NASA RASC-AL

2020 Moon to Mars Ice and Prospecting Challenge, Final Design Report

Sub-lunar Tap-Yielding eXplorer, STYX

June 13, 2020

Team Members

All student members are undergraduates studying Mechanical Engineering at the California Polytechnic State University, San Luis Obispo. This team was formed on 10/9/2019 and volunteered to take on this challenge as part of a capstone project.

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Statement of Disclaimer

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Abstract

To diversify the idea pool that NASA has to draw from for future manned and unmanned missions to the Moon and Mars, a design/build competition has been posed to collegiate teams across the country. The challenge is to reach, extract, and purify underground ice reserves in a setting analogous to mars. Along the way, teams will be collecting telemetry to mimic prospecting objectives on the moon.

The Sublunar Tap-Yielding eXplorer, STYX, is the team's proposed design for the 2020 NASA RASC-AL competition. The name STYX was chosen in reference to the mythological underground river that acts as a gateway to the underworld. Some novel design features STYX will use are a rotary tool changer with swappable tools, a sleeve driving mode, and a pivoting heating probe. The STYX drill head will translate on two axes, use a rotary hammer drill to bore holes, sleeve boreholes with pipe to prevent collapse, and deliver water via a peristaltic pump and a two stage filtration system. Several of these design elements are innovative and conceptually proven through preliminary testing. These efforts are expected to net increased performance and differentiate STYX from other prototype submissions.

In conjunction with Cal Poly's Senior Project curriculum, the team's initial efforts focused on ideation, preliminary calculations, thorough CAD modeling, and concept model testing to ensure design feasibility. At the completion of this phase, the team switched focus to purchasing hardware and other necessary materials, creating drawings for manufacturable parts, and constructing the frame and motion components of the robot. Programming efforts and manufacturing of parts are ongoing and nearing completion. The final phase of the project will require full integration of all hardware and software, sub-system testing, full system testing, a live demonstration for NASA in Langley, Virginia, and generating NASA's required design documentation.

Due to COVID-19 complications, the timeline of the project has been extended into the summer. The live demonstration has been rescheduled for 8/31-9/3. Manufacturing capabilities for the team have been greatly diminished due to closure of the Cal Poly campus. Several tools required late-stage redesign to be compatible with less complex manufacturing methods, but no major changes to team strategy were required. As a result of these additional hurdles, major testing to verify the complete design has not occurred yet and is planned for late July and August. The team is on track to demonstrate the prototype at competition.

The following report will discuss the complete design process, final design, completed and planned testing, and Senior Project curriculum deliverables.

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1.0 Introduction

This Senior project is a competition entry for the 2020 NASA RASC-AL Moon to Mars Ice and Prospecting Challenge.

1.1 Document Overview

The preliminary design review is typically submitted to obtain sponsor approval for continuing with a chosen design. However, because this team is participating in a competition, sponsor approval was obtained through the submission of a “Project Plan”. This report serves instead to explain the research, critical design choices, justification for decisions, and plan for execution for the project advisor, Peter Schuster, and future teams.

1.2 Problem

With future space missions reaching further and further into the bounds of space, the creation of a martian base capable of sustaining human life has become a potential endeavor. In order to sustain human life in future space missions to Mars, this martian base needs access to water for human consumption as well as hydrogen fuel production (1). In recent NASA missions, collected data has shown that there are large ice deposits beneath the rocky martian surface. This discovery is a step in the right direction towards one day sending humans to Mars, as having accessible water is a necessity to establish a presence.

The purpose of this project is to build a prototype device that demonstrates the feasibility of a method that could be used to extract and treat water from beneath the surface of Mars and collect prospecting data on the moon. 10 teams from college institutions nationwide will be selected to present and test their designs at a competition hosted by NASA at Langley Research Center. The goal of this competition is to extract as much clean water as possible from a simulated martian surface testbed over a 12 hour period and collect accurate overburden thickness and hardness information. The participating teams will control and monitor their device remotely to simulate the device being used on a foreign planetary body.

1.3 Competition History

The competition began in 2016 and has been broadcast via NASA each year. Past winners of the NASA ice prospecting challenge were West Virginia University for overall score, MIT for best technical paper, and Carnegie Mellon University for lightest system mass. In the first year of the competition, barely any teams reached ice. In the most recent year, almost all teams reached ice within the first day and the competition was focused on quantity and clarity. Enormous progress has been made in this competition over the years, but there is still significant progress to be made. This year's NASA RASC-AL 2019-2020 competition has asked teams to propose testbed enhancements in order to more accurately simulate martian or lunar operations.

2.0 Background

The following section presents all research and other forms of inspiration that contributed to the design choices made for the STYX prototype.

2.1 Research

Research topics include drilling methods, telemetry, and ice extraction. The drilling team looked into industrial drilling for inspiration and information on drill head types and chip clearing methods. The telemetry team called a local drilling company and discussed the pros and cons of gamma ray detection as well as tactile sensing, to be used to map out the ground composition under the drill. The ice extraction team looked at electrical and liquid heating systems available for ice extraction. Additionally, some members of the team were specifically tasked with reviewing competition footage from previous years to identify common solutions and areas for improvement.

2.1.1 Telemetry

The research identified several viable means of collecting data on the regolith layers presented to us at competition. Two main telemetry methods were identified through discussions with companies in industry, gamma concentration and resistivity. An additional method that teams used in previous NASA RASC-AL Moon to Mars Ice and Prospecting Challenges, is a direct force feedback system using a load cell. Gamma concentration requires dropping a gamma sensor down the bore hole and measuring the amount of gamma radiation given off by each layer (2). This value would be compared to a list of known materials for identification. However, current gamma concentration methods are not yet accurate enough to resolve the relatively small layer thickness that the team will encounter in the competition. This inaccuracy results in the misidentification of materials, as well as marginally incorrect layer data. Resistivity measuring requires characterization of the electrical or natural frequency properties of the regolith layers for comparison to a list of known materials (3). The resistivity method would require exceptionally expensive equipment and significantly more testing to ensure reliability in implementation (4). The direct force feedback system uses a load cell directly attached to the drill, which records the forces it experiences during drilling operations.The data collected by the load cells is compared to a table of known materials from real-world preliminary testing to make an educated guess at the material hardness.

2.1.2 Drill

The research done on effective drilling systems identified three methods of drilling that are plausible for this competition given the low axial force and power allowances: rotary drilling, percussive rotary drilling, and ultrasonic drilling. Chip removal was also identified as a huge factor in the efficacy of any drilling system. “Drilling in Extreme Environments” includes information about the three types of drills previously mentioned, and goes into detail about how they can be used on the surface of the Moon or Mars (5). Drill bit selection is dependent on the type of drilling operation used, so those options will be discussed later.

Rotary drilling has only one benefit over the other methods. Telemetry data with a drill bit that is not being actuated percussively would be significantly less noisy. Unfortunately, the drawbacks of this method are numerous given the project constraints. Rotary drilling requires significant axial force to cut through hard materials. With the force maximum of 150N, drill bit wear would be a significant issue. Some studies found a reduction in penetration rate of 50% in under 2 minutes when drilling harder materials with low axial force (6). Rotary drilling also makes drill bits freezing into the icy underlayer a significant issue, as any reduction in downwards pressure will allow for the ice to refreeze, capturing the drill bit in the process.

Percussive rotary drilling is currently identified as the most viable candidate for overburden penetration. The percussive action is capable of breaking up harder materials when combined with the correct drill bit, and the rotary action is effective for softer dirt and will aid significantly with chip removal. Winning teams of previous years have used this drilling method with great success. The only disadvantage of percussive rotary drilling is that the frequency of percussion is lower than optimal, with some higher end models of hammer drills only reaching about 10Hz. Vibrations with a frequency of 50Hz or greater show greatly improved soil penetration and chip removal abilities, as the soil exhibits fluidic properties at these higher frequencies (5).

Ultrasonic drilling is an area of ongoing research for JPL and NASA. Drilling into rock with frequencies in excess of 20kHz has a significant effect for harder materials. This method uses almost no axial force (~10N) and very little power (100W). Penetration rate has been shown to be viable as well, with the MIDAS project, by Alliance in partnership with JPL, reaching a penetration rate of 120cm/hr through simulated martian soil (5). There are no economically viable commercial units available for the drilling depth the project requires, but there are ample resources available to design a custom apparatus, likely constructed from components used in industrial-grade ultrasonic cleaners. Chip removal remains a problem, but compressed air has been identified as an effective solution. The non-rotating method of cutting is also capable of coring small diameter holes effectively.

In the rotary drilling category, auger drilling is a viable option. The augers lift chips up and out of the hole as it is drilled, allowing for more time to be spent on drilling, and not evacuating chips from the hole. Auger drills can be configured to bore through rock, as shown in Figure 1, allowing the device to have the capability to bore through the toughest overburden layers possible.

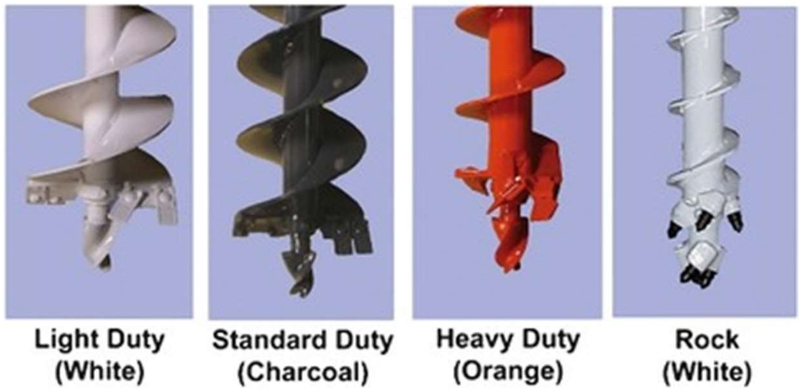


Figure 1: Auger Drill Types (7)

Another rotary drilling type is coring drills. These drills allow for faster drilling due to reduced contact area, however most of the time is spent evacuating the core from the drill. Diamond coring heads allow holes to be bored through very hard rock layers; Figure 2 displays the variety in diamond coring bits available. Additionally most diamond coring bits are larger than 1” in diameter which provides more room for water extraction, but increases drilling time by expanding the hole size.

Figure 2: Diamond Coring (8)

Research was also aimed towards other NASA projects. One such project is the Icebreaker Life mission proposed by NASA’s Discovery program (9). The purpose of this program is to send a drill to Mars to sample ice in the northern plains region. The lander would be similar to the InSight spacecraft that had already landed on Mars and has since started collecting science. Icebreaker Life uses rotary-percussive drilling to penetrate one meter into the ground. In this lander setup, the weight on bit (WOB) while drilling may not exceed 100 N. The drill bit used is a fusion between an ice cutting bit and a rock cutting bit. The bit is made of tungsten carbide, allowing the tip to be both tough and hard. A 0°rake angle is also utilized, which works well for drilling through both rock and ice. All these research topics served to inform the decisions described in section 4.0.

2.1.3 Ice Extraction

The ice extraction team made significant preliminary progress towards identifying effective harvesting systems that will work under low power allowances. For the ice melting process, both a water heating and recirculating system, as well as a direct electrical heating system were compared. A direct heating element eliminates the need to waste energy by heating the water substantially past the freezing point. Many types of heating elements and their data sheets are available on the Tempco website, an electric heating corporation based in Illinois (10).

Another option remains in which the drilling mechanism also serves as the water extractor. Various methods employing this design strategy were prototyped by Honeybee Robotics. One such prototype is called the “sniffer”. This device functions similarly to a natural gas extraction unit. A fluted auger with holes is used to drill into an ice rich area. Heaters within the auger are then used to sublimate the ice, where it is collected through the holes in the auger and run through a cold trap on the surface. Another option explored by this company was a deep-fluted auger that retracts into a heated cylinder where ice is converted to a gas and extracted. The third prototype Honeybee Robotics designed is a dual-wall coring auger. Here, the ice is heated and extracted while the drill continues to operate, in order to be more time efficient. Honeybee Robotics performed substantial testing, and released some of their findings (11). The sniffer was not consistently able to extract water. Vapor sublimed but ultimately did not enter the auger. Both of the two remaining auger systems were able to extract ice. Test results show that smaller diameter augers are more energy efficient and they could capture a larger percentage of the sublimated ice. The biggest problem with the coring device is that it is difficult to control the device’s ability to hold a core sample, and extract the remaining solid after the ice is extracted.

The next topic researched by the ice extraction team was methods of pumping water from the bottom of the drill hole. There are two main types of pumps: positive and non-positive displacement. An article titled, *Positive Displacement Pumps- Performance and Application*, by David Parker, confirmed that a positive displacement (pd) pump is a better choice for this application (12). The article shows that non-positive displacement pumps are generally less able to handle a wide range of flow rates, are less efficient in low flow, high pressure situations, and most importantly they are unable to produce suction lift without introducing extra equipment to prime the pump. Mr. Parker also discusses the differences between rotary and reciprocating pd pumps. Reciprocating pumps utilize check valves which the team believes can fail to seal properly when the pumped fluid contains solid particles. Rotary pd pumps such as gear pumps can also jam or wear prematurely by solids in the pumped fluid, which is due to the tight fits required between stationary and rotating parts. When researching peristaltic pumps, it was found that this type of pd pump is used effectively in pumping concrete (13). This type of pump is highly resilient to abrasives and works well with both low and high viscosity fluids. Since the device will be drilling through concrete and introducing water to the drilled concrete powder, it is highly likely that the system will experience moments where a high viscosity fluid will need to be pumped.

The final stage of ice extraction is water purification. One of the initial water purification ideas was a mechanical skimmer similar to a wastewater clarifier. These devices work to take load off of later purification equipment, but will not produce sufficiently clear water for the prototype, as it can not remove suspended particles of any size (14). This idea was not pursued as the team found it to be unnecessarily complex and energy consuming for the low flow rates expected. Similarly, electrocoagulation was not pursued, and the team moved towards a more favorable, less energy consuming, passive separation system. The Interstate Technology & Regulatory Council Mining Waste Team released a technology overview on electrocoagulation showing that water conductivity must be high for this process to work (15). This may pose a problem, as the STYX team will not know the quality of the ice block being mined at the NASA test site. Also, electrocoagulation requires a consumable electrode. Designing a mass-efficient system would be difficult, as there are many variables that contribute to the rate of electrode decay.

Extensive research was put into mechanical filters. After viewing photos of the testbeds from last year's competition, it was determined that both small and large particles would be present, which requires a two-stage filtration process.

Research into coarse, primary filters yielded metal mesh screens and sand filters as potential options. Mesh filters stop solids that are larger than the mesh size from passing through. In continuous operation, these filters can clog, inhibiting flow, but their thin construction means there is not a great head loss across the mesh. Sand filters do not lose performance as they are used, but they are not backflushable and require a substantial amount of mass. One readily available component is the Rusco Sediment trapper (16). This design is promising because it combines a settling tank and a metal mesh filter that allows large sediment to settle out and medium size particles to be filtered. The cleaning valve in its base also makes this option practical for automated, remote cleaning processes. For a secondary filter, extensive research was put into what is commercially available for drinking water filtration. Pelican Water Systems is one commercially available option that supplies many different types of filters suitable for drinking water (17). Culligan Water is another commercially available in-home drinking water filter brand (18). However, these types of units are rated for much higher flow rates than is needed. These products may end up being too large and heavy for practical use. Carbon filters, such as those made by Brita, may be a valid option. Its downside, however, is that like Brita water filters, carbon filters must be replaced periodically. Another possibility was the LifeStraw (19). This filter is much smaller and more compact, and can filter down to 0.2 microns. Lastly, the team did research into sintered metal filters. One such brand is Sintertech which produces metal filters in a broad range of shapes, sizes, and porosity (20). These types of filters are extremely robust, and they require much less pressure as compared to membrane filters.

2.2 Existing Implementations

NASA has sent two previous missions to Mars with drilling equipment installed: Curiosity and InSight. Curiosity's drill uses an enclosed auger to collect the sample from the hole it's drilling. It then uses a masonry bit and hammer action to break through the rocks. The rover then places stabilizing arms on the rock face it will drill on, then advances the drill forward into the rock. It uses percussion to start a pilot hole and then it proceeds to drill 2.5 inches into the rock (21). InSight's mission is not about collecting samples, instead, Insight's "mole" burrows into the martian surface to collect data about the planet's constitution. The process for drilling works like a hammer drill. The mole is a metal spike with a motor, a weight and a spring. The weight is gradually lifted up and then released. The dropped weight drives the mole into the ground by a small amount, and the process is repeated. Currently the mole's tip is submerged 14 inches under the martian surface.

2.3 Past Competition Designs

Using the archives of the RASC-AL website the team can access the technical reports written by past competing teams. Additionally, Youtube has videos from previous years' competitions. Some issues from previous competitions included poor stabilization of the drill bit, which caused the drill tip to sway drastically when attempting to start a new hole. Other teams used a tube to constrain the end of the drill bit and were able to drill a more accurate hole (22). Teams that used a water extraction device separate from their drill bit were unable to extract water because the freshly drilled hole would often cave in when extracting the drill bit. Frame stability appeared to be a frequent issue for many teams. One team attempted to solve this issue using a floating drill design, however, this design resulted in uncontrollable bouncieness. Teams that used roller wheels or low quality structural supports could not drill a hole with much precision.

By viewing some clever designs, some questions the team had were answered. Most teams at the last competition successfully used peristaltic pumps to move the contaminated water from the bottom of the hole to the filter system (23). This helped alleviate the team's concern of how to pump water filled with small pieces of dirt, mud, and sand. In this competition one objective is to retrieve the most water. To achieve this, one team used an articulating heating probe and was able to extract 4 gallons of water during the competition. Another design choice up for discussion was if using a load cell for telemetry would be accurate enough to determine the composition of each layer. Previous competitors proved that load cells were capable of delivering the level of accuracy required for the competition (24). This reinforced the team's decision to incorporate load cells into the STYX prototype.

2.4 Patents

Existing patents for drilling and filtration methods proved useful for later ideation. It is noteworthy that several patents specifically referenced prospecting applications. Table 1 lists the relevant patents for drilling systems and table 2 lists the relevant patents for filtration implementations along with brief descriptions.

Table 1. Relevant Drilling Patents

Patent Number	Patent Name	Description
US8038630B2	Floating Probe for Ultrasonic Transducers	The invention is a novel device with an ultrasonic based drill and corer. The invention uses ultrasonic vibrations, which are produced by a frequency compensation coupler, to produce a hammering action with a relatively low axial-force.
WO2001083933A1	Smart-ultrasonic/ sonic driller/corer	This invention is a concept for an ultrasonic based drill and corer. This iteration uses a free mass that vibrates back and forth to transfer the vibratory force to the bit, rather than having the bit directly affixed to the piezoelectric transducer.
US6550549B2	Core Break-off Mechanism	A mechanism for breaking off and retaining a core sample from a drill drilled into the ground. This device utilized two offset cores, that when spun relative to each other, create an offset that breaks the desired core from the ground, allowing the sample inside of the coring bit to be brought out of the bore hole.
US6619413B2	Rock auger drill	A flightless rock auger capable of drilling through hard material such as concrete. This is used for low speed drilling.
US5487434A	Rock drill with conveying groove	A drill bit capable of drilling through rocks, that also has a fluted shank to help keep the hole clear of debris.

Table 2. Relevant Pumping and Filtration Patents

US7578662B1	Peristaltic Pump	A peristaltic roller pump that includes a rotor carrying a pumping roller on one end and an occluding roller on the other end. Occluding roller is designed to not cause any pumping of fluid through the section of the tubing under that roller. This is a low power, low flow pump that can move liquids with high particulate concentrations.
US4049366A	Diaphragm pump	A diaphragm pump includes at least one diaphragm extending into the pump housing. A driver connected to the diaphragm moves it between a suction stroke for intake and a compression stroke for outflow.
US4443169A	Gear pump	A gear pump uses an eccentric toothed gear in an annular internal gear to create pressure by rotating the internal gear.
CN203264409	Low-pressure self-cleaning continuous filter	The low-pressure self-cleaning continuous filter is simple in structure, self cleans the filter, low in cost, and capable of uninterrupted filtration.
US9308584B2	Sintered fiber filter	Sintered fiber filters have high particle capture efficiency and low pressure drop across the filter.
US1933595A	Sand or sediment trap for pumping wells	The object provides means to capture and contain sand or other sediment being pumped out of a well.
ES2394467T3	Water filtration membrane	This filter is made of aquaporin water transport proteins that are made into a layer and supported by a solid support, together making a membrane for water filtration.

While several technologies useful to this mission profile have been investigated, only the peristaltic pump appeared completely appropriate. Some other design philosophies will be carried forward in the design, while others were useful for ruling out other paths.

3.0 Objectives

The objectives of this project are clearly presented by competition organizers. Specifications and guidelines are provided. This team's interpretation of the problem statement is as follows.

3.1 Problem Statement

The competition is broken up into two distinct parts that can be accomplished simultaneously. The first goal of the competition is to produce a digital core of the test bed. This can be created from any form of hands-off operation of the device. The digital core is created through any means of data collection, and must give the number of overburden layers present, the thickness of each layer, and the compressive strength of each layer, as accurately as possible.

The second goal is to deliver as much clean water as possible. Underneath the overburden layers of the test bed will be a solid block of ice. Teams must find a way to access this ice and extract as much as possible during a 12 hour time frame. The competition will be graded on a point based system, where water extracted during remote control of the system will be weighted more than water extracted while in "hands on" mode. The NASA competition guidelines use the terms "hands on" and "hands off" to distinguish between times when the device is being operated either autonomously or remotely, and times when the operators are in physical contact with the system.

3.2 Boundary Diagram

Although the goal of this competition is to test concepts that could be implemented on Mars, the competition lays out very specific guidelines for designing the device to work in a specific testbed. The system boundary diagram shown in Figure 3 depicts the bounding box of the entire system. The dimensions are supplied by NASA. The device must mount on top of the test stand, and may not overhang past the test bed's edges.

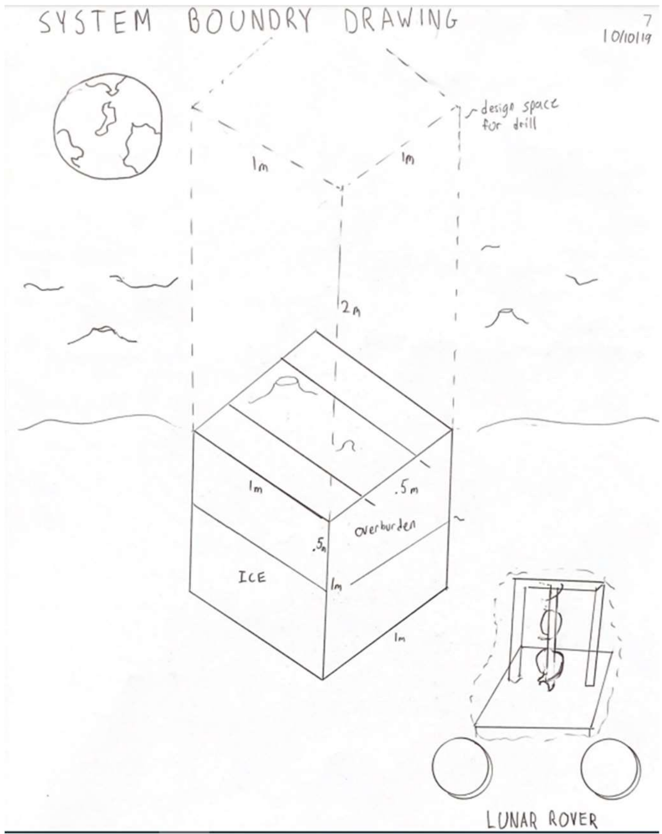


Figure 3. System Boundary Diagram

The test stand mounting constraints are defined in Figure 4. To conform to the mounting dimensions and provide damping between the test stand and the drilling apparatus, rubber shock absorbers have been placed at all test stand mounting points. Currently a four point mounting solution is being implemented, but more analysis needs to be completed before ruling out a six or eight point solution.

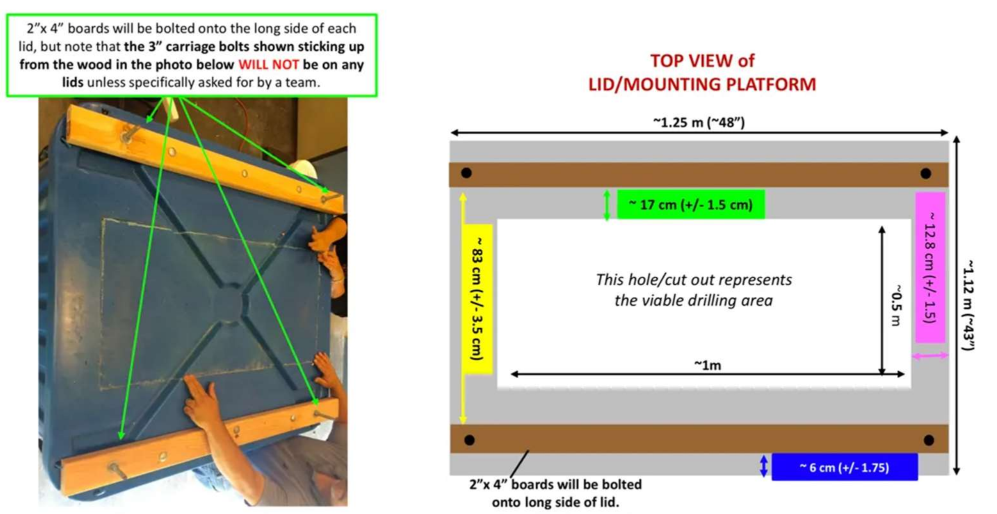


Figure 4. Test Stand Dimensions Provided by NASA

3.3 Customer Needs/Wants

The customer's overarching goal of hosting this project/competition is to collect novel ideas and compare the efficacy of several different solutions to water extraction and prospecting data collection. To do this, detailed information on the evaluation metrics were supplied to the collegiate teams. Several of these metrics are quantitative, while others are qualitative in nature. Point values were recently provided for many metrics, while others are to be determined at competition. This ambiguity, along with the ranked nature of the competition, muddies the definition of need vs. want. The discernible 'needs' are listed below. Other high level metrics that the customer is interested in are listed below, while detailed specifications can be found in section 3.4. The recently released scoring matrix is attached as Appendix A.

Needs

- Project Plan document to apply for the competition
- Mid-Project Review document to qualify for continued funding and competition qualification
- Technical Report at project completion
- Poster summarizing design
- Prototype capable of:
    - Drilling through Mars simulated overburden
    - Extracting water from buried ice deposit
    - Collecting telemetry data regarding overburden layer thickness and hardness

Quantitative Metrics

- Quantity of water collected
- Mass of >5 micron particulate remaining in water after filtration
- Electrical power monitoring to remain under limit
- Calibrated force monitoring to remain under limit
- Accuracy of layer hardness data
- Accuracy of layer thickness data
- System mass to remain under limit
- System dimensions to remain under limit

<u>Qualitative Metrics</u>

- Maximize ‘hands-off’ operation
- Minimize system mass
- Maximize water clarity
- Ease of adaptability to spacecraft compatibility
- Debris mitigation
- Document quality
- Poster quality

In addition to meeting the specific requirements for prototype performance, NASA has also asked that teams propose methods and mechanisms that would more accurately represent implementation on a rover platform for the surface of the Moon or Mars. Our proposed methods are explained in detail in section 4.11.

3.4 Specifications

Table 4 lists all of the quantifiable specifications and requirements that the prototype is expected to meet. NASA’s competition rules assign point values to several of these requirements and points will be lost for each requirement that is not met. The tolerance column describes what type of limit the requirement is. The risk column describes how difficult it will be to meet the specification. The compliance column represents the method by which the specification will be verified. A, I, T, and S represent analysis, inspection, test, and similarity, respectively. The measurement tool column describes the specific method of collecting the compliance data.

Table 3. Specifications Table and Customer Requirements

Spec. #	Specification Description	Requirement or Target	Tolerance	Risk	Compliance	Measurement Tool
1	Height	2 m	Max.	L	A, I	Tape Measure
2	Length	1 m	Max.	L	A, I	Tape Measure
3	Width	1 m	Max.	L	A, I	Tape Measure
4	Mass	60 kg	Max.	H	A, T, S	Scale
5	Power Use	1 kW	Max.	H	A, T, S	Clamp Meter / Voltmeter
6	Weight on Bit	150 N	Max.	M	T, S	Load Cell
7	Drill Bit Length	96.52 cm	Max.	M	A, S	Tape Measure
8	Hole Temperature Compatibility	-26 ℃	Min.	M	A, S	Thermocouple
9	Overburden Penetration	0.5 m	Min.	L	A	Stepper Motor Position
10	Ice Extraction Depth	0.5 m	Min.	M	A	Stepper Motor Position
11	Overburden Compressive Strength	25 MPa	Max.	L	I	Load Cell
12	Hands off Operation	Device must work autonomously or via remote control	N/A	L	T, S	N/A
13	Operating Package	Entire system must remain directly above the test station	N/A	L	A	N/A
14	Mounting Height	Device must leave 7-13cm between mounting platform and overburden	N/A	M	A	N/A
15	Data Logging	Team must log all power consumption and WOB measurements.	N/A	L	A, S	N/A
16	Power Supply	Teams must not augment the power supply	N/A	L	I	N/A
17	Dust Abatement	The device must not blow material away from the test stand	N/A	L	T, I	N/A
18	Digital Core	Report the number of layers, layer thickness, and layer hardness of overburden	N/A	M	A, T, S, I	N/A

4.0 Concept Design

The goal of concept design ultimately is to define a design direction. To determine an appropriate design direction, ideation, prototyping, and decision making were required. This section details the design methodology, decisions, and justifications made at the PDR stage of the project. Several, but not all, elements were carried into the final design discussed in section 5.0.

To split the project into appropriate subsystems, the team completed a functional decomposition of the system requirements. Through this process, shown in table 5, several dependent and independent subsystems were identified. Ideation began for each subsystem via brainstorming and some concept prototypes were created. Pugh, morphological attribute, and weighted decision matrices were used to select final concepts for each subsystem.

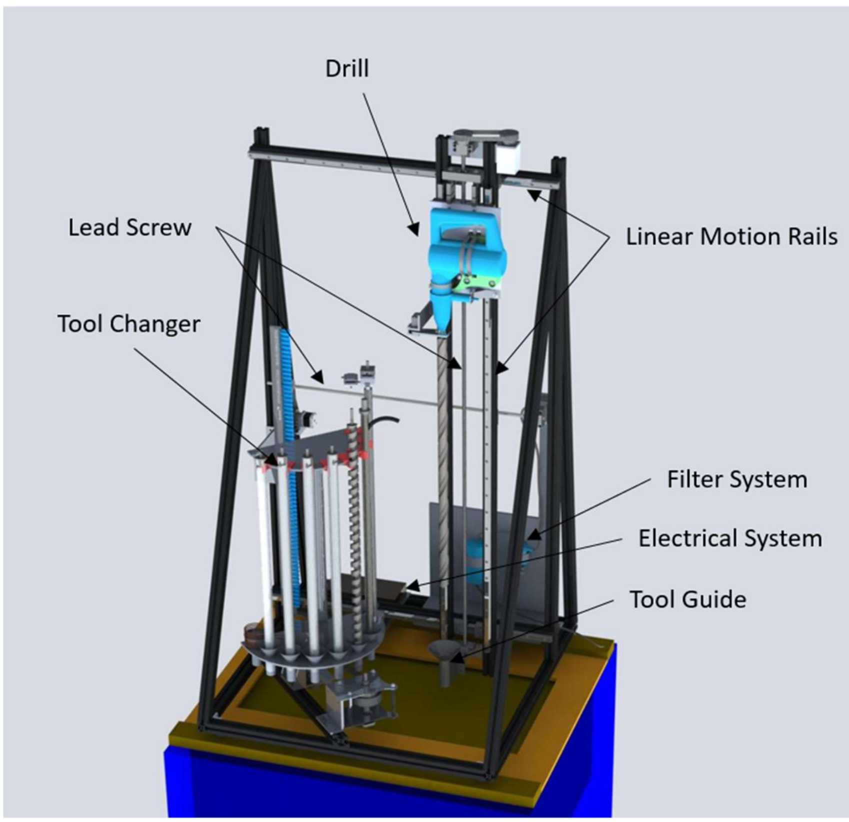


Figure 5: Annotated Concept Design

This section of the report is broken up mostly by subsystems. The brainstorming process and decision matrix process are common to all subsystems and are therefore presented as its own section. Subsystem sections are broken down into the following subsections: decision matrices, concept models, selected concepts, preliminary analysis, and design risks/challenges. Not all subsections are represented for each subsystem, as not all processes were conducted for each subsystem.

4.1 Brainstorming

To generate a wide breadth of ideas for consideration, brainstorming was used. A combination of individual and group brainstorming was found to be most effective for this group. Figure 6 shows both an example of a group brainstorming session and an example of individual brainstorming. The group brainstorming activity consisted of creating the largest possible quantity of ideas on post-it notes with respect to a particular subsystem. Individual brainstorming occurred mostly within each team member's log book, with sketches drawn for the better ideas. A similar methodology was followed for all subsystems. Lists of ideas generated for several subsystems are reproduced in Appendix B.

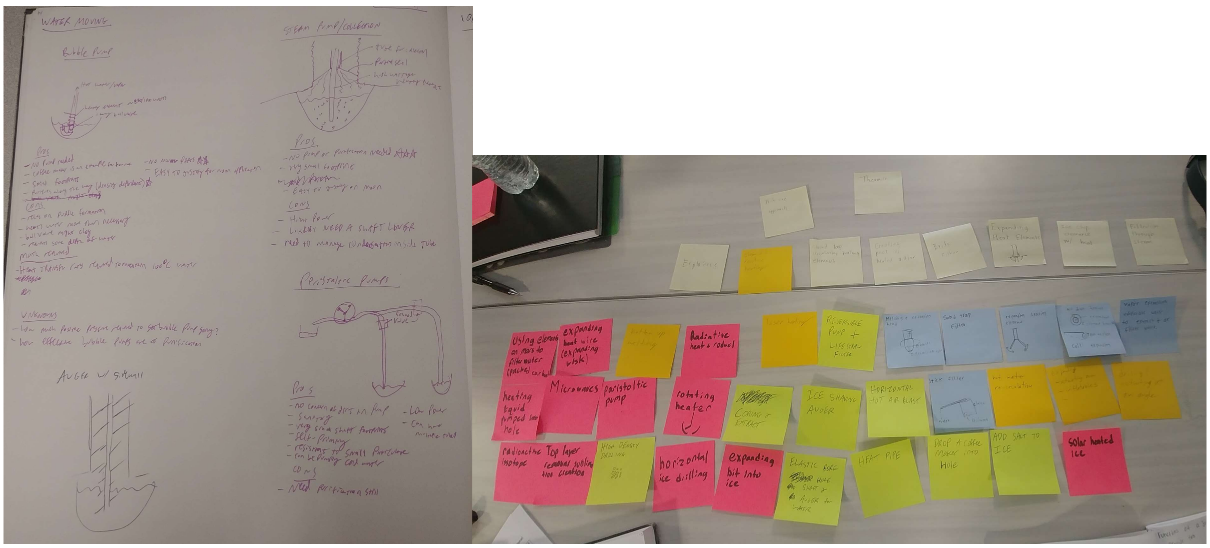


Figure 6. Ideation Methods

4.2 Decision Matrices - Overview

Several types of matrices were used to narrow down the suggestions from ideation. For dependent functions, 5.3ed in red on table 5, Pugh matrices were constructed to determine the best options for each function. These matrices are attached in Appendices B, C, and D. Once the best options from the Pugh matrices were identified, they were combined through a morphological attribute matrix to help visualize potential combinations of concepts. The best options from these morphological attribute matrices were then compared using weighted decision matrices. The weighting values are chosen based on a combination of importance to the competition and relative performance between considered concepts. For independent functions, marked in yellow on table 5, only weighted decision matrices were required.

The approach this team chose is to reach the ice via several consecutive drilling tools, followed by a heater probe that will melt the ice into liquid water. The water will then be extracted via a metal straw integrated into the heater probe, with vacuum applied via a peristaltic pump mounted above ground level.

Table 4. Functional Decomposition

<table>
<tr><td rowspan="13">Project Deliverables</td><td rowspan="9">Deliver as much pure water as possible</td><td rowspan="4">Reach ice through overburden</td><td rowspan="4">Clear overburden</td><td>Break through Layers</td></tr>
<tr><td>Maintain Clearance</td></tr>
<tr><td>Remove Debris</td></tr>
<tr><td>Apply Power</td></tr>
<tr><td rowspan="2">Extract water</td><td>Move ice/water</td><td></td></tr>
<tr><td>Melt ice</td><td></td></tr>
<tr><td rowspan="2">Purify water sustainably</td><td>Remove particulate</td><td></td></tr>
<tr><td>Self-cleaning filter</td><td></td></tr>
<tr><td>Maximize yield</td><td>Reach as much ice as possible</td><td></td></tr>
<tr><td rowspan="2">Generate Digital Core</td><td>Measure layer hardness</td><td></td><td></td></tr>
<tr><td>Measure layer thickness</td><td></td><td></td></tr>
<tr><td rowspan="2">Traverse Test Bed</td><td>Drive Motion</td><td></td><td></td></tr>
<tr><td>Transfer Loads to Frame</td><td></td><td></td></tr>
<tr><td>Dependent Topics</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Independent Topics</td><td></td><td></td><td></td><td></td></tr>
</table>

4.3 Drilling Process

To complete the objective of extracting subterranean water, the overburden must first be cleared. This process was split into three base functions via the functional decomposition process shown in Table 5. These three basic functions are: break through the overburden, remove debris, and maintain clearance. These activities must be completed through various unknown layers in the competition environment.

4.3.1 Decision Matrix and Considered Concepts

The Pugh matrices in Appendix C show the various comparisons between concepts and functional qualities. The morphological matrix in Table 6 depicts the best options for each functional descriptor and led towards some of the final combinations analyzed in the weighted decision matrix, Table 7. In the morphological matrix, it became clear that different tools excelled in different functional areas.

UltraSonic drilling methods interested the team because very low force on bit was required. With the 150N downwards force competition limit, this was an attractive option.

Additionally, NASA is looking for innovative ideas and no ultrasonic drilling has been employed yet on other planets. Despite these benefits, the complexity of designing a custom ultrasonic system, the costs involved, and lack of large diameter implementations, it was rejected. Other drilling options considered such as shoveling, drilling, augering, and jackhammering were also rejected due to failures at previous competitions, tool wear considerations, and power considerations.

To maintain hole clearance, several options considered appeared viable. These options are shown in Table 6 and all appeared to be valid options, with some being more effective than others. Finally to remove debris, augering was the most effective option presented, yet air blast was also a competitive option to include in the weighted decision matrix.

Table 5. Morphological Attribute Matrix - Drilling Process

Function	Concept					
Break Through Overburden	Percussive Drill	Drill	Auger	Jackhammer	Shovel	Ultrasonic Drill
Maintain Clearance	Simple Hole	Sheathed Hole	Shallow Grade	Air Blast		
Remove Debris	Auger	Auger	Drill	Percussive Drill	Air Blast	Shovel
First Choice						
Second Choice						
Third Choice						

Table 6. Weighted Decision Matrix - Drilling Process

Criteria	Weighting (1-5)	Percussive Drill, Sheathed Hole and Auger		Ultrasonic Drill and Airblast		Auger and Simple Hole	
		Score	Total	Score	Total	Score	Total
Power Efficiency	2	2	4	3	6	1	2
Axial Force Requirement	3	2	6	3	9	1	3
Cost	2	3	6	1	2	3	6
Complexity	4	2	8	1	4	3	12
Chip Clearance	4	3	12	2	8	2	8
Tool Life	2	3	6	2	4	1	2
TOTALS			**42**		**33**		**33**

‘Percussive Drill, Sheathed Hole, and Auger’ received the highest ranking and appears to be the best all around process. This process will leverage the best attributes of each tool. Sketches of alternative concepts are available in Appendix D.

4.3.2 Preliminary Analysis

Our team acquired a rotary hammer drill early in the quarter to allow testing to begin early, and help drive design decisions on drilling methods. Figure 7 shows a test rig that was used for collecting preliminary data. Results from the first round of testing showed that the rotary hammer drill could bore through fourteen inches of concrete in approximately one minute. The data was collected with a 7/8” drill bit and testing was performed on inconsistently mixed concrete; therefore, data was not conclusive enough to draw trends from. The qualitative conclusion that the hard overburden could be penetrated allowed the team to finalize the decision to utilize rotary hammer drilling in the final prototype. One concerning finding, shown in Figure 7, is that the drilled holes almost immediately filled with chips after the drill bit was removed. To combat this, tests were done with both vacuum clearing and air blast clearing, but neither was deemed appropriate for NASA’s debris containment requirement. The alternative explored was using a pile-driving method to insert a sleeve into the drilled hole, isolating much of the broken up material for later removal via auger. This methodology was explored with a proof of concept using a piece of ¾” conduit being hammer drilled into the previously drilled ⅞” hole. The sleeve went in easily and was satisfactory to continue along this design path.

Figure 7. Test Stand for Drilling Process

4.3.3 Selected Concept

To achieve a borehole that is resistant to collapse and clear of debris, a 5-step, multi-tool process will be used. This process requires tool changes, increasing system complexity, but reducing risk by allowing each tool to be optimized for a single task. This innovative solution was a result of identifying the value of each tool in the morphological matrix. The 5-step process is outlined in table 8 and the mission profile is displayed in Figure 8.

Table 7. 5-Step Drilling Process

Process/Tool	Drill Mode	Purpose
1.5” Masonry Drill	Hammer Drill	Break through all layers of overburden and 4” into the ice sheet.
1.5” OD, .875” ID Sleeve	Hammer Only	Drive a sleeve into the hole to prevent hole collapse, isolate chips for evacuation, and align/prevent dust ingress for the heater probe.
~.85” Auger	Drill Only	Clear out remaining material from inside the sleeve.
.75” Heater Probe	Off, Rotation Lock	Melt 8” deep into ice and begin extraction. See section II part E and section III part A for additional detail.
Sleeve Extraction	Drill Only	Retrieval of sleeve for subsequent holes.

The masonry drill bit diameter was chosen from the following three factors; combination of extrapolated test data, required bore envelope for the heater probe, and the drill manufacturer’s recommended maximum hole diameter in concrete. The test report in Appendix E shows that there was a roughly exponential trend between drill bit diameter and penetration rate. Extrapolating this trend gives an anticipated penetration rate of 1.6 in/minute using a 1.25” masonry drill in concrete.

Preliminary chip clearance testing with simulated overburden resulted in frequent hole collapse. ‘Lessons learned’ from previous years’ competitions also identified chip evacuation and hole collapse to be a critical design issue. To address this common problem, a pile-driving solution was conceptualized and found to be extremely effective in small scale testing. In testing, documented in Appendix E, The hammering action of the drill provided enough force to drive a pipe into a pre-drilled hole, despite debris partially filling the hole. Remaining debris within the tube was then cleared with an auger. Based on this success, STYX will be moving forward with a reusable, bore-sleeving technique.

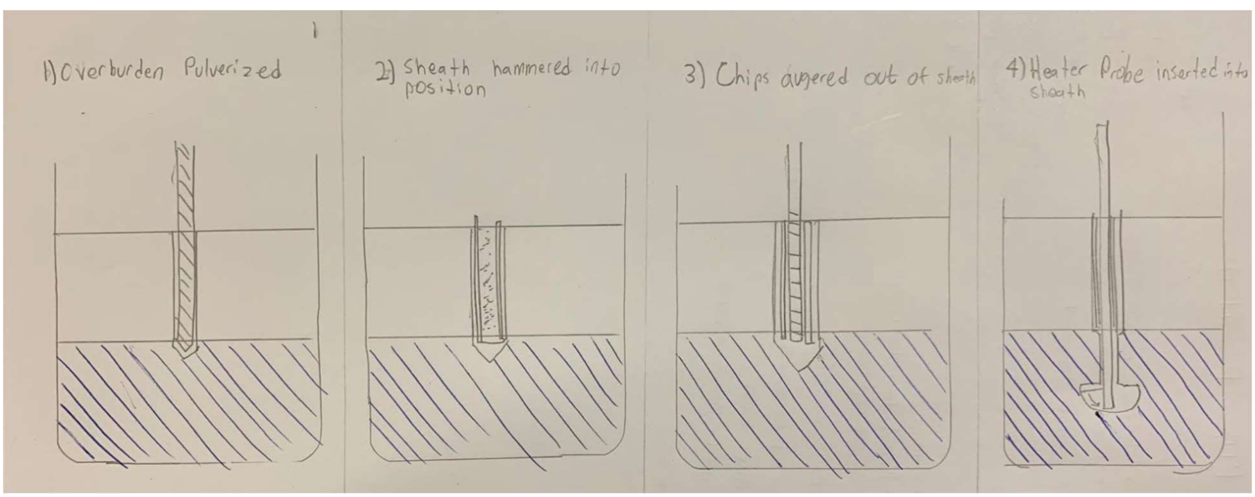


Figure 8. Drilling Process Mission Profile

4.3.4 Design Challenges and Risks

One concern the team has is the effect of low temperatures on the drilling speed. To reduce the effects of temperature on any drilling process, an induction heater coil capable of providing 1000W of heat will be mounted to the tool changer. At regular intervals, tools can be retracted from an in-progress hole and reheated to reduce the effects of freezing temperatures. Heating tools will also mitigate the risk of them becoming stuck or frozen in the overburden or ice. Keeping constant motion within the borehole, peck drilling to extract chips, and regularly cleaning tools off with the frame-mounted brush will also mitigate this risk. In the event that a tool does become stuck, it is anticipated that a hammer drilling action and up to 400N of upwards force will be enough to free any tool. Sizing of the vertical axis motor included consideration for this contingency. Another risk is exceeding the power budget of the entire system. The selected drill can pull 8.5 amps; the team is limited by a 9 amp fast blow fuse. However, power budget has been considered when sizing the stepper motors and the fuse should not blow if the system is programmed safely.

4.4 Drill

The drill subsystem fulfills the functional requirement of ‘apply power’ as shown in Table 5. This subsystem must be capable of removing the overburden that covers the ice, but remain within the project specifications listed in Table 4. The main specifications that affect this subsystem will be maximum weight on bit and power limits.

4.4.1 Decision Matrix and Considered Concepts

Several overburden penetration methods were investigated, including ultrasonic drilling, traditional drilling, and core-drilling. Each of the alternatives had issues. These concepts were compared using the weighted decision matrix shown in Table 9. Power efficiency and force requirements were considered to be some of the most important criteria since breaking through concrete is usually a power intensive and high impulse task, yet 1kW and 150N are the upper limits allowed for this competition. Penetration rate was deemed less important as the competition duration is 12 hours. An effective hole that takes a while to construct would be more useful than several poorly maintained holes.

Table 8. Weighted Decision Matrix - Penetration System

Criteria	Weighting (1-5)	Rotary Hammer Drill		Hammer Drill		Conventional Drill		Ultrasonic Drill	
		Score	Total	Score	Total	Score	Total	Score	Total
Penetration Rate	2	3	6	2	4	1	2	1	2
Cost	3	2	6	3	9	3	9	1	3
Complexity	2	3	6	3	6	3	6	1	2
Power Efficiency	4	2	8	1	4	1	4	3	12
Force Required	4	2	8	2	8	1	4	3	12
Tool Life	3	3	9	2	6	1	3	2	6
TOTALS			**43**		**37**		**28**		**37**

Ultrasonic drilling is typically used for smaller diameter holes and is very expensive and complex to implement correctly. Traditional drilling in concrete applications suffers from slow penetration rates and poor drill bit life, especially with low axial forces. Finally, core-drilling is rarely used in dry applications with high length/depth ratios and would present additional tool cleaning challenges. Sketches of these alternative concepts are available in Appendix D.

4.4.2 Selected Concept

Figure 9. Selected Drill, Bosch RH432VCQ Rotary Hammer Drill (25)

For creating, clearing, and maintaining the holes necessary to reach ice, the team has decided to use a multi-function Bosch RH432VCQ rotary hammer drill with a quick change chuck (Bosch Power Tools). Hammer drilling was chosen because abundant data is available on the topic, similar technology is already being used on interplanetary missions, and past teams have used hammer drills with great success. The drill chosen has multiple operating modes, including hammer drill, drill-only, and hammer only, which will be selectable remotely via a servo. Forward and reverse directions are selectable as well. This particular model of drill was chosen because of its desirable features and because it has the highest drilling force within the specified power limit.

4.4.3 Design Challenges and Risks

While this drill selection is a good choice, there are several challenges to overcome moving forward. First, while this drill is designed for heavy construction applications, it is likely not designed to run for hours continuously. The team is planning on implementing additional cooling for the motor of the drill. Second, the hammer drill will need extensive testing with several overburden types to characterize the amount of force coming into the frame so that STYX does not accidentally exceed the 150N downwards force limit.

4.5 Tool Changer

Because of the complex drilling process chosen, multiple tools are required. Due to the strict weight limit, using only one drill is the only viable option.

4.5.1 Decision Matrix and Considered Concepts

Two solutions appeared obvious to the team to integrate multiple tools. Tool changing and multiple Z-axes were considered. Because of the added weight, expense, and complexity of implementing multiple Z-axes, this solution was rejected. Multiple implementations of toolchangers were compared using the weighted decision matrix shown in Table 10. The concepts presented break the issue down into two categories, rack orientation and chuck actuation. For rack orientation, linear and rotational axes were considered. For chuck actuation, movement of a chuck depressor and movement of the drill itself are compared. The combination of these two concepts generates the four options shown in Table 10. These two concepts were considered together since there would be interference considerations dependent on each other.

Packaging was prioritized in Table 10 because it is possible that the tool changer would limit the axis travel of STYX, thereby reducing the amount of potential harvesting area. Cost was considered less important for this decision matrix as the options considered were relatively close in cost. Table 11 summarizes the reasons for rejection of certain concepts. Sketches of alternative concepts are available in Appendix D.

Table 9. Weighted Decision Matrix - Tool Changer

Criteria	Weighting (1-5)	Linear Rack and Servo Depressor		Linear Rack and Lead Screw Depressor		Rotational Rack and Servo Depressor		Rotational Rack and Lead Screw Depressor	
		Score	Total	Score	Total	Score	Total	Score	Total
Weight	3	2	6	1	3	3	9	2	6
Cost	2	2	4	1	2	3	6	2	4
Packaging	4	2	8	2	8	3	12	3	12
# Tools	3	2	6	2	6	3	9	3	9
Complexity	3	2	6	1	3	3	9	2	6
TOTALS			**30**		**22**		**45**		**37**

Table 10. Rejection Criterion - Tool Changer

Concept	Rejection Criterion
Linear Actuated tool changer	Not very compact, horizontal travel is reduced or tools crash into horizontal rails
Lead screw chuck depressor	More complex than a simple servo, packaging is difficult because both ends of screw is supported
Chuck swapper	Adds weight and cost, could just switch tools

4.5.2 Selected Concept

The rotary tool changing method with stationary chuck depressor tool swapping was chosen because of the compact design, potential for expanded envelope, and maximized horizontal travel. The tool holder is rotated by a stepper motor belt driving the hexagonal axle at the bottom of the tool holder. The belt drive allows the motor to be farther away from the tool changer and is primarily a packaging consideration. The operation of the tool changer follows a four step process:

1. Stepper motor rotates tool into plane of drill
2. Servo actuates to depress chuck
3. Tool falls into rack and new tool is rotated into position
4. Servo moves to allow the chuck to interface with a tool.

Figure 10. CAD Model of Concept Design Tool Changer Mounted to STYX Frame

4.5.3 Preliminary Analysis

Qualitative data from preliminary testing helped define the locating cones at the base of the tool changer; a swing angle was estimated and the mouth of the cone was designed to accommodate for it. Additionally, packaging constraints were determined while the CAD was being completed. The rotational tool rack retains an equal number of tools that a linear rack would while saving approximately 4 inches of horizontal travel.

4.5.4 Design Challenges and Risks

The biggest challenge with the tool changer is the clocking of the tool into the correct position such that it will line up with and insert into the drill chuck. Currently this obstacle will be overcome with a procedure in the programming that runs the drill motor for short bursts to allow a new clocking position to be attempted. The process will repeat until the correct clocking is found and the tool can lock into the chuck. Another potential solution is to affix a potentiometer to the drill and allow it to run in closed loop position control for tool changing. This would add undesirable complexity and will be reserved as a backup to the procedural method. A risk of the tool changer is it adds more single point failure modes to the system. If the motor stops working, the belt snaps, or a tool jams the rotation the team will be forced to enter hands on mode and the score for that drilled hole will be reduced by a factor of 5.

4.6 Linear Motion

The linear motion system is divisible into actuation and load carrying. Integrated into the linear motion system is the force gauge portion of the telemetry system, also noted in section 4.9. To measure downwards force accurately, a dual spring-damper load cell arrangement is being used, as depicted in Figure 14. The integrated damper material will serve to reduce noise in the load cell data and vibratory loads while hammer drilling to the leadscrew and frame. The compression springs will allow for greater resolution in force application, reduced shock loading to the leadscrew and frame, and compensation for feed rate in the event that the drill were to suddenly transition from a soft to a hard material. When the system is loaded in tension, the load is taken by rigid fasteners rather than springs. The integration of this telemetry system is noteworthy when considering criteria by which to gauge each of the three linear actuation methods and four load carrying options.

4.6.1 Decision Matrix and Considered Concepts

To compare considered concepts in a systematic manner, both the load carrying system options and the actuation system options were compared using weighted decision matrices.

Linear Actuation

Three common methods of linear actuation were considered for the linear motion system. These are reflected in the weighted decision matrix, Table 12. Rigidity was considered most important based on past teams' experiences and the inherent accuracy required for the drilling process to function properly. Safety is also a concern as there will be significant mass approximately two meters in the air, supported by a single axis actuation method. Finally, resolution is important for consideration as the drill needs to align precisely with both the holes drilled and the tool changer at different points in time. Cost and weight were considered to be less important as there are only small relative differences between the presented options in Table 11.

Table 11. Weighted Decision Matrix - Linear Motion, Actuation

Criteria	Weighting (1-5)	Belt Drive		Lead Screw		Ball Screw	
		Score	Total	Score	Total	Score	Total
Cost	2	3	6	2	4	1	2
Weight	2	3	6	2	4	2	4
Rigidity	5	1	5	3	15	3	15
Resolution	4	2	8	3	12	3	12
Backlash	2	2	4	2	4	3	6
Debris Tolerance	2	3	6	2	4	1	2
Safety	4	1	4	3	12	2	8
	TOTALS		**39**		**55**		**49**

Load Carrying

For load carrying, four options were considered in the final weighted decision matrix phase. This matrix is shown in table 12. Rigidity was considered the most important factor based on prior competition footage. Teams that employed less rigid methods of load carrying suffered from extreme deflection of their frame as an obstacle was met by the drill. Accuracy is also considered important for the same reasons discussed for the actuation method. Debris tolerance was considered less important because there are dust mitigation methods available. Cost was considered less important as the difference between these options was minimal. Finally, adaptability is considered the least important of these options as the team intends to complete assembly and testing of the unit with time to spare before competition. Any issues found in construction or during testing can be mitigated on campus before shipping the device fully assembled.

Table 12. Weighted Decision Matrix - Linear Motion, Load Carrying

Criteria	Weighting (1-5)	Round Guide Rod		V-Track Wheels		Sliding Frame		Linear Rail	
		Score	Total	Score	Total	Score	Total	Score	Total
Cost	2	2	4	2	4	3	6	1	2
Weight	4	1	4	3	12	3	12	2	8
Rigidity	5	2	10	1	5	1	5	3	15
Debris Tolerance	2	2	4	3	6	3	6	1	2
Accuracy	4	3	12	2	8	1	4	3	12
Adaptability	1	1	1	3	3	3	3	1	1
TOTALS			**35**		**38**		**36**		**40**

4.6.2 Concept Prototyping

Simple concept prototypes were produced to assist with discussion about axis and bearing orientation. Examples of these are shown in Figure 11. In addition to simple models, a more robust concept prototype was constructed to conduct preliminary testing, shown in Figure 7. The concept prototype, shown in Figure 11 is an example of a ‘sliding frame’. The physical model confirmed that a rectangular frame with play in the bearing surfaces is not a rigid enough solution for the application. A noteworthy observation from the concept prototype was that the drillbit wanders significantly and likely needs to be constrained when starting a new hole.

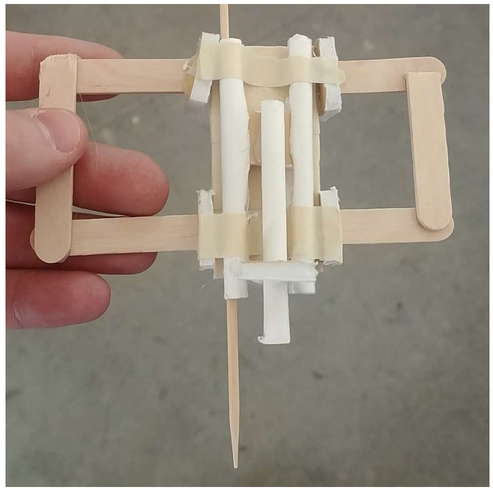


Figure 11. Conceptual Design of the Linear Motion System

4.6.3 Selected Concept

The chosen combination to support linear motion are lead screws and linear rails. The lead screws will be driven by a belt drive for packaging reasons, but retain a desirable self-locking characteristic. In the instance of an electrical fault, power outage or power-saving strategy involving the axis motors, the heavy drill head will remain passively supported by the lead screw. To move the drill head around the drillable envelope, the team chose a two-axis configuration. Preliminary torque, buckling, and mechanical resolution analyses were performed in MATLAB (Appendix F), and were used to justify this design choice and determine sizing. Two axis travel was chosen as a compromise between expanding the drillable area, reducing complexity, and retaining necessary rigidity for drilling operations. Styx will be capable of translating 0.8m horizontally and 1.4m vertically.

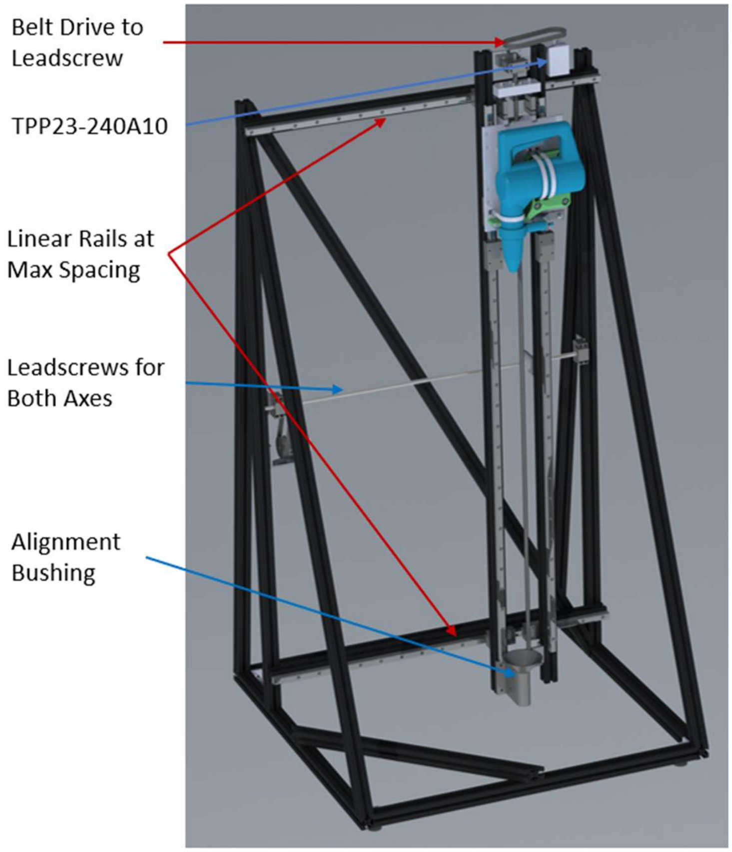


Figure 12. Concept Motion Design

TPP23-240A10 stepper motors with current-controllable drivers were selected to power the lead screws based on their high degree of controllability, cost-effectiveness, and well-specified torque characteristics (TPP23 Stepper Motor). The motor's torque curve can be found in Appendix G. Travel speed, mechanical resolution, torque capacity, and power consumption were important factors considered while choosing motors.

In addition to the load carrying and linear actuation components, another part will be implemented to improve drilling accuracy. To constrain the drill bit tip and keep it plunging vertically in the right location, a 4" long bushing will encircle tools used by the drill. While teams in previous years have used this type of solution with moderate success, this team believes that their implementations were too short to provide much resistance against deflection. Testing will be conducted to ensure a 4" bushing is long enough.

4.6.4 Preliminary Analysis

Preliminary torque, buckling, and mechanical resolution analyses were performed in MATLAB (Appendix F). Assumptions made for load cases were conservative and a factor of safety of 2 was applied. This analysis was useful for determining the necessary lead screw and linear bearing characteristics. CAD was used to assist with designing in the largest possible travel range for the unit. The final travel dimensions are .8m horizontally and 1.4m vertically.

4.6.5 Design Challenges and Risks

A major challenge to having a linear rail system is exposure to debris that could jam the screw and prevent linear actuation. To prevent this, flexible sleeves will be fitted over the lead screws to prevent debris from collecting on the screw. Additionally, no grease will be used on the screw to keep dust from mixing with the grease and creating an abrasive slime. Another challenge faced on the linear actuation system is difficulty aligning linear rails. If the linear rails are skewed the system will bind and introduce extra friction, or worse stop completely. To overcome this challenge the frame will be made as stiff as possible, and careful attention to parallelism will be observed when mounting. The final challenge faced with the linear motion system is the quality of the acquired parts. To decrease the cost of high tolerance linear actuation parts the team is buying from China. Buying lower quality parts means increased risk of failure and incompatibility between components. Planning for this will entail ordering parts early, and ordering duplicates in case of failure.

4.7 Control and Electrical Design

To actually control the motors, supply power to components, and collect telemetry data from sensors, relatively complicated control and electrical implementations are necessary.

For linear motion control, the team proposed two ideas. The first idea was to use an off the shelf 3D printer controller. This method is quick and easy, as it requires no programming for linear motion control. This method does not provide the capability to integrate the types and number of sensors without extensive firmware editing, however. The other idea was to program an entirely new control system using Arduino. The team decided to move forward with programming a new control system, as the team has prior experience programming microcontrollers. Because the barrier to entry for 3D printer firmware is so high, microcontroller programming was deemed the only valid solution remaining. Decision matrices were not employed for this subsystem.

4.7.1 Selected Concept

The following electronics concepts relating to the control system and electrical circuit design were chosen to be integrated with our final design.

ELECTRICAL DESIGN

The electrical control system for STYX will be based on a primary digital logic system with backup analog overrides available for all critical sub-systems. During normal operation, the Arduino will actuate AC components using solid state relays and DC components using Mosfets. Pulse-width modulated signals will be applied for the necessary components, along with the necessary shielding to prevent any electrical interference between components. During a fault situation, independent and redundant analog components can provide remote, manual control. An example circuit diagram is shown in Figure 13.

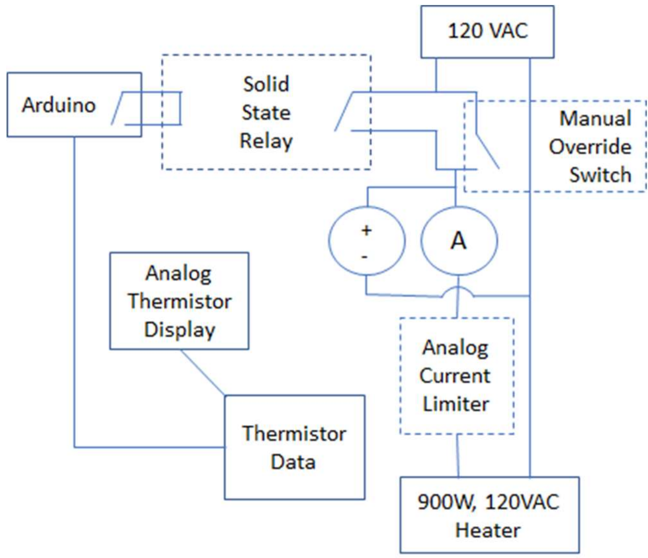


Figure 13. Preliminary Electrical Layout

A. *AC Components*

When possible, components were designed to run natively on 120VAC to avoid DC conversion losses. The heating element used in the heat probe is composed of three 120VAC, 2.5A cartridge heaters wired in parallel for a combined 7.5A current draw and 900W heating capacity. The Bosch drill chosen is rated for 8.5A at 120VAC.

B. *DC Generation and Components*

To convert AC to DC, STYX will utilize multiple switched-mode power supplies. A 1000W, 24VDC supply will power the high power stepper motors and induction coil heater. A 30W, 12VDC supply will power the peristaltic pump and Arduino Mega. Finally, 2A, 5V supplies will provide power for on-board telemetry cameras, servos, low-power stepper motors, and other miscellaneous equipment.

C. *Power Management*

Using the required 9A fast blow fuse requires that current consumption be carefully monitored. The current curve for the Bussmann BK/AGC-9-R model fuse, provided in Appendix H, shows some headroom above 9A for both starting current and continuous current. Current limiting may be used to mitigate start up loads and marginal continuous power modes. Standard operating procedures will be developed during testing. In addition, an Arduino controlled GUI will be implemented that prompts the operator before powering a component on if an over-current scenario is likely. Table 14 shows the anticipated load in different operating modes at the maximum and minimum expected line voltages. Component-level power draw is captured in Appendix I. DC components were conservatively assumed to have an AC/DC conversion efficiency of 85%.

Table 13. Power Budget Divisions

Operation	Components	Power (W)	Amps @ 120V	Amps @ 110V
Always On	Controls and Camera	27	0.23	0.25
Drilling	Z-Axis and Drill	1104	9.20	10.03
Drill bit Heating	Induction Heater	874	7.28	7.95
Melting and Extraction	Heater, Steppers A and B, Z-axis stepper, Pump	1033	8.61	9.39
Tool Change	X-axis, Z-axis, and A-axis steppers	152	1.26	1.38
Telemetry	Z-Axis Stepper	84	0.70	0.76

SYSTEM CONTROL

The team intends to operate STYX in ‘hands-off’ mode for the entire duration of the competition in order to maximize the prototype’s score. To do this, remote control systems with robust telemetry and some autonomous capability will be implemented. Whenever possible, digital control will be used with closed-loop PID controlled systems. The system stability for each operating mode will be thoroughly tested using both simulation and real world operation. In addition, programmed logic and status checks will prevent operational conflicts. To reduce the risk of a critical programming failure, each sub-system will also be operational in an open-loop, manual override mode. A graphical user interface (GUI) will provide the STYX operator with real-time system telemetry and prompts when system conditions approach operating limits.

Data logging, closed-loop operation, and the GUI will be managed via MATLAB’s Simulink. This Simulink model will control an Arduino Mega via serial interface. The Arduino will manage all component switching and analog data acquisition. Given the differences in available telemetry and risk associated with different operating modes, it is expected that drilling operations will be conducted autonomously, while tool changing and water extraction operations will be conducted remotely.

4.7.2 Design Challenges and Risks

There are common challenges between the electrical and control systems. With a team of all mechanical engineering students and only one team member pursuing a mechatronics concentration, designing and manufacturing software and electrical hardware will have a steep learning curve. With respect to the electrical systems, approval will be needed by university faculty due to the high voltage requirements of several subsystems. In addition to controlling all the components with software, the team intends to implement a GUI and logical checks based on system parameters to prevent incorrect or dangerous system configurations. Software will require extensive testing to ensure that each of these goals is met. Additionally, closed loop systems will need thorough testing to ensure stability. Because these tests are required at the system level, this will be some of the highest risk testing, as there will be little flexibility in the schedule by this point. These challenges will be mostly overcome by frontloading the learning curve. Team members will begin learning how to code arduino and reviewing controls theory before integration is complete. Block diagrams can be constructed and checked well in advance of the final implementation.

4.8 Telemetry Generation

STYX will be capable of collecting temperature, power consumption, vertical force, water pressure, position and video telemetry. Some of these channels are solely to provide the operator with performance metrics, while others will be used to generate the required digital core.

To monitor performance metrics, thermocouple data will be collected from the heater probe tip and intermittent infrared temperature data will be collected from drilling tools. Electrical component temperatures may be monitored, but will also have integrated thermal protections. Power will be monitored at the system and component level via ammeters and voltmeters. Water flow rate data will be used to monitor filtration and extraction rate. Positional data will be provided by stepper motor index. Finally, video telemetry will be used in a 'telemetry probe' for determining layer thickness and for monitoring tool changing operations.

4.8.1 Decision Matrix and Considered Concepts

Several concepts were initially considered for the creation of the digital core via telemetric process. Two concepts considered by the team were proposed by a contact working at Scientific Drilling: gamma ray detection and resistivity logging (3, 26). The other methods considered utilized more traditional telemetric equipment, a load cell and camera probe, to create the digital core. These concepts were then compared using pugh matrices found in Appendix C. Following the completion of Pugh matrix analysis, further comparison was conducted via a weighted matrix found below in Table 15. The key characteristics compared in the weighted decision matrix were chosen to be resolution, accuracy and complexity. Although cost was not weighted as heavily in the decision matrix, gamma ray detection as well as resistivity logging were discounted as viable methods with this consideration. Sketches of alternative concepts are available in Appendix D.

Table 14. Morphological Attribute Matrix - Telemetry Process

Function	Concept			
Measure Layer Hardness	Rate v. Force	Brinell	Rate v. Force & Brinell	
Measure Layer Thickness	Rate v. Force	Camera Probe	Gamma Ray	Resistivity
First Choice				
Second Choice				
Third Choice				

Table 15. Weighted Decision Matrix - Telemetry Process

Criteria	Weighting (1-5)	Rate v. Force and Camera Probe		Rate v. Force & Brinell, Camera Probe		Rate V. Force	
		Score	Total	Score	Total	Score	Total
Resolution	5	2	10	3	15	1	5
Accuracy	5	2	10	3	15	2	10
Complexity	3	2	6	1	3	3	9
Cost	1	2	2	2	2	3	3
Path to Flight	3	3	9	3	9	3	9
TOTALS			**37**		**44**		**36**

4.8.2 Selected Concept

The finalized process for digital core creation will be split into two operations, layer thickness and hardness. To determine layer thickness, the telemetry camera probe will be inserted into a previously harvested hole. Unlike other borehole sleeves, this telemetry hole will utilize a clear, polycarbonate tube. A live video feed from the borehole, coupled with Z-axis position data will provide layer thickness data. Hardness data will be collected via force vs. feed rate data while drilling and a Brinell style hardness test. Load cell telemetry will be able to compare drilling force and rate to a list of previously tested materials. This type of telemetry can be collected during all drilling operations throughout the competition. For at least one hole, the telemetry probe will be used to measure force and deflection of each layer material using a Brinell style hardness test to produce another data set for comparison. This style of test will be especially useful on softer layers, where drilling data may have too much noise. If the drilling telemetry and probe telemetry agree, the layer's compressive strength will be recorded. If not, the sample size will be increased.

4.8.3 Design Challenges and Risks

The largest challenge surrounding the telemetric processes will be the calibration of the load cells as well as the amplification of the data to an arduino. The load cells STYX will ultimately utilize are simple S type load cells with loose wiring to integrate into an electrical system to interpret voltages. This will leave all calibration work and arduino interpretation up to the STYX team. A secondary challenge facing the STYX team will be the illumination of the hole walls for adequate footage. Without proper illumination, the camera will be unable to identify color changes between layers, failing to properly map all layers. One risk that STYX is currently considering is the structural stability and strength of the clear tubing inserted for the camera probe path.

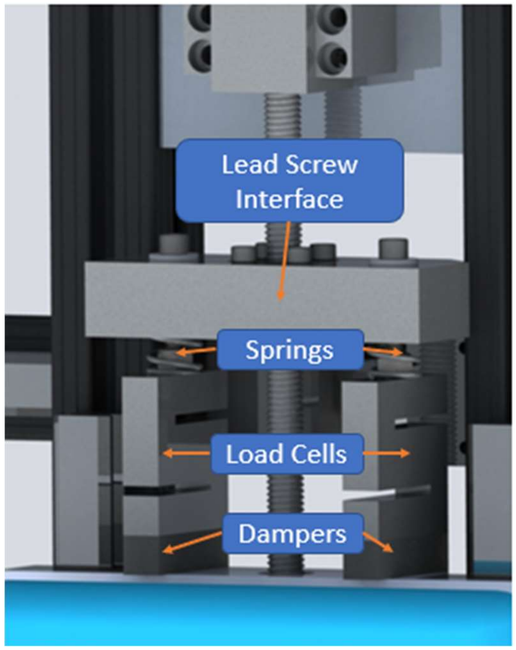


Figure 14. Load Cell Configuration Interfacing to Lead Screw.

4.9 Harvesting Process

The water extraction subsystem will pump liquid water from the heating unit to the water holding tanks provided at the competition. It will also extract impurities from the water before delivering it to the holding tanks.

4.9.1 Decision Matrices and Considered Concepts

The first objective for the water harvesting unit was to determine whether ice should be cut and extracted as a solid, melted and extracted as a liquid, or boiled and extracted as a gas. The next stage covers water purification techniques. The functions that may be required of the water harvesting system were compared using Pugh matrices in Appendix C. The general decisions made are summarized in Table 17.

Table 16. Morphological Attribute Matrix - Harvesting Process

Function	Concept					
Move Ice/Water	Peristaltic Pump	Bubble Pump	Centrifugal pump	Evaporative Collection	Ice Block Extraction	Ice shaving Extraction
Melt Ice	Water Convection	Conduction	Air Convection	Radiation		
Remove Particulate	Sand Trap	One Stage Membrane Filtration	Two Stage Filtration	Centrifugal Filtration	Density Stack	
Filter Longevity	Oversizing	Backflow	Physical Clean	Filter Replacement		
Maximize Water Yield	Passive Heating Element	Expandible Heating Element	Actuating Heating Element	Two Axis Movement	Three Axis Movement	
First Choice						
Second Choice						
Third Choice						

The morphological attribute matrix shown in Table 16 helped the team determine the three best possible courses of action to deliver the clean water. These options were further considered in the weighted decision matrix found in Table 17.

