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QuickCut Waterjet Cutter

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QUICKCUT WATERJET CUTTER

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Final Report for 4600:497 Senior/Honors Design, Spring 2021

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Abstract

The QuickCut Waterjet Cutter was created in 2019 as a senior design project. This is the third iteration of the waterjet cutter. The goal of this project was to create an operable CNC waterjet cutter that is able to cut 1/16" tensile specimens consisting of nonferrous metal or plastic. This machine will be utilized in the Manufacturing Laboratory at the University of Akron to provide education to interested students on the waterjet cutting process, how it operates, and industrial application of the technology. Waterjet cutting is a subtractive manufacturing process which is recognized for its specialized applications such as cutting dangerous materials or preserving heat treatment. Waterjet cutting utilizes high pressurized water with entrained garnet to cut through materials with precision and accuracy. The QuickCut Waterjet Cutter aims to bring the applications of industrial waterjet cutting operations to the smaller, tabletop scale to cut softer materials with precision. This report goes in depth on what defines an abrasive waterjet cutter, important components and the benefits of the waterjet cutting process. Detailed steps on how the newest rendition of the QuickCut Waterjet Cutter was created are covered. This includes brainstorming, design of components, design of controls, manufacturing process, as well as testing and future work to be completed.

Contents

1. Introduction

1.1 Problem Opportunity Definition

The objective of this project was to revive a previously designed waterjet cutter to make it operable with accurate cuts. A waterjet cutter is a computer numerical control (CNC) machine that functions by using highly pressurized fluid to cut a precise line in a stock material. When cutting harder materials, a garnet abrasive is required to improve the cutting capabilities.

To complete this project a few requirements needed to be met. Firstly, the cutting head needed to be redesigned to ensure minimal vibrations. There were a few reasons that these vibrations were happening based on the initial setup including the motor being mounted to the frame, the frame being too small, and the hoses connecting the water to the nozzle being too stiff. This vibration from the system causes losses in cutting precision. The most important objective was to create a machine that is user friendly and safe to operate. Since the water is being released from the nozzle at such high pressure it was important to ensure that users will not get hurt while operating the machine.

1.2 Background Research

Waterjet cutting is the subtractive manufacturing process that projects high pressure water through a nozzle to cut material. Subtractive manufacturing refers to the type of manufacturing that begins with excess stock material and methodically removes material until a desired component is created. This is the opposite of an additive manufacturing process such as fused deposition modeling that layers material on a printing bed to create components.

There are various types of CNC material cutting techniques including plasma cutting, laser cutting, and waterjet cutting. Each of these have their pros and cons, however, waterjet cutting uses the most easily accessible fluid on earth, water. Due to using water, waterjet cutting creates little waste during operation, making it environmentally friendly. For plasma cutting, harmful fumes are released into the air during the cutting process. In laser cutting, substantial power is needed to run the machine and produces heat on the materials when cutting. Alternatively, Waterjet cutting does not produce heat and therefore does not release any gases into the air and does not create deformation or discoloration on the material. Waterjet cutters also create a better surface finish than other machining methods. As an example, carbon fiber is utilized for many lightweight applications and when being machined, it releases carbon dust which is harmful to inhale. The advantage to utilizing a waterjet cutter is that there is less carbon dust released due better collection of the dust by the water[1].

In industrial applications, waterjet cutting requires substantial pressures to generate the cutting power for harder materials such as steel. It is common to see pressures above 50,000 psi for large waterjet cutters[2]. To reach these pressures, powerful pumping systems are required. Established companies in industry have found suitable solutions to this high-pressure requirement such as WardJet using an intensifier-style pump while Omax uses a direct drive style for their system[2][3]. Secondary to the pressure requirement is the need for consistent pressures. When selecting pumps for an application such as a waterjet cutter, the chosen pump must create a constant pressure that is not causing cyclical spikes. These spikes would introduce vibrations into the system at the cutting head by causing a resulting cyclical force on the gantry.

Industrial waterjet cutters are equipped with a tank that is filled with water underneath the material. This tank works to dissipate the energy from the high-pressure water to stop the machine from damaging the area underneath the cutting table. This tank also provides the ability for the stock material to be submerged and the process to be conducted under water. When submerging the waterjet cutting process, air does not become entrained into the water stream which causes a considerable amount of noise. This lack of air in the process causes the cutting to be done at a much lower noise level which is helpful for operators who would be exposed to the hazardous noise levels.

Industrial waterjet cutters utilize abrasives in the stream in order to increase cutting power. When no abrasive material is added to the cutting stream, the water is the cutting medium. Using water alone is capable of cutting softer materials or etching designs on metals, but for harder materials such as steel, abrasive must be added. Abrasives are composed of small, jagged objects that resemble sand. When the abrasives are added to the stream, the water becomes the mode of transport, and the abrasive is the cutting medium. Abrasives come in various materials but the most common is garnet. Garnet's prevalence stems from the fact that it has low purchase price and is chemically inert. Operators are safe from unnecessary hazards that could be imposed by using abrasive that is harmful to humans. The garnet also does not react chemically with cutting material which fosters clean and efficient cutting. This abrasive can be recycled by separating all the small particles from the large particles. The small particles that can no longer be reused are suitable for the landfill. The large particles can be dried out and reused. When the abrasive is separated from the water, the water can be disposed of through the drain. This abrasive is safe to send to the landfill, but it is more cost effective when recycled.

When waterjet cutters are in operation, the stock material being cut needs to be held stationary. To achieve this, a table is made that sits inside of the waterjet tank. Common structure for these tables is a grid made of meshed sheet metal. This table is designed with the purpose of revealing as little surface area as possible in the x-y plane. When this surface area is minimized, the frequency that the water jet breaks through the stock material and harms the table is also minimized. Events where the table is cut by the waterjet still occur, but it causes minimal damage to the table's performance and the table can be periodically repaired. To restrain the stock material during operation, special clamps are inserted into the table grid that clamp the bottom edge of the table with the top edge of the stock material. These aspects of the waterjet cutting table result in a stable surface that produces reliable finished parts.

The gantry refers to the section of the waterjet cutter that holds and moves the cutting head. This gantry is often in the style of a bridge where the cutting head is able to move in two axes. The beam moves forward and backward along the y-axis of the cutting table. The cutting head is also able to move along the beam which allows movement in the x direction. Important structural analysis is conducted on this system to determine that the beam will not deflect in a way that causes the cutting head to be positioned improperly. This analysis includes bowing from the weight of the beam and cutting head forces due to accelerating and decelerating the cutting head during operation, and the resultant force from the high-pressure water exiting the nozzle. Movement of the cutting head is not restricted to planar motion in the x and y direction, however. Mechanisms can be added to the gantry assembly to introduce multiple additional movement axes. Commonly, movement in the z-axis is added to be able to cut many material thicknesses and irregular sized objects. Rotational axes in the cylindrical coordinate system also are often used to cut at angles differing from the z direction. This additional movement axis adds to the waterjet's ability to cut irregular objects as well as counteract the taper that is often created from the waterjet process. This taper originates from material throughout the thickness of the stock material experiencing a disproportionate amount of time exposed to the cutting stream.

Following the assembly of the structure of the waterjet cutters, controls of the machine must be implemented. Proper control over the machine depends on the number of axes that the waterjet cutter is designed to move in. With a simple machine that moves in two directions, stepper motors are often implemented due to their precision and torque capabilities. With the simple movement case, two stepper motors may be used. One motor to move the gantry in the y direction and another to move the cutting head in the x direction. Additional motors may be added to accommodate axis requirements such as adding a motor to move the cutting head in the z direction or one that corresponds to angular movement of the cutting head. These motors can be connected to the control system by belt or screw movement systems. Industrial waterjets, similar to other computer numerical control machines, use G-code to instruct cutting head movements. This is a coding language that these automated manufacturing machines use. Many computer aided design (CAD) software packages come equipped with G-code generating capabilities. After the G-code for a required part is created, it can be input into the machine. Industrial machines often have a human-machine interface (HMI). Some HMIs are even capable of converting CAD files into G-code for the waterjet to use. The control system is then able to move the cutting head using coordinates given by the G-code. G-code is written to tell the machine how to move the cutting head from a point on the machine called the global origin. This point (0,0) is where every other point of the cutting table is referenced from. Some waterjet machines are able to provide an additional coordinate method for ease of use. This additional method involves manual movement of the cutting head to a desired location on the cutting bed, called jogging. When the desired location is reached, a local origin can be cut based off this initial position. This makes the machine easier to work with since operators do not have to be accurate when clamping stock material to the cutting bed, they can simply tell the waterjet cutter where to start the process.

1.3 Customer Need/Requirements

The waterjet cutter will be utilized by Dr. Gopal Nadkarni in the Manufacturing Laboratory at the University of Akron. The purpose of the machine is to cut thin tensile specimens, including nonferrous metallic or plastic up to 1/16” thick. This machine will be utilized as a teaching tool for future engineering students to learn about waterjet cutting.

2 Design

2.1 Scope & Plan Detail

To complete this project the team worked through many different steps including the conceptual design, the embodiment design, the detailed design, purchasing materials, manufacturing the prototype, testing the initial design, and the redesign of any parts. The plan was to utilize the Fall 2021 semester to brainstorm and develop a project timeline. The Spring 2022 semester was to be utilized to build the machine and make any fine-tuning needed. To stay on top of the deadlines, the group met twice weekly during the Fall Semester to discuss independent progress and plan next steps. During the Spring Semester, the team met every Tuesday and Thursday to manufacture and discuss next steps. Every other week throughout the semesters, the team joined an online meeting with the project advisor, Dr. Gopal Nadkarni to update him on the progress and discuss any roadblocks the team has encountered.

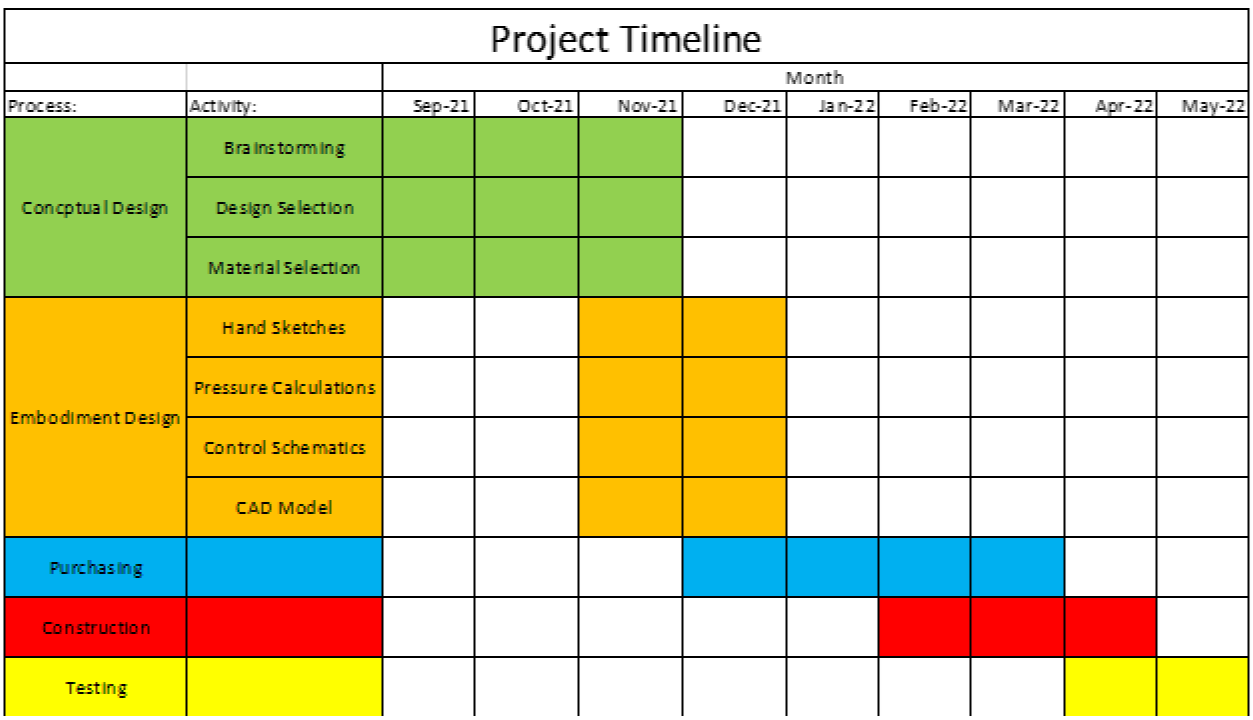

Figure 1: Tentative Schedule for Completion

2.2 Conceptual Design

The conceptual design portion of the project is the framework for establishing all the brainstorming done for the design along with the evaluation of each design. By looking at customer requirements, important design factors, and risk involved with the design, all ideas can be evaluated and compared to determine a final design.

An objective tree was created to help visualize what aspects of the design were most favored. These factors play an important role in filtering out designs during the brainstorming phase. Based on the table shown below, quality was decided to be the most important design factor out of quality, cost, and operations. From the quality design factor, the team decided that reliability of the machine is the most important design factor.

