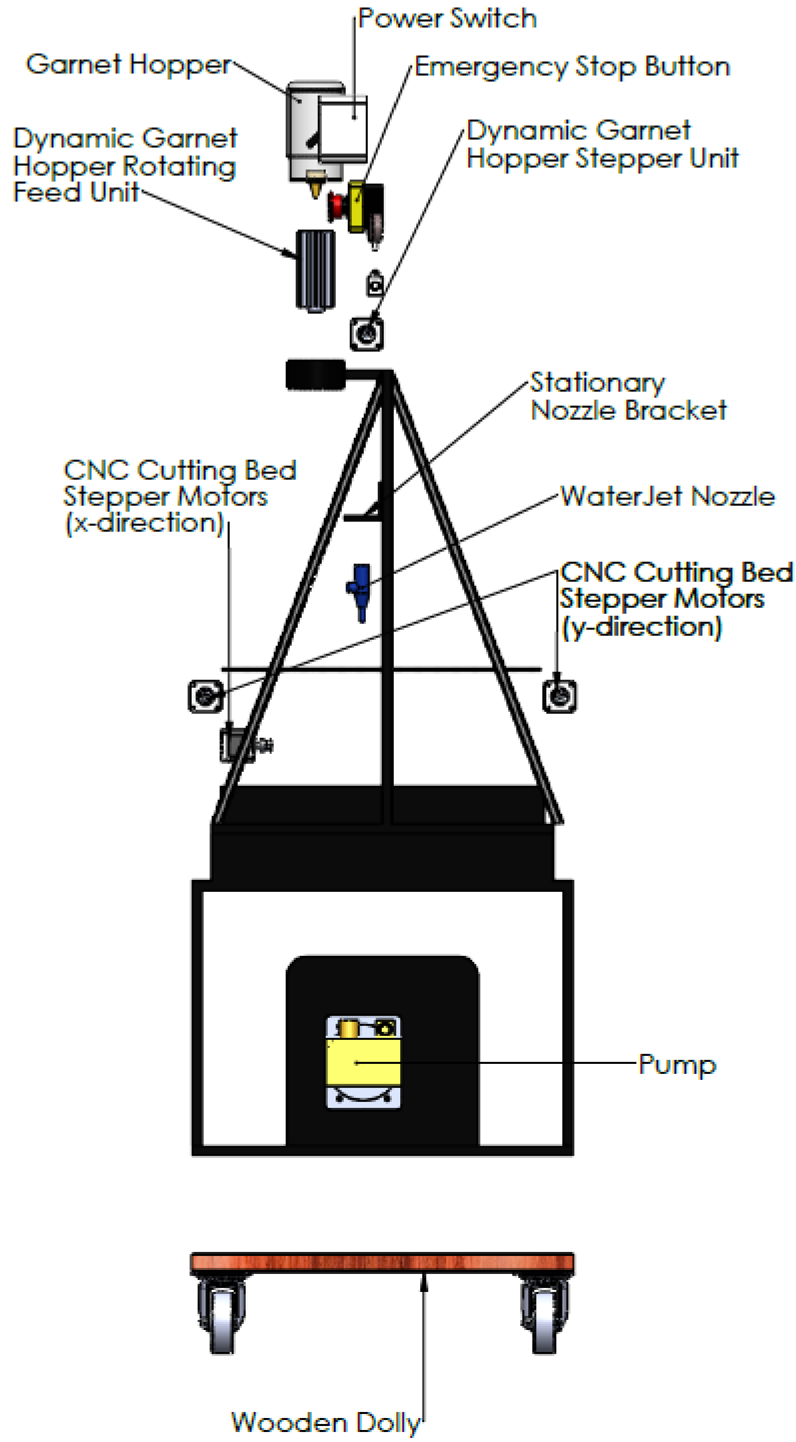


Figure 16: Exploded Component View of Final WaterJet Cutter (Side View)