Table 17. Weighted Decision Matrix - Harvesting Process

Criteria	Weighting (1-5)	Peristaltic Pump, Conduction, Two-Stage Membrane, Backflow, Actuating Heating Element, Two Axis Motion		Centrifugal Pump, Conduction, Sand Trap, Oversizing, Expandible Heating Element		Bubble Pump, Water Convection, One Stage Membrane Filter, Backflow, Passive Heating Element, Three Axis Movement	
		Score	Total	Score	Total	Score	Total
Cost	2	2	4	1	2	3	6
Complexity	3	2	6	1	3	3	9
Throughput	4	3	12	2	8	2	8
Water Clarity	4	3	12	3	12	2	8
Path to Flight	4	2	8	2	8	1	4
Water Efficiency	3	2	6	3	9	2	6
Power Efficiency	3	3	9	3	9	2	6
TOTALS			**57**		**51**		**47**

4.9.2 Selected Concept

An actuating heat probe that deploys into the drilled hole was chosen as the method for melting ice. This device is capable of actuating vertically, rotationally, and angularly. The drill actuates the entire probe up and down within the hole. The pivot actuation motor raises the heater out to the side, and the axial rotation motor allows the probe to spin about its vertical component. These actuators are shown in Figure 15.

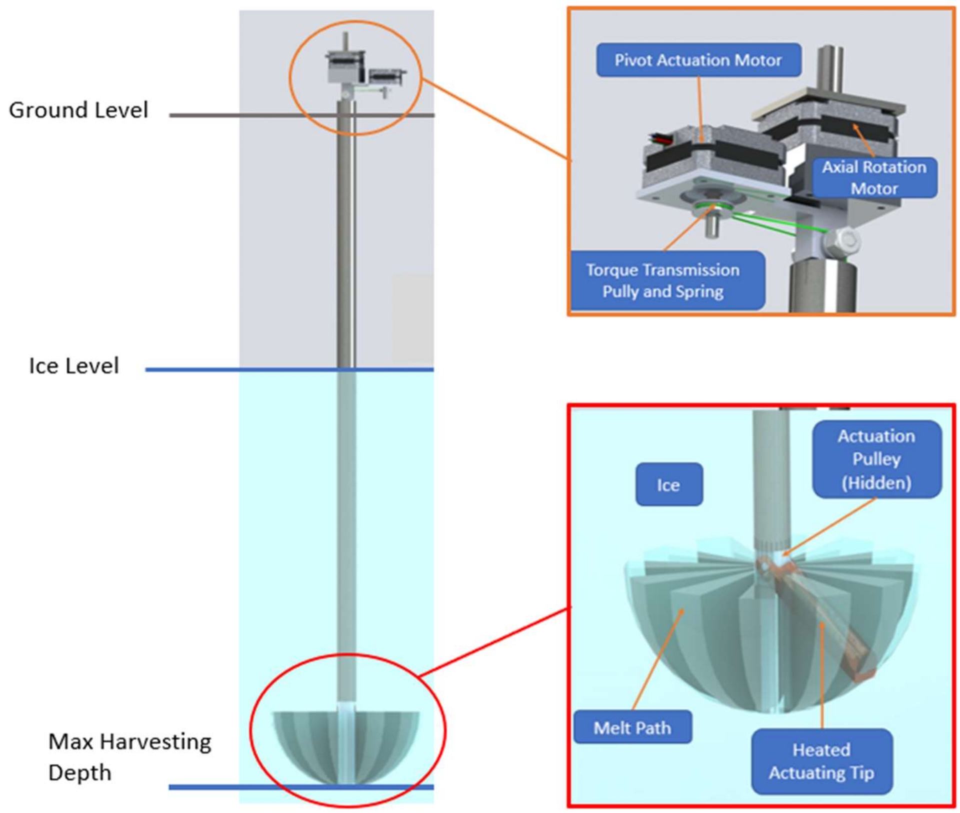


Figure 15. Heater Probe Subsystem Annotated

The purpose of this heating design is to maximize the volume of ice melted in each drilled hole. Currently, the probe is designed to fit through a 1 ¼” drilled hole. When the heating arm is fully actuated outward and spun around, it will deliver an 8” diameter cylindrical melting pattern.

A peristaltic pump was determined to be the best option for extracting liquid water from the hole. The pump was chosen for its self-priming capability and its resilience to debris. It is also fully reversible, allowing this pump to also be used for backflushing the filtration system. The inlet to the pump will be connected to the heater probe so that liquid water can be extracted as quickly as possible, in order to avoid re-freezing.

A two-stage filtration system will be implemented, which allows for separate coarse and fine filter functions, protecting the finer stage from most of the fouling. The first stage of the filtration system is a spin-down sediment trap designed to isolate large particulates. The sediment trap will feature an electronic ball valve designed to periodically purge collected debris. Final filter dimensions will be chosen based on real world ice melting rates, pump flow rate, and fouling characteristics.

The second stage of the filtration system relies on an extra-fine sintered stainless steel filter to remove particulates sized 5 microns and larger. This level of filtration should produce clear, potable water in the competition environment. Sintered filters are physically strong, corrosion resistant, and backflushable. Heat and vibration may be used to augment the backflow cleaning process. Heating causes the filter pores to expand, while vibration is effective for knocking particulates loose. This filter design and backflow strategy will minimize the required back pressure and flow velocity when cleaning the filter, ultimately preserving as much water as possible for collection. Sketches of alternative designs are available in appendix D.

4.9.3 Concept Prototyping

An initial concept was 3D-printed and tested with moderate success, it was a scaled down version of the final product. It successfully separated the particles from the water, and allowed the debris to settle to the bottom of the filter reservoir. Figure 16 shows this filter.

Figure 16. Filter Prototype.

Preliminary filter testing, documented in Appendix J, showed that tube blockage and sediment coagulation will be design hurdles. Tube blockage can occur when particles larger than .1” across enter the system. To prevent this, the heater probe tip will integrate a coarse, passive screen before the pump tube entrance. Testing verified the need for a multi-stage filter in order to mitigate filter degradation from coagulating sediment. Because of this hands-on experience, the first-stage filter will be designed to operate under a fouled condition and will be optimized for thorough backflow. While the second stage filter will be as fine as possible.

4.9.4 Preliminary Analysis

Preliminary calculations for determining the minimum required filter surface area is in Appendix K. These calculations showed that for a 5 micron sintered steel filter, a 37 in^2 surface area would be required to maintain a 400 mL flow rate. Under these conditions, 0.53psi would be required from the pump in order to maintain this flow. Further testing will be used to determine fouling rates, which will determine the operational flow rate.

4.9.5 Design Challenges and Risks

For the heater probe, the main concern with the design is the pivot point. The team has to be especially careful of thermal expansion because the joint will be composed of two different metals: steel and copper. Another issue with the pivot is dirt ingress and wear. Since the heater is submerged into the overburden, the pivot mechanism must be shielded from particulate to avoid potential failures such as binding and breaking.

4.10 Frame Design

The frame was designed with constraints of size, weight, adjustability, and ease of interface in mind.

4.10.1 Considered Concepts

The concepts considered for frame construction were square tube with bolted connections, square tube with welded connection, and aluminum extrusion. Because of anticipated changes in design and location, the ease of assembly and adaptability of 8020 t-slot extrusion was considered to be extremely valuable and was chosen for the first design iteration. This concept design is shown below in Figure 17.

The 8020 is a structurally inefficient material and added too much weight to the frame with the frame base alone weighing ~123lbs. This issue was noted just before PDR with the intent to redesign using square tube to reduce weight, despite the reduction in adjustability and added complexity associated with bolted connections. This redesign is discussed in section 5.0.

Figure 17. Frame concept design A frame X-rail.

4.11 Path to Fight

Competition rules require consideration of ‘path to flight’, critical design changes that would be necessary to be compatible with either Mars or lunar operations. STYX is designed to function on Earth in standard temperature and pressure conditions. To be fully operational in a lunar or martian environment STYX would require several intensive modifications. Protection from radiation, galling, off-gassing, and other space related hazards would be required. Additionally, modifications to the operational strategy would be necessary to accomplish the mission objectives.

4.11.1 Water Extraction on Mars

Mars has a thinner atmosphere than Earth with an average atmospheric pressure of 600 to 700 Pa, roughly 1% of Earth's (28). This low atmospheric pressure paired with low surface temperatures, averaging at -81º Fahrenheit, results in sublimation of ice (29). STYX's martian ice extraction would be done by heating solid ice to assist in sublimation. Water vapor would be collected via the borehole sleeve, through which it would flow into a holding tank, where a cold plate would be used to refreeze the gas. To produce liquid water, the tank would occasionally be sealed and heated to obtain the necessary pressure and temperature to support liquid water. This process eliminates the need for pump-based extraction, filtration for particulates or dissolved perchlorates, and solves the issue of atmospheric pressure. Despite these numerous benefits, a slower yield rate than direct liquid extraction would need to be considered for mission planning.

Another consideration is the average surface temperature of Mars, -81 ºF (29). Because the bore sleeve is subjected to surrounding atmospheric, overburden, and ice temperatures, it is possible for water vapor to prematurely re-freeze within the sleeve, eventually blocking flow. To overcome this problem, the bore sleeve would implement heating elements to maintain sublimation temperatures.

Finally, Styx's current design inserts and retracts rigid sleeves into each drilled hole to prevent hole collapse. STYX's sleeves will be 0.6 meters long, which is enough to confidently reach the ice layer given the known test bed layout. Recent research has estimated that ice deposits would be at least half a meter below the surface in the Arcadia Planitia region (31). In order for STYX to be effective on Mars, the drilling, sleeving, and extraction operations need to reach deeper. Instead of expanding the frame and travel dimensions of the system, drilling and extraction systems could be implemented in a mole-style system demonstrated on the InSight mission, while sleeving is handled with a telescoping pipe (30). Mole-style systems would only be limited by the length of cable available, which is lighter and more space-efficient than solid tools. A telescoping system, although more complex than rigid sleeves, would retain the reusability characteristic of the current sleeve design.

4.11.2 Prospecting on the Moon

The extreme temperature range of the lunar environment requires special consideration. Designing STYX to tolerate differential thermal expansion within assemblies and changing material properties would be critical. One example of a critical fit that would need a redesign is between the brass lead screw nuts and stainless steel lead screws, as binding would occur with differential expansion. As temperature fluctuates, the changes in material property would require a recalibration of certain telemetry components such as load cells. Other components such as rubber belt drives would need to be replaced with more stable alternatives as rubber would become brittle or melt in lunar temperatures.

Lunar prospecting would only require drilling and telemetry systems, not extraction or purification systems. Additionally, mobility would be more highly valued for scientific purposes. To accommodate a mobile rover platform, extraneous systems would be removed to reduce weight and envelope. Additionally, adding a coring bit to the tool changer may be useful, since a central shaft is not required on every hole and core samples have more scientific value.

A critical consideration unique to the moon is dust ingress. The lunar surface is covered in a thin layer of highly abrasive, very fine particulate that has proven problematic since the Apollo program. To mitigate dust ingress, seals would be implemented at every moving interface, and the operational profile would be adjusted to reduced dust-producing activities. An example of this would be to use a ‘drill only’ mode rather than ‘hammer drilling’ whenever possible.

4.11.3 Testbed Enhancements

To better mimic martian and lunar operating conditions, vibration dampening may be integrated at the mounting points of STYX and between the drill assembly and the frame. Any non-terrestrial implementation would benefit from reduced vibratory loads. Another necessary modification for lunar and martian readiness will be the sealing of all electrical control components within a Faraday cage to protect components from solar radiation. Grounding all electrical components will also be critical to prevent differential charging and mitigate the risk of arcing between equipment. STYX will be enclosing its on-board electronics in a sheet metal box and ensuring the entire system runs on a common ground connected to the provided 3-prong outlet.

5.0 Final Design

This section will highlight the final design choices of the prototype by each subsystem.

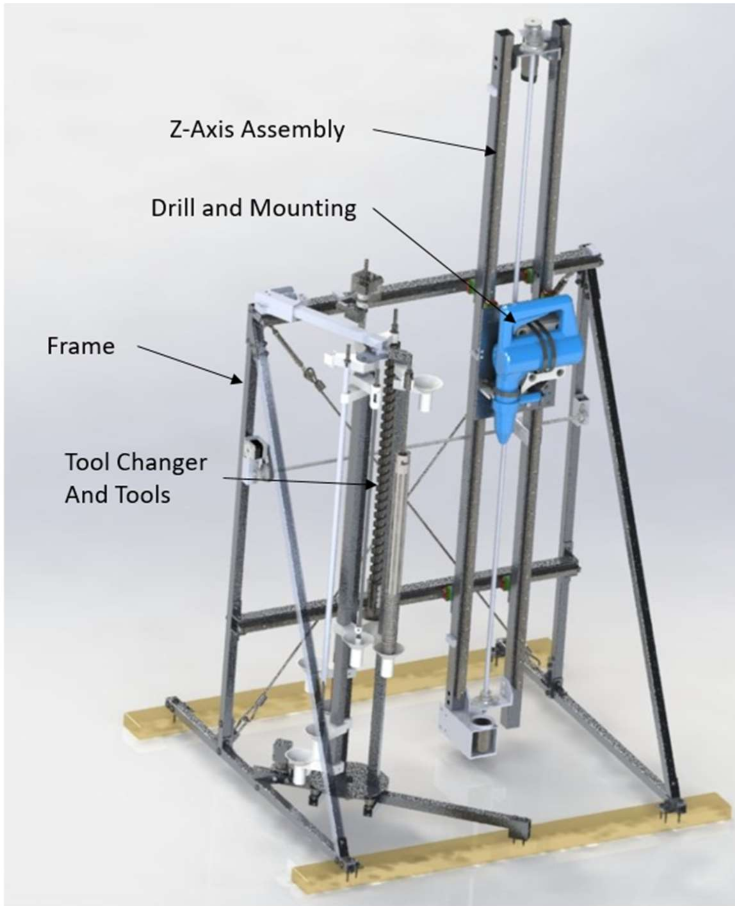


Figure 18: Final design (filtration and electronics subsystems not pictured. Mounting solution pending final electrical box dimensions and placement)

5.1 Frame

The frame was designed to transfer drilling loads from the drill to the test stand, support a linear actuation system, and provide mounting points and support for all other subsystems.

5.1.1 Frame Design Features

To improve the design the A frame structure was abandoned for a single gusset design. This design decision was justified because the angle on the A frame was preventing it from efficiently transferring the horizontal load to the base. Additionally, the height of the frame was reduced to the minimum height necessary to effectively carry the bearing loads to reduce wasted weight in height. Finally, the diagonal cross member was removed in favor of lighter cross cables. The revised frame is shown in Figure19.

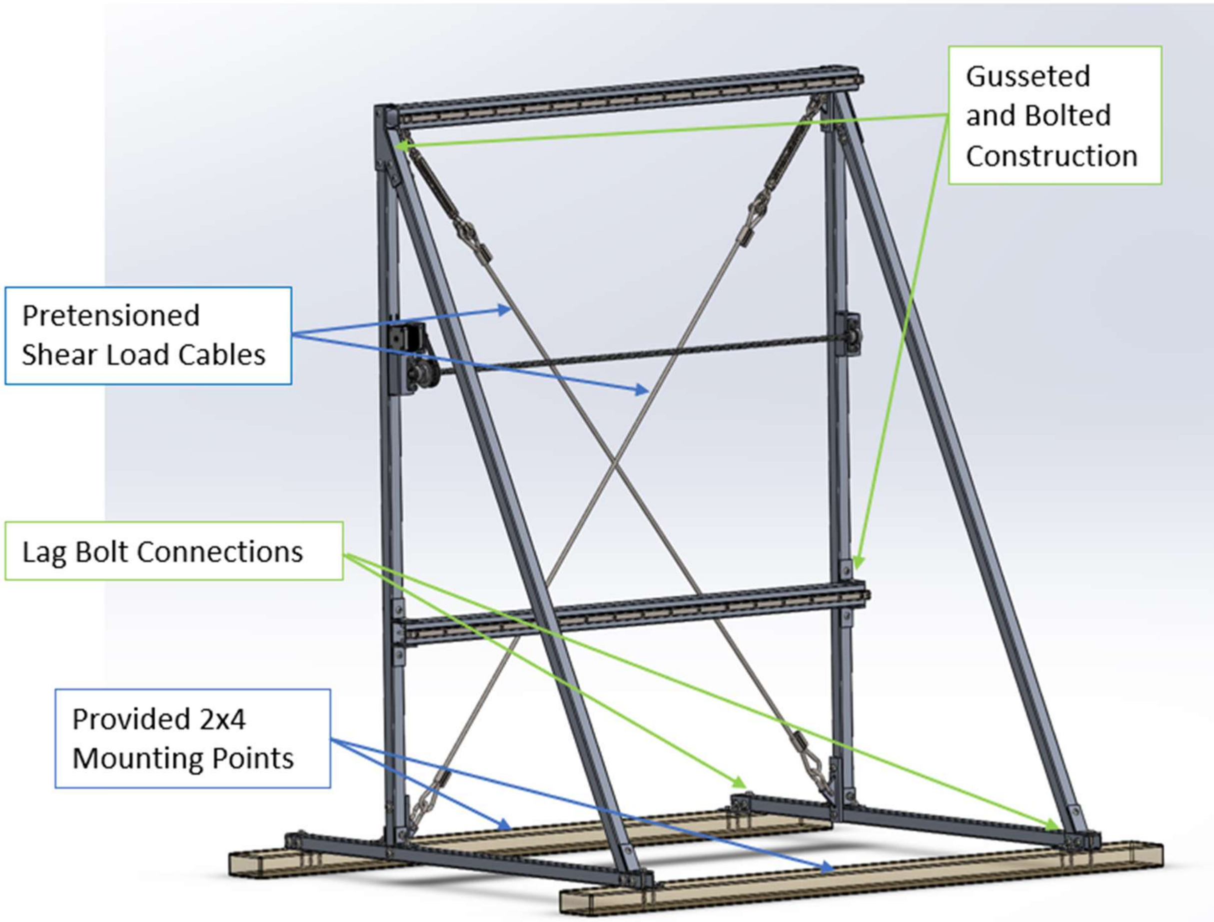


Figure 19. Frame Optimized design gusset square tube aluminum.

The frame is made of thin wall aluminum selected to be the largest size tube for the thinnest wall thickness. This is because the extra tube size adds bending stiffness to the system, as the tube walls are further from the neutral axis then a thicker walled and smaller tube. Members are mounted together in a bolted up assembly style. This alleviates the need for difficult welds and allows the frame to be disassembled for easier transport to competition. The frame also features a cross cable stabilization feature, where two cables create an X frame across the center of the drilling apparatus. The frame interfaces with the provided test rig 2x4's via 12 ¼" lag bolts.

Below in Table 19 a breakdown of the weight of each subsystem is tabulated. Currently the total system is over the weight budget by ~ 6 lbs, however weight saving measures are planned such as: using kevlar string in lieu of steel cable, adding lightening holes into low stress areas of the frame, redesigning the drill plate with ⅛ in aluminum instead of ¼ in plate, and replacement of the thick walled aluminum diagonal members with thin walled members.

Table 19. Drilling System Weight Breakdown

Subsystem	Weight (lbf)
Frame Base	42.2
Z-Axis Assembly	21.5
Tool Changer	9.7
Drill & Mounting	19.6
Tools	30
Filter	6.6
Electronics	9
Estimated Total	138.6
Allowed Total	132.3

Weights are determined using a combination of weighing and Solidworks mass properties

5.1.2 Frame Analysis

Hand calculations and Matlab calculations were completed for all significant members of the frame. The process for completing the analysis involved comparing the Von Mises stress in each member to the yield stress of the 6061-T6 aluminum being used for the frame. This calculation was completed from every combination of stock dimensions considered for purchase. The stress surface was plotted alongside a plane of the yield stress and the stock size was selected based on weight and bending efficiency considerations. Buckling, compressive stress, and bending stress were examined for significant members. This analysis is documented in Appendix L. Once members were selected and the buildup in CAD was completed, FEA was used to ensure smaller details were captured in the analysis. The primary load case was selected to be as conservative as possible with a Factor of Safety (F.S.) of 1.5 being applied to the loads. The primary load case was that of the drill being as far out of the hole as possible, the drill at max torque catching on a rocky inclusion, and the z axis motor pulling out with 150lbf. With this load case the FEA showed no failure of members and predicted a maximum deflection of ~0.8in. The FEA buildup is documented in Appendix M.

5.2 Drilling Assembly

An Off-The-Shelf (OTS), hand held rotary hammer drill was chosen for this prototype. The drill requires a custom 3D printed component to hold it securely to the linear rails and lead screw that actuates it up and down.

Analysis of past competition designs showed that keeping drilling forces below 150N was possible, but these designs were not able to utilize the upper limit to the fullest extent. From the data shared by other teams, it was apparent that in order to avoid spikes in drilling force that exceeded 150N, the average drilling force had to be closer to 100N. These spikes in Weight-On-Bit (WOB) came when the drill transitioned from drilling a soft material to a hard material.

In order to maximize weight on bit, but allow compliance for transition between soft and hard materials, a spring-damper system is employed.Figure 20 shows the springs and dampers that can compress and absorb impact loading from the hammer drilling action with no major updates since the concept design. The springs chosen have a combined maximum load of 60 lbf and 1 inch of travel, giving significant margin for the downward force requirement. Less stiff springs are being considered and may be integrated if a need is found during testing as the drill gantry itself already weighs approximately 18 lbf.

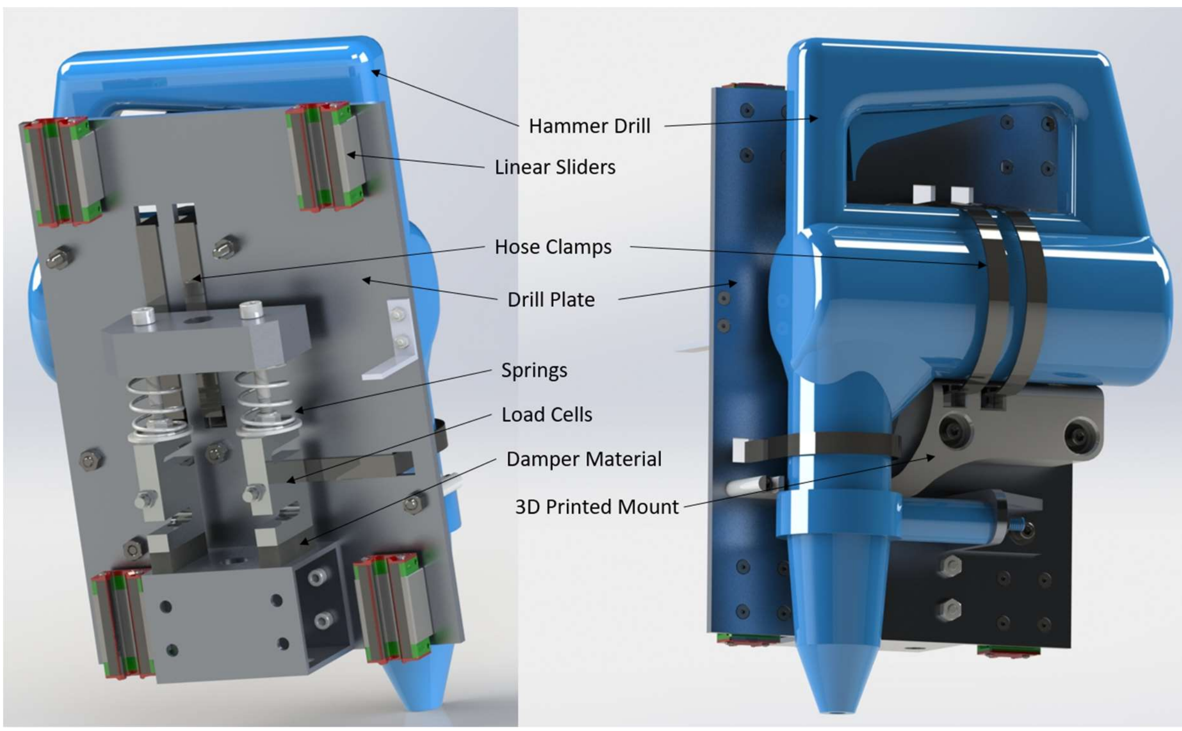


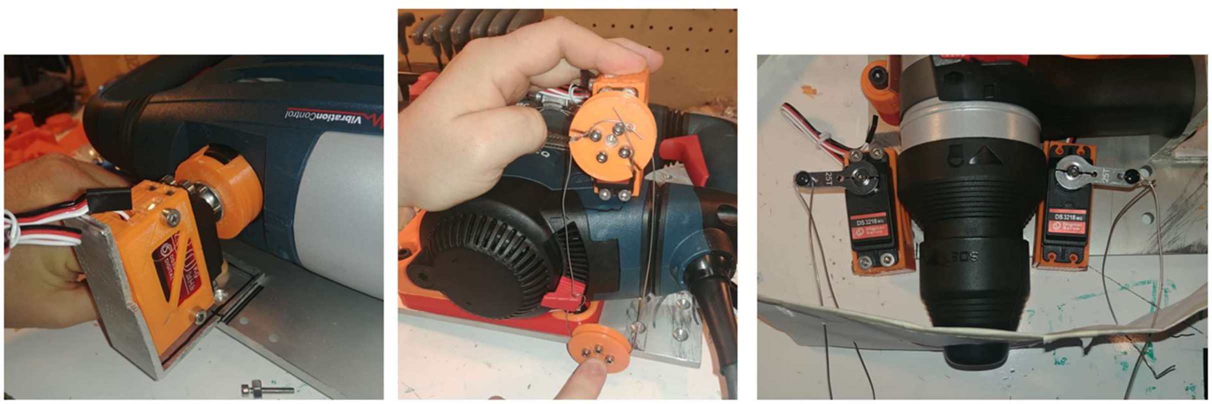
Figure 20. Drilling Assembly

The finalized method of mounting the hammer drill to the drill plate is via a 3D printed mount and hose clamps. Silicone rubber is sandwiched between the drill and 3D print to absorb any pressure points arising from imperfect modeling or printing of the 3D print geometry. Shimming methods are to be used between the 3D printed mount and the drill plate to tram the drill. The linear sliders will be discussed in the linear motion section.

Not shown in Figure 20 are the electromechanical means of interfacing with the drill. The trigger of the drill will simply be zip-tied to a fully on position and the power will be controlled via a triac circuit, described in a later section. The remainder of the controls will be interfaced with using 20 kg-cm servo motors as shown in Figure 21.

To actuate the quick-release chuck on the rotary hammer drill, two servos were chosen. The actuation force for the chuck release is approximately 15 lbf. The calculation for servo motor strength chosen is shown in appendix N. Servos are lighter than linear actuators and more compact, making them an ideal choice for short stroke applications such as this. The servos will pull on strings attached to a plate that will pull on the chuck. This plate will be able to move far enough downwards to completely clear the chuck, ensuring no rubbing occurs while the drill is operating. Depressing the chuck requires approximately 0.3” of stroke, which the servo rotation can easily handle.

A drilling mode rotary switch on the top of the drill changes between four modes: hammer drill, drill, freely rotating hammer, and locked rotation hammer. A forward/reverse switch located on the bottom of the drill will be actuated with a servo driven pulley system. To size the servo motors, the mode selector actuation torque was tested with a torque wrench, while the forward/reverse actuation force was measured with a scale since a translational actuation method was chosen. A factor of safety of 2 was chosen and all the required torques were between 7 and 10 kg-cm. Based on the factor of safety requirement, ease of use, and an inconsequential difference in price, 20 kg-cm was chosen to be the common servo type.



Mode Selector Switch — Forward/Reverse Switch — Quick Release Chuck Depressor

Figure 21. Servo Interface Mockups for Drill Controls

5.3 Linear Motion

Only minor changes from the concept design of linear motion have been made. The motors driving the leadscrew axes have been replaced and the lead screws were repurchased from a domestic source due to Covid-19 complications. As a result of domestic purchase, the thread pitch is now in english units, rather than metric, but retains a very similar value and the same critical self-locking characteristic. Thorough analysis was conducted for each axis of motion as well to ensure compatibility with existing load cases.

X-Axis

The motor choice for the X-axis changed from the TPP23 stepper motor to a generic nema 17 stepper motor. Due to the mechanical advantage provided by the lead screw and the low frictional and inertial loads caused by the gantry, very little torque is required to drive the X-axis. The selected motor is approximately 90% cheaper than the original motor choice and has a maximum torque of 59 N-cm. The calculations shown in APPENDIX X use a conservative load case for horizontal actuation loads and find a factor of safety >20. Other analyses shown calculate the maximum travel speed and time, maximum torque given the belt reduction, and positional resolution available based on step resolution of the motor, belt reduction, leadscrew pitch and typical frictional coefficients of the leadscrew and linear bearings.

Z-Axis

The motor choice for the Z-axis is now a planetary geared DC motor with encoder feedback from AndyMark. This motor and gearing combination was chosen for its superior speed and torque over the original TPP23 motor and provides a greater travel speed and torque margin. The same analyses discussed for the X-axis were performed for the Z axis, updated with the revised leadscrew pitch and motor characteristics, and are also shown in Appendix X. The major difference between the X-axis and Z-axis is the load case where a tool is stuck in the overburden. 200 lbf of pull out force was deemed reasonable for this load case and the motor/leadscrew combination used has a torque margin of >500%.

5.4 Tool Changer

The final design of the tool changer now incorporates a support at the top and the bottom. After constructing the original design, testing proved that extra support was necessary. A single bend test was performed on the system without the top support bar, and there was an unacceptable displacement of ⅝” at the clip when 5 lbf was applied. Also, due to a change in drilling operations and sequencing, the only tool that will extend above the tool changer’s top support is the heater probe. The implication of this change is that a top support is feasible and reaching all the different tool slots simply requires rotating forwards and backwards to not crash the heater probe into the support, rather than rotating a full 360 degree, one direction rotation.The final design is illustrated in Figure 22.

A geared stepper motor was chosen for driving the tool changer as positional accuracy and holding torque were considered critical over speed. Given an output shaft torque of 200N-cm, a belt ratio of 3, and a radius of 5 inches, a maximum tool loading/unloading force of ~10 lbf was determined, as shown in appendix N. The positional resolution is calculated to be ±0.01” based on the steps per revolution of the motor and the total gear reduction including the planetary gearbox and belt drive. These two metrics more than satisfy the desired design constraints of a 5 lbf tool loading/unloading force and positional resolution <.06”.

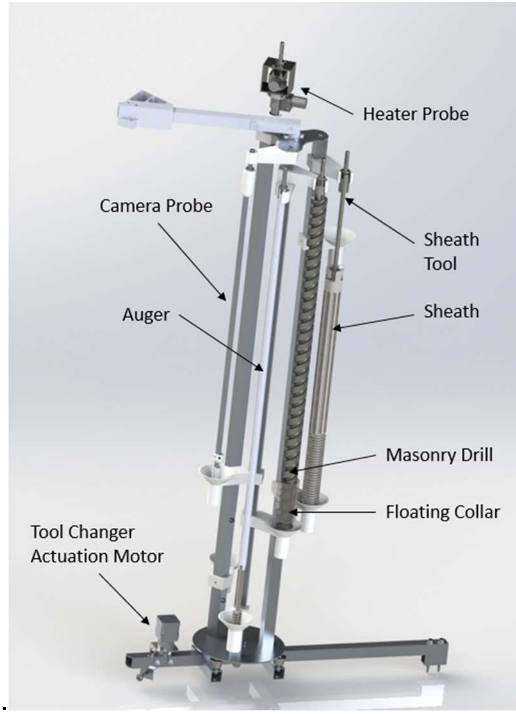


Figure 22. Tool Changer Assembly with Tools

5.5 Drill Bit

The first step in the water extraction process is to drill through all layers of overburden and into ice. This step will be performed with a 1.5” masonry drill bit. Initial testing proved that the carbide-tipped masonry bit was effective at penetrating hard, solid materials such as concrete, as well as soft, loose materials such as dirt and sand. Test data is located in Appendix E. The drill is designed to penetrate 1 inch into ice, then stop. The drill diameter choice was driven by the necessary features on the sheath, which will be discussed in 5.5.

Figure 23. Drill with Floating Collar

The drill bit is manufactured using three components. The drill bit purchased for this project is longer than the competition rules allow. This was necessary to achieve the required flute length necessary to be compatible with a new alignment collar system. The end of the drill bit will be cut to remove the SDS-max type spline and a custom-designed adapter incorporating an SDS+ spline will be welded on to interface the drill bit with the rotary hammer drill.

As mentioned above, an alignment collar system will be used to ensure the drilled hole is started at the expected location on the X-axis and is made as straight as possible for subsequent tools to easily interact with the hole axis. Though this collar system serves the same purpose as the bushing system described in the concept design phase, this new implementation is two piece design that can accommodate the true drill bit geometry. The collar system consists of a floating collar that is radially constrained against the flutes of the drill bit. It is frictionally constrained axially using magnets so that gravity alone or small bumps will not move the floating collar, but being pressed inside a stationary collar will allow it to move as the drill plunges. The stationary collar will be mounted to the Z-axis frame so that it is permanently aligned with the drilling axis. It is large enough to allow the largest tools through the opening, but small enough that it helps locate other tools like the sheath without needing subsequent floating collars.

5.6 Sheath

After the drill bit is retracted from the hole, the sheath is hammered in. The sheath tool consists of two parts, the carrier and the sheath. The carrier is held in the chuck of the rotary hammer drill, and it in turn holds the sheath. The carrier has three dowel pins that line up with three slots in the top of the sheath. Rotating the drill locks the carrier into the sheath, allowing the drill to hammer in and pull out the sheath from the hole. The sheath has two distinct outer features. The outer diameter is 1.5” to be a tight fit in the drilled hole. At the bottom, a coarse thread is cut into the sheath to help constrain it vertically within loose dirt. The top features are fins that constrain the sheath from rotating while the auger is working inside of it. The size of these features were determined by informal testing of a 3D printed prototype and a smooth pipe. Testing showed that the features do help resist rotation and axial motion, but were not large enough on the 3D printed prototype to adequately resist the forces expected during augering.

Finally, a row of holes down the length of the sheath act as view ports for a camera that is intended to look out and determine the composition and thickness of various layers. These holes are clocked intentionally on the sheath with an asymmetric feature at the top for alignment purposes. The final design is shown in Figure 24.

Stress analysis was performed to ensure the sheath and carrier will be strong enough in torsion to withstand a drill stall torque load case with a factor of safety >2. This analysis is found in Appendix N. Additionally, FEA was used to simulate maximum pull-out loading conditions through the dowel pins and interlock slots and were found to have factors of safety >2, as shown in Appendix N.

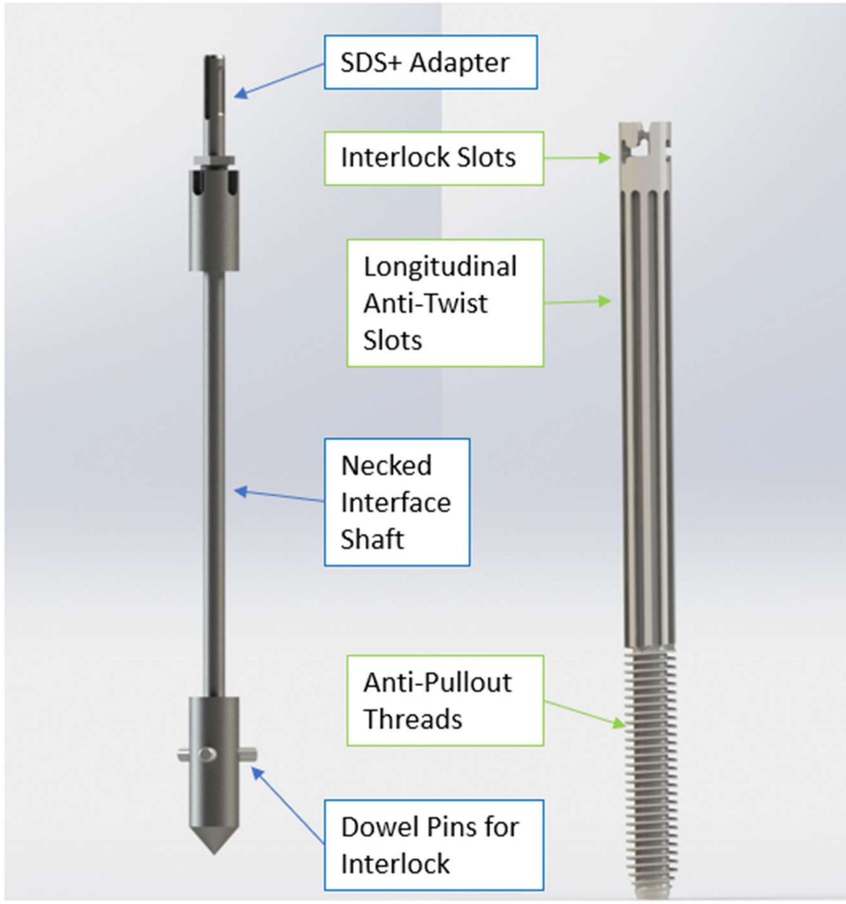


Figure 24. Sheath Carrier (left) and Sheath (right)

5.7 Auger

The auger is used to clear the inside of the sheath of loose material to make room for the heater probe. The final design has flutes running only 3 inches up the shaft due to manufacturability constraints, as shown in Figure 25. This means that the auger will likely take multiple plunges to fully clear out the hole. Flute geometry was driven by ease of manufacturing and expected debris sizes derived from drill geometry. No geometry larger than 0.15” in any dimension is expected and the flutes have a width and depth in excess of 0.18”.

Stress analysis and FEA were performed to validate the final auger dimensions. Both the hollow shaft and the solid auger tip core dimensions were driven by torsional loads in a drill stall scenario. These calculations are shown in Appendix N.

The auger is composed of three separately machined parts. The fluted tip will be machined separately and welded to the shaft. An SDS Plus adapter will be welded to the other end of the shaft so that it can interface to the drill. The auger will be used in ‘drill only’ mode to prevent damage, although it is expected that the tool should be able to handle ‘hammer drill’ mode if it is determined necessary during testing.

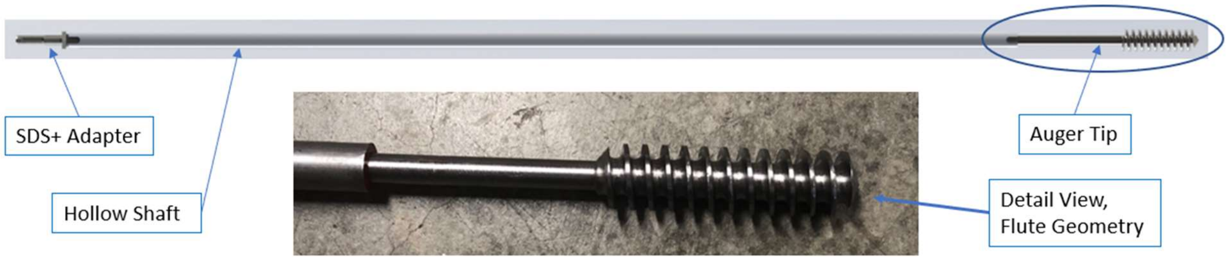


Figure 25. Auger

5.8 Camera Probe

The camera probe is designed to enclose a small wireless camera and a 45 degree mirror to see out through the holes in the sheath. The camera has integrated LEDs and will stream the view to an operator's phone. The structure of the probe consists of 3D printed parts, an SDS Plus adapter, and a square tube. The top 3D print part shown in the figure below has asymmetric dowel pins that match slots on the sheath. The mating of these features will ensure the camera view aligns with the holes in the sheath.

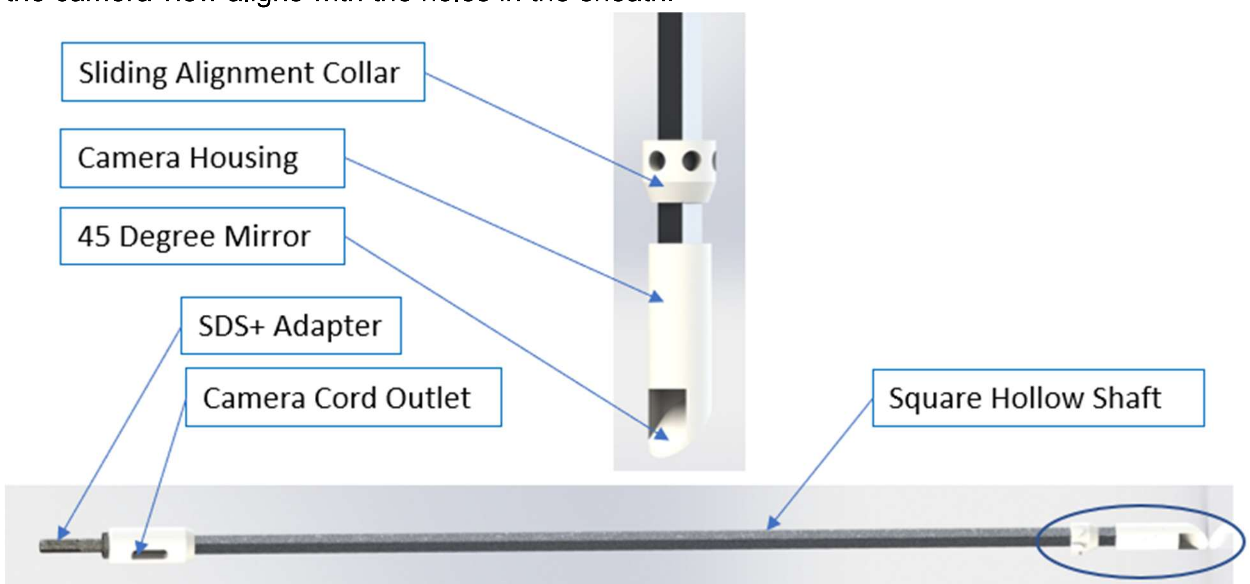


Figure 26. Camera Probe

5.9 Heater Probe

The heater probe has seen a few changes since conceptualization. First, the shaft and heating tip have been reduced to 0.75" diameters. Minimizing this dimension allows for a smaller drilling hole, thus saving on time spent drilling and overall system mass. The copper heating tip is 7" in length, allowing a 14" diameter half-sphere of water to be extracted. In order to increase positional resolution and decrease power usage, the two actuating stepper motors were replaced with worm drive DC motors with encoder feedback. The worm drive setup provides significantly increased torque and allows the copper heating tip to maintain its position without requiring the motor to be powered.

The heater probe contains two thermocouples. One monitors the heating element in order to avoid burning out the element. The other monitors the entrance of the water suction line to ensure that the suction line is not frozen shut. There is a possibility that the collected water at the bottom of the melt zone would have time to re-freeze while the heater probe is in an actuated position, blocking its path back to the vertical position. The thermocouple at the straw inlet will be able to determine if the water is below the freezing point, letting operators know to be more careful when retracting the heater probe.

To ensure the heater probe is robust within an extremely small package, several calculations were performed to make sure operating methods were compatible with mechanical constraints. One example of this is how to determine that the heater tip has reached full actuation. Because there will inevitably be stretch in the kevlar string, position feedback will not tell the whole story. While position feedback data from the actuation motor is recorded, this information will mostly be used for approximating an actuation angle based on test data. The solution for this inaccuracy is to actuate the tip until stall, continue heating, and then actuate again. If no more travel is achieved, the heater tip is likely stalled against its own shaft, as it was designed to make contact at precisely 90 degrees. The same methodology can be used for retraction. As a result of this operating method, it is necessary that nothing be damaged when stalling in both directions. It is also necessary that excess torque is available at the maximum actuation angle to be sure that motor power is not a limitation or that the strength of the kevlar string is adequate. Calculations supporting these capabilities and FEA supporting stress margins at stall conditions are shown in Appendix N.

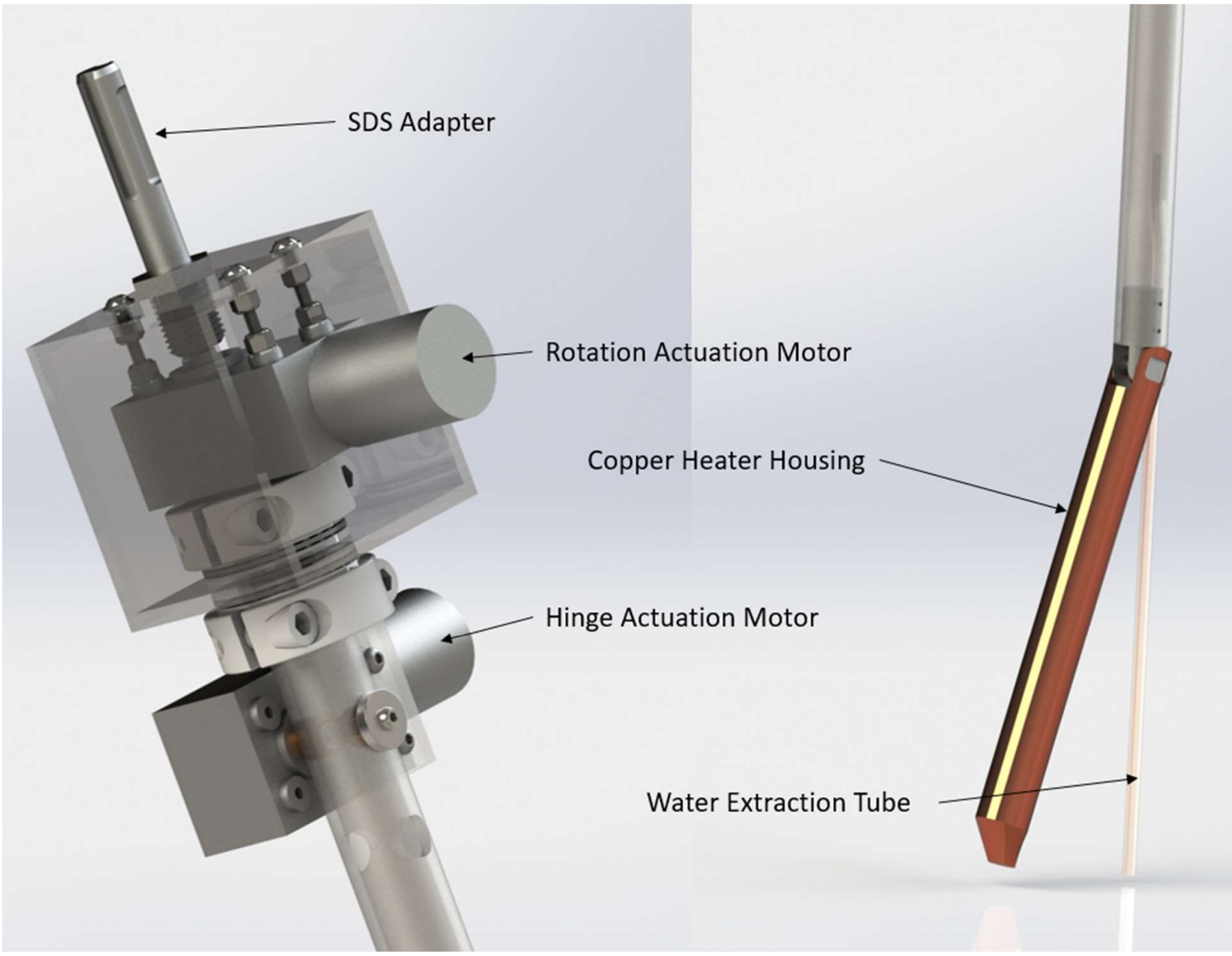


Figure 27. Heater Probe

5.10 Water Processing

This subsystem starts within the heater probe, and ends where the clean extracted water is deposited for weighing. The small stainless steel tube in Figure 27 remains stationary while the heater probe actuates. A peristaltic pump creates suction in this tube, drawing up water into 3/16" ID flexible silicone tubing. The flexible tubing is necessary as the heater probe can move while the pump and filters remain stationary on the frame. After the water is drawn up and out of the hole, it flows into a sediment trap. Here, flow velocity slows down as flow area increases. This gives large solid particles in the water the chance to fall to the bottom of the sediment trap. The water then continues through a 40 micron stainless steel mesh to the pump. Also connected to the sediment trap is a ball valve. In the event that the sediment trap fills with solid material, the valve can be opened, allowing the sediment to fall out.

After the water flows through the peristaltic pump, it is pushed through the secondary filter. This is a 5 micron, sintered bronze filter that was manufactured and sponsored by Capstan California. This filter is fully backflushable. In the event that this filter or the primary filter clogs, two pressure sensors, placed before and after the pump, will tell us which filter is clogged so that action can be taken to reverse flow and backflush the filters.

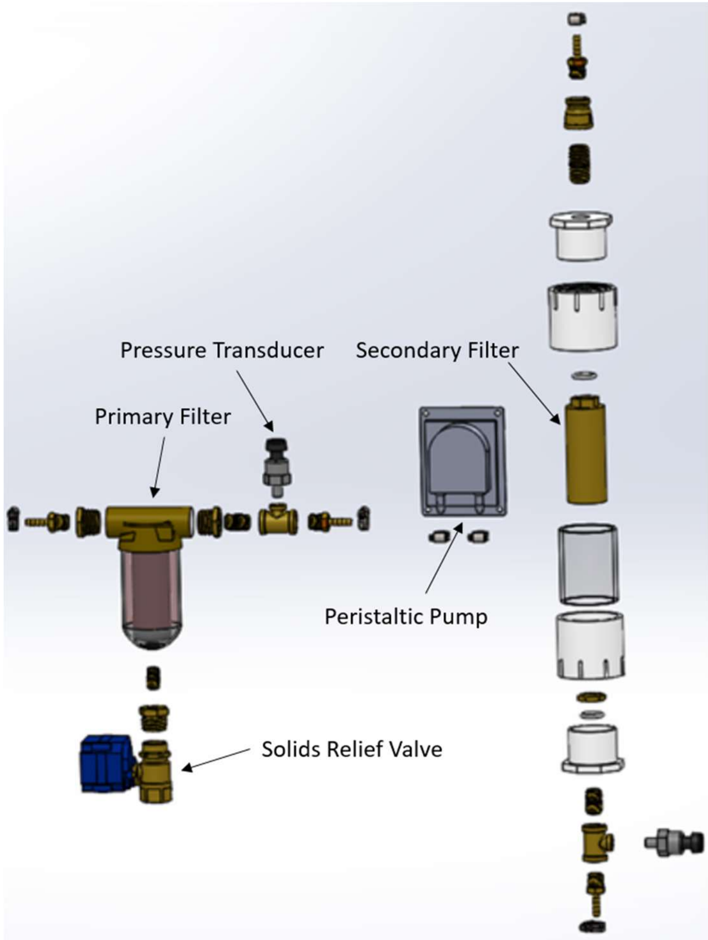


Figure 28. Exploded view of the filtration/pumping system. Pictured left to right are the primary filter with drain valve, peristaltic pump, and secondary filter.

Head loss through each part of the system was calculated to verify that the desired flow rate could be achieved through each filter, and that the pump could supply both the necessary suction and discharge pressures. These calculations can be found in Appendix K. Mounting locations have not yet been determined for these components, but the available suction head allows the components to be placed anywhere on the frame.

5.11 Electrical Equipment

The prototype consists of three main electrical sections. 120V AC is used to power the drill and the heating element. 120V AC will be provided for the prototype to run on. The device will contain two other power levels; 12V and 5V DC. These will be transformed by two separate power supplies from AC power. The 12V system will be used to power stepper motors, DC motors, and the electronics cooling system. The 5V system will be used for small servos. Figure 29 shows the wiring diagram for the system. The power budget for the system has not changed appreciably and Table X.X remains accurate.

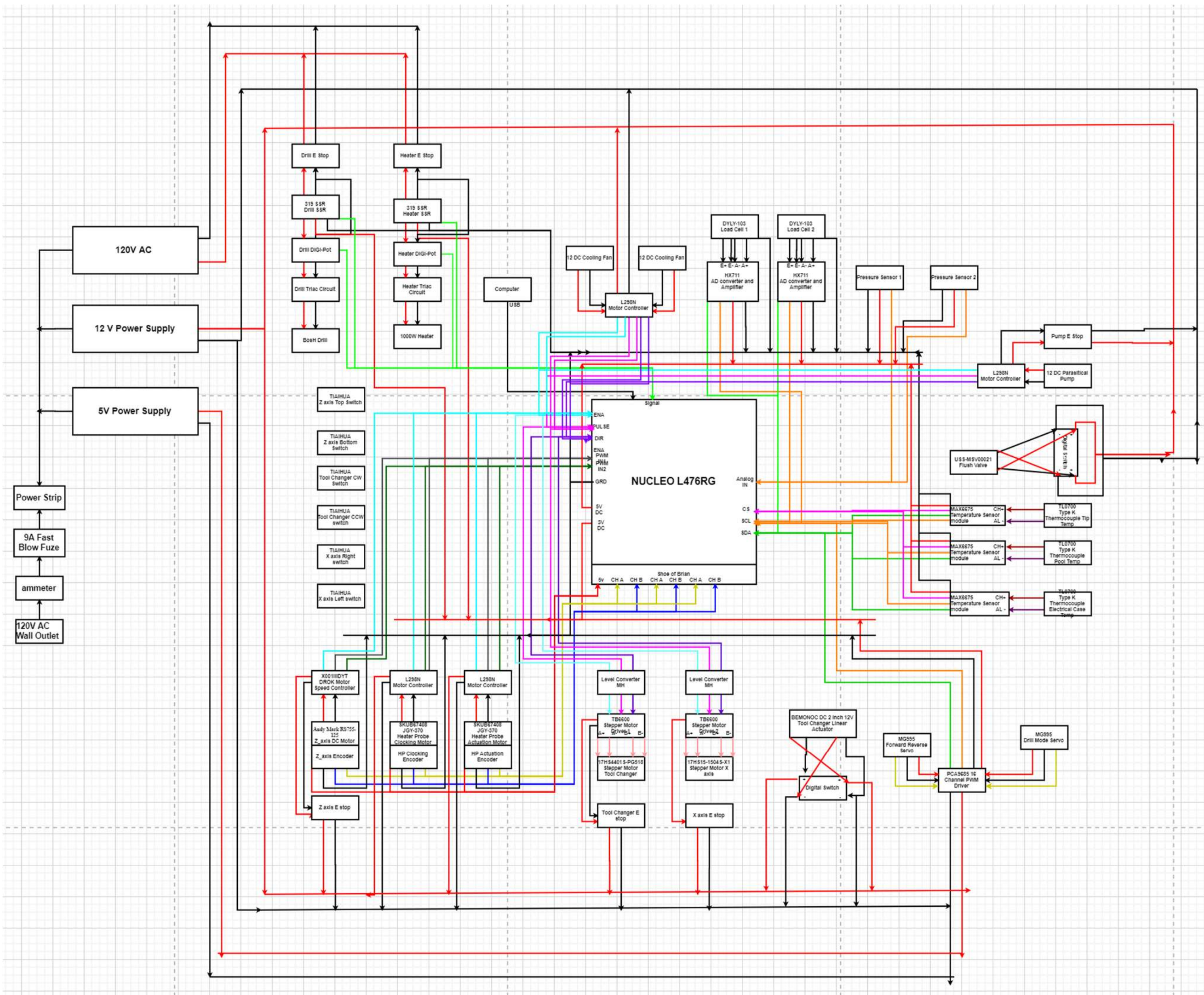


Figure 29. Wiring layout for All Systems. See Appendix O for enlarged.

Routing the electrical wires to the correct locations on several different moving components proved to be slightly complicated. The cabling and service locations necessary is tabulated in Table 19. Figure 30 shows an image of routing paths. Several components do not need to move relative to the frame and their cabling will simply be routed and zip-tied via stationary frame components. For cables that need to move relative to the frame, a drag chain was selected to get the cables from the electrical box to a point on the X-axis gantry. Cables that need to move with the Z-gantry will be routed through another drag chain that is oriented vertically, mounted on the X-axis gantry. Cables that only need to move with the X-axis gantry, as well as cables that need to interface with tools, will be routed through the X-gantry square tube frame. Wires and tubing to tools will exit from the very top of the machine and be routed to their respective tools with long springs providing and taking up slack as necessary.

Table 19. Wire/Tubing routing

Termination Location	Services Routed

Frame	X-axis endstops, X-axis motor, tool changer motor
X-axis gantry	Z-axis end stops, Z-axis motor
Z-axis gantry	Drill power, 4x Drill control servos, 2x load cells
Heater Probe	1 Tube, 2x thermocouple leads, heater power, 2x motor/encoder wires,
Camera Probe	Battery power, Camera snake

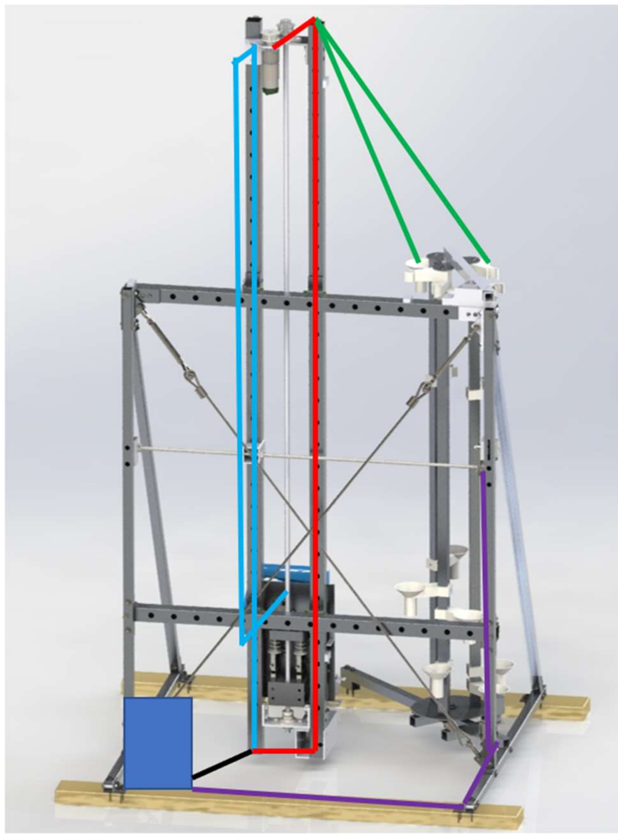


Figure 30. Wire Routing for Prototype. Purple indicates frame components. Red indicates x-axis gantry, heater probe, and camera probe. Green indicates heater probe and camera probe. Blue indicates Z-axis gantry.

5.12 Programming

The programming is being completed on micropython. This language was selected because of its potential to rapidly generate functioning systems without sacrificing too much direct access to features on hardware. The microprocessor being used is the NUCLEO L476RG and was selected for its superior number of pins, with over 70 being available on this model. A drawback of the NUCLEO L476RG is it natively compiles code in binary, which is not ideal for micropython. To get around this the professors in the mechatronics department at Cal Poly designed a Printed Circuit Board (PCB) to allow programs to be flashed onto the board. The components of the PCB were soldered on by a novice PCB manufacturer and are prone to disconnection errors. Additionally replacement PCBs need to be ordered and manufactured as spares.

5.12.1 Programming Design Features

The prototype requires that many closed loop operations be running simultaneously: such as closed loop position control with encoders, closed loop load control with the load cells, and closed loop heater control with the thermocouple. To achieve the functionality of closed loop operation and also be able to issue commands in a procedural fashion a task scheduler was implemented. Every significant system gets its own task that is addressed as quickly as specified by the programmer. To allow many different tasks to be issued commands simultaneously, an operations task was implemented. This task assigns key values to shares or queues that each task is monitoring separately. When a queue or share is modified, the task that is monitoring that queue or share jumps into action for a millisecond and then yields its state. The task doesn't stop operating until some monitored parameter is reached. The task will then either set a done flag and change state to paused or the operations task will be directly monitoring the critical parameter and send a pause command through a share or queue. Figure 31 shows the task structure. Additionally there was not enough timer channels to control all components on one board so a micropie board will be used in series with the NUCLEO to control the filter system and remaining components. UART protocol and key words will be used to communicate between the boards. Commands for teleoperated control will be issued through UART to the NUCLEO and then either addressed or relayed to the secondary board.

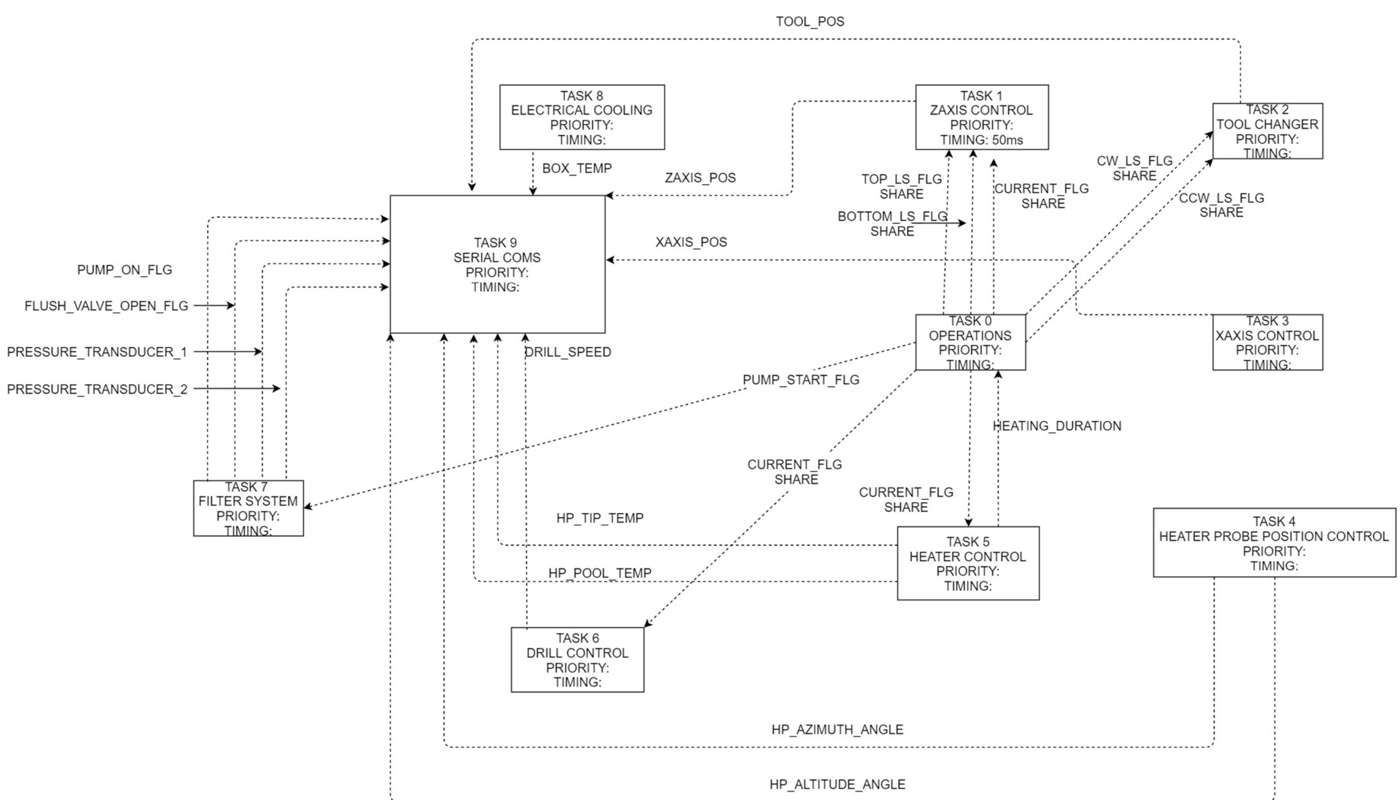


Figure 31. Task Diagram for STYX Prototype

The state diagram structure is still being developed as challenges and compromises are being made when the actual code is being written. A comprehensive list of operations that the bot will need to undergo has been created in a flowchart form and is shown in Figure 32.

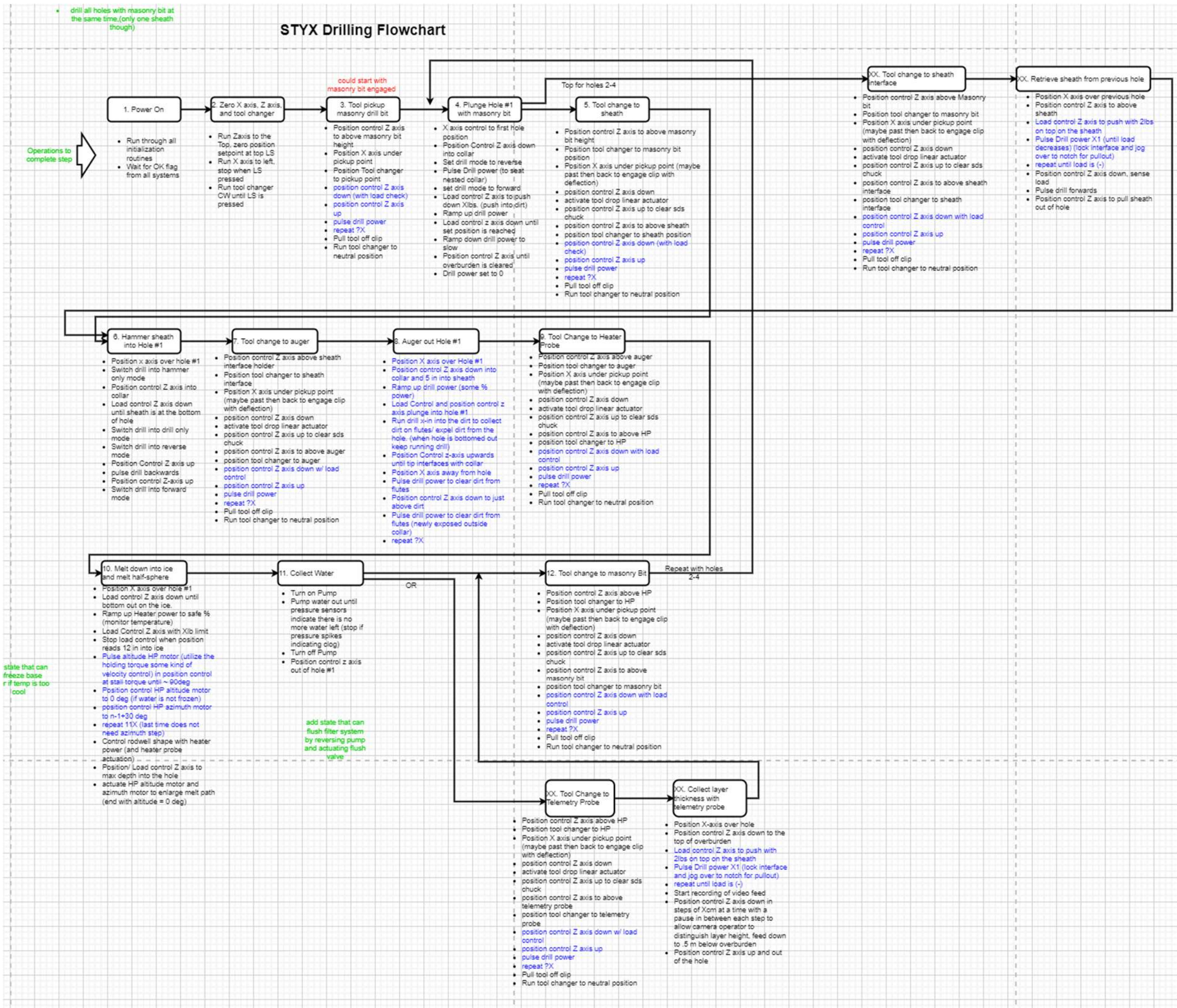


Figure 32. Flowchart of Operations to Complete Competition. See Appendix P for enlarged.

5.13.2 Programming Development Schedule

The programming schedule is driven first and foremost by the competition date and secondarily by the programmer’s availability with class and work. Table 20 displays the tentative design schedule.

Table 20. Programming Development Schedule

Goal	Date
Program Z axis task	5/18/20
Program operations task to change closed loop types cooperatively	5/23/20
Program load cell task	5/28/20
Program serial communications protocol	6/2/20
Program load cell data processing script on computer	6/7/20
Program drill control task	6/12/20
Program servo control task	6/17/20
Program heater control task	6/22/20
Program ammeter safeties and limit switch safeties	6/24/20
Program pump and filter tasks	6/27/20
(If time) program joystick control	tbd
Program complete testing commences	8/10/2020
Competition in Langley	8/31/2020

5.13 Safety, Maintenance, and Repair

Because of the electromechanical nature of the project, the requisite use of 120VAC power, rotating parts, heating elements and other hazards, considerable effort has gone into documenting potential hazards and mitigating risks. Also because of the need to perform at competition, maintenance and repair plans have been drafted for preventative use before competition and use at competition in the event of a component failure.

5.13.1 Safety Plan

During the design and build phase of the project a set of hazards specific to STYX operations were compiled into a safety plan, which were determined using the design hazard checklist in Appendix Q. The list and relative severity of hazards were assessed using several methods including FMEA and risk assessment software. The results of these are in Appendix R. The resulting safety plan table is included below. PPE requirements include safety glasses, face shields, dust masks, and hearing protection.

Table 21. Safety Plan with Corrective Actions

Description of Hazard	Planned Corrective Action
Revolving drill bit	- Competition rules prohibit touching the device while it is in operation - Stay >3 feet away from rotating components - Remove any clothing/items that may get caught in machinery before operating
Falling Weight Hazard	The use of lead screws will keep heavy moving components in place in the event of a power failure.
Sharp edges	Drill bits will be contained in sheathes during transportation Drill bit tips will be fully encased while in the tool changer.
High voltage electrocution risk	All high-voltage circuitry will be approved by faculty before use. All devices will be properly grounded and insulated
Loud noise during drilling operation	Use earplugs during hammer drilling procedure.
Burn risk from heaters and drill bits	All component temperatures will be checked with IR thermometer to verify <40°C before handling
System is used in an unsafe manner	System will only be operated by designers. Designated group members will be specially trained.
Pinch points	All motion components will be de-energized before handling the system.
Tipping hazard	Connect the frame to the mounting rails provided at the competition before installing heavy subassemblies
Required emergency stop	- A physical kill switch will be accessible on the control station and the robot, in case an immediate shutdown is required.

5.13.2 Maintenance Plan

During testing and competition, regular maintenance will have to be performed to keep STYX running smoothly. The parts that will need the most attention are the water system, heater probe, tool changer, and linear rails. Basic operational maintenance such as cleaning, and lubrication will be the most common type of work done on the machine.

After each use of the water system, it will have to be cleaned and dried. First clean water should be run through the tubing and filter system, both forwards and backwards, to dislodge any stuck dirt. Next both the primary and secondary filters should be removed, scrubbed in clean water, and dried. Allow as much airflow as possible through tubing to avoid any moisture left in tubing during storage. The heater probe may have particles stuck in its water extraction tube, and compressed air can be used to remove them. Any dirt stuck on the hinge mechanism should be brushed out, and if the string is dirty, it should be removed and replaced before the next official operation of the machine. The tool changer's belt drive, 3D printed brackets, and positioning need to be inspected to avoid misalignment of tools during operation. The linear rails need to be brushed clean and lubricated after every use to prevent rust accumulation and ensure consistent feed pressure.

5.13.3 Repair Plan

During competition accidents can happen and parts can break. To be able to successfully finish the competition, a repair plan has been thought through. Extra parts and hardware will be brought to competition, but we can't bring replacements for all of our parts so we have decided on some essential tools and hardware that we should have to be successful.

For replacement parts, we plan on having an extra drill, an extra five micron water filter, extra 3D printed brackets, and a small selection of extra hardware. Tools specific to our hardware will be selected ahead of time and sent with the robot to competition. In previous years some teams brought 3D printers to manufacture spare parts. While this seems to be a good solution for physically small and relatively low load parts, we are still discussing the merits of this solution.

5.14 Cost Analysis

All components that are utilized within the prototype have been purchased. These components cost a total of $,4155.91. This figure omits duplicate purchases for items deemed viable to break or otherwise need replacement before or during the final testing at competition. This is strictly the material cost to build one complete prototype. The breakdown of this cost by subsystem is presented in Table 22, and the breakdown by component is shown in Appendix S. Project funding has also been spent on testing equipment. Concrete, buckets, and wood were purchased in order to run tests on the system. More of these purchases will be made in the future as the project moves forward into full-system testing. Due to the recent closure of the Cal Poly machine shops, some tooling was also purchased so that manufacturing could be completed with outside help. As of 6/13/2020, the STYX team has spent $5,930.75 of its $14,983.85 budget.

Table 22. Prototype Material Cost by Subsystem

Subsystem	Cost
frame	1134.13
electrical	182.44
tool changer	285.29
water processing	418.15
heater probe	263.07
camera probe	79.31
drill mount	581.44
drill bit	185.19
auger	83.60
sheath	249.99
PLA	40.00
Tax	253.94
Shipping	399.36
Total	4155.91

6.0 Manufacturing

Manufacturing for a project of this magnitude is challenging for many reasons. The sheer number of manufactured parts, organization of procurement, tolerance inspections, opportunities for error, and above average complexity have made this portion of the project the most time-consuming. Restrictions on machine resources due to COVID increased these hurdles, costing additional lead-time in procurement, redesigning for reduced manufacturing capabilities, and remote work slowing team cooperation. Despite this, the manufacturing aspect has also been the most rewarding and we are continuing manufacturing efforts to finish the competition prototype in time. The strategies this team is using for procurement, manufacturing steps, and coordinated assembly are detailed below.

6.1 Procurement

All standard metal stock was purchased through Onlinemetals.com. Hardware, including fasteners, bearings, lead screws, and piping, were purchased through McMastercarr. Electronic equipment, including stepper motors and pulleys, motor drivers, DC power supplies, the hammer drill, and a water pump, were all purchased through Amazon.com. Capstan California offered to sponsor the project, and supplied the project's sintered bronze filters for a reduced cost.

In addition to acquiring raw stock materials, outsourced labor became necessary due to COVID-19's impact on campus resources. After the machine shop's closure, manufacturing of all tooling has been outsourced. An acquaintance of one of the team members has agreed to manufacture several components requiring power tool access. These include the heater probe, sheath, auger, and drill bit interfaces. The manufacturing will take place in a private, recreational machine shop and team member Ryan has been appointed as the direct contact for any manufacturing issues or design interpretation questions.

6.2 Manufacturing Steps

Manufacturing of the entire system is being completed in two distinct phases. The first phase contains all of the general framing and motion components. This is the frame, X and Z-axis motion equipment, and the tool changer. This phase was completed in early March. The second phase contains all of the tools the device uses, as well as tight-toleranced parts used to constrain the tools during use. This phase is currently in progress, and is set to be completed by the end of May. A compilation of part drawings are in Appendix T.

During the first phase, the majority of framing pieces are manufactured from aluminum square-tube that is cut to length, drilled for hardware, and mounted to other framing components with bolts. The design called for a high necessity of joint stiffness, so oversizing bolt holes to allow for slight misalignments was not an option. Since some frame members are multiple feet long and require precise hole spacing across its entire length, the team took advantage of match drilling to avoid the possibility of misalignment. Although this process takes longer than making a part directly from a drawing, it eliminates the possibility of stacked measurement errors, and greatly decreases the chance of two parts not fitting together properly. This process was especially necessary for mounting the linear rails.