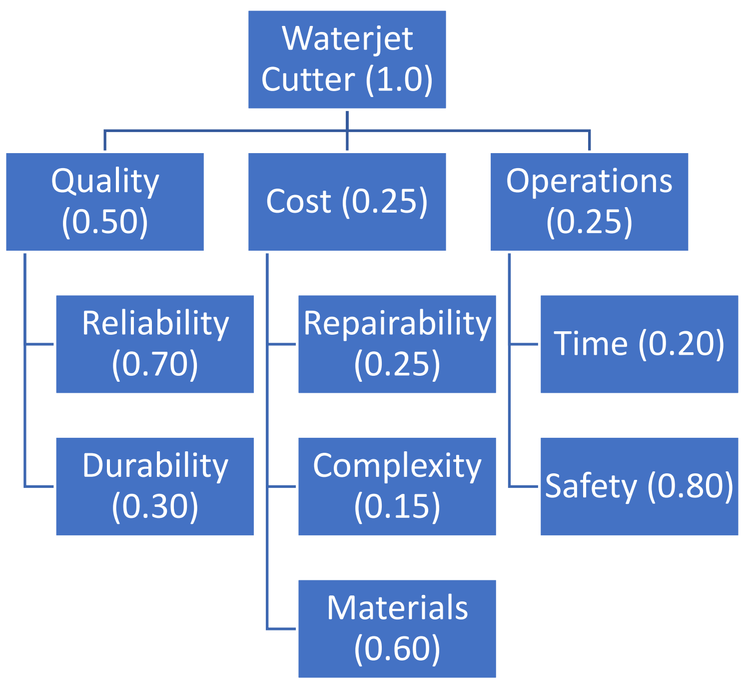

Figure 2: Objective Tree for the waterjet cutter to determine the important design factors

A function structure diagram represents the functions the machine will perform through inputs and outputs. This diagram shows the flow of materials, electrical power, and time.

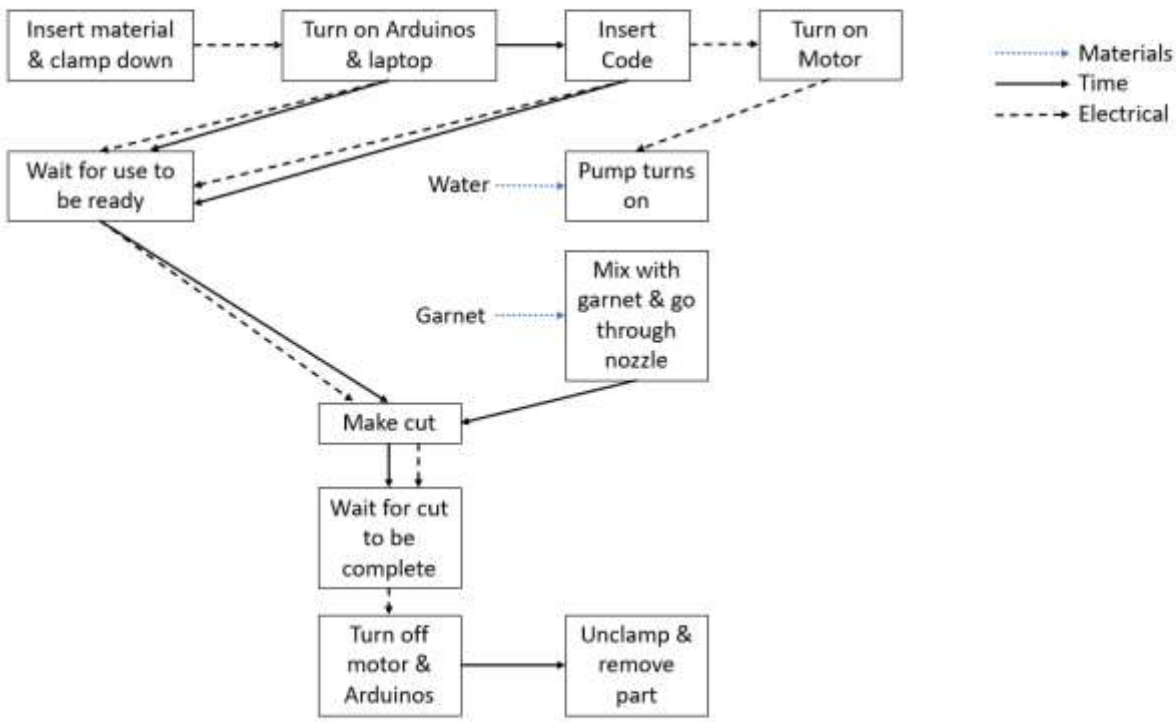

Figure 3: Function Structure Diagram

2.2.1 Quality Function Development

A quality function development chart (QFD) is utilized to make sure the customer's voice is input into every aspect of the design process. Based on the QFD shown below, the accuracy of the cut measured is going to be the most important design variables that will be utilized when evaluating potential designs.

Table 1: Quality Function Development Chart

		Engineering Characteristics							
Improvement Direction		↑	↑	↑	↓	↓	↓	↑	↓
Units		N/m	mm	kPa	W	N	N	m/s	dB
Customer Requirements	Importance Weight Factor	Stiffness	Accuracy of cut	Pressure	Power	Forces from moving gantry	Forces from nozzle pressure	Speed	Sound
Moves in x direction	**5**	7	9		1	7		8	1
Moves in y direction	**5**	7	9		1	7		8	1
Works with or without garnet	**4**		6	3		1			
Cuts through 1/16 aluminum	**4**		9	7	6			6	5
Works with a square foot of cutting area	**3**		5	5				3	
Precision cuts	**5**	7	9	6		6	6	5	
Quietness	**2**	4		7	6				9
Raw Score (792)		**113**	**209**	**99**	**51**	**104**	**30**	**138**	**48**
Relative Weight (%)		**14.3**	**26.4**	**12.5**	**6.4**	**13.1**	**3.78**	**17.4**	**6.06**
Rank Order		**3**	**1**	**5**	**6**	**4**	**8**	**2**	**7**

2.2.2 Brainstorming Solution Approach

To make decisions and evaluate all possible solutions, the group brainstormed different options for many of the main components of the machine. The original setup along with cost and availability of materials were taken into consideration when generating ideas.

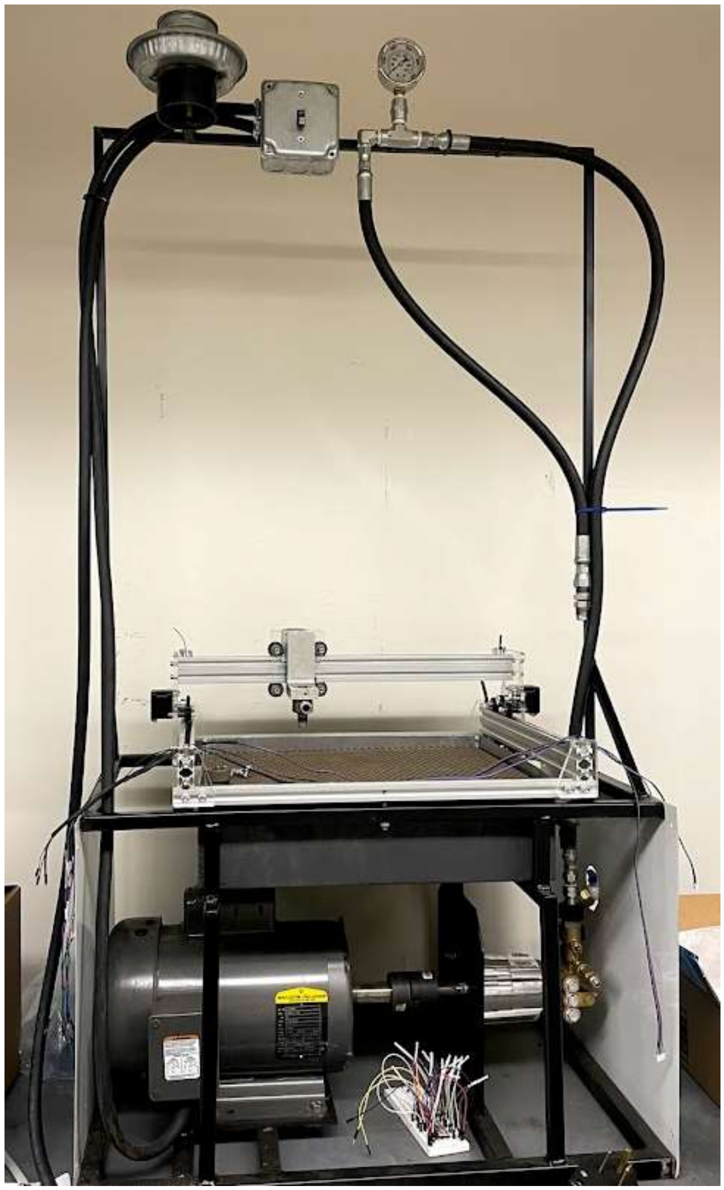

Figure 4: The original setup from previous groups work

The first and most important idea the group had to brainstorm was how to reduce the vibration the machine was experiencing when the motor was on. This vibration would cause inaccurate cuts as well as create more noise. The first solution was to remove the motor from the structure. By turning the motor on, it showed that it introduced considerable undamped vibrations to the system. Through separating the cutting assembly from the pump assembly, the group would expect the vibrations in the system to decrease significantly and should therefore foster more precise cuts. Another idea was to change the structure itself. The original design is made from small steel tubing that is welded together. To reduce vibrations, a larger steel box tubing could be incorporated. However, with creating a larger structure, this incorporates a larger cost.

Ideas for the clamping mechanism also needed to be generated. The original setup did not incorporate a method for clamping. The group wanted to employ a simple solution due to WardJet's simple and effective design for their clamping mechanism. The group came up with several ideas. The first idea was to utilize a C clamp to hook underneath the bed and tighten down on the material. The second idea was to create a customized C clamp that better fit the required heights with an adjustable top bar that could be moved forward and backwards on the material. Another solution was to simply put weights on the material. The last solution the group came up with was take a piece of aluminum and bend it at a 45-degree angle and use T-slot bolts to connect it to the controls frame.

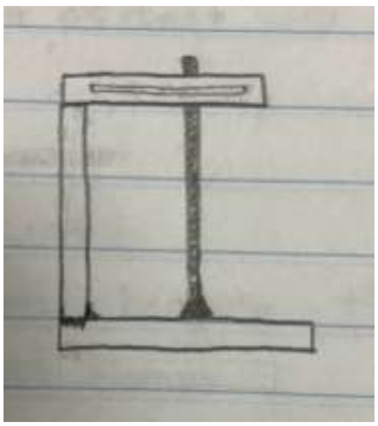

Figure 5: Customized C-clamp sketch

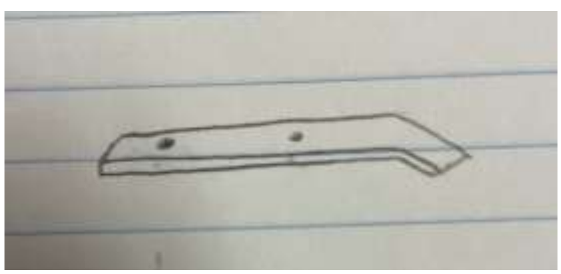

Figure 6: Angled aluminum arm sketch

The safety of the machine was a very important aspect of the design and therefore, the group decided a shield was necessary to prevent the users from being able to access the nozzle while running. The group had some ideas to utilize the already purchased metal sheet or purchasing plexiglass. Based on the materials available and to reduce cost, the metal sheets that a previous group had purchased to cover the motor would be utilized to create the shield. Brainstorming was done to decide how the material would be designed for the purpose of the shield. One idea was to cut the sheet towards one side vertically and put hinges on the other side to create a door like shield. Another idea was to cut the sheet in half and put hinges along with hooks on the sides to hold it in place when the machine is running.

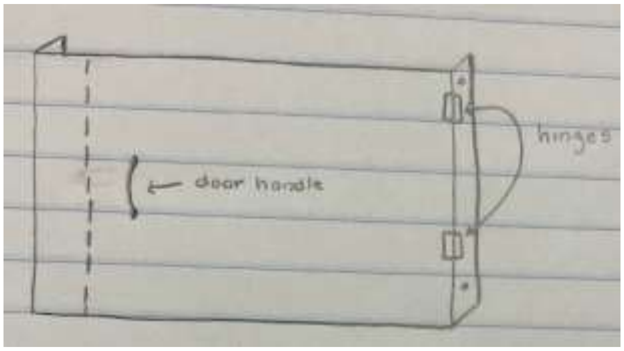

Figure 7: Shield sketch with hinges and door handle

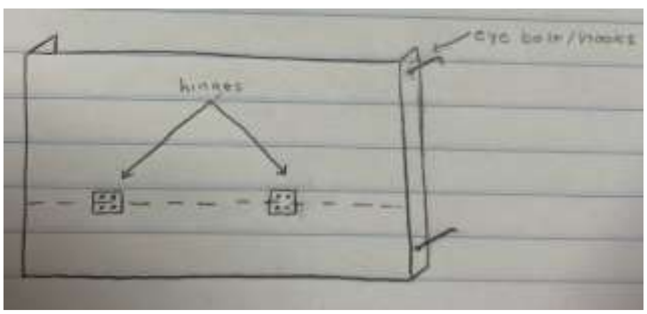

Figure 8: Shield sketch with hinges and eye bolt hooks

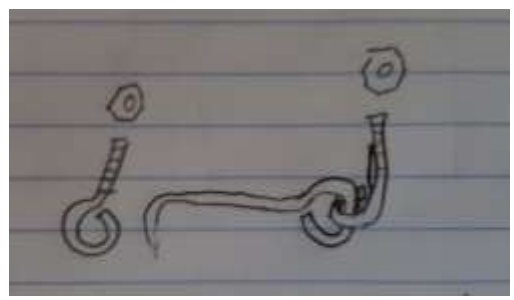
Figure 9: Sketch of eye bolt hooks to be used with shield

The bed of the machine was also examined to determine whether the original setup would be sufficient. When talking to Nisan Lerea, one of the founders of Wazer, he suggested the depth of the tank should be increased to remove excess energy and prevent the waterjet from piercing through the tank. This was also apparent at WardJet where the tanks were a large part of the machine. The group decided to test the original tank before making any depth changes. A change to the original tank the group brainstormed was to add a drain tube at the bottom of the tank to release all the water after using the waterjet cutter. Without adding this drain, the tank would have to be removed from under the gantry after each use which would add unnecessary operation time. Without draining this water after each use, the bed and material in the bed could slowly be damaged and have to be replaced. The original setup only included a drain towards the top of the tank which is used when running the waterjet to ensure it doesn't overflow.

