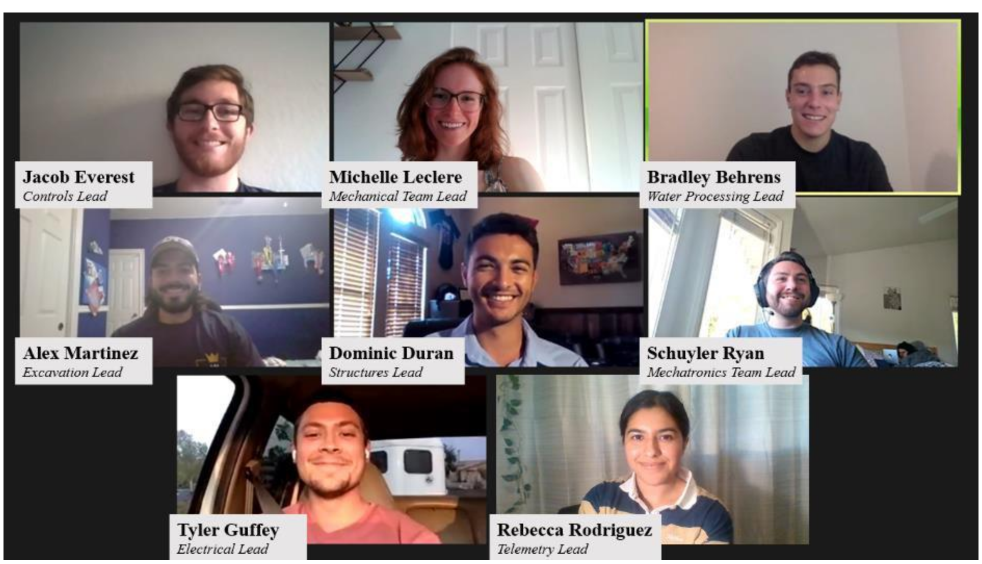
CAL POLY
College of Engineering

STYX & STONES

Sub-lunar **T**ap **Y**ielding e**X**plorer & **S**urface **T**elemetry **O**perations and **N**ext-generation **E**xcavation **S**ystem



Advisor: Dr. Peter Schuster

Executive Summary

The STYX & STONES prototype is a fully autonomous water extraction and digital core prospecting system capable of drilling through regolith and extracting water from ice sheets below. Our design and prototype, STYX & STONES (**S**ub-lunar **T**ap **Y**ielding e**X**plorer & **S**urface **T**elemetry **O**perations and **N**ext-generation **E**xcavation **S**ystem), uses a single rotary hammer for drilling through overburden material and a heated auger mechanism for removing any remaining material and melting subsurface ice deposits. A peristaltic pump and two stage mechanical filtration system are used to pump sediment-free water from the tip of the heated auger to the collection tank.

Prospecting for the digital core is achieved using collected Weight-On-Bit (WOB) data. The prototype collects WOB during drilling using two S-type load cells and compares it to drill depth using an onboard computer program developed by our telemetry lead. The result produces insights to overburden layer thickness and relative hardness allowing us to produce the digital core.

Fully autonomous control is achieved by a TI MSP432 microcontroller that has been programmed to control all subsystems. Control system hardware includes limit switches, relays, and motor drivers. A thermocouple is also used to monitor the temperature of the heating element in the heated auger tool.

Testing revealed that the drilling process was effective at clearing the overburden and extracting water from ice below. The telemetry system succeeded at determining the varying hardness layers in the test bed. Ultimately, we are confident that the STYX & STONES design is valid and efficient. We look forward to the competition, and strongly believe that future RASC-AL Special Edition efforts at Cal Poly will be well-suited continuing where we have left off.