The framing phase also contains a few welded features. These features are the brackets that hold the cross-tensioning cables, and the bottom plate of the tool changer. For easier alignment for welding, a waterjet was used to cut features into the tool changer plate that constrains the three vertical members both positionally and rotationally against the plate. The top plate could also be installed on the three vertical members before welding to ensure the tubes remain perpendicular to the plate. This part is shown in Figure 33. The four cable brackets required a T-joint weld to connect the cable ends to the frame. These welds did not require any alignment features, as the cable’s turnbuckle allowed for proper tensioning should the distance between brackets not be exactly right.

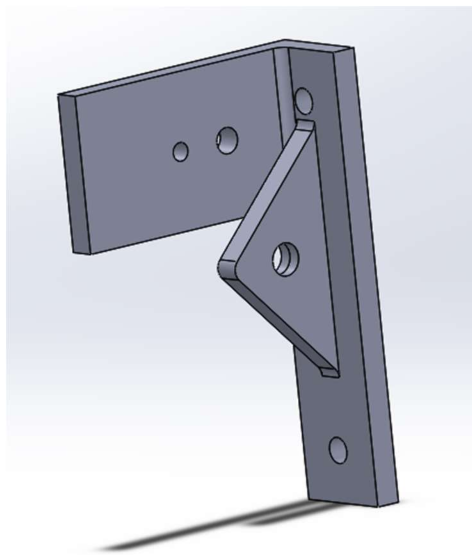


Figure 33. Welded Cross-Tensionsing Cable Bracket

The second phase of manufacturing consists of high tolerance and complex parts. Each of these parts require the use of a mill or lathe, and contain at least one feature that needs to be sized or located precisely. Unfortunately, COVID-19 significantly reduced manufacturing capabilities. One external machinist with access to a small mill and a small lathe became available, but the reduced capability of these machines drove late-stage design changes on some sub-systems, especially tools. Detailed consideration of fixturing methodology, maximum part dimensions, imperfect tooling, and reduced tolerances became critical. Daily meetings were necessary to mitigate many of these issues.

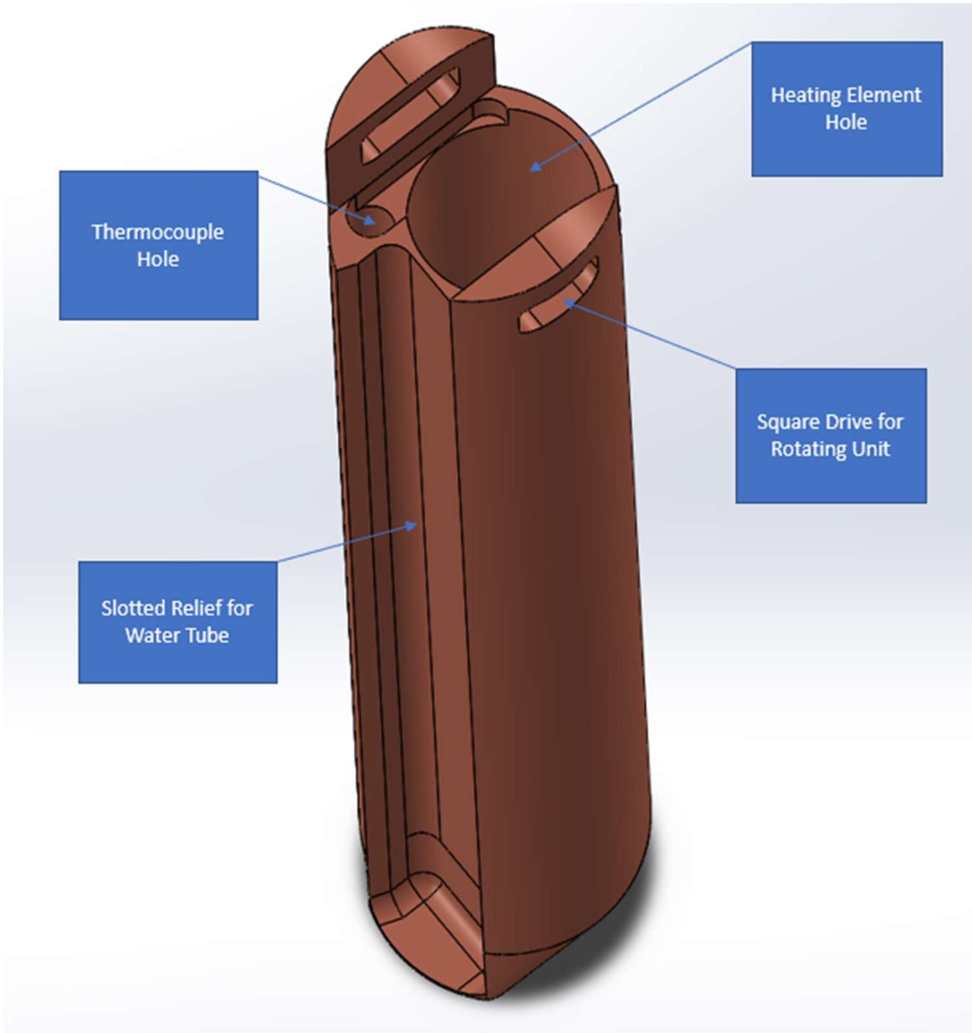


Figure 34. Copper Heater Jacket Annotated

The first of these parts manufactured was the copper jacket shown in Figure 34 that holds the heating element and allows it to rotate outward. Due to constraints on available equipment, many manufacturing steps had to be added in order to complete the part. This part required four milling setups and two turning setups. This part contains an offset 0.5” hole for holding the heating element, an external slot to fit the water straw, a 0.125” hole to accompany a thermocouple for monitoring heating temperatures, and two square holes that allow the jacket to rotate on an axle. The 0.5” hole required an aircraft length drill bit to achieve the 6” required depth. A fixture was manufactured to achieve the desired hole offset while boring with a lathe. This method of boring proved to be effective in properly aligning the drill to the desired location and minimizing part runout, as the wall thickness is only 0.020” for the entire depth.

The rest of the components of the heater probe were manufactured under similar conditions, with the one exception being the steel shaft which required a weldment. Every other operation for the steel shaft, knuckle, and axle, were straightforward turning or milling operations. The square ends with rounded corners on the axle were achieved on a manual mill using a time-consuming process of 20 serial plunge cuts at each of the 8 corners. A light sanding was required to fit the axle to the copper jacket. A substantial amount of filing was required on the knuckle to ensure that the lifting string would not fray on a sharp edge. These rounded edges could not be achieved on the mill.

The sheath, sheath tool, drill bit interface, and drilling collars will all be manufactured with the same equipment used for the heater probe. These parts do not require any specialized tooling.

6.3 Assembly

Component assembly for this prototype is generally divided into three groups: big picture considerations, complex subassembly construction, and common construction methods. The big picture considerations of assembly will be discussed in the following section. The complex subassembly nuances will be covered within the operator's manual in Appendix X, along with other important cleaning and operating discussion. These include subassemblies such as the pump/filtration and heater probe components. Other subsystems not mentioned in Appendix X should be gleaned from the CAD model provided, including hardware sizing. For a prototype with over 1000 parts, we believe a combination of these three communication methods will be most effective.

Due to manufacturing tolerances, errors, tool access issues, and other sources of imperfection, assembly also will be imperfect for this prototype. Through many rounds of assembly and disassembly, it has become clear that consistency, rather than perfection is more important. While the frame may not have perfect right angle joints, the features that matter are the position of the tool changer relative to the gantry’s motions, the drill being trammed perfectly with the stationary collar, and the best alignment possible for the Z-axis motion components. Each of these issues are annotated in Figure 35. Liberal application of shim stock is not encouraged, but accepted as necessary for this first-attempt prototype.

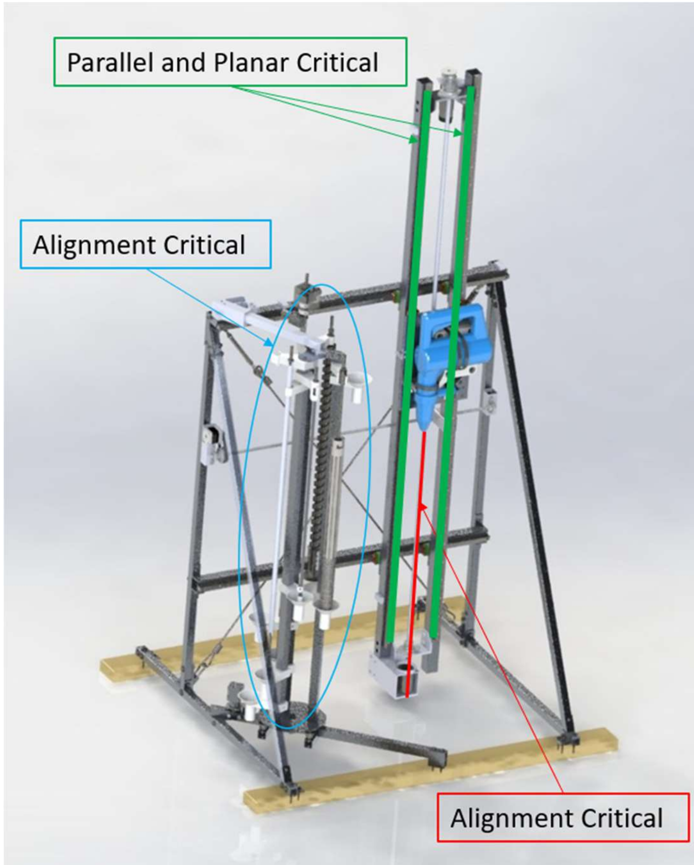


Figure 35. Critical Assembly Characteristics

Having consistent alignment of the tool changer relative to the gantry motion is critical to ensure tool changing occurs as expected. While it is possible to adjust across a certain range of misalignment using software, unexpected side-effects such as increased tool clipping/unclipping force may be an unfortunate result. The easiest alignment method for the tool changer is to manually load a tool into the drill and jog the drill to the expected tool change location, adjusting the tool changer to match before tightening all fasteners.

The drill being well-trammed is critical because the drilling strategy employed by STYX requires repeatable hole generation and locations. If the drill is not perfectly aligned with the stationary collar meant to guide the drill bit as it begins the plunge, stresses will be imparted to the drill bit and frame as the tool rubs, or the hole may be in a completely unforeseen location, with subsequent tools failing to reach the necessary destination.

Finally, the Z-axis motion components are critically toleranced due to the effects misalignment has on the load cell readings. Binding caused by non-parallel and/or non-planar linear rails is immediately measurable and unpredictable over the full range of motion. Failure to verify that binding forces are minimal before competition or calibration would likely result in a failure to meet the specified project requirements.

6.4 Lessons Learned

Having such a large project and working through some unprecedented challenges has provided several lessons that may be valuable to future teams and potentially future employment. Several of these are listed below.

1. Despite being advised to triple manufacturing time estimates, it is always advisable to triple them again. In this team's experience, the first tripling accounts for inexperience, unforeseen issues, or tooling limitations, while the second tripling will account for unpredictable workloads in other classes stealing time from senior project work.
2. If outsourcing work, leave enough time to seek a second source if a primary falls through. In addition, it is critical to assign a single point of contact from the team that is completely knowledgeable about the components and design implications so that on-the-fly questions and modifications can be accommodated.
3. Design parts to be manufactured using the simplest possible means. Don't waste time making parts overly precise or using an overcomplicated machine to produce a simple part. Buy the correct stock size every time; turning off ½" diameter of steel wastes time and kills morale.
4. Be understanding that people have different levels of experience and different notions of what 'quality work' means. Assume the best of people and if the part produced works, leave it at that.

7.0 Design Verification

In order to verify specific aspects of the STYX machinery the STYX team developed a set of necessary tests. The following section briefly covers each test specification and provides a brief description of the necessary tests. Some of these tests were completed and the results are briefly discussed. Testing specifications and a general test plan are included in the STYX DVPR included as Appendix U. Each test also has a set of designated testing procedures and plans, including a section to record desired results. These testing documents are included as Appendix V.

a. *Mounting: Frame and Lid Interface*

Stability testing during extended drilling is currently the only required and planned test for the framing system. This test hopes to confirm sufficient structural strength and stiffness of frame members, joints, and mounts. This test will involve observations of the frame under drilling operations as well as a check of all joints, fasteners and members following drilling operations. After pretensioning the cables, the frame became much stiffer as observed through inspection. When the drill was running at full speed there was no nodal frequency excitation and little shaking.

b. System Control

The control system has multiple safeties designed into it. The first is limit switches on the X-axis and Z-axis linear motion systems to prevent a crash into the frame or overburden. Next, ammeter sensors will be added into the system to allow for pre-emptive shutoff in the case of power overdraw. Thermocouples will be connected to the heater to prevent overheating, and temperature will be monitored such that power can be adjusted accordingly. In the case of a loss of connection while drilling, two emergency stops will interrupt power; one by the remote operator and the other on the machine. Exceptions will be included to allow programmatic pause if serial communication is lost. The task timing will be handled by a task scheduler and testing will ensure our latency does not exceed the limits required for stable closed loop control. A manual override platform will be created to allow each component to be easily moved in the case of autonomous system failure, but the goal is an entirely autonomous drilling, extracting, tool changing, and filtering operation. These control and safety systems will be repeatedly tested in all operating modes.

c. Excavation: Drilling Operations

The STYX team has already conducted sufficient testing to prove that the selected drill is capable of penetrating through all types of potential overburden. This testing was completed in the early phases of the project utilizing a set of masonry bits, and is documented in appendix E. Using a rudimentary initial frame, the team was able to penetrate through layers of dirt, sand, concrete and rock material using only the weight of the drill and no other downward force.

Several tests remain for the excavation system including a sheath test and auger test. For the sheath test the team hopes to confirm proper insertion and removal of the sheath can be accomplished without exceeding the WOB limit using both percussive and standard drilling techniques. Several sheath iterations will be tested with various teeth designs for sufficient locking. For the test, the team will insert each shaft into varied material bases noting the difficulty and force necessary for insertion as well as the relative hold that teeth provided when embedded into a base. No testing equipment will be utilized for this test. The team will also test hole sizing for the sheath windows that will prevent material collapse but still allow the telemetry probe to identify layers. This test is described in appendix V and will iterate various hole sizes noting the relative material collapse for each shaft. The test will also confirm the hole sizing sufficient to prevent hole collapse is also large enough to resolve layers of material using the camera.

For the auger test in appendix V the team aims to prove structural stability of the auger itself during operations, as well as functionality of the auger and its ability to remove pulverized material up the sheath. Both of these specifications can be verified during observation of operations without testing equipment.

d. Rotary Tool Changer

Testing of the 3D printed tool clips for the tool changer subsystem has been completed, with various iterations of similar designs being tested for adequate strength under tool changer depression. Ultimately a design was chosen to be lightweight yet still withstand the force required for release or pickup of different tools.

The next necessary test will test the chuck depressing system to ensure the tool changer can properly engage and disengage the drill chuck allowing the tool changer operations. For said test, listed in appendix V-12, the team will repeatedly command the tool changer to continuously rotate through tools confirming proper engagement as well as disengagement. No testing equipment outside of the STYX unit is necessary. The second test will determine the relative accuracy of the programming control of the rotating base ensuring adequate alignment for tool changing operations and reliability of rotary actions. This test can be completed via a programming test, repeatedly inputting a command motion and measuring the locational accuracy of each trial.

e. Heater Probe

The motors driving actuation will need thorough endurance testing to ensure that they can be stalled for short periods of time without being damaged.

Additionally, the maximum melt rate of the tool needs to be tested. The maximum operating temperature has yet to be determined, but we expect it to be between 200C and 300C depending on future test results. For this test, described in appendix V-6, the group will utilize a testbed with a known ice layer to test the melting rate. The melted water can then be weighed to determine the mass of melted ice. This coupled with thermocouples, outputting heater probe temperatures, and a timing device will allow the team to deduce the maximum melt rate. The team also plans on conducting a motor tall endurance test. This will involve repeatedly actuating the probe to a 90 degree angle and noting the current that the motor stalls at.

Finishing the manufacturing of the heater probe, the team assembled the actuating components of the probe and were able to successfully actuate the heater arm by pulling the kevlar string.

f. Pump/Filtration System

The team conducted a simple initial test to prove functionality of the pump and dual filter system for the mid point review submission to NASA. The team assembled the pump and two filters in series. The team successfully pumped unfiltered contaminated water through the dual filter configuration and successfully removed all contaminants in the water.

Simple testing is required for the filtration system to ensure continual flow despite partial filter blockage. Both filters will be integrated in series to ensure nothing larger than 5 microns passes through the system. The test, shown in appendix V-4, will also tell us if a finer primary filter is required to avoid unnecessary clogging of the secondary filter. For said test the team plans to use dust or debris generated from drilling operations to pass through the filtration system. The team will then assess the degree of filtration in the same manner as the competition, first with a visual clarity test (requiring no equipment) and then passing the filtered water through an almond mesh bag and weighing the remaining sediment.

Both the inlet and outlet of the pump will be fitted with pressure transducers that will allow us to determine which filter is fouled first. Calibration and testing of the pressure sensors is necessary and is expected to take place before July.

g. Telemetry System

Although preliminary results look good, further testing will confirm the accuracy and precision of the Z-axis load cells. The current programming of the load cell utilizes a rough calibration constant determined in preliminary testing necessary for NASA's MPR and does not account for uncertainty propagation. Due to current delays regarding senior project's new rules and restrictions, the final test, in appendix V-7, will be delayed until approval is granted.

The other major test for the telemetry system will be the resolution and connectivity of the wireless camera probe and its ability to identify layer changes. This test will involve several group members, one group that creates a stratified test bed with known layer heights and a group that attempts to identify said layers using a live feed from a camera probe. An initial test proved the mirror attachment included with the camera was two clouded and scratched to resolve layers. The team will complete further resolution testing following the completion of a new mirror piece.

8.0 Project Management

In response to the COVID pandemic all Cal Poly students were officially moved to online learning following spring break. With the transition to online learning many students were forced to move home and all Cal Poly machine shops were closed. With students working from home a new set of rules and regulations were implemented halting any further progress with manufacturing, assembly and testing. Unlike many other groups who were unfortunately prevented from completing their project in entirety, STYX was able to find methods to continue progress. Group member Ryan was able to outsource manufacturing to a contact of his while observing all of the manufacturing processes. In order to effectively divide up work for the spring quarter the team re-evaluated team member abilities and responsibilities from individual perspective locations. The responsibilities of each team member have been tabulated below.

Table 23: Member Responsibilities

Alex	Primary	Hand-tool manufacturing, integration, hardware redesign, Purchasing, Travel planning, Test execution
	Secondary	Remote machining support, 3D printing, SP deliverables support
Ryan	Primary	Local machining support, Hardware integration support, Budget
	Secondary	SP deliverables support, Test execution
Aaron	Primary	Programming, software integration, weight-savings, software testing
	Secondary	Python onboarding, SP deliverables support
Chris	Primary	3D printing, test procedures, test stand design/build
	Secondary	SP deliverables
Westin	Primary	SP deliverables, Onboarding documentation, SP Website
	Secondary	Hand-tool manufacturing, test stand design
Teenie Weenie Incoming Genie-uses (TWIGs)	Primary	Drawings, Onboarding documentation
	Secondary	Design assistance, design familiarization

NASA responded to the pandemic by pushing the dates of the competition to later in the summer between August 31 - September 3. NASA also offered all teams three options for continuing on with the competition. The first option simply consisted of submitting a report and a video of your functioning machinery without traveling to the physical competition. The second option allowed teams to participate in a modified competition and specify their designs while removing a component or subsystem that was incomplete due to the transition to at home learning. The final option was participating in the full competition with the same requirements and assessment as initially presented by NASA. The STYX team decided to participate in the full competition.

In order to ensure progress on the project and keep all members updated on the project details the team will have weekly planned weekly meetings with all group members attending unless deemed unnecessary. Weekly status review meetings will occur every Tuesday from 10:30 to 11:00 AM PST, with project advisor Dr Schuster. For each WSR meeting a WSR document will be created for review with Dr. Schuster. Outside of WSR meetings and several designated class meeting times, the group will also meet via Zoom one day a week, Monday from 11:00 to 12:00 to go over responsibilities for the week. The team will utilize the same contract from previous quarters in regards to items like work responsibility and punitive measures.

With fewer face to face interactions, quality documentation of work has become a high priority. A frequently updated Gantt chart, as shown in Appendix W, helps track progress as well. The group also plans to increase the priority of onboarding documentation creation moving into the summer to ensure a smooth transition when this year's project is passed on to next year’s project team.

9.0 Conclusions

STYX has finished the main construction of their robot and are on track to be competition ready by the end of August. Tests done on the robots motion, tool change, and water extracting ability have given confidence that our design will be able to complete all the competition goals.

Our progress in manufacturing before COVID-19 has put us down a path where we can complete the original goals required of the RASC-AL challenge. To stay on our timeline, tasks have been split between members and design simplification has been undertaken to ensure manufacturability in home shops. The remaining manufacturing tasks mostly consist of high tolerance and/or complex parts. Each of these parts require the use of a mill or lathe, and contain at least one feature that needs to be sized or located precisely. Integration work is continuing into the summer as a result, with test bed construction scheduled for late-June. Additional summary information regarding project status is reflected in Tables 24 and 25.

In addition to the remaining manufacturing tasks, programming, electrical integration, testing, onboarding documentation, and NASA documentation responsibilities remain. For the upcoming full integration tests, proper supervision from Cal Poly professors is required to ensure safety for the team and comply with Cal Poly policies. Even with the complications of COVID-19, we are creating new ways to finish this project and prepare it for the next Cal Poly team.

We anticipate being able to present the prototype in Langley, Virginia at the end of August, albeit with less testing time than is desirable. We are relatively confident in the overall design, but recognize the complexity of this challenge and prototype will be working against us as we finish final integration and begin testing. We look forward to the opportunity to demonstrate our best efforts and bring home lessons learned for the next Cal Poly team.

Table 24: Current State of Project Build

	Frame	Motion systems	Drilling Assembly	Tool Changer	Water Processing	Electronics	Programing
State of Completion	Finished	Motors and lead screws operational	Drill is attached to the load cell and the motion system	Generally complete	Finished	In process	Closed loop position and velocity controllers, encoder, stepper, and motor drivers coded
Testing	Observations during manufacturing	Confirmed motors could drive lead screws	Drill is stable in drill mount during operation	Tool clips don't break when exposed to load	Pump is strong enough, and filter system order proved to function	Tests occurring during development	Logic tests occurring during development
Next Steps	Mount remaining equipment and wiring	Integrate with electronics and programing	Install mode switch servo and chuck depressor plate	3D print tool clips Align with drill path	Install on frame, Integrate with electronics and programing	Use electronics to integrate STYX subsystems together	See Table 20

Table 25: Current State of Tools Build

	Tools				
	Drill	**Sheath**	**Auger**	**Heater probe**	**Camera probe**
State of Completion	Drill purchased, adapter manufactured	3D printed prototype	Manufactured	Manufactured, basic assembly is completed	Designed, camera purchased
Testing	Tested against various materials	3D printed friction test	Simulations done to prove the auger could take the required torque loads	String can support load at the heater probe axle	Camera, visual layer testing
Next Steps	Manufacture sliding collar, weld sds adapter	Manufacture sheath and sheath tool	Assembly of head, shaft, and SDS adapter	Integration with electronics and motors.	Manufacture, assemble, and integrate

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Appendix

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Appendix A: Scoring Matrix

2019 Moon to Mars Ice & Prospecting Challenge Scoring Matrix

Teams must collect at least 50 mL of water to be eligible for the 1st or 2nd overall prize

Team:____

Total Possible Points = 490 (*including 40 potential bonus points – see Prospecting Section*)

Water Extraction (Max 180 points) – 40% of overall score	"x"	Water Volume	Max Points	Actual Points	Comments/Notes
Number of points assigned for hands-on water collection			25		
Number of points assigned for hands-off water collection			125		
Water Clarity			30		

Each team's water volume will be collected (separately for hands-off and hands-on periods) and measured at the end of each day. Silt that has settled to the bottom of the containers will also be measured at the end of the day and subtracted from the water volume measurements to give each team their total water volume for that day's hands-off and hands-on collections. <u>The most total volume collected over the two day period by any one team in the following modes of operation = "x":</u>

> **Scoring for hands-on water collection (Max of 25 points):** The team with the most water collected during hands-off operations is given a score of 25. Other teams' points are scaled linearly: [(Team volume/x) *25]
>
> **Scoring for hand-off water collection (Max of 125 points):** The team with the most water collected is given a score of 125. Other teams' points are scaled linearly: [(Team volume/x) *125)]

Scoring for water clarity (Max of 30 points): Teams will be awarded up to 30 points based on the clarity of the water extracted. Turbidity tests will be conducted at the end of each day, with points being awarded to each team's sample with the best clarity over the 2-day period. See Page 2

Prospecting: Drilling Telemetry (Max 90 pts) – 20% of overall score (+40 add'l bonus points available!)	Max	Actual	Comments/Notes
Identify the correct number of overburden layers	10		
Sequence the layers in order from softest to hardest	40		
Identify the thickness of each layer within an established margin of error (MOE)	40		
BONUS POINTS: Up to 40 bonus points will be awarded if teams can accurately determine the true hardness of individual layers in terms of MPa (within a 10% MOE)	**40**		

Technical Paper (Max 135 points) – 30% of overall score	Max	Actual	Comments/Notes
Quality of Path-to-Flight description, including rationale behind various trades and critical modifications made to the system for extracting water from sub-surface ice on Mars **<u>and</u>** prospecting on the moon.	45		
Technical quality, feasibility, and innovation of design for use off-Earth	35		
Quality of integration video and summary description	30		
Quality of summary of production and testing approach	15		
Adherence to Technical Paper guidelines	10		

Poster Presentation (Max 45 points) – 10% of overall score	Max	Actual	Comments/Notes
Discussion of the Earth system (How team got from here to the off-Earth system). **Note:** The Poster should be a summary of the technical paper with emphasis on modifications made for extracting water from sub-surface ice on Mars **<u>and</u>** prospecting on the moon.	25		
Technical Content, Style, Coherence	10		
Engagement with judges (all team members should participate) and quality of response to questions	10		

Water Extraction (max 180 pts) ____________

Prospecting (max 90 pts) ____________

Technical Paper (max 135 pts) ____________

Poster Presentation (max 45 pts) ____________

Bonus Points (max 40 pts) ____________

Sub-Total Score ____________

Note: In the event of a tie, total water volume collected may become the deciding factor.
(The team who collected the most water will emerge as the winner)

Continue to Page 2

2019 Moon to Mars Ice & Prospecting Challenge Scoring Matrix

Teams must collect at least 50 mL of water to be eligible for the 1st or 2nd overall prize

Penalties			
Penalty Points are deducted from a team's total score	Max Points	Points Deducted	Comments/Notes
Exceeding the Volume Limit (10 points off total score for every 1 cm over the size limit of 1m x 1m x 2m)	–		
Exceeding the Mass Limit (20 points off total score for every 1 kg of extra weight over the weight limit of 60 kg)	–		
Exceeding 9A Current/Amperage limit by blowing a fuse (80 points off total score and disqualification for the top prize)	80		
Failure to provide a WOB data logger that can provide real-time data (60 points off total score and disqualification for the top prize)	60		
Misalignment between what was proposed in the Mid-Project Review and/or Technical Paper and the system brought to the competition (up to 200 points off total score at the discretion of the judges)	200		
Solid debris in collection bag (1 point per 10 grams)	–		# of grams: Day 1__________ # of grams: Day 2__________
Excessive dirt outside of the 12' x 12' tarp under team test station (up to 20 points off the total score at the discretion of the judges)	20		

Sub-Total Score (1st page) ___________________

Subtract Total Penalty Points ___________________

Total Score ___________________

Scoring for Water Clarity

Scoring for water clarity (Max of 30 points): Teams will be awarded up to 30 points based on the clarity of the water extracted. Turbidity tests will be conducted at the end of each day, with points being awarded to each team's sample with the best clarity over the 2-day period.

NTU (Nephelometric Turbidity Unit): Measurement of Reflected Light from a Sample
Note: All samples with an NTU above 1,000 will be calculated using a dilution

Turbidity (NTU)	Points
Less than 5 NTU (Minimum Standard for Waste Water)	30 points
5.1 – 50 NTU	25 – 29 Points
51 – 1,000 NTU	20 – 24 Points
1,001 – 5,000 NTU	15 – 19 Points
5,001 – 25,000 NTU	10 – 14 Points
25,001 – 50,000	1 – 9 Points
Greater than 50,000	0 Points

Appendix B: Idea List

Drilling Process	Harvesting Process	Telemetry Process
Horizontal ice drilling	Expanding heat wire whisk	Gamma concentration telemetry
Coring bit	Microwaves	Force feedback
High density drilling	Heating liquid circulated into hole	Imaging system
Drilling at an angle	Radioactive isotope in heater head	Resistivity
Explosive mining	Rotating heater probe	Core sampling
Thermite drilling	Coring and extraction	Photoelectric sensor
Percussive rotary drilling	Peristaltic pump to move fluid	Electrical density gauge
Rotary drilling	Laser heating	Hole sheath with gaps for sample extraction
Ultrasonic drilling.	Reversible pump with Life Straw filter	Drill attachment for telemetry sensor
Auger drilling	Sand trap filter	
3D drilling	Dual arm articulating ice melter	
"Mole" style drilling	Flexible/Expandable heater	
Reinforce drilled hole with a sheath	Vaporize water to extract it	
Enclosed auger drilling/excavation (Curiosity)	Ice shaving auger	
Drill bit heater for ice drilling	Hot air blast to melt ice	
Rotary tool changer for bit exchange	Heat pipe	
Auger that self cleans the dirt	Add salt to ice	
Linear tool changer for bit exchange	Use solar power to heat ice (lens)	
	Inflatable heat probe	
	Brillo filter	
	Heat pool of water before extraction	

Appendix C: Pugh Matrices

Drilling Process

Function: Break Through Overburden Layers	Percussive Drill	Drill	Auger	Jackhammer	Shovel	Ultrasonic Bit
Penetration Power	S	-	-	+	-	-
Axial Force Required	S	-	S	-	-	+
Torque Required	S	-	-	-	-	+
Penetration Rate	S	-	-	+	-	-
Tool Wear	S	-	-	+	+	+
Cost	S	S	S	S	S	-
RESULT	**0**	**-5**	**-4**	**1**	**-3**	**1**

Function: Maintain Clearance	Simple Hole	Sheathed Hole	Shallow Grade	Air Blast
Resistance to large debris ingress	S	+	+	-
Resistance to small debris ingress	S	+	+	+
Resistance to vibration effects	S	+	+	+
Complexity	S	-	-	-
RESULT	**0**	**2**	**2**	**0**

Function: Remove Debris	Auger	Drill	Percussive Drill	Air Blast	Shovel
Thoroughness	S	-	-	+	-
Power Efficiency	S	S	+	-	-
Debris Containment	S	S	S	-	-
Complexity	S	S	S	-	-
RESULT	**0**	**-1**	**0**	**-2**	**-4**

Harvesting Process

Function: Move Ice/Water	Peristaltic Pump	Bubble Pump	Centrifugal pump	Evaporative Collection	Ice Block Extraction	Ice shaving Extraction
Path to Flight	S	-	S	+	-	S
Power Efficiency	S	-	-	-	-	-
Debris Tolerance	S	S	-	+	+	+
Throughput	S	-	-	--	-	-
Water Efficiency	S	S	S	-	+	+
RESULT	**S**	**-3**	**-3**	**-2**	**-1**	**0**

Function: Melt Ice	Water Convection	Conduction	Air Convection	Radiation
Power Efficiency	S	+	-	-
Watt Density	S	+	-	-
Path to Flight	S	+	-	+
RESULT	**S**	**3**	**-3**	**-1**

Function: Remove Particulate	Sand Trap	One Stage Membrane Filtration	Two Stage Filtration	Centrifugal Filtration	Density Stack
Efficacy	S	S	+	-	S
Longevity	S	-	-	-	+
Cleanability	S	+	+	+	+
Path to Flight	S	-	-	+	S
Water Efficiency	S	+	S	'+	+
Throughput	S	+	+	+	-
RESULT	**S**	**0**	**1**	**1**	**2**

Filtration Longevity	Oversizing	Backflow	Physical Clean	Filter Replacement
Efficacy	S	+	+	+
Water Efficiency	S	-	+	+
Path to Flight	S	+	-	--
RESULT	**S**	**1**	**1**	**0**

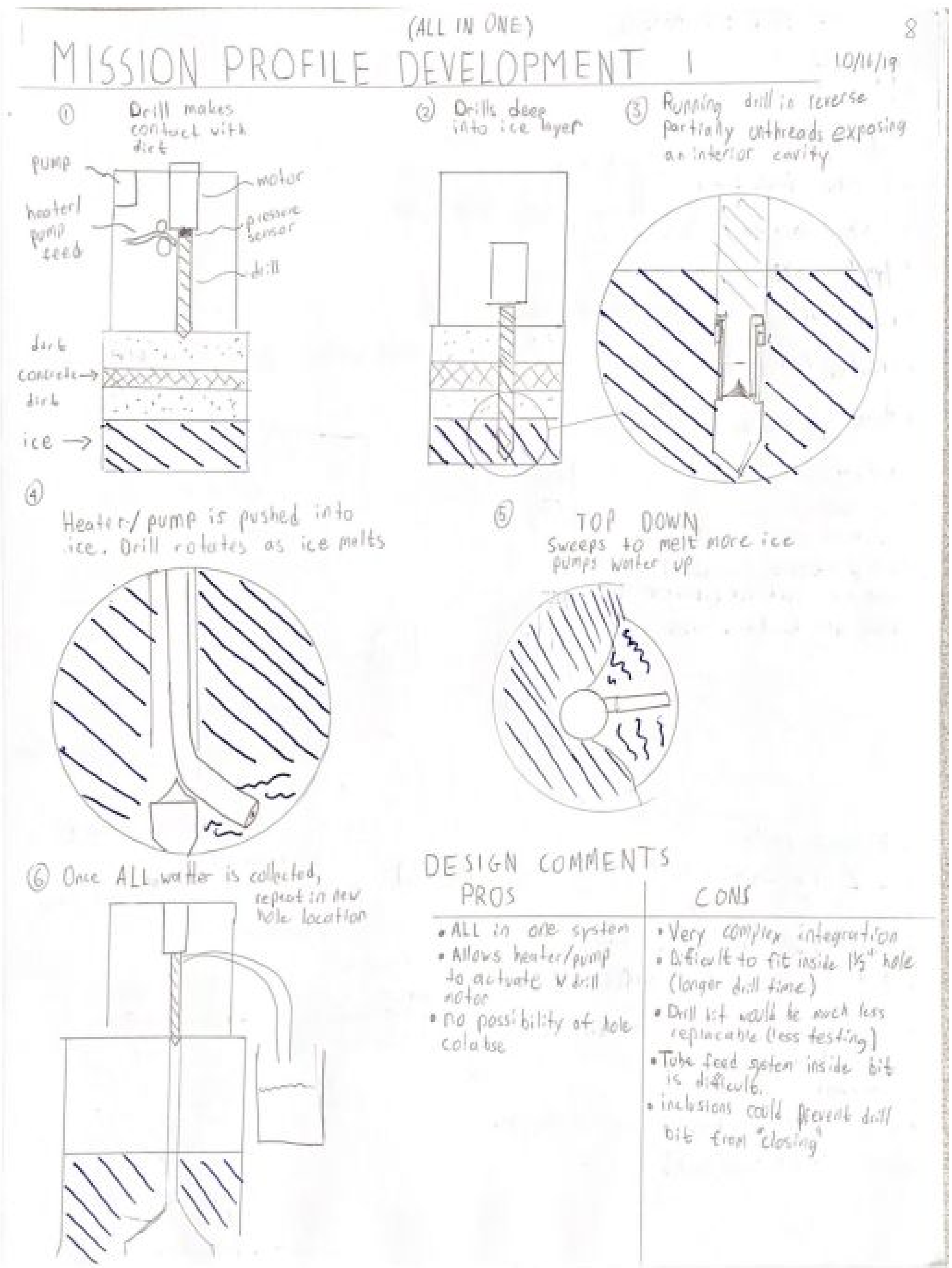
Function: Maximize Water Yield	Passive Heating Element	Expandible Heating Element	Actuating Heating Element	Two Axis Movement	Three Axis Movement
Reliability	S	-	-	S	-
Range	S	+	+	S	+
Complexity	S	-	-	S	-
Cost Effectiveness	S	-	S	S	-
Path to Flight	S	S	S	S	S
Weight	S	S	S	S	-
RESULT	**S**	**-2**	**-1**	**S**	**-3**

Telemetry Process

Function: Measure Layer Hardness	Rate v. Force	Brinell	Rate v. Force & Brinell
Resolution	S	+	+
Noise	S	-	+
Accuracy with Hard stuff	S	-	+
Accuracy with Soft Stuff	S	+	+
RESULT	**S**	**0**	**4**

Function: Measure Layer Thickness	Rate v. Force	Camera Probe	Gamma Ray	Resistivity
Resolution	S	+	-	-
Accuracy	S	+	-	+
Complexity	S	-	-	-
Cost	S	S	-	-
RESULT	**S**	**1**	**-4**	**-2**

Appendix D: Alternate Concept Sketches

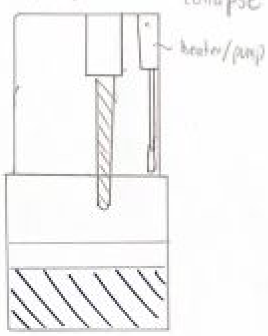


MISSION PROFILE DEVELOPMENT (Modular sheathed or unsheathed) 10/16/19

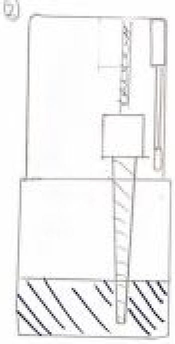
9

DRILLING ONLY

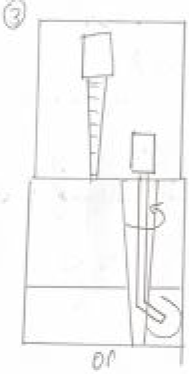
① Drill w/ tapered bit for less collapse



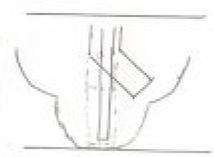
② Drills deep into ice



③ Melter/Pump drops into hole, turns and melts ring



or



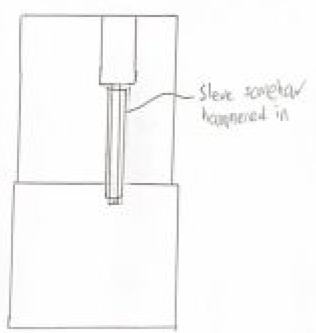
Dip deep with heater then come up and sweep leaving pump in first hole

④ Extract all water / Repeat

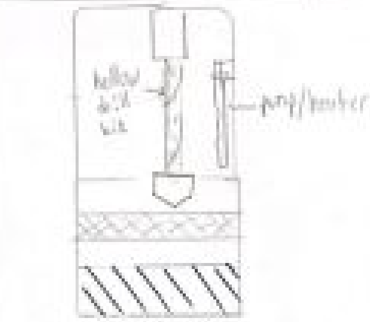
DESIGN COMENTS

PROS	CONS	NEUTRAL
• simple modular design	• losses with tapered drill	• Does tapered bit buy you anything • does tapered hole colapse just as easy

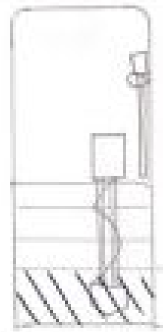
ALTERNATE DRILLING OPTIONS



Mission Profile Development (Modular, hollow drill)

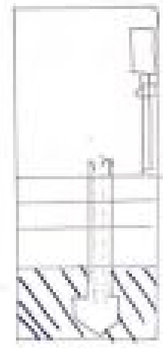


- Drilling begins
- Chips cleared with low chip load flute
- only chips for volume of shaft need to be cleared

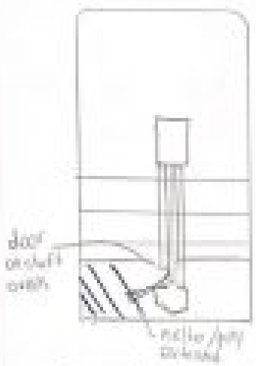


- Hole is drilled to ice

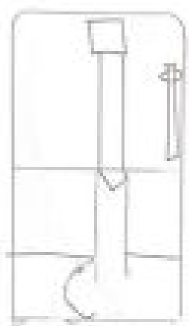
(door can also be opened before decoupling)



- linear actuator decouples from drill bit & grabs heater/pump

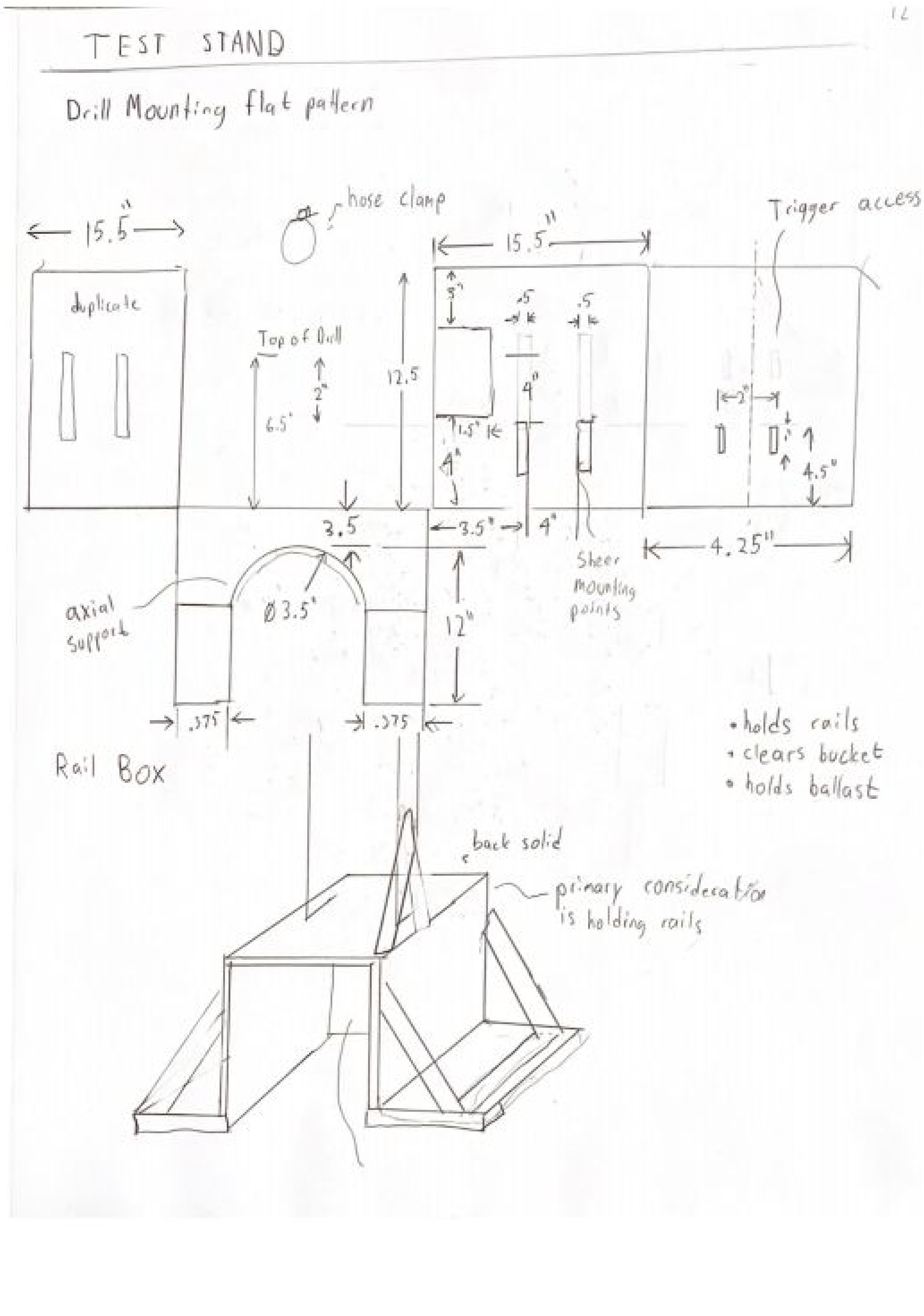


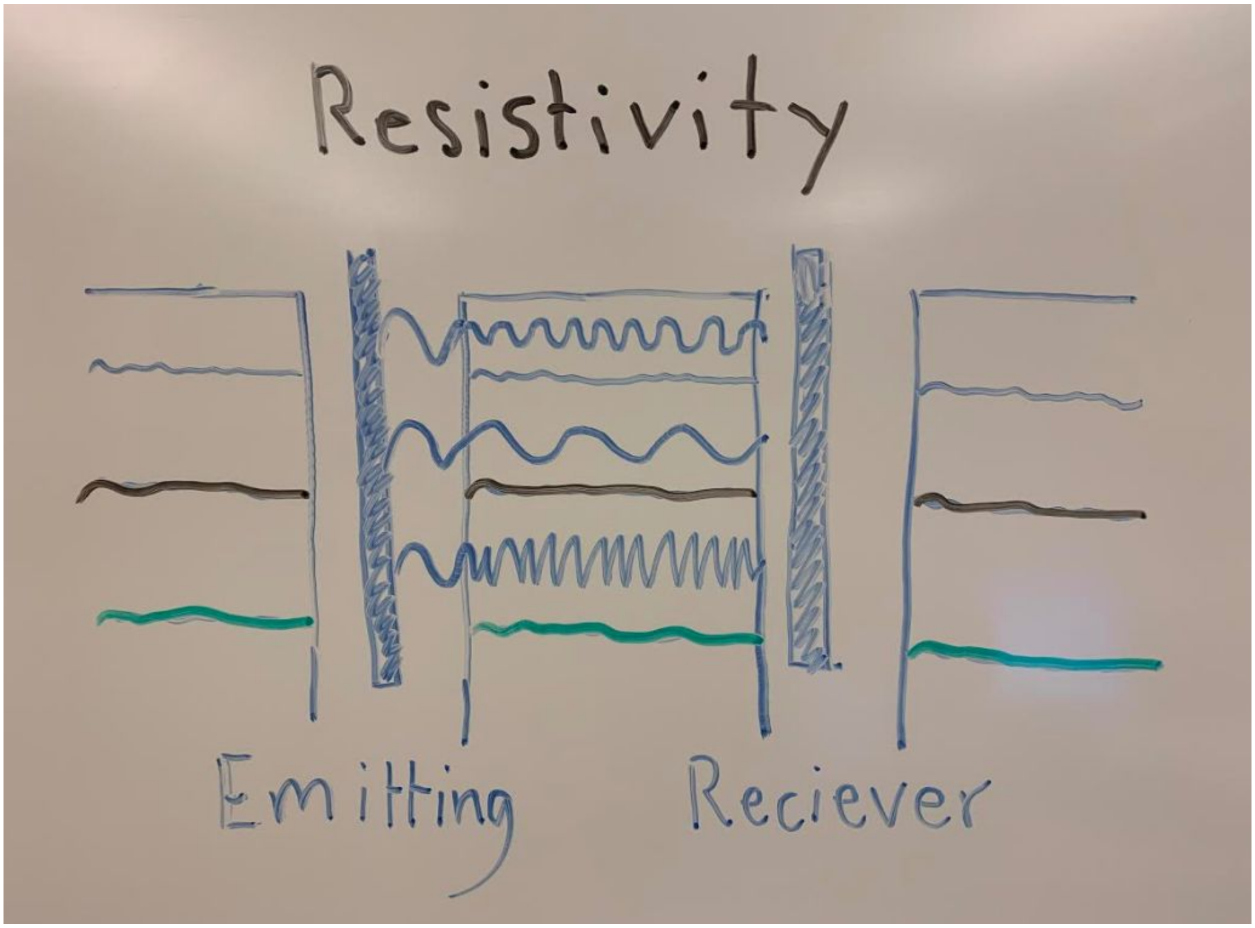
- ice melter is inserted into ice
- water is collected

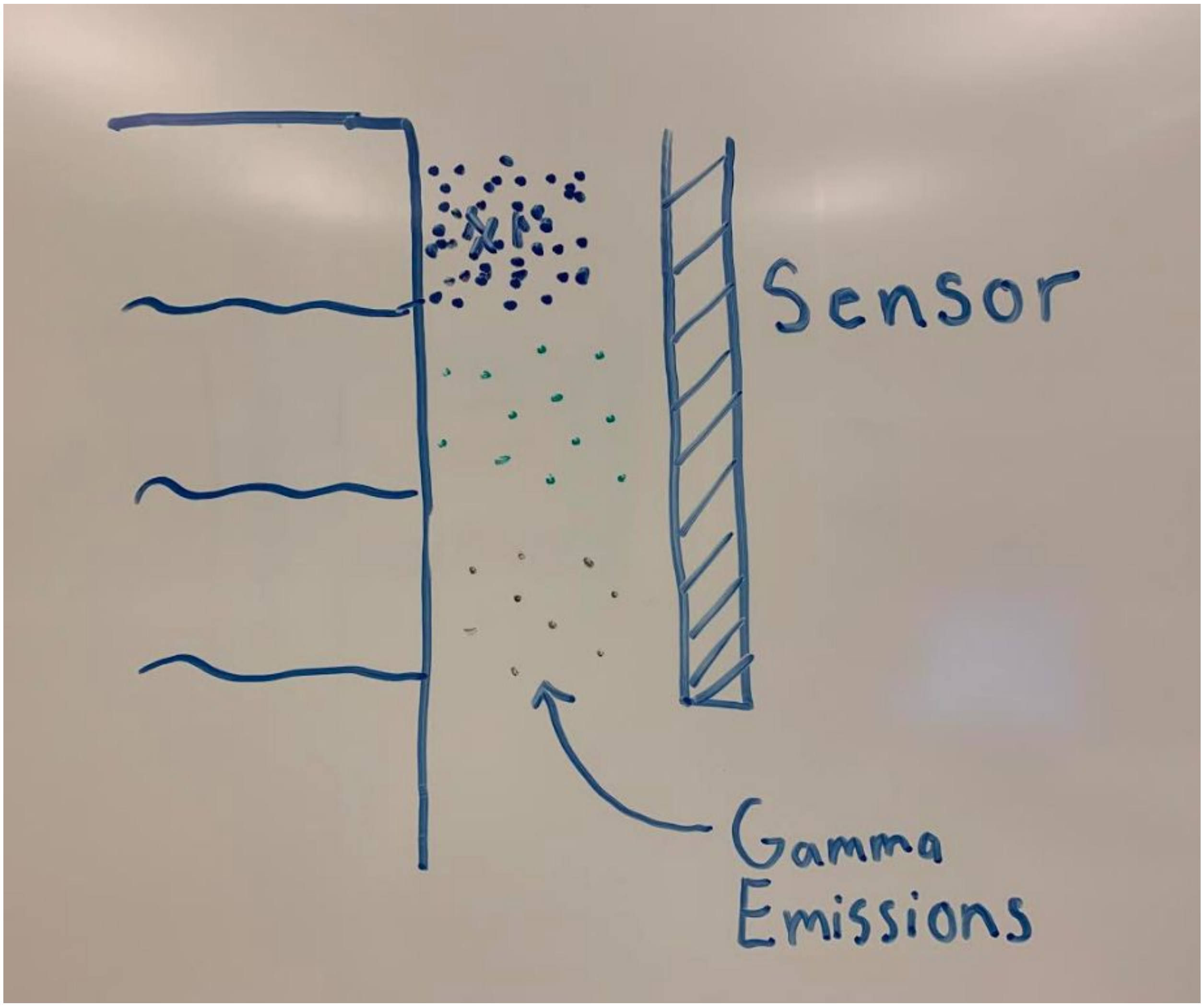


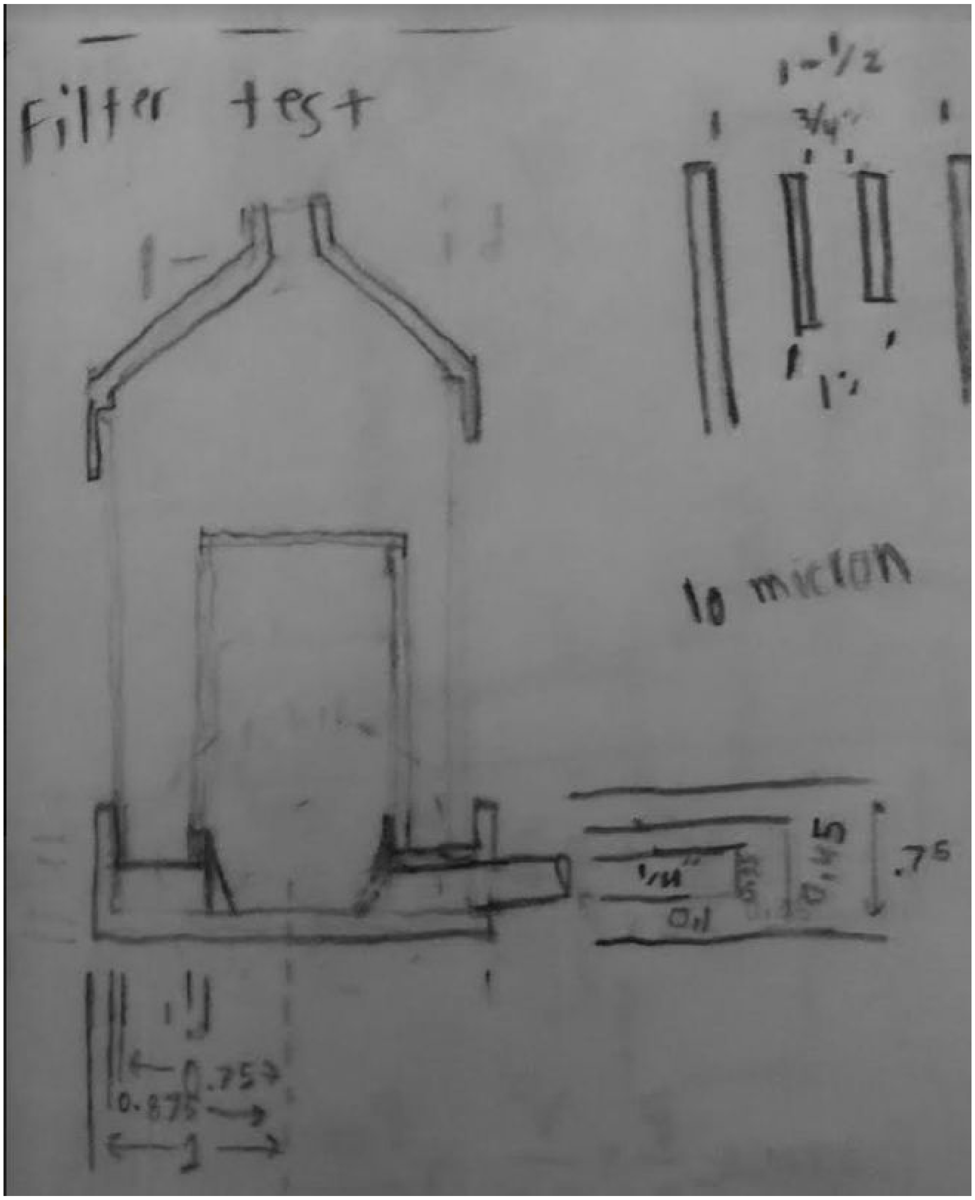
- pump/heater is put back
- bit is recoupled
- retracted to pos

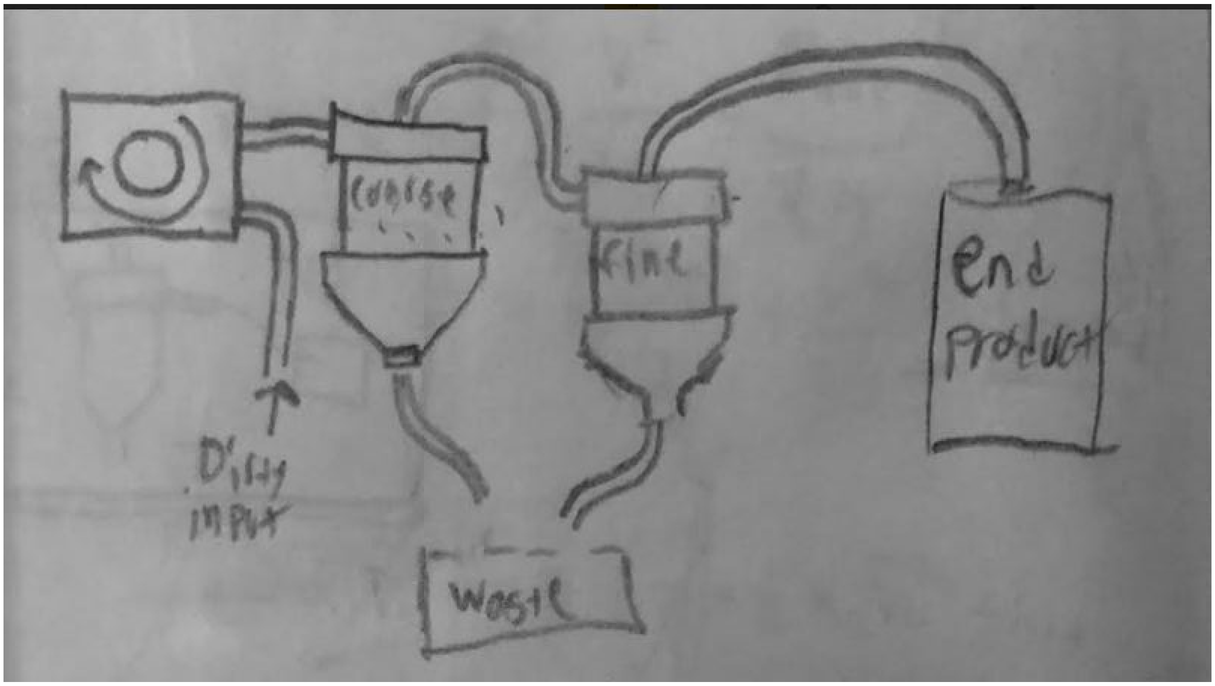
pros	cons
• solves sheath problem • allows linear actuation of drill & heater on same motor	• limited space inside tube for heating device

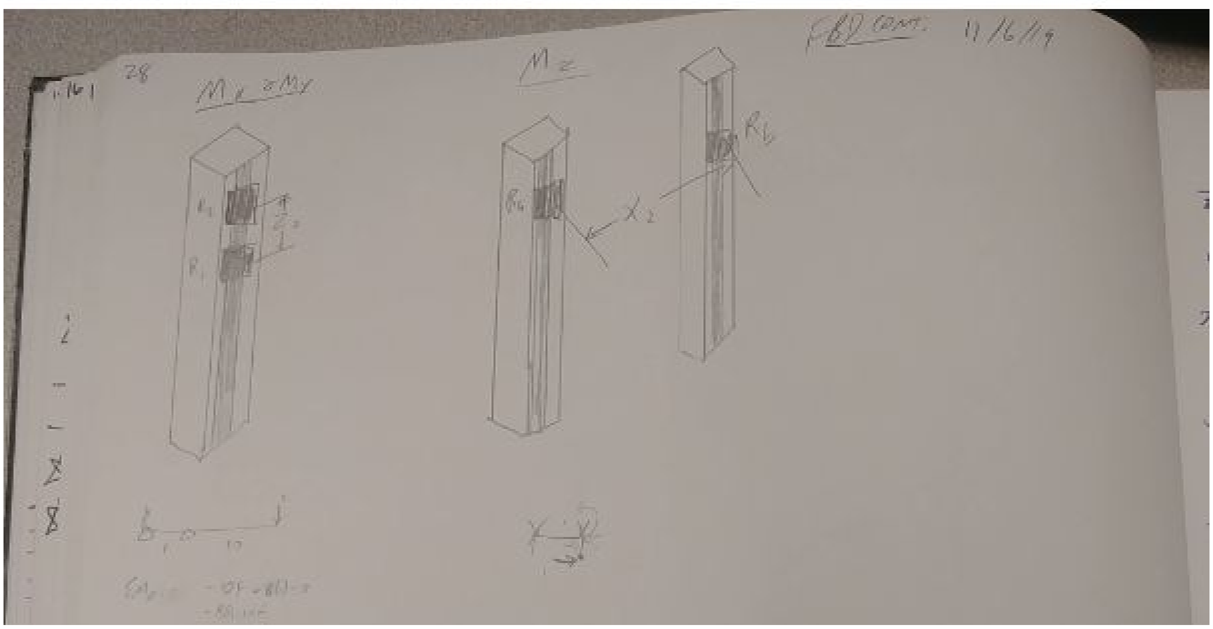

12
TEST STAND
Drill Mounting flat pattern
15.5"
duplicate
hose clamp
Top of Drill
6.5"
2"
12.5
15.5"
3"
.5
.5
4"
1.5"
4"
3.5
3.5"
4"
Trigger access
2"
4.5"
4.25"
Sheer mounting points
axial support
Ø3.5"
12"
.375
.375
Rail Box
• holds rails
• clears bucket
• holds ballast
back solid
primary consideration is holding rails

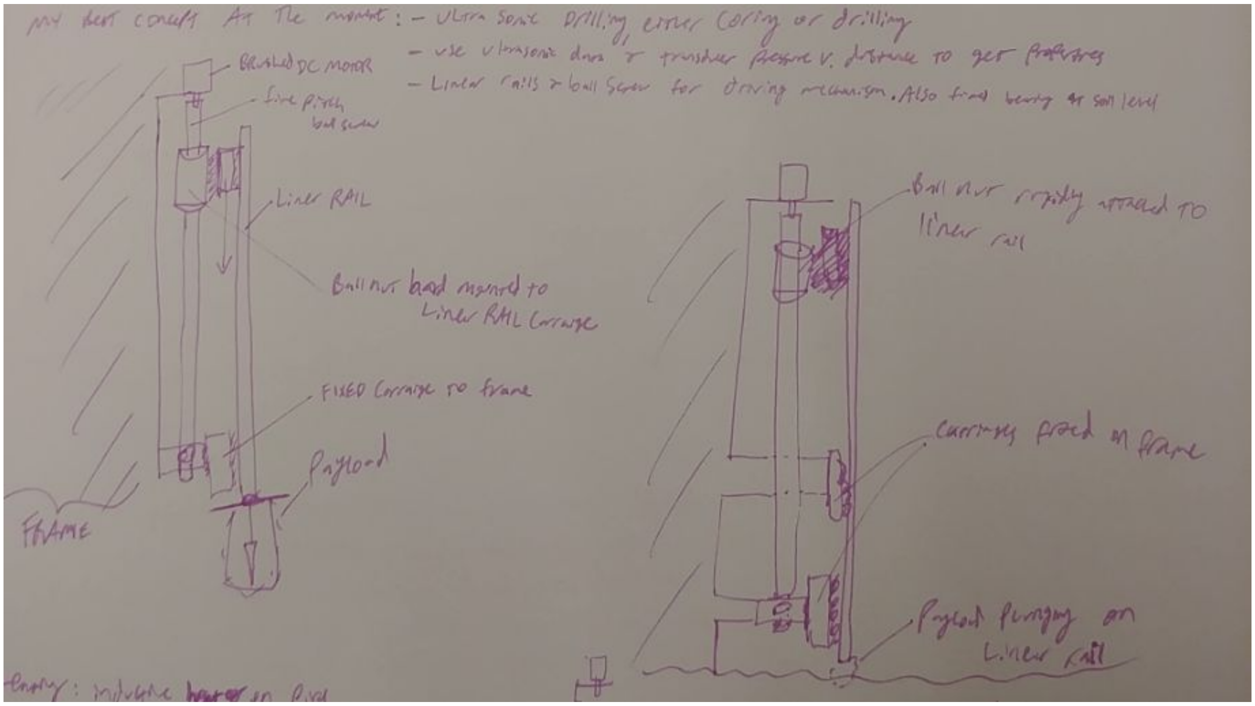

Resistivity
Emitting
Reciever

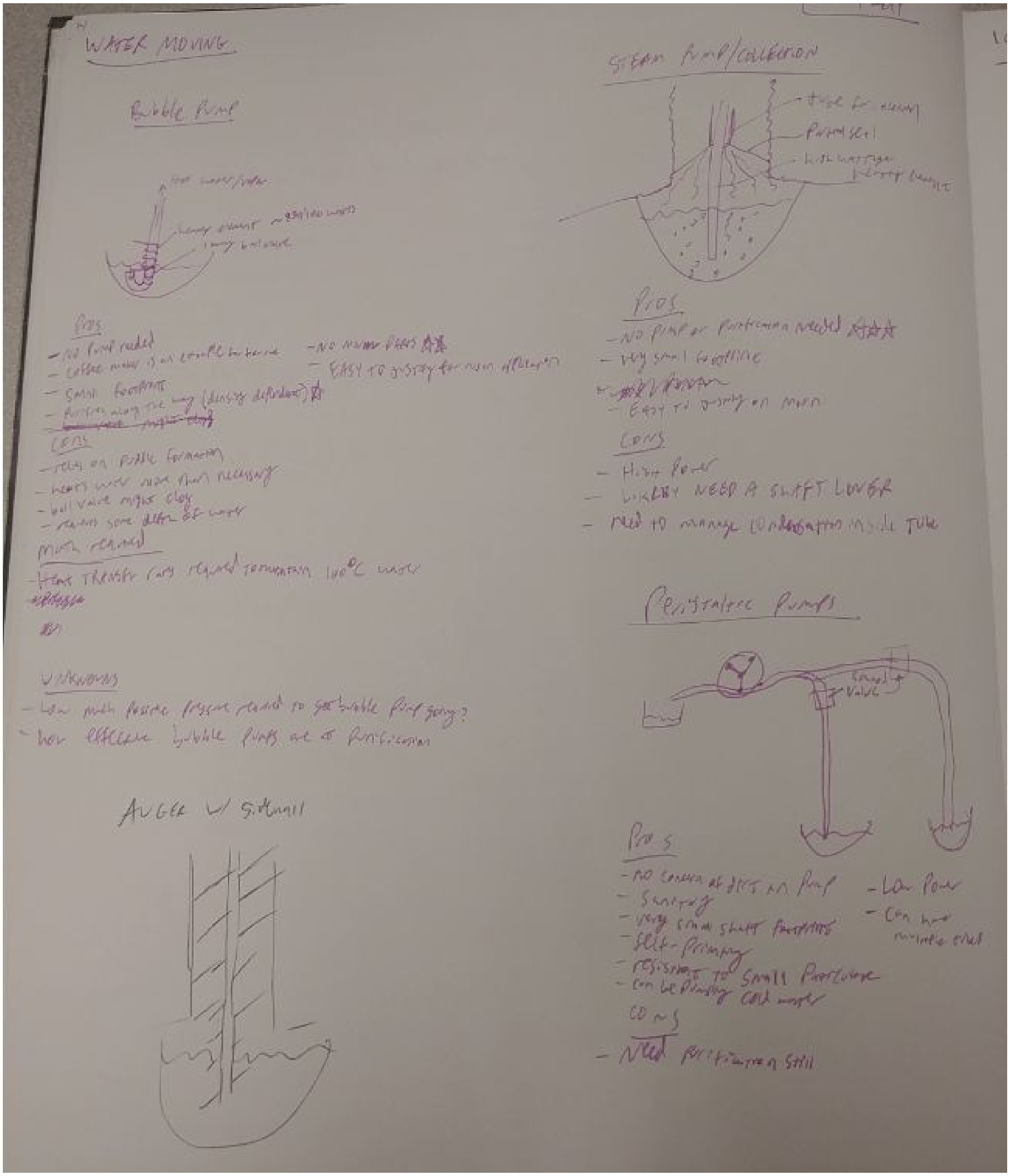

Xe
Sensor
Gamma
Emissions


Filter test
1-1/2
3/4"
10 micron
1/4"
0.445
.75
0.1
0.757
0.875
1


coarse
fine
End Product
Dirty input
Waste




- Ultra Sonic Drilling either Coring or drilling
- Linear rails & ball screw for driving mechanism. Also fixed bearing at soil level
BRUSHED DC MOTOR
Liner RAIL
FIXED Carriage to frame
Payload
FRAME
Carriage fixed on frame
Payload plunging on Linear rail


WATER MOVING
Bubble Pump
Pros
- No pump needed
- Small footprint
- No moving parts
- Easy to justify for main application
Cons
- relies on bubble formation
- heats water more than necessary
- ball valve might clog
Unknowns
- how efficient bubble pumps are at purification
AUGER W/ SIDEMILL
STEAM PUMP/COLLECTION
Pros
- No pump or purification needed
- very small footprint
- Easy to justify on main
Cons
- High power
- LIKELY NEED A SHAFT LINER
- need to manage condensation inside tube
Peristaltic Pumps
Check valve
Pros
- Low power
- Self-priming
- resistant to small particulate
Cons
- Need purification still

Appendix E: Drilling Preliminary Test Data

Test Title: Drill Rig 1, Penetration Rate and Chip Clearance

Test Date: 11/3/19

Test Goals: Verify drill function, determine maximum drill diameter, determine ideal weight on bit, test chip clearance methods, and find starting and continuous current.

Test Equipment Required:

- Hammer Drill, drill bits, and test stand
- Buckets of concrete for testing
- Safety Glasses - for ALL attendees
- Dust Masks - for ALL attendees
- (1) Face Shield
- (1) Extension cord

Test Procedure:

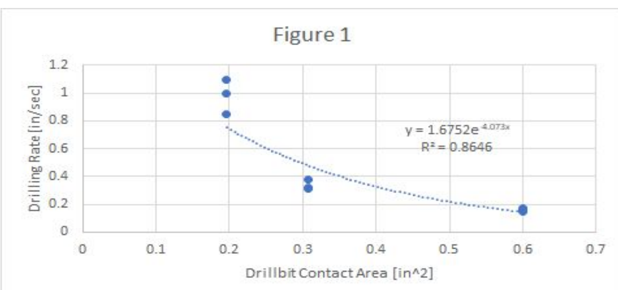
1. Verify all test participants are wearing proper safety equipment. These include Closed toed shoes, long pants, safety glasses, and dust masks.
2. Place Concrete bucket under test stand.
3. Mount Drill to test stand via hose clamps. Verify function via trigger.
4. Apply a constant downward force of less than 150N, and record.
5. Mark starting height of drill on frame's scale. Mark ending height (1" above bucket bottom).
6. Have stopwatch ready.
7. Test penetration rate with ½", ⅝",and ⅞" Carbide masonry bits by recording test time and depth of hole.

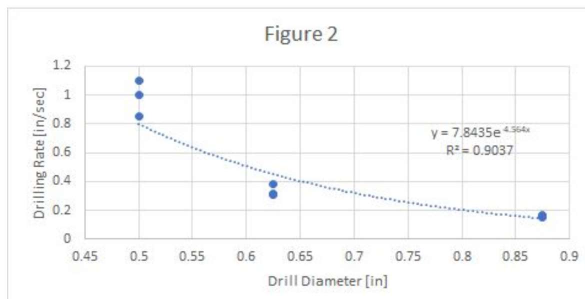
Results:

As expected, penetration rate decreased as drill bit diameter increased. Test data is recorded in Table 1. Plots comparing penetration rate and drill bit contact area and drill or drill bit diameter are reproduced as Figures 1 and 2, respectively. A stronger correlation was found between diameter and feed rate than for area and feed rate. Extrapolating this data to a 1.25" drill bit diameter results in an expected penetration rate of 1.6 inches per minute in concrete.

During testing, several tangential observations were made. Holes frequently collapsed after the drill bit was removed and typical masonry bits are not very effective at chip clearing. These issues will need to be addressed in future design considerations. Additionally, an impromptu test was conducted to test the feasibility of a pile driving mechanism. The tube was forced into a previously bored hole very easily, despite the borehole having collapsed.