It was important for the nozzle to be placed as close to the material as possible. To do this, either the bed of the machine or the nozzle fixture can be moved. The group brainstormed for both options. To rise the bed of the machine, lifts could be 3D printed and sit under the bed on the support bars. To lower the nozzle fixture closer to the bed, the group discussed adding extra settings along the fixture to be able to modify the height based on the thickness of the material.

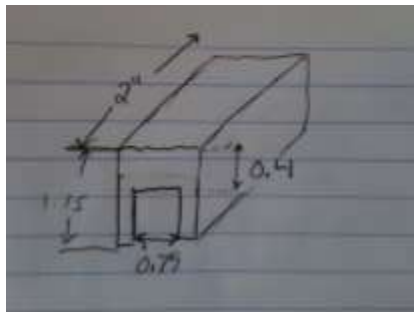

Figure 10: Sketch of a lift to be rise the bed closer to the nozzle fixture

2.2.3 Risk Assessment

A risk assessment evaluates the potential risk that can occur while operating the machine. For this project, there are a few different events that could happen causing a potential hazard. Most of these risks are unlikely to happen and are very minor if they do. The group accepted all the risk and did not feel the need to review any of them based on their likelihood and severity.

Table 2: Risk Assessment Chart

Event	Description	Likelihood	Severity	Risk
Hose Failure	The hose disconnects from the system	1 Unlikely	2 Minor	Acceptable
Motor Fault	Motor overheats, shorts	1 Unlikely	3 Major	Acceptable
Clamp Failure	Part is no longer fixed to cutting table	3 Rare	2 Minor	Acceptable
Controls Fault	Wires become shorted or unattached	4 Occasional	2 Minor	Acceptable
Guard Misplacement	Guard isn't placed and exposes cutting head	3 Rare	3 Major	Acceptable

2.3 Embodiment Design

The embodiment design section of this project follows the conceptual design section. This section includes deciding on the materials needed for each component of the machine and also deciding on the manufacturing process that will be used to construct the machine. Following the embodiment design will be the detail design which leads into the manufacturing and production of the final machine.

2.3.1 Material Selection

To best select the materials utilized in the manufacturing process the group looked at cost, availability of material, and lead time of material. Due to the COVID-19 pandemic, these factors were very important to ensure the machine was manufactured by the end of the semester at a low cost.

The group decided that the original frame would be separated into two, to meet the requirements. This meant no material selection was needed for the frame. However, by separating the frame into two components, more hosing would be necessary for the water to reach the nozzle. The top half of the machine that included the gantry would be put on a table while the bottom half of the machine including the motor and water pump would be on the ground. The group discussed with Cody Sarmiento, the Connector Territory Manager at Parker Hannifin and decided on a 3/8” high pressure hydraulic hosing. To connect the hosing, JIC fittings were chosen. The group also decided that purchasing dampening matts would be beneficial to reduce the vibration even more.

For the clamping mechanism, after considering all brainstormed options, the group decided that the aluminum bar was the best option. The aluminum would be free and easy to access due to its availability in the Mechanical Engineering Lab. There would need to be M5 T-slot bolts purchased to connect the bar to the gantry system.

The shield would be constructed out of the already purchased sheet metal that the previous group had purchased. There are other components that would need to be purchased including hinges, bolts for the hinges, bolts to connect the shield to the frame, as well as hooks to connects the front shield to the side shields. After looking at possible options, a 1.5” hinge was decided on based on its weight and the size compared to the shield. M5 12 mm long bolts were also decided on based on holes that were drilled out where the metal panel previously sat on the frame.

For the bed of the machine, some materials would need to be selected for the additional drain that would be added. The group wanted to add tubing that was large enough to drain the bed at a reasonable speed while also being cost effective. It was decided to use a 3/4” OD, 5/8” ID vinyl tubing due to its size and cost. The drain would also need a valve to close or open the tubing based on whether the bed needed to be drained or not. To make sure there are no leaks within the tubing, two hose clamps would be purchased to fit on both sides of the valve. The last material needed for the bed is a type of caulking which would be used to attach the tubing to the bed and to ensure no leaks.

2.3.2 Manufacturing Selection

From the material selection, the manufacturing process can be determined. The manufacturing process was based upon the availability of machinery and the skill level needed to operate the machinery available. For each of the mechanisms that needed to be manufactured, the group used the Mechanical Engineering Lab in the basement of the Auburn Science and Engineering Center at the University of Akron.

2.3.3 Calculations

To solve for the theoretical maximum pressure the pump assembly should be able to produce, the team attained the flow rate and brake horsepower from Annovi Reverberi about the RMV25G30D-EZ pump[4]. This pump was given by the supplier to have a 2.5 gallon per minute flowrate with a 5.1 brake horsepower measured in horsepower.

$$D = \frac{231*Q}{f} \tag{1}$$

Equation 1 relates the volume of the displaced water in each cycle to the flow rate and pump speed. D is the displaced volume of water with each cycle in cubic inches, Q is the volumetric flowrate in gallons per minute, and f is the rotational speed of the rotor in revolutions per minute.

$$\tau = \frac{63025*\dot{W}}{f} \tag{2}$$

Equation 2 is used to relate torque to input power and rotational speed[5]. In the equation, τ is the torque in inch-pounds, $\dot{W}$ is the input power in horsepower, and f is the rotational speed of the rotor in revolutions per minute.

$$\tau = \frac{P*D}{6.28} \tag{3}$$

Equation 3 relates the input torque to water pressure and displaced volume of water. τ is the input torque in inch-pounds, D is the displaced volume of water in cubic inches, and P is the water pressure in pounds per square inch.

$$\frac{63025*\dot{W}}{f} = \frac{P*D}{6.28} \tag{4}$$

Equation 4 equates the previous two torque equations so that water pressure may be determined.

$$P = \frac{63025*6.28*\dot{W}}{231*Q} \quad (5)$$

$$P = 3478.65\,psi$$

Equation 5 shows the result after substituting equation 1 into equation 4 and rearranging to solve for pressure. The flow rate through the orifice can be determined from this calculated water pressure. This can be done by utilizing Bernoulli's equation[6] which can be written as:

$$\frac{P_1}{\rho g} + \frac{{V_1}^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{{V_2}^2}{2g} + z_2 \quad (6)$$

Equation 6 shows that pressure, velocity, and elevation are related at two points in a water stream using variables P, V, and z, respectively. In this case the two points being related are the outlet of the pump (1) and the exit of the orifice (2). In this equation ρ is the density of water and g is acceleration due to gravity.

$$V_1 = \frac{Q_1}{A_1} \quad (7)$$

Equation 7 relates the velocity of the water stream to the volumetric flow rate and cross-sectional area of the hosing using V_1, Q_1, and A_1, respectively. This equation is only applied to the first state since the volumetric flow rate and cross-sectional area is known for the outlet of the pump.

$$\frac{P_1}{\rho g} + \frac{{Q_1}^2}{2g{A_1}^2} + z_1 = \frac{P_2}{\rho g} + \frac{{V_2}^2}{2g} + z_2 \quad (8)$$

Equation 8 shows equation 7 substituted into equation 6 so that the only unknown in equation 8 is the velocity at the second state.

$$V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho} + \frac{{\dot{V}_1}^2}{{A_1}^2} + 2g(z_1 - z_2)} \quad (9)$$

Equation 8 can be rearranged so that the velocity of the water stream at the exit of the orifice is solved for as shown in equation 9.

$$V_2 = \sqrt{\frac{2(3478.65*144^{lbf}/_{ft^2} - 2116.22^{lbf}/_{ft^2})(\frac{32.2\ lbm^{ft}/_{s^2}}{1\ lbf})}{(62.4^{lbm}/_{ft^3})} + \frac{(0.0055700231^{ft^3}/_{s})^2}{\left[\pi \frac{\frac{0.375}{12}ft}{2}\right]^2} + 2(32.2\,^{ft}/_{s^2})(0 - 3ft)} \qquad (10)$$

$$V2 = 717.36\ ^{ft}/_{s} = 489.1 \text{ mph}$$

Equation 10 shows values plugged into equation 9. It is found that the water stream leaves the orifice at 717.36 ft/s or 489.1 mph. This is approximately 64% of the speed of sound.

$$Q = V * A = 717.36^{ft}/_{s} * \pi \left(\frac{0.014}{12*2} ft\right)^2 = 7.66 * 10^{-4} \frac{ft^3}{s} = 0.3442\ GPM \qquad (11)$$

Equation 11 is used to determine the volumetric flow rate through the orifice. This is calculated using the previously determined velocity of the stream shown as V and the cross-sectional area of the orifice shown as A. The orifice used is 0.014 inches in diameter which is then converted to a radius in feet as shown above. This volumetric flowrate is significantly lower than the supplied volumetric flowrate of the pump. This explains why problems were occurring with overpowering the motor and tripping the breaker of the electrical circuit the motor was ran from. This problem will be explained further in the testing section of the report. To fix this problem, an auxiliary line was added into the system to take the additional flowrate. This is shown in the following equation.

$$Q = Q_1 + Q_2 \qquad (12)$$

$$Q_2 = Q - Q_1 = 2.5 - 0.3442 = 2.1558\ GPM \qquad (13)$$

Equation 12 shows how the supplied volumetric flowrate, shown as Q, is related to the orifice flowrate and the required auxiliary line flowrate which are shown in the equation as Q_1 and Q_2. Equation 13 is a rearrangement of equation 12 that shows the new auxiliary line needs to output 2.1558 GPM to allow the pump to work without causing the motor to draw a current that is over its nameplate specification.

2.4 Design Detail

The detail design section of this report follows the embodiment design section. This section includes the detailed drawings for the main components created in SolidWorks along with all the specifications for the components. These drawings will be utilized during the manufacturing process. More detailed drawings can be found for all components in the appendix of this report.

Since the frame was already welded, few changes could be made to the original design. The team decided to separate the top and bottom frames from each other. The following figures are envelope drawings for the waterjet cutter with measurements in inches.

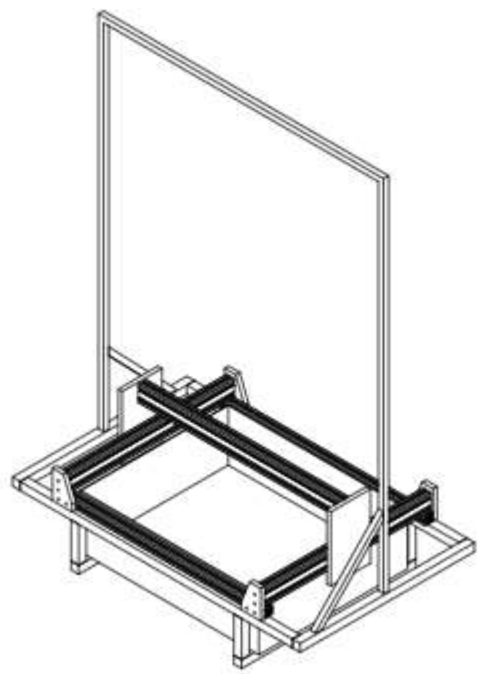

Figure 11: Isometric View of Top Frame

As seen in Figures 10 through 12, the top frame has a height of 40.25", a width of 17.13", and a length of 28".

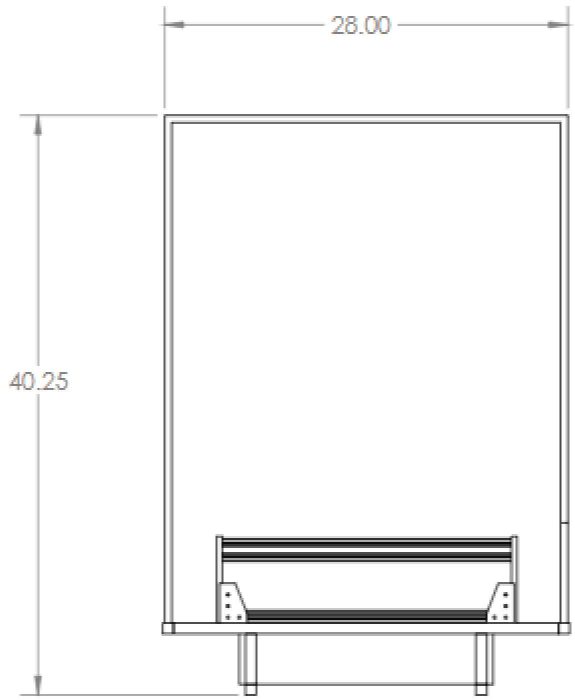

Figure 12: Front View of Top Frame

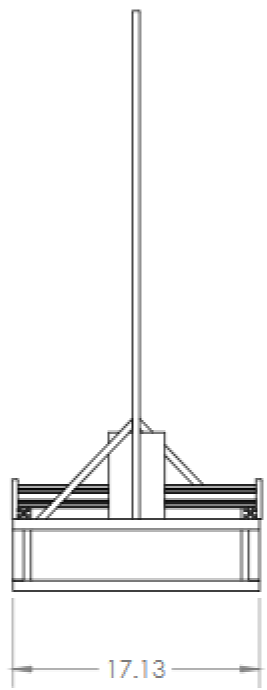

Figure 13: Side View of Top Frame

As seen in Figures 10 through 12, the top frame has a height of 40.25", a width of 17.13", and a length of 28".