System Description

The major elements of STYX & STONES include a rotary hammer, heated auger apparatus, peristaltic pump and tubing, two-stage filtration system, sensors providing data for the digital core system, and various motors, control, and power systems to enable autonomous operations. The prototype utilizes a rotary hammer and heated auger tool, side-by-side. The coordinate system referenced in this report is shown in Figure 1 below. Each tool can be moved along the vertical (Z) axis independently, and the two tools can move together across the face of the frame along the horizontal (X) axis. The final STYX & STONES technical specifications are listed in Table 1.

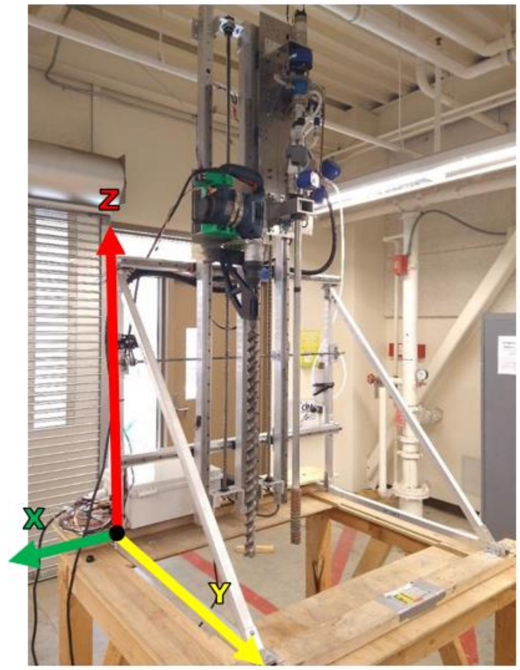


Figure 1. *STYX & STONES Coordinate system*

Table 1. Technical Specifications

Electrical Requirements	< 9A current load, 120 VAC power source, lower voltages are converted internally.
Rotary Hammer Specs	BOSCH 432VCQ, 0-760 RPM, 0-3600 BPM, SDS+ quick release interface
Tooling Specifications	1.5” diameter, carbide masonry drill bit - 36” length, custom 1.4” diameter copper auger - 38” penetration depth
Mass/ Volume	63 kg, 1m x 1m x 1.9m
System Telemetry	3x Type K thermocouples, 2x pressure transducers, 3x motor encoders, 2x load cells
Electromechanical Systems	3x Gearmotors, 1x Stepper Motors, 1x Peristaltic Pump, 3x Motorized Ball Valve, 2x Load Cells (and amplifiers), 2x Thermocouples (and amplifiers), 1x Heater Cartridge, 4xMotor Drivers, 1x Micro-stepper Driver, 2x 120 VAC Relays, 4x 12 VDC Relays, 1x 12VDC Power Supply, 1x 5 VDC Power Supply
Filtration Capability	Backflush-able 40-micron pre-filter with debris dump valve, 5-micron primary sinteredbronze filter
Maximum Loading	Z-axis gear motor stall torque of 6.3 ft-lbf, maximum downward force of 35 lbf WOB,heated auger stall torque of 6.3 ft-lbf, rotary hammer stall torque of 3.1 ft-lbf
Computer System	TI MSP432 microcontroller
Software	C
Communications Interface	USB

Mounting System: The frame is made from various sizes of square, thin-walled 6061-T6 aluminum tubing. Bolts with both stock and custom brackets are used for ease of assembly. A single X- and two Z-rails aligned with the axes are supported for tool translation. To secure the system to the testbed, three ¼" lag bolts and one anglebracket connect each corner of the frame base to the 2x4's provided by NASA. After a detailed structural analysis using extreme loading cases in addition to frame deflection tests during system operation, the team verified that the design provides sufficient rigidity to avoid disturbing the operation of the drilling and extraction tools.

Mine Through the Overburden Layers: To excavate through the overburden and gain access to the ice layers beneath, the STYX & STONES prototype uses a multi-step process as depicted in Figure 2 below. The first half of operation includes using a rotary hammer and 1.5" diameter masonry drill bit to break through the regolith layers. The second involves using a specialized heated auger tool to dig through any loose debris remaining in the hole. One major benefit of the two-tool design is that it divides risk of failure into subsystems making it convenient to identify and rectify problems.