TABLE 1. Drilling Test Data, 10/28/2019				
Drilling depth [in]	11			
Drill Diameter [in]	Drill Contact Area [in^2]	Trial	Drilling Time [s]	Drilling Rate [in/sec]
0.5	0.196	1	10	1.1
0.5	0.196	2	11	1
0.5	0.196	3	13	0.85
	1/2" Average		11	0.98
0.625	0.307	1	36	0.31
0.625	0.307	2	29	0.38
0.625	0.307	3	34	0.32
	5/8" Average		33	0.34
0.875	0.601	1	66	0.17
0.875	0.601	2	72	0.15
0.875	0.601	3	70	0.16
	7/8" Average		69	0.16





Appendix F: Matlab Preliminary Analysis

Contents


```
% Alex Krenitsky
% Senior Project
% MATLAB 1
% Last Updated 11/3/2019
```

CODE NOTES

CODE IS MEANT TO BE RUN IN SECTIONS. FIND APPROPRIATE SECTION AND ONLY RUN THAT SECTION. NO VARIABLES ARE CARRIED BETWEEN SECTIONS.

```
clear all;
close all;
format short;
format compact
clc;
```

Drill Forces

See drawing on Alex's page 27 of senior project notebook

```
clc;
clear all;
close all;
format short;
format compact;

r10=[5,-5,-36];     % Vector from R1 to drillbit tip
r21=[0,0,-7];  % Vector from second block to first block for Mx and My
rba=[-10,0,0];     % Vector from second block to first block for Mz
F=[20,20,35];       % Force Applied at Drillbit tip
M=[0,0,3.7*12];       % Moment applied at drillbit tip
Mr1=[r10(2)*F(3)-r10(3)*F(2)+M(1),-(r10(1)*F(3)-r10(3)*F(1))+M(2),r10(1)*F(2)-r10(2)*F(1)+M(3
)];

% From Mr1(1)
Fyr2=-Mr1(1)/r21(3);
```

```
Fyr1=-(Fyr2+F(2));

% From Mr1(2)
Fxr2=Mr1(2)/r21(3);
Fxr1=-(Fxr2+F(1));

% From Mr1(3)
Fyrb=Mr1(3)/rba(1);
Fyra=-(Fyrb+F(3));

FS=4;
PureMoment=Mr1*FS
R1=[Fxr1/2,Fyr1/2+Fyra/2,0]*FS
R2=[Fxr2/2,Fyr2/2+Fyra/2,0]*FS
R3=[Fxr1/2,Fyr1/2+Fyrb/2,0]*FS
R4=[Fxr2/2,Fyr2/2+Fyrb/2,0]*FS
```

```
PureMoment =
   1.0e+03 *
    2.1800   -3.5800    0.9776
R1 =
 -295.7143 -216.8343         0
R2 =
  255.7143  134.5943         0
R3 =
 -295.7143 -244.5943         0
R4 =
  255.7143  106.8343         0
```

Z Ballscrew and motor calcs

```
%SOURCE: https://www.linearmotiontips.com/calculate-motor-drive-torque-ball-screws/
clear all;
clc;
close all;
format short;
format compact;

F=50;      % Force in z-axis desired [N]
m=20;        % mass of entire z-axis gantry [kg]
g=9.8;       % acceleration due to gravity [m/s^2]
mu=1;        % Rail friction coefficient
FS=1.5;         % Z-axis factor of safety
Fa=F+m*g*mu;     % Total force required for Z-axis including FS [N]
P=10;          % Z axis ball screw lead [mm]
Feed=12.5    % min feedrate at max load [mm/sec]
RPS=Feed/P
etanom=.85;     % Ball screw efficiency, nominal
etared=.1;      % Ball screw efficiency reduction, degradation due to dirt
eta=etanom-etared;   % Z axis ball screw efficiency

Td=(Fa*P)/(2000*pi*eta);     % torque to drive the load [Nm]
ANS_Td=[num2str(Td),' Nm '];
Tp=0;                        % Torque from nut preload, provided by manufacturer [Nm]
```

```
ANS_Tp=[num2str(Tp),'Nm'];
Tf=0;                        % Torque due to friction of support bearings, provided by manufac
turer [Nm]
ANS_Tf=[num2str(Tf),'Nm'];
Tc=(Td+Tp+Tf)*FS*100;                 % Total torque required at constant speed, [N-cm]
ANS_Tc=['Constant Speed Torque [Nm] =',num2str(Tc)]


% Acceleration forces
N=10;       % RPM
t=1;        % Acceleration time [s]
Jm=0;       % Inertia of motor, provided by manufacturer, [kg-m^2]
Js=0;       % inertia of screw shaft, provided by manufacturer [kg-m^2]
Jl=0;       % Inertia of load [kg-m^2]

w_prime=(2*pi*N)/(60*t);    % Angular acceleration
J=Jm+Js+Jl;         % Inertia of system [kg-m^2]
Tacc=J*w_prime;     % Torque ndue to acceleration [nm]
Ta=Tacc+Tc;         % Total torque during acceleration [Nm]
ANS_Ta=['Acceleration Torque [Nm] =',num2str(Ta)];

% COMPARE OUTPUTS TO TORQUE/SPEEED/AMP CURVES PROVIDED AT ELECTROCRAFT.COM
% https://www.electrocraft.com/products/stepper/TPP34/

steps_rev=200;
max_resolution=P/steps_rev      % [mm]
```

```
Feed =
   12.5000
RPS =
    1.2500
ANS_Tc =
    'Constant Speed Torque [Nm] =78.3042'
max_resolution =
    0.0500
```

Z axis Leadscrew Calcs

```
clear all;
clc;
close all;
format short;
format compact;

F=50;       % MAX Vertical load being reacted during drilling or lifting [lbf]
W=30;       % Weight of entire z-axis gantry [lbf]
F=(F+W)*4.448;  % TOTAL load converted Newton [N]
do=12;      % Nominal (outer) diameter [mm]
p=2;        % Pitch of screw
l=4;        % Lead of screw [mm]
starts=l/p;
dr=do-1.299038*p;    % Minor diameter of screw [mm]
dm=(do+dr)/2;      % Average diameter of screw [mm]
f=.25      % Friction coefficient. Lower is conservative if calculating min self-locking forc
```

```
e
y=atand(l/(pi*dm));
Lockcheck=tand(y)
if f>Lockcheck
    disp('self-locking')
else disp('NOT self-locking')
end
FS=1.5;      % FACTOR OF SAFETY
Tr=((F*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10*FS    % Raising Torque (Not relevant in horiz
ontal) [N-cm];
Tl=((F*dm)/2)*((-l+(pi*f*dm))/((pi*dm)+(f*l)))/10*FS    % Lowering Torque (Not relevant in hor
izontal) [N-cm];

steps_rev=200;      % Motor characteristic
max_resolution=l/steps_rev     % max resolution of screw [mm]
disp('mm')
```

```
f =
    0.2500
Lockcheck =
    0.1190
self-locking
Tr =
  108.6077
Tl =
   36.3358
max_resolution =
    0.0200
mm
```

X Ballscrew and motor calcs

```
%SOURCE: https://www.linearmotiontips.com/calculate-motor-drive-torque-ball-screws/
clear all;
clc;
close all;
format short;
format compact;

F=50;      % Force in axis desired [N]
m=20;        % mass of entire axis gantry [kg]
g=9.8;       % acceleration due to gravity [m/s^2]
mu=.2;        % Rail friction coefficient
FS=1.5;         % Z-axis factor of safety
Fa=F+m*g*mu;     % Total force required for axis including FS [N]
P=10;          % Z axis ball screw lead [mm]
Feed=25    % min feedrate at max load [mm/sec]
RPS=Feed/P
etanom=.85;     % Ball screw efficiency, nominal
etared=.1;      % Ball screw efficiency reduction, degradation due to dirt
eta=etanom-etared;   % Z axis ball screw efficiency

Td=(Fa*P)/(2000*pi*eta);     % torque to drive the load [Nm]
ANS_Td=[num2str(Td),' Nm '];
```

```
Tp=0;                         % Torque from nut preload, provided by manufacturer [Nm]
ANS_Tp=[num2str(Tp),'Nm'];
Tf=0;                         % Torque due to friction of support bearings, provided by manufac
turer [Nm]
ANS_Tf=[num2str(Tf),'Nm'];
Tc=(Td+Tp+Tf)*FS;                  % Total torque required at constant speed, [Nm]
ANS_Tc=['Constant Speed Torque [Nm] =',num2str(Tc)]


% Acceleration forces
N=10;       % RPM
t=1;        % Acceleration time [s]
Jm=0;       % Inertia of motor, provided by manufacturer, [kg-m^2]
Js=0;       % inertia of screw shaft, provided by manufacturer [kg-m^2]
Jl=0;       % Inertia of load [kg-m^2]

w_prime=(2*pi*N)/(60*t);    % Angular acceleration
J=Jm+Js+Jl;         % Inertia of system [kg-m^2]
Tacc=J*w_prime;     % Torque ndue to acceleration [nm]
Ta=Tacc+Tc;         % Total torque during acceleration [Nm]
ANS_Ta=['Acceleration Torque [Nm] =',num2str(Ta)];

% COMPARE OUTPUTS TO TORQUE/SPEEED/AMP CURVES PROVIDED AT ELECTROCRAFT.COM
% https://www.electrocraft.com/products/stepper/TPP34/

steps_rev=200;
max_resolution=P/steps_rev      % [mm]
```

```
Feed =
    25
RPS =
    2.5000
ANS_Tc =
    'Constant Speed Torque [Nm] =0.28393'
max_resolution =
    0.0500
```

X axis Leadscrew Calcs

```
clear all;
clc;
close all;
format short;
format compact;

rail_fric=.2    % Bearing Friction
N=50;       % Entire x-axis carraige weight [lbf]
F=N*rail_fric*4.448;  % Convert Load to Newton [N]
do=12;      % Nominal (outer) diameter [mm]
p=2;        % Pitch of screw [mm]
l=4;        % Lead of screw [mm]
starts=l/p;
dr=do-1.299038*p;    % Minor diameter of screw [mm]
dm=(do+dr)/2;      % Average diameter of screw [mm]
```

```
f=.15      % Friction coefficient. Lower is conservative if calculating min self-locking forc
e
y=atand(l/(pi*dm));
Lockcheck=tand(y)
if f>Lockcheck
    disp('self-locking')
else disp('NOT self-locking')
end
FS=1.5;          % Torque Factor of Safety
Tr=((F*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10*FS;    % Raising Torque (Not relevant in hori
zontal) [N-cm];
Tl=((F*dm)/2)*((-l+(pi*f*dm))/((pi*dm)+(f*l)))/10*FS;    % Lowering Torque (Not relevant in ho
rizontal) [N-cm];
Tavg=(Tr+Tl)/2;
steps_rev=200;       % Motor characteristic
max_resolution=l/steps_rev     % max resolution of screw [mm]
disp('mm')
```

```
rail_fric =
    0.2000
f =
    0.1500
Lockcheck =
    0.1190
self-locking
max_resolution =
    0.0200
mm
```

Y axis belt Calcs

```
clear all;
clc;
close all;
format short;
format compact;

F=10;      % Force in axis desired [N]
m=10;        % mass of entire axis gantry [kg]
g=9.8;       % acceleration due to gravity [m/s^2]
mu=.2;        % Rail friction coefficient
FS=1.5;        % Y-axis factor of safety
Fa=(F+m*g*mu)*FS;     % Total force required for axis including FS [N]

D=10;           % Pitch diameter of 16T GT2 pulley [mm]
r=D/2/1000;      % pitch radius of 16T GT2 pulley [m]
T=r*Fa*100         % Torque required at constant speed [N-cm]
disp('N-cm')

% COMPARE OUTPUTS TO TORQUE/SPEEED/AMP CURVES PROVIDED AT ELECTROCRAFT.COM
% https://www.electrocraft.com/products/stepper/TPP34/
```

```
T =
```

```
   22.2000
N-cm
```

Heater Lifter Motor - AKA Axis B

```
clear all;
clc;
close all;
format short;
format compact;
% NOTES:
% 1 CORRESPONDS TO THE DRIVEN SHAFT INSIDE THE HEATER
% 2 CORRESPONDS TO THE DRIVER SHAFT, EITHER BEFORE OR AFTER GEARING. READ
% COMMENTS.

D1=.5;      % Effective diameter of pulley inside heater [in]
D2=.5;      % Effective diameter of pulley on driving motor [in]
R1=D1/2;
R2=D2/2;
COM=3;      % COM distance from pivot point [in]
W=2;        % Weight of pivot arm [lbf]
Gearing=10; % Gear reduction from motor thru driver shaft
FSmotor=2;  % FS of motor torque
Tmotor=(D2/D1)*W*COM*FSmotor/Gearing;     %[in-lb]
Tmotor=Tmotor*.11298*100           % Convert to N-cm
disp('N-cm')
N2=.5;      % RPS of motor shaft
N1=D2/D1*N2/Gearing % RPS of driven shaft
deg_sec=N1*360  % Max Deployment speed [deg/sec]
```

```
Tmotor =
   13.5576
N-cm
N1 =
    0.0500
deg_sec =
    18
```

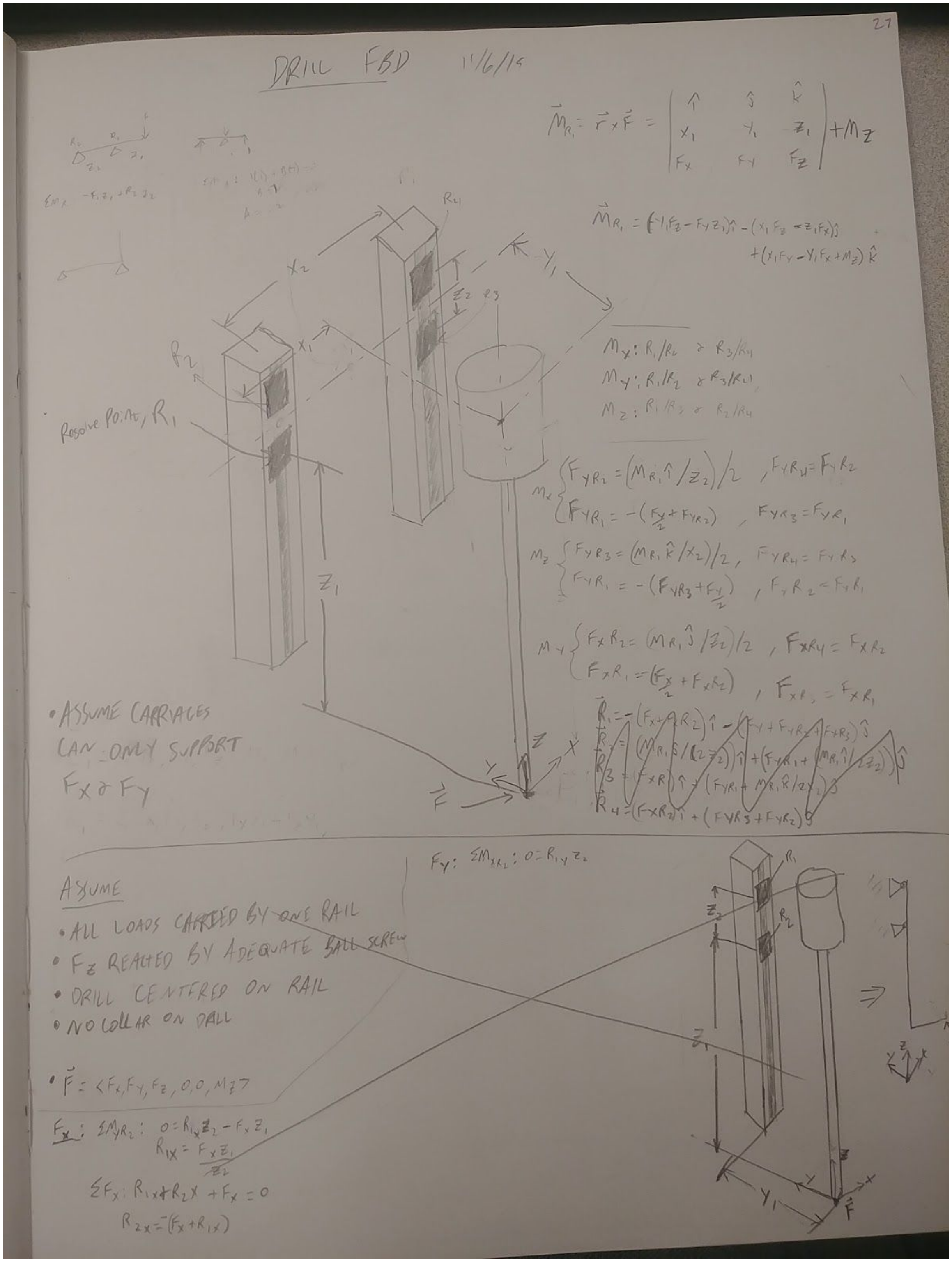
Heater Spring - ARCHIVED, NOT USED ANYMORE

```
clear all;
clc;
close all;
format short;
format compact;

A=201e3;  % for music wire, from table 10-4 [kpsi-in^m]
m=.145; % for music wire, from table 10-4
d=.088; % Wire diameter, chosen [in]
OD=.6;   %  Specified OD of spring
Wmax=.6625;    % Max width envelope for spring
N=8;     % Number of turns integer
b=.625;   % Fraction of turns
```

```
Angle=135; % Angle Used
Nb=N+b; % Total number of turns
L1=OD+1.25;       % Distance Force is applied on Leg 1
L2=OD+.25;       % Distance Force is applied on Leg 2
E=28.5e6;   % Material property from Table 10-5
Dpin=.125;    % Pin diameter that spring is throughmounted to
Weight=7/16+.15       %Weight of Pivot mechanism [lb]
COM=3.5          %COM of pivot mechanism from pin
Mresist=0;
Mreq=Weight*COM+Mresist;     % In-lb required at deployed position

Sut=A/(d^m);    %Tensile strength [ksi]
Sy=.78*Sut;     % Yield strength [ksi]
D=OD-d;         % Mean wire diameter [in]
C=D/d;      % Spring index
Ki=(4*C^2-C-1)/((4*C)*(C-1));   % Bending Stress correction factor
M=pi*d^3*Sy/(32*Ki);         % Max Torque
thetaC=10.8*M*D*Nb/(d^4*E); % Number of turns within coil body
Na=Nb+(L1+L2)/(3*pi*D);
k=(d^4*E)/(10.8*D*Na);      %Spring rate [in-lb/turn]
ThetaPrime=M/k;                 %Max spring location [turns]
ThetaPrimeDeg=ThetaPrime*360;       % Max spring location[deg]

Dprime=Nb*D/(Nb+thetaC);    % loaded mean coil diameter
Clear=Dprime-d-Dpin;       % Diametral clearance between pin and spring
Width=Na*d;                 % Width of spring

Mstowed=k*(Angle/360);
Mdeploy=k*((Angle-90)/360);

%ADD FATIGUE CALCS

if ThetaPrimeDeg<Angle
    disp('UNDER ROTATE')
end
if Mdeploy<Mreq
    disp('UNDER TORQUE')
end
if Mstowed>M
    disp('OVERSTRESS')
    Overstress=Mstowed-M
end
if Width>Wmax
    disp('TOO WIDE')
    overwidth=Width-Wmax
end

COM=3.5;                 % COM of moving Mechanism, origin pivot point
FS=Mdeploy/Mreq


% NOTES
% given a .875 Heater Probe, 4 inch radius. requires >=1 inch bore, prefer
% 1.125 inch bore
% given a 1.000 heater probe, 7 inch radius requires >=1.125 inch bore,
% prefer 1.25 inch bore
```

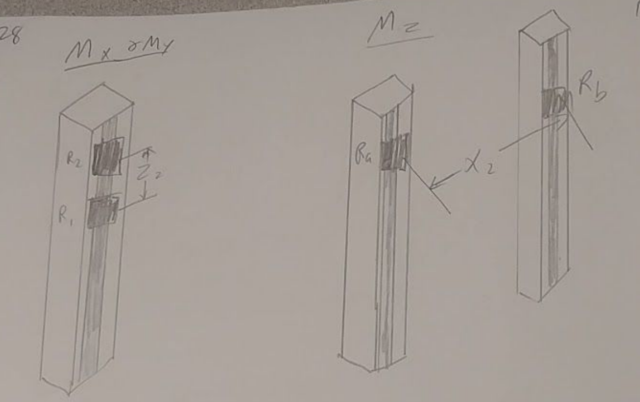
```
Weight =
    0.5875
COM =
    3.5000
TOO WIDE
overwidth =
    0.1457
FS =
    2.0458
```

Published with MATLAB® R2019b


27
DRILL FBD 11/6/15
$\vec{M}_{R_1} = \vec{r} \times \vec{F} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ x_1 & y_1 & z_1 \\ F_x & F_y & F_z \end{vmatrix} + M_z$
$\vec{M}_{R_1} = (y_1 F_z - F_y z_1)\hat{i} - (x_1 F_z - z_1 F_x)\hat{j} + (x_1 F_y - y_1 F_x + M_z)\hat{k}$
$M_x: R_1/R_2 \; \& \; R_3/R_4$
$M_y: R_1/R_2 \; \& \; R_3/R_4$
$M_z: R_1/R_3 \; \& \; R_2/R_4$
$M_x \begin{cases} F_{yR_2} = (M_{R_1}\hat{i}/z_2)/2, & F_{yR_4} = F_{yR_2} \\ F_{yR_1} = -(\frac{F_y}{2} + F_{yR_2}), & F_{yR_3} = F_{yR_1} \end{cases}$
$M_z \begin{cases} F_{yR_3} = (M_{R_1}\hat{k}/x_2)/2, & F_{yR_4} = F_{yR_3} \\ F_{yR_1} = -(F_{yR_3} + \frac{F_y}{2}), & F_{yR_2} = F_{yR_1} \end{cases}$
$M_y \begin{cases} F_{xR_2} = (M_{R_1}\hat{j}/z_2)/2, & F_{xR_4} = F_{xR_2} \\ F_{xR_1} = -(\frac{F_x}{2} + F_{xR_2}), & F_{xR_3} = F_{xR_1} \end{cases}$
$\vec{R}_4 = (F_{xR_2})\hat{i} + (F_{yR_3} + F_{yR_2})\hat{j}$
Resolve Point, R1
x2
x1
y1
z2
z1
R2
R3
R4
• ASSUME CARRIAGES CAN ONLY SUPPORT Fx & Fy
ASSUME
• ALL LOADS CARRIED BY ONE RAIL
• Fz REACHED BY ADEQUATE BALL SCREW
• DRILL CENTERED ON RAIL
• NO COLLAR ON DRILL
• $\vec{F} = \langle F_x, F_y, F_z, 0, 0, M_z \rangle$
$F_x: \sum M_{yR_2}: 0 = R_{1x} z_2 - F_x z_1$
$R_{1x} = \frac{F_x z_1}{z_2}$
$\sum F_x: R_{1x} + R_{2x} + F_x = 0$
$R_{2x} = -(F_x + R_{1x})$
$F_y: \sum M_{xR_2}: 0 = R_{1y} z_2$
R1
R2
z2
z1
y1
$\vec{F}$

FBD CONT. 11/6/19

28



$\Sigma M_A = -10F - B(1) = 0$
$-B(1) = 10F$
$B = -10F$
$A + B + F = 0$
$-10F + F + A = 0$
$-9F + A = 0$

* ASSUMES DRILL IS CENTERED BETWEEN UPRIGHTS

HGW-20 LINEAR RAILS < 1500mm for Z AXIS (x2) / 1000mm for X-AXIS (x2)

1610 BALL SCREW — 1500 mm for Z AXIS

BALL SCREW BUCKLING CALC

$P_{cr} = \frac{\pi^2 E I}{L^2}$, $E = 28\ KSI$

$I = \pi r^4/4 = \pi(.5)^4/4 = .049087$

$P_{cr} = \frac{\pi^2\ 28E3\ (.049087)}{(59 in^2)}$

$P_{cr} = 4 lbs$ TOO LOW, probably not reference

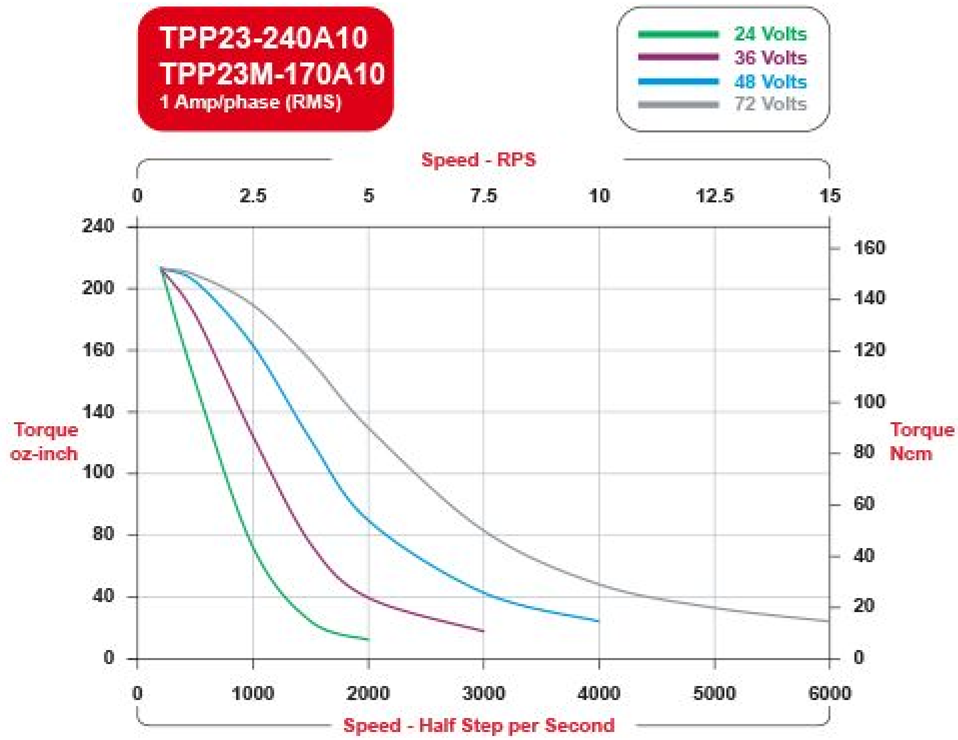
RAIL = HGW 20CA

$F_c = f_b \cdot \left(\frac{d_1^4}{L^2}\right) \cdot 10^4$, $d_1 = 13$ mm, $L = 1500$ mm, $f_b \approx 40$

$F_c = 5077\ N$ ← WAY HIGHER THAN NEEDED

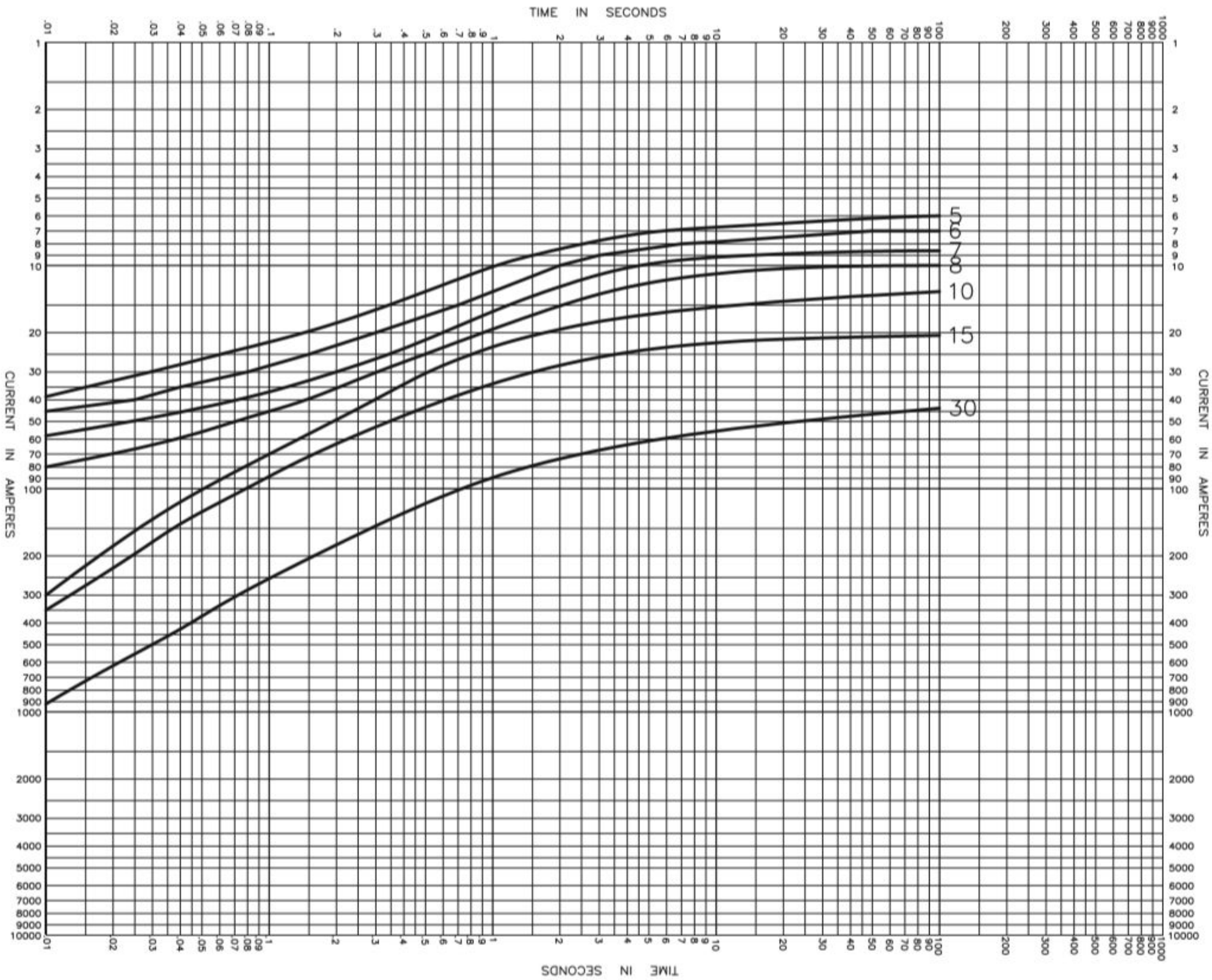
* re-size Down

Appendix G: Lead Screw Stepper Motor Torque Curve



Torque curves for stepper motors are dependent on applied amperage and rotational speed for a given motor. STYX uses this motor at 24V, 1A. (TPP23 Stepper Motor)

Appendix H: Fuse Amp-Time Curve



Maximum current curve for the Bussman BK/AGC-9-R Fuse (Bussmann Series TDS).

Appendix I: Component Power Budget

ALL SYSTEMS					
Subsystem	Component	Operating Voltage [V]	Operating Current [A]	Conversion Efficiency	Power (W)
Drilling	Drill	120	8.5	1	1020
	Induction Coil Heater	24	30	0.85	847
Axis Motion	X-Axis Stepper	24	2	0.85	56
	Z-Axis Stepper	24	2	0.85	56
	Rotary Stepper	5	2	0.85	12
Heating	Heater	120	7.5	1	900
	Heater Stepper A	5	3	0.85	18
	Heater Stepper B	5	3	0.85	18
Extraction	Pump	12	1	0.85	14
Control	Arduino	12	0.5	0.85	7
	Cameras	12	0.5	0.85	7
	DAQ Amplifiers	12	0.5	0.85	7
	Servos	5	1	0.85	6

Appendix J: Filtration Preliminary Test Data

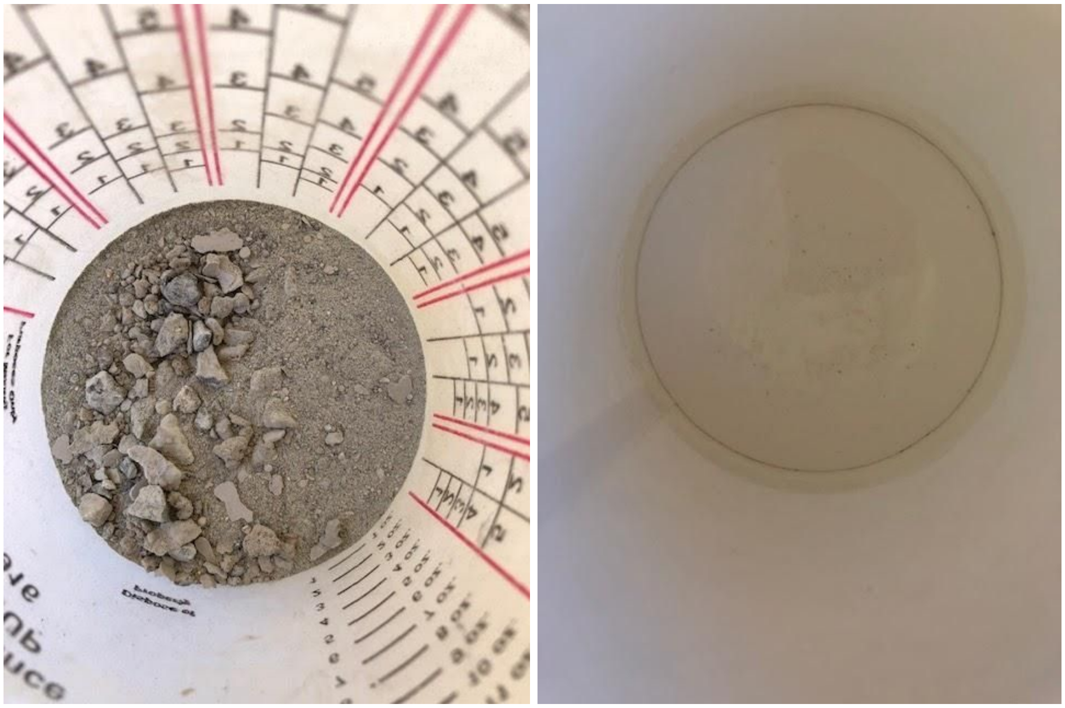
Test Procedure:

1. Wear a dust mask while moving the dry contaminants.
2. Prep the contaminated water samples. Start by adding 1 oz of solid material to a measuring cup, and top off with water to the 16 oz line. Concrete powder taken from previous drilling tests will be used in test 1. Test 2 will be repeated with sand.
3. Place the water sample at an elevation of 2 ft above the filter and prime the siphon.
4. After all the water flows through the filter, disassemble the filter to observe how obstructed the filter material has become, and note the amount of sediment left in the bottom.
5. Perform a visual check on clarity and sediment in the filter output.

Test Results

During the first test, the team came across two major problems. First, large pieces of broken concrete (dia > ⅛”) constantly created blockages at the intake. Second, concrete powder tended to coagulate when subjected to liquid water. This phenomenon caused blockages throughout the intake tube. Although this first test was stopped before completion due to the constant clogging, the test yielded valuable data. The 20 micron filter was sufficient enough to produce clear water. For the next test, the team will increase the intake line to ¼”, and implement a coarse screen at the inlet to avoid having large solids clog the tube.

In the second test, the particles of sand passed into the filter without causing a backup. The sediment trap design worked well, as all of the course sand settled out below the suspended filter. This data ensures the team that the filter will not become quickly impacted by large material. However, the sand had a lot of fine particulate within it, and after the test, roughly 50% of the filter surface area (2 in^2) was covered in fine particulate. This means that filter surface area will have to be increased to avoid backflushing the system too often. Also, the water output was visibly darker in this sample. The team was not satisfied with the final water clarity. The next step will involve testing a 5 micron filter for output clarity.



Test 1 : Dry concrete sample prepared for test (left), final filtered water (right)

Test 2 : Sand sample prepared for test (left), final filtered water(right)

Appendix K: Preliminary Water System Calculations

Sintered Filter Pressure Calculations

Sintered filter pressure Calculations

Sinter-tech Poral filtration solutions : jaygoinc.com

for laminar / low volume flow:

$$\frac{\Delta P}{e} = \alpha \times \eta \times \frac{Q_v}{S}$$

ΔP : pressure drop [Pa] Q_v : volumetric flow rate [m^3/s]

S = filtration effective surface

e : filter wall thickness [m]

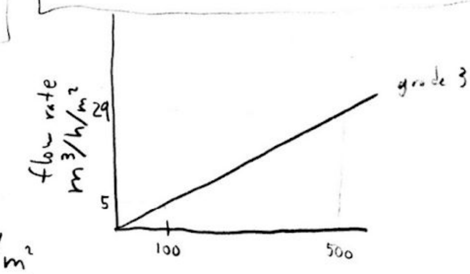
α : viscous permeability coefficient [m^{-2}]

η = dynamic viscosity [Pa·s]

Choose poral grade 03 for Stainless filter : 98% of 3.2 μm particles stopped, 99.9% of 5 μm

→ $\alpha = 455 \times 10^{10}\ m^{-2}$

$e = 3mm$ →



$m^3/h/m^2 = 16{,}667\ cc's/min/m^2$

$$\frac{m^3}{h}\left(\frac{100cm}{1m}\right)^3\left(\frac{1h}{60min}\right)$$

$$\frac{16{,}667\ cc's/min}{m^2\left(\frac{100cm}{m}\right)^2} = \frac{1.67\ cc's/min}{cm^2} = \frac{1.67\ mL/min}{.155\ in^2} = \frac{10.8\ mL/min}{1\ in^2\ filter}$$

pump can handle 400 mL/min so $\frac{400 mL/min}{}$

37 in² filter surface area required

36

Water Collection and Pump Calculations

- Calculating friction factor in tube

$Re = \frac{\rho u D}{\mu}$

$\rho = 997\ kg/m^3$

$D = 3/16'' = 0.00476m$

$\mu = 8.90\times10^{-4}\ Pa\cdot s$

$u = (0.000144\ m^3/min)(\pi(\frac{D}{2})^2)$

$u = 8.157\times10^{-10}\ m/min = 1.360\times10^{-11}\ m/s$

$Re = 7.25\times10^{-8}$

fluid will experience Stokes flow - expect a high loss coefficient.

$f = (100\ Re)^{-1/4}$ coefficient of friction (Blasius eq)

$f = 19.27$

- head loss across primary filter

chosen filter is rated for 20 GPM at 60 psi differential

for a flow rate of 143.7 mL/min, there is a pressure drop of 0.114 psi.

- total head loss on suction-side

- 6 feet of lift
- 10 feet of tubing
- primary filter

units

$H = (6\ ft)(\frac{1\ psi}{2.31\ ft}) + 19.27(\frac{120\ in}{.1875\ in})(\frac{(1.36\times10^{-11} m/s)^2}{2\cdot 9.81 m/s^2}) + .114\ psi$

$H = 2.597\ psi + \sim 0 + .114\ psi$: pipe loss is negligible

$H = 2.711\ psi$ suction, pump must deliver this much priming suction head.

$H = 6.26$ feet of head

Water collection/processing calculations.

- Minimum required pump flow rate is determined by the maximum theoretical ice melting rate.

  - neglecting heat transfer through the ice or into the overburden.:

$$q = m(\Delta H_f + c\Delta T)$$

$$\Delta H_f = 330{,}000\ J/kg$$

$$c = 2{,}108\ J/kg \cdot K$$

$$\Delta T = 20K$$

$$q = 900W$$

$$900\ J/s = m(330{,}000\ J/kg + (2{,}108\ J/kgK)(20K))$$

$$m = 2.4 g/s$$

max melt rate = 143.7 mL/min

This value is high because of unaccounted heat transfer, but this value will give a safety factor to the chosen pump.

- the choice to use two-stage filtration was made due to the large variance in potential particulate. A 40 micron pre-filter is used for rocks and sand, and a 5 micron filter is used for drilled concrete powder.

- the pump will be placed between the filters so that it is protected from large particulate. Pumps generally can create more discharge head than suction head, so the secondary filter will come after the pump. Placing the secondary filter on the discharge side of the pump will also limit the suction head required to self-prime the pump, which will be necessary in this application.

- due to size restrictions of the heater probe and its necessity to move, 3/16" vinyl tubing will be used for all water transport. This is approximated as smooth pipe, so the Blasius equation can be used for determining the friction factor.

- Pump, Choice
  - 20 feet max suction : Safety factor : 3.2
  - 1270 mL/min max flow rate : Safety factor : 8.8
  - 30 psi max discharge pressure, 18 psi continuous

must verify that secondary filter does not exceed limits of pump.

- secondary filter head loss

  smallest filter SA. commercially available : 23.25 in^2

$\Delta P = \frac{\alpha \cdot e \cdot \eta \cdot Q_v}{S}$

5 micron brass filter : $e = 0.002 m$

$\alpha = 455 \times 10^{10} m^{-2}$

water : $\eta = 8.9 \times 10^{-4}$ Pa's

Q_v : 143.7 cm^3/min : $2.395 \times 10^{-6} m^3/s$

$\Delta P = 0.834$ psi required

add usage factor : occlusion = 80%

$\Delta P = 4.17$ psi = 9.64 feet of head

- net system head loss

$\Delta P = 4.17$ psi + 2.71 psi

$\Delta P = 6.88$ psi, 30 psi allowed by pump

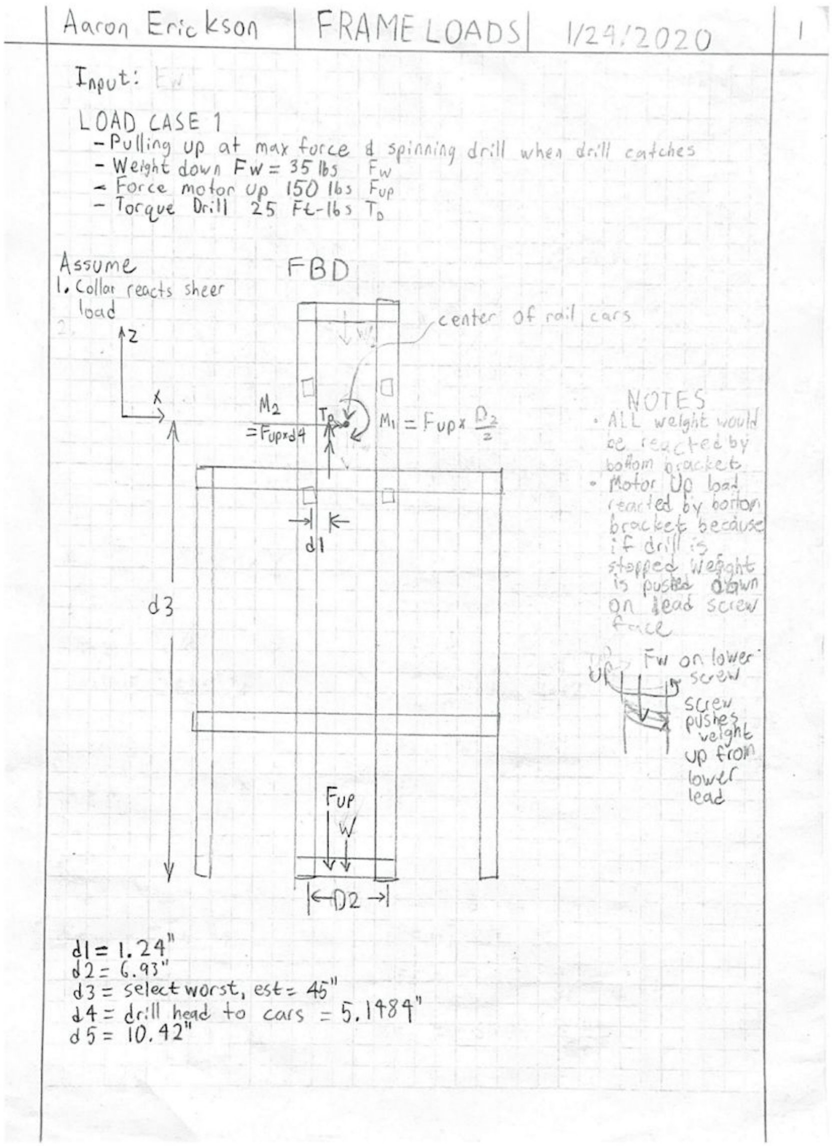
Safety factor : 4.36

The chosen pump and filters all meet the requirements.

Appendix L: Frame Hand Calculations and Matlab

Q.6

Frame Calculations



Aaron Erickson | FRAME LOADS | 1/24/2020 | 1

Input:

LOAD CASE 1
- Pulling up at max force & spinning drill when drill catches
- Weight down Fw = 35 lbs F_W
- Force motor up 150 lbs F_{UP}
- Torque Drill 25 Ft-lbs T_D

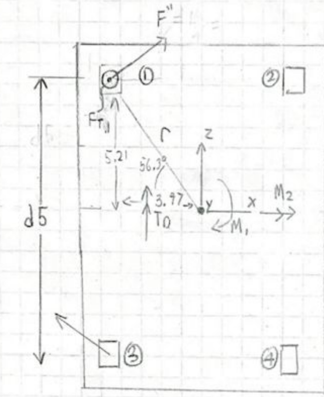
Assume
1. Collar reacts sheer load

d1 = 1.24"
d2 = 6.93"
d3 = select worst, est = 45"
d4 = drill head to cars = 5.1484"
d5 = 10.42"

Q.7

Aaron Erickson | FRAME LOADS CONT. | 2

LOAD CASE 1



r = 6.26 in
θ = 56.3

$$F'' = \frac{M_1}{4r} = F_{up} \times \frac{D_2}{2} \times \frac{1}{4}\,\frac{1}{r}$$

$$F'' = \frac{F_{up} \cdot D_2}{8r}$$

①

$F_{T1(Y)} = T_D / d1$

$F_{M2}(Y) = \dfrac{F_{up} \times d4 \times 2}{d5}$

$F''_z = \cos(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

$F''_x = \sin(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

②

$F_{T2}(Y) = \dfrac{-T_D}{(D_2 - D_1)}$

$F_{M2}(Y) = \dfrac{F_{up} \times d4 \times 2}{d5}$

$F''_z = -\cos\theta\,\dfrac{F_{up} \cdot D_2}{8r}$

$F''_x = \sin\theta\,\dfrac{F_{up} \cdot D_2}{8r}$

③

$F_{T3} = T_D / d_1$

$F_{M2}(Y) = -\dfrac{F_{up} \times d4 \times 2}{d5}$

$F''_z = \cos(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

$F''_x = -\sin(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

④

$F_{T3} = \dfrac{-T_D}{D_2 - D_1}$

$F_{M2}(y) = -\dfrac{F_{up} \times d4 \times 2}{d5}$

$F''_z = -\cos(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

$F''_x = -\sin(\theta)\,\dfrac{F_{up} \cdot D_2}{8r}$

Q.8

Table of Contents

Frame Loads

Aaron Erickson Team Styx 1/29/2020

```
close all
clear all
clc
format ShortG

%open('FrameLoadsFBD.pdf')

% Input Forces
Fw = -35;     % lbf
Fup = 150;    % lbf
Td = 25*12;   % in-lbs

% Input Distances see Frame Loads Sheet for FBD
d1 = 1.24;    % in
d2 = 6.93;    % in
d3 = 49;      % in
d4 = 5.614;   % in
d5 = 10.42;   % in
theta = 56.3;% degrees
r = 6.26;     % in
```

Car Loads

```
% F1 top left car
Ft1y = Td./d1;                          % lbf
Fm1y = (Fup.*d4.*2)./d5;                % lbf
F1y = Ft1y+Fm1y;                        % lbf
F1z = cosd(theta).*(Fup.*d2)./(8.*r);  % lbf
F1x = sind(theta).*(Fup.*d2)./(8.*r);  % lbf

% F2 top right car
Ft2y = -Td./(d2-d1);                    % lbf
Fm2y = (Fup.*d4.*2)./d5;                % lbf
F2y = Ft2y+Fm2y;                        % lbf
F2z = -cosd(theta).*(Fup.*d2)./(8.*r);% lbf
```

Q.9

```
F2x = sind(theta).*(Fup.*d2)./(8.*r); % lbf

% F3 bottom left car
Ft3y = Td./d1;                        % lbf
Fm3y = -(Fup.*d4.*2)./d5;             % lbf
F3y = Ft3y+Fm3y;                      % lbf
F3z = cosd(theta).*(Fup.*d2)./(8.*r); % lbf
F3x = -sind(theta).*(Fup.*d2)./(8.*r);% lbf

% F4 bottom right car
Ft4y = -Td./(d2-d1);                   % lbf
Fm4y = -(Fup.*d4.*2)./d5;              % lbf
F4y = Ft4y+Fm4y;                       % lbf
F4z = -cosd(theta).*(Fup.*d2)./(8.*r); % lbf
F4x = -sind(theta).*(Fup.*d2)./(8.*r); % lbf

%F = cell(5, 4)
%C{1,1} = 'Frame Loads'
F = {'Frame Loads' 'x' 'y' 'z';'Car 1' F1x F1y F1z;'Car 2' F2x F2y
 F2z;'Car 3' F3x F3y F3z;'Car 4' F4x F4y F4z;'Total' F1x+F2x+F3x+F4x
 F1y+F2y+F3y+F4y F1z+F2z+F3z+F4z}
```

```
F =

  6×4 cell array

    {'Frame Loads'}    {'x'      }    {'y'      }    {'z'      }
    {'Car 1'      }    {[ 17.269]}    {[ 403.57]}    {[ 11.517]}
    {'Car 2'      }    {[ 17.269]}    {[ 108.91]}    {[-11.517]}
    {'Car 3'      }    {[-17.269]}    {[ 80.304]}    {[ 11.517]}
    {'Car 4'      }    {[-17.269]}    {[-214.36]}    {[-11.517]}
    {'Total'      }    {[      0]}    {[ 378.42]}    {[      0]}
```

Cable Loads

inputs

```
Stainless18_8Yield = 31200; % psi
diam = .125; % in
E = 28000000; % psi
L = [58]; % in
v = 25; % sheer
% Calculated Values
Fpre = 2*(v/cosd(53))

A = pi()*sqrt(diam/2); % in^2
sigma = Fpre/A; % psi
Margin = (Stainless18_8Yield/sigma)-1

k = (E.*A)./L % lbf/in;

K = {'Member' 'X';'k lbf/in' k(1) ;'Length in' L(1)}
```

Q.10

```
% X cable loads
```

```
Fpre =

       83.082


Margin =

       293.94


k =

   3.7916e+05


K =

  3×2 cell array

    {'Member'   }    {'X'          }
    {'k lbf/in' }    {[3.7916e+05]}
    {'Length in'}    {[         58]}
```

Diagonal Strut Loads

```
n = 1.5;
thetad = 62; %degrees
Fdiag = cell2mat(F(6,3))*n/cosd(thetad)
```

```
Fdiag =

       1209.1
```

Verticle Strut Loads

```
Fvert = -1*n*(-Fup - Fdiag*sind(thetad))
```

```
Fvert =

       1826.3
```

Horizontal Member

output from excel load calculation sheet

Q.11

```
Mhoz = 5386 % in lbs
```

```
Mhoz =

        5386
```

Base Member

```
Fb = (n*Fup)+(132*1.5)
Mbase = 2753 % in lbs from utility sheet
```

```
Fb =

   423


Mbase =

        2753
```

Save data to MAT file

```
save('data','F','Fup','Fw','Fpre','Fdiag','Fvert','Mhoz','Mbase')
```

Published with MATLAB® R2019b

Table of Contents

Aaron Erickson

Team STYX Frame Analysis

```
close all
clear all
clc
format ShortG

load('data')     % Loads Force data from "FrameLoads"
```

Veritcal Struts

Sections

```
b = [.5 1 1.5 2];
h = [.5 1 1.5 2];
t = [.062,.065,.125,.1875,.25]';
%bsxfun(@minus,b,t)
A = Area('rectangleTube',0,b,h,t);
I = MOI('rectangleTube',0,b,h,t);
% k = radiusGyration(I,A) radius of gyration form of Euler buckling is
 too approximate
% Materials
Sy6063T5 = 21000; % psi
E6063T5 = 10000000 ;% psi
Sy6061T6 = 40000; % psi
E6061T6 = 10000000; % psi

% Buckling
Pcr1 = LongColumnCentral(1.2,E6061T6,I,50.5)
Pcr2 = LongColumnCentral(1.2,E6061T6,I,63.2)
figure;
subplot(1,2,1)
s = mesh(b,t,Pcr1);
s.FaceColor = 'flat';
FupPlane = (Fup+Fpre)* ones(length(t),length(b));
hold on
s1 = mesh(b,t,FupPlane);
s1.FaceColor = 'red';
hold off
```

Q.13

```
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Pcr for Euler buckling (lbs)")
title("Buckling trade study verticle column")

% Compressive Analysis
subplot(1,2,2)
sigmaxx = CompressiveStress(Fvert,A);
s = mesh(b,t,sigmaxx);
s.FaceColor = 'flat';
FcompPlane = (Sy6061T6)* ones(length(t),length(b));
hold on
s1 = mesh(b,t,FcompPlane);
s1.FaceColor = 'red';
hold off
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Compressive stress psi")
title("Compressive Analysis of Vertical Member")
```

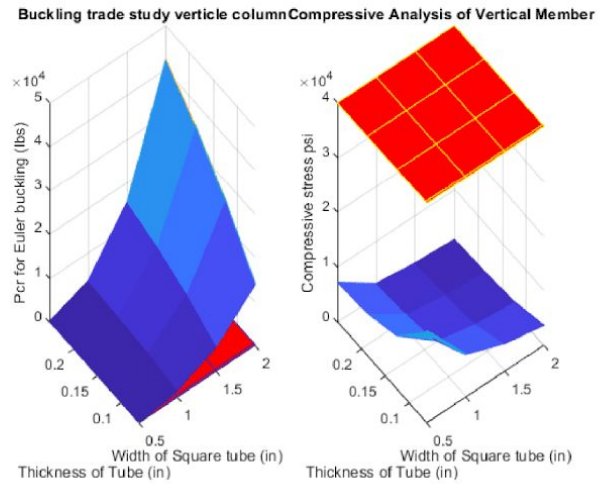
Pcr1 =

164.53	1591.1	5718.5	13986
169.35	1652.9	5958.9	14597
226.76	2645.5	10144	25624
240.93	3279.5	13393	34935
241.88	3628.2	15722	42329

Pcr2 =

105.05	1015.9	3651.2	8930
108.13	1055.4	3804.7	9319.7
144.78	1689.1	6476.6	16360
153.83	2093.9	8551.2	22306
154.43	2316.5	10038	27026

Q.14



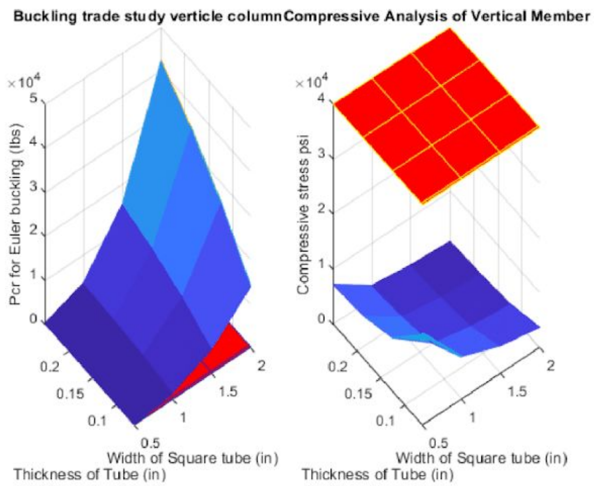
Diagonal Strut

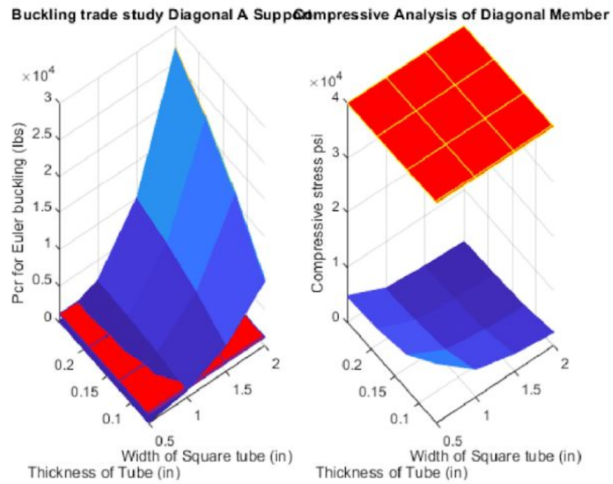
Buckling

```
figure;
subplot(1,2,1)
s3 = mesh(b,t,Pcr2);
s3.FaceColor = 'flat';
FdiagPlane = Fdiag* ones(length(t),length(b));
hold on
s4 = mesh(b,t,FdiagPlane);
s4.FaceColor = 'red';
hold off
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Pcr for Euler buckling (lbs)")
title("Buckling trade study Diagonal A Support")

% Compresive Analysis
subplot(1,2,2)
sigmaxx = CompressiveStress(Fdiag,A);
s = mesh(b,t,sigmaxx);
s.FaceColor = 'flat';
FcompPlane = (Sy6061T6)* ones(length(t),length(b));
hold on
s1 = mesh(b,t,FcompPlane);
```

Q.15

```
s1.FaceColor = 'red';
hold off
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Compressive stress psi")
title("Compressive Analysis of Diagonal Member")
```





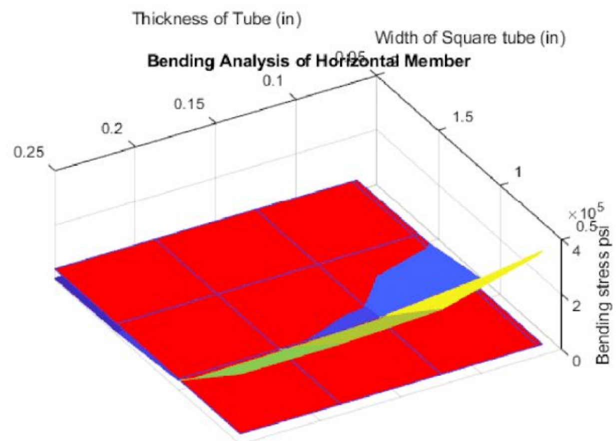
Horizontal Member

```
figure;
sigmaxx = BendingStress(Mhoz,b./2,I);
s = mesh(b,t,sigmaxx);
s.FaceColor = 'flat';
FbendPlane = (Sy6061T6)* ones(length(t),length(b));
hold on
s1 = mesh(b,t,FbendPlane);
s1.FaceColor = 'red';
hold off
view(60,120)
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Bending stress psi")
title("Bending Analysis of Horizontal Member")
```

sigmaxx =

3.8007e+05	78602	32805	17884
3.6925e+05	75663	31482	17136
2.7576e+05	47274	18494	9761.5
2.5954e+05	38135	14007	7159.8
2.5853e+05	34470	11932	5909.2

Q.17



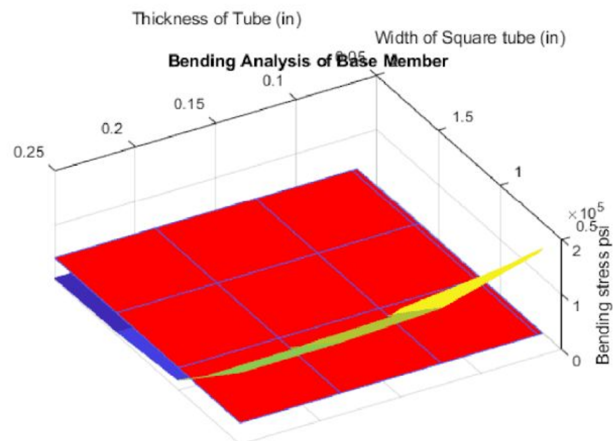
Base Member

```
figure;
sigmaxx = BendingStress(Mbase,b./2,I);
s = mesh(b,t,sigmaxx);
s.FaceColor = 'flat';
FbendPlane = (Sy6061T6)* ones(length(t),length(b));
hold on
s1 = mesh(b,t,FbendPlane);
s1.FaceColor = 'red';
hold off
view(60,120)
xlabel("Width of Square tube (in)")
ylabel("Thickness of Tube (in)")
zlabel("Bending stress psi")
title("Bending Analysis of Base Member")
```

sigmaxx =

1.9427e+05	40177	16768	9141.1
1.8874e+05	38675	16092	8758.9
1.4095e+05	24163	9452.9	4989.5
1.3266e+05	19492	7159.5	3659.6
1.3214e+05	17619	6099	3020.4

Q.18



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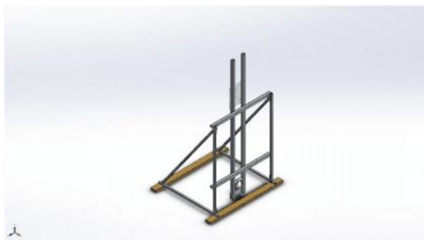
Appendix M: FEA Frame Analysis

Q.19

Frame FEA Calculations – Concept Stage Design, applicable for most loading conditions of Final Design.



Simulation of Master_Assembly_V2_ Analysis

Date: Monday, February 10, 2020
Designer: Aaron Erickson
Study name: Static Max Stall Case
Analysis type: Static

Table of Contents

Description

No Data

0

Q.22

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Model name: Master_Assembly_V2_Analysis
Current Configuration: Default

Solid Bodies

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
LPattern2	Solid Body	Mass:1.20062 kg Volume:0.000444674 m^3 Density:2,700 kg/m^3 Weight:11.7661 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Drill_V1\Backing Plate_V1.SLDPRT Feb 2 21:23:02 2020
Fillet2	Solid Body	Mass:0.389834 kg Volume:0.000144383 m^3 Density:2,700 kg/m^3 Weight:3.82037 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1_1x1_tube.SLDPRT Feb 9 21:20:25 2020
Fillet2	Solid Body	Mass:0.389834 kg Volume:0.000144383 m^3 Density:2,700 kg/m^3 Weight:3.82037 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1_1x1_tube.SLDPRT Feb 9 21:20:25 2020
Fillet2	Solid Body	Mass:0.494023 kg Volume:0.000182972 m^3 Density:2,700 kg/m^3 Weight:4.84143 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1x1_Verts.SLDPRT Feb 9 21:20:25 2020

Q.23

Fillet2	Solid Body	Mass:0.494023 kg Volume:0.000182972 m^3 Density:2,700 kg/m^3 Weight:4.84143 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1x1_Verts.SLDPRT Feb 9 21:20:25 2020
Draft2	Solid Body	Mass:0.579808 kg Volume:0.000214744 m^3 Density:2,700 kg/m^3 Weight:5.68212 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1x1_diagonal.SLDPRT Feb 9 21:20:25 2020
Draft2	Solid Body	Mass:0.579808 kg Volume:0.000214744 m^3 Density:2,700 kg/m^3 Weight:5.68212 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\1x1_diagonal.SLDPRT Feb 9 21:20:25 2020
Fillet1	Solid Body	Mass:0.658828 kg Volume:0.00411793 m^3 Density:159.99 kg/m^3 Weight:6.45651 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\2x4.SLDPRT Feb 9 21:29:36 2020
Fillet1	Solid Body	Mass:0.658828 kg Volume:0.00411793 m^3 Density:159.99 kg/m^3 Weight:6.45651 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\2x4.SLDPRT Feb 9 21:29:36 2020
Fillet2	Solid Body	Mass:0.600748 kg Volume:0.000222499 m^3 Density:2,700 kg/m^3 Weight:5.88733 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\4_1.5x1.5_tube.SLDPRT Feb 9 21:20:25 2020
Fillet2	Solid Body	Mass:0.600748 kg Volume:0.000222499 m^3 Density:2,700 kg/m^3 Weight:5.88733 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\4_1.5x1.5_tube.SLDPRT Feb 9 21:20:25 2020
Split Line1	Solid Body	Mass:0.0577622 kg Volume:2.13934e-05 m^3 Density:2,700 kg/m^3 Weight:0.566069 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\Frame_5_Bottom Clevis.SLDPRT Feb 9 21:20:25 2020
Split Line1	Solid Body	Mass:0.0577622 kg Volume:2.13934e-05 m^3 Density:2,700 kg/m^3 Weight:0.566069 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\Frame_5_Bottom Clevis.SLDPRT Feb 9 21:20:25 2020
Split Line1	Solid Body	Mass:0.0823151 kg Volume:3.04871e-05 m^3	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\F

		Density:2,700 kg/m^3 Weight:0.806688 N	rame_6_Top_Angle_Clevis.SLDPRT Feb 9 21:20:25 2020
<Frame_6_Top_Angle_Clevis>-<Split Line1>	Solid Body	Mass:0.0823152 kg Volume:3.04871e-05 m^3 Density:2,700 kg/m^3 Weight:0.806689 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Frame_V2\Frame_7_Top_Angle_ClevisRH.SLDPRT Feb 9 21:20:25 2020
Boss-Extrude1	Solid Body	Mass:1.39573 kg Volume:0.000174466 m^3 Density:8,000 kg/m^3 Weight:13.6781 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Analysis\Simplified_Frame_Assy_V2\HGH15_39_Horizontal_Analysis.SLDPRT Feb 10 20:44:52 2020
Boss-Extrude1	Solid Body	Mass:1.39573 kg Volume:0.000174466 m^3 Density:8,000 kg/m^3 Weight:13.6781 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Analysis\Simplified_Frame_Assy_V2\HGH15_39_Horizontal_Analysis.SLDPRT Feb 10 20:44:52 2020
Fillet2	Solid Body	Mass:1.21882 kg Volume:0.000451413 m^3 Density:2,700 kg/m^3 Weight:11.9444 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Z_Axis_Assembly_V1\1_5x1_5_Verts.SLDPRT Feb 9 21:20:25 2020
Fillet2	Solid Body	Mass:1.21882 kg Volume:0.000451413 m^3 Density:2,700 kg/m^3 Weight:11.9444 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Z_Axis_Assembly_V1\1_5x1_5_Verts.SLDPRT Feb 9 21:20:25 2020
Cut-Extrude2	Solid Body	Mass:0.595158 kg Volume:7.43948e-05 m^3 Density:8,000 kg/m^3 Weight:5.83255 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Z_Axis_Assembly_V1\BK10_Bracket.SLDPRT Feb 2 21:22:58 2020
Cut-Extrude1	Solid Body	Mass:0.495417 kg Volume:0.000183488 m^3 Density:2,700 kg/m^3 Weight:4.85509 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Z_Axis_Assembly_V1\Drill_Bit_Collar.SLDPRT Feb 2 21:22:57 2020
Split Line1	Solid Body	Mass:2.05177 kg Volume:0.000256472 m^3 Density:8,000 kg/m^3 Weight:20.1074 N	C:\Users\Aaron\Desktop\NASA_Drill_V1\Analysis\Simplified_Frame_Assy_V2\HGH15_39_Analysis.SLDPRT Feb 10 21:38:46 2020
Split Line1	Solid Body	Mass:2.05177 kg Volume:0.000256472 m^3 Density:8,000 kg/m^3	C:\Users\Aaron\Desktop\NASA_Drill_V1\Analysis\Simplified_Frame_Assy_V2\H

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		Weight:20.1074 N	**GH15_39_Analysis.SLDPRT** Feb 10 21:38:46 2020

Study Properties

Study name	Static Max Stall Case
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\Aaron\Desktop\NASA_Drill_V1\Analysis\Simplified_Frame_Assy_V2)

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Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

Model Reference	Properties	Components
	**Name:** 6061-T6 (SS) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Yield strength:** 2.75e+08 N/m^2 **Tensile strength:** 3.1e+08 N/m^2 **Elastic modulus:** 6.9e+10 N/m^2 **Poisson's ratio:** 0.33 **Mass density:** 2,700 kg/m^3 **Shear modulus:** 2.6e+10 N/m^2 **Thermal expansion coefficient:** 2.4e-05 /Kelvin	SolidBody 1(LPattern2)(Drill_V1_Analysis-1/Backing Plate_V1-1), SolidBody 1(Fillet2)(Frame_V2-1/1_1x1_tube-4), SolidBody 1(Fillet2)(Frame_V2-1/1_1x1_tube-5), SolidBody 1(Fillet2)(Frame_V2-1/1x1_Verts-1), SolidBody 1(Fillet2)(Frame_V2-1/1x1_Verts-2), SolidBody 1(Draft2)(Frame_V2-1/1x1_diagonal-1), SolidBody 1(Draft2)(Frame_V2-1/1x1_diagonal-2), SolidBody 1(Fillet2)(Frame_V2-1/4_1.5x1.5_tube-4), SolidBody 1(Fillet2)(Frame_V2-1/4_1.5x1.5_tube-5), SolidBody 1(Split Line1)(Frame_V2-1/Frame_5_Bottom Clevis-2), SolidBody 1(Split Line1)(Frame_V2-1/Frame_5_Bottom Clevis-3), SolidBody 1(Split Line1)(Frame_V2-1/Frame_6_Top_Angle_Clevis-2), SolidBody 1(<Frame_6_Top_Angle_Clevis>-<Split Line1>)(Frame_V2-1/Frame_7_Top_Angle_Clevis RH-1), SolidBody 1(Fillet2)(Zaxis_V2_Analysis-1/1_5x1_5_Verts-1),

		SolidBody 1(Fillet2)(Zaxis_V2_Analysis-1/1_5x1_5_Verts-2), SolidBody 1(Cut-Extrude1)(Zaxis_V2_Analysis-1/Drill_Bit_Collar-1)
Curve Data:N/A		
	**Name:** Pine (2) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Yield strength:** 2e+07 N/m^2 **Elastic modulus:** 1.048e+10 N/m^2 **Poisson's ratio:** 0.29 **Mass density:** 159.99 kg/m^3 **Shear modulus:** 3e+08 N/m^2	SolidBody 1(Fillet1)(Frame_V2-1/2x4-1), SolidBody 1(Fillet1)(Frame_V2-1/2x4-2)
Curve Data:N/A		
	**Name:** AISI 316 Annealed Stainless Steel Bar (SS) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Yield strength:** 1.37895e+08 N/m^2 **Tensile strength:** 5.5e+08 N/m^2 **Elastic modulus:** 1.93e+11 N/m^2 **Poisson's ratio:** 0.3 **Mass density:** 8,000 kg/m^3 **Thermal expansion coefficient:** 1.6e-05 /Kelvin	SolidBody 1(Boss-Extrude1)(Frame_V2-1/HGH15_39_Horizontal_Analysis-3), SolidBody 1(Boss-Extrude1)(Frame_V2-1/HGH15_39_Horizontal_Analysis-4), SolidBody 1(Cut-Extrude2)(Zaxis_V2_Analysis-1/BK10_Bracket-4), SolidBody 1(Split Line1)(Zaxis_V2_Analysis-1/HGH15_39_Analysis-1), SolidBody 1(Split Line1)(Zaxis_V2_Analysis-1/HGH15_39_Analysis-2)
Curve Data:N/A		

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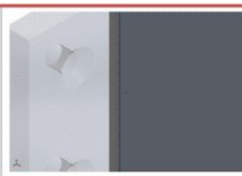
Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 2 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	2,279.62	-6.10352e-05	-153.908	2,284.81
Reaction Moment(N.m)	0	0	0	0

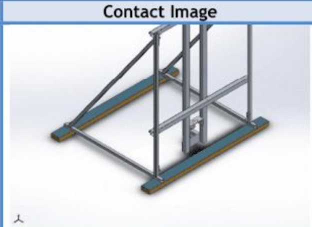
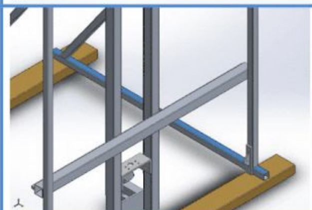
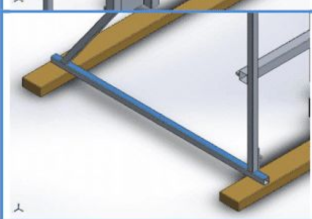
Load name	Load Image	Load Details
Force-1		**Reference:** Face< 1 > **Type:** Apply force **Values:** 17.3, 11.5, 403.57 lbf
Force-2		**Reference:** Face< 1 > **Type:** Apply force **Values:** -17.3, 11.5, 80.3 lbf

Force-3		**Entities:** 1 face(s) **Type:** Apply force **Values:** 17.3, -11.5, 108.91 lbf
Force-4		**Reference:** Face< 1 > **Type:** Apply force **Values:** -17.5, -11.5, -,214.4 lbf

Connector Definitions

Connector Name	Connector Details	Connector Image
Spring Connector-1	**Entities:** 2 vertex(s) **Type:** Spring(Two locations)(Extension only) **Axial stiffness value:** 379,160 lbf/in **Tangential Stiffness:** 0 lbf/in **Rotational stiffness value:** 0 lbf.in/rad **Pre-tension value:** 83 lbf	 Spring Connector-1
Spring Connector-2	**Entities:** 2 vertex(s) **Type:** Spring(Two locations)(Extension only) **Axial stiffness value:** 379,160 lbf/in **Tangential Stiffness:** 0 lbf/in **Rotational stiffness value:** 0 lbf.in/rad **Pre-tension value:** 83 lbf	 Spring Connector-2

Contact Information

Contact	Contact Image	Contact Properties
Contact Set-1		**Type:** Bonded contact pair **Entities:** 4 face(s)
Contact Set-2		**Type:** Bonded contact pair **Entities:** 3 face(s)
Contact Set-3		**Type:** Bonded contact pair **Entities:** 3 face(s)

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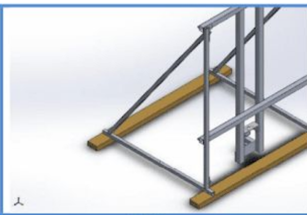
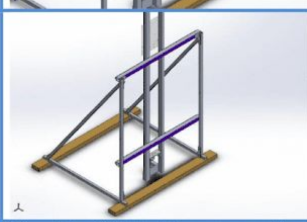
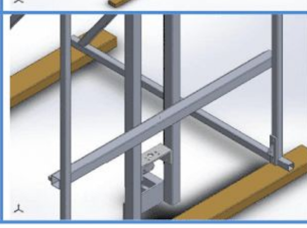
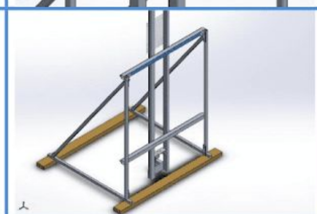
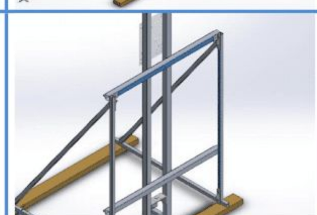
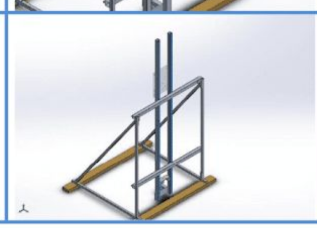
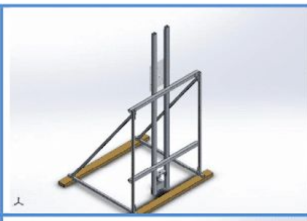
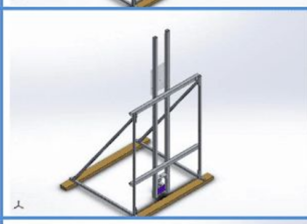
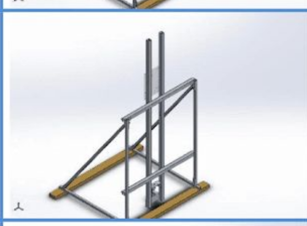
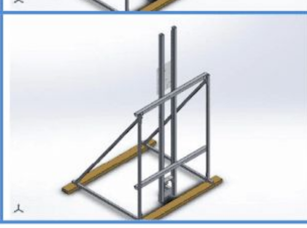
Contact Set-4		**Type:** Bonded contact pair **Entities:** 3 face(s)
Contact Set-5		**Type:** Bonded contact pair **Entities:** 3 face(s)
Contact Set-6		**Type:** Bonded contact pair **Entities:** 6 face(s)
Contact Set-7		**Type:** Bonded contact pair **Entities:** 2 face(s)

Contact Set-8		**Type:** Bonded contact pair **Entities:** 2 face(s)
Contact Set-9		**Type:** Bonded contact pair **Entities:** 4 face(s)
Contact Set-10		**Type:** Bonded contact pair **Entities:** 4 face(s)
Contact Set-11		**Type:** Bonded contact pair **Entities:** 4 face(s)

Contact Set-12		**Type:** Bonded contact pair **Entities:** 4 face(s)
Contact Set-13		**Type:** Bonded contact pair **Entities:** 3 face(s)
Contact Set-14		**Type:** Bonded contact pair **Entities:** 2 face(s)
Contact Set-15		**Type:** Bonded contact pair **Entities:** 2 face(s)

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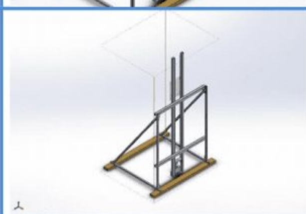
Contact Set-16		**Type:** Bonded contact pair **Entities:** 10 face(s)
Global Contact		**Type:** Bonded **Components:** 1 component(s) **Options:** Compatible mesh

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Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.3 in
Tolerance	0.01 in
Mesh Quality Plot	High
Remesh failed parts with incompatible mesh	Off

Mesh information - Details

Total Nodes	670097
Total Elements	376326
Maximum Aspect Ratio	7.5352e+05
% of elements with Aspect Ratio < 3	46.6
% of elements with Aspect Ratio > 10	5.17
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:01:01
Computer name:	

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Sensor Details

No Data

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	2,279.62	-6.10352e-05	-153.908	2,284.81