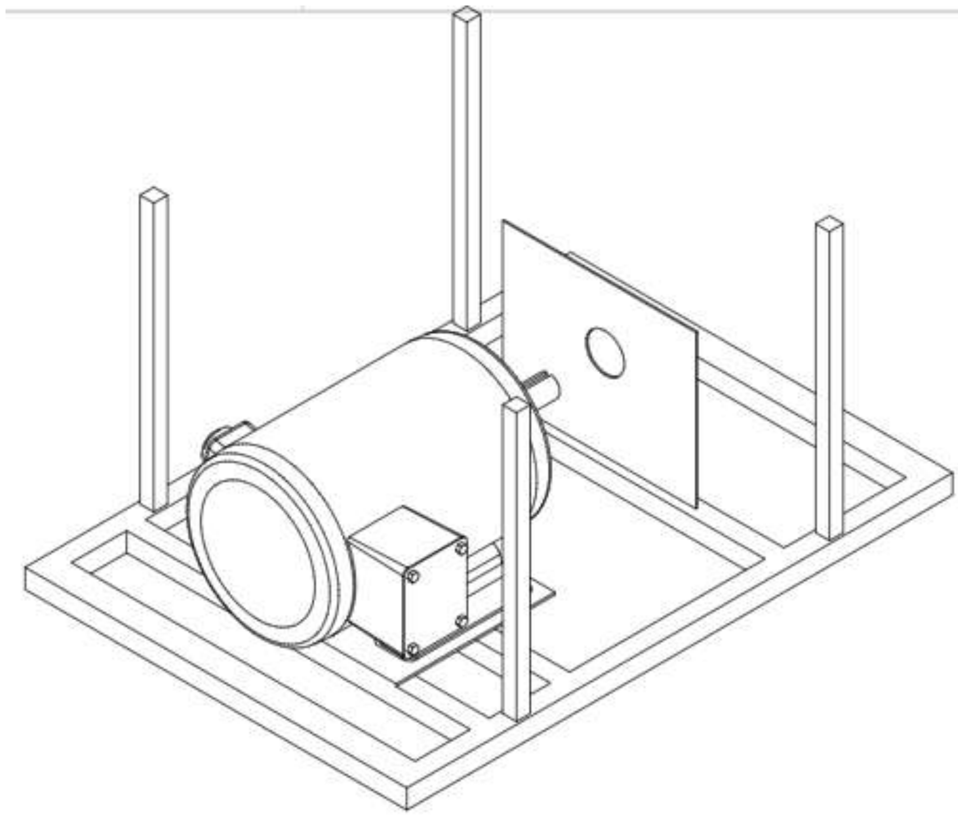

Figure 14: Isometric View of Motor and Bottom Frame

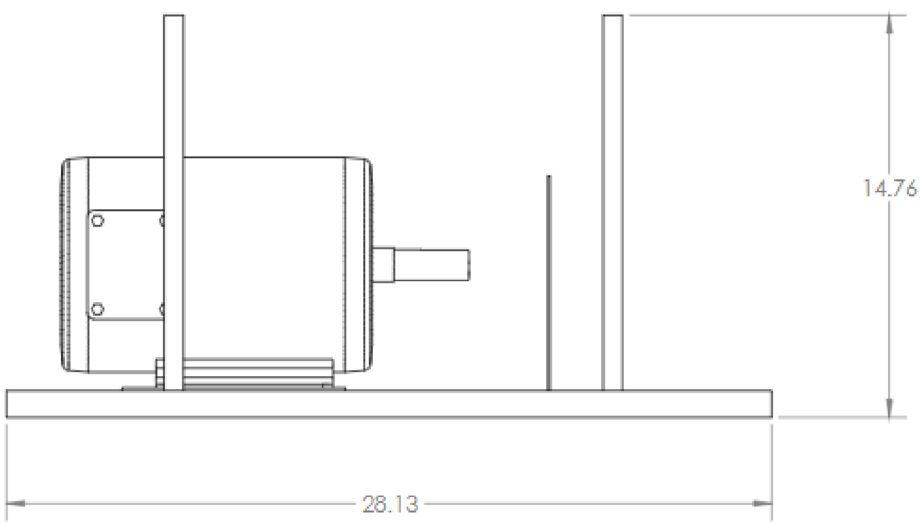

Figure 15: Side View of Motor and Bottom Frame

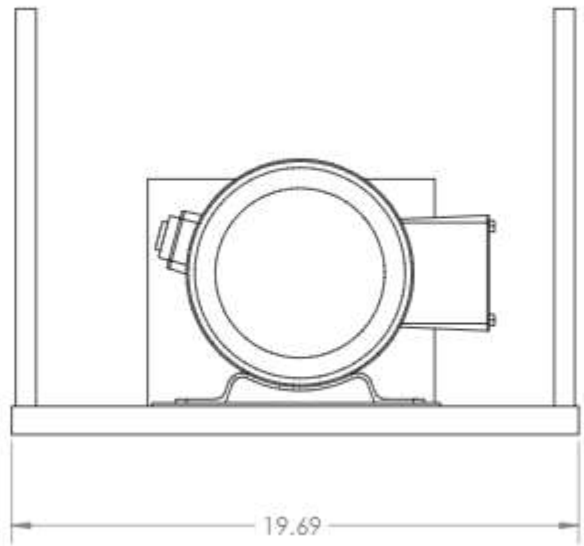

Figure 16: Front View of Motor and Bottom Frame

As seen in Figures 13 through 15, the motor and bottom frame has a height of 14.76”, a width of 19.69”, and a length of 28.13”.

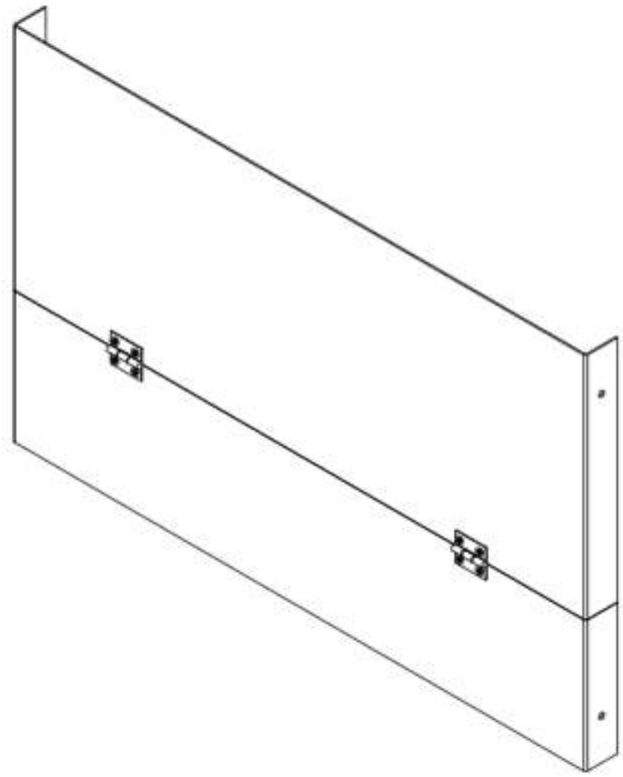

Figure 17: Isometric View of Shield

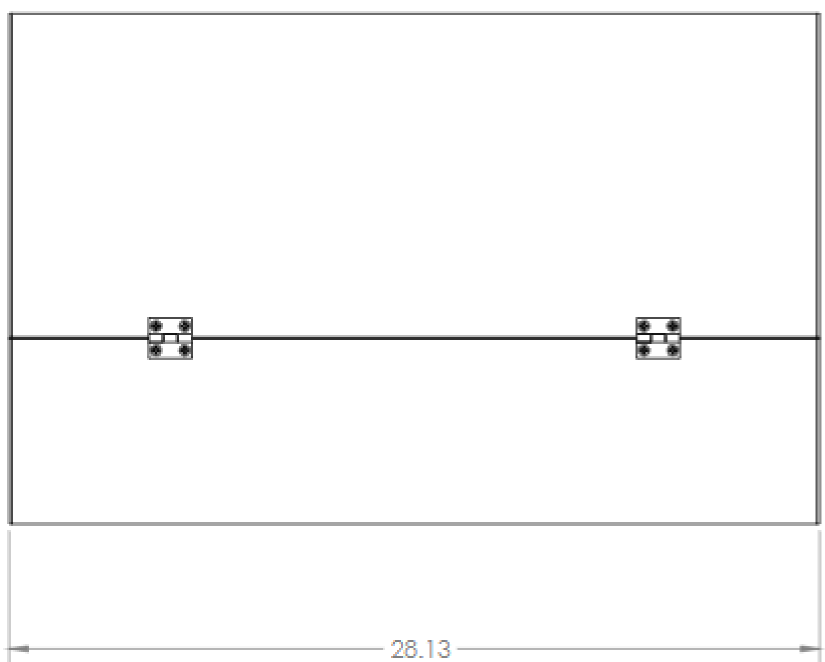

Figure 18: Front View of Shield

Figure 19: Thickness of Shield

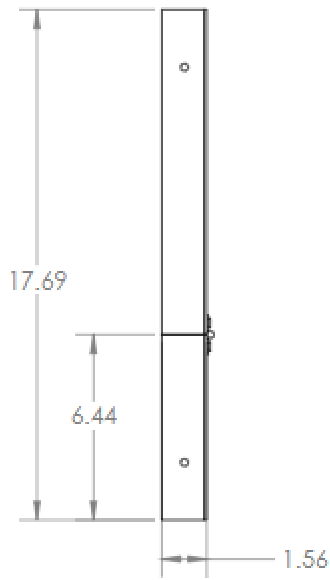

Figure 20: Side View of Shield

As seen in Figures 16 through 19, the shield has a height of 17.69”, a width of 1.56”, a length of 28.13”, and a thickness of 0.06”.

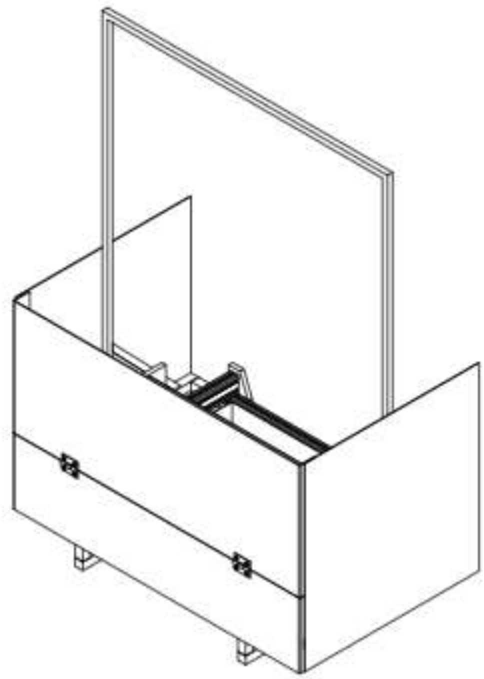

Figure 21: Isometric View of Top Frame with Shield

As seen in Figure 20, this is what the top frame looks like with the shield on. The hinges allow team members to reach into the cutting area to complete any necessary steps before running the machine.

3. Design Verification

3.1 Manufacturing

From the detail design drawings, the materials were purchased, and the manufacturing began. Most of the manufacturing was completed in the Mechanical Engineering Lab under the supervision of Aaron Trexler. Some components were manufactured using an at-home 3D printer owned by one of the group members. The 3D printer was an Ender 3 V2 that utilized black PLA filament. 3D printing was utilized in manufacturing of quick prototypes for guarding of the stepper motor from water and risers to change spacing between the cutting bed and the nozzle. During the manufacturing process, the team ensured safety by wearing the appropriate PPE and following any enforced safety protocol.

To separate the frame into two parts, the group utilized a reciprocating saw which was borrowed from Aaron Trexler. To make the appropriate cuts without damaging any of the existing parts of the machine, all the parts on the top of the frame including the gantry, the bed, parts of the metal cover, and the hosing had to be removed. A total of four cuts were made to the vertical beams to ensure the top frame would sit flat on the table. This job took three people to hold the frame and make the cuts.

Figure 22: Team cutting the frame using a reciprocating saw

Once the frame was cut, the aluminum sheet that remained on the bottom of the frame had to be removed. This was challenging to remove due to the types of screws originally used to secure the sheet metal to the frame. To remove these, the screws had to be drilled through using a hand drill as shown below.

Figure 23: Aaron Trexler assisting in drilling out the side panels on the bottom frame

To manufacture the clamping mechanism, the aluminum bar was measured to the appropriate length of 9.5 inches. The horizontal saw was used to cut the aluminum bar as shown below.

Figure 24: The horizontal saw being utilized to cut the aluminum bar for the clamping mechanism

Once the aluminum bar was cut, the two holes that would be drilled out for the t-bolt screws were marked out. One hole was made at 1” from the end and the second hole was made 5” from the end. The drill press was used to drill out these holes with a 3/16” drill bit.

Figure 25: The drill press being utilized to drill out the holes to connect the T-bolt screws to the gantry frame

The last step to manufacturing the clamping mechanism was to bend the cutting table contact end of the bars to a 45-degree angle so they can press into the table. To complete this task, the aluminum bars were placed in a bench vise. The end of the aluminum bars were bent until they reached the correct angle. To manufacture the shield, first, the shield was marked in the appropriate place to cut it horizontally where the hinges would be applied. The aluminum shield was then cut using the band saw as shown in the figure below.

Figure 26: The band saw being utilized to cut the aluminum shield

After the shield was cut into two, the holes for the hinges were measured out and marked. Using a hand drill, the holes were drilled out using a 3/16" drill bit. The hinges were then attached using the appropriate bolts and nuts. Once the side and front shields are attached to the frame, there is a hole in which a pin can be inserted to keep the shield latched.

To construct the drain for the bed of the machine, Aaron Trexler aided the group in cutting a ¾" hole into the bed. Epoxy gorilla glue was utilized to attach the tubing to the bed. A ¾" valve shut off was placed in the tubing with hose clamps on each side to ensure there would be no leaks.