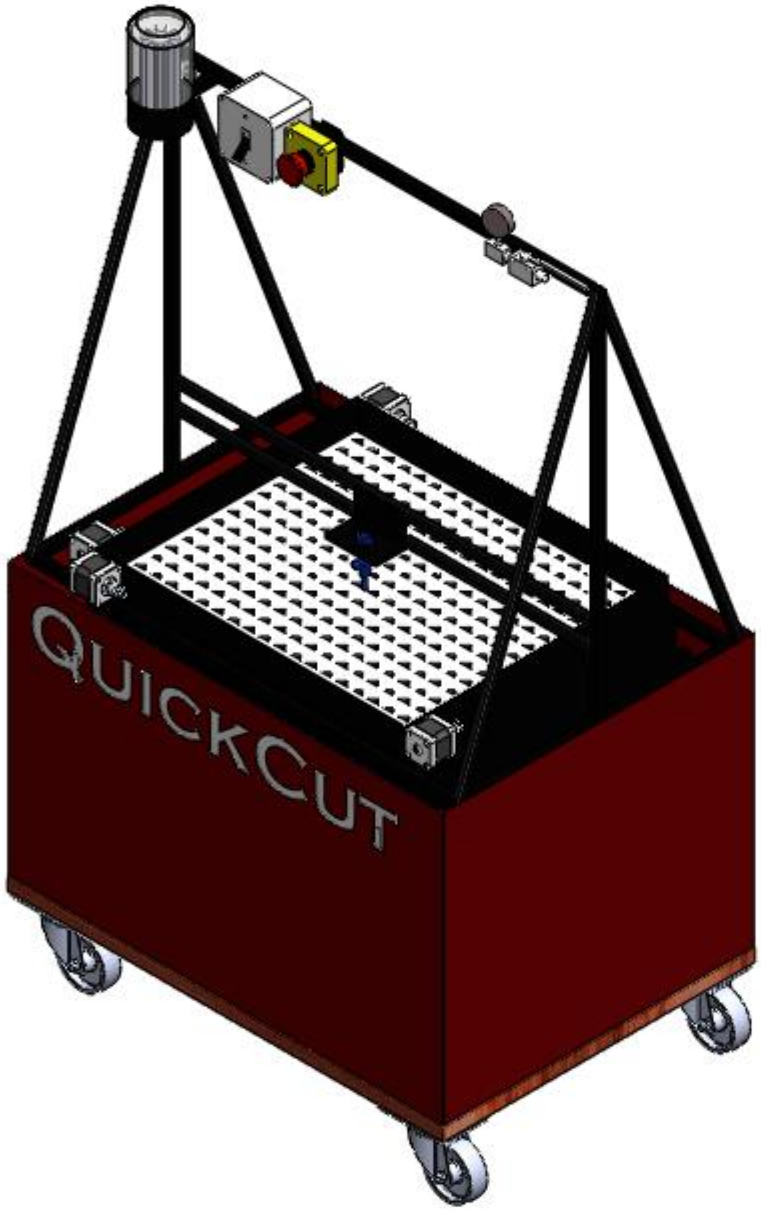


Figure 17: Final WaterJet Cutter (Isometric View)