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

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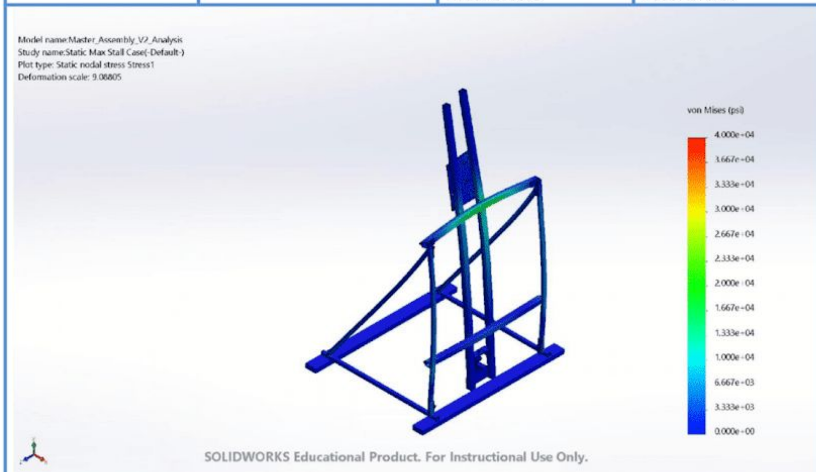
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.000e+00 psi Node: 216803	5.924e+04 psi Node: 216755



Master_Assembly_V2_Analysis-Static Max Stall Case-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00 in Node: 24978	8.829e-01 in Node: 505263

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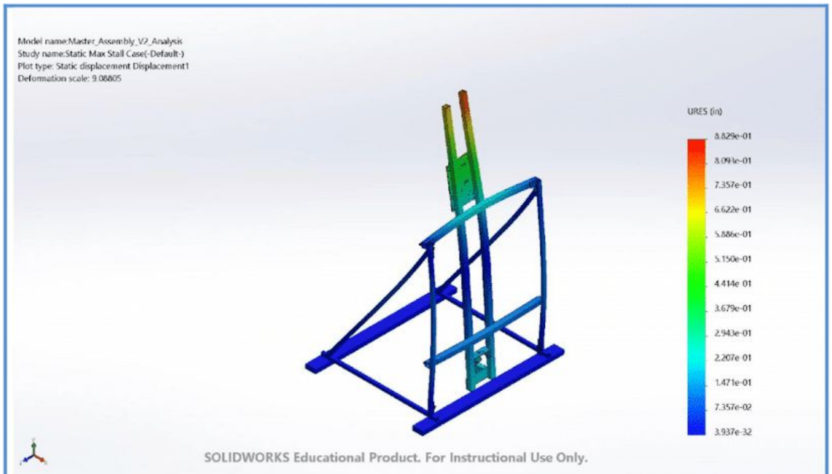

Master_Assembly_V2_Analysis-Static Max Stall Case-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	0.000e+00 Element: 109513	3.231e-03 Element: 318012

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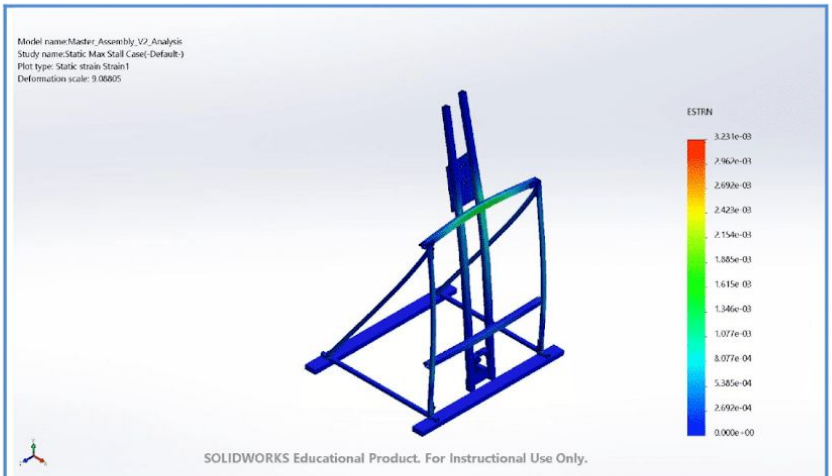

Master_Assembly_V2_Analysis-Static Max Stall Case-Strain-Strain1

Conclusion

Appendix N: Matlab Calculations for Axis travel and Tools

MATLAB Calculations for Axis Travel Characteristics, Tool Torsion, and Heater Probe Loading

Contents


```
% Matlab Calculations for STYX
% Last Updated: 4/08/2020
```

Z axis Leadscrew Calcs

```
clear all;
clc;
close all;
format short;
format compact;

% Check typical lifting Torques required and if self-locking

F=30;       % MAX Vertical load being reacted during drilling
% or lifting [lbf]
W=30;       % Weight of entire z-axis gantry [lbf]
F=(F+W)*4.448;  % TOTAL load converted Newton [N]
do=12.7;      % Nominal (outer) diameter [mm]
p=2.54;        % Pitch of screw [mm]
l=2.54;        % Lead of screw [mm]
starts=l/p;
dr=do-1.299038*p;    % Minor diameter of screw [mm]
dm=(do+dr)/2;      % Average diameter of screw [mm]
f=.25;      % Friction coefficient. Lower is conservative if calculating
% min self-locking force .1-.25
y=atand(l/(pi*dm));
Lockcheck=tand(y);
if f>Lockcheck
    disp('self-locking')
else disp('NOT self-locking')
end
FS=1.5;     % FACTOR OF SAFETY
T_raise=((F*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10*FS
% Raising Torque (Not relevant in horizontal) [N-cm];
disp('N-cm');
T_lower=((F*dm)/2)*((-l+(pi*f*dm))/((pi*dm)+(f*l)))/10*FS
% Lowering Torque (Not relevant in horizontal) [N-cm];
disp('N-cm')

%Calculate maximum lifting force available
MaxT=6.3;   % Max T of Chosen motor and gearset (Andymark PG27) [ft-lbf]
MaxT=MaxT*135.58; %Max T of chosen motor and gearset [N-cm]
```

```
Fmax=1000; %Maximum lifting force [lbf]
Fmax=(Fmax+W)*4.488;    %Add weight of Z-axis gantry and convery to [N]
TrMax=((Fmax*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10;
% Torque required by screw at max lifting capacity[N-cm]

MaxLift=['Max Torque of chosen motor is ',num2str(MaxT)...
    ,'[N-cm] and with ',num2str(Fmax)...
    ,'N Load, The screw liting torque required is '...
    ,num2str(TrMax),'[N-cm]'];
disp(MaxLift)


%Calculate maximum Z-Axis Speed
rpm=198;    % No load rpm of motor and gearset
dist=1600;  % Max Z-axis travel [mm]
MaxSpeed=rpm/60*l;   % Maximum jog speed [mm/s]
Travel_time=dist/MaxSpeed;
MaxSpeed=['Max Z-Axis Jog Speed is ',num2str(MaxSpeed),'mm/s'];
Travel_time=['Estimated Z-axis jog time is ',num2str(Travel_time)...
    ,' seconds.'];
disp(MaxSpeed)
disp(Travel_time)

%Calculate buckling
E=2e11;    % Modulus of elasticity, steel [pa]
r=(dr/2)/1000;     % Radius of screw minor diameter [m]
I=pi()/4*r^4;   % Moment of inertia for circle [m^4]
L=2;     % Length of screw [m]
k=1;     % End condition, both fixed
Pcr=pi()^2*E*I/(k*L)^2/4.448   % Critical load in [lbf]
disp('Pcr > Max allowable load of 30 lbf')
```

```
self-locking
T_raise =
   72.8102
N-cm
T_lower =
   38.4097
N-cm
Max Torque of chosen motor is 854.154[N-cm] and with 4622.64N Load, The screw liting torque r
equired is 840.7658[N-cm]
Max Z-Axis Jog Speed is 8.382mm/s
Estimated Z-axis jog time is 190.8852 seconds.
Pcr =
   42.5273
Pcr > Max allowable load of 30 lbf
```

X axis Leadscrew Calcs

```
clear all;
clc;
close all;
format short;
format compact;
```

Q.45

```
rail_fric=.2    % Bearing Friction
N=50;       % Entire x-axis carraige weight [lbf]
F=N*rail_fric*4.448;  % Convert Load to Newton [N]
do=9.5;      % Nominal (outer) diameter [mm]
p=3.175;        % Pitch of screw [mm]
l=3.175;        % Lead of screw [mm]
starts=l/p;
dr=do-1.299038*p;     % Minor diameter of screw [mm]
dm=(do+dr)/2;      % Average diameter of screw [mm]
f=.25      % Friction coefficient. Lower is conservative if
% calculating min self-locking force
y=atand(l/(pi*dm));
Lockcheck=tand(y)
if f>Lockcheck
    disp('self-locking')
else disp('NOT self-locking')
end
FS=1.5;          % Torque Factor of Safety
Tr=((F*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10*FS;
% Raising Torque (Not relevant in horizontal) [N-cm];
Tl=((F*dm)/2)*((-l+(pi*f*dm))/((pi*dm)+(f*l)))/10*FS;
% Lowering Torque (Not relevant in horizontal) [N-cm];
Typical_Torque=(Tr+Tl)/2
% Average raising and lowering torque to cancel out gravity
disp('N-cm')

dist=900;           % Max jog distance [mm]
Tmotor=59;           % Motor Torque, nema 17 stepper [N-cm]
rpm=600;             % Typical stepper max speed of 10rps. ;
ratio=3;             % Belt gear ratio
Tout=Tmotor*ratio      % Max Torque to screw
disp('N-cm')
Speedout=rpm/ratio % Max output speed to screw [rpm]
disp('rpm')
JogSpeed=Speedout/60*l
disp('mm/s')
JogTime=dist/JogSpeed
disp('seconds')
steps_rev=200;      % Motor characteristic of Nema23 stepper
max_resolution=l/(steps_rev*ratio)      % max resolution of screw [mm]
disp('mm')

%Max torque Case
Max_force=1850  % Max load test, [N]
disp('N')
Tr=((Max_force*dm)/2)*((l+(pi*f*dm))/((pi*dm)-(f*l)))/10;
% Raising Torque (Not relevant in horizontal) [N-cm];
Tl=((Max_force*dm)/2)*((-l+(pi*f*dm))/((pi*dm)+(f*l)))/10;
% Lowering Torque (Not relevant in horizontal) [N-cm];
Max_Torque=(Tr+Tl)/2;       %Compare this output [N-cm] to Tout.
```

```
rail_fric =
    0.2000
f =
```

Q.46

```
    0.2500
Lockcheck =
    0.1359
self-locking
Typical_Torque =
    6.3249
N-cm
Tout =
   177
N-cm
Speedout =
   200
rpm
JogSpeed =
   10.5833
mm/s
JogTime =
   85.0394
seconds
max_resolution =
    0.0053
mm
Max_force =
        1850
N
```

Tool Changer Resolution

```
clear all;
close all;
clc;

steps=200;                        %Steps/rev nema17 stepper motor
gear_ratio=5.18;                 % included planetary gear ratio
belt_ratio=3;
% Belt ratio connecting motor to tool changer
ratio=gear_ratio*belt_ratio;     % Total ratio
Tgeared=2*belt_ratio;
% rated gearbox output torque multiplied by belt ratio [Nm]
Tgeared=Tgeared*8.8507;          % Convert torque to in-lbf
Angular_resolution=360/(steps*ratio)
% theoretical angular resolution of tool changer
disp('degrees')
r=5;                             % Tool holder radius [in]
Position_resolution=r*tand(Angular_resolution)
% Theoretical positional resolution of tool changer
disp('inches')
Max_tool_force=Tgeared/r
% Max force allowable for tool changer clip in [lbf]
disp('lbf')
```

```
Angular_resolution =
    0.1158
degrees
```

```
Position_resolution =
    0.0101
inches
Max_tool_force =
   10.6208
lbf
```

Sheath Hollow Tube Torsion

```
clear all;
close all;
clc;

Tdrill=20*12;      %Drill's maximum torque [in-lbf]
FS=2;         %Factor of safety
Do=1;      % Chosen outer diameter, minor diameter of thread features [in]
Di=.875;        % Chosen inner diameter based on stock availability [in]
r=Do/2;
s_yield=63100;          % yield strength 4130 [psi]
tau_max=s_yield*.58     % conservative max torsional stress
disp('psi')
ks=2;             %worst case stress concentration factor
J=pi()/32*(Do^4-Di^4);  % Polar Moment  of inertia
tau=(Tdrill*FS*r/J)*ks  % Actual torsional stress
disp('psi')
disp('tau < tau_max')
```

```
tau_max =
       36598
psi
tau =
   1.1815e+04
psi
tau < tau_max
```

Auger Torsion

```
clear all;
close all;
clc;

% HOLLOW TUBE CONNECTION
disp('Auger Shaft Calcs')
Tdrill=20*12;      %Drill's maximum torque [in-lbf]
FS=2;         %Factor of safety
Do=.625;     % Chosen outer diameter, minor diameter of thread features [in]
Di=.39;      % Chosen inner diameter based on stock availability [in]
r=Do/2;
s_yield=63100;   % yield strength 4130 [psi]
tau_max=s_yield*.58     % Conservative max torsional stress
disp('psi')
ks=2;             % Worst case stress concentration factor
J=pi()/32*(Do^4-Di^4);
```

```
tau=(Tdrill*FS*r/J)*ks
disp('psi')
disp('tau < tau_max, adequate margin')

% SOLID ROUND BAR, AUGER CORE
disp('Auger Core Calcs')
FS2=1.4;  % Reduced FS.
% Safe since we don't plan to run at full speed anyway.
D2=.39;    % Chosen outer diameter, minor diameter of thread features [in]
r2=D2/2;
s_yield2=103000;   % yield strength 4130 [psi]
tau_max2=s_yield2*.58 %conservative max torsional stress
disp('psi')
ks=2;           %worst case stress concentration factor
J2=pi()/32*D2^4;
tau2=(Tdrill*FS2*r2/J2)*ks
disp('psi')
disp('tau < tau_max, adequate margin')
```

```
Auger Shaft Calcs
tau_max =
       36598
psi
tau =
   2.3605e+04
psi
tau < tau_max, adequate margin
Auger Core Calcs
tau_max2 =
   5.9740e+04
psi
tau2 =
   5.7696e+04
psi
tau < tau_max, adequate margin
```

Heater Probe Calculations

```
clear all;
close all;
clc;

Tmotor=22.5;        % Rated torque [kg-cm]
Tmotor=Tmotor*.868; % Convert to in-lb
Mcopper=180;        %Mass of copper [g]
Mheater=.34;        %Mass of heater [lbs]
M=Mcopper/454+Mheater;  %combined mass [lbs]
cg=3.5;             % radius to cg [in]
Torque_Raise=M*cg  % Minimum torque needed to actuate to 90 degrees [in-lb]
disp('in-lb')
Torque_margin=Tmotor-Torque_Raise %Torque margin [in-lb]
disp('in-lb')

r_axle=.125;         % Axls radius that holds string
```

Q.49

```
Fstring=Tmotor/r_axle    % String force
disp('lbf')
Strength_String=1000*.2;
% Manufacturere recommends working load of 20% Rating [lbf]
FSstring=Strength_String/Fstring    % Factor of safety on string choice
disp('factor of safety')
```

```
Torque_Raise =
    2.5777
in-lb
Torque_margin =
   16.9523
in-lb
Fstring =
  156.2400
lbf
FSstring =
    1.2801
factor of safety
```

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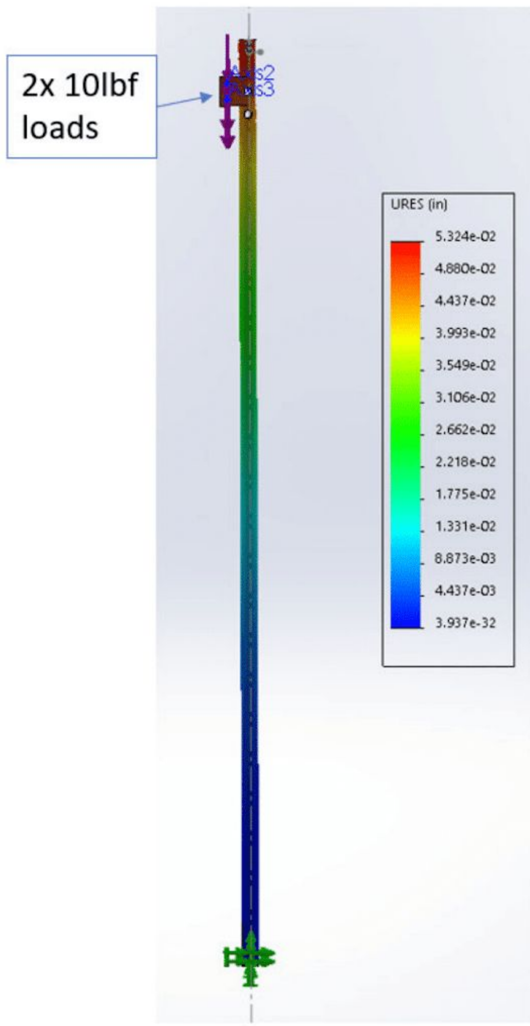
Tools FEA

Q.50

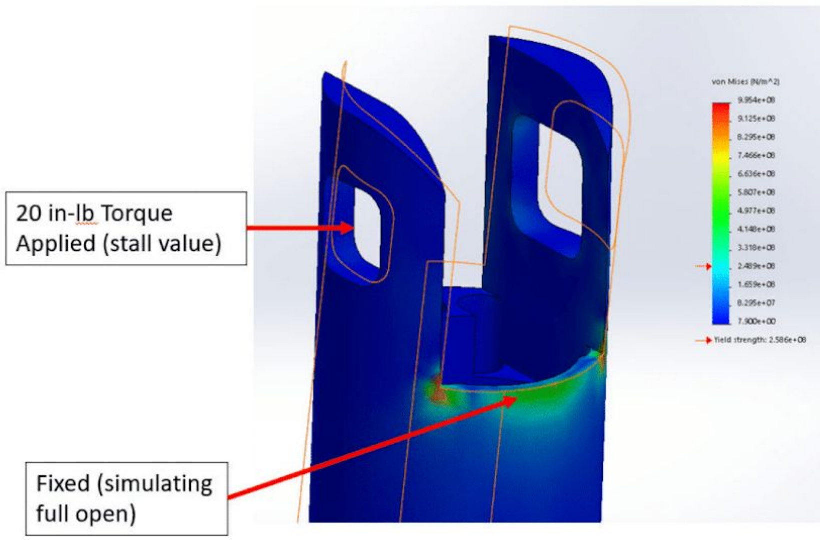
Heater Probe FEA Load Cases

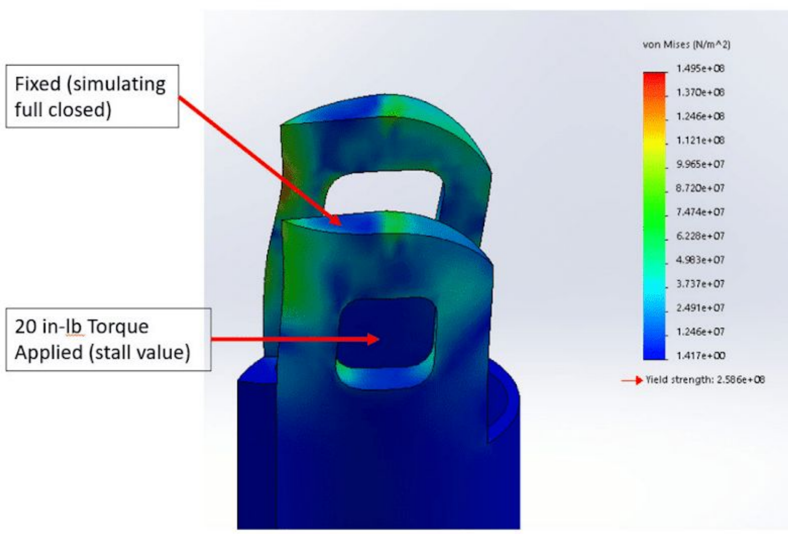
Load Case 1. Bending caused by maximum actuation motor torque. Metric of Interest: Deflection



Q.51

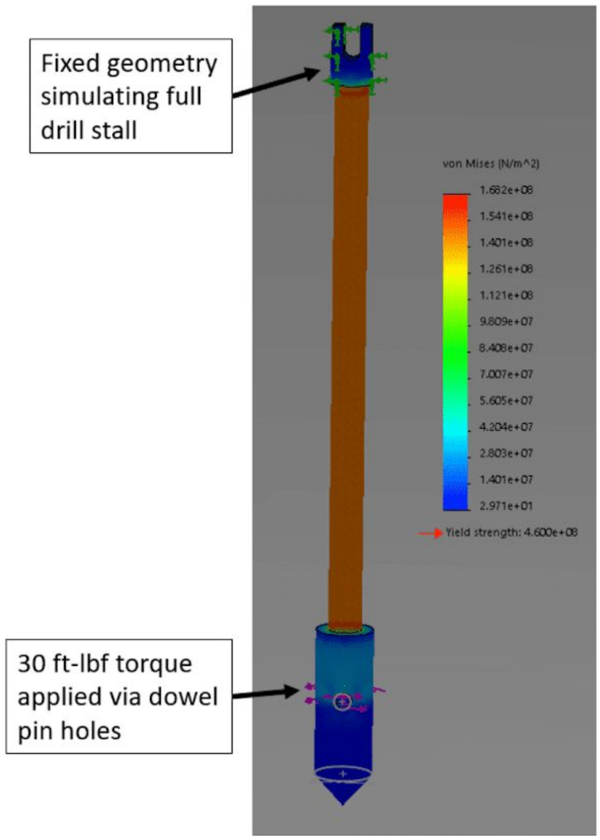
Load Case 2. Stalling open and closed. Metric of Interest: Stress





Sheath FEA Load Cases

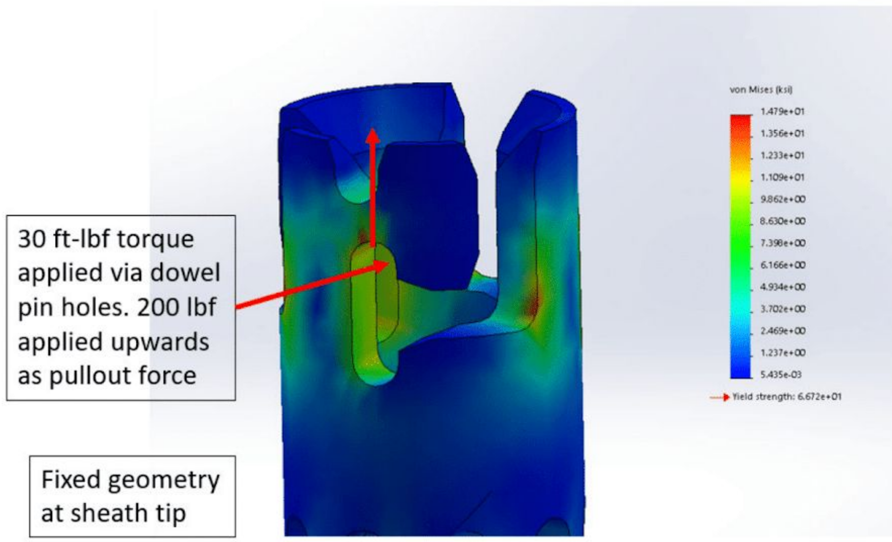
Load Case 1. Sheath Tool Dowel Pins at motor stall torque. Metric of Interest: Stress



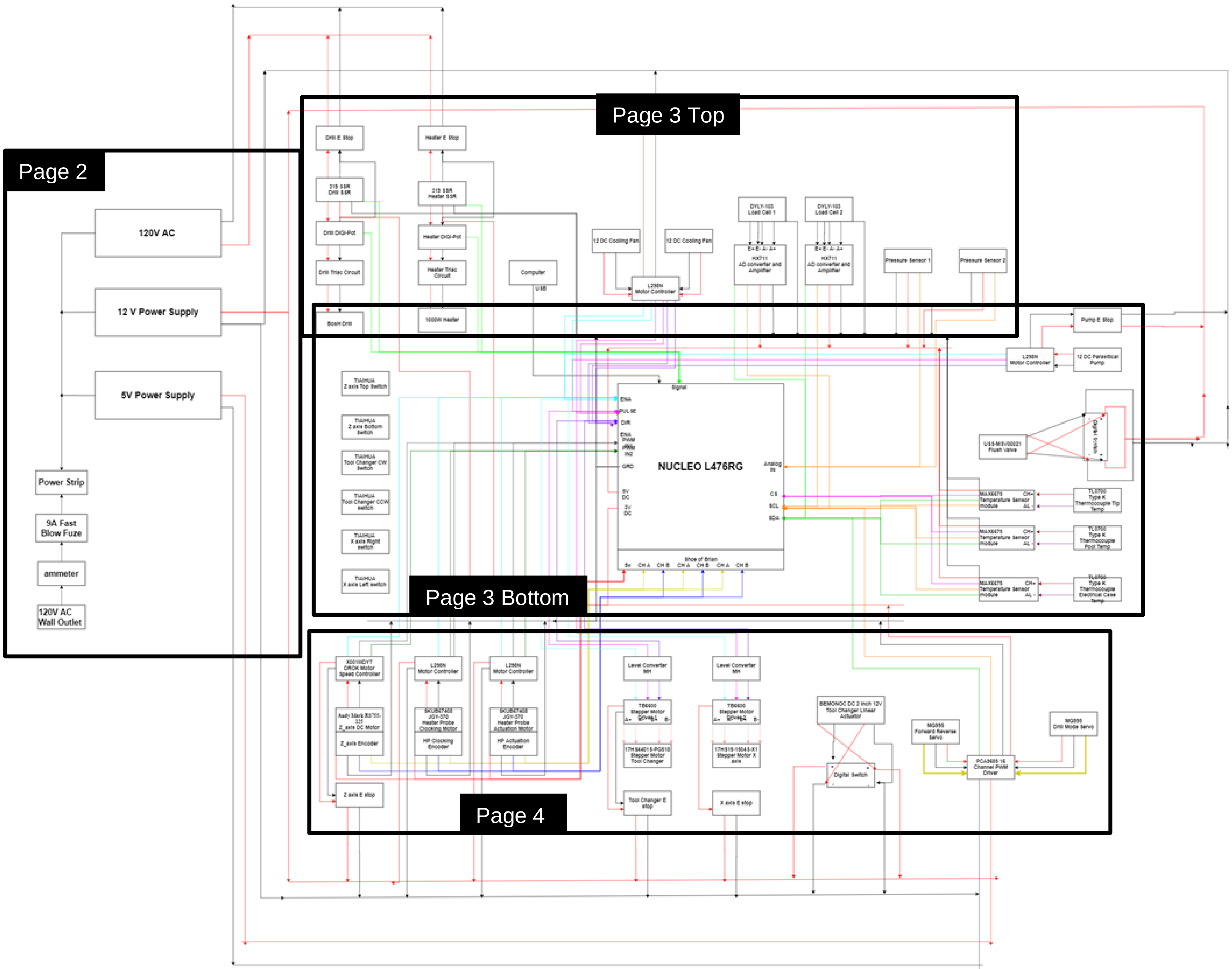
Q.53

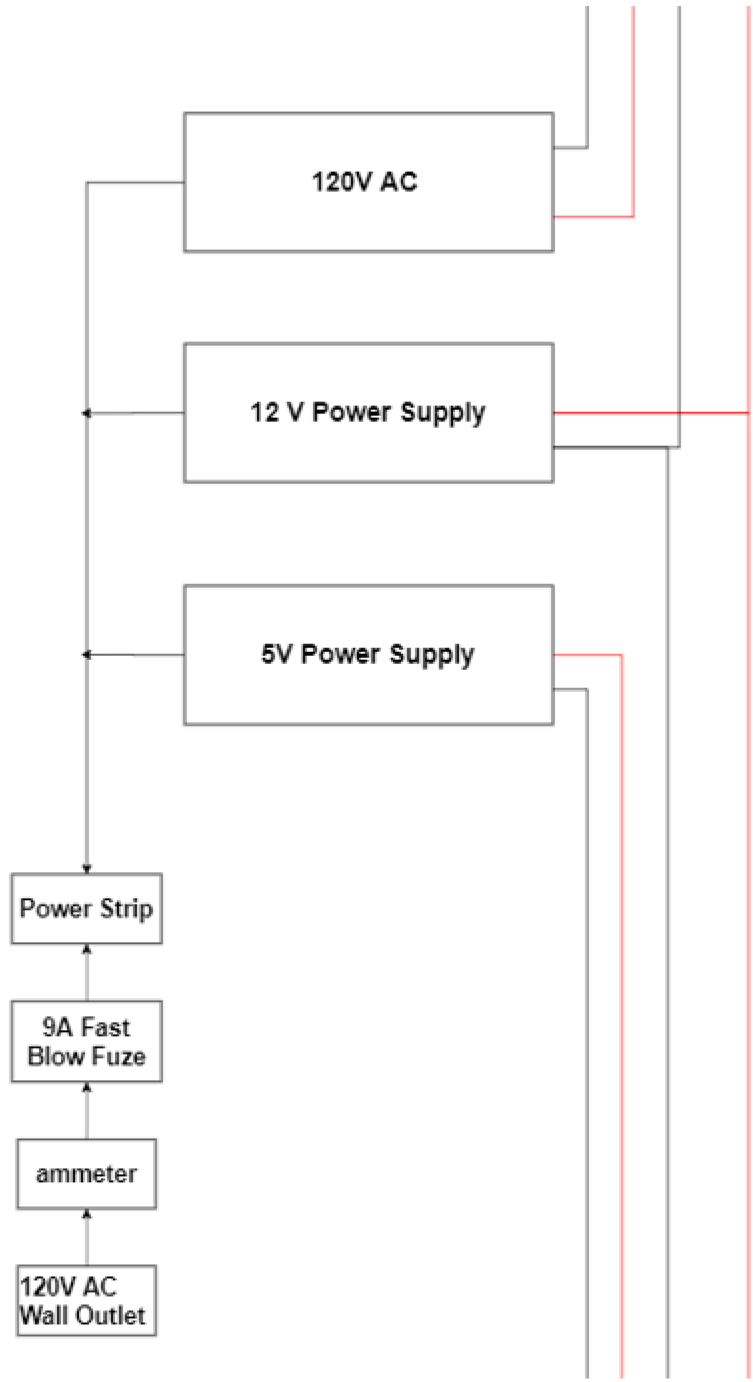
Load Case 2. Sheath dowel pin locations at motor stall torque and 200lbf pull out force.

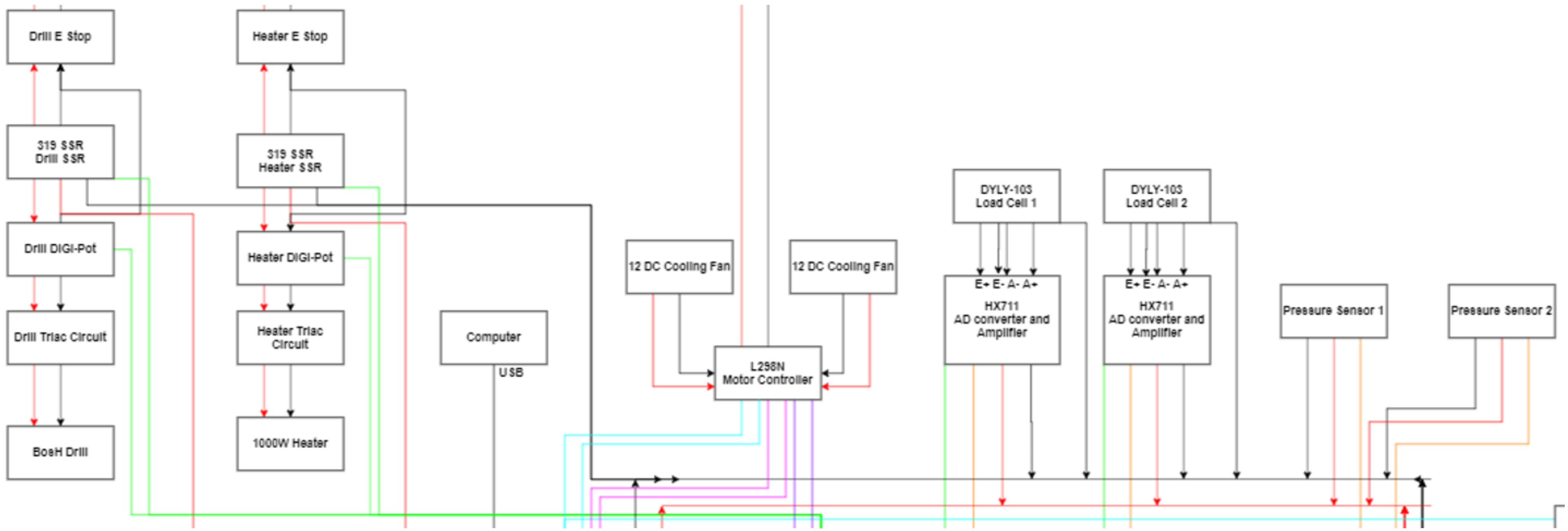
Metric of Interest: Stress



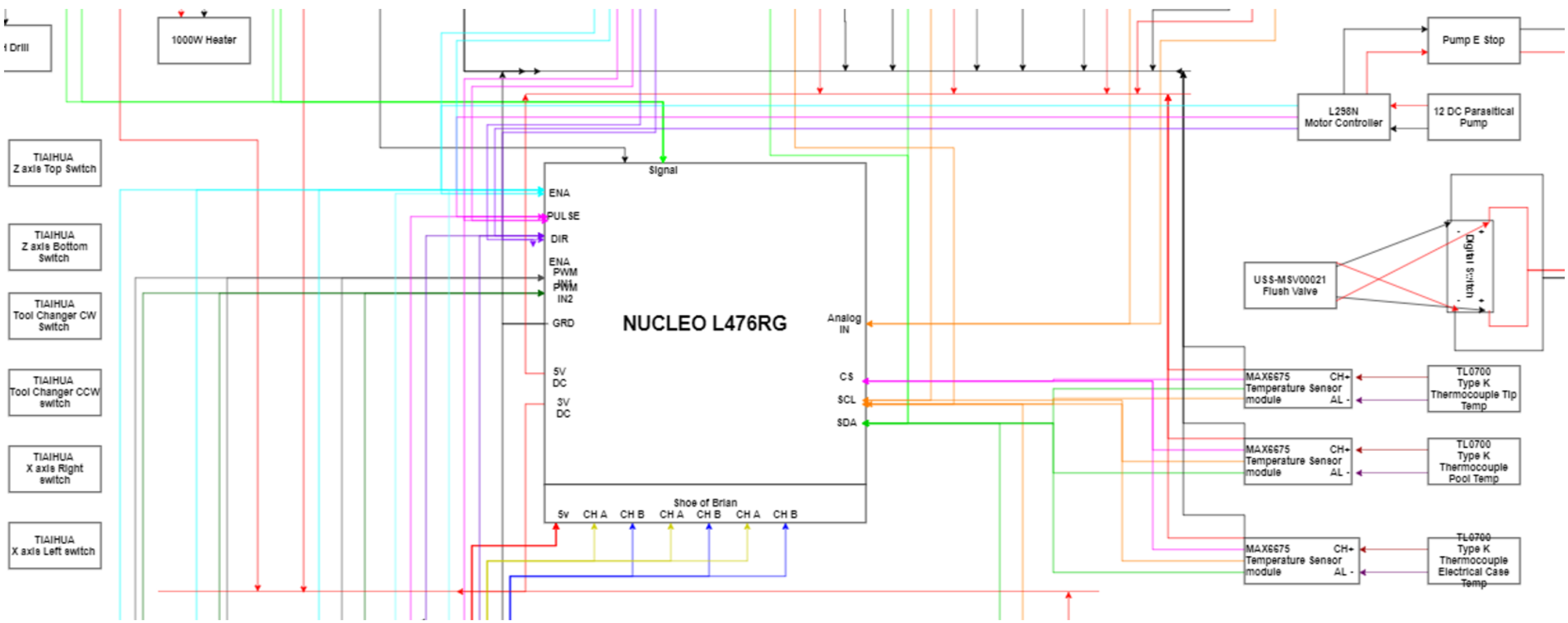
Appendix O: Wiring layout for All Systems



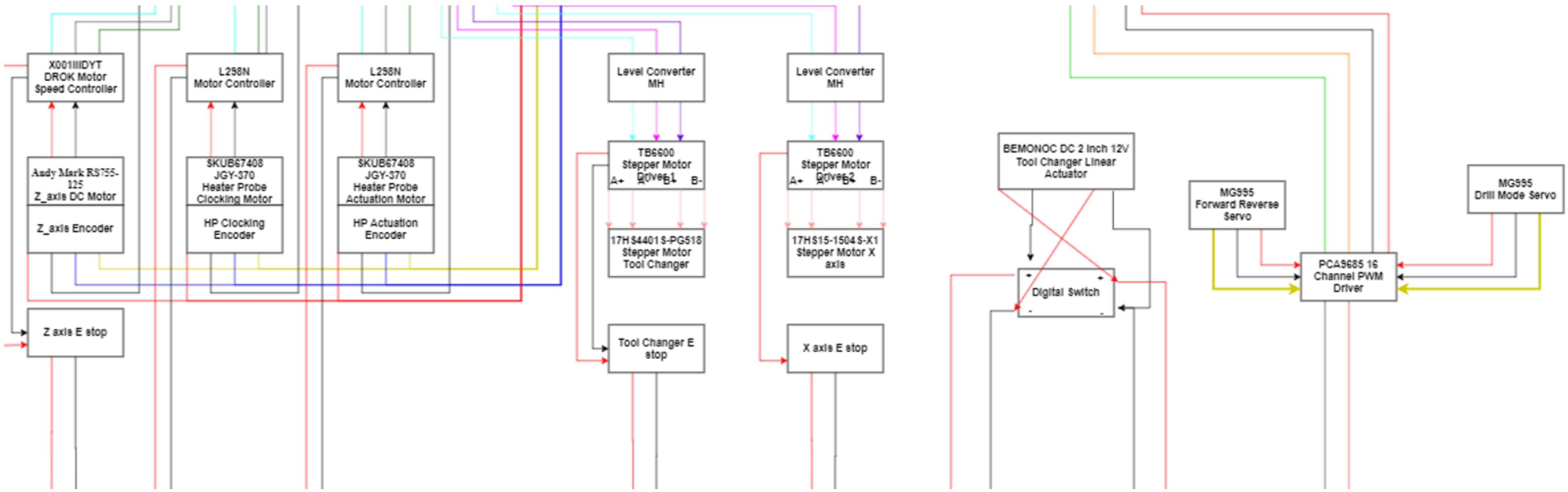

120V AC
12 V Power Supply
5V Power Supply
Power Strip
9A Fast Blow Fuze
ammeter
120V AC Wall Outlet



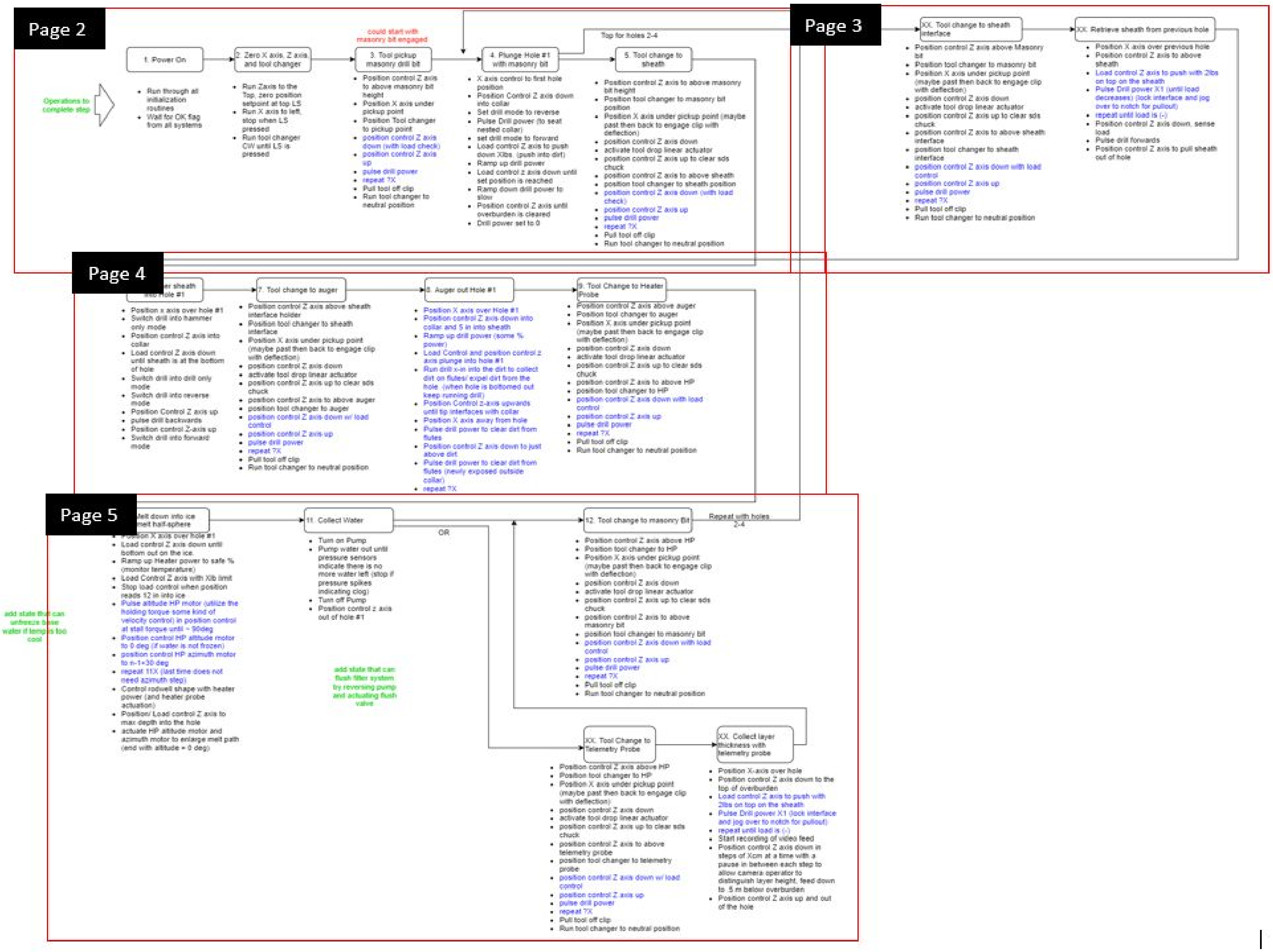
Drill E Stop
Heater E Stop
319 SSR
Drill SSR
319 SSR
Heater SSR
DYLY-103
Load Cell 1
DYLY-103
Load Cell 2
Drill DIGI-Pot
Heater DIGI-Pot
12 DC Cooling Fan
12 DC Cooling Fan
E+ E- A- A+
HX711
AD converter and
Amplifier
E+ E- A- A+
HX711
AD converter and
Amplifier
Pressure Sensor 1
Pressure Sensor 2
Drill Triac Circuit
Heater Triac
Circuit
Computer
USB
L298N
Motor Controller
BosH Drill
1000W Heater

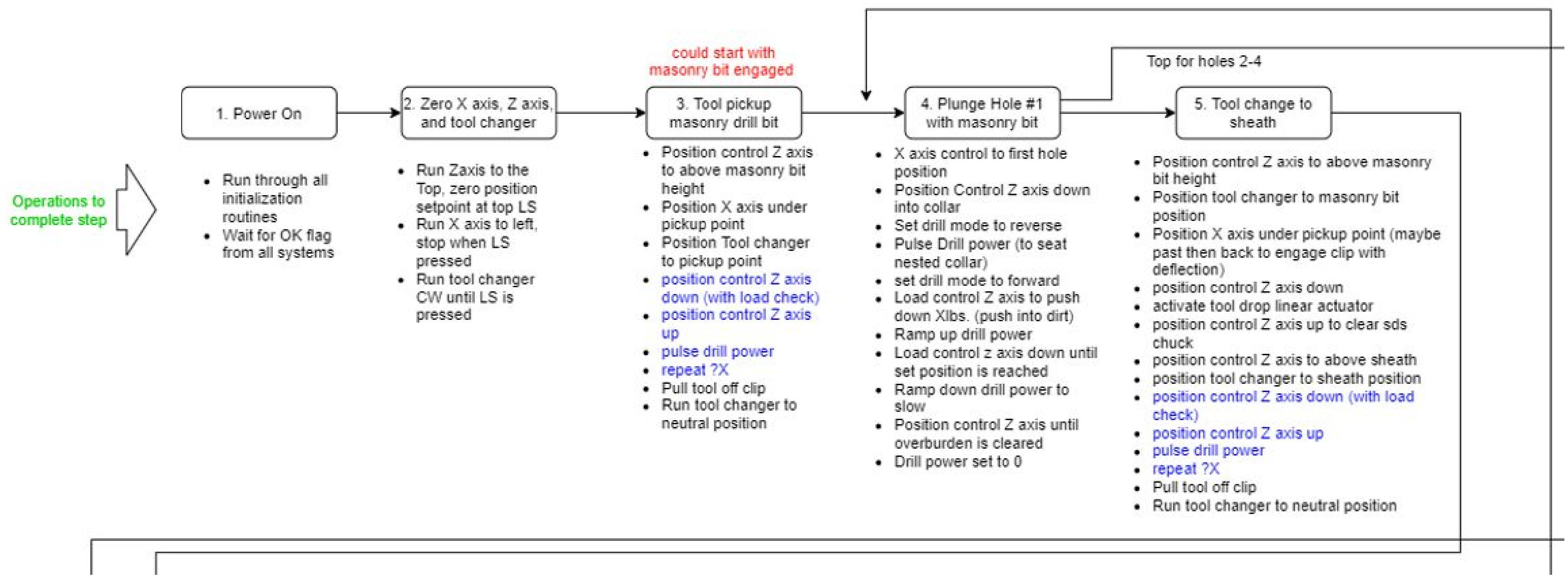


1000W Heater
Pump E Stop
L298N
Motor Controller
12 DC Parasitical
Pump
TIAIHUA
Z axis Top Switch
Signal
ENA
PULSE
DIR
ENA
PWM
IN1
PWM
IN2
GRD
5V
DC
3V
DC
NUCLEO L476RG
Analog
IN
CS
SCL
SDA
TIAIHUA
Z axis Bottom
Switch
TIAIHUA
Tool Changer CW
Switch
TIAIHUA
Tool Changer CCW
switch
TIAIHUA
X axis Right
switch
TIAIHUA
X axis Left switch
USS-MSV00021
Flush Valve
Digital Switch
MAX6675
Temperature Sensor
module
CH+
AL -
TL0700
Type K
Thermocouple Tip
Temp
TL0700
Type K
Thermocouple
Pool Temp
TL0700
Type K
Thermocouple
Electrical Case
Temp
Shoe of Brian
5v
CH A
CH B
CH A
CH B
CH A
CH B


X001IIIDYT
DROK Motor
Speed Controller
L298N
Motor Controller
L298N
Motor Controller
Level Converter
MH
Level Converter
MH
Andy Mark RS755-
125
Z_axis DC Motor
Z_axis Encoder
SKUB67408
JGY-370
Heater Probe
Clocking Motor
HP Clocking
Encoder
SKUB67408
JGY-370
Heater Probe
Actuation Motor
HP Actuation
Encoder
TB6600
Stepper Motor
Driver 1
TB6600
Stepper Motor
Driver 2
17HS4401S-PG518
Stepper Motor
Tool Changer
17HS15-1504S-X1
Stepper Motor X
axis
BEMONOC DC 2 inch 12V
Tool Changer Linear
Actuator
MG995
Forward Reverse
Servo
MG995
Drill Mode Servo
PCA9685 16
Channel PWM
Driver
Digital Switch
Z axis E stop
Tool Changer E
stop
X axis E stop

Appendix P: Flowchart of Operations to Complete Competition



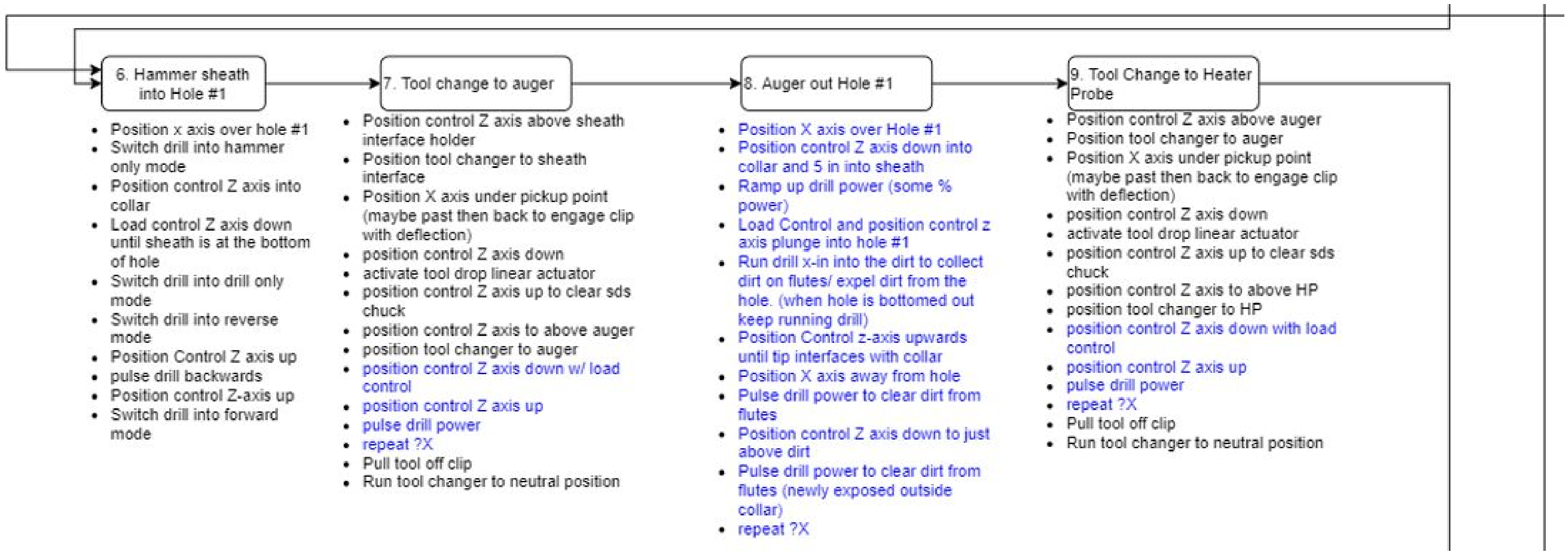

could start with masonry bit engaged
Top for holes 2-4
1. Power On
2. Zero X axis, Z axis, and tool changer
3. Tool pickup masonry drill bit
4. Plunge Hole #1 with masonry bit
5. Tool change to sheath
Operations to complete step
Run through all initialization routines
Wait for OK flag from all systems
Run Zaxis to the Top, zero position setpoint at top LS
Run X axis to left, stop when LS pressed
Run tool changer CW until LS is pressed
Position control Z axis to above masonry bit height
Position X axis under pickup point
Position Tool changer to pickup point
position control Z axis down (with load check)
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position
X axis control to first hole position
Position Control Z axis down into collar
Set drill mode to reverse
Pulse Drill power (to seat nested collar)
set drill mode to forward
Load control Z axis to push down Xlbs. (push into dirt)
Ramp up drill power
Load control z axis down until set position is reached
Ramp down drill power to slow
Position control Z axis until overburden is cleared
Drill power set to 0
Position control Z axis to above masonry bit height
Position tool changer to masonry bit position
Position X axis under pickup point (maybe past then back to engage clip with deflection)
position control Z axis down
activate tool drop linear actuator
position control Z axis up to clear sds chuck
position control Z axis to above sheath
position tool changer to sheath position
position control Z axis down (with load check)
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position

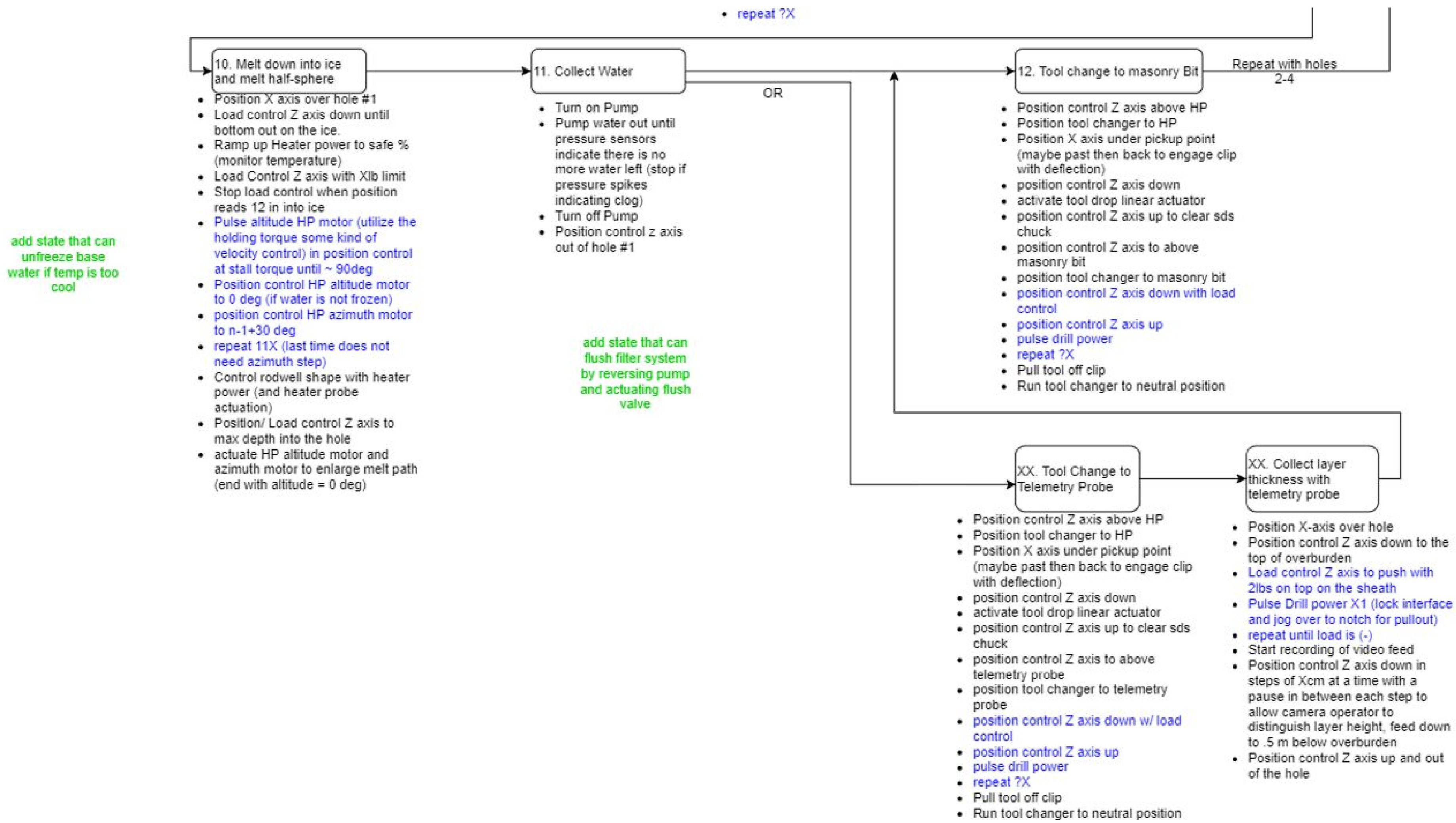
XX. Tool change to sheath interface

- Position control Z axis above Masonry bit
- Position tool changer to masonry bit
- Position X axis under pickup point (maybe past then back to engage clip with deflection)
- position control Z axis down
- activate tool drop linear actuator
- position control Z axis up to clear sds chuck
- position control Z axis to above sheath interface
- position tool changer to sheath interface
- position control Z axis down with load control
- position control Z axis up
- pulse drill power
- repeat ?X
- Pull tool off clip
- Run tool changer to neutral position

XX. Retrieve sheath from previous hole

- Position X axis over previous hole
- Position control Z axis to above sheath
- Load control Z axis to push with 2lbs on top on the sheath
- Pulse Drill power X1 (until load decreases) (lock interface and jog over to notch for pullout)
- repeat until load is (-)
- Position control Z axis down, sense load
- Pulse drill forwards
- Position control Z axis to pull sheath out of hole


6. Hammer sheath into Hole #1
Position x axis over hole #1
Switch drill into hammer only mode
Position control Z axis into collar
Load control Z axis down until sheath is at the bottom of hole
Switch drill into drill only mode
Switch drill into reverse mode
Position Control Z axis up
pulse drill backwards
Position control Z-axis up
Switch drill into forward mode
7. Tool change to auger
Position control Z axis above sheath interface holder
Position tool changer to sheath interface
Position X axis under pickup point (maybe past then back to engage clip with deflection)
position control Z axis down
activate tool drop linear actuator
position control Z axis up to clear sds chuck
position control Z axis to above auger
position tool changer to auger
position control Z axis down w/ load control
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position
8. Auger out Hole #1
Position X axis over Hole #1
Position control Z axis down into collar and 5 in into sheath
Ramp up drill power (some % power)
Load Control and position control z axis plunge into hole #1
Run drill x-in into the dirt to collect dirt on flutes/ expel dirt from the hole. (when hole is bottomed out keep running drill)
Position Control z-axis upwards until tip interfaces with collar
Position X axis away from hole
Pulse drill power to clear dirt from flutes
Position control Z axis down to just above dirt
Pulse drill power to clear dirt from flutes (newly exposed outside collar)
repeat ?X
9. Tool Change to Heater Probe
Position control Z axis above auger
Position tool changer to auger
Position X axis under pickup point (maybe past then back to engage clip with deflection)
position control Z axis down
activate tool drop linear actuator
position control Z axis up to clear sds chuck
position control Z axis to above HP
position tool changer to HP
position control Z axis down with load control
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position



repeat ?X
10. Melt down into ice and melt half-sphere
Position X axis over hole #1
Load control Z axis down until bottom out on the ice.
Ramp up Heater power to safe % (monitor temperature)
Load Control Z axis with Xlb limit
Stop load control when position reads 12 in into ice
Pulse altitude HP motor (utilize the holding torque some kind of velocity control) in position control at stall torque until ~ 90deg
Position control HP altitude motor to 0 deg (if water is not frozen)
position control HP azimuth motor to n-1+30 deg
repeat 11X (last time does not need azimuth step)
Control rodwell shape with heater power (and heater probe actuation)
Position/ Load control Z axis to max depth into the hole
actuate HP altitude motor and azimuth motor to enlarge melt path (end with altitude = 0 deg)
add state that can unfreeze base water if temp is too cool
11. Collect Water
Turn on Pump
Pump water out until pressure sensors indicate there is no more water left (stop if pressure spikes indicating clog)
Turn off Pump
Position control z axis out of hole #1
add state that can flush filter system by reversing pump and actuating flush valve
OR
12. Tool change to masonry Bit
Repeat with holes 2-4
Position control Z axis above HP
Position tool changer to HP
Position X axis under pickup point (maybe past then back to engage clip with deflection)
position control Z axis down
activate tool drop linear actuator
position control Z axis up to clear sds chuck
position control Z axis to above masonry bit
position tool changer to masonry bit
position control Z axis down with load control
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position
XX. Tool Change to Telemetry Probe
Position control Z axis above HP
Position tool changer to HP
Position X axis under pickup point (maybe past then back to engage clip with deflection)
position control Z axis down
activate tool drop linear actuator
position control Z axis up to clear sds chuck
position control Z axis to above telemetry probe
position tool changer to telemetry probe
position control Z axis down w/ load control
position control Z axis up
pulse drill power
repeat ?X
Pull tool off clip
Run tool changer to neutral position
XX. Collect layer thickness with telemetry probe
Position X-axis over hole
Position control Z axis down to the top of overburden
Load control Z axis to push with 2lbs on top on the sheath
Pulse Drill power X1 (lock interface and jog over to notch for pullout)
repeat until load is (-)
Start recording of video feed
Position control Z axis down in steps of Xcm at a time with a pause in between each step to allow camera operator to distinguish layer height, feed down to .5 m below overburden
Position control Z axis up and out of the hole

Appendix Q: Design Hazard Checklist

ME 428/429/430 Senior Design Project 2019

DESIGN HAZARD CHECKLIST

Team: Space Investigation Force Faculty Coach: Dr. Peter Schuster

Y	N	
☒	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☒	☐	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☒	☐	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☒	☐	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☒	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☒	☐	14. Can the system generate high levels of noise?
☒	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☒	☐	16. Is it possible for the system to be used in an unsafe manner?
☒	☐	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure 4: Design Hazard Checklist, Page 1

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Revolving drill bit	- Competition rules prohibit touching the device while it is in operation - Stay >3 feet away from rotating components - Remove any clothing/items that may get caught in machinery before operating	7/1/20	TBD
Falling Weight Hazard	- The use of lead screws will keep heavy moving components in place in the event of a power failure.	7/1/20	TBD
Sharp edges	- Drill bits will be contained in sheathes during transportation - Drill bit tips will be fully encased while in the tool changer.	7/1/20	TBD
High voltage electrocution risk	- All high-voltage circuitry will be approved by Jim Gerhardt before use. - All devices will be properly grounded and insulated	7/1/20	TBD
Loud noise during drilling operation	- Use earplugs during hammer drilling procedure	7/1/20	TBD
Burn risk from heaters and drill bits	- All component temperatures will be checked with IR thermometer to verify <40°C before handling	7/1/20	TBD
System is used in an unsafe manner	- System will only be operated by designers. Designated group members will be specially trained.	7/1/20	TBD
Pinch points	- All motion components will be de-energized before handling the system.	7/1/20	TBD
Tipping hazard	- Connect the frame to the mounting rails provided at the competition before installing heavy subassemblies	7/1/20	TBD

Appendix R: Failure Modes and Effects Analysis and Risks Analysis

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Actions Taken	Severity	Occurence	Criticality	RPN
Heating Element	Power Cable Break	No heat	10	Over extension of probe	-Ample Cable -Play at hinge -Rounded edges	3	Temp Sensor	7	210	Ample Cable	Alex / Others		10	1	7	70
	Overheat (burn out)	No heat	10	Lack of temp control resulting in overheating	-Monitor Temp -Variable Power Control	4	Temp Sensor	6	240	Sensitive Temp Control	Alex / Others		10	3	6	180
	Temp Sensor Failure	Improper Temp Control	6	Improper Calibration, Seneor Burn out	-Monitor Temp -Variable Power Control	4	Temp Sensor	3	72							0
Heating Actuation	Actuation Motor Failure	No Actuation	6	Motor over exertion	-Speced Motors	2	Resistance on Motor Disapears	3	36							0
	Actuation Cable Break	No Actuation	8	Wear and tear with friction, over actuation	-Ample Cable -Play at hinge -Rounded edges	5	Resistance on Motor Disapears	7	280	Ample Cable	Alex / Others		8	3	7	168
	Faulty Hinge	No accuation	8	Poor hinge selection, introduction of dust	-Nice Hinge -Dust Prevention -Lubricant	3	Resistance on Motor Increases	6	144							0
	Surface Contact Failure	Killing Motor / Overheat Element	6	Improper motor control / Improper heat control	-Motor Control and Feedback	4	Resistance on Motor Increases / Temp Sensor	8	192							0
Filtration	Clogging	lowered flow rate	4	Insufficient Back flushing	-Back flow ability	5	Pressure Sensor	4	80							0
	Not Sufficient Flow rate	lowered flow rate	4	Cloging, improper pump selection	-Properly Speced Pump and Filter	5	Pressure Sensor	5	100							0
	Leaking	loss of valuable water	4	Waer and tear of tubing	-Proper Tubing -NP Standards	3	Pressure Sensor / Visual Inspection	5	60							0
Pumping	Clogging	lowered flow rate	4	Insufficient Back flushing and filtration	-Back flow ability	5	Pressure Sensor	4	80							0
	Tube wear and tear	loss of suction	6	Kinking / material wear and tear	-Proper Tubing -Norprene Tubing	5	Pressure Sensor	8	240	Abrasion Resistant Tubing	Ryan / Westin		6	3	8	144
	Gear Box Failure	Pump Failure	8	Poor chinese manufacturing / over torqued		2	STOPS	8	128							0
Piping	Leaking	loss of valuable water	4	Improper piping connections	-Proper Tubing -NP Standards	2	Visual Inspection	5	40							0
	Piping Kinking	lowered flow rate	4	Sharp bends turns	-Proper Tubing -NP Standards	4	Pressure Sensor / Visual Inspection	4	64							0
	Clogging	lowered flow rate	4	Insufficient Back flushing and filtration	-Back flow ability	5	Pressure Sensor	4	80							0
Drilling Control	System Failure	Cannot Properly Control	10	Bug in the code	-Solid Programing	3	Visual Inspection	2	60							0
Drilling Servo Control	Directional Failure	Inability to disconnect from sheath	8	Bug in the code	-Rigid -Over Speced	2	Visual Inspection	2	32							0

												Action Results				
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality	RPN
Drilling Mode Selection	Mode Selection Failure	switch no longer actuates	6	Bug in the code		3	Visual Inspection	2	36							0
Drilling Rotary	Mode Failure	Doesn't rotate	8	Bug in the code / Faulty Drill		3	Visual Inspection	2	48							0
Drilling Hammering	Mode Failure	Doesn't hammer	8	Bug in the code / Faulty Drill		3	Visual Inspection	2	48							0
Auger Drill Chip Clearance	Clogging	Cannot Clear	6	Not sufficiently pulverized	-Suficiently Pulverize	6	Visual Inspection	2	72							0
	Auger Stuck	Auger Stuck	6	Not sufficiently pulverized	-Suficiently Pulverize	6	Visual Inspection / Force Data	2	72							0
Pile Drive Sheath	Exced Force Req.	WE LOSE POINTS	2		-Feedback	8	Force Data	4	64							0
	Sheath Failure	Sheath Collapse	6	Buckling	-Properly Speced	4	Force Data	4	96							0
Tool Changer Rotation	Inproper rotation control	spinny thing spins out of controll	6	Bug in code / stepper motor slips downs the stairs	-Feedback	4	Visual Inspection	2	48							0
Quick Change Servo	Not releasing tool	Inability to use variable tools	4	Improper diengagment	Test Chuck Release	3	Visual Inspection	2	24							0
	Not Grabbing Tool	Not using tools at all	6	Missalignment	Change Plunge Depth	3	Visual Inspection	2	36							0
Frame	break	WE LOSE	10	FEA did not function / Trucker Failure	Over Spec Frame / Design For Proper Loads	2	Visual Inspection	2	40							0
	exceeds desired weight	WE LOSE POINTS	2		Redesign	7	Weigh Before	1	14							0
Linear Motion x axis	motor underpowered	Load Changes / Lose Travel Ability	8	rails go out of parallel	Overspec Motor	2	Power Pull / Torque Output	6	96							0
	rails go out of parallel	Load Changes / Lose Travel Ability	8	Improper Assembly	Assemble with precision / Shim it	7	Visual Inspection / Stepper Motor Data	6	336	PRECISION ASSEMBLY!!	Aaron / Others		8	4	6	192
	screws fill with debris	Binding / Motion stop	8	Not sufficiently clearing material	Seal Open Operating Areas	5	Visual Inspection / Stepper Motor Data	4	160							0
Linear Motion z axis	motor underpowered	Inability to pull sheaths	8	Motor sizing incorrect / not sufficient power	Overspec Mototr	2	Power Pull / Torque Output	6	96							0
	rails go out of parallel	Load Changes / Lose Travel Ability	8	Improper Assembly	Assemble with precision / Shim it	7	Visual Inspection / Stepper Motor Data	6	336	PRECISION ASSEMBLY!!	Aaron / Others		8	4	6	192
	screws fill with debris	Binding / Motion stop	8	Not sufficiently clearing material	Seal Open Operating Areas	5	Visual Inspection / Stepper Motor Data	4	160							0
Camera Connection	does not connect	No video	6	Interference with wifi / Distance feom camera	Test Connection / Define Distance of Operation	4	No Video	2	48							0
	poor frame rate	Inability to resolve layers	4			3	Loss of Resolution	3	36							0
Camera Resoltion	Faulty Mirror	Inability to resolve layers	4	Scratches Mirror	Replace Current Mirror / Protect From Abrasion	5	Loss of Resolution	2	40							0

												Action Results					
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality	RPN
Lack of resolution through sheath	Scratched Tubing	Inability to resolve layers	4	Material scratches tubing while pile driven	Protect From Abrasion / Don't Use Windows	4	Loss of Resolution	3	48							0
Load Cell Calibation	Improper Calibration	Inacurrate force data	6	Improper Calibration	Calibrate Properly	4	Innacurate Data	7	168							0
Load Cell Failure	Exceed Max Force	Load Cell no longer resolves	4	Exceed Max Force	Monitor Force and Do not Exceed	4	Innacurate Data	7	112							0
	Do not meet 10% error	LOSE POINTS	2	Improper Calibration	Calibrate Properly	4	Innacurate Data	7	56							0

Risk Level Report

Application: STYX R.A.