3.2 Controls

The CNC application of the waterjet cutter was implemented with an Arduino UNO as the main controller. Arduino is an open-source electronics platform that makes it easy to implement controls systems for various types of electronics. For this application, rather than using the programming language associated with the Arduino, GRBL software is uploaded to the board. When GRBL is uploaded to the Arduino UNO, the board is able to act as a CNC machine[7]. This is accomplished by connecting a CNC shield to the Arduino UNO. The CNC shield offers a simple way of integrating stepper motors and stepper motor drivers to the system. Once the hardware is connected properly, the CNC portion of the machine is ready to be controlled.

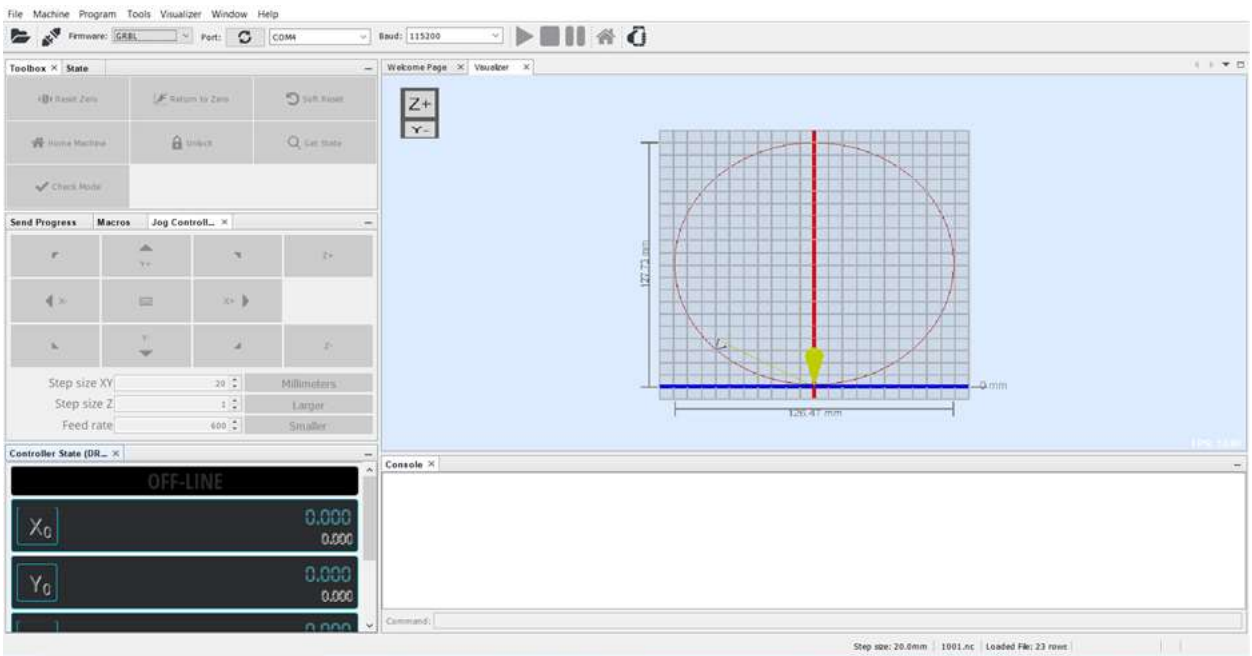

Figure 27: Picture of the Universal G-code Sender graphical user interface

For this project, the group decided to continue using open-source systems and utilized the Universal G-Code Sender (UGS) software to send instructions to the Arduino UNO. The UGS software is able to interface with the GRBL software to send G-code file instructions to the Arduino UNO and therefore control the motors[8]. G-code is a simplistic programming language that sends short lines of actions and coordinates to control the cutting head of machines in CNC applications[9]. The program must be calibrated so the commands that the UGS software sends correspond to the correct motor movements. The G-code file was created using Fusion 360 but could be made in many standard CAD programs. Once uploaded, the G-code program can be ran, which results in the nozzle tracing out the correct path.

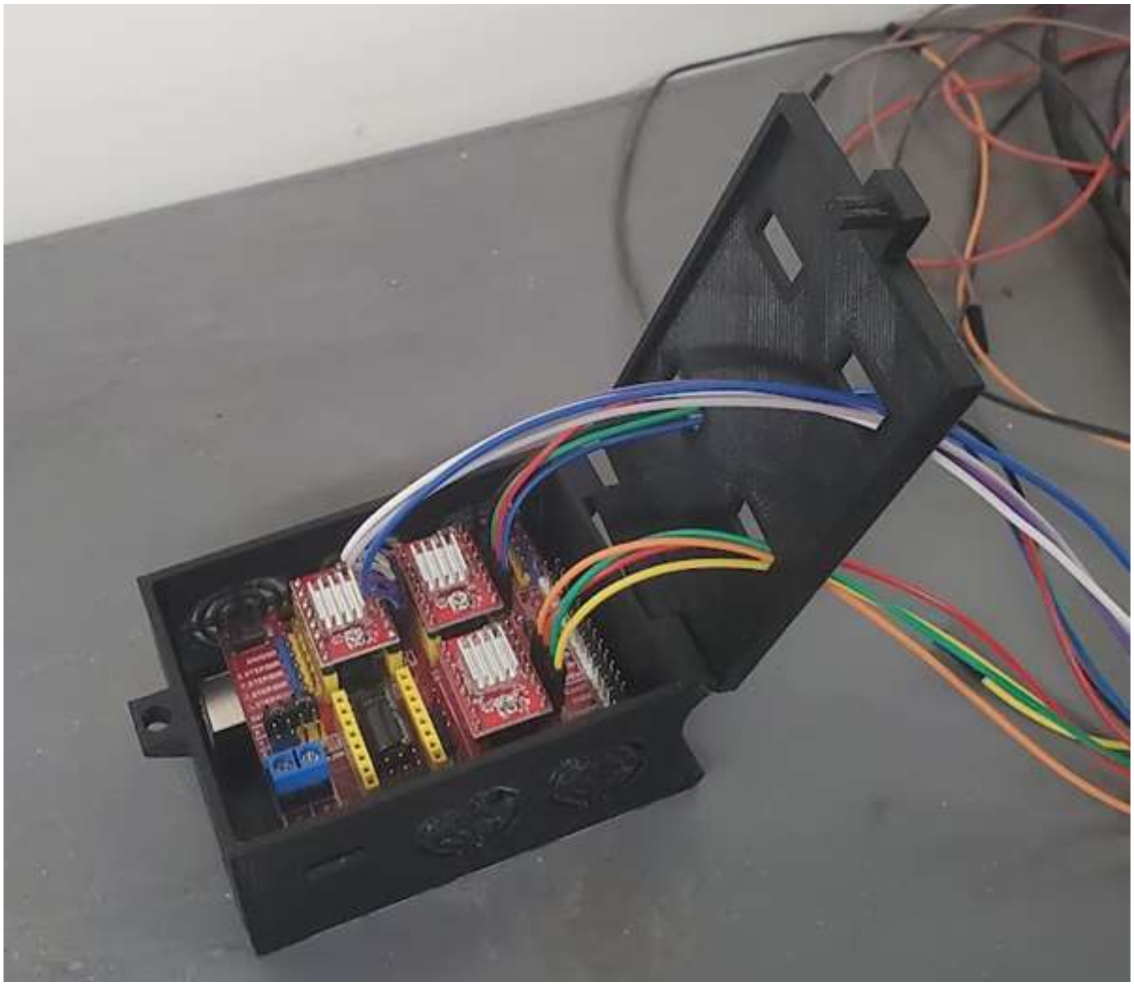

Figure 28: Arduino UNO, CNC Shield, and stepper motor drivers attached to stepper motors

3.3 Testing

Following the manufacturing of the machine along with the design of the control system, the machine entered the testing phase.

The first test resulted in leaks in various connectors. This was due to the connections not being tight enough. After, the team added thread tape to each connection and tightened them thoroughly. Once that was established, the team tried testing again. Once the motor was turned on, there would be a sudden and powerful stream of water exiting the nozzle but very quickly it would gradually wind down to a complete stop because it had tripped the breaker. The group contacted the Physical Facilities Operations Center (PFOC) at the University of Akron to have them check the wiring of the breaker and confirm the wiring for the motor was correct. The workers for PFOC verified the wiring in the motor and replaced the breaker sized to the specifications found on the motor. They tested and found that the motor was able to run without water. The team then tried testing the motor and pump with the new improvement but still found that when adding water to the system, the breaker was still being tripped. This means that the water was creating too much resistance for the motor to maintain its proper speed. Upon further investigation, it was also found that the motor was rated for three horsepower while the pump required four to seven horsepower and therefore kept tripping the breaker.

The team proceeded to look for a motor with more horsepower, as reducing the pump would decrease the maximum pressure. This would mean that the machine would not be able to cut through as thick of material. Purchasing a new motor for the project would introduce a large addition to the budget as well as delay testing even further. The team contacted Ben Adams from WardJet for advice on how to proceed. Mr. Adams suggested that the team either control the speed of the motor or divert some of the water after it exited the pump to a drain which would reduce the pump resistance. Provided that the exhaust hosing can be restricted by a valve, the pressure rated by the pump should still be able to be achieved. This is due to the nature of the positive displacement pump outputting a predefined volume of water with each reciprocation of the pump. If the exhaust valve is restricted so that the additional hosing's flowrate and the orifice's flowrate add up to the pump's 2.5 GPM set point, the pressure should be maintained.

To divert the water, the team purchased a JIC tee fitting, extra hosing, and a control valve. This additional line was implemented into the current system after the outlet of the pump. Testing then resumed using the exhaust line completely open at first and then slowly closing it to determine the operational point that the new system could run at. When this process was followed, the pump was able to make it to around 1800 psi before showing signs of resistance and ultimately tripped the breaker around 2400 psi. With these values now known, it was determined that a reasonable operation point could be at 2000 psi as running the motor too close to the breaker trip point would still be causing the motor to draw too much current even if the breaker itself had not tripped yet.

Once the operational point was set, cutting of materials could begin. Materials initially tested with included soft foam, hard foam insulation, and wood. Without abrasive added into the system, 6.25 mm thick foam was able to be completely cut, 38.61 mm hard foam insulation was able to be cut to a depth of 19.53 mm, and the wood was able to be slightly engraved. These materials were cut using the CNC controls in the shape of a dog-bone specimen. The model of dog-bone used had an inner width of 10 mm, outer width of 14 mm, and overall length of 150.492 mm as shown in the figure below.

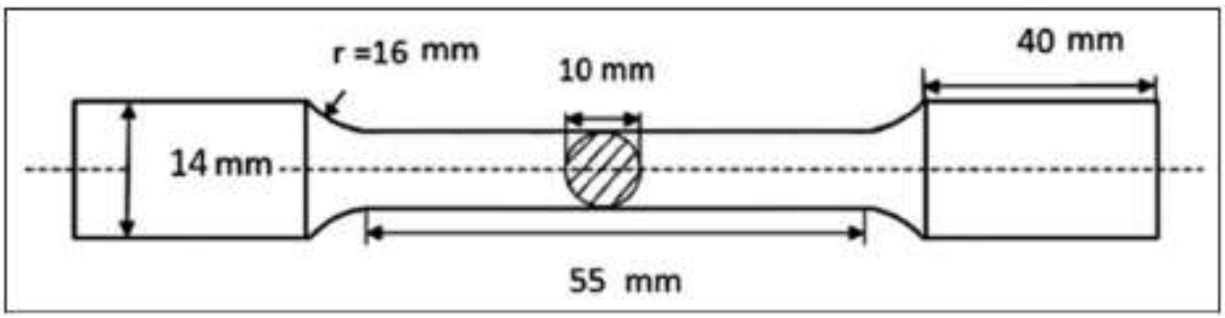

Figure 29: Referenced drawing for the dimensions of a dog-bone specimen

Table 3: Measurements of dog-bone specimen cuts when no abrasive was used. Dimensions are in millimeters.

Material	Center Width (error)		End Width (error)		Overall Length (error)	
Soft Foam	9.82	(-0.18)	14.36	(0.36)	149.32	(-1.172)
Hard Insulation Foam	9.98	(-0.02)	14.03	(0.03)	149.22	(-1.272)
Wood	10.17	(0.17)	14.21	(0.21)	150.06	(-0.432)

As shown in table 3, the error is minimal in most cases and close to the tolerance limit of ±0.2 mm commonly given to the widths of the dog-bone specimen. The overall length error is also acceptable due to tolerance for this measurement often being a minimum of 140 mm. Another source of error can be due to the difficulty of measuring the specimens as the foams were quite pliable and the outline in the wooden cut was splintered.

Abrasive has not yet been successfully implemented into the system as during transient operation of the pump assembly, water is introduced to the abrasive line which causes the abrasive to become immoveable by the vacuum that should be pulling the abrasive into the mixing chamber.

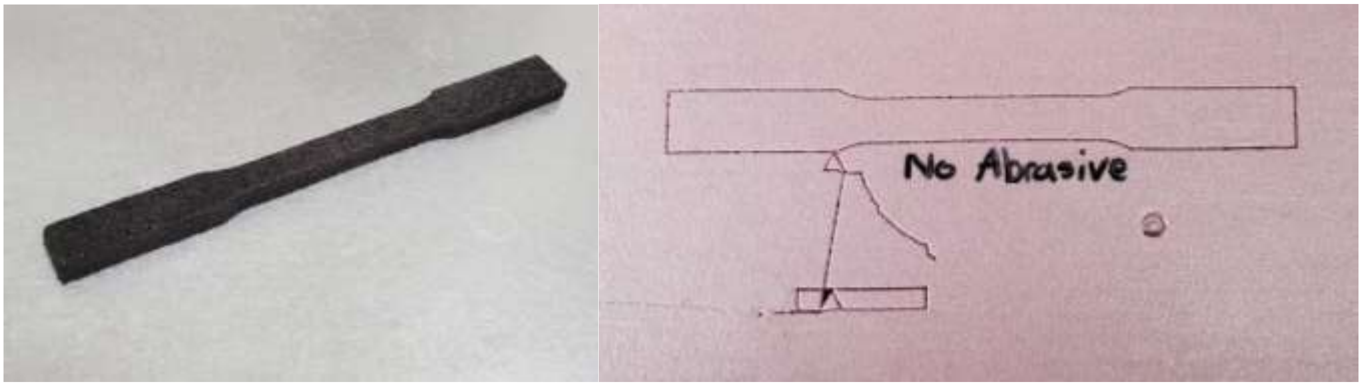

Figure 30: The completed soft foam tensile specimen (left) and the hard insulation foam test (right)

4. Costs

The cost of this project is broken down into two components including parts and labor. The parts include the original components purchased by the first group who worked on this project as well as the components purchased during the current revision.