First, the rotary hammer is operated in "hammer-drill" mode which combines typical rotary drilling motion with hammering motion. To ensure the maximum WOB is not exceeded, load cells connected to the rotary hammer record live force readings; these readings are used to control the Z-axis motor and alter the plunge rate of the tool. The tool drills through all layers of overburden and automatically stops after cutting a 4" pilot hole into the ice. This is based on a set distance method of drilling given prior knowledge of the depth of the ice sheet. Next, the rotary hammer is stopped, the direction is reversed, and the drill bit is removed from the hole. This sequence was designed such that the bit makes a minimal impacton the integrity of the drilled hole during removal.

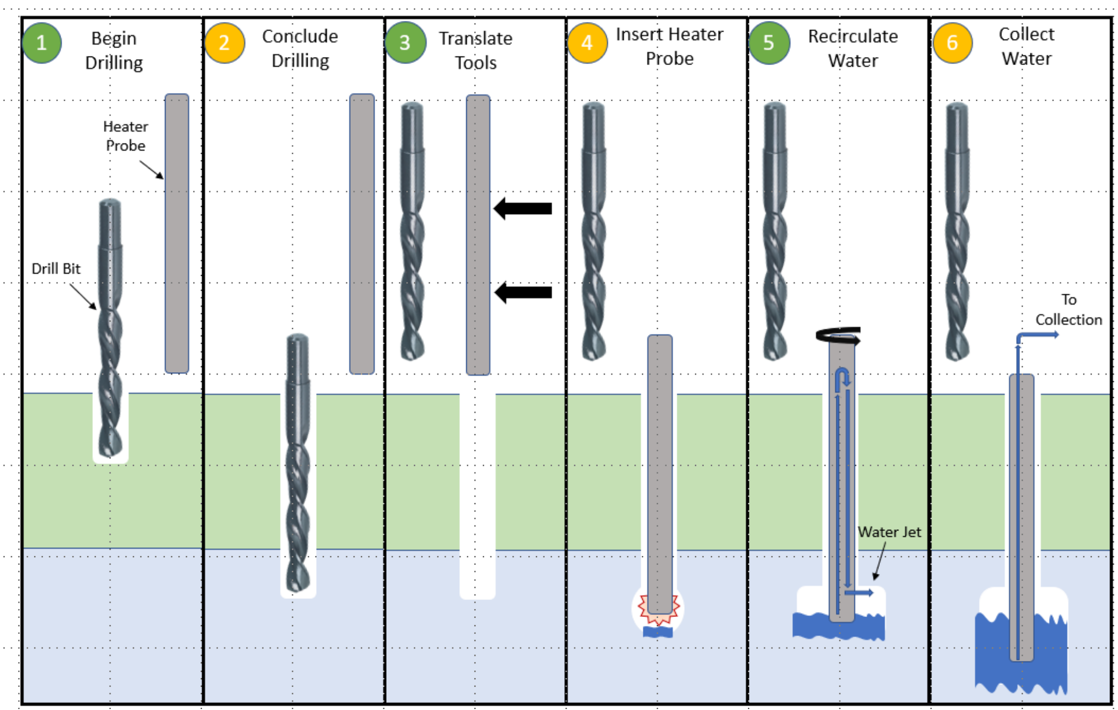


Figure 2. *Sequence of Operations for STYX & STONES on the Moon and Mars*

Avoiding Tool Refreezing: Tool freezing is a frequently discussed point of failure, both in feedback from NASA engineers from prior reports, and in lessons learned from prior years' teams. If the masonry drill bit freezes in the ice, a servo motor is in place to flip the switch on the rotary hammer that reverses the direction of rotation. The drill bit will begin hammer drilling to back out of the ice shelf, and the excavation process can be resumed.