Description:

Product Identifier: STYX Unit

Assessment Type: Detailed

Limits:

Sources: ANSI Standard, Cal Poly Risk Assesment

Risk Scoring System: ANSI B11.0 (TR3) Two Factor

Analyst Name(s): Chris, Westin, Aaron, Alex, Ryan

Company: STYX

Facility Location: Cal Poly

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Unlikely	Medium	1-2-2	adult first use / test	mechanical : drawing-in / trapping / entanglement spinning tools or linear motion	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Likely	High	
Serious Unlikely	Medium	1-3-2	adult normal use	mechanical : drawing-in / trapping / entanglement spinning tools, tool changer, or linear motion	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Likely	High	
Serious Unlikely	Medium	1-10-2	adult disassembly	mechanical : drawing-in / trapping / entanglement spinning tools, tool changer, or linear motion	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Likely	High	
Serious Unlikely	Medium	1-12-2	adult misuse	mechanical : drawing-in / trapping / entanglement spinning tools or linear motion	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Likely	High	
Serious Remote	Low	1-2-1	adult first use / test	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-2-3	adult first use / test	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Catastrophic Remote	Low	1-2-4	adult first use / test	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Unlikely	Medium	
Serious Remote	Low	1-2-5	adult first use / test	mechanical : unexpected start lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-2-6	adult first use / test	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-2-7	adult first use / test	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-2-8	adult first use / test	electrical / electronic : shorts / arcing / sparking exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-2-9	adult first use / test	electrical / electronic : improper wiring exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-2-11	adult first use / test	electrical / electronic : water / wet locations leakage/improper storage	separate hazard / people in time or space	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-2-12	adult first use / test	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-2-15	adult first use / test	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-2-16	adult first use / test	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-2-18	adult first use / test	fire and explosions : hot surfaces heater probe on outside hole	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-2-20	adult first use / test	heat / temperature : burns / scalds Heater Probe Exposure	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-2-21	adult first use / test	heat / temperature : severe heat exposed heater probe	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-2-22	adult first use / test	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Moderate Unlikely	Low	1-2-23	adult first use / test	ventilation / confined space : air contaminants Drilling dust	safety glasses, respiratory protection	Moderate Likely	Medium	
Serious Remote	Low	1-3-1	adult normal use	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-3-3	adult normal use	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Catastrophic Remote	Low	1-3-4	adult normal use	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Remote	Low	
Serious Remote	Low	1-3-5	adult normal use	mechanical : unexpected start lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-3-6	adult normal use	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-3-7	adult normal use	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-3-8	adult normal use	electrical / electronic : shorts / arcing / sparking exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-3-9	adult normal use	electrical / electronic : improper wiring exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-3-11	adult normal use	electrical / electronic : water / wet locations leakage/improper storage	separate hazard / people in time or space	Serious Unlikely	Medium	
Serious Remote	Low	1-3-15	adult normal use	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-3-16	adult normal use	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-3-18	adult normal use	fire and explosions : hot surfaces heater probe on outside hole	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-3-19	adult normal use	heat / temperature : burns / scalds Heater Probe Exposure	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-3-20	adult normal use	heat / temperature : severe heat exposed heater probe	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-3-21	adult normal use	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Moderate Unlikely	Low	1-3-22	adult normal use	ventilation / confined space : air contaminants Drilling dust	safety glasses, respiratory protection	Moderate Likely	Medium	
Serious Remote	Low	1-4-1	adult aggressive use	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	
Serious Remote	Low	1-4-2	adult aggressive use	mechanical : drawing-in / trapping / entanglement spinning tools, tool changer, or linear motion	restricted users, standard procedures	Serious Likely	High	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-4-3	adult aggressive use	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Unlikely	Medium	
Catastrophic Remote	Low	1-4-4	adult aggressive use	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Remote	Low	
Catastrophic Remote	Low	1-4-5	adult aggressive use	mechanical : unexpected start lack of communication	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Likely	High	
Serious Remote	Low	1-4-8	adult aggressive use	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-4-9	adult aggressive use	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-4-10	adult aggressive use	electrical / electronic : shorts / arcing / sparking exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-4-11	adult aggressive use	electrical / electronic : improper wiring exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-4-13	adult aggressive use	electrical / electronic : water / wet locations leakage/improper storage	standard procedures	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-4-14	adult aggressive use	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-4-17	adult aggressive use	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-4-18	adult aggressive use	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-4-21	adult aggressive use	fire and explosions : hot surfaces heater probe on outside hole	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-4-22	adult aggressive use	heat / temperature : burns / scalds Heater Probe Exposure	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-4-23	adult aggressive use	heat / temperature : radiant heat exposed heater probe	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-4-24	adult aggressive use	heat / temperature : severe heat exposed heater probe	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-4-25	adult aggressive use	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Moderate Unlikely	Low	1-4-27	adult aggressive use	ventilation / confined space : air contaminants Drilling dust	safety glasses, respiratory protection	Moderate Likely	Medium	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-5-1	adult maintenance / lubrication	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	
Serious Remote	Low	1-5-2	adult maintenance / lubrication	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-5-4	adult maintenance / lubrication	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-5-5	adult maintenance / lubrication	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-5-6	adult maintenance / lubrication	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-5-7	adult maintenance / lubrication	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-5-8	adult maintenance / lubrication	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-6-1	adult repair tasks	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-6-2	adult repair tasks	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-6-3	adult repair tasks	mechanical : unexpected start lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-6-5	adult repair tasks	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-6-6	adult repair tasks	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-6-7	adult repair tasks	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-6-8	adult repair tasks	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-6-9	adult repair tasks	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-8-1	adult cleaning	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-8-2	adult cleaning	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-8-3	adult cleaning	mechanical : unexpected start lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-8-5	adult cleaning	electrical / electronic : water / wet locations leakage/improper storage	standard procedures	Serious Unlikely	Medium	
Serious Remote	Low	1-8-6	adult cleaning	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-8-7	adult cleaning	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-9-1	adult assemble	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	
Serious Remote	Low	1-9-2	adult assemble	mechanical : drawing-in / trapping / entanglement spinning tools or linear motion	restricted users, standard procedures	Serious Likely	High	
Serious Remote	Low	1-9-3	adult assemble	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Unlikely	Medium	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Catastrophic Remote	Low	1-9-4	adult assemble	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Remote	Low	
Moderate Unlikely	Low	1-9-5	adult assemble	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Likely	Medium	
Serious Remote	Low	1-9-7	adult assemble	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-9-8	adult assemble	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-10-1	adult disassembly	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	
Serious Remote	Low	1-10-3	adult disassembly	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users,, standard procedures, supervision	Serious Unlikely	Medium	
Catastrophic Remote	Low	1-10-4	adult disassembly	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Remote	Low	
Serious Remote	Low	1-10-7	adult disassembly	electrical / electronic : water / wet locations leakage/improper storage	standard procedures	Serious Unlikely	Medium	
Serious Remote	Low	1-10-8	adult disassembly	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-10-9	adult disassembly	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-12-1	adult misuse	mechanical : crushing Z axis drop	restricted users, standard procedures	Serious Remote	Low	
Serious Remote	Low	1-12-3	adult misuse	mechanical : pinch point limits of x axis, between drill and test bed	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Serious Unlikely	Medium	
Catastrophic Remote	Low	1-12-4	adult misuse	mechanical : stabbing / puncture drill through apendages	E-stop control, awareness barriers, restricted users, standard procedures, supervision	Catastrophic Remote	Low	
Moderate Unlikely	Low	1-12-5	adult misuse	mechanical : unexpected start lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-12-8	adult misuse	electrical / electronic : energized equipment / live parts exposed live wires	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-12-9	adult misuse	electrical / electronic : lack of grounding (earthing or neutral) not properly grounded	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-12-10	adult misuse	electrical / electronic : shorts / arcing / sparking exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious Remote	Low	1-12-11	adult misuse	electrical / electronic : improper wiring exposed hot wires/ faulty connections	Separate hazard / people in time or space, E-stop control	Serious Unlikely	Medium	
Serious Remote	Low	1-12-13	adult misuse	electrical / electronic : water / wet locations leakage/improper storage	standard procedures	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-12-14	adult misuse	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Serious Remote	Low	1-12-16	adult misuse	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	
Serious Remote	Low	1-12-17	adult misuse	slips / trips / falls : trip cabling or frame	Duct Tape to floor	Serious Unlikely	Medium	
Serious Remote	Low	1-12-23	adult misuse	fire and explosions : hot surfaces heater probe on outside hole	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-12-24	adult misuse	heat / temperature : burns / scalds Heater Probe Exposure	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Serious Remote	Low	1-12-25	adult misuse	heat / temperature : radiant heat exposed heater probe	standard procedures, supervision, gloves	Serious Unlikely	Medium	
Moderate Unlikely	Low	1-12-26	adult misuse	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Serious Remote	Low	2-1-1	passer-by / non-user walk near	slips / trips / falls : slip wet floor	standard procedures, supervision	Serious Unlikely	Medium	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Moderate Unlikely	Low	2-1-3	passer-by / non-user walk near	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Moderate Unlikely	Low	2-1-4	passer-by / non-user walk near	ventilation / confined space : air contaminants Drilling dust	safety glasses, respiratory protection	Moderate Likely	Medium	
Moderate Unlikely	Low	2-2-1	passer-by / non-user observe / watch	noise / vibration : noise / sound levels > 80 dBA operational drill	hearing protection	Moderate Likely	Medium	
Moderate Unlikely	Low	2-2-2	passer-by / non-user observe / watch	ventilation / confined space : air contaminants Drilling dust	safety glasses, respiratory protection	Moderate Likely	Medium	
Minor Unlikely	Negligible	1-2-10	adult first use / test	electrical / electronic : overloading activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-2-13	adult first use / test	electrical / electronic : overvoltage /overcurrent activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-2-14	adult first use / test	electrical / electronic : power supply interruption Improper rate of power / unplugged. Power supply failure.	standard procedures	Moderate Unlikely	Low	
Minor Remote	Negligible	1-2-17	adult first use / test	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Minor Remote	Negligible	1-2-19	adult first use / test	fire and explosions : ignitable dust excess dust		Minor Remote	Negligible	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Minor Unlikely	Negligible	1-2-24	adult first use / test	fluid / pressure : fluid leakage / ejection faulty tubing/ faulty seals/ clogging	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-3-10	adult normal use	electrical / electronic : overloading activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-3-12	adult normal use	electrical / electronic : unexpected start up / motion lack of communication	E-stop control, restricted users, awareness barriers, standard procedures	Serious Likely	High	
Minor Unlikely	Negligible	1-3-13	adult normal use	electrical / electronic : overvoltage /overcurrent activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-3-14	adult normal use	electrical / electronic : power supply interruption Improper rate of power / unplugged. Power supply failure.	standard procedures	Moderate Unlikely	Low	
Minor Remote	Negligible	1-3-17	adult normal use	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection	Minor Likely	Low	
Minor Unlikely	Negligible	1-3-23	adult normal use	fluid / pressure : fluid leakage / ejection faulty tubing/ faulty seals/ clogging	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-4-6	adult aggressive use	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Unlikely	Low	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Moderate Remote	Negligible	1-4-7	adult aggressive use	mechanical : product instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	
Minor Unlikely	Negligible	1-4-12	adult aggressive use	electrical / electronic : overloading activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-4-15	adult aggressive use	electrical / electronic : overvoltage /overcurrent activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-4-16	adult aggressive use	electrical / electronic : power supply interruption Improper rate of power / unplugged. Power supply failure.	standard procedures	Moderate Unlikely	Low	
Minor Remote	Negligible	1-4-19	adult aggressive use	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-4-20	adult aggressive use	slips / trips / falls : instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	
Moderate Remote	Negligible	1-4-26	adult aggressive use	ventilation / confined space : smoke drill burnout		Moderate Remote	Negligible	
Minor Unlikely	Negligible	1-4-28	adult aggressive use	fluid / pressure : fluid leakage / ejection faulty tubing/ faulty seals/ clogging	standard procedures	Minor Likely	Low	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Minor Unlikely	Negligible	1-5-3	adult maintenance / lubrication	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Likely	Medium	
Minor Unlikely	Negligible	1-5-9	adult maintenance / lubrication	ergonomics / human factors : posture improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-5-10	adult maintenance / lubrication	ergonomics / human factors : lifting / bending / twisting improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-6-4	adult repair tasks	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Likely	Medium	
Minor Unlikely	Negligible	1-6-10	adult repair tasks	ergonomics / human factors : posture improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-6-11	adult repair tasks	ergonomics / human factors : lifting / bending / twisting improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-8-4	adult cleaning	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Likely	Medium	
Minor Unlikely	Negligible	1-8-8	adult cleaning	ergonomics / human factors : posture improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-9-6	adult assemble	mechanical : product instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	

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Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Minor Remote	Negligible	1-9-9	adult assemble	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-9-10	adult assemble	slips / trips / falls : instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	
Minor Unlikely	Negligible	1-9-11	adult assemble	ergonomics / human factors : duration long hours of operation	job rotation, scheduled rest periods	Minor Likely	Low	
Minor Unlikely	Negligible	1-9-12	adult assemble	ergonomics / human factors : lifting / bending / twisting improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Minor Unlikely	Negligible	1-9-13	adult assemble	biological / health : unsanitary conditions clean space and robot		Minor Unlikely	Negligible	
Minor Unlikely	Negligible	1-10-5	adult disassembly	mechanical : head bump on overhead objects Hands-on operation or inspection.	head protection, supervision	Moderate Likely	Medium	
Moderate Remote	Negligible	1-10-6	adult disassembly	mechanical : product instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	
Minor Remote	Negligible	1-10-10	adult disassembly	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-10-11	adult disassembly	slips / trips / falls : instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Minor Unlikely	Negligible	1-12-15	adult misuse	electrical / electronic : overvoltage /overcurrent activating x axis while in hole / running z axis and/or heater probe and/or drill concurrently	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-12-18	adult misuse	slips / trips / falls : fall hazard from elevated work Competition Environment Test Stand		Moderate Remote	Negligible	
Moderate Remote	Negligible	1-12-19	adult misuse	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-12-20	adult misuse	slips / trips / falls : instability unsecured use	restricted users, standard procedures	Moderate Unlikely	Low	
Minor Unlikely	Negligible	1-12-21	adult misuse	ergonomics / human factors : excessive force / exertion lots of lifting	standard procedures	Moderate Likely	Medium	
Minor Unlikely	Negligible	1-12-22	adult misuse	ergonomics / human factors : lifting / bending / twisting improper lifting/ carrying/ or transporting techniques	standard procedures	Minor Likely	Low	
Moderate Remote	Negligible	1-12-27	adult misuse	noise / vibration : product / equipment damage Improper handling or manufacturing	restricted users	Moderate Unlikely	Low	
Minor Unlikely	Negligible	1-12-28	adult misuse	noise / vibration : interference with communications camera distance to control center		Minor Unlikely	Negligible	
Minor Unlikely	Negligible	1-12-30	adult misuse	fluid / pressure : fluid leakage / ejection faulty tubing/ faulty seals/ clogging	standard procedures	Minor Likely	Low	

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Moderate Remote	Negligible	2-1-2	passer-by / non-user walk near	slips / trips / falls : debris Drilling dust	safety glasses, respiratory protection, standard procedures	Minor Likely	Low	
Serious		1-12-29	adult misuse	biological / health : lack of first aid dont have first aid	REMOVE THIS, WE WILL BRING SOME.	Serious Remote	Low	
		1-1	adult Common Tasks	<None>				
		1-7	adult trouble-shooting / problem solving	<None>				

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Appendix S: BOM with Purchase Prices

				Indented Bill of Material (BOM) STYX						
Part Number		Description				Manufacturing Method	Vendor (#)	Qty	Cost / Unit	Total Cost
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
	Final Assy									3382.96
F-100		Frame Assembly								693.31
			Structure							349.63
F-101-m				Mounting Board	Wood 2"x4"x48"	cut to length	Home Depot	2	3.22	6.44
F-102-m				Horizontal Bar	1"x1/16" thick 6061 aluminum square tube	cut, drill	OnlineMetals (20737)	2	6.71	13.43
F-103-m				Left Vertical Member	1"x1/16" thick 6061 aluminum square tube	cut, drill	OnlineMetals (20737)	1	8.61	8.61
F-104-m				Angled Member	1"x1/8" thick 6061 aluminum square tube	cut, drill	OnlineMetals (18014)	2	17.44	34.88
F-105-m				Top Rail Mount	1.5"x1/16" thick 6061 aluminum square tube	cut, drill	Industrial Metal Supply (61ST15006)	1	25.29	25.29
F-106-m				Bottom Cross-Cable Mount Bracket	0.25" 6061 Aluminum plate	waterjet, tig weld	OnlineMetals (1248)	2	3.26	6.52
F-107-m				Top Right Cross-Cable Mount Bracket	0.25" thick x 3" 6061 Aluminum Angle, 0.25" 6061 Aluminum plate	cut, drill, tig weld	OnlineMetals (1000)	1	7.38	7.38
F-108-m				Top Left Cross-Cable Mount Bracket	0.25" thick x 3" 6061 Aluminum Angle, 0.25" 6061 Aluminum plate	cut, drill, tig weld	OnlineMetals (1000)	1	7.38	7.38
F-109-m				Right Vertical Member	1"x1/16" thick 6061 aluminum square tube	cut, drill	OnlineMetals (20737)	1	8.61	8.61
F-110-m				Triangle Bracket	0.125" 6061 Aluminum plate	waterjet	OnlineMetals (23087)	2	3.50	6.99
F-111-m				Obtuse Angle Bracket	0.125" 6061 Aluminum plate	cut, drill, bend	OnlineMetals (23087)	2	1.49	2.98
F-112-m				Bottom Right Angle Bracket	0.125" thick x 1.25" 6061 Aluminum Angle	cut, drill	OnlineMetals (974)	2	0.35	0.70
F-113-m				Mid-Bar Right Angle Bracket	0.125" thick x 1.5" 6061 Aluminum Angle	cut, drill	OnlineMetals (978)	4	1.05	4.20
F-114-m				Wood-Mounting Brackets	0.125" thick x 1.25" 6061 Aluminum Angle	cut, drill	OnlineMetals (974)	4	0.68	2.71
F-115-m				Bottom Riail Mount	1.5"x1/16" thick 6061 aluminum square tube	cut, drill	Industrial Metal Supply (61ST15006)	1	25.29	25.29
F-116-m				Linear Guide Rail	HGH15 Linear Guide Rail, 1000mm	cut	Lishui Hengli Automation	2	48.73	97.46
F-217-m				X-axis Bearing Mount	1"x1/16" thick 6061 aluminum square tube	cut, drill	OnlineMetals (20737)	2	0.64	1.28
F-118-m				Shim Stock	Use as necessary for allignment	cut	McMaster (9513K42)	2	37.19	74.38
F-121-m				1" Tube Spacer	1/2" OD, 1/16" thick aluminum round tube	cut	OnlineMetals (4352)	12	1.09	13.10
F-122-m				1.5" Tube Spacer	1" OD, 1/16" thick aluminum round tube	cut	OnlineMetals (1211)	2	1.01	2.01
			Hardware							305.95
91478A546				Frame Mounting Lag Bolt, Short	1/4" Hex Head Wood Screw 1.5"	store bought	McMaster (91478A546)	8	0.09	0.70
91478A552				Frame Mounting Lag Bolt, Long	1/4 Hex Head Wood Screw 2.5"	store bought	McMaster (91478A552)	4	0.14	0.55
91860A029				1/4" Washer	1/4" ID Stainless Steel Flat Washer	store bought	McMaster (91860A029)	32	1.25	40.00
92949A546				1/4-20 Screw, 1.5"	1/4-20 Stainless Steel Button Head Hex Drive Screw, 1-1/2"	store bought	McMaster (92949A546)	18	0.26	4.59
95462A029				1/4-20 Nut	1/4-20 Grade 5 Stainless Steel Hex Nut	store bought	McMaster (95462A029)	42	0.05	2.05
92949A837				1/4-20 Screw, 1-5/16"	1/4-20 Stainless Steel Button Head Hex Drive Screw, 1-5/8"	store bought	McMaster (92949A837)	6	0.29	1.76
92949A834				1/4-20 Screw, 9/16"	1/4-20 Stainless Steel Button Head Hex Drive Screw, 9/16"	store bought	McMaster (92949A834)	12	0.16	1.92
91251A189				Linear Rail End Screw	8-32 Black-Oxide Socket head Screw, 3-1/4"	store bought	McMaster (91251A189)	4	1.74	6.97
91525A107				#8 Washer	#8 Oversized Stainless Steel Washer	store bought	McMaster (91525A107)	4	0.13	0.53
91841A009				8-32 Nut	8-32 Stainless Steel Hex Nut	store bought	McMaster (91841A009)	36	0.04	1.31
92949A540				1/4-20 Screw, 3/4"	1/4-20 Stainless Steel Button Head Hex Drive Screw, 3/4"	store bought	McMaster (92949A540)	2	0.15	0.30
92949A548				1/4-20 Screw, 1-3/4"	1/4-20 Stainless Steel Button Head Hex Drive Screw, 1-3/4"	store bought	McMaster (92949A548)	4	0.27	1.07
92196A427				8-32 Screw, 2-3/8"	8-32 Stainless Steel Socket Head Screw, 2-3/8"	store bought	McMaster (92196A427)	2	0.18	0.37
3440T56				Cross Cable	Wire Rope, Unfinished Steel, 1/4" Diameter	store bought	McMaster (3440T56)	2	16.90	33.80
3897T9				Compression Sleeve	Wire Rope Compression Sleeve, 1/4" Diameter	store bought	McMaster (3897T9)	2	1.67	3.34
3001T82				Turnbuckle	Clevis-to-Clevis Turnbuckle, 800lb.	store bought	McMaster (3001T82)	2	38.82	77.64
3583T11				Shackle	Stainless Steel Screw Pin Shackle	store bought	McMaster (3583T11)	2	7.38	14.76
8600N5				X-axis Lead Screw Bearing	Low-Profile Mounted Shielded Steel Ball Bearing, 3/8" Shaft Diameter	store bought	McMaster (8600N5)	2	39.76	79.52
90128A221				Bearing Mount Screw	10-24 Zinc-Plated Alloy Steel Socket Head Cap Screw	store bought	McMaster (90128A221)	4	0.14	0.57
90480A011				Bearing Mount Nut	10-24 Zinc Plated Steel Hex Nut	store bought	McMaster (90480A011)	4	0.02	0.08
1428N32				Driven Pulley	T5 Series Timing Belt Pulley, 27 teeth	store bought	McMaster (1428N32)	1	12.94	12.94
F-119-b				Motor Mount	Nema 17 Angled Stepper Motor Mount	store bought	Anndason	1	2.50	2.50
F-123-b				X-axis Drive Motor	Nema 17-17HS4401 Stepper Motor	store bought	Usongshine (17HS4401)	1	9.99	9.99
1428N2				Drive Pulley	T5 Series Timing Belt Pulley, 10 teeth	store bought	McMaster (1428N2)	1	8.70	8.70
F120-b				Drive Belt	T5 Series Timing Belt, 260mm	store bought				37.73
6435K13				X-axis Lead Screw Collar	3/8" Carbon Steel Clamping Shaft Collar	store bought	McMaster (6435K13)	1	2.31	2.31
90295A470				Pulley Spacer	3/8" Screw Nylon Washer	store bought	McMaster (90295A470)	6	0.09	0.54
98935A211				X-axis Lead Screw	3/8-8 Carbon Steel ACME Lead Screw, 6ft	store bought	McMaster (98935A211)	1	31.56	31.56
91251A196				Linear Rail Mounting Screw	8-32 Alloy Steel Socket Head Screw, 5/8"	store bought	McMaster (91251A196)	29	0.11	3.32

				Indented Bill of Material (BOM) STYX						
Part Number		Description				Manufacturing Method	Vendor (#)	Qty	Cost / Unit	Total Cost
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
Z-100		Z-axis Assembly								440.82
			Framing							255.50
Z-103-m				Vertical Linear Rail	HGH15 Carbon Steel Liner Rail, 2000mm	cut	Lishui Hengli Automation	2	48.73	97.46
Z-104-m				Top Bearing Mount	1/4" Thick Aluminum c-channel, 2-1/4" tall, 5" wide	cut, drill	OnlineMetals (15230)	1	10.92	10.92
Z-105-m				Bottom Bearing Mount	1/4" Thick Aluminum c-channel, 2-1/4" tall, 5" wide	cut, drill	OnlineMetals (15230)	1	10.92	10.92
Z-101-m				Left Vertical Member	1.5"x1/16" thick 6061 aluminum square tube	cut, drill	Industrial Metal Supply (61ST15006)	1	25.29	25.29
Z-102-m				Right vertical Member	1.5"x1/16" thick 6061 aluminum square tube	cut, drill	Industrial Metal Supply (61ST15006)	1	25.29	25.29
Z-206-m				X-axis Lead Screw Nut Mount	1-3/4" x 1/8" Thick Aluminum Square Tube	cut, drill, mill	OnlineMetals (18017)	1	11.38	11.38
Z-207-m				Drill Collar Mount	3" x 1/8" Thick Aluminum Square Tube	cut, drill, mill	OnlineMetals (4602)	1	15.59	15.59
Z-214-m				Stationary Collar	2" OD, 0.075" Thick Stainless Steel Round Tube	cut	OnlineMetals (14897)	1	48.71	48.71
Z-215-m				Stationary Collar Bottom Cap	1/8" Aluminum Plate	cut, drill	OnlineMetals (23087)	1	2.80	2.80
Z-216-p				Collar Alignment Cone	PLA	3D print		1		0.00
Z-113-m				Z-axis Motor Mount	3", 1/8" Thick Aluminum Angle	cut, drill	OnlineMetals (19846)	1	6.70	6.70
Z-114-m				Limit Switch Arm	1/8" Aluminum Plate	cut, drill	OnlineMetals (23087)	1	0.45	0.45
			Hardware							185.32
94815A011				X-Axis Lead Screw Nut	3/8" Right Hand Carbon Steel ACME Hex Nut	store bought	McMaster (94815A011)	1	3.00	3.00
5913K710				Z-axis Lead Screw Bearing	1/2" Shaft Diameter Low-Profile Mounted Steel Ball Bearing	store bought	McMaster (5913K710)	2	11.33	22.66
95606A250				motor Pulley Shaft Spacer	Nylon Washer for 5/8" Screw SIze	store bought	McMaster (95606A250)	2	0.16	0.33
6435K140				Z-axis Lead Screw Collar	1/2" Shaft Diameter Steel Clamping Shaft Collar	store bought	McMaster (6435K140)	2	2.63	5.26
90295A187				Lead Screw Pulley Spacer	Nylon Washer for 1/2" Screw SIze	store bought	McMaster (90295A187)	2	0.08	0.15
98935A913				Z-axis Lead Screw Nut	Right Hand 1/2"-10 Carbon Steel ACME Lead Screw, 8ft	store bought	McMaster (98935A913)	1	18.64	18.64
5862K101				Collar Magnet	1/8" OD, 1/8" Thick Neodymium Magnet	store bought	McMaster (5862K101)	40	0.26	10.40
Z-115-b				Z-axis Motor	am-3651 hex-drive motor	store bought	AndyMark	1	85.00	85.00
6495K140				Z-axis Drive Pulley	L Series Timing Belt Pulley, 14 Teeth	store bought	McMaster (6495K140)	1	26.20	26.20
92949A834				Bearing Bracket Screw	1/4-20 Stainless Steel Button Head Hex Drive Screw, 9/16"	store bought	McMaster (92949A834)	8	0.16	1.28
95462A029				Assorted Nuts	1/4-20 Zinc-Plated Steel Hex Nut	store bought	McMaster (95462A029)	18	0.05	0.88
91841A009				Linear Rail Mounting Nut	8-32 Stainless Steel Hex Nut	store bought	McMaster (91841A009)	62	0.04	2.26
91251A196				Linear Rail Mounting Screw	8-32 Alloy Steel Socket Head Screw, 5/8"	store bought	McMaster (91251A196)	62	0.11	7.10
92949A539				Bearing Mounting Screw	1/4-20 Stainless Steel Button Head Hex Drive Screw, 5/8"	store bought	McMaster (92949A539)	4	0.13	0.53
92949A537				Motor Mount Screw	1/4-20 Stainless Steel Button Head Hex Drive Screw, 1/2"	store bought	McMaster (92949A537)	3	0.11	0.34
91294A190				Motor Face Screw	M4x0.7mm Steel Hex Drive Flat Head Screw, 10mm	store bought	McMaster (91294A190)	4	0.05	0.21
90592A090				Limit Switch Arm Nut	M4x0.7mm Steel Hex Nut	store bought	McMaster (90592A090)	2	0.01	0.03
91290A148				Limit Switch Arm Screw	M4x0.7mm Steel Socket Head Screw	store bought	McMaster (91290A148)	2	0.09	0.18
90276A139				X-axis ACME Nut Mounting Screw	5-40 Steel Round Head Slotted Screw, 2"	store bought	McMaster (90276A139)	4	0.20	0.80
90480A006				X-axis ACME Nut Mounting Nut	5-40 Zinc-plated Steel Hex Nut	store bought	McMaster (90480A006)	4	0.02	0.07
D-100		Drill Mount								581.44
			Manufactured Parts							77.30
D-101-m				Drill Plate	1/4" Aluminum Plate	Waterjet	OnlineMetals (1248)	1	30.72	30.72
D-102-p				Drill Mount	PLA	3D Print		1		0.00
D-103-m				Drill Handle Mount	3" x 0.25" Thick Aluminum Angle	cut, drill	OnlineMetals (1000)	1	1.48	1.48
D-104-m				Load Cell Mount	2.5" x 1/8" Thick Aluminum Square Tube	cut, drill	OnlineMetals (18018)	1	13.16	13.16
D-105-m				Load Cell Damper	1/2" Thick Rubber Sheet	cut, drill	McMaster (8716K58)	1	31.21	31.21
D-106-m				ACME Nut Support	PLA	3D Print		1		0.00
D-107-m				Z-axis Limit Switch Arm	3" x 1/8" Thick Aluminum Angle	cut, drill	OnlineMetals (19846)	1	0.73	0.73
			Hardware							504.14
D-201-b				Hammer Drill	RH432VCQ Bosh Rotary Hammer	store bought	Amazon	1	362.52	362.52
D-202-b				Linear Guide Bearing	HGH15CA	store bought	Lishui Hengli Automation	4	27.52	110.08
D-203-b				Drill Body Mounting Clamp	5" Hose Clamp	store bought	Home Depot	2	2.28	4.56
D-204-b				Drill Neck Mounting Clamp	4" Hose Clamp	store bought	Home Depot	1	1.73	1.73
92235A520				Drill Mount Screw Type 1	1/4-20 Flanged Socket Head Screw, 1-1/4"	store bought	McMaster (92235A520)	2	5.02	10.04
91251A550				Drill Mount Screw Type 2	1/4-20 Alloy Steel Socket Head Screw, 2"	store bought	McMaster (91251A550)	3	0.28	0.83

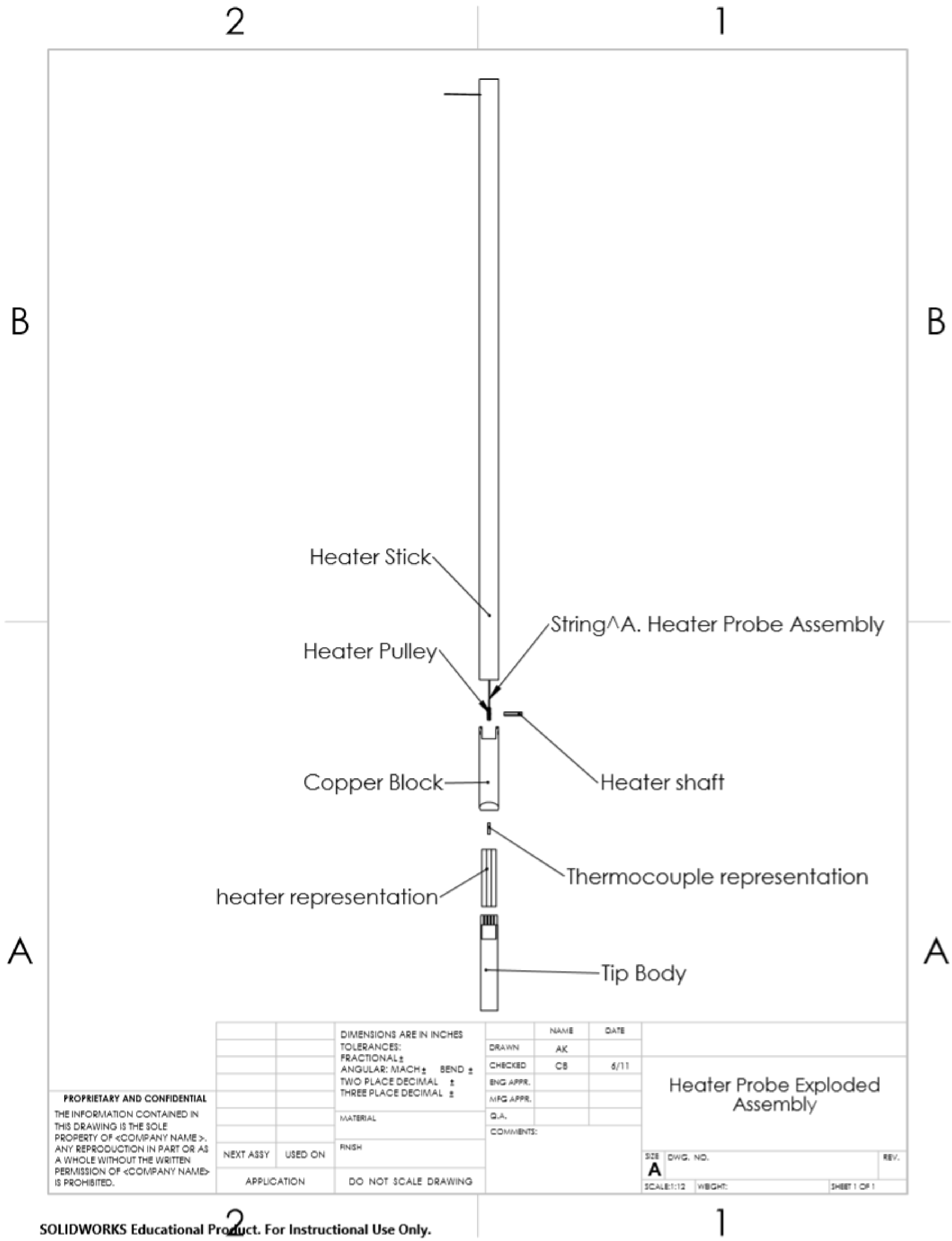
				Indented Bill of Material (BOM) STYX						
Part Number		Description				Manufacturing Method	Vendor (#)	Qty	Cost / Unit	Total Cost
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
95462A029				Drill Mount Nut	1/4-20 Zinc-plated Steel Hex Nut	store bought	McMaster (95462A029)	11	0.05	0.54
90107A029				Drill Mount Washer	1/4" Screw Size Stainless Steel Washer	store bought	McMaster (90107A029)	4	0.07	0.28
91251A540				Drill Handle Mount Screw	1/4-20 Alloy Steel Socket Head Screw, 3/4"	store bought	McMaster (91251A540)	2	0.16	0.31
91294A190				Linear Bearing Mount Screw	M4x0.7mm Alloy Steel Hex Drive Flat Head Screw, 10mm	store bought	McMaster (91294A190)	16	0.05	0.85
95462A030				Drill Handle Mounting Nut	5/16-18 Zinc-plated Steel Hex Nut	store bought	McMaster (95462A030)	1	0.07	0.07
94645A210				Load Cell Mounting Nut	M8x1.25mm Nylon-Insert Locknut, 8mm High	store bought	McMaster (94645A210)	2	0.19	0.37
90377A165				Spring Washer	5/16" Screw Size Stainless Steel Washer	store bought	McMaster (90377A165)	2	0.73	1.46
9657K541				Spring	Compression Spring 1.5" Long, 1.225" OD, 1.033" ID	store bought	McMaster (9657K541)	2	3.04	6.09
94815A107				Z-axis Lead Screw Nut	1/2-10 Steel ACME Hex Nut	store bought	McMaster (94815A107)	1	2.68	2.68
90592A090				Limit Switch Arm Nut	M4x0.7mm Steel Hex Nut	store bought	McMaster (90592A090)	2	0.01	0.03
91294A193				Limit Switch Arm Screw	M4x0.7mm Alloy Steel Hex Drive Flat Head Screw, 14mm	store bought	McMaster (91294A193)	2	0.10	0.21
91251A539				D-104 Mounting Screw	1/4-20 Alloy Steel Socket Head Screw, 5/8"	store bought	McMaster (91251A539)	4	0.16	0.65
91290A461				Spring Guide Bolt	M8x1.25mm Alloy Steel Socket Head Screw, 75mm	store bought	McMaster (91290A461)	2	0.42	0.85
C-100		Tool Changer								205.64
			Motor Assembly							47.30
C-101-b				Tool Changer Drive Motor	Nema 17 geared stepper motor 5.18:1	store bought	Amazon (Usongshine)	1	28.29	28.29
C-102-b				Motor Mount	Nema 17 geared stepper mounting bracket	store bought	Amazon (stepperonline)	1	5.66	5.66
C-103-b				Drive Pulley	GT2 20 tooth-8mm bore timing belt pulley	store bought	Amazon (uxcell)	1	4.99	4.99
91290A111				Motor Face Screw	M3x.5mm, 6mm long	store bought	McMaster (91290A111)	4	0.09	0.35
90044A517				Motor Mount Screw	10-24 Steel Socket Head Cap Screw, 1.75"	store bought	McMaster (90044A517)	2	0.46	0.91
90107A011				Motor Mount Washer	10-24 Stainless Steel Washer	store bought	McMaster (90107A011)	2	0.04	0.07
90480A011				Motor Mount Nut	10-24 Steel Hex Nut	store bought	McMaster (90480A011)	2	0.02	0.04
C-108-b				Drive Belt	GT2 430mm closed belt, 6mm width	store bought	Amazon (LICTOP)	1	6.99	6.99
			Support assembly							46.00
C-201-m				Main Support Bar	1" 6061 Aluminum square tube, 1/16"thick	saw cut/ drill	OnlineMetals (20737)	1	8.00	8.00
C-202-m				Support Bar Spacer	1" 6061 Aluminum square tube, 1/16"thick	saw cut/ drill	OnlineMetals (20737)	1	0.69	0.69
6460K210				Ball Roller	1/4" stud mounted ball transfer	store bought	McMaster (6460K210)	4	7.28	29.12
C-204-m				Roller Mount	1" 6061 Aluminum square tube, 1/16"thick	cut, drill, weld	OnlineMetals (20737)	2	2.90	5.79
95462A029				Frame Mounting Nut	1/4" Steel Hex Nut	store bought	McMaster (95462A029)	10	0.05	0.49
92141A029				Ball Roller Washer	1/4" Steel Washer	store bought	McMaster (92141A029)	14	0.03	0.49
92949A546				Frame Mounting Screw	1/4-20 Steel Button Head Screw, 1.5"	store bought	McMaster (92949A546)	2	0.26	0.51
91478A554				Support Bar Lag Bolt	1/4" wood lag bolt, 3" long	store bought	McMaster (91478A554)	2	0.17	0.34
C-209-m				Frame Mounting Bracket	1/8" Thick, 1" Angle Aluminum	saw cut/ drill	OnlineMetals (971)	1	0.57	0.57
			Bottom Rotating Assembly							26.93
C-301-m				Driven Pulley	GT2 60 tooth 5mm bore timing belt pulley (25mm flange od)	drill/tap	uxcell - Amazon	1	8.29	8.29
90630A121				Lock Nut	3/8-16 nylon lock nut	store bought	McMaster (90630A121)	1	0.16	0.16
92141A031				Washer	3/8" ID Stainless Steel Washer	store bought	McMaster (92141A031)	1	0.05	0.05
90807A138				Shoulder Bolt	3/8-16 Shoulder Bolt, 1.5" long, 3/8" Shoulder	store bought	McMaster (90807A138)	1	7.36	7.36
5909K250				Thrust Bearing	3/8" ID Thrust Roller Bearing	store bought	McMaster (5909K250)	1	3.05	3.05
5909K251				Thrust Bearing Washer	3/8" ID Thrust Bearing Washer	store bought	McMaster (5909K251)	2	1.12	2.24
60355K504				Pulley Bearing	3/8" ID Roller Ball Bearing	store bought	McMaster (60355K504)	1	5.78	5.78
			Rack							85.41
C-401-m				Bottom Plate	1/8" 6061 Aluminum Plate	water jet	OnlineMetals (23087)	1	27.97	27.97
C-402-m				Top Plate	1/8" 6061 Aluminum Plate	water jet	OnlineMetals (23087)	1	27.97	27.97
C-403-m				Vertical Tube	1" x 1/16" Thick 6061 Aluminum Square Tube	weld	OnlineMetals (20737)	3	8.69	26.07
91251A110				Pulley Mounting Screw	#4-40 Socket Head Cap Screw, 0.5" Long	store bought	McMaster (91251A110)	6	0.09	0.55
92949A540				Top Plate Mounting Screw	1/4-20 Steel Button Head Screw, 3/4" Long	store bought	McMaster (92949A540)	3	0.15	0.44
C-406-p				Top Plate Mount	PLA top plate plug	3d print		3		0.00
C-407-p				Drill Bit Clip	PLA clip type 1	3d print		1		0.00
C-408-p				Sheath Clip	PLA clip type 2	3d print		1		0.00
C-409-p				Auger Clip	PLA clip type 3	3d print		1		0.00
C-410-p				Camera Probe Clip	PLA clip type 4	3d print		1		0.00

				Indented Bill of Material (BOM)						
				STYX						
Part Number		**Description**				**Manufacturing Method**	**Vendor (#)**	**Qty**	**Cost / Unit**	**Total Cost**
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
C-411-p				Heater Probe Clip	PLA clip type 5	3d print		1		0.00
C-412-p				Not In Use	PLA clip type 6	3d print		1		0.00
C-413-b				Not In Use	PLA clip type 7	3d print		1		0.00
C-414-p				Drill Bit Cup	PLA cup type 1	3d print		1		0.00
C-415-p				Sheath Cup	PLA cup type 2	3d print		1		0.00
C-416-p				Auger Cup	PLA cup type 3	3d print		1		0.00
C-417-b				Camera Probe Cup	PLA cup type 4	3d print		1		0.00
C-418-b				Heater Probe Cup	PLA cup type 5	3d print		1		0.00
C-419-p				Not In Use	PLA cup type 6	3d print		1		0.00
C-420-p				Not In Use	PLA cup type 7	3d print		1		0.00
C-421-p				Not In Use	PLA cup type 8	3d print		1		0.00
90480A011				Clip Set Screw	10-24 Steel hex Nut	store bought	McMaster (90480A011)	18	0.02	0.34
94355A238				Clip Set Screw Nut	10-24 1/4" Steel Set Screw	store bought	McMaster (94355A238)	18	0.11	1.95
95505A601				Top Plate Mounting Nut	1/4-20 Steel Hex Nut	Store bought	McMaster (95505A601)	3	0.04	0.12
			Top Support							9.05
5972K910				Upper Bearing	3/8" Shaft Diameter Steel Ball Bearing	store bought	McMaster (5972K910)	1	4.70	4.70
C-501-p				Top Bearing Housing	PLA	3D Print		1		0.00
C-502-p				Upper Bearing Spacer	PLA	3D Print		1		0.00
C-503-p				Upper Support Bar Mount	PLA	3D Print		1		0.00
C-504-m				Upper Support Bar	1" x 1/16" Thick 6061 Aluminum Square Tube	saw cut	OnlineMetals (20737)	1	4.35	4.35
			Chuck depressor							70.60
C-601-b				Servo Motor w/ arm	20 Kg, 270 degree 5V servo motor	store bought	Amazon	4	16.88	67.52
C-602-p				Servo Mount	PLA	3D print		4		0.00
C-605-b				M5 x 6mm Socket Head Cap Screw	Servo Mount Screw	store bought	Amazon	8	0.05	0.40
C-606-b				M4 x 6mm Socket Head Cap Screw	Servo Mount Screw	store bought	Amazon	24	0.05	1.20
C-607-b				M3 x 6mm Socket Head Cap Screw	Servo Screw	store bought	Amazon	14	0.05	0.70
C-608-b				M5 nut	Mounting Nut	store bought	Amazon	2	0.03	0.06
C-609-b				M4 nut	Mounting Nut	store bought	Amazon	24	0.03	0.72
C-603-p				Mode Switch Adapter	PLA	3D print		1		0.00
C-604-p				Mode Switch Pulley	PLA	3D print		2		0.00
F-100		Filtration / Pump								418.15
			Filter1							88.59
F-101-b				Primary Filter	HQMPC 40 micron Sediment Filter	store bought	Amazon	1	42.00	42.00
F-102-b				Motorized Ball valve	3/4" Brass Motorized ball valve	store bought	U.S. Solid	1	37.99	37.99
50785k69				Reducing Adapter	Bushing Straight Reducing Adapter w/ Hex Body 3/4 and 3/8	store bought	McMaster (50785k69)	2	4.30	8.60
			Pump							107.00
PMB310F				Pump	PMB310F Peristaltic Pump, 3/16" tube	store bought	Simply Pumps (PMB310F)	1	107.00	107.00
			Filter 2							141.34
49035k48				Secondary Filter Housing	Clear Schedual 40 PVC 2" ID	store bought	McMaster (49035k48)	1	19.00	19.00
4880K86				Housing End Caps	2" Socket-Connect Female x 2" NPT Female	store bought	McMaster (4880K86)	2	2.00	4.00
4880k546				Housing Screw Plugs	2" PVC NPT Plug	store bought	McMaster (4880k546)	2	5.00	10.00
FAP102				Secondary Filter	FAP102 5 Micron Sintered Bronze Filter	store bought	Capstan (FAP102)	1	100.00	100.00
50785K143				Locknut	3/8" NPT Brass Locknut	store bought	McMaster (50785K143)	1	3.04	3.04
2725k55				Pipe Reducer	1/2 m to 3/8 f NPT Low Presure Bushing Straight Reducing Adapter	store bought	McMaster (2725k55)	1	4.30	4.30
9561K18				O-ring	3/4" NPT O-ring	store bought	McMaster (9561K18)	2	0.50	1.00
			Repeated Hardware			store bought				81.22
F-201-b				Flexible Water Tube	Proline 3/16" ID Clear Vinyl Tubing	store bought	HOME DEPOT	1	6.00	6.00
5346k179				Barb to Thread Adapter	Metal Barbed Hose Fitting (3/8" MPT Fitting)	store bought	McMaster (5346k179)	4	8.20	32.80
5388k14				Hose Clamp	7/32 to 5/8 " Wormdrive Clamp	store bought	McMaster (5388k14)	1	6.26	6.26
4568k151				Male-Male Pipe Adapter, 1"	3/8" by 1" Long m-m NPT	store bought	McMaster (4568k151)	3	3.32	9.96
4429k827				Pressure Transducer Tap	Female 3/8" to 1/8" TEE Reducer	store bought	McMaster (4429k827)	2	13.10	26.20

				Indented Bill of Material (BOM) STYX						
Part Number		Description				Manufacturing Method	Vendor (#)	Qty	Cost / Unit	Total Cost
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
0T000		Tools								861.16
			Telemetry Probe							79.31
4T001				Probe Shaft	3/8" Square, 0.020" Thick Steel Tube	Saw-Cut Stock	McMaster (6582K21)	1	7.83	7.83
4T002				Camera	Yugoo Wireless Endoscope, 5.5mm	Store Bought	Amazon	1	37.99	37.99
4T003				Angled Mirror	ACRYLIC MIRROR SHEET | CLEAR EXTRUDED MIRROR	Water Jet / Laser Cutter	Interstate Plastics	1	33.49	33.49
4T004				Index Collar	PLA collar for aligning camera with sheath holes	3D Print		1		0.00
4T005				Thread Interface	PLA print to connect probe to SDS+ adapter	3D Print		1		0.00
4T006				Camera Tip	Camera Protective Cap	3D Print		1		0.00
			Hammer Drill Bit Assem							185.19
1T001				Drill Bit	1.5" SDS Max Masonry Drill Bit, 36"	turn	Amazon	1	123.99	123.99
1T003				Floating Collar	2" x 0.313" Mild Steel Tube	cut, turn	OnlineMetals (15549)	1	37.18	37.18
1T004				SDS+ Interface	SDS+ 5/8" Ground Rod Driver	Store Bought	Amazon	1	24.02	24.02
			Auger Bit Assem							83.60
3T001				Auger Tip	0.875" Alloy Steel Round	turn		1	19.99	19.99
3T002				Auger Shaft	0.625" x 0.12 Mild Steel Tube	cut, mig weld	OnlineMetals (7763)	1	39.59	39.59
3T003				SDS+ Interface	SDS+ 5/8" Ground Rod Driver	Store Bought	Amazon	1	24.02	24.02
			Sheath Assem							249.99
2T001				Inserting Tool	0.875" Alloy Steel Round	Lathe & Rotary Mill	OnlineMetals (7367)	1	39.99	39.99
2T002				Dowel Pin	1/4" D, 5/8" long alloy steel dowel pin	Store Bought	McMaster (98381A539)	3	1.40	4.19
2T003				SDS+ Interface	SDS+ 5/8" Ground Rod Driver	Store Bought	Amazon	1	24.02	24.02
2T004				Sheath	1.625" OD x 0.375" Wall Alloy Steel Round Tube	turn, mill	OnlineMetals (21552)	1	181.79	181.79
			Heater Probe							263.07
H001S				Copper Tip	.75" dia. copper round bar 110-H04	turn, mill	OnlineMetals (1617)	1	43.46	43.46
H002B				Cartridge Heater	Swaged Cartrige Heater- 0.5" Dia. 1000W	store bought	Amazon	1	47.84	47.84
H101S				Axle	0.75" Alloy Steel Round Bar	turn, mill	OnlineMetals (7388)	1	3.72	3.72
H102M				#4-40 Flanged SHCS - MODIFIED	4-40 Alloy Steel Flanged Buttom Head Screw, 1/4"	turn	McMaster (96660A151)	2	6.81	13.62
97633A150				Snap Ring	External Retaining Ring for 5/16" OD	store bought	McMaster (97633A150)	1	9.20	9.20
H003S				Knuckle	0.75" Alloy Steel Round Bar	turn, mill	OnlineMetals (7388)	1	4.25	4.25
H004S				Straw	304 Stainless Steel Tube, 0.028" Wall Thickness, 3/16" OD	bend	McMaster (8457K52)	1	16.20	16.20
H005S				Shaft	0.75" OD x 0.56" ID Mild Steel Round Tube	cut, drill, mill	OnlineMetals (15523)	1	21.32	21.32
5909K330				Thrust Bearing	Needle-Roller Thrust Bearing for 3/4" Shaft	store bought	McMaster (5909K330)	2	3.40	6.80
5909K460				Thrust Bearing Washer	Washer for 3/4" Shaft Diameter Needle-Roller Thrust Bearing	store bought	McMaster (5909K460)	4	1.23	4.92
6436K160				Shaft Collar	3/4" Clamping Two-Piece Shaft Collar	store bought	McMaster (6436K160)	2	6.00	12.00
H201B				Heater Actuation Motor	12V 10 rpm DC motor worm drive with encoder	store bought	Amazon	1	18.99	18.99
6658K725				Motor Shaft Bushing	Oil-Embedded SAE 841 Bronze Sleeve Bearing for 6mm Shaft	store bought	McMaster (6658K725)	2	1.10	2.20
95608A112				Bushing End Screw	M3x0.5mm Stainless Steel Ultra-Wide Flanged Button Head Screw	store bought	McMaster (95608A112)	1	3.72	3.72
H006S				Plastic Motor Spacer	PLA	3D print		1		0.00
H007M				Twisting Motor	6V Double Shaft Worm gear Motor, 10rpm	store bought	Amazon	1	44.61	44.61
91306A656				Heater Actuation Motor Screw	M3x0.5mm Zinc-plated Button Head Hex Drive Screw, 6mm	store bought	McMaster (91306A656)	1	0.10	0.10
H008S				Twisting Motor Mount	2.5" x 1/8" Thick Aluminum Square Tube	cut, drill	OnlineMetals (18018)	1	6.80	6.80
91375A238				Twisting Motor Set Screw	10-24 Alloy Steel Cup-Point Set Screw	store bought	McMaster (91375A238)	2	0.12	0.24
90576A102				Motor Mount Nut	M3x0.5mm Steel Nylon-Inserted Locknut	store bought	McMaster (90576A102)	8	0.04	0.28
90965A130				Washer	M3 Stainless Steel Washer	store bought	McMaster (90965A130)	4	0.03	0.11
91352A115				Twisting Motor Mount Screw	M3x0.5mm Steel Button Head Hex Drive Screw, 20mm	store bought	McMaster (91352A115)	4	0.11	0.42
H009S				SDS+ Adapter	1/2-20 Threaded SDS+ Adapter	store bought	Amazon	1	2.27	2.27
		Power and Controls								182.44
E001				Drill Speed Controller	2000W AC Motor Speed Control Module	store bought	HiLetgo	1	5.89	5.89
E002				Copper Wire	12 Gauge 100 feet CCA Bonded Zip Cord	store bought	GS Power	1	20.95	20.95
E003				Grounded 120V AC Plug	3W102-E Clapmtite Straight Blade Cord Connector	store bought	Leviton	1	3.29	3.29
E004				Power Strip	6-outlet Surge Protector Power Strip, 200 Joule	store bought	Amazon	1	11.49	11.49
E005				Digital Potentiometer	MCP4132-104E/SN Digital Potentiometer, 100Kohm, 129 Steps	store bought	Amazon	1	2.48	2.48

				Indented Bill of Material (BOM)						
				STYX						
Part Number		Description				Manufacturing Method	Vendor (#)	Qty	Cost / Unit	Total Cost
	Lvl0	Lvl1	Lvl2	Part Name	Part Description					
E006				Load Cell Amplifier	HK721 Weighing Sensor Amplifier	store bought	Amazon	1	5.90	5.90
E007				Stepper Motor Driver	Two Axis Stepper Motor Driver Expansion Board for L6470 Nucleo	store bought	Amazon	1	48.33	48.33
E008				Stepper Motor Driver	tb6600 Single Axis Hybrid Stepper Motor Driver	store bought	Amazon	1	13.01	13.01
E009				Stepper Motor Driver	tb6600 4A Stepper Motor Driver	store bought	Amazon	1	25.60	25.60
E010				Thermocouple	Huaban MAX6675 K Type Thermocouple	store bought	Amazon	2	8.76	17.52
E011				DC Motor Speed COntroller	DROK DC Motor Speed Controller, 12V-36V, 12A Drive Regulator	store bought	Amazon	1	19.37	19.37
E012				5V to 3.3V Shifter	KeeYees 4 Channel IIC 12C Logic Level Converter, Bi-directional	store bought	Amazon	1	8.61	8.61

Appendix T. Drawing Package (Omitting Digitally Fabricated Parts)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Heater Stick
String^A. Heater Probe Assembly
Heater Pulley
Copper Block
Heater shaft
Thermocouple representation
heater representation
Tip Body
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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WEIGHT:
SHEET 1 OF 1
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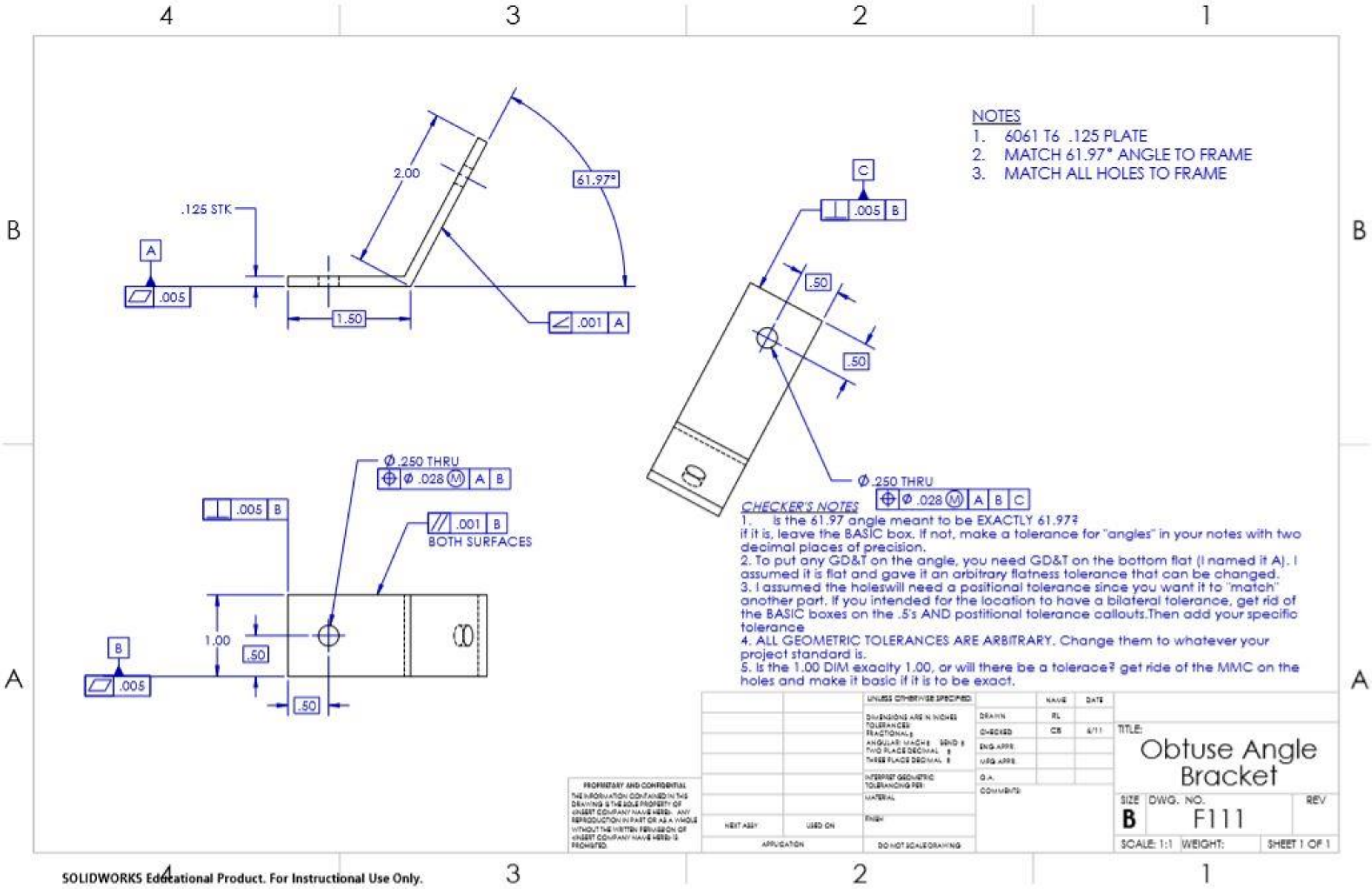

NOTES

1. 6061 T6 .125 PLATE
2. MATCH 61.97° ANGLE TO FRAME
3. MATCH ALL HOLES TO FRAME

CHECKER'S NOTES

1. Is the 61.97 angle meant to be EXACTLY 61.97?
if it is, leave the BASIC box. If not, make a tolerance for "angles" in your notes with two decimal places of precision.
2. To put any GD&T on the angle, you need GD&T on the bottom flat (I named it A). I assumed it is flat and gave it an arbitrary flatness tolerance that can be changed.
3. I assumed the holeswill need a positional tolerance since you want it to "match" another part. If you intended for the location to have a bilateral tolerance, get rid of the BASIC boxes on the .5's AND postitional tolerance callouts.Then add your specific tolerance
4. ALL GEOMETRIC TOLERANCES ARE ARBITRARY. Change them to whatever your project standard is.
5. Is the 1.00 DIM exacity 1.00, or will there be a tolerace? get ride of the MMC on the holes and make it basic if it is to be exact.

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UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	RL			
	CHECKED	CB	6/11	TITLE: Obtuse Angle Bracket	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL	COMMENTS:			SIZE B	DWG. NO. F111	REV
FINISH					
NEXT ASSY / USED ON					
APPLICATION / DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT:	SHEET 1 OF 1

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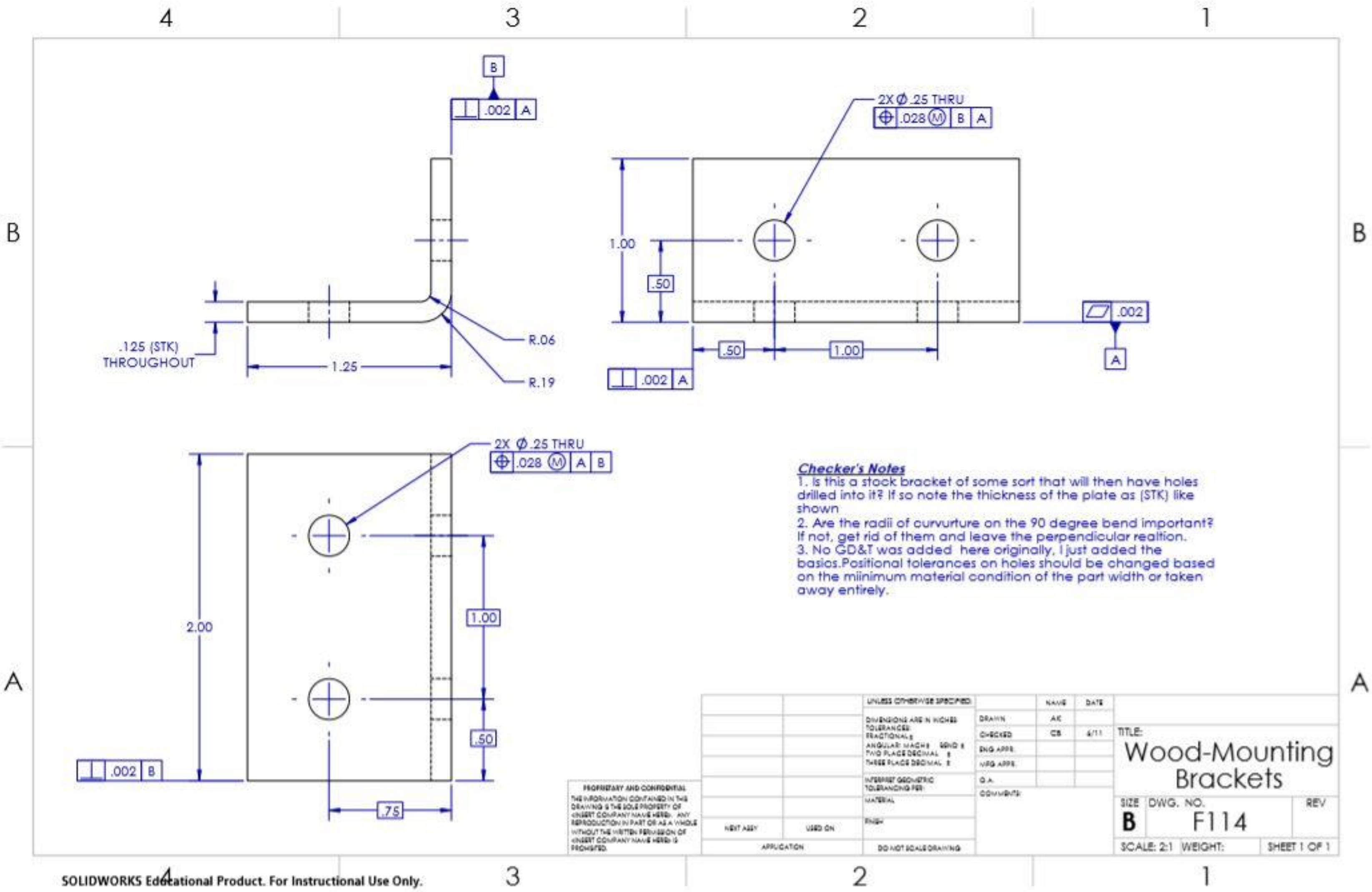

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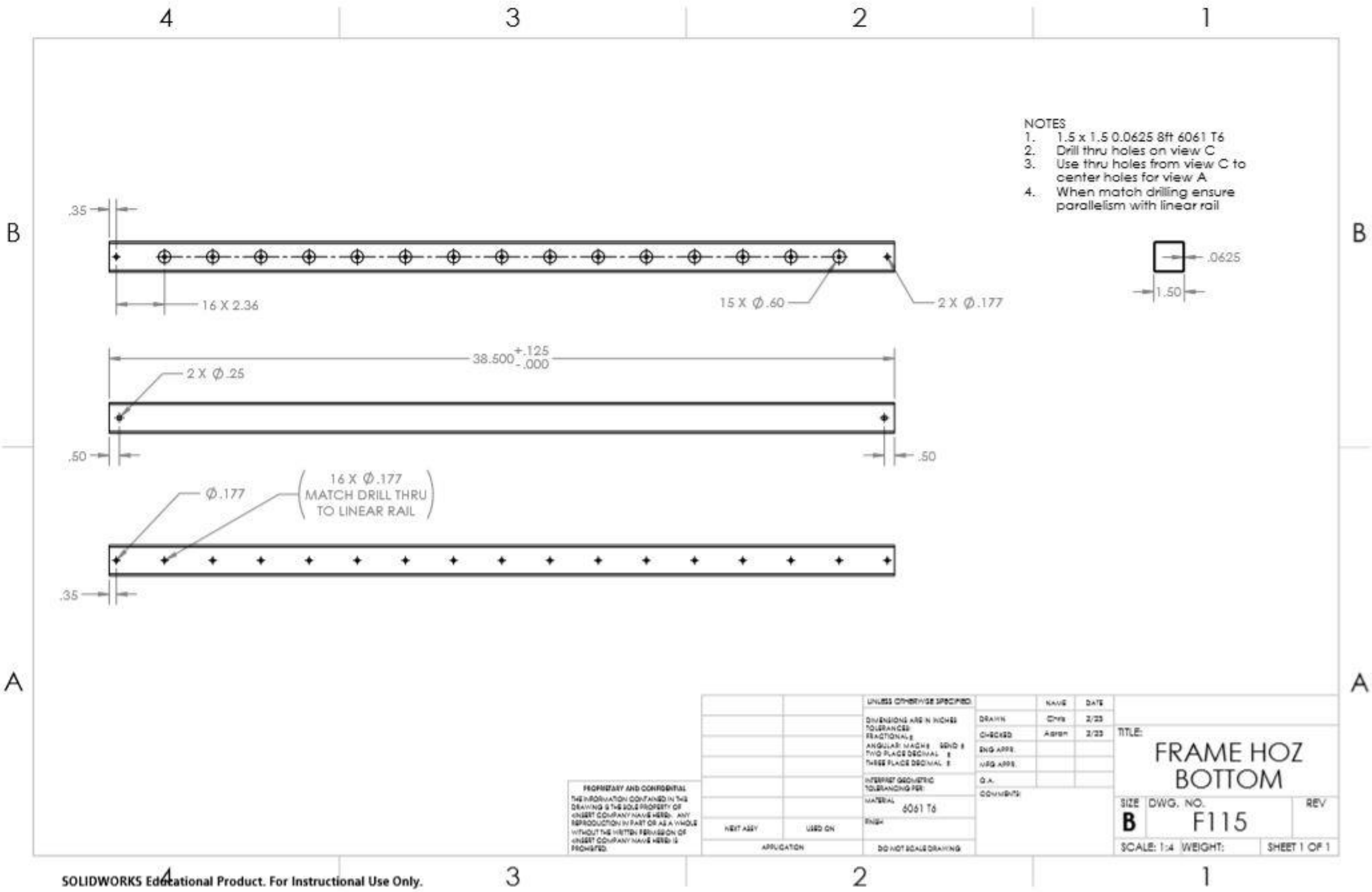
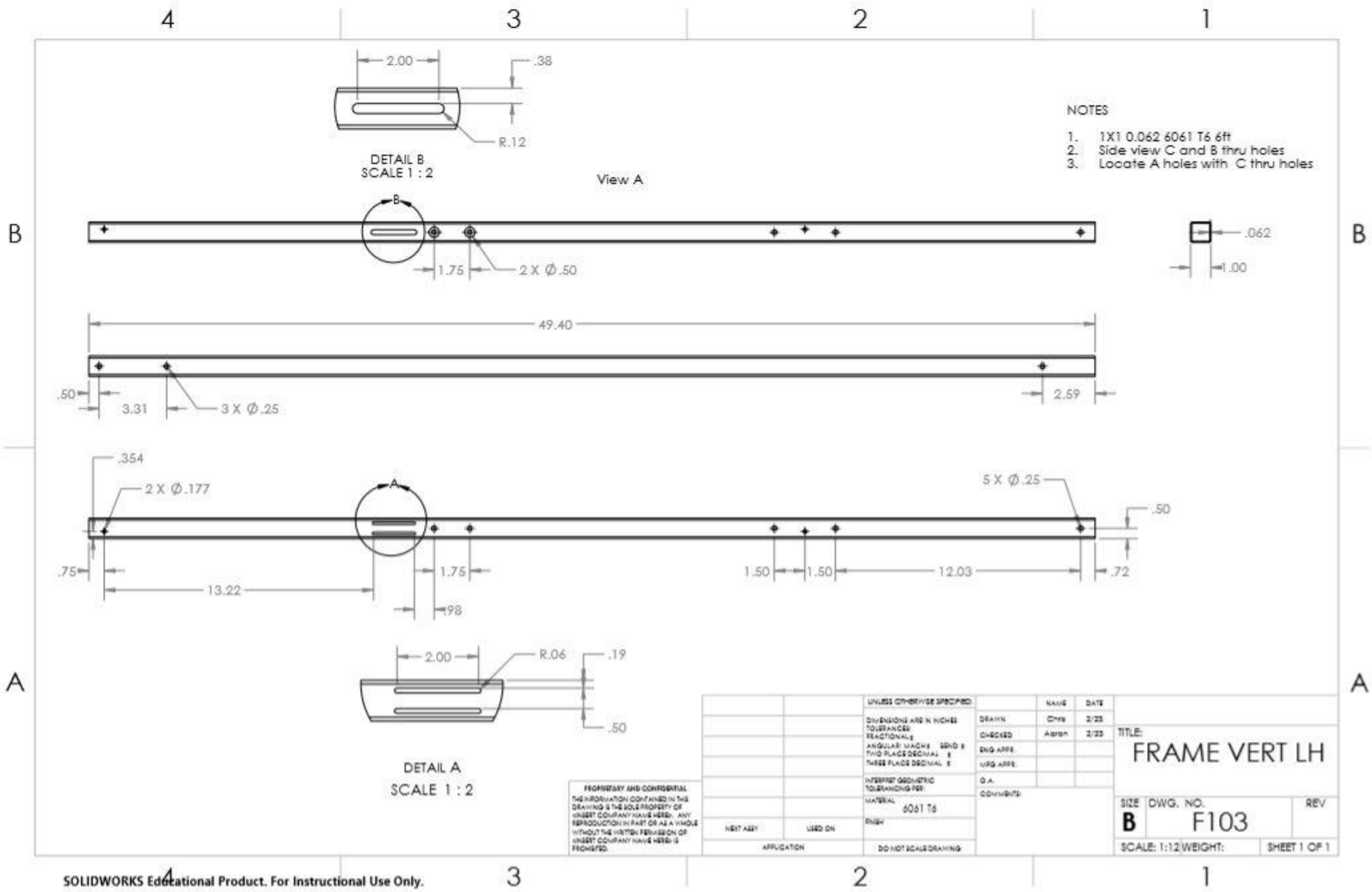


SOLIDWORKS Educational Product. For Instructional Use Only.


2.00
.38
R.12
DETAIL B
SCALE 1 : 2
View A
NOTES
1. 1X1 0.062 6061 T6 6ft
2. Side view C and B thru holes
3. Locate A holes with C thru holes
B
1.75
2 X Ø.50
.062
1.00
49.40
.50
3.31
3 X Ø.25
2.59
.354
2 X Ø.177
5 X Ø.25
A
.50
.75
13.22
1.75
.98
1.50
1.50
12.03
.72
2.00
R.06
.19
.50
DETAIL A
SCALE 1 : 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 6061 T6
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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NAME DATE
DRAWN Chris 2/23
CHECKED Aaron 2/23
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
FRAME VERT LH
SIZE B
DWG. NO. F103
REV
SCALE: 1:12
WEIGHT:
SHEET 1 OF 1
4 3 2 1
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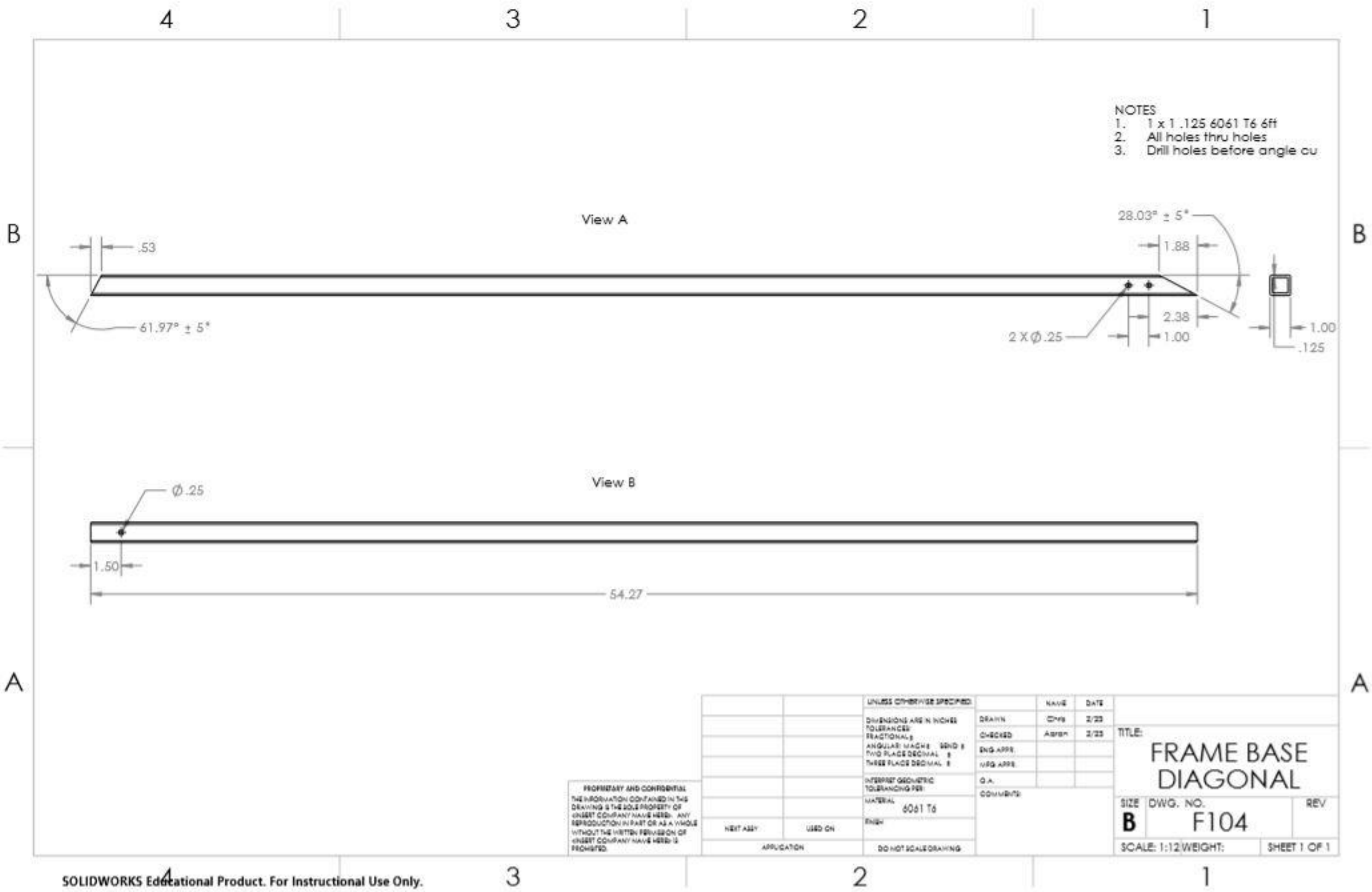
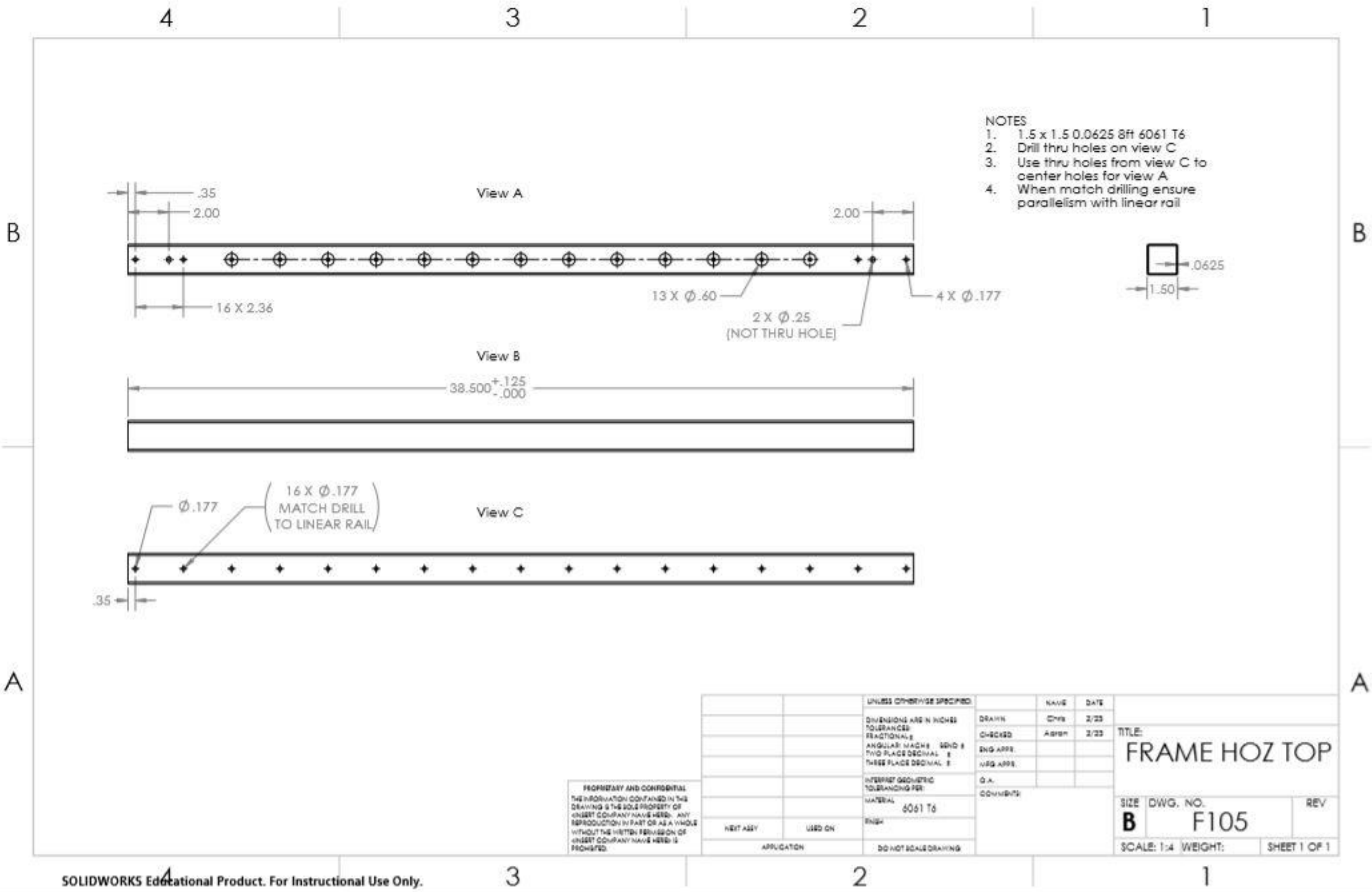


SOLIDWORKS Educational Product. For Instructional Use Only.