4.1 Parts

The first group created a purchase list as shown below in Table 4. The group spent about $1,400 on the machine. This does not include the nozzle donated to the project from WardJet.

Table 4: The purchase list given by the first iteration group

Item	Product Use	Price
Axial Water Pump	Pressurize water	$ 119.00
Water Guage/Adapter	Water gauge	$ 25.78
Ball valve	Safety shut off valve	$ 80.27
Water Pan/Square Tubing	Water Pan/Bottom Steel Frame (3/4")	$ 62.21
LoveJoy Couplers	Motor to pump connection	$ 36.43
Hose Connection/Bulk Hose	Pump Outlet to Tee	$ 56.51
Swivel Connection/Bulk Hose	Cutting Head Hose	$ 37.06
Hose Connection/Bulk Hose	Cutting Head to Tee Connection	$ 66.99
Water Valve Adapter	Pump Inlet Garden Hose Connection	$ 2.99
Hose Clamp/Valve	Abrasive Shutoff and Connection	$ 11.22
Sheet Metal	Body Panels	$ 40.00
Screws	Panel Screws	$ 2.55
Brass Jet/Plastic Jar/Adapter	Abrasive Container/feed	$ 13.90
Square Tubing	Middle – Top Steel Frame (1/2" Tubing)	$ 60.06
3Hp Electric Motor	Power the Pump	$ 550.00
Electric Panel/Supplied	On/Off Switch, plug	$ 94.00
X – Y Axis Kit	Automate X – Y Gantry	$ 142.00
	TOTAL	$ 1,400.97

This group spent $277.34 on all the components that were added during the current iteration of the project. The goal was to utilize as much material from the first two iterations as possible to minimize the total cost. These costs can be seen in Table 5.

Table 5: Purchase list for the current iteration group

Item	Purchased From	Price
Metric M5 x 25 mm Thread T slot Bolts	Amazon	$ 11.49
M5 Hexagon Flange Nuts	Amazon	$ 7.49
CNC Drive Expansion Board Shield	Amazon	$ 6.79
3/8" x 48" Hydraulic Hose Assembly	Ebay	$ 18.50
Needle Valve 3/8" Flare x 3/8" M.P.T	Ebay	$ 17.98
Parker Paraflex Hydraulic Hose 3/8"	Ebay	$ 23.70
Threaded JIC Nipple 3/8"	Glacier Tanks	$ 10.18
Flarder Fitting Adapter 3/8" Tube OD x 1/4 NPT Female	McMaster-Carr	$ 22.08
High Pressure Flow Adjustment Valve, 1/4 NPT Male	McMaster-Carr	$ 35.52
Header Pin Jumpers	Amazon	$ 6.99
3/16" x 2" Clevis Pins	Amazon	$ 11.00
24" Bungee Cord	Home Depot	$ 3.48
36" Bungee Cord	Home Depot	$ 4.48
M4 Machine Screws (2 pks)	Home Depot	$ 1.92
1.5" Hinge	Home Depot	$ 2.58
3/8 OD x 1/4 ID x 10' Vinyl Tube	Home Depot	$ 2.73
Hose clamp 3/4"x2 3/4"	Home Depot	$ 1.96
#10 x 3/8 Zinc Screws	Home Depot	$ 1.28
3/4 OD x 5/8 ID x 10' Vinyl Tube	Home Depot	$ 8.71
Gate Hook and Eye (2)	Home Depot	$ 2.56
5M Machine Screws (4)	Home Depot	$ 2.52
Machine Screw Nut #6	Home Depot	$ 1.28
Hose clamp 1/2"x1 1/4" (2)	Home Depot	$ 2.96
Extension Cord 12'	Home Depot	$ 3.97
Gorilla Glue Epoxy	Home Depot	$ 6.47
5/8 OD x 1/2 ID x 10' Vinyl Tube	Home Depot	$ 5.43
3/4 inch ID in line ball valve shut off switch	Amazon	$ 9.99
3/8" JIC Hose adapter (Tee fitting)	Grainger	$ 21.29
Multi-Purpose Funnel	Lowes	$ 3.98
	Taxes:	$ 18.03
	TOTAL:	$ 277.34

4.2 Labor

Because this was a Senior Design Project, there was no cost associated with labor. In the case that there was a cost, each of the three members of the team worked on this project for about 4-5 hours per week for 30 weeks. This is about 120 hours per person, for a total of 360 hours for the group. At the average hourly rate of $21 for an engineering co-op, this project would have cost about $7,500 in labor for the current revision. This value, of course, only considers time during the meetings that the group had throughout the weeks. A better estimate would be two to three times more but due to the unrecorded time of the independent work, only the meeting times were considered.

5. Conclusion

5.1 Accomplishments

At the end of this project the team was able to accomplish much of what it set out to do. The team was able to drastically reduce vibrations by separating the motor assembly from the gantry assembly and added a mat to absorb the motor's vibrations. The team also made a clamping mechanism to hold down specimens when being cut and added shields that make it easy to access the specimen while also keeping the operators safe when the water jet is being ran. Stepper motors were implemented to create accurate cuts and G-code files to create dog bone tensile specimens were generated.

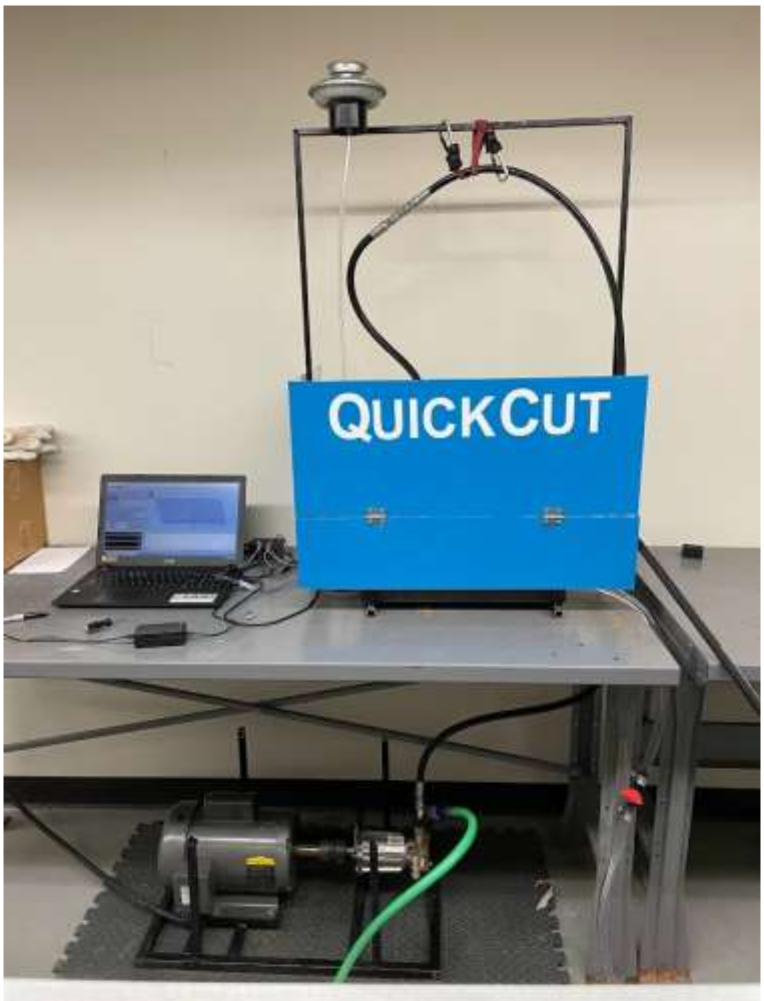

Figure 31: The final machine

Figure 31 shows the current state of the QuickCut CNC Waterjet Cutter. The added controls can be seen to the left of the machine where the Universal G-code Sender software is connected to the Ardiuno UNO. The pumping assembly has been completely separated from the gantry system with the results of significantly reduced vibrations in the cutting head. Another issue addressed in the redesign was the hosing reroute to minimize resultant forces on the gantry due to stiff hosing. Water and electric hook-ups were also added to the manufacturing laboratory to allow operation of the machine. A safety shield was added as a protection for operators using the waterjet cutter. The previous rigid abrasive tubing was replaced with tubing that was flexible and able to move along with the gantry as the machine functions. Drainage was added to the tank of the waterjet cutter so that standing water is not left in the system. Lifts for the cutting bed and shields for the stepper motors were 3D printed and implemented. Clamping mechanisms were created so cutting material can be held in place while cutting operations commence. Finally, work instructions were generated so that operators and students in the future may be trained on the constructed operating system and run the supplied G-code files.

5.2 Challenges

The team experienced many challenges throughout the project. The waterjet was placed in the Manufacturing Laboratory in the basement of the Auburn Science and Engineering Building at the University of Akron. This laboratory did not include the required outlet for the 3 horsepower Baldor motor or a water source for the pump. The team had to contact the PFOC at the University of Akron and requested for these necessary outlets to be added. The team also contacted the original designer of the project in order to receive insight and fully understand previous design choices and accomplishments. Unfortunately, the group was never able to contact this designer. With this, the team felt that the previous groups had not passed along important information to their advisor. The team and advisor were told that the pump assembly had been ran before however, after the motor repeatedly tripped the breaker from drawing too much current, this would have been impossible or dangerous.

5.3 Uncertainties

To find the uncertainty of the linear motion of the stepper motor, the group ran tests in each direction. To do this, the controls were placed into jog mode and programmed to move 2 inches on command. A ruler precise to 1/64th of an inch was attached to the gantry system to measure the actual distance the motor moved. Each direction was measured five times. The table below, Table 6, has the results from the test. This indicates that the one stepper motor that moves in the x direction which include the right and left movements has more of an error than the two stepper motors that move in sequence in the y direction. The y direction stepper motors include the forwards and backwards movements. The results also indicate that the error in each stepper motor is the same for each direction it moves.

Table 6: The error results from the stepper motors

Direction	Axis	Avg. Error (in.)	Avg. Error %
Right	x	0.021875	1.09%
Left	x	0.021875	1.09%
Forward	y	0.00625	0.31%
Backward	y	0.00625	0.31%

5.4 Ethical Considerations

An engineer's number one priority is to “Hold paramount the safety, health and welfare of the public” as described in the Code of Ethics[10]. The team believes it has achieved this by implementing safety procedures and measures to protect operators. The second cannon is to “Perform services only in areas of their competence.” The team did not deviate from their area of competence by requesting assistance in areas outside of mechanical engineering, such as when PFOC was contacted for the electrical issues. Lastly, the team has not done any deceitful acts to break any cannons from the Code of Ethics.

5.5 Future Work

Improvement to the current system design can be made. This includes the current use of the abrasive feeding system. Presently, the abrasive tubing receives a minor flow of water while the pump assembly is in its transient state before the 2000 psi operating point is reached. During this time, a portion of abrasive at the bottom of the line becomes wet and clumps together which results in the inability for abrasive to flow into the mixing chamber. One possible solution to this problem is to wait to begin feeding abrasive into the system until the operational point is reached. This has the possibility of only clumping in a minor way since the tube will be drained shortly after the mixing chamber vacuum is creating at the operational point. Additionally, Ben

Adams from WardJet has been contacted for advice on the matter. Once the abrasive system is operational, testing of harder materials may commence.

Harder materials may pose an issue for the waterjet cutter in its current state even with operational abrasive. The pump assembly is only able to create 2000 psi safely which will make it difficult to cut metal. To combat this, a 7.5 hp motor has been suggested to be purchased to replace the current undersized motor. This new motor has the same dimensions as the current motor with a minor difference in distance between base mounting holes. This will allow the recommended motor to be easily swapped out so that the 3000 psi that the pump is rated for may be reached.

Future steps also may consist of implementing a solenoid valve that is actuated with the current control system. With the current configuration, the water is manually turned on, followed by the motor, and then the control system. Upon completion of the G-code file, the water is still running through the nozzle and must be manually turned off. With a solenoid valve, the water can run continuously and be diverted until it is necessary to use. This would allow cuts that are performed on the inside of shapes such as cutting a hole out of the center of an object without having to cut a line through the exterior as the gantry moves to the center position. Another future step could be to add a system to the machine that will be able to reuse the garnet in the system to cut down on economic costs of running the machine.

5.6 Standards

The hosing system has a Joint Industry Council (JIC) fitting for mating. From SAE J514, JIC fittings have a 37° flare seating surface and can withstand pressures up to 10,000 psi. These fittings have a variety of applications and uses but are particularly useful in systems with high pressures[11]. In the waterjet cutter project, JIC flare fittings were used as they provide secure connections at pressures much higher than that of the pressure seen in the tabletop waterjet cutter system. Fittings based on National Pipe Thread (NPT) standards were also used in addition to the JIC fittings. NPT standardizes the sizing of pipe threading in accordance with ANSI/ASME B1.20.1-1983 so that piping from different suppliers may be reliably mated[12].