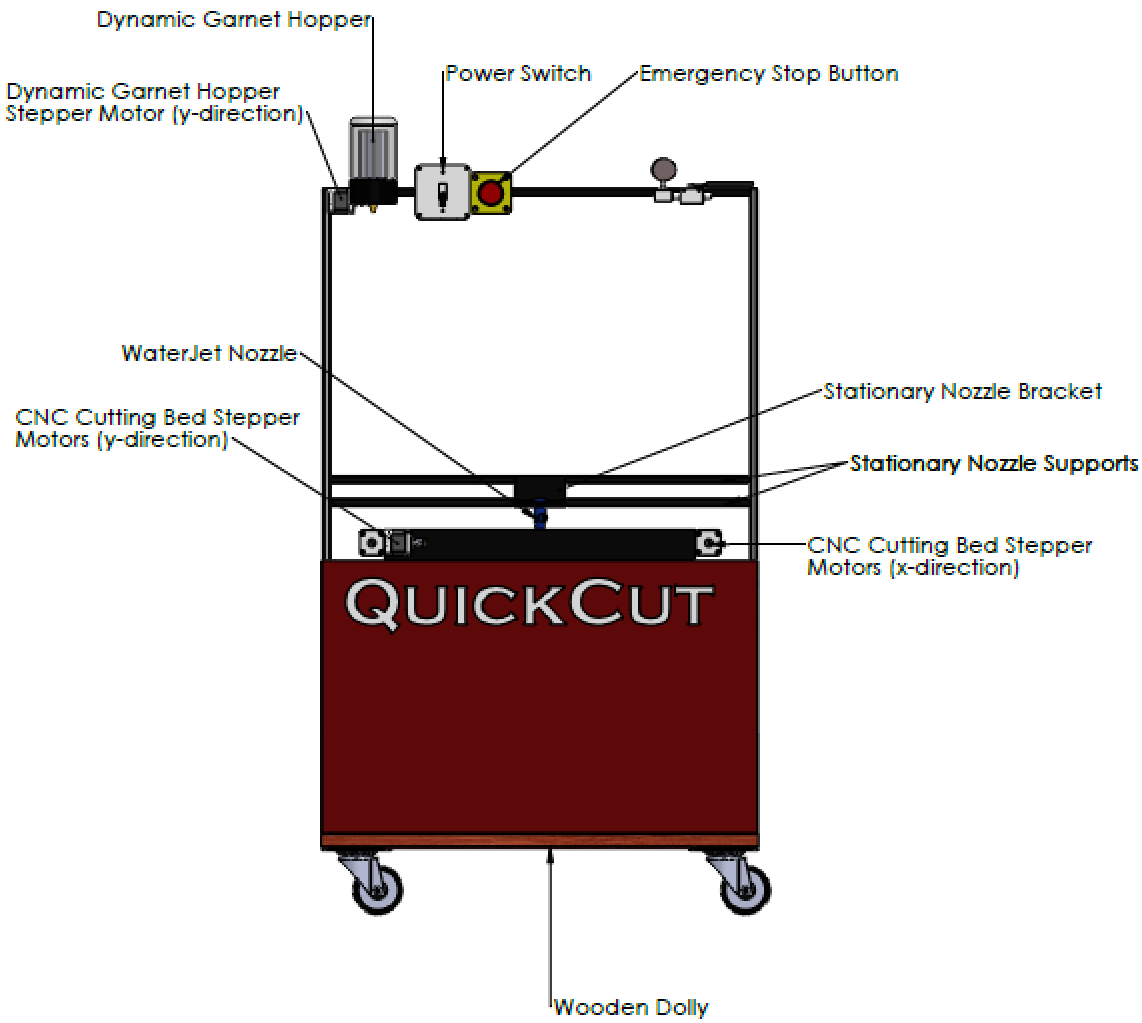


Figure 18: Final WaterJet Cutter (Side View)

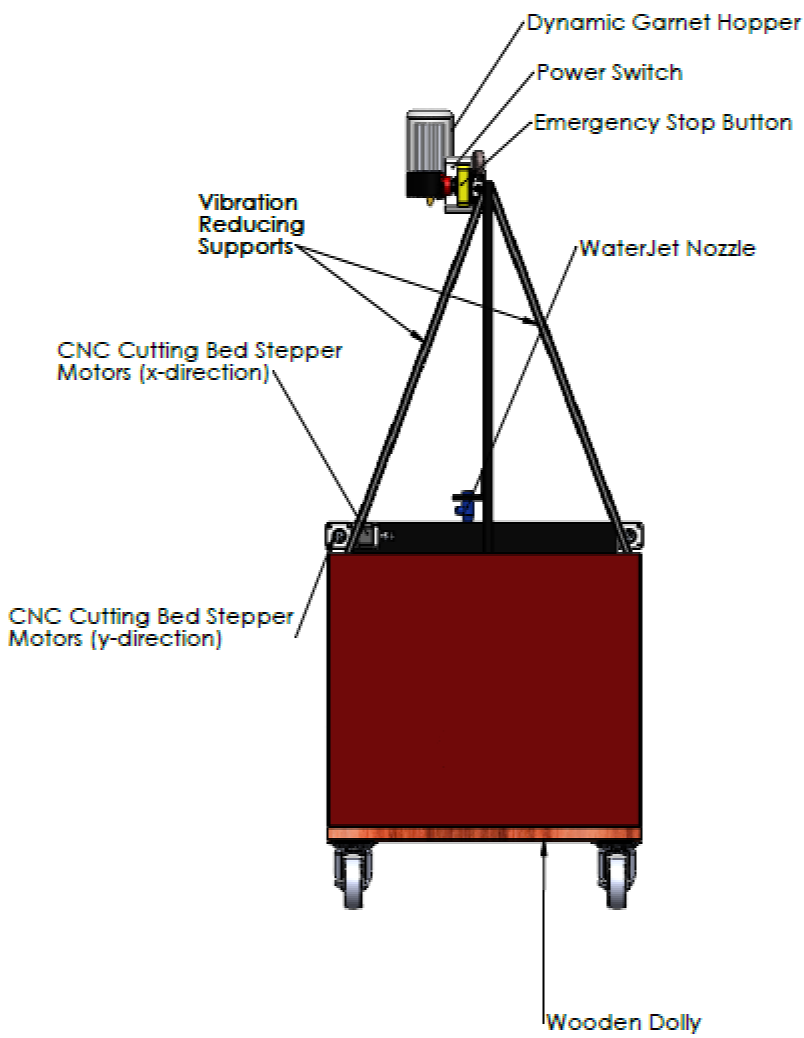


Figure 19: Final WaterJet Cutter (Side View)

i.) References

How to Determine the Motor Size for Your Project? (2020, February 24). Retrieved May 02, 2020, from https://realpars.com/motor-size/