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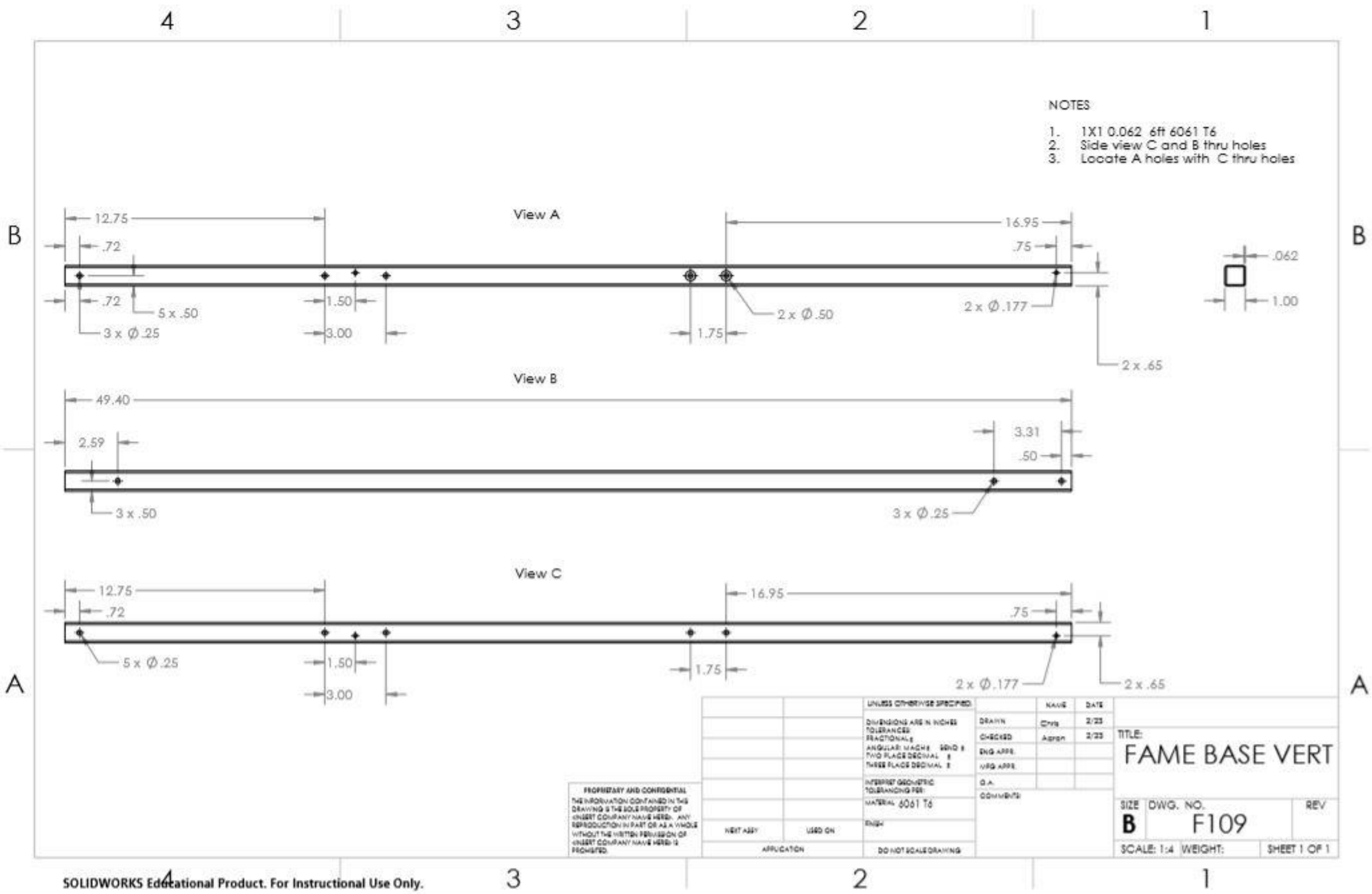

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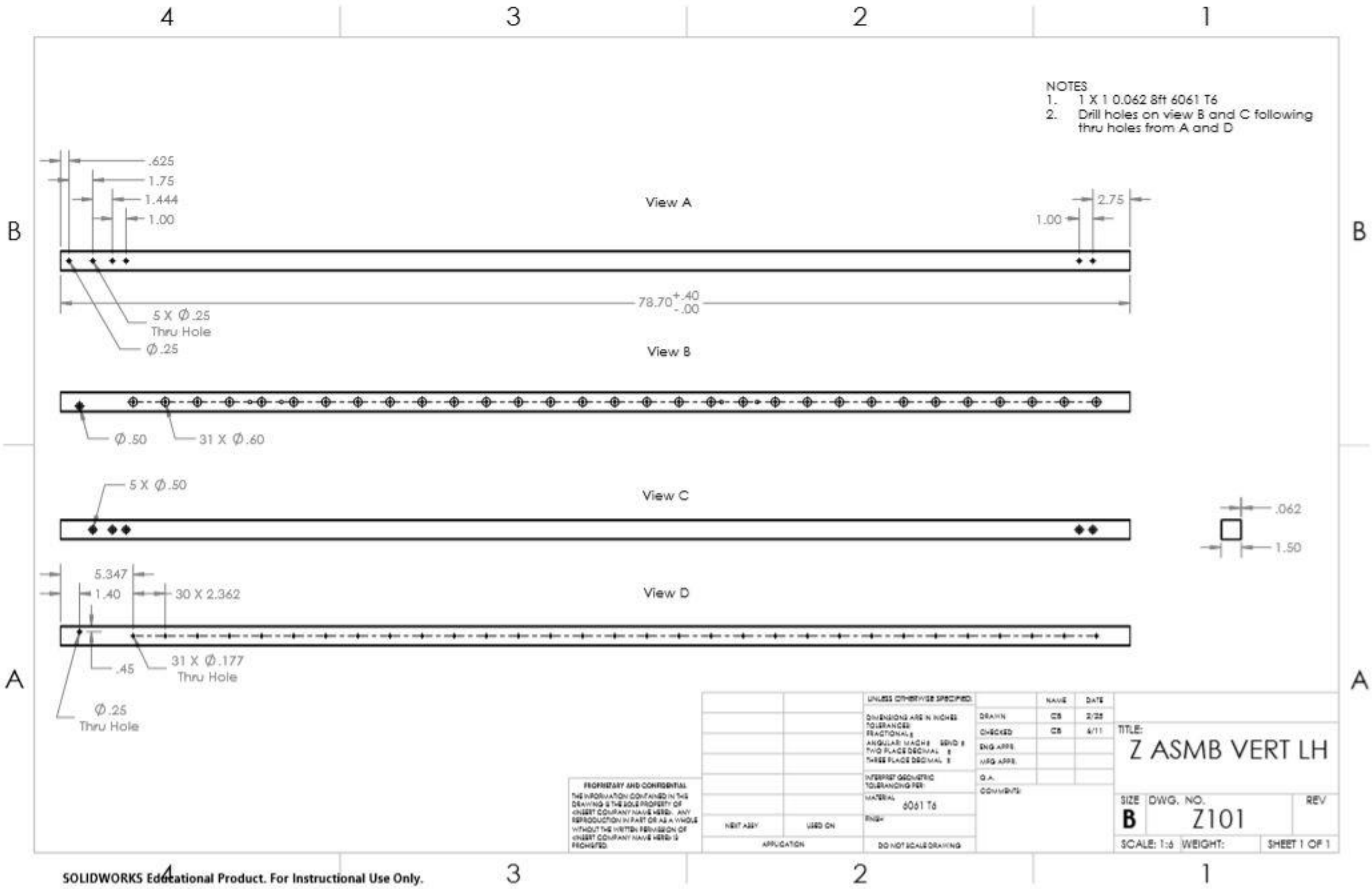

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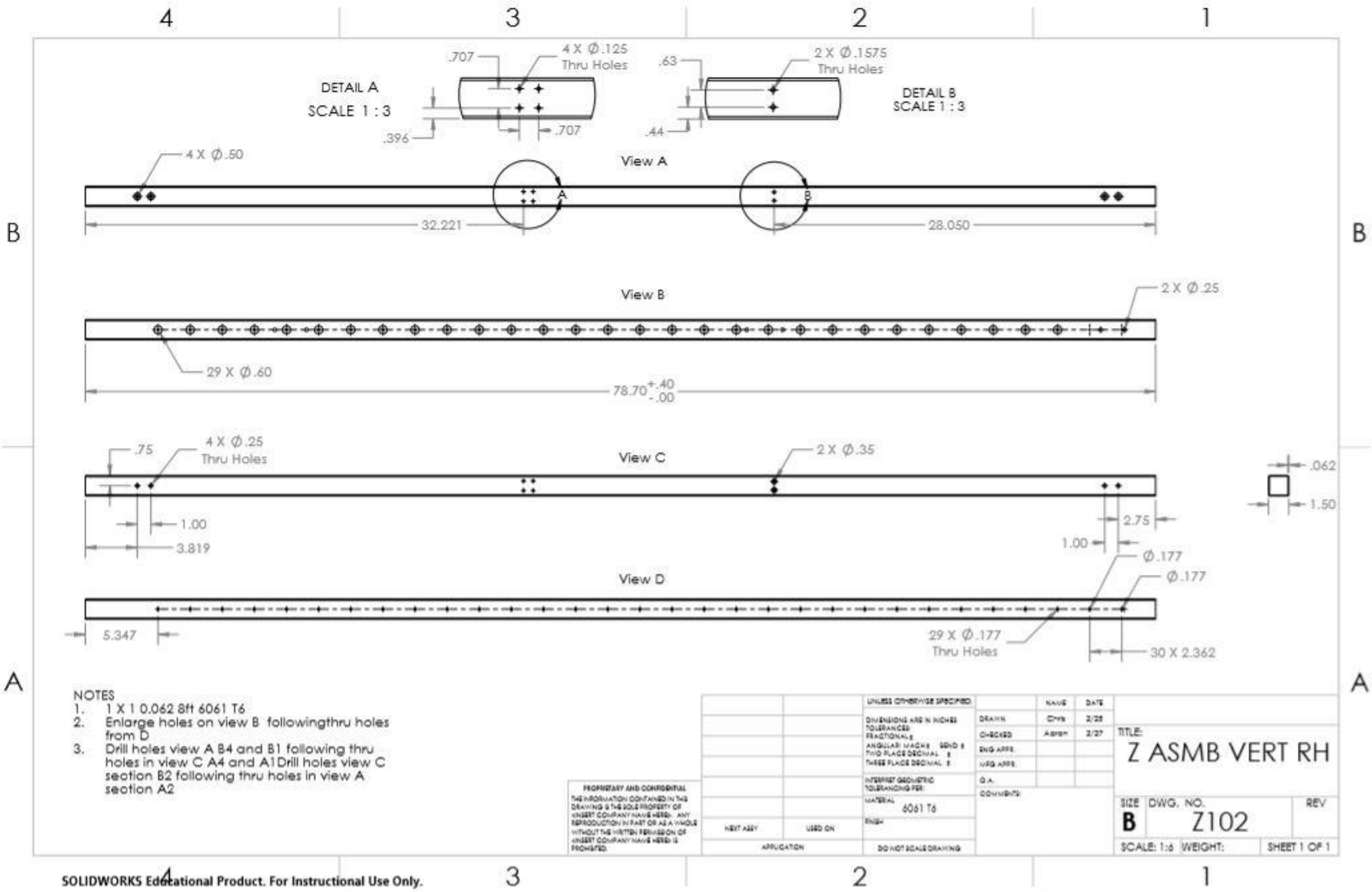

DETAIL A
SCALE 1 : 3
.707
4 X Ø.125
Thru Holes
.396
.707
.63
2 X Ø.1575
Thru Holes
.44
DETAIL B
SCALE 1 : 3
4 X Ø.50
View A
A
B
32.221
28.050
View B
2 X Ø.25
29 X Ø.60
78.70 +.40 -.00
.75
4 X Ø.25
Thru Holes
View C
2 X Ø.35
1.00
3.819
2.75
1.00
.062
1.50
Ø.177
Ø.177
View D
5.347
29 X Ø.177
Thru Holes
30 X 2.362
NOTES
1. 1 X 1 0.062 8ft 6061 T6
2. Enlarge holes on view B followingthru holes from D
3. Drill holes view A B4 and B1 following thru holes in view C A4 and A1Drill holes view C section B2 following thru holes in view A section A2
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NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 T6
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
Chris
2/25
CHECKED
Aaron
2/27
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Z ASMB VERT RH
SIZE
B
DWG. NO.
Z102
REV
SCALE: 1:6
WEIGHT:
SHEET 1 OF 1
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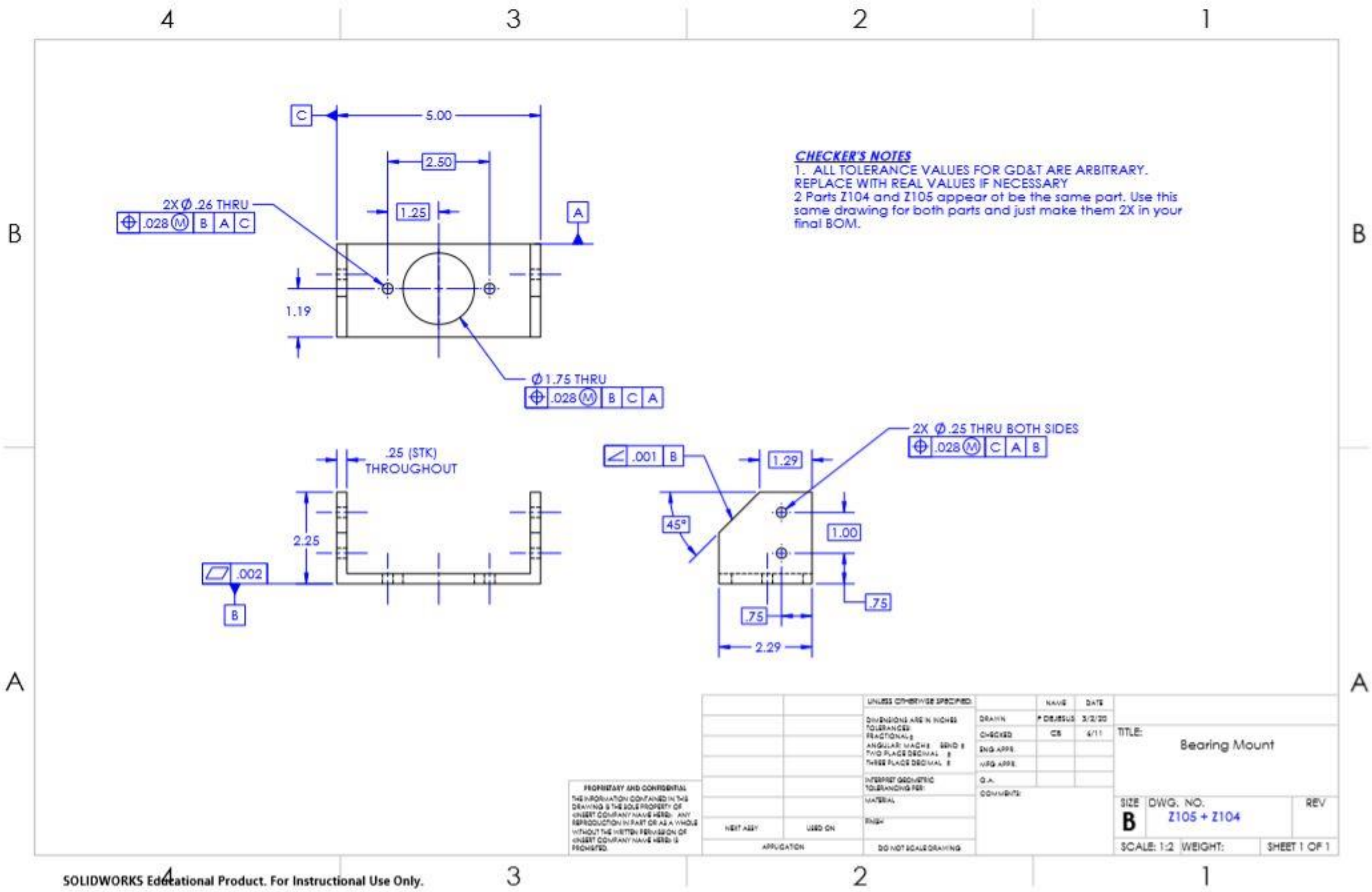

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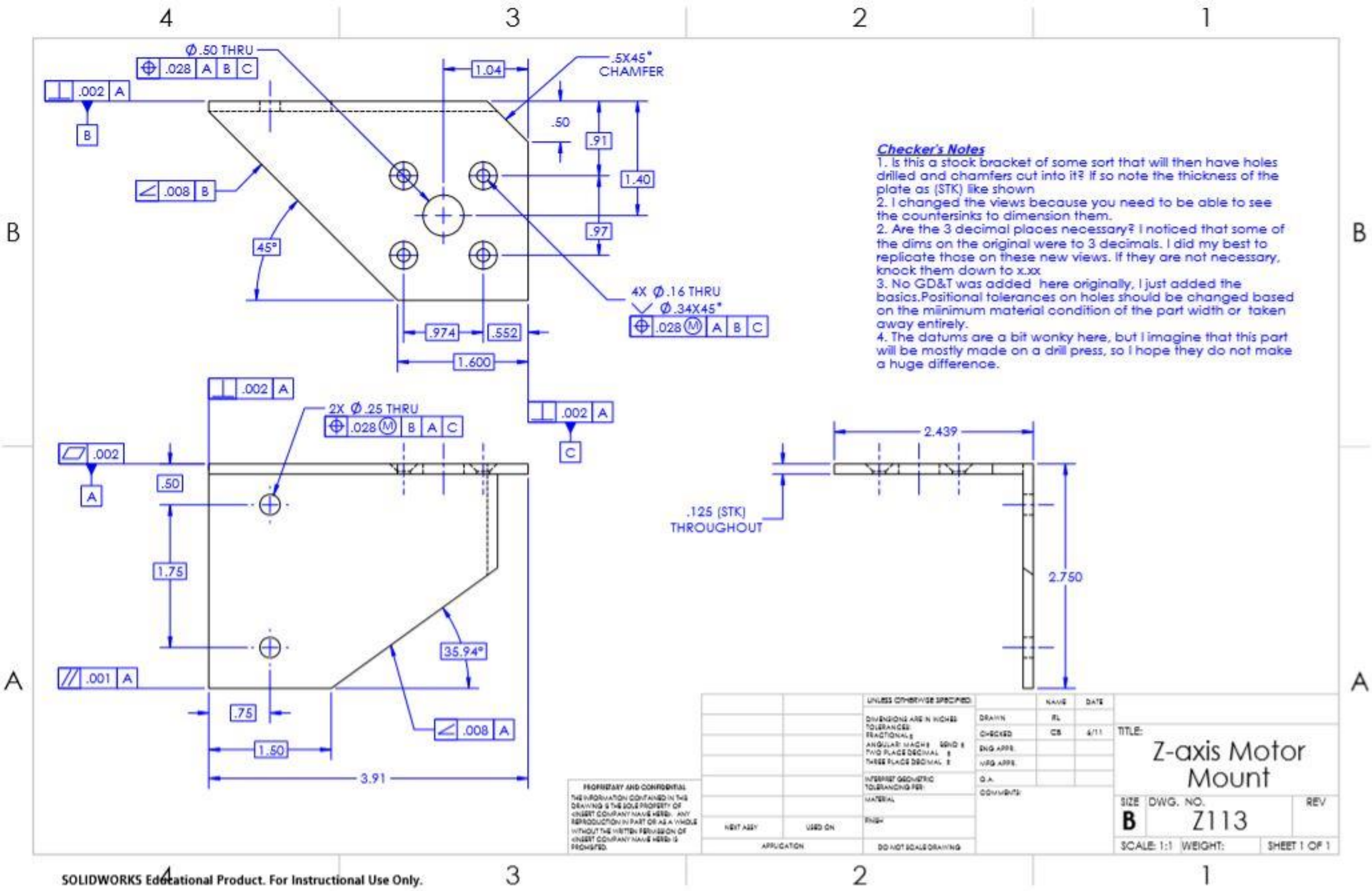
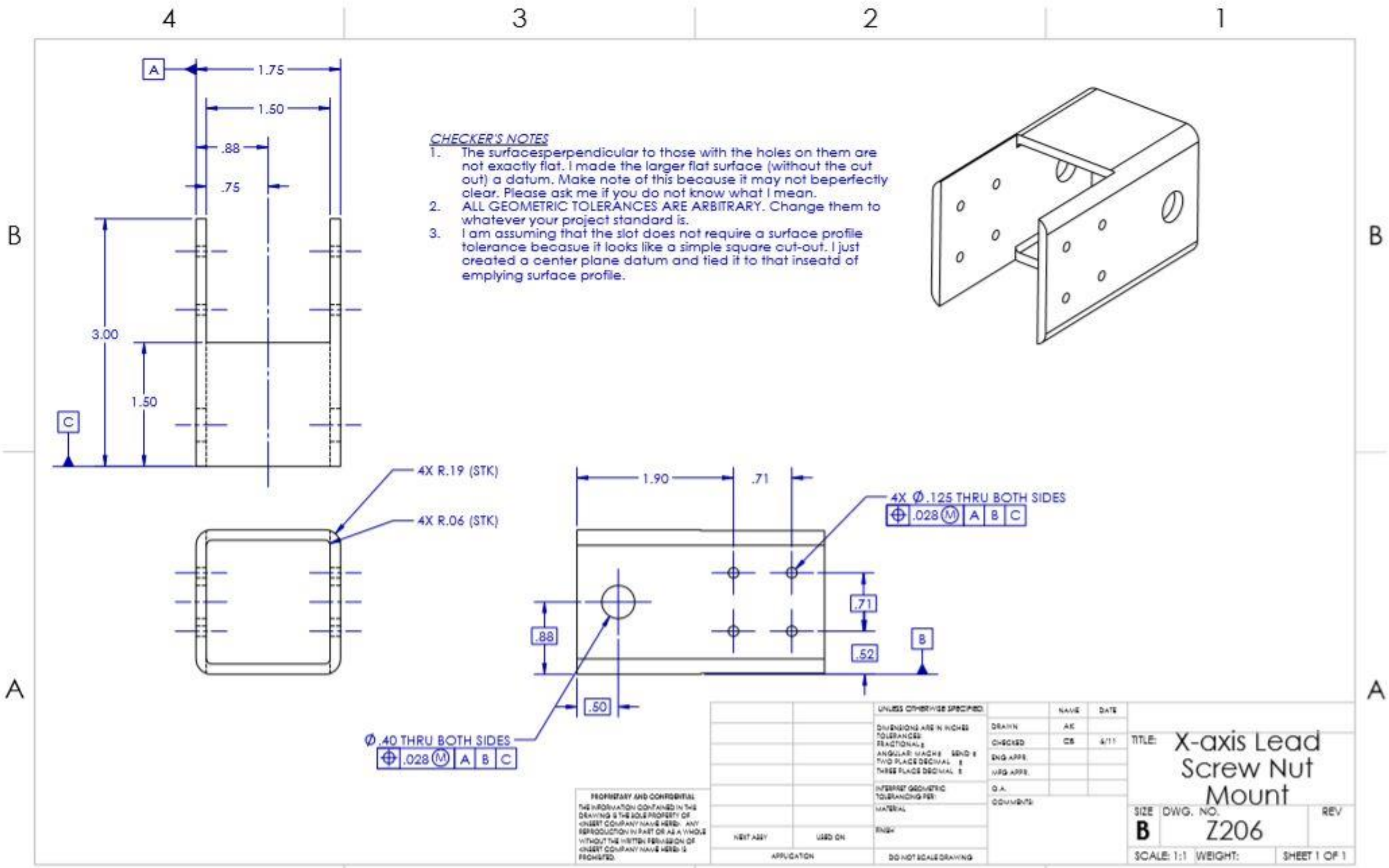

Ø.50 THRU
.028 A B C
.002 A
B
.5X45°
CHAMFER
1.04
.50
.91
1.40
.97
.008 B
45°
4X Ø.16 THRU
Ø.34X45°
.028 Ⓜ A B C
.974
.552
1.600
.002 A
C
2X Ø.25 THRU
.028 Ⓜ B A C
.002
A
.50
1.75
35.94°
.001 A
.75
1.50
3.91
.008 A
2.439
.125 (STK)
THROUGHOUT
2.750
Checker's Notes
1. Is this a stock bracket of some sort that will then have holes drilled and chamfers cut into it? If so note the thickness of the plate as (STK) like shown
2. I changed the views because you need to be able to see the countersinks to dimension them.
2. Are the 3 decimal places necessary? I noticed that some of the dims on the original were to 3 decimals. I did my best to replicate those on these new views. If they are not necessary, knock them down to x.xx
3. No GD&T was added here originally, I just added the basics.Positional tolerances on holes should be changed based on the miinimum material condition of the part width or taken away entirely.
4. The datums are a bit wonky here, but I imagine that this part will be mostly made on a drill press, so I hope they do not make a huge difference.
TITLE:
Z-axis Motor Mount
SIZE DWG. NO. REV
B Z113
SCALE: 1:1 WEIGHT: SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



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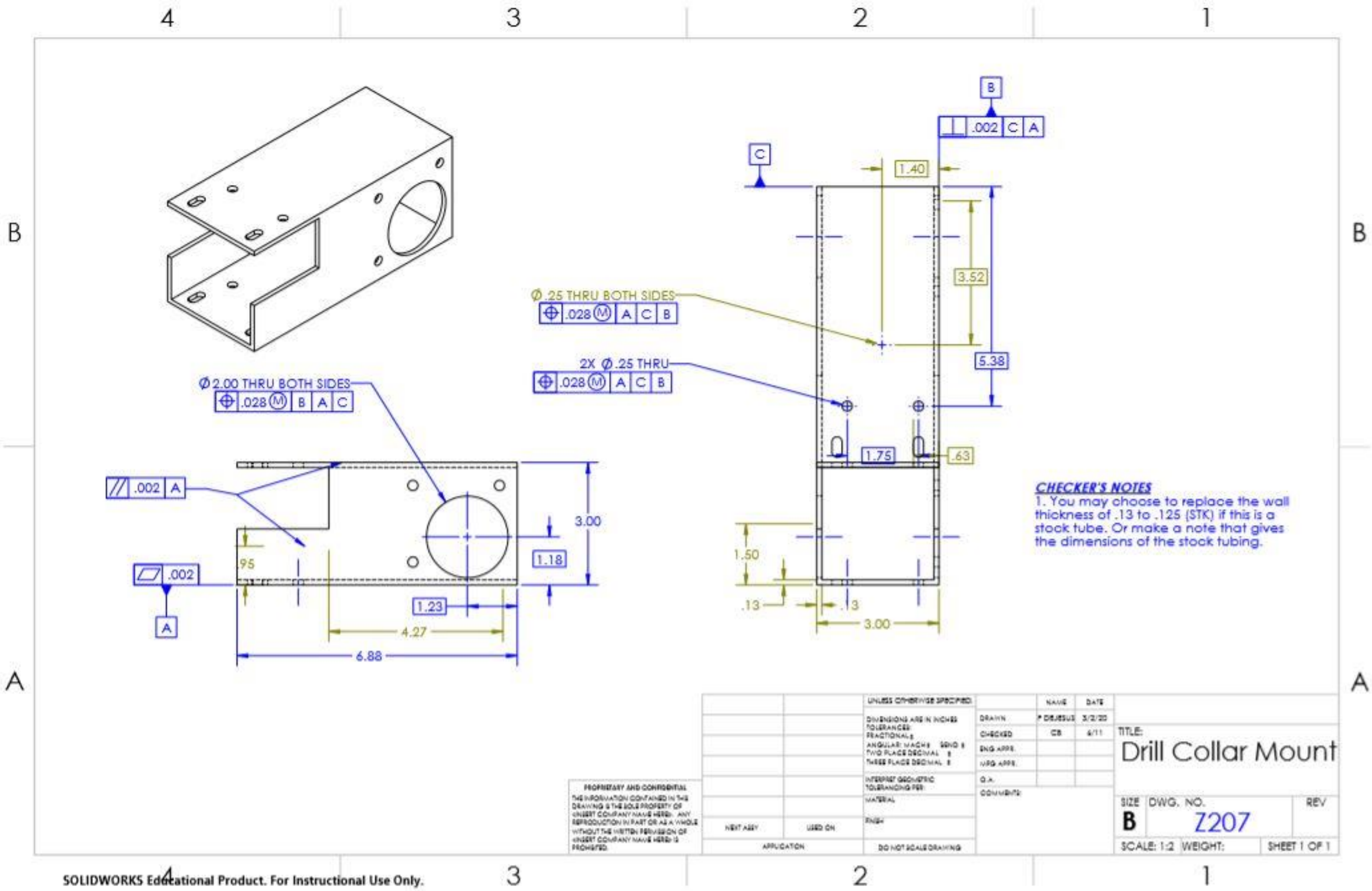

Ø .25 THRU BOTH SIDES
.028 Ⓜ A C B
2X Ø .25 THRU
.028 Ⓜ A C B
Ø 2.00 THRU BOTH SIDES
.028 Ⓜ B A C
.002 A
.002
.002 C A
1.40
3.52
5.38
1.75
.63
3.00
1.18
1.23
4.27
6.88
.95
1.50
.13
.13
3.00
CHECKER'S NOTES
1. You may choose to replace the wall thickness of .13 to .125 (STK) if this is a stock tube. Or make a note that gives the dimensions of the stock tubing.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
CB
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
TITLE:
Drill Collar Mount
SIZE
B
DWG. NO.
Z207
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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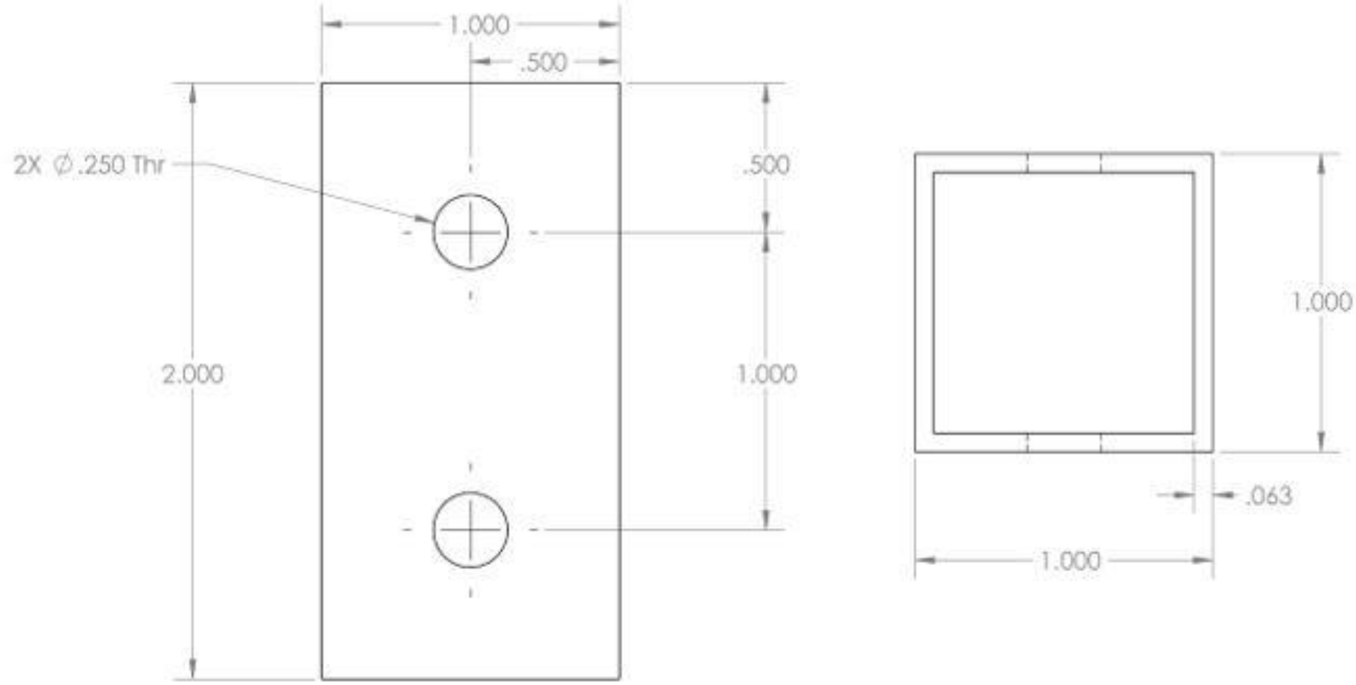

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	WM	2/25/20
CHECKED	CB	6/11
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

NEXT ASSY | USED ON
APPLICATION

<COMPANY NAME>

TITLE: Support Bar Spacer

SIZE A | DWG. NO. C-202-m | REV

SCALE: 2:1 | SHEET 1 OF 1

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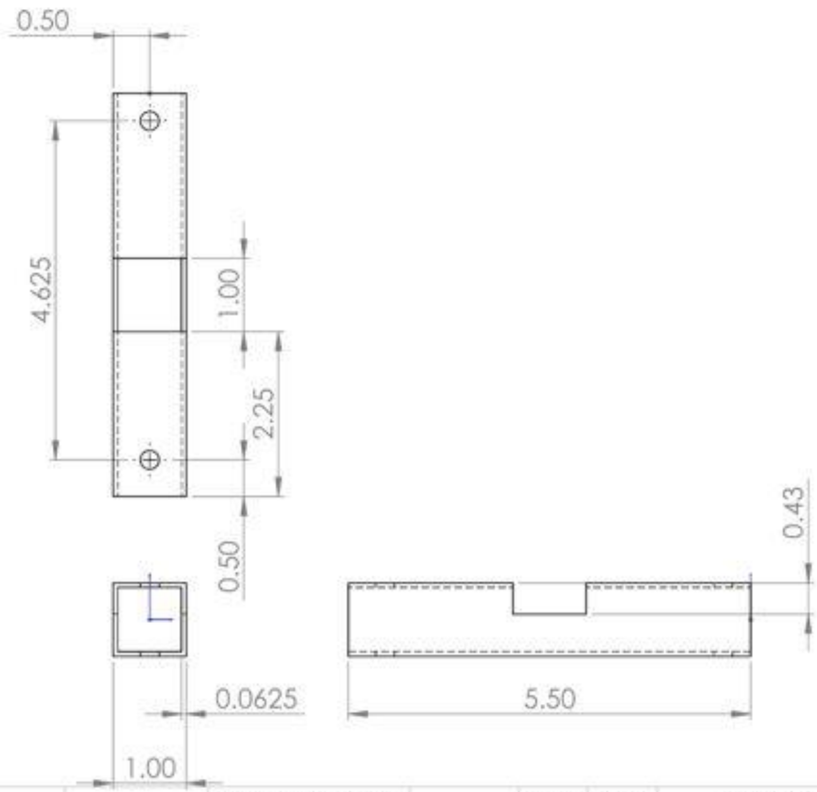
2 1

B B



A A

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	RL	
CHECKED	CB	6/11
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

<COMPANY NAME>

TITLE:

Roller Mount

SIZE	DWG. NO.	REV
A	C-204-m	

SCALE: 1:2 SHEET 1 OF 1

2 1

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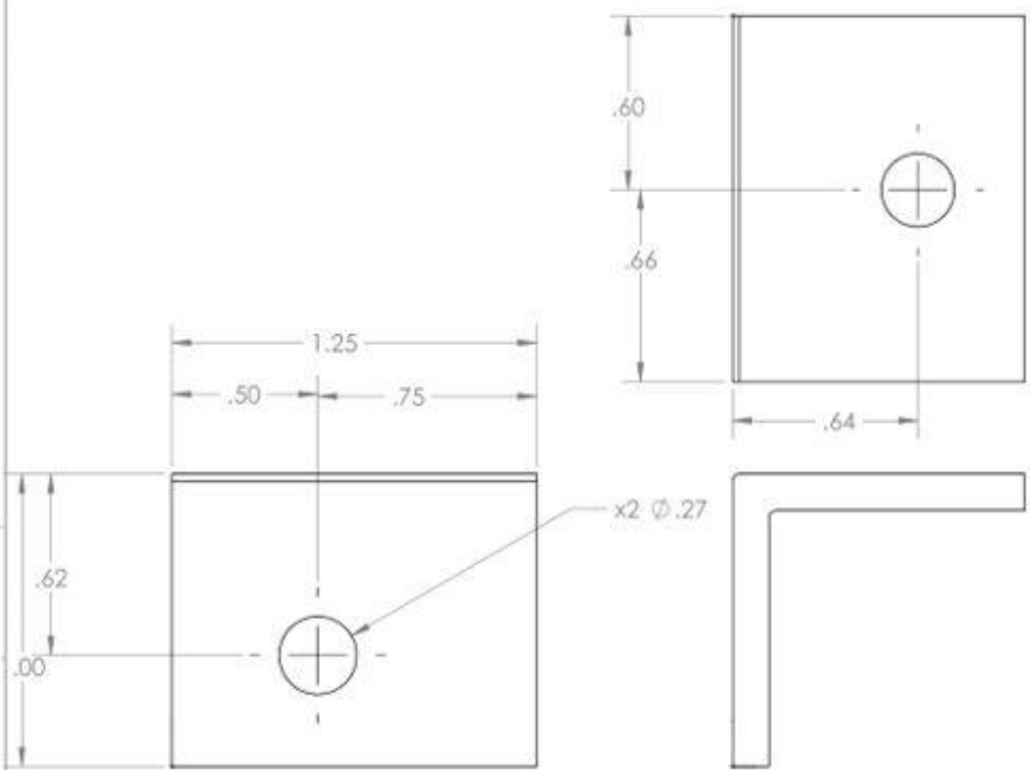
Notes
1. Use 1"x1" L bracket



UNLESS OTHERWISE SPECIFIED:		NAME / DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	WM 2/25/20
	CHECKED	CB 6/11
	ENG APPR.	
	MFG APPR.	
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.	
MATERIAL	COMMENTS:	
FINISH		
DO NOT SCALE DRAWING		

NEXT ASSY | USED ON

APPLICATION

<COMPANY NAME>

TITLE: Frame Mounting Bracket

SIZE A | DWG. NO. C-209-m | REV

SCALE: 2:1 | SHEET 1 OF 1

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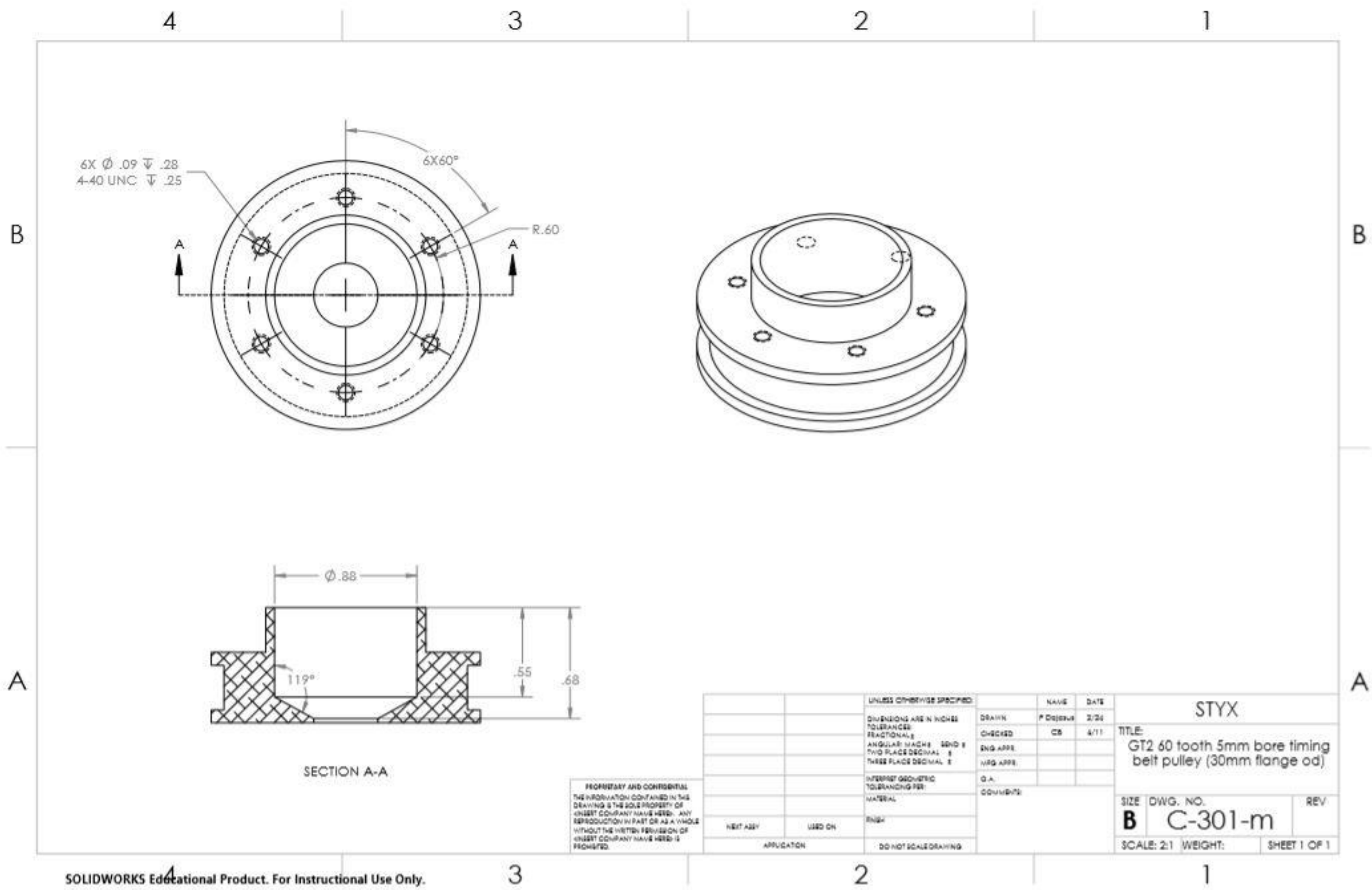

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NOTES:
1. STOCK: 1"X1" 0.0625"T, 6061,48" LONG

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NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED:		
APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		
		INTERPRET GEOMETRIC TOLERANCING PER:		
		MATERIAL		
		FINISH		
		DO NOT SCALE DRAWING		

	NAME	DATE
DRAWN	P DEJESUS	2/26
CHECKED	CB	6/11
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:
1", .0625"t, 6061, 48" long square tube

SIZE	DWG. NO.	REV
B	C-403-m	
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

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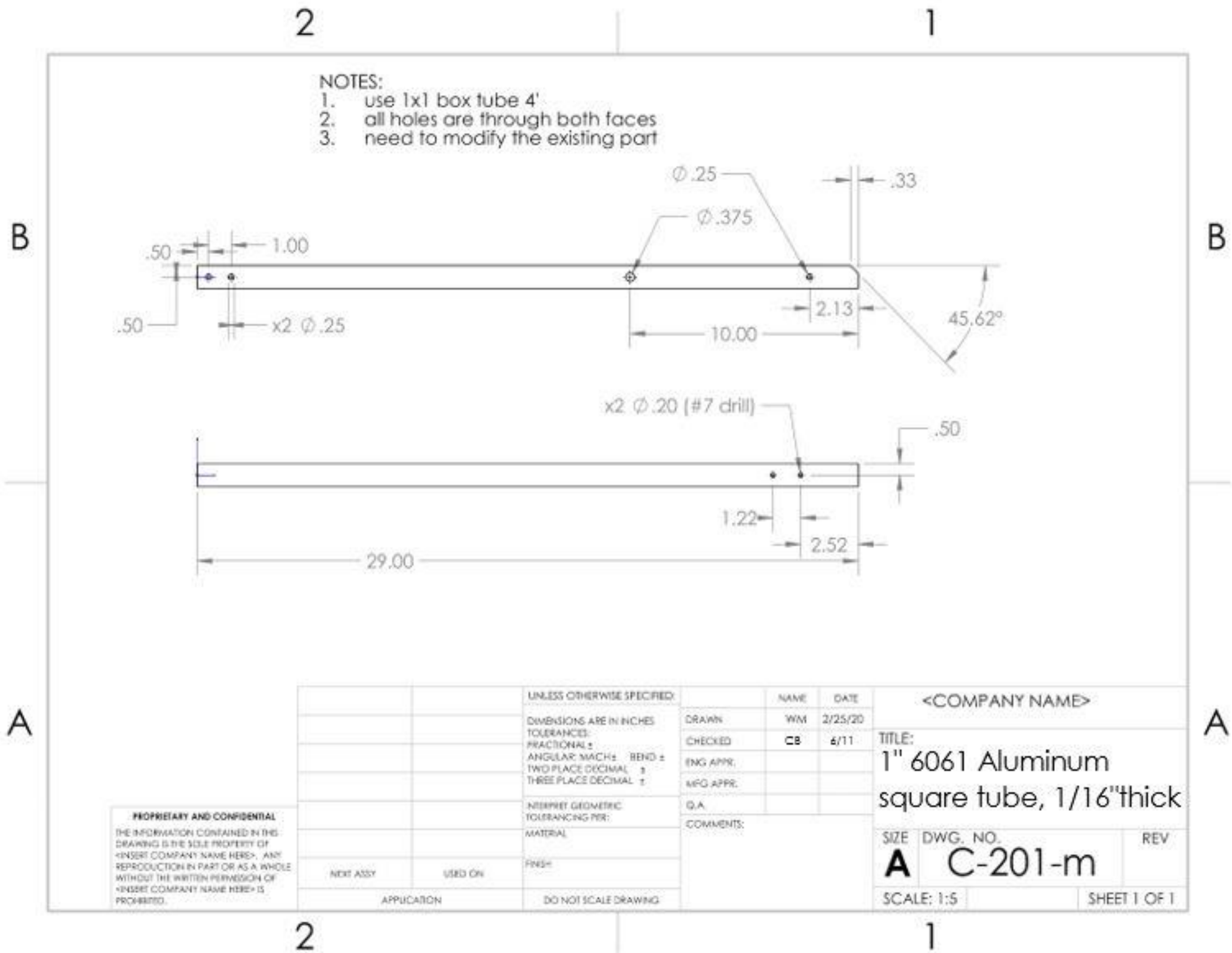
NOTES:
1. use 1x1 box tube 4'
2. all holes are through both faces
3. need to modify the existing part
∅.25
.33
∅.375
.50
1.00
.50
x2 ∅.25
2.13
10.00
45.62°
x2 ∅.20 (#7 drill)
.50
1.22
2.52
29.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
WM
2/25/20
CHECKED
CB
6/11
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
<COMPANY NAME>
TITLE:
1" 6061 Aluminum square tube, 1/16"thick
SIZE
A
DWG. NO.
C-201-m
REV
SCALE: 1:5
SHEET 1 OF 1
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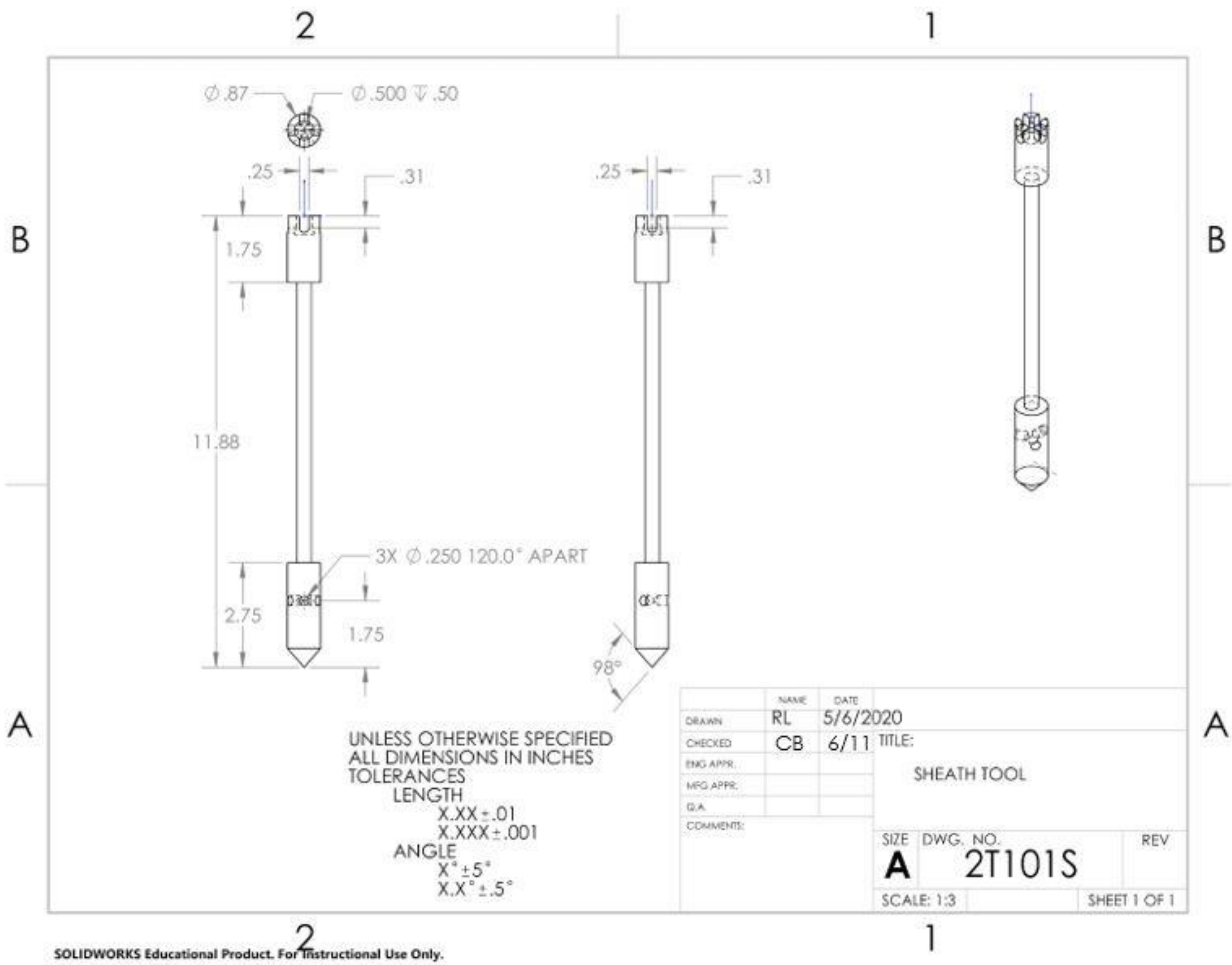
2
1
B
A
Ø.87
Ø.500 ↧ .50
.25
.31
1.75
11.88
3X Ø.250 120.0° APART
2.75
1.75
98°
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
TOLERANCES
LENGTH
X.XX ±.01
X.XXX ±.001
ANGLE
X° ±5°
X.X° ±.5°
NAME
DATE
DRAWN
RL
5/6/2020
CHECKED
CB
6/11
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SHEATH TOOL
SIZE
DWG. NO.
REV
A
2T101S
SCALE: 1:3
SHEET 1 OF 1
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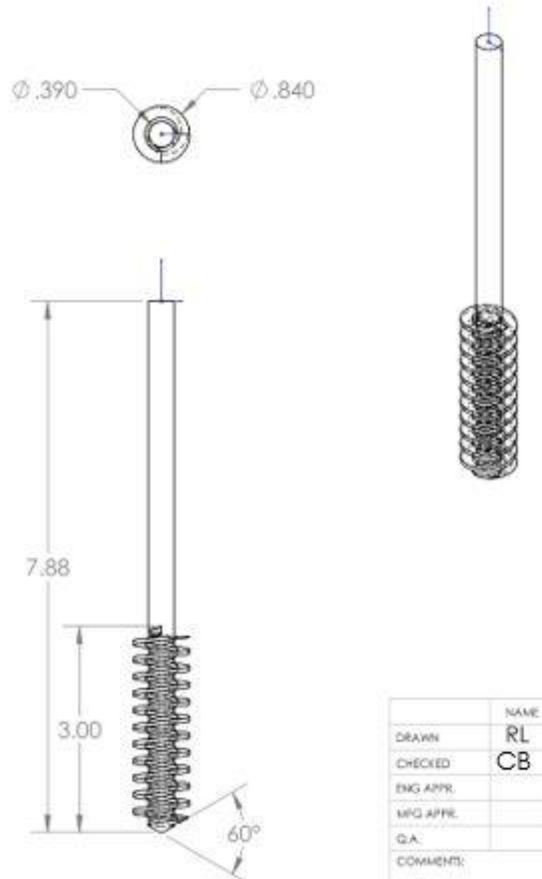

NOTES:
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
TOLERANCES
X.XX ± .05
X.XXX ± .001

NOTES ON THREADS:
FLUTES ARE 4 TPI
DEPTH OF CUT: .233"
WIDTH OF CUT: .1875"
CUTTER: 3/16" HSS, 1/16" CORNER RADII

	NAME	DATE	
DRAWN	RL	5/6/2020	
CHECKED	CB	6/11	TITLE:
ENG APPR.			AUGER TIP
MFG APPR.			
Q.A.			
COMMENTS:			

SIZE	DWG. NO.	REV
A	3T001S	
SCALE: 1:2		SHEET 1 OF 1

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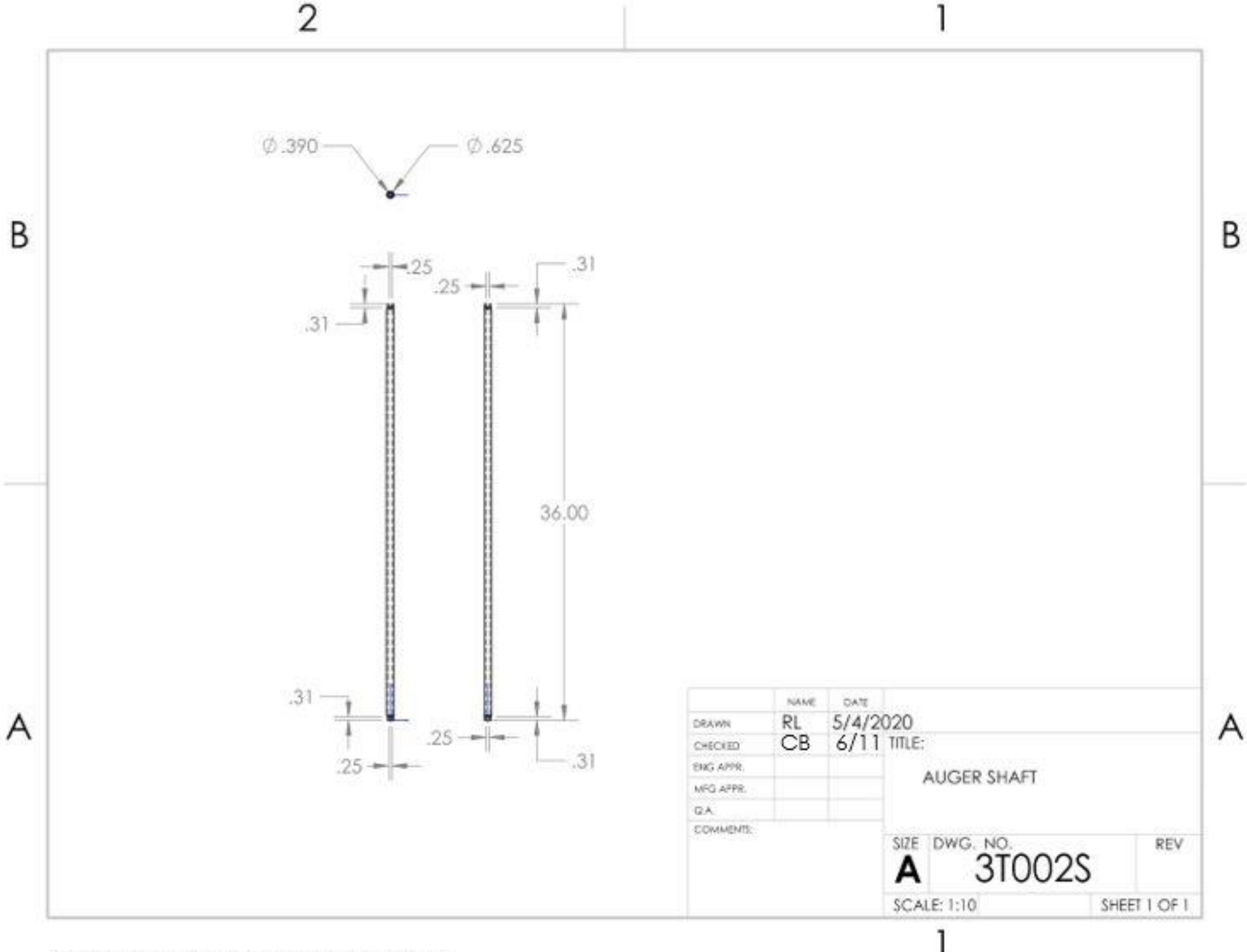

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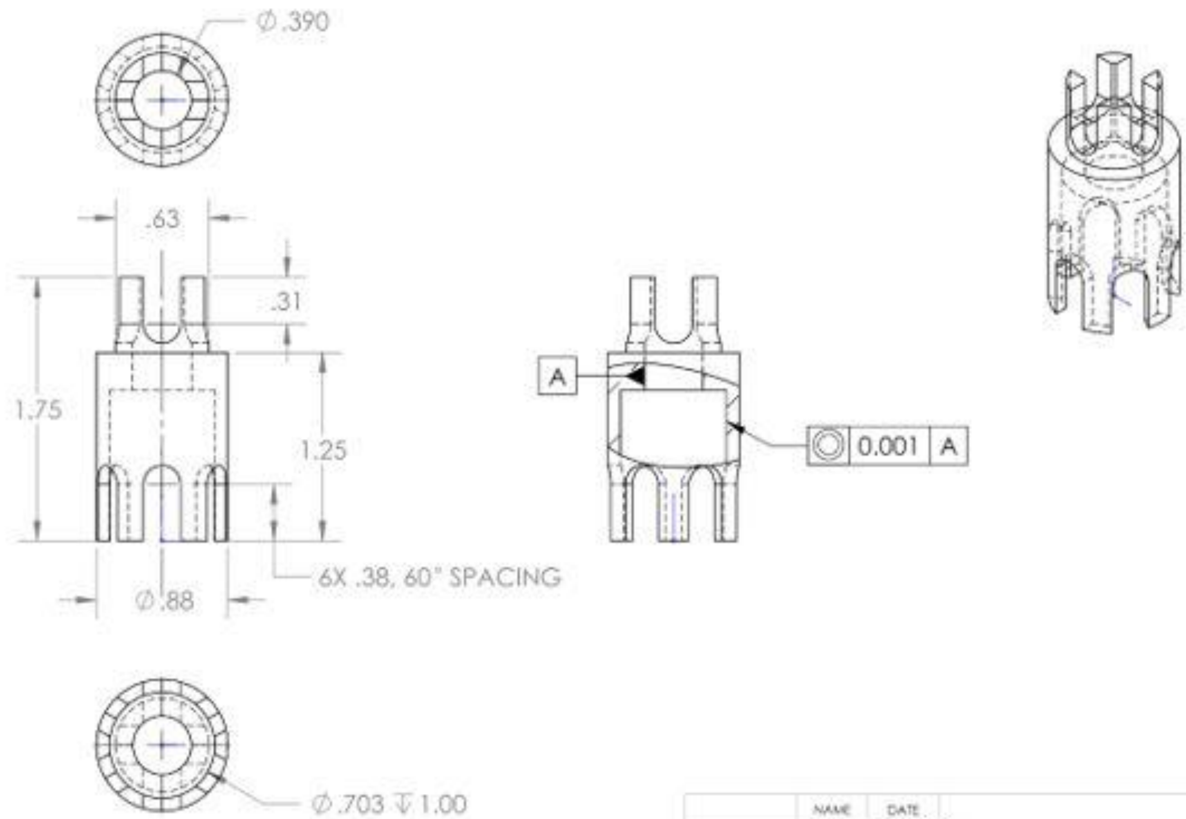

NOTES
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
TOLERANCES
X.XX ±0.005
X.XXX ±0.001

	NAME	DATE
DRAWN	RL	5/4/20
CHECKED	CB	6/11
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

DRILL ADAPTER

SIZE	DWG. NO.	REV
A	1T001S	

SCALE: 1:1 SHEET 1 OF 1

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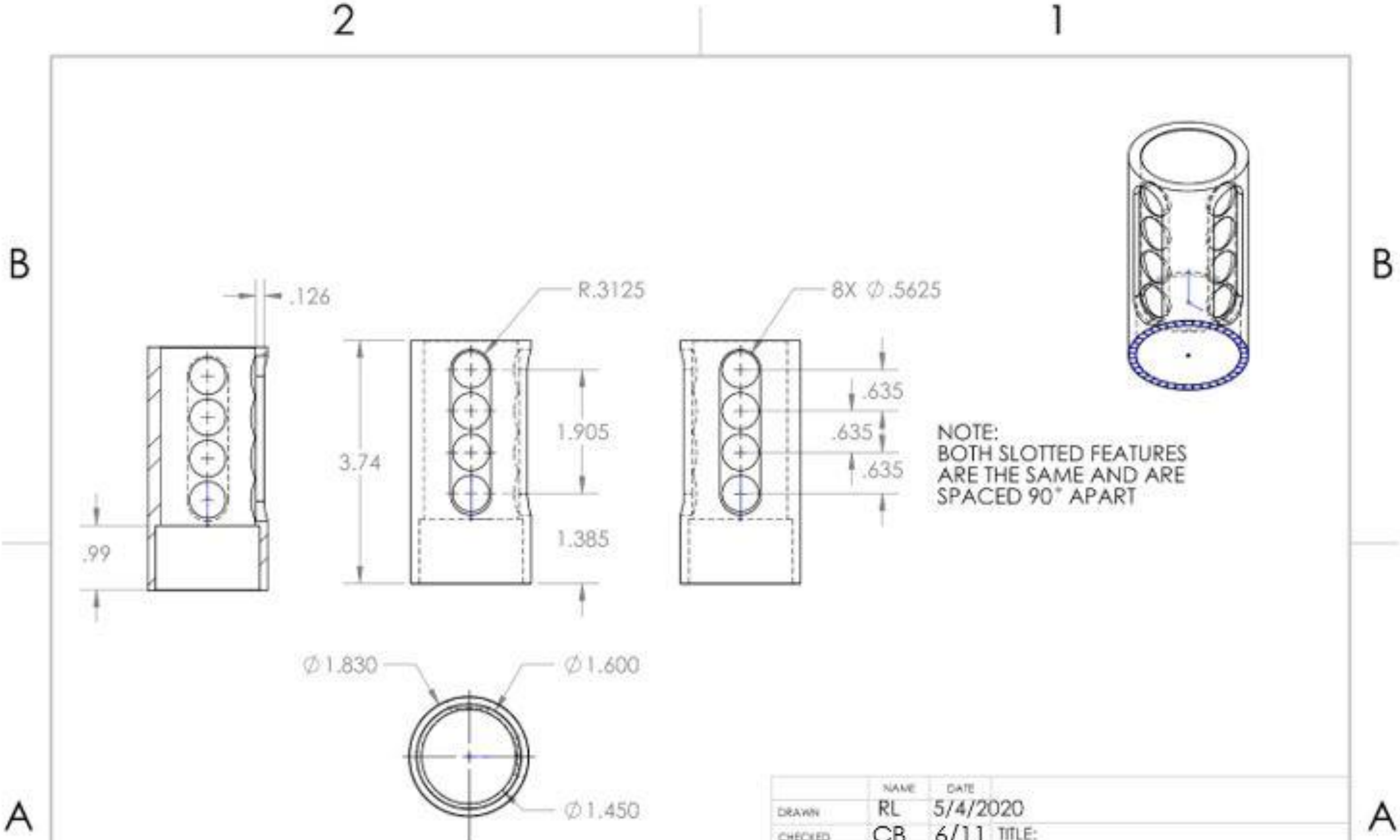

NOTES
UNLESS OTHERWISE SPECIFIED
ALL UNITS IN INCHES
TOLERANCES
X.XX ± .005
X.XXX ± .001

	NAME	DATE	
DRAWN	RL	5/4/2020	
CHECKED	CB	6/11	TITLE: FLOATING COLLAR
ENG APPR.			
MFG APPR.			
Q.A.			
COMMENTS:			SIZE A, DWG. NO. 1T003S, REV
			SCALE: 1:2, SHEET 1 OF 1

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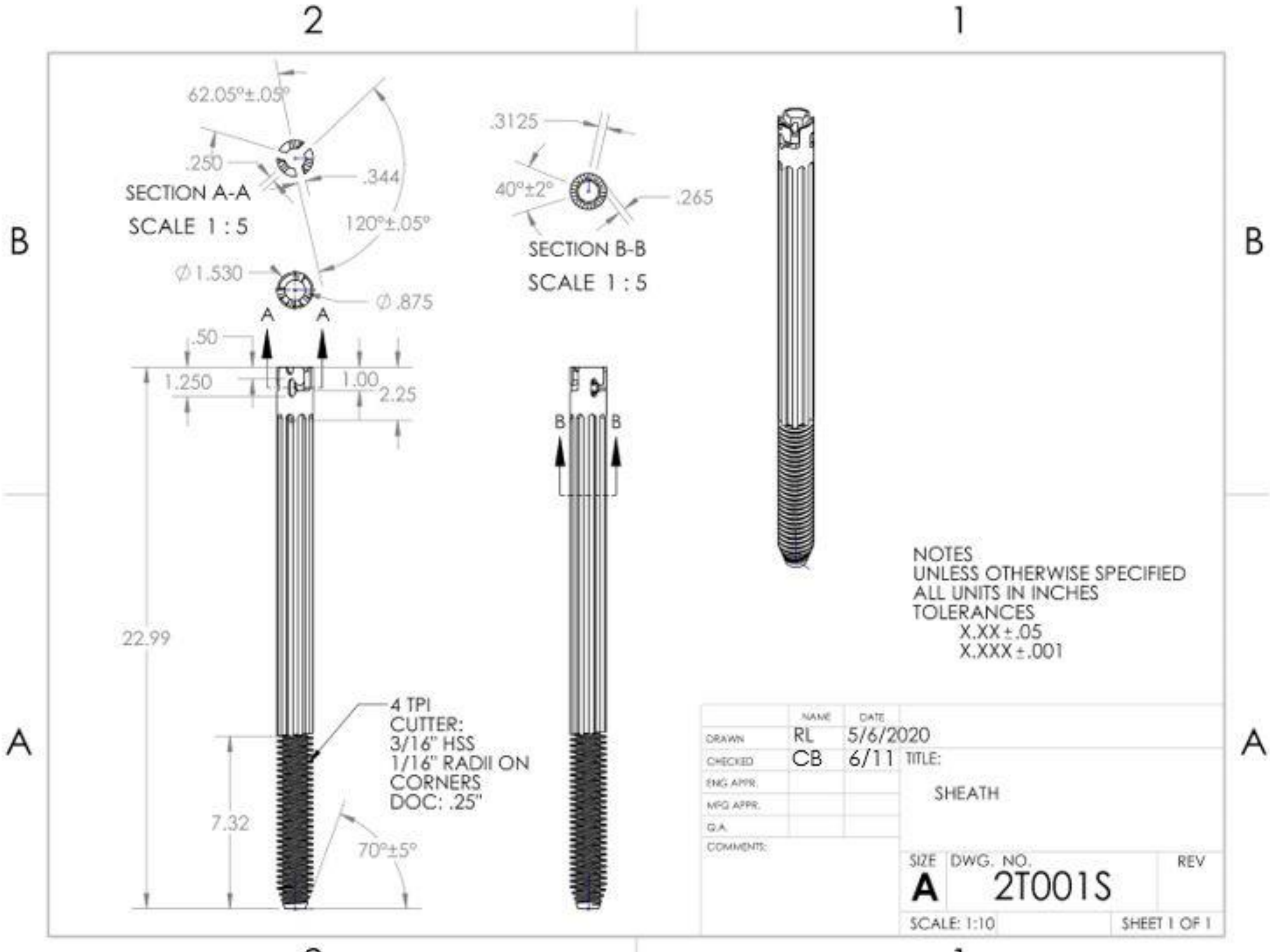

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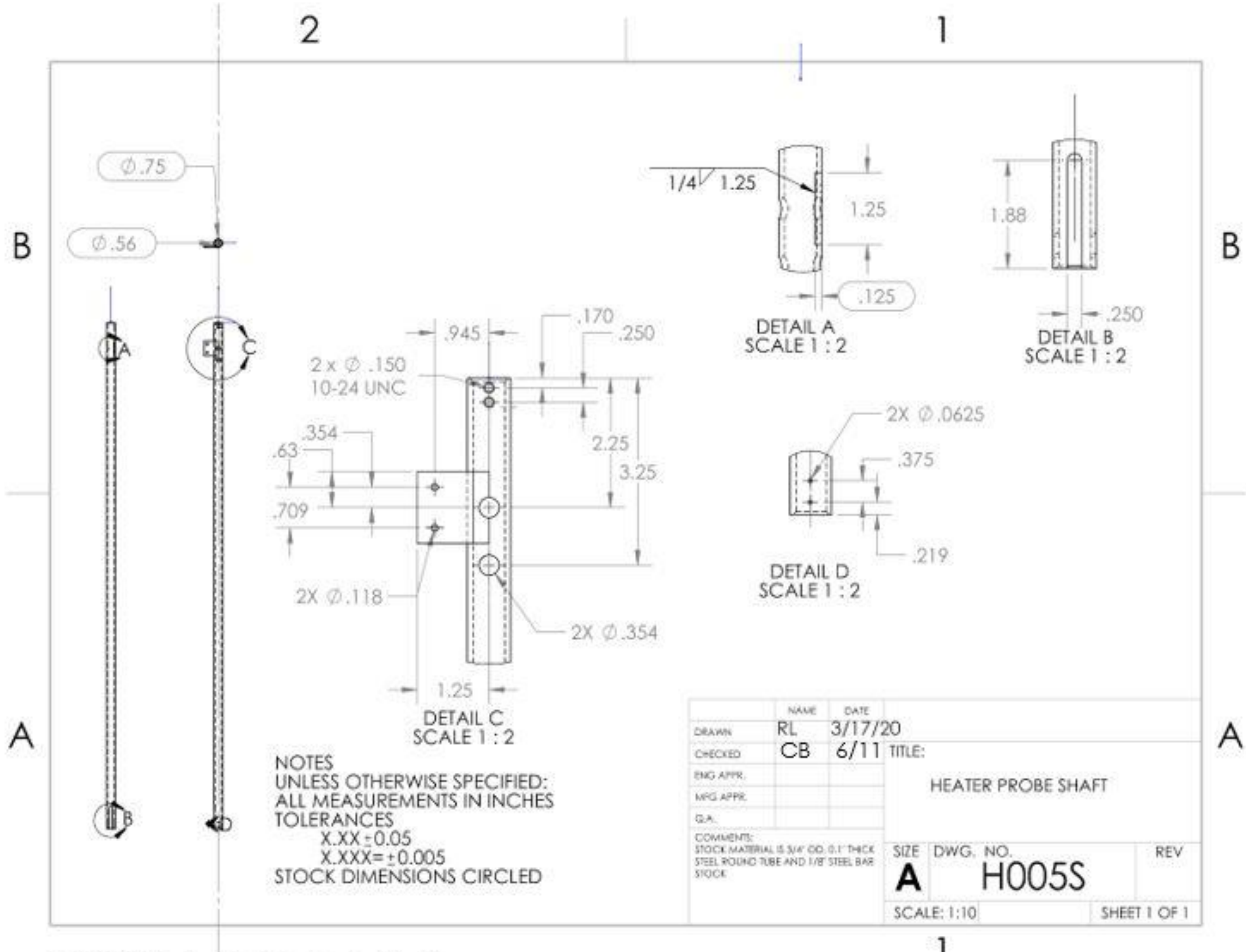