Next, the heated auger tool is used to clear caved-in debris and melt the ice beneath. The auger depicted in Figure 3 was manufactured out of copper for its excellent thermal conductivity. The auger flutes have an outer diameter (OD) of 1.4” providing 0.05” of hole clearance. The auger core OD is 1” and was designed to be as small as possible while fitting the necessary plumbing and heating elements inside for water extraction. The tip of the auger houses a 5/8” OD cartridge heater used to melt the ice layer. Three suction holes on the outer surface of the auger allow liquid water to enter the internal suction cavity where it is pulled upwards by a pump. Above the suction cavity, another radial hole was drilled for a water jet. The goal of the water jet is to use heated water to carve out an ice cavity during the melting process and obtain more water. Shown in Figure 3, the copper auger is attached to a hollow aluminum shaft via threads and set screws for a non-permanent joint if later access is needed. To maximize the shaft length while verifying the competition requirement that a tool cannot go deeper than 38” from the mounting platform, we calculated the shaft length to be 52”.

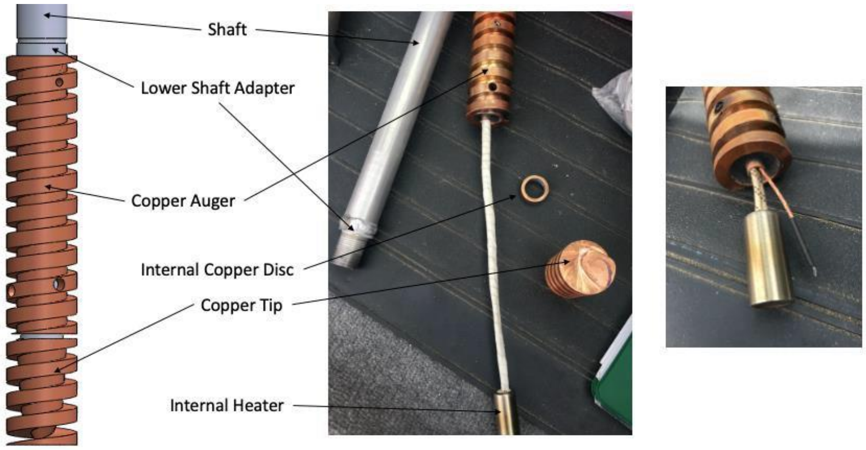


Figure 3. *Manufactured parts in the Heated Auger assembly*

Prospecting for a Digital Core: The digital core will be derived from recording the change in WOB with respect to the depth of the drill bit during drilling. Testing proved this approach is reliable if the load cells are accurately calibrated. Extreme temperature changes and excessive vibrations can diminish the accuracy of the load cell readings. To combat these sources of error the load cells were calibrated over numerous runs and a rubber damper was integrated in the load cell platform to reduce inaccuracies due to vibration. Figure 4 shows a sample of our recorded WOB overlaid with the composition of our test overburden. The distinction between layers will help us deduce the compositionof a multilayer testbed and produce insight into the varying overburden layer thicknesses and relative hardness.