Learn About Waterjets: Abrasive Water Jet Cutting Machine. (n.d.). Retrieved May 02, 2020, from https://www.omax.com/learn/waterjet-cutting

Stepper Motor Basics. (n.d.). Retrieved May 02, 2020, from https://www.orientalmotor.com/stepper-motors/technology/stepper-motor-basics.html?gclid=Cj0KCQjwm9D0BRCMARIsAIfvfIZrWP3Us59rSjO1UfGdWrd1we3nwqdsc-ZfLx5clZZOBPsBMehT05MaAufqEALw_wcB

Stepper Motor Calculations. (n.d.). Retrieved May 02, 2020, from https://wiki.cnc.xyz/Stepper_Motor_Calculations

ii.) Appendix

Sizing Results

Load Inertia	J_L	= 1.273	[oz·in ^{2}]		
Required Speed	V_m	= 10	[r/min]		
Required Torque	T	= 2.357	[lb·in] =	37.70	[oz·in]
Acceleration Torque	T_a	= 2.1581e-4	[lb·in] =	3.4529e-3	[oz·in]
Load Torque	T_L	= 1.571	[lb·in] =	25.13	[oz·in]
Required Stopping Accuracy	$\Delta\theta$	= 30	[deg]		

Figure 20: Dynamic Garnet Hopper Stepper Motor Requirements

Sizing Results

Load Inertia	J_L	= 5.070	[oz·in ^{2}]		
Required Speed	V_m	= 38.20	[r/min]		
Required Torque	T	= 20.83	[lb·in] =	333	[oz·in]
Acceleration Torque	T_a	= 1.0945e-3	[lb·in] =	1.7512e-2	[oz·in]
Load Torque	T_L	= 13.89	[lb·in] =	222.2	[oz·in]
Required Stopping Accuracy	$\Delta\theta$	= 22.92	[deg]		

Figure 21: CNC Cutting Bed Stepper Motor Requirements

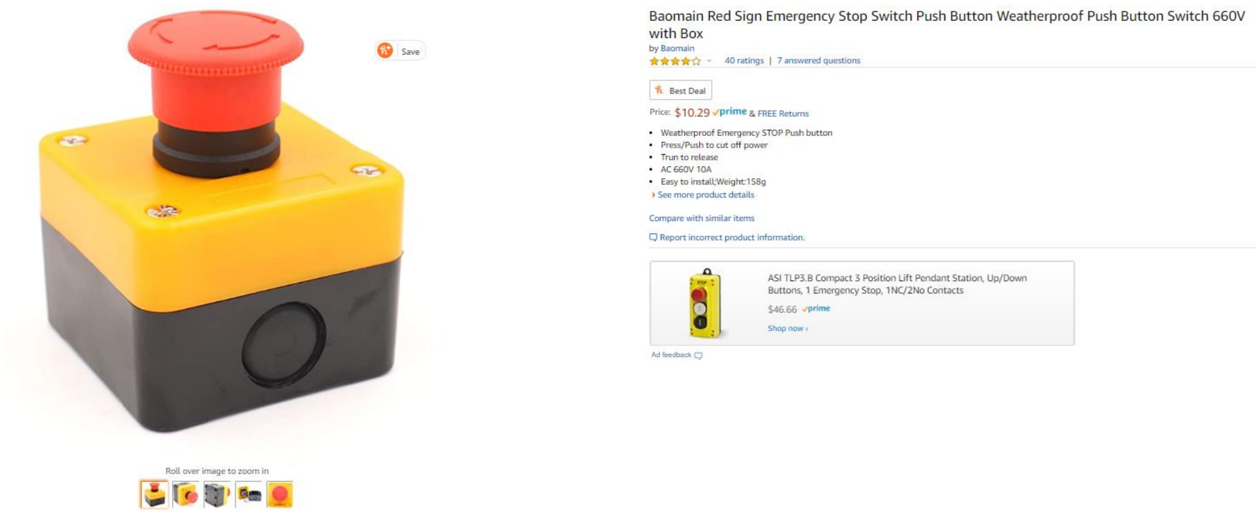


Figure 22: Emergency Stop Button from Amazon