The Baldor motor's specifications are based off the standards from the National Electrical Manufacturers Association (NEMA)[13]. NEMA standardizes the information that can be found on a motor's nameplate. This was utilized during the CNC waterjet project to size the breaker correctly to be able to safely run the motor. Utilizing the provided motor specifications, namely amperage and voltage, the breaker for the circuit was sized appropriately. This resulted in the preservation of the motor since electric was stopped when the undersized motor was attempting to run the pump under high impedance.

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[10] https://www.nspe.org/resources/ethics/code-ethics

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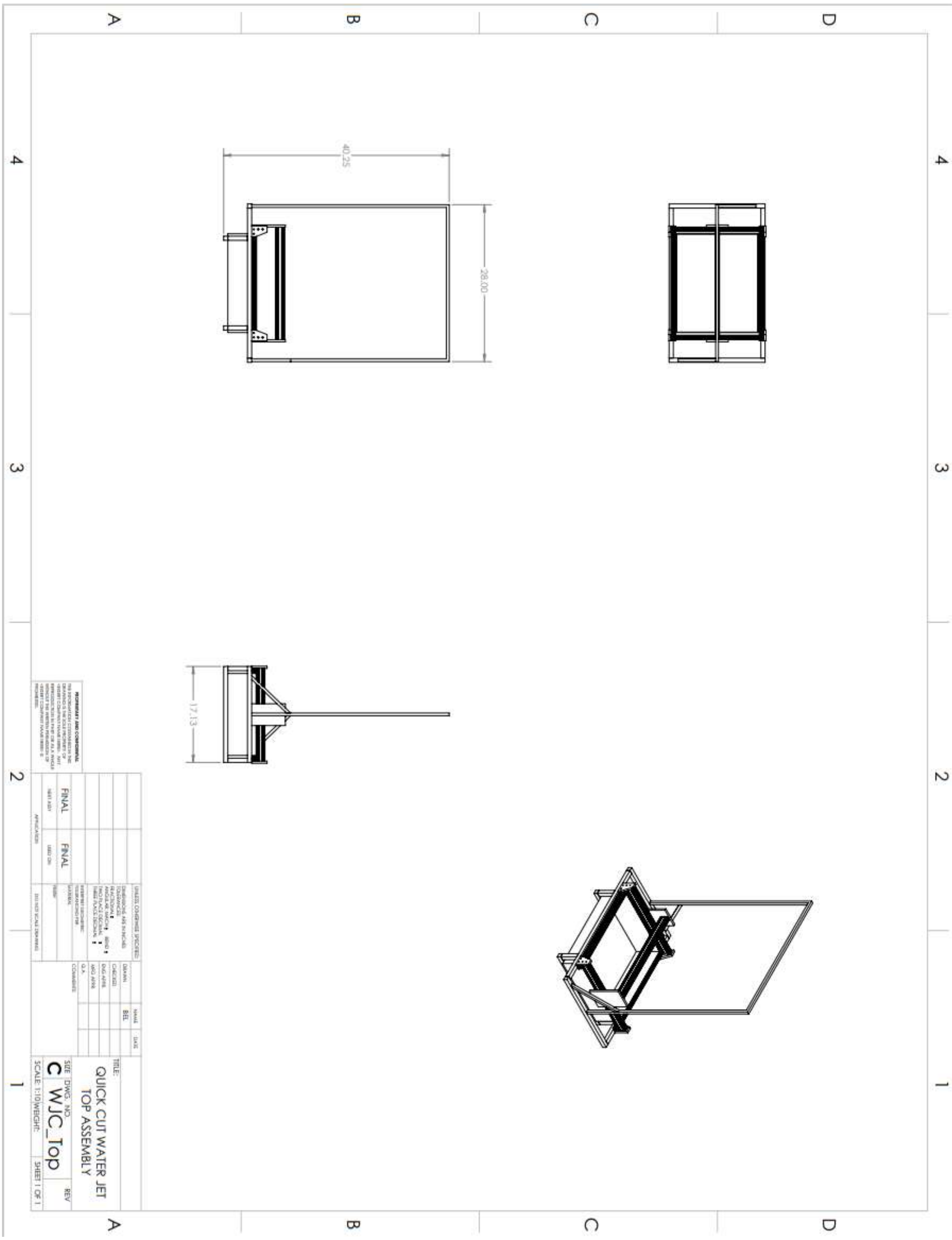
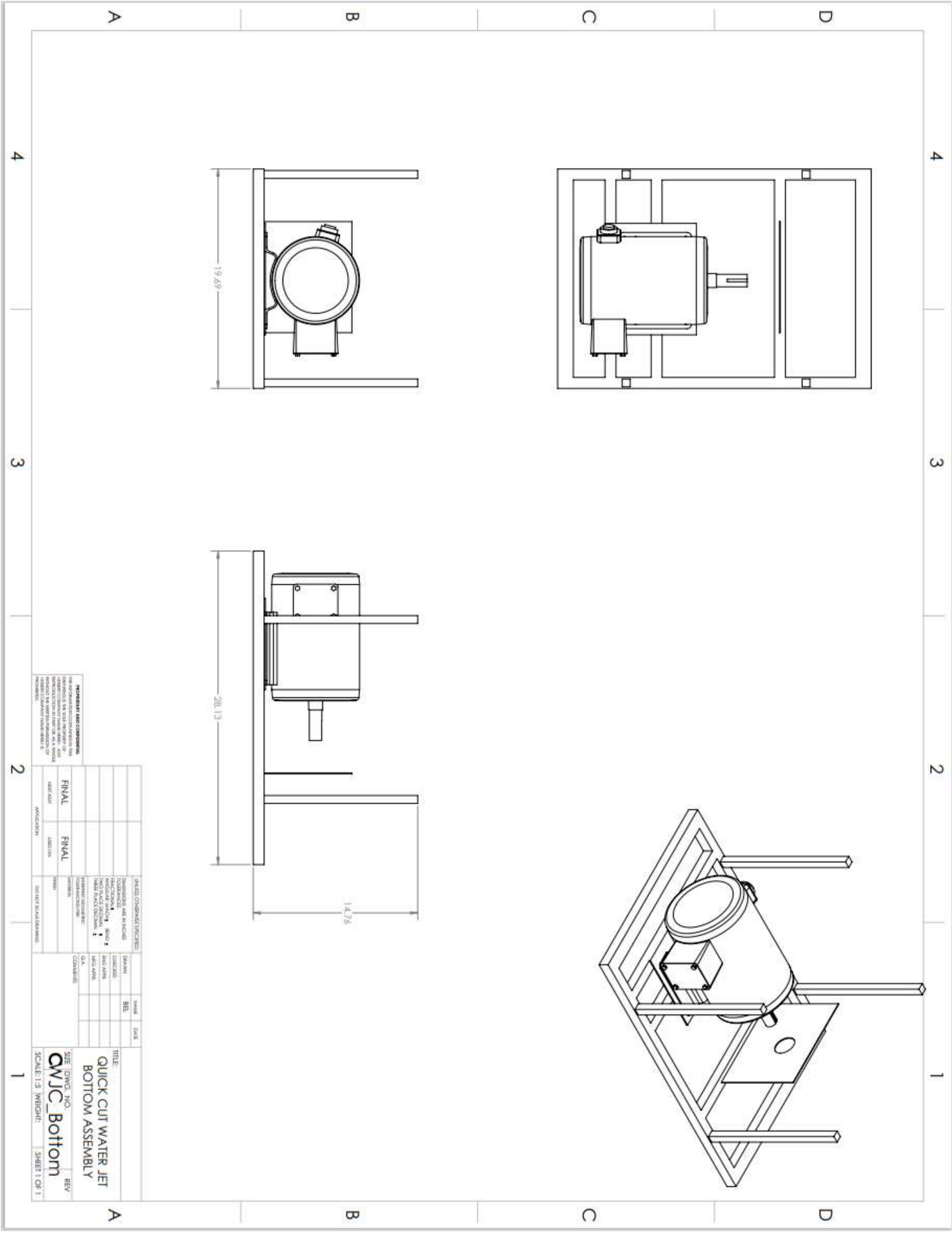
[12] https://www.engineersedge.com/hardware/taper-pipe-threads.htm

[13] https://www.nema.org/standards

Appendix A

The following documents include detailed drawings of the components of the machine. These drawings were created in SolidWorks and are dimensioned in inches.