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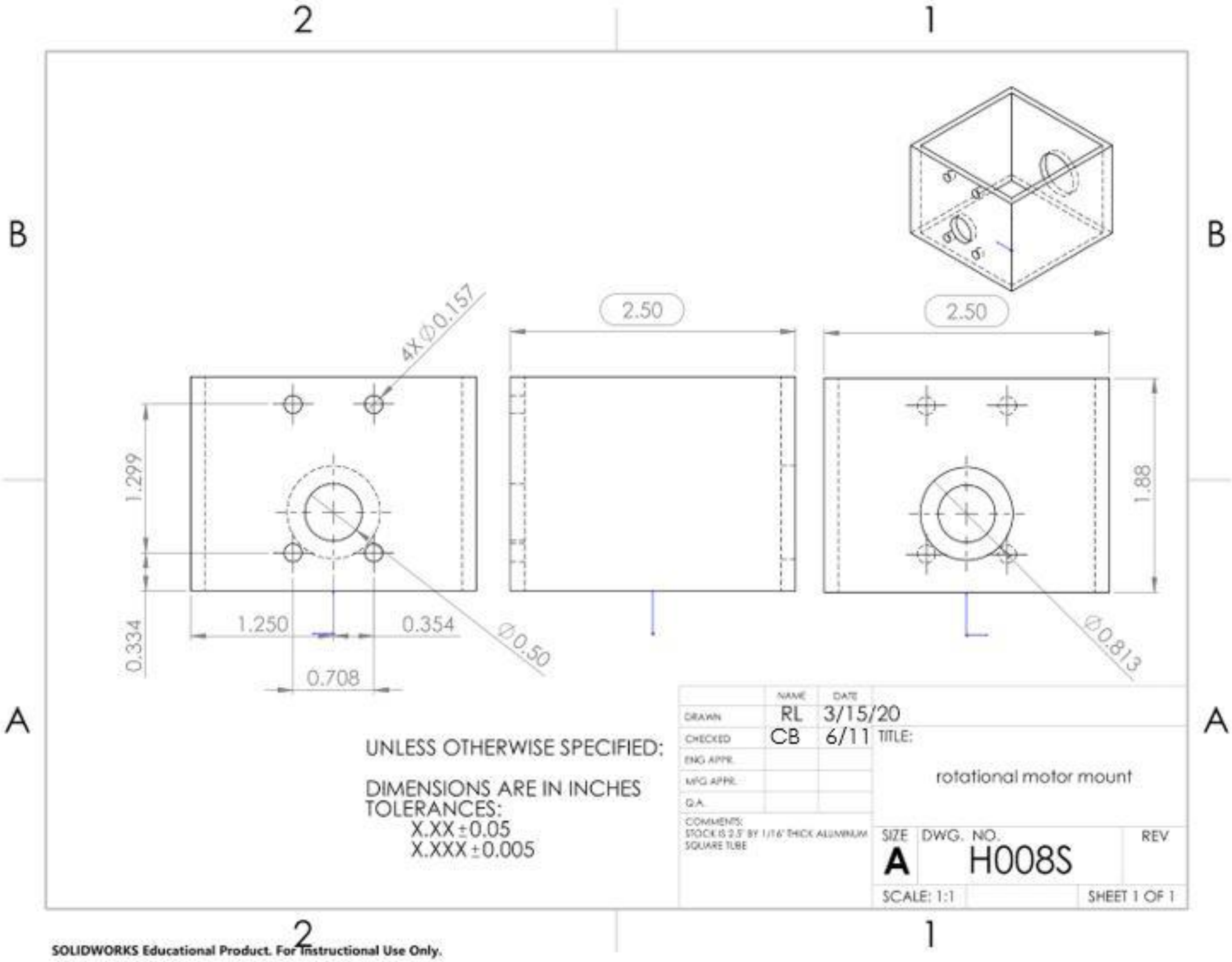
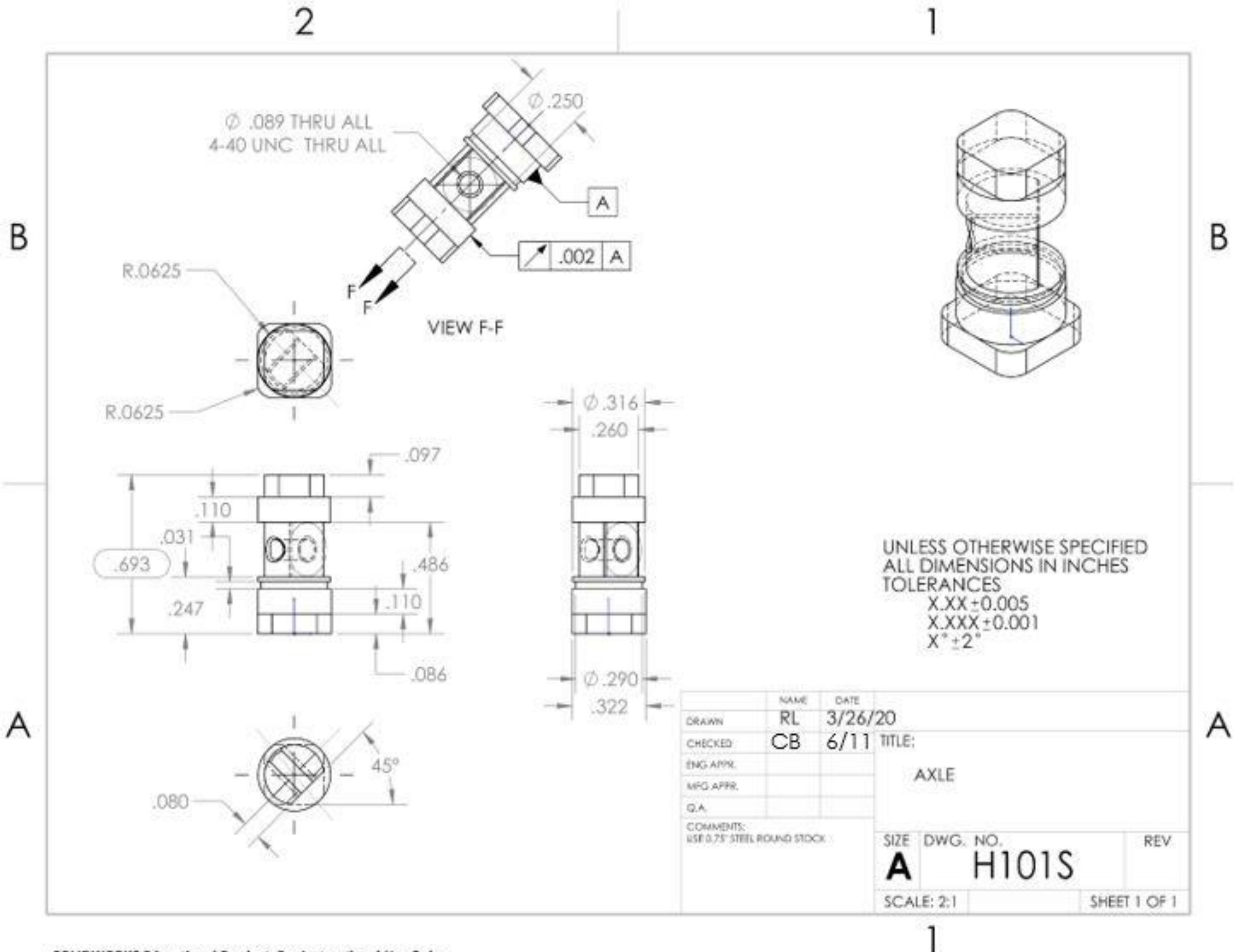

2
1
B
A
4X Ø0.157
2.50
2.50
1.299
1.88
0.334
1.250
0.354
0.708
Ø0.50
Ø0.813
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.XX ±0.05
X.XXX ±0.005
NAME
DATE
DRAWN
RL
3/15/20
CHECKED
CB
6/11
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
STOCK IS 2.5" BY 1/16" THICK ALUMINUM SQUARE TUBE
TITLE:
rotational motor mount
SIZE
A
DWG. NO.
H008S
REV
SCALE: 1:1
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



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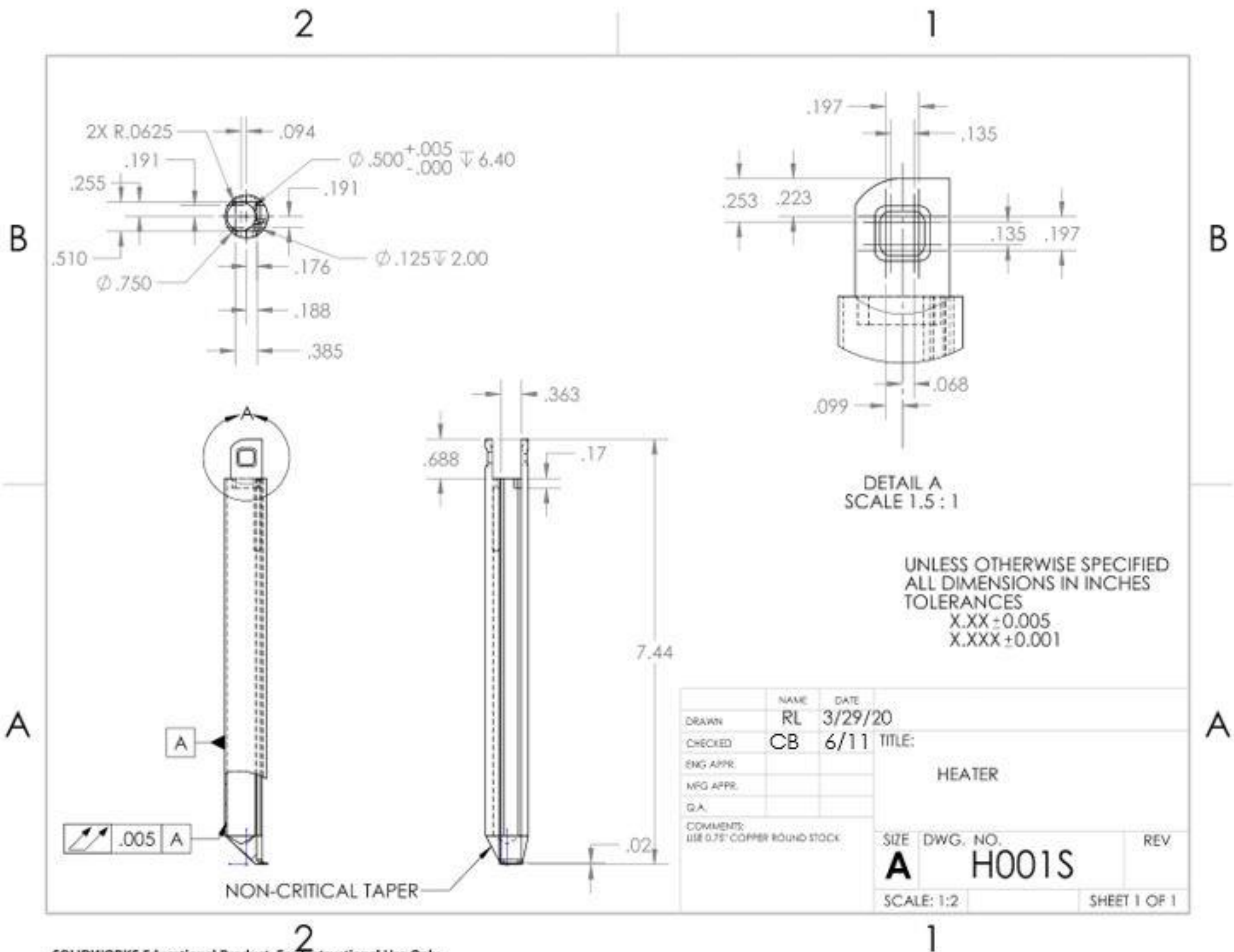
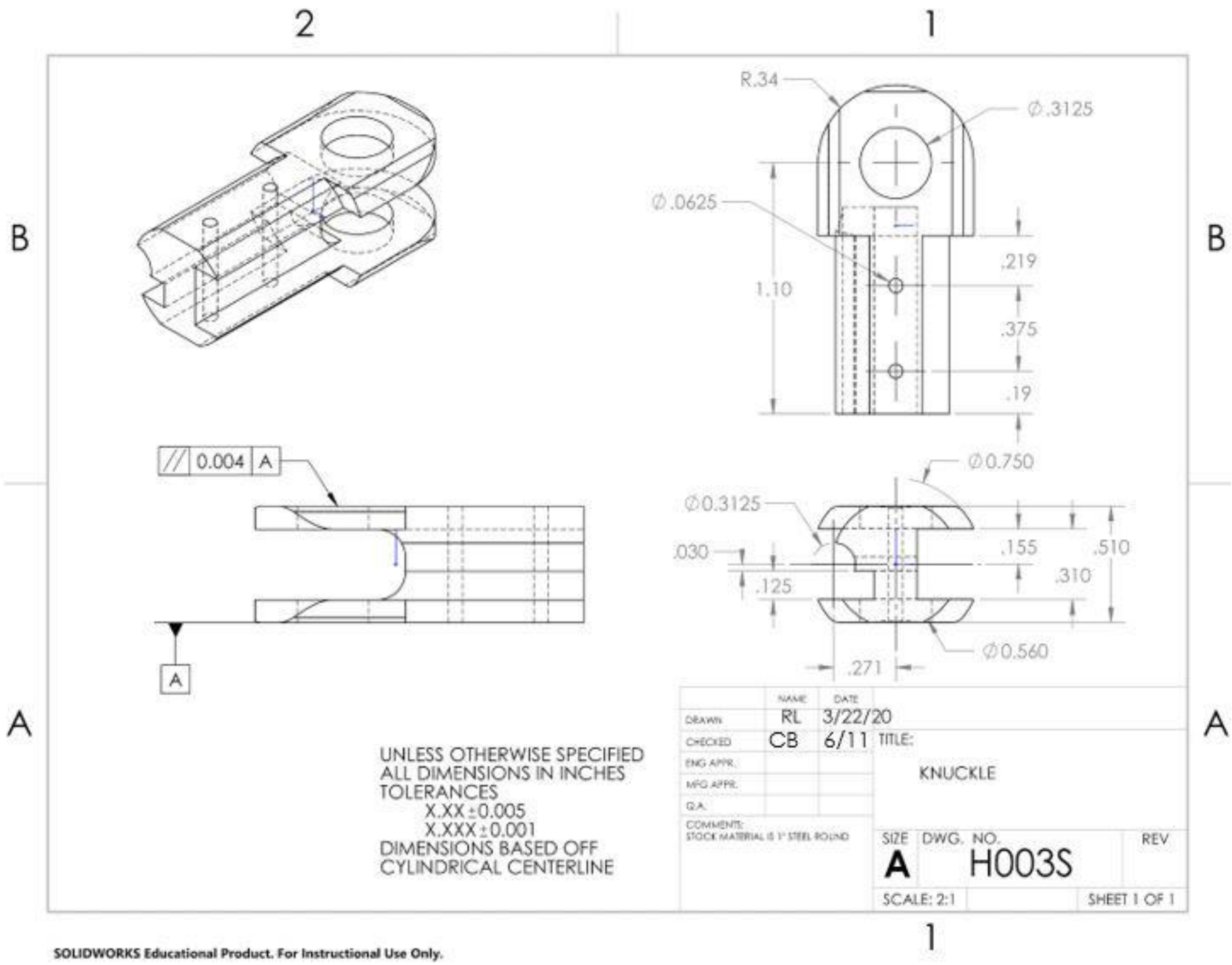


SOLIDWORKS Educational Product. For Instructional Use Only.



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Appendix U: DVPR

Senior Project DVP&R

Date: 4/22/2020	Team: STYX	Sponsor: Schuster		Description of System: Overburden Drilling, Ice/Water Extraction Rig		DVP&R Engineer: Chris Boone

TEST PLAN											TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	Test Procedure	SAMPLES TESTED: Quantity	SAMPLES TESTED: Type	TIMING: Start date	TIMING: Finish date	TEST RESULTS: Test Result	TEST RESULTS: Quantity Pass	TEST RESULTS: Quantity Fail	NOTES
	Specification number from Specification table AND/OR External specification reference (ANSI, SAE, etc.) T =Test, I = Inspection, A = Analysis,	From Specification Table: brief description of test being undertaken (i.e. Max deflection under 300 lb. load)	Pass / Fail targets and Pass / Fail criteria e.g cycles, volts, minimum values, no fail etc.	Student on team who takes responsibility to make sure test is completed	CP= Concept prototype SP= Structural prototype FP= Final prototype			C = Component Sub = Subsystem Sys = Complete system						
1	(T)	Calibration equation or tables with mv/V load cell data for known forces	±10% from scale measured forces	Aaron A.	SP	y		C						
2	(T)	Required force to break tool changer clips and Max Deflection at 10lbf	> 20 lbf to break <.0625" deflection of clip under 10lbf load	Alex K.	SP	N/A		C						
3	(I)	Frame stabity during operation	No lossened members, fastners or joints	Ryan L.	FP	y		Sys						
4	(T)	Sheath insertion and removal Force	Sheath can be inserted or removed with less than 150N	Alex K.	SP	N/A		C						
5	(T)	Window sizing that allows adequate resolution while preventing material collapse	Clear resolution of material layers, minimal material collapse	Alex K.	SP	y		C						
6	(T / I)	Auger Endurance, No visible deflection/damage	Minimal deflection and vibration during operations	Alex K.	SP	y		C						
7	(T / I)	Volume of debris within hole after Auger	Removal of majority of material from sheath	Alex K.	SP	y		C						
8	(T / I)	Toolchanger Misalignment Tolerance	Toolchanger can align with desired input position	Ryan L.	FP	y		Sub						
9	(T / I)	Chuck engagemnet or disengagement	Toolchanger can pick up and drop tools using chuck depressor	Alex K.	FP	y		Sub						
10	(T / I)	Heater Probe actuation motor stall endurance/temperature	After period of stalling motor visual inspection to ensure no damge	Aaron E.	FP	y		C						
11	(T / A)	Heater Probe Melt Rate	Testing the melting rate of heater probe in bed of ice utilizing timer, thermocouple and mass of melted water	Alex K.	FP	y		Sub						
12	(T / I)	Unfiltered Debris Weight and Water Clarity	Visual clarity of water after passing through double filters. Weigh leftover debris using almond bag	Ryan L.	FP	y		Sys						
15	(T)	Pressure Drop across filters	Accurate real time pressure data from Pressure Transducers	Aaron E.	FP			C						

Appendix V: Draft Test Procedures

Auger Material Removal Effectiveness

Desired Results and Sources of Uncertainty

- Volume of debris left in hole after clearance by auger

Priority List of Measurements to be Undertaken

- The goal of this test is to determine the total amount of debris remaining in the hole after auger removal

Safety

- Keep hands clear of rotating drill bits and augers
- Safety Goggles

Test Steps and Procedures

1. Assemble Upper testbed area with fixed plywood divider and no ice bed
2. Drill initial hole up to plywood divider
3. Insert sheath into the pre-drilled hole
4. Using auger process begin clearing hole
5. After auger process drill hole through plywood base allowing remaining lose material to fall through to ice drawer
6. Remove drawer and weigh material noting material composition (dust, sand, rock and pebbles)

Results

	Weight	Notes on Composition
Trial 1:	__________ (g)	____
Trial 2:	__________ (g)	____
Trial 3:	__________ (g)	____
Trial 4:	__________ (g)	____

Auger Stability Test

Desired Results and Sources of Uncertainty

- Confirm the structural stability of the shaft of the new segmented auger design

Priority List of Measurements to be Undertaken

- N/A

Test Steps and Procedures

1. Using a small bucket (home depot 5 gal) or project test bed, fill with stratified layers including sand, rock, dirt and concrete
2. Insert sheath into the stratified layers. Using the auger begin clearing the material from the sheath
3. Observe each section of the auger that is visible noting the apparent structural stability and vibration

Safety

- Keep hands clear of rotating drill bits and augers
- Safety Goggles

Results

Observations On Various Auger Sections During Operations:

____
____
____
____
____
____

Chuck Engagement and Disengagement

Desired Results and Sources of Uncertainty

- Confirmation of chuck proper engagement and disengagement

Priority List of Measurements to be Undertaken

- The goal of this test is to confirm the adequate and repeatable engagement and disegagent

Test Steps and Procedures

1. Assemble tool changer, frame and drilling subsystems
2. Utilizing programmable controls pick up random tool using chuck depression and rotation
3. Move tool to center of machinery axis
4. Command tool changer to change to random tool observing chuck disengagement and tool pick up

Safety

- Keep hands clear of rotating tool changer, chuck engagement zone and pinch points on axis
- Safety Goggles

Results

	Success	Notes
Tool 1:	__________	____
Tool 2:	__________	____
Tool 3:	__________	____
Tool 4:	__________	____

Filtration Testing

Desired Results and Sources of Uncertainty

- Clarity of debris filled water after passing through two filters in series
- After collection of filtered water pour the water through a almond bag and weigh the remaining debris
- Sources of uncertainty:
    - Scale

Priority List of Measurements to be Undertaken

- The goal of this test is to confirm the effectiveness of our two filters at removing debris from water

Test Steps and Procedures

1. Assemble the two filters in series with the peristaltic pump
2. Fill a bucket with XX liters of water and add debris (sand, small pebble and concrete dust) before adding the debris record its initial weight
3. Using water with debris, start pumping the water through the filters and collecting the output water
4. Visually inspect the water designated a rating of: transparent, opaque, cloudy, or murky
5. Put output water through almond bag and weigh the remaining debris

Safety

- Possible spill resulting in wet / slippery floor

Results

	Before	After	
Trial 1:	_________ (g)	_________ (g)	_________ (g)
Trial 2:	_________ (g)	_________ (g)	_________ (g)
Trial 3:	_________ (g)	_________ (g)	_________ (g)

Frame Stability

Desired Results and Sources of Uncertainty

- Confirmation of stability and structure with functionality

Priority List of Measurements to be Undertaken

- The goal of this test is to confirm adequate stability of the frame structure of STYX machinery during operations with high applied forces or large amounts of vibration

Test Steps and Procedures

1. Attach the drilling unit to the STYX frame and attach the frame to the test bed
2. Begin drilling operations into a testbed with a sizeable concrete portion
3. During operations observe the machinery and record any observation during operations, specific areas of instability or potential failure points
4. Power down the STYX machinery
5. Check all joints and fasteners noting ny that seem to have loosened during operation

Safety

- Keep hands clear of rotating drill bits and pinch points on axis
- Safety Goggles

Results

Observations During Operation:

____
____
____
____
____
____

Observations After Operation:

____
____
____
____
____
____

Heat Probe Melt Rate

Desired Results and Sources of Uncertainty

- Heater probe melting rate

Priority List of Measurements to be Undertaken

- The goal of this test is to determine the ice melting rate of the heater probe

Test Steps and Procedures

1. Assemble the heater probe in entirety
2. Using the project testbed set up a bed with a large ice layer chuck and weigh the ice
3. Drill an initial hole in the ice and insert the heater probe
4. Utilizing max current allow heater probe to reach max current
5. Begin timer and actuation of heater probe
6. Record total time to melt full bell shape from ice
7. After evacuating all water from bell remove the ice block and record its new weight
8. Using the differences between the weights and time deduce melt rate
9. Repeat several time

Safety

- Keep hands clear of rotating drill bits and pinch points on axis
- DO not touch heating elements while power is supplied
- Safety Goggles

Results

Trial 1: ________ (L/min)

Trial 2: ________ (L/min)

Trial 3: ________ (L/min)

Trial 4: ________ (L/min)

Load Cell Test Plans / Procedure

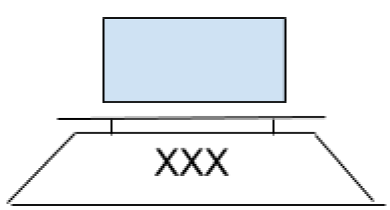
Desired Results and Sources of Uncertainty

- Comparison of load cell output of mV/V to defined forces. Acceptable uncertainty is $\pm 10\%$
- Sources of uncertainty:
  - Scale Used to determine known weights
  - Load Cell
  - HX711 amplifier
  - Nucleo board interpretation

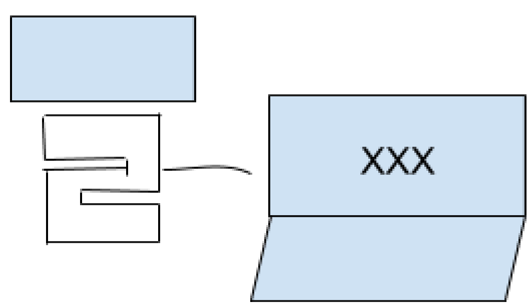
Priority List of Measurements to be Undertaken

- Known weights confirmed with scale
- mV/V reading from S-Type load cell coupled with amplifier and nucleo board

Diagram of Apparatus and Instrumentation



Scale



S Type Load Cell

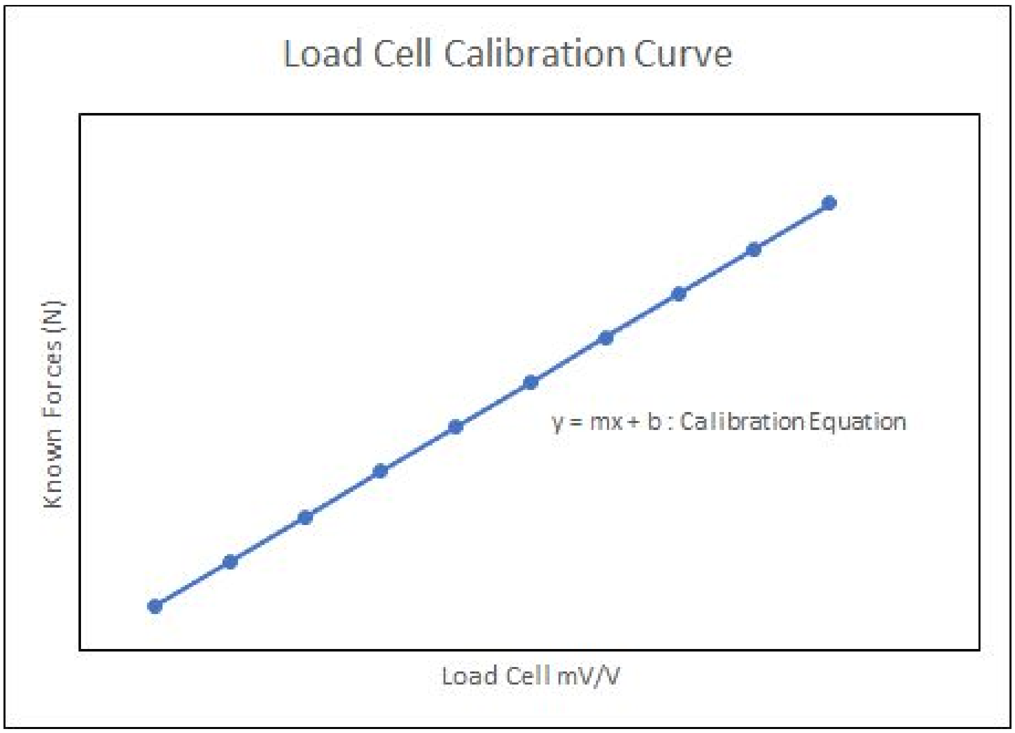
Test Steps and Procedures

1. Use scale to determine weights of 10 specimen in order to have sufficient data for extrapolation
2. Use the load cell nucleo board system to collect mV/V data for predetermined masses. Define baseline for no force load cell output
3. No zero / tare steps required

Data Analysis equations / spreadsheet with uncertainty

- Equate load cell data in mV/V to predetermined mass values, create calibration equation to be utilized by nucleo board for force output
  Mass

Expected Results:



Note: If results are nonlinear tabulated data will be used instead via extrapolation

Safety

- No safety concerns

Results

Note: The following data sets were collected and utilized for a simple closed force feedback loop created for the STYX Mid Point Review submission to NASA. As this was an expedited test conducted in the final nights before submittal no uncertainty analysis was conducted. This test is currently a placeholder until a more sufficient and in depth test is conducted. The results from the preliminary test are tabulated below.

Twos Compliment Digital Output	Weight on Load Cell (lbf)
3548.59	0
-11141.73	0.215
-23936.75	0.415
-124962.3	1.91
-335652.2	5.085
-461637.4	7
-614930.7	9.25
-693411.5	10.49
-739428.9	11.17
-949592.5	14.36
-1028489	15.58

Table 1. Load Cell Calibration Test

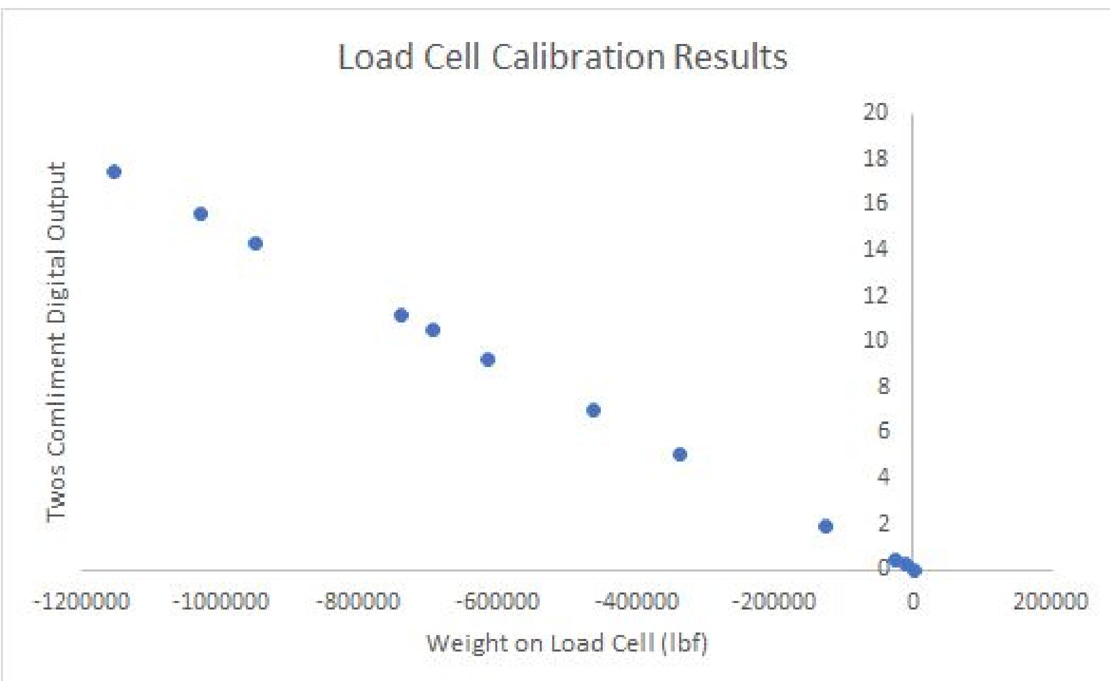


Table 1. Load Cell Calibration Test Plotted

Motor Stall Endurance Test

Desired Results and Sources of Uncertainty

- Current Value of Motor Stall
- Sources of uncertainty:
    - Ammeter

Priority List of Measurements to be Undertaken

- The goal of this test is to determine the current value of motor stall for the heater probe actuation motor

Test Steps and Procedures

1. Assemble the heater probe in entirety
2. Connect an ammeter to the motor
3. Powering the actuation motor of the heater probe observe the ammeter, once the motor stalls at a fully extended heater probe position record the current
4. Repeat Experiment several times to confirm value

Safety

- Keep hands clear pinch points on heater probe

Results

Trial 1: ________ (Amps)

Trial 2: ________ (Amps)

Trial 3: ________ (Amps)

Trial 4: ________ (Amps)

Trial 5: ________ (Amps)

Sheath Window Sizing

Desired Results and Sources of Uncertainty

- Window sizing for sheath that will allow camera resolution without too much hole collapse

Priority List of Measurements to be Undertaken

- The goal of this test is to determine the proper window sizing of the sheath to allow camera resolution and mapping for digital core

Test Steps and Procedures

1. Using a small bucket (home depot 5 gal) stand the sheath up and fill with stratified layers noting each layers height surrounding the sheath
2. Insert camera probe assembly into the sheath ith live stream video
3. Passing the probe down the hole at a fairly constant rate record what time intervals a material layer change occurs
4. Utilizing feed rate and recorded times attempt a digital core
5. Compare core to known layer heights
6. If material collapse occurs and prevents resolution, or window sizing prevents resolution iterate through window sizes until system is determined adequate

Safety

- No safety concerns

Results

	Window size	Hole Collapse	Resolution	Accuracy of Core
Trial 1:	_________ (in)	_________ (y/n)	_________ (y/n)	_______________
Trial 2:	_________	_________	_________	_______________
Trial 3:	_________	_________	_________	_______________
Trial 4:	_________	_________	_________	_______________
Trial 5:	_________	_________	_________	_______________

Toolchanger Alignment Test

Desired Results and Sources of Uncertainty

- Accuracy of tool changer alignment

Priority List of Measurements to be Undertaken

- The goal of this test is to confirm the accuracy of tool changer alignment for adequate tool changer operations

Test Steps and Procedures

1. Assemble the tool changer subsystem
2. Connect tool changer to control board
3. Starting at a random location attempt to align tool changer with specified tooling location
4. Note degree of accuracy of tool changer alignment
5. Repeat several trials from varying starting positions.

Safety

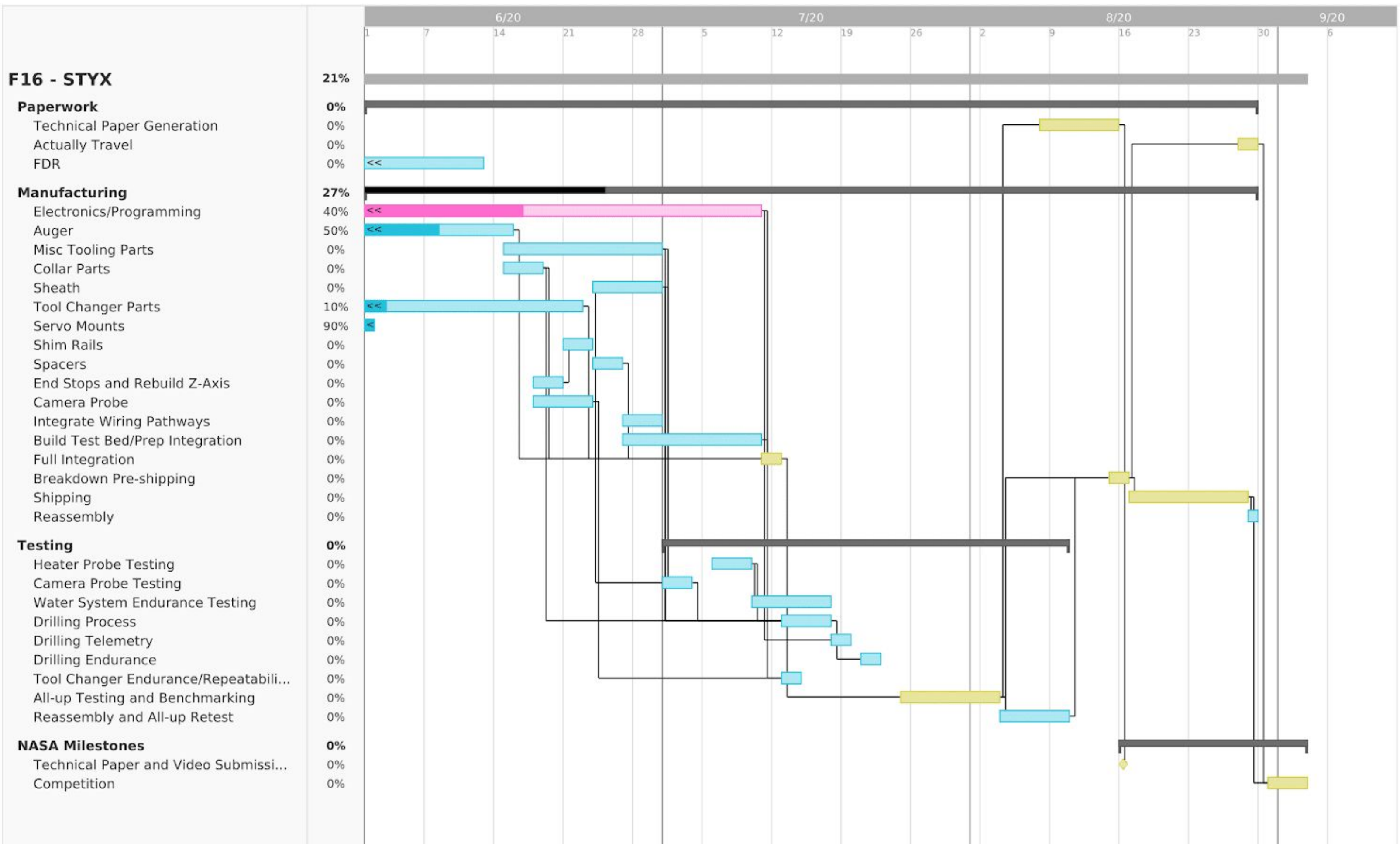
- Keep hands clear of rotating tool changer, chuck engagement zone and pinch points on axis

Results

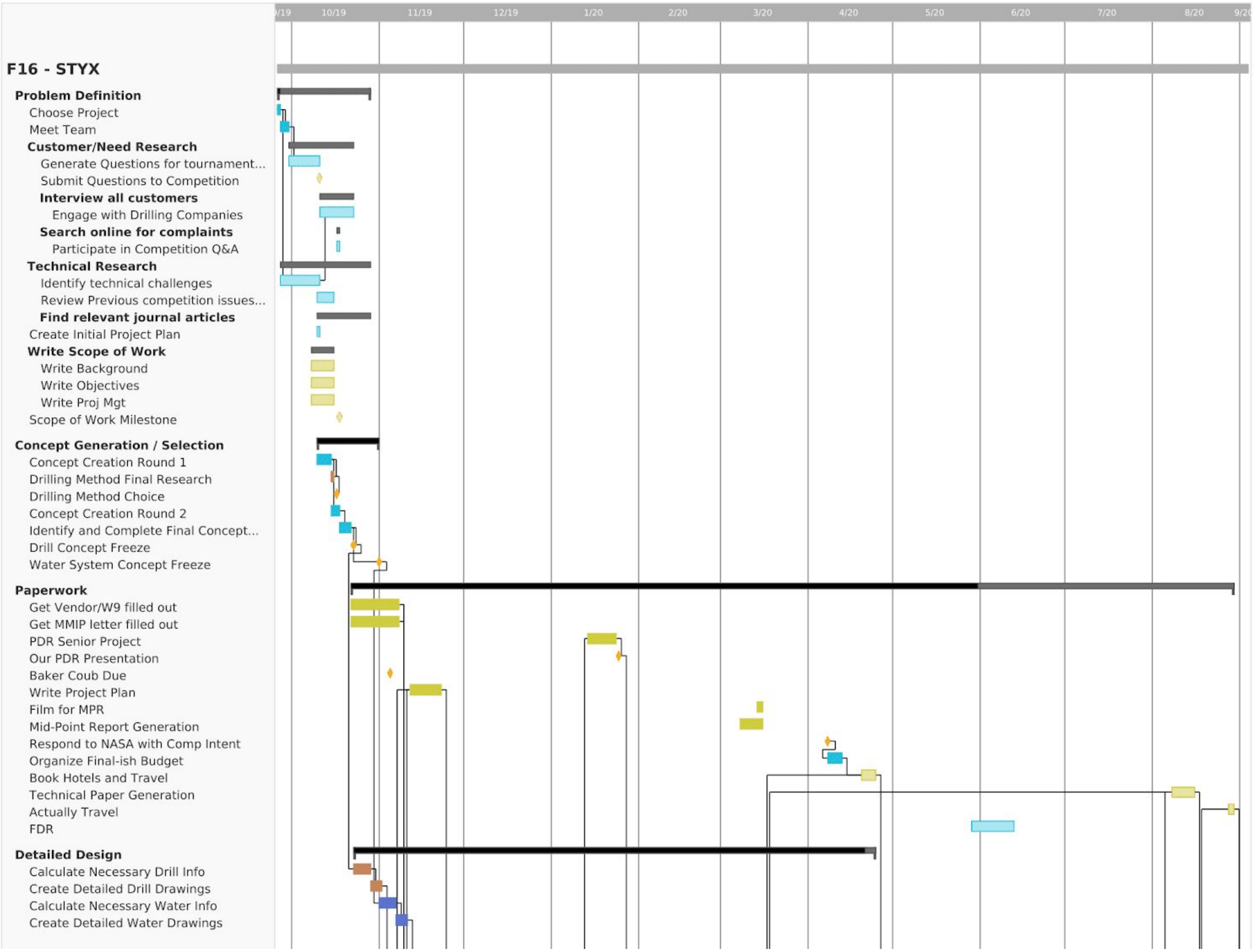
	Misalignment	Success
Trial 1:	____________ (In)	________
Trial 2:	____________ (In)	________
Trial 3:	____________ (In)	________
Trial 4:	____________ (In)	________
Trial 5:	____________ (In)	________

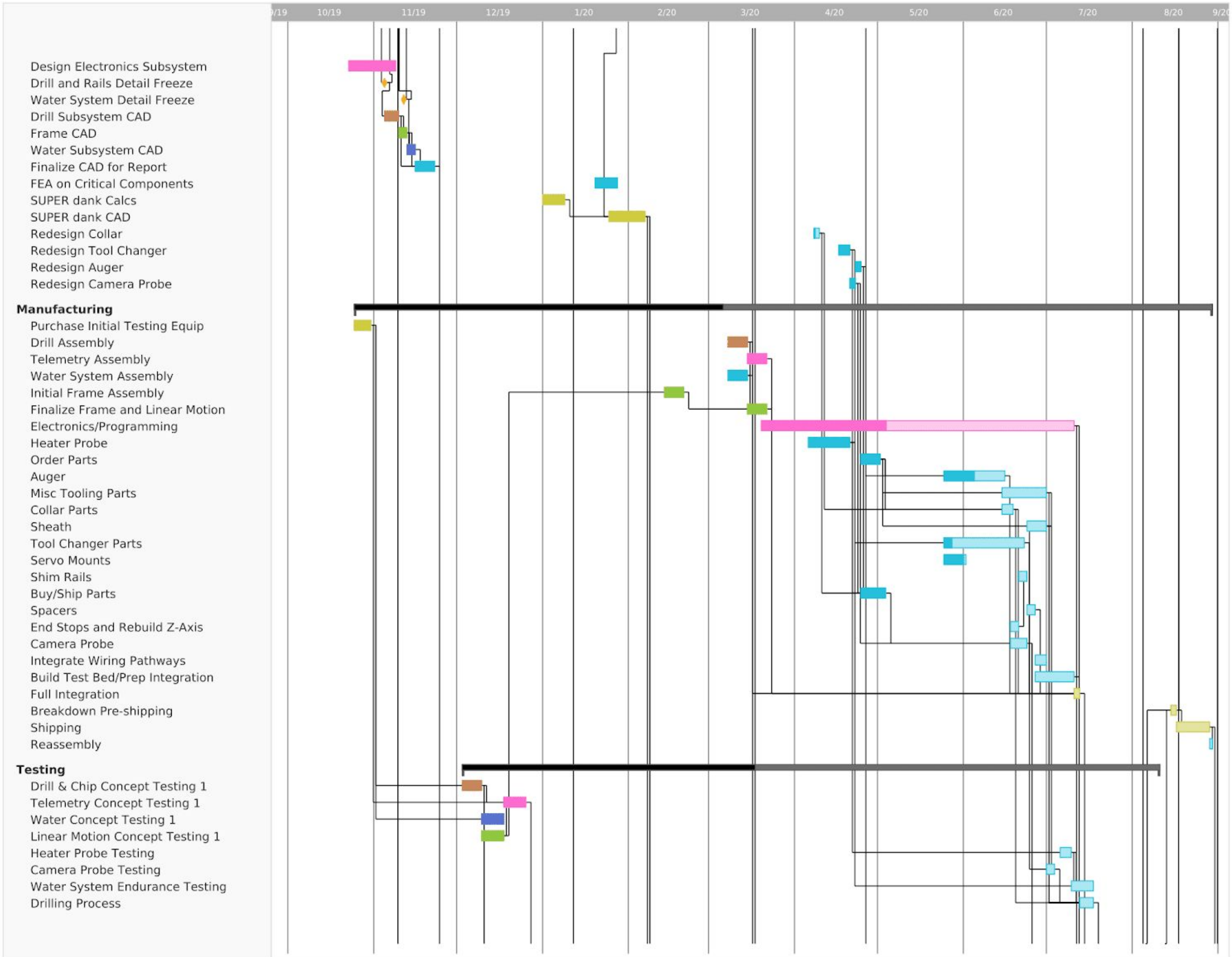
Appendix W: Gantt Chart

Summer Gantt Chart



Complete Project Gantt Chart




10/19
11/19
12/19
1/20
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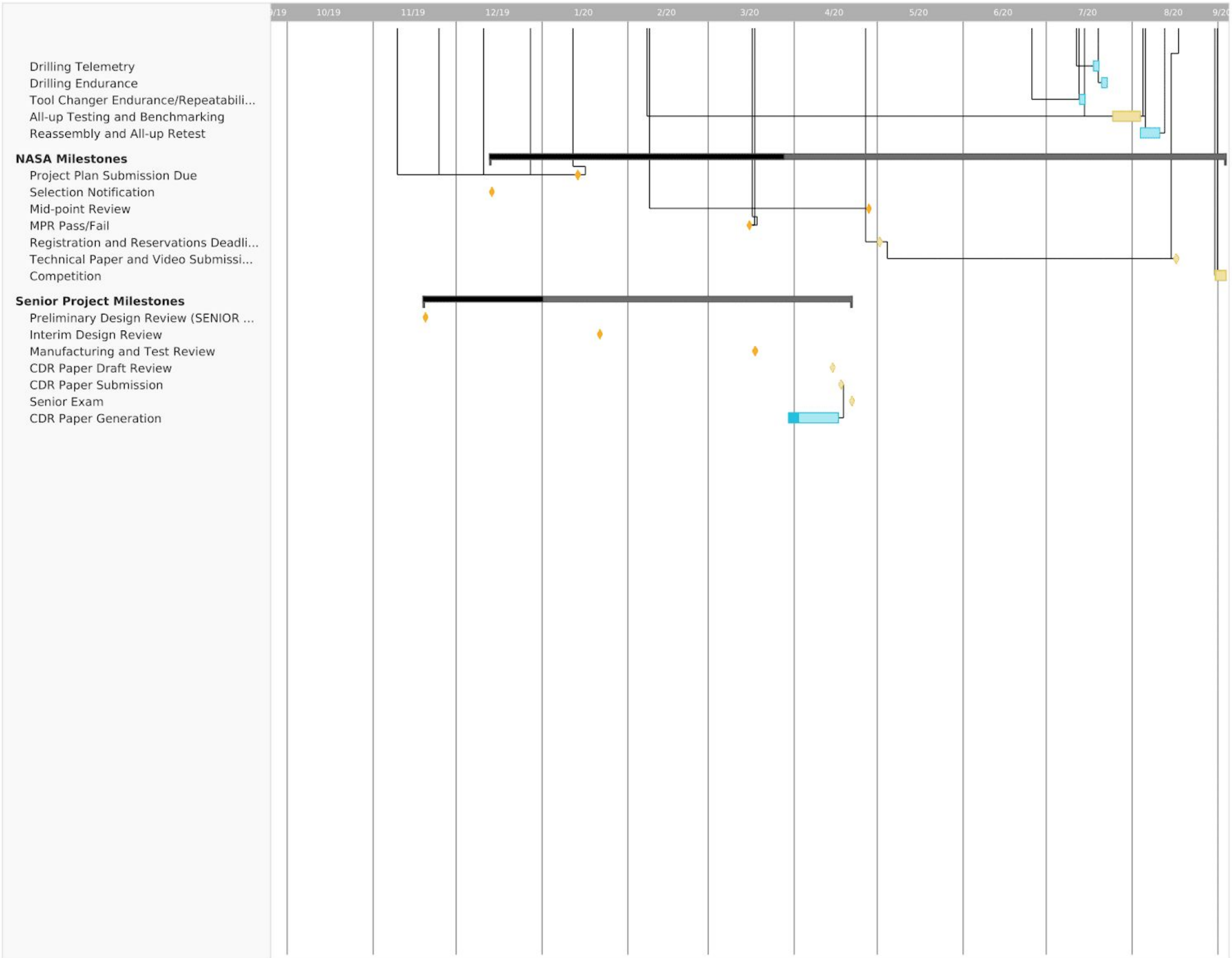
7/20
8/20
Design Electronics Subsystem
Drill and Rails Detail Freeze
Water System Detail Freeze
Drill Subsystem CAD
Frame CAD
Water Subsystem CAD
Finalize CAD for Report
FEA on Critical Components
SUPER dank Calcs
SUPER dank CAD
Redesign Collar
Redesign Tool Changer
Redesign Auger
Redesign Camera Probe
Manufacturing
Purchase Initial Testing Equip
Drill Assembly
Telemetry Assembly
Water System Assembly
Initial Frame Assembly
Finalize Frame and Linear Motion
Electronics/Programming
Heater Probe
Order Parts
Auger
Misc Tooling Parts
Collar Parts
Sheath
Tool Changer Parts
Servo Mounts
Shim Rails
Buy/Ship Parts
Spacers
End Stops and Rebuild Z-Axis
Camera Probe
Integrate Wiring Pathways
Build Test Bed/Prep Integration
Full Integration
Breakdown Pre-shipping
Shipping
Reassembly
Testing
Drill & Chip Concept Testing 1
Telemetry Concept Testing 1
Water Concept Testing 1
Linear Motion Concept Testing 1
Heater Probe Testing
Camera Probe Testing
Water System Endurance Testing
Drilling Process


10/19
11/19
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5/20
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8/20
Drilling Telemetry
Drilling Endurance
Tool Changer Endurance/Repeatabili...
All-up Testing and Benchmarking
Reassembly and All-up Retest
NASA Milestones
Project Plan Submission Due
Selection Notification
Mid-point Review
MPR Pass/Fail
Registration and Reservations Deadli...
Technical Paper and Video Submissi...
Competition
Senior Project Milestones
Preliminary Design Review (SENIOR ...
Interim Design Review
Manufacturing and Test Review
CDR Paper Draft Review
CDR Paper Submission
Senior Exam
CDR Paper Generation

Appendix X: STYX OPERATOR MANUAL

To safely assemble and operate this machine, one should study this operator manual and familiarize oneself with its contents. After reading, the operators should understand how to assemble the subsystems into the finished prototype after shipping, how to interface with safety features, operate the robot via the program command line, and what to clean before shipping.

Frame Assembly

Assembly of the STYX robot starts with the frame, it is free standing so it can be assembled before being mounted to the competition platform.

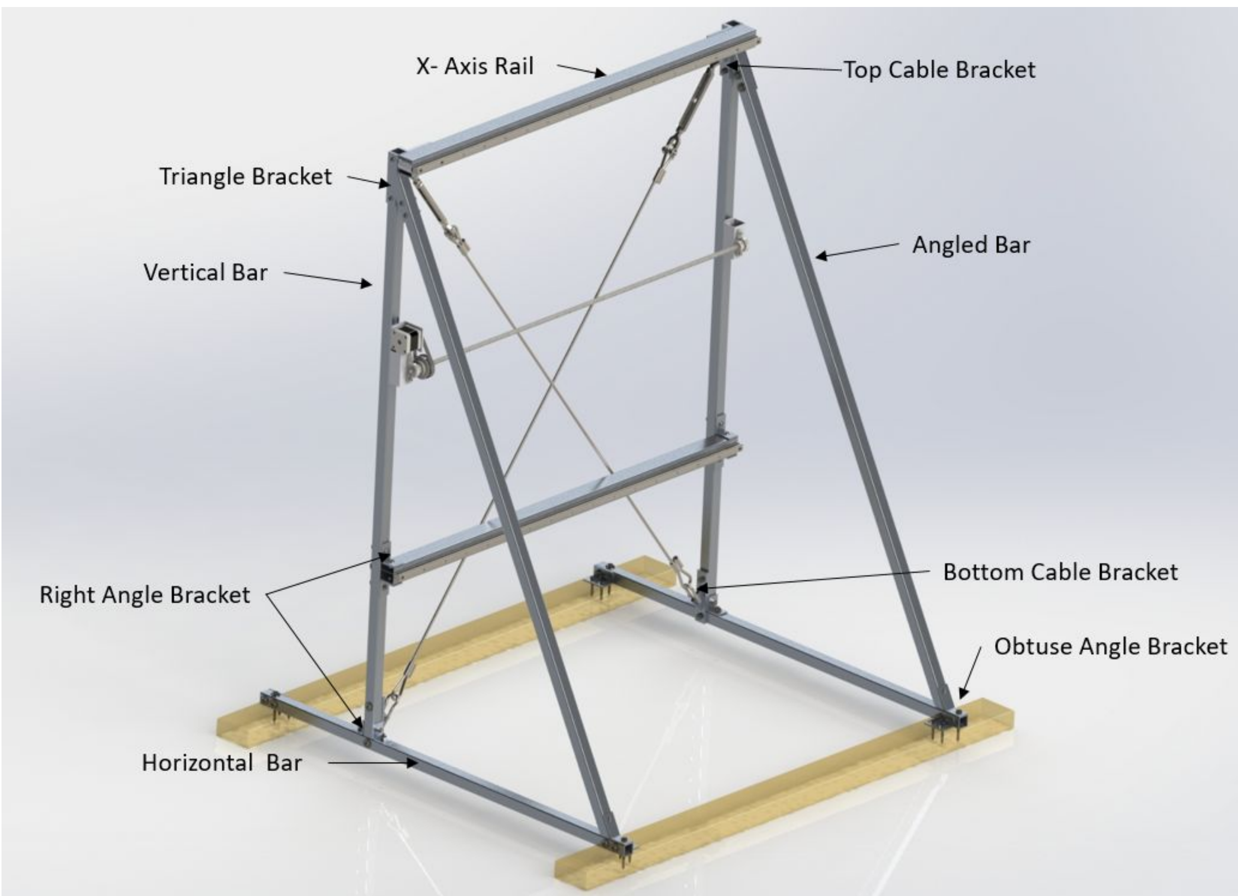

Figure 1: Frame

First assemble the side support triangles from the vertical, horizontal, and angled bars shown in Figure 1. Using the right angle brackets, connect the vertical bar to the horizontal bar. Connect the diagonal bar to the horizontal member with the obtuse angle bracket and then mount the triangle bracket to the vertical bar and then attach the angled bar to the triangle bracket. Next attach the bottom cable brackets between the horizontal bar and vertical bar. Then connect the two triangles together using the lower x-axis rail and secure with right angle brackets. Mount the other x-axis rail at the top and secure with hardware and the upper frame bracket shown in Figure 2. Install and pretension the crossed cables with the turnbuckles to 50 lbs of tension, which can be roughly approximated to be the first audible ringing the cable can make.

Figure: 2 upper frame brackets

Z-axis Assembly

First, slide the four linear sliders onto the X-axis rails with the mounting plates pre attached. Position the Z axis mounting holes with the linear sliders and attach. Then attach the X-axis lead screw by inserting through one pillow block bearing, the nut attached to the gantry, and through the other pillow block bearing, securing it with the pulley on the drive side. Make sure to slip the belt onto the X-axis pulley before securing into the pillow block. Reference Figure 3.

Next install the drill plate, shown in Figure 4, onto the Z-axis from the top. Stop the drill plate from sliding off the bottom of the linear rails with a clamp or similar device. Install the Z-axis leadscrew from the top mounted bearing, through the Z-axis drive nut, and through the bottom mounted bearing. Secure the leadscrew with shaft collars on either side of the bottom mounted bearing. Then Install the pulley and belt at the top of the leadscrew as shown in Figure 5.

Finally, ensure the drill is trammed with the stationary collar. Insert the 3-jaw chuck with bore laser into the drill and jog the Z-axis up and down, verifying that the laser point remains centered within the stationary collar throughout the entire range of travel. Shim behind the 3d printed drill mount as necessary to adjust the tram.

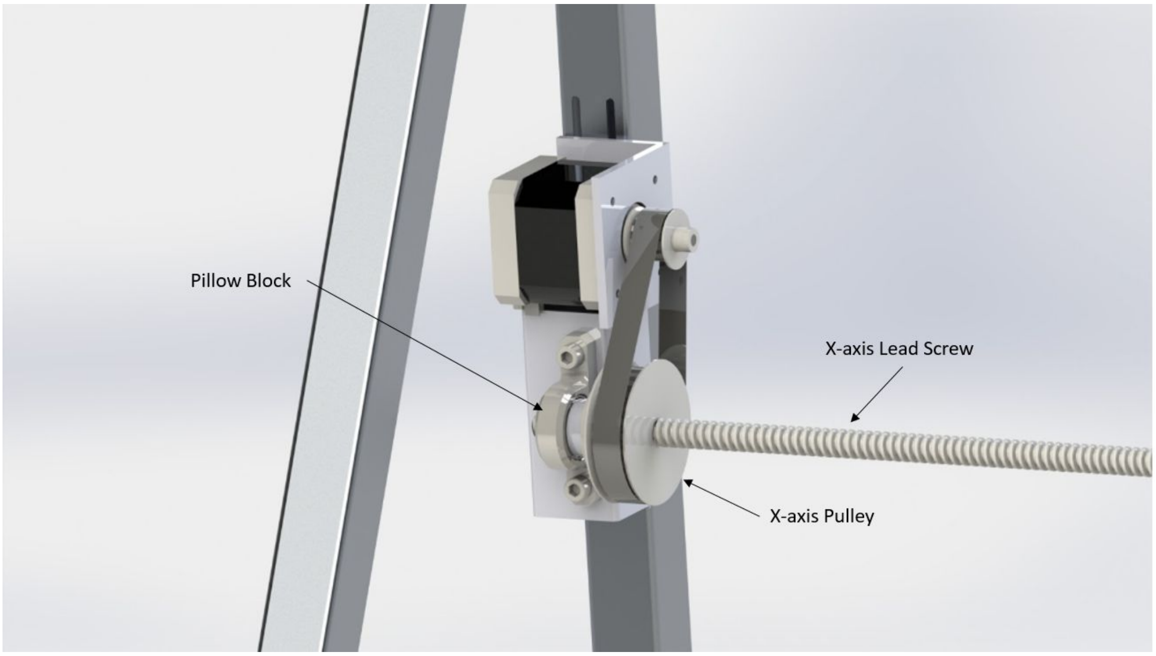

Figure 3: X-axis Lead Screw and Driving Motor

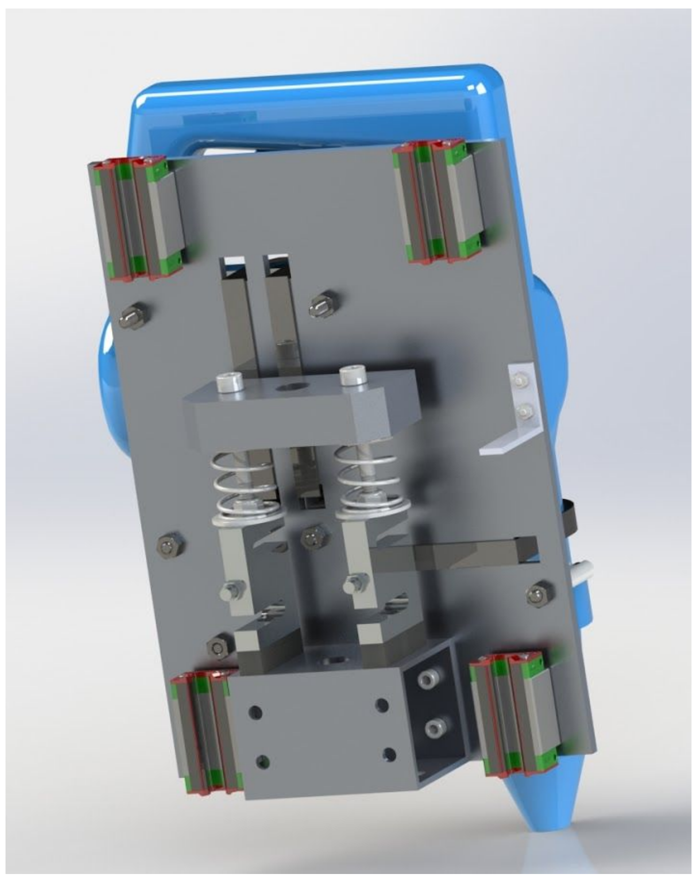

Figure 4: Drill Plate

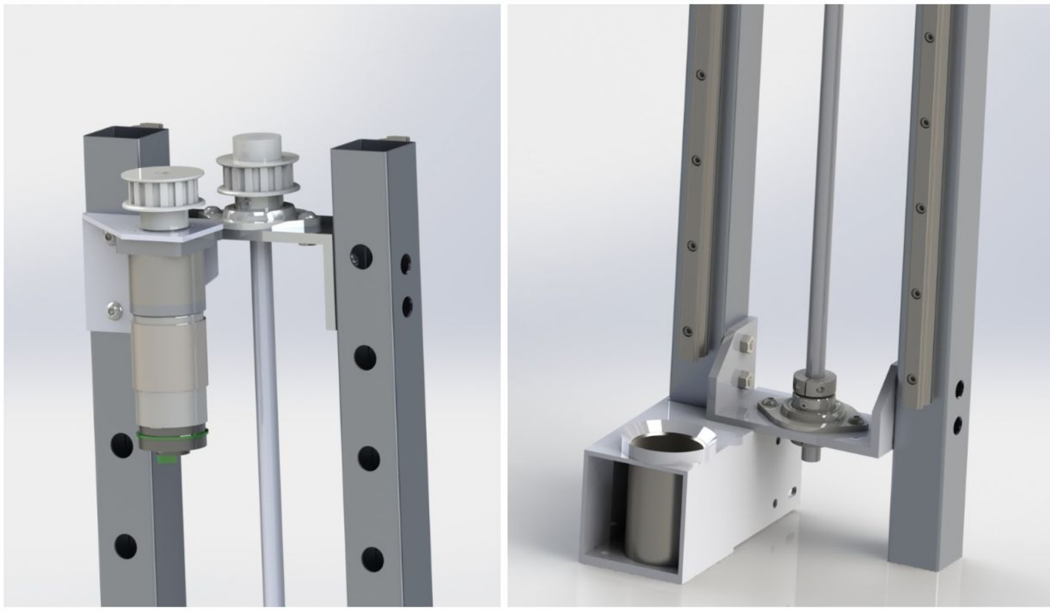

Figure 5: Z-axis Lead Screw attachment points

Tool Changer Assembly

The tool changer is composed of three main components, the top support, bottom support, and the tool holder. Reference Figure 6. To mount the tool changer, first attach the tool holder to the bottom support, then attach the drive belt between the pulley on the drive motor and the pulley on the tool holder. Mount the bottom support to the left side of the frame securing with the pre-attached right angle bracket. Then, using the 3d printed bracket, mount the top support bar to the top horizontal frame member. Perform fine adjustments of the tool changer position by inserting a tool in the drill manually matching the corresponding tool clip position before inserting lag-bolts into the provided 2x4 mounting bracket.

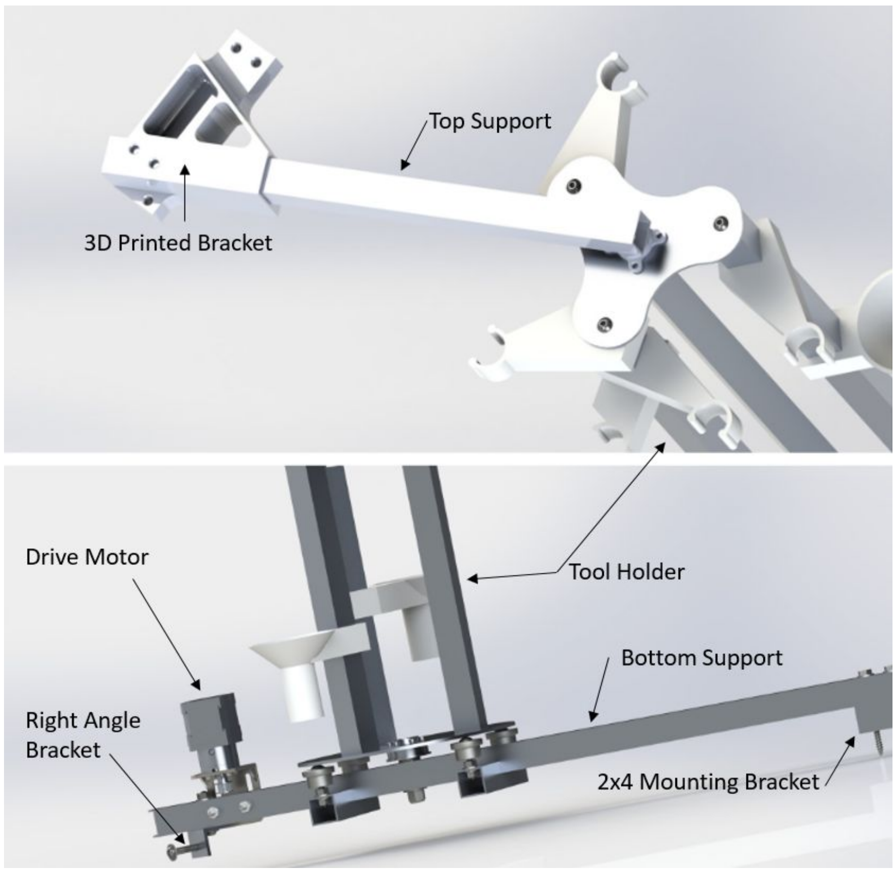

Figure 6: Tool Changer

Water Filter Assembly

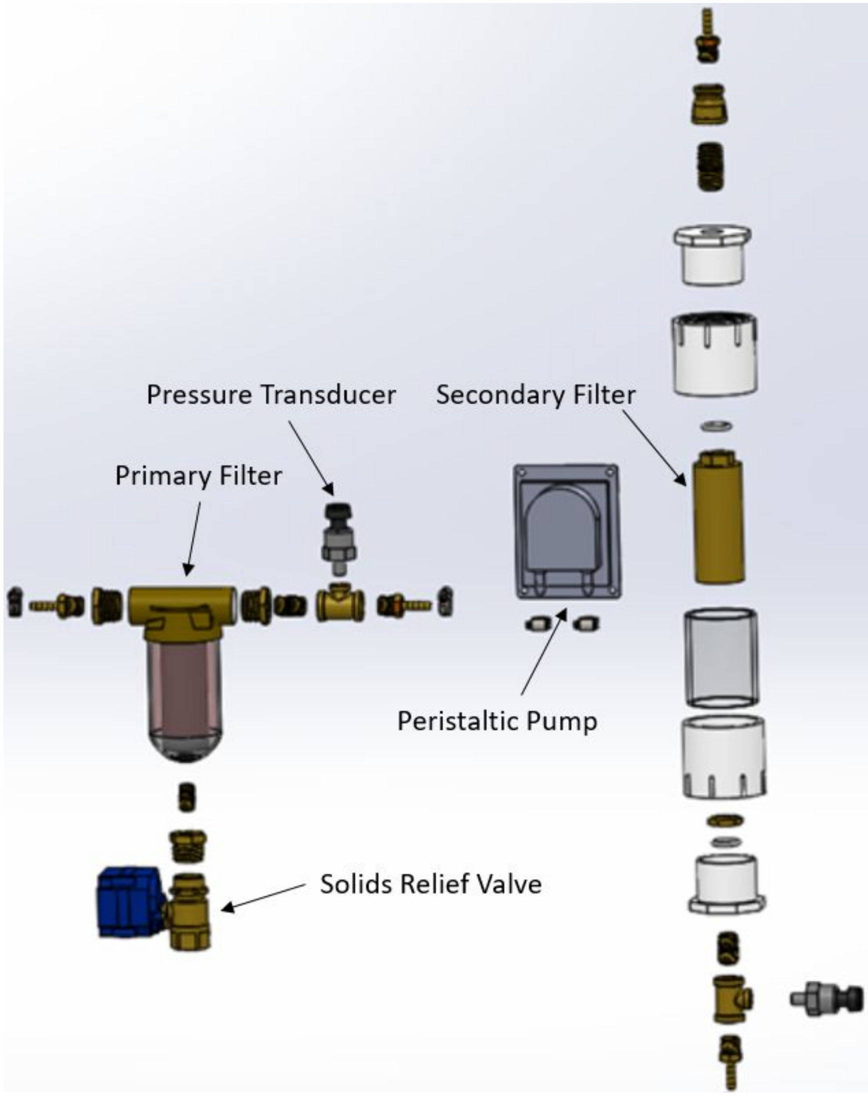

Figure 7: Exploded View of Filter System

The filter system will require very little assembly when at competition. The Primary and secondary filters, as well as the peristaltic pump will be pre-mounted to the outside of the electrical box. Reference the electrical Installation section for more information. Connect plastic tubing with hose clamps. Secure the primary filter's inlet to the heater probe's water tube outlet. Next, connect the outlet of the primary filter to the peristaltic pump. Connect the peristaltic pump outlet to the secondary filter inlet. Finally,y connect the outlet of the secondary filter to a long piece of clear tubing, so clean water can be deposited into the collection bucket.

Mounting Procedure

To mount the robot to the competition platform, there are 5 locations that need lag bolts installed. The lag bolt connecting the tool changer support to the competition platform has to be attached last per the tool changer assembly instructions above.

Begin the mounting procedure by roughly positioning the mounting points on the 2x4s provided and installing one of the corner's 3 lag bolts. Position the other corners according to the distance between them. Match the most recent calibration distances as noted in the google drive document titled "Calibration Values, mm/dd/yyyy". This will ensure that the adjustments made during manufacturing behave as expected for each setup.

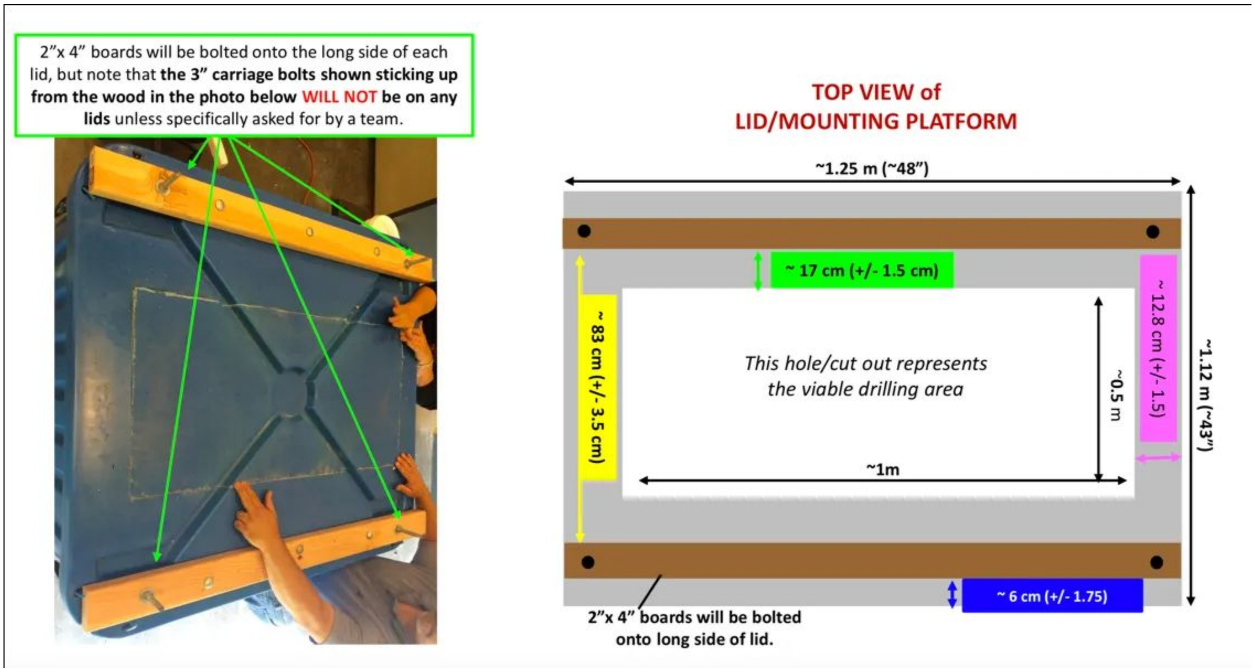

Figure 8: Competition Platform Description

Heater Probe Assembly

For assembly of the heater probe, reference Figure 9. The terminology and detail views will be critical for understanding.

First, insert the actuation motor with bushings into the associated shaft hole and fasten using the external M3 shaft screw. Wrap a 6ft length of kevlar string twice around the motor shaft and pinch the string using the flanged #4-40 screw. Guide the excess string down the shaft and out the bottom. Insert a length of silicone tube through one of the open holes at the top of the shaft and guide it out the bottom.

Second, join the copper tip with the knuckle via the square drive axle and snap ring. Note that the square drive axle is directional and can only be inserted one way. Route the wires from the heater tip up the shaft from the bottom, exiting through the unoccupied hole near the top of the shaft. Next, connect the silicone tube to the straw. Join the knuckle to the shaft using two 1/16" roll pins. Use extreme caution to not bend or damage the fragile straw during this process. Route the kevlar string on either side of the axle, looping once around each side. Pull the string tightly and pinch the string against the axle using another #4-40 flanged screw.

Finally, integrate the orientation motor assembly. Use the long M3 fasteners and hardware to attach the orientation motor to the square mounting tube. Install the stackup of shaft collars and thrust bearings shown in Figure 9 and tighten the set screw on the shaft against the orientation motor shaft.

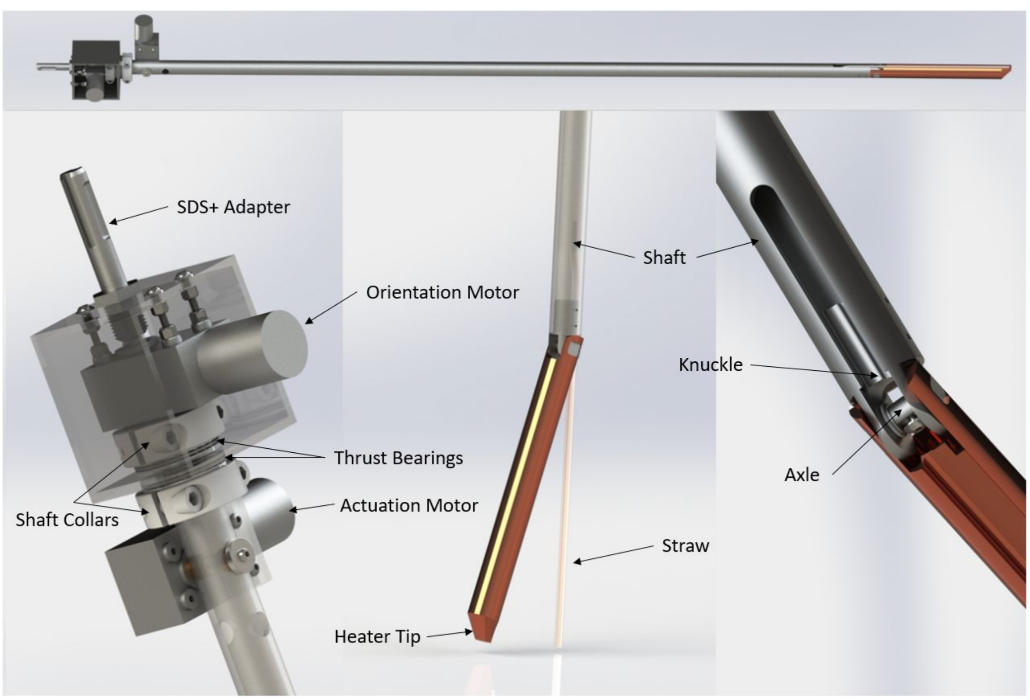

Figure 9: Heater Probe Assembly

Operation of Robot

Before powering on the machine, ensure the main emergency stop is in the ‘stopped’ position. Check continuity across the 8 amp and 9 amp fast blow fuses and replace if damaged. Next, power on the provided power strip and move all emergency stops to the ‘on’ position.

Operation of the STYX robot should usually be simple because all operations are controlled by an automated program. In theory, no human input is necessary during the length of the competition. The robots programming will be a one click to start operation and will not need to be interacted with unless an emergency occurs or the program needs to be shut down. Data readouts will automatically update graphs as applicable based on the automated operating mode. As an example, load data and travel speed graphs will automatically open and begin logging during the telemetry cycle.

Because individual actions may need to be controlled during calibration/setup and/or in a fault situation during competition, a table of commands and variable descriptions will be made available via google drive. Commands can be copy/pasted into the program with the desired variables changed. Additionally, Manual jogging of the gantry and tool changer may be done through an analog stick interface after the proper command is input.

Cleaning for Storage

After operation of the STYX robot, the parts and tools need to be cleaned for long term storage or transport.

The Filter system will be the dirtiest part of the robot and will require the most care. To avoid particle build up and mold growth it needs to be cleaned after each use. First, run the peristaltic pump with the water inlet suspended in air to push the majority of the water through the system. Next, empty the remaining water out of the system by opening the solids valve. Disconnect the plastic tubes from the filters and remove the filter systems from their mounts. The primary and secondary filters need to be removed from their housings for further air-drying prior to storage or shipment.

The rest of the robot needs minor cleaning. The tools and tool changer need to have the excess dirt brushed off before disassembly and packing. The X and Z-axis linear rails will have dirt build up from the drilling operations. These must be carefully cleaned with a rag and protected with a light coat of WD-40 before shipment.