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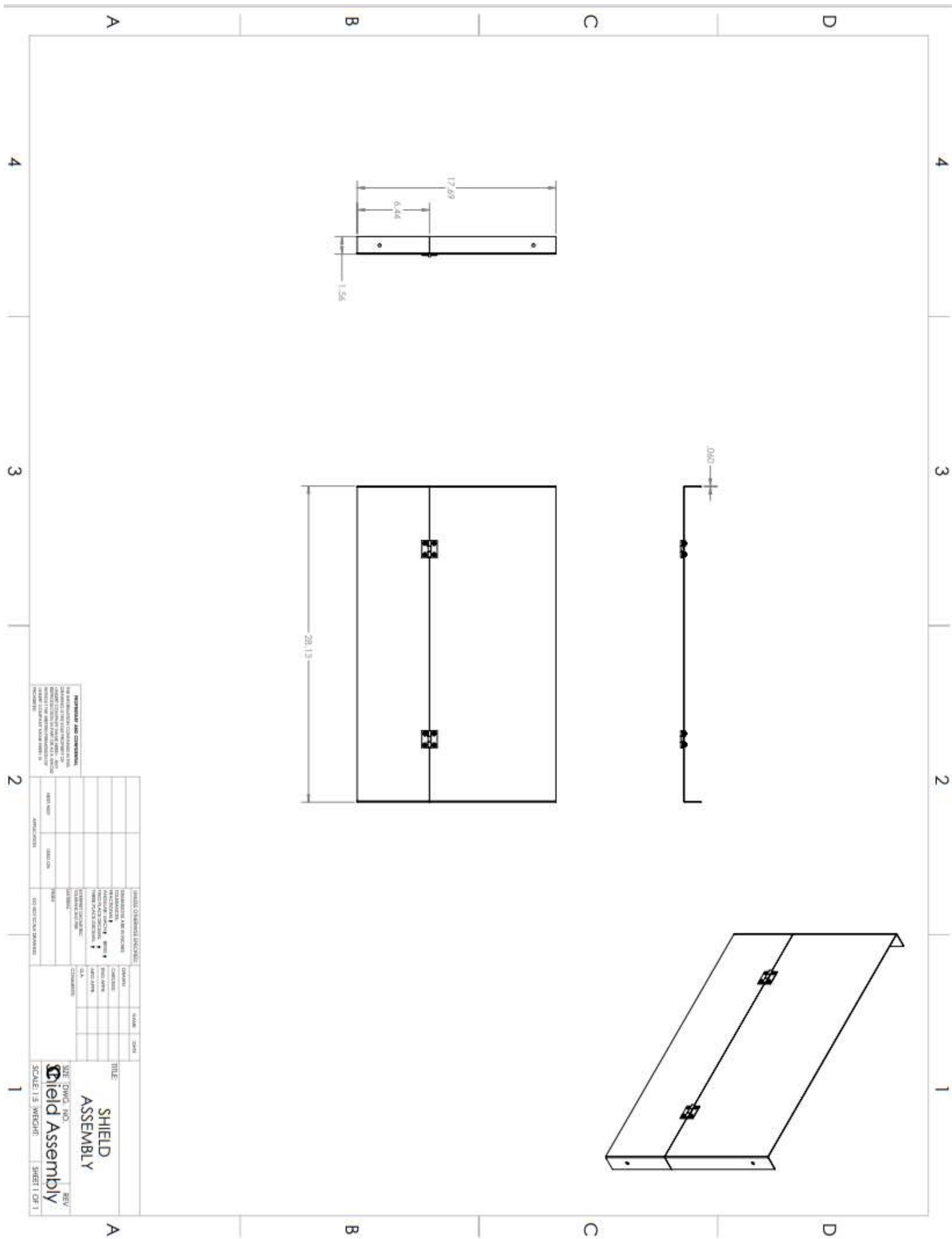
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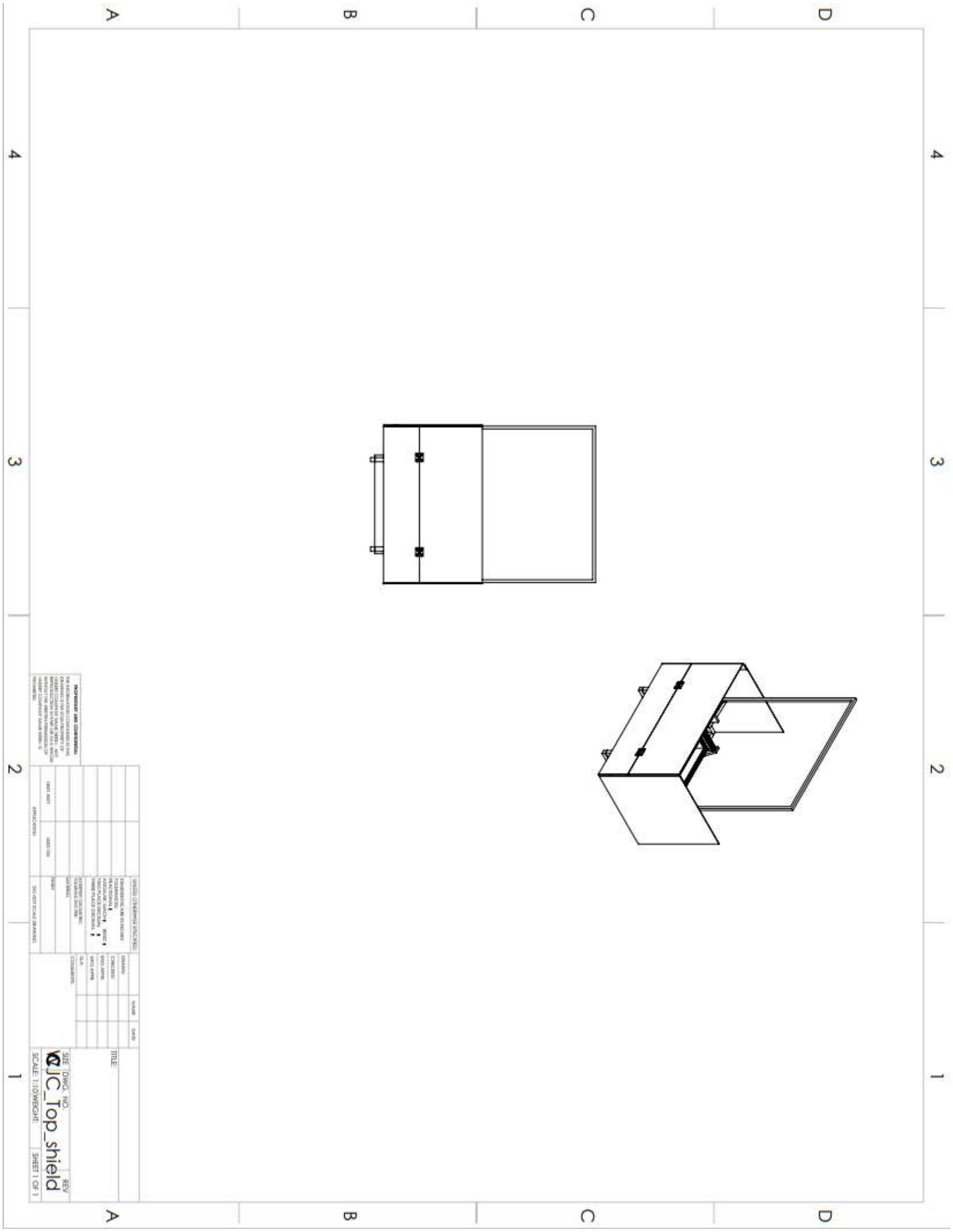
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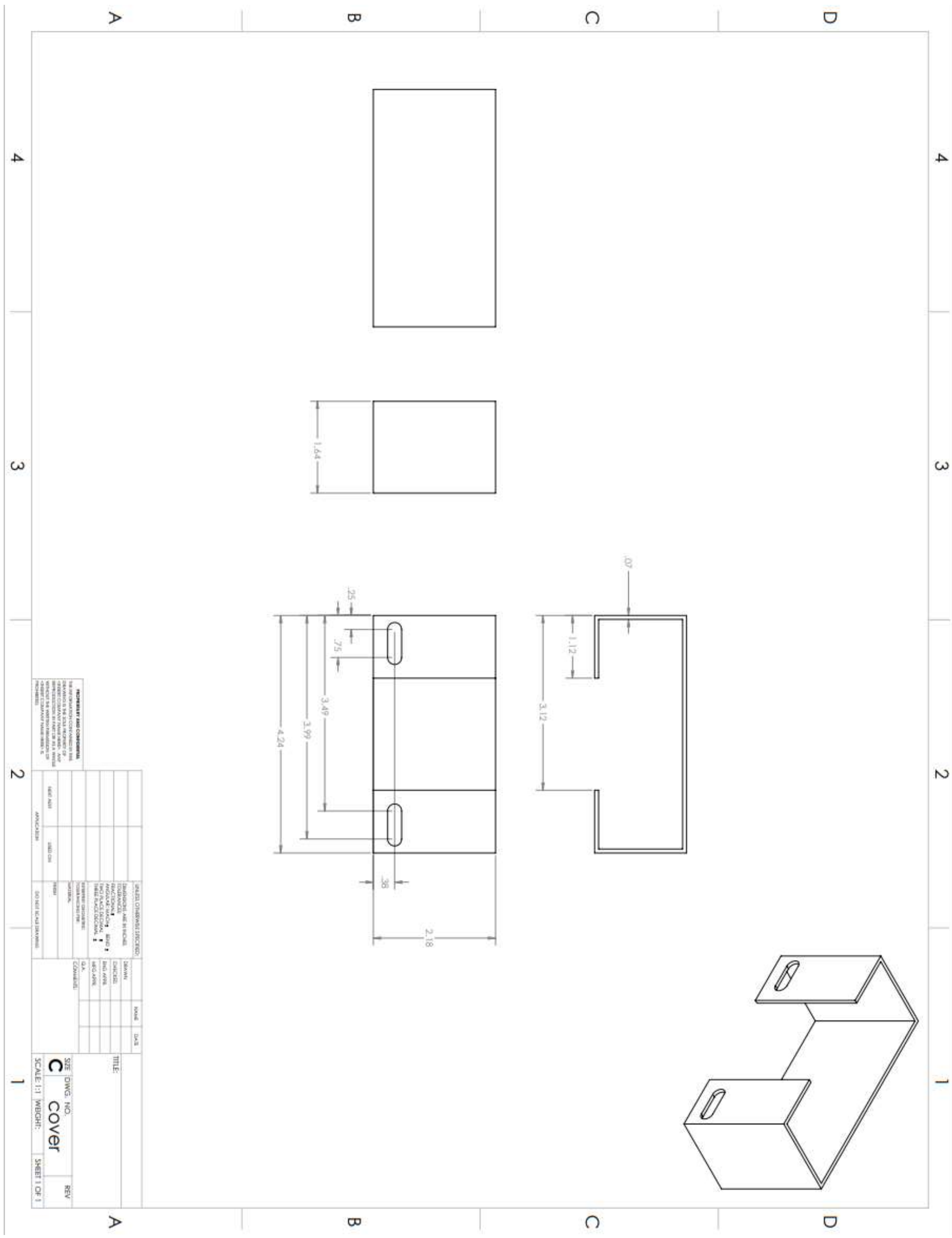
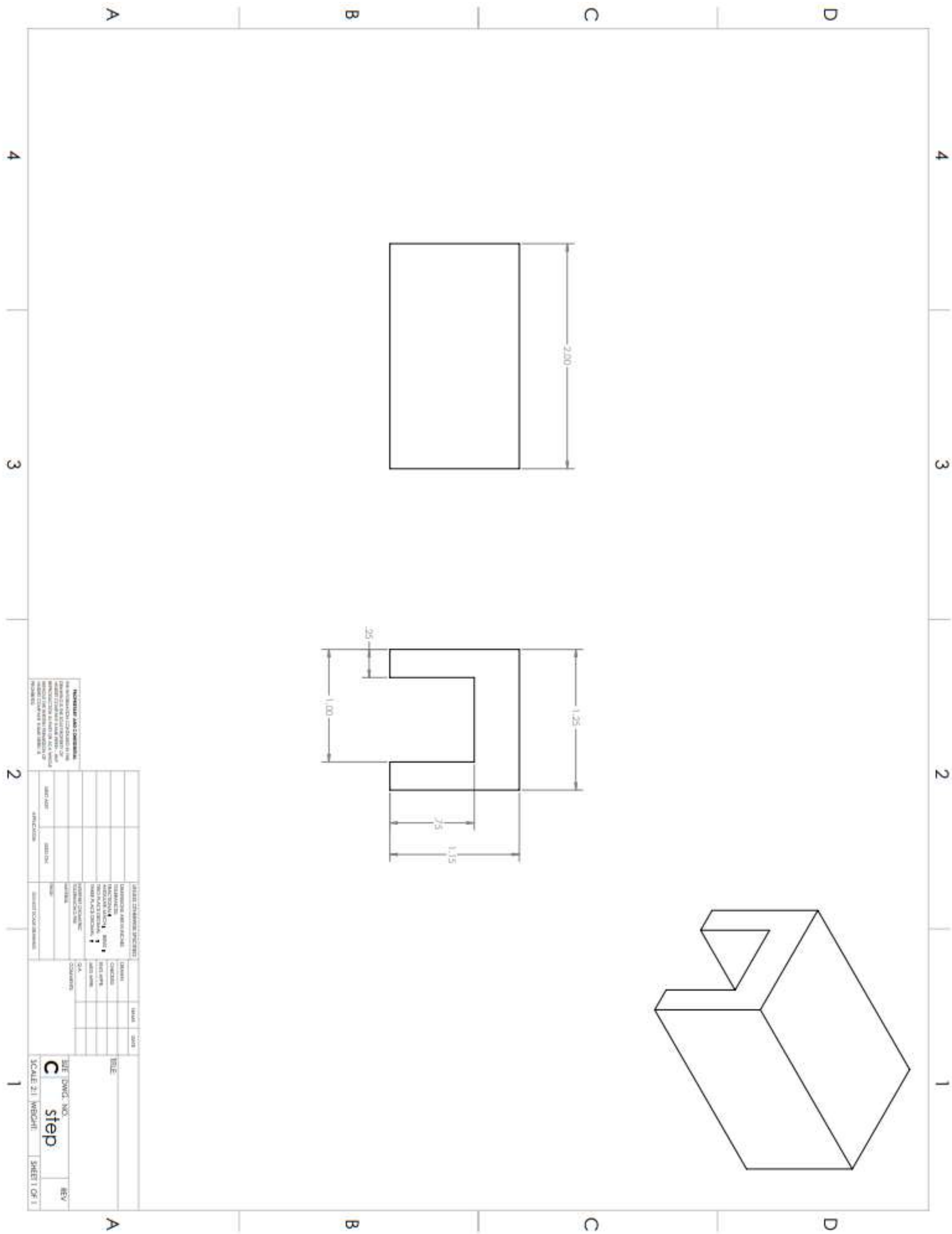
SIZE DWG. NO. REV
JC_Top_shield
SCALE: 1:10 WEIGHT: SHEET 1 OF 1



1.64
.25
.75
3.49
3.99
4.24
.38
2.18
.07
1.12
3.12
TITLE:
SIZE
C
DWG. NO.
cover
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1


2.00
.25
1.00
1.25
.75
1.15
SIZE DWG. NO.
C
step
REV
SCALE 2:1 WEIGHT:
SHEET 1 OF 1

Appendix B

The following documents are standard works for operations and processes dealing with this machine. A standard work is a detailed document with step-by-step procedures with corresponding pictures. These documents must be used to produce the most efficient and safe process or operation. It is to be noted that while operating the machine, all personnel in the room must be wearing proper PPE including safety glasses.

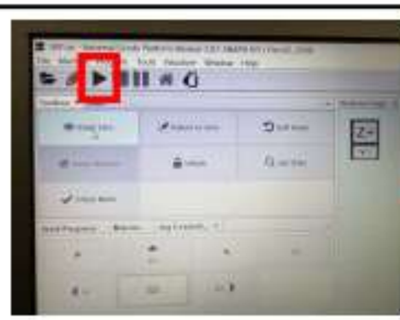
Starting the Machine

Requires two people

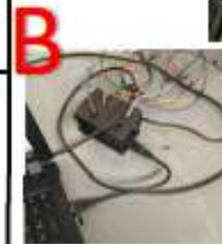
● Safety		▲ Critical Step
Step	Description	Photo
1 ▲	Ensure drain valve is closed and placed at the "off" position **(A)**	
2 ●	Have operator A hold hose over the bed of the machine **(B)**	
3	Have operator B turn on the water by opening the valves **(C)**	
4	Fill bed to the top outlet (red line) and turn off water **(D)**	
5	Attach the hose and open the valve **(E)**	
6	Clamp down the cutting material **(F)**	

Starting the Machine

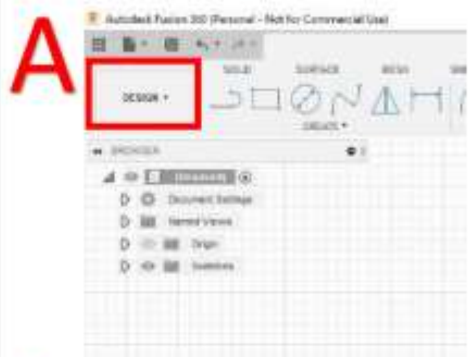
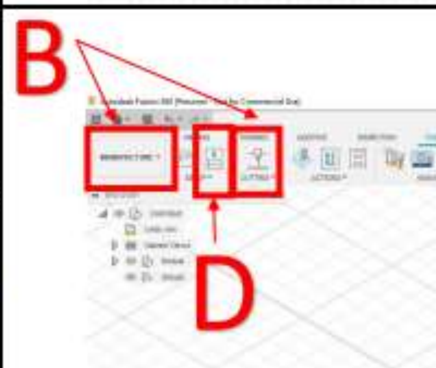
Requires two people

Safety (●)		Critical Step (▲)
Step	Description	Photo
7 ●	Put the safety shield up **(G)**	 G
8	Plug in the motor **(H)**	H 
9	Have operator B turn on the water **(C)**	 I
10	Have operator A flip the switch to turn on the motor **(I)**	
11	Have operator B press start on the controls to start cutting the material **(J)**	 J

Connecting & Programming the Controls

Step	Description	Photo
	Safety	Critical Step
1	Plug in the cable to the extension cord (A) and connect the USB to the computer (B)	
2	Open the flashdrive. Follow the following folders: ugs-platform-app-win > ugsplatform-win > bin > ugsplatform64 (C)	 
3	Confirm the Firmware setting is at "GRBL" (D) and confirm the Port setting is set to your device (E). If not, click the refresh button next to the word Port. Then press the connect button(F)	
4	Select the File button (G) and open the G-code file to be traced	
5	Using the Jog Controller, move the nozzle to the starting position (H)	
6	Click the Reset Zero button in the Toolbox (I). This will place the starting point at the origin on the software	

Creating G-code files through Fusion 360

Safety		Critical Step
Step	Description	Photo
1	Open Fusion 360	
2	Create desired cutting shape in the design tab (A)	
3	Switch tab to manufacture. Select waterjet cutting as the process (B)	
4	Select appropriate tool setting (C)	
5	Click to save as a Numerical control (NC) file (D)