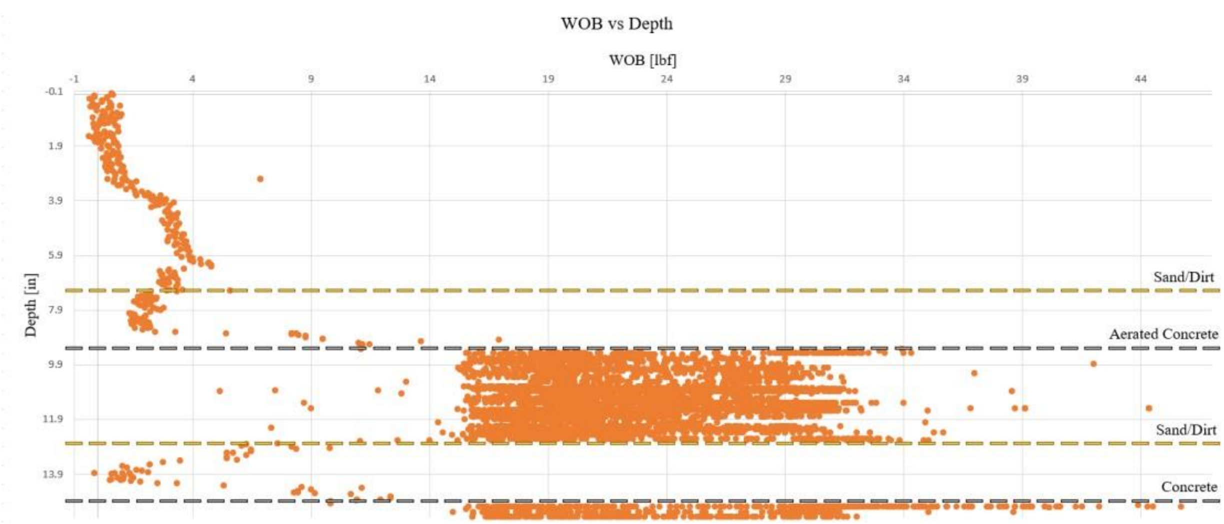


Figure 4. *Prospecting for Digital Core using WOB Recordings*

Filtration and Water Collection: Once the copper auger meets the ice layer, the internal heater is turned on, and the entire tool slowly melts downward. After melting ~5 cm into the ice (the calculated depth required to fill the plumbing volume with water), the pump is turned on to move water through the auger and shaft. As shown in Figure 5, the water flows through a pre-filter into the rotor of a rotary joint (RJ), out the RJ stator, and to a 12V brushless DC peristaltic pump. Meanwhile, the valve at the bottom of the tank (V3) is closed while the side valve (V2) is open so that the tank fillsup to the collection branch. After the pump has been runningfor ~30s, V3 opens and V2 closes allowing water to recirculate from the tank through another passage in the rotary joint and back to the auger. At this point, recirculated water is shot out horizontally from a water jet in the side of the auger to increase the tool's melting capability. Once the cavity has been opened, V3 will close, and V2 will open to begin collecting water.

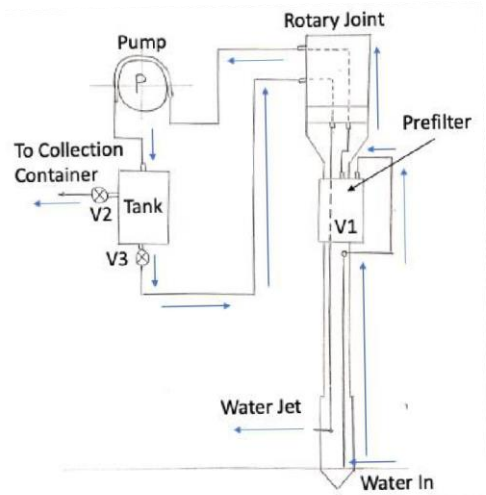


Figure 5*. Water extraction schematic*

Figure 6 shows the rotary joint subsystem. At the top, the shaft is attached to a gear motor that rotates the tool. Since the system needs to transfer electrical energy and water from the rotating tool to the stationary control system and pump, the design includes a slip ring (SR) for theelectrical signals, and the RJ for the water.The blue parts in the model do not rotate with the shaft. To minimize the potential ofdamage to the seals in the RJ, we designed a back-flushable pre-filter that rotates with the shaft. The pre-filter includes an internal 40-micron stainless steel mesh that catches debris directly above a ¾" motorized ball valve (V1). During pumping, V1 can be opened while the pump briefly reverses its flow direction to drain any debris collected in the pre-filter. The final filtration component (not shown in the figure) is a 5-micron sintered bronze filter located just upstream of the collection container. STYX & STONES inherited the filter from last year's Cal Poly team, and several tests have been conducted to verify the filter's ability to produce silt-free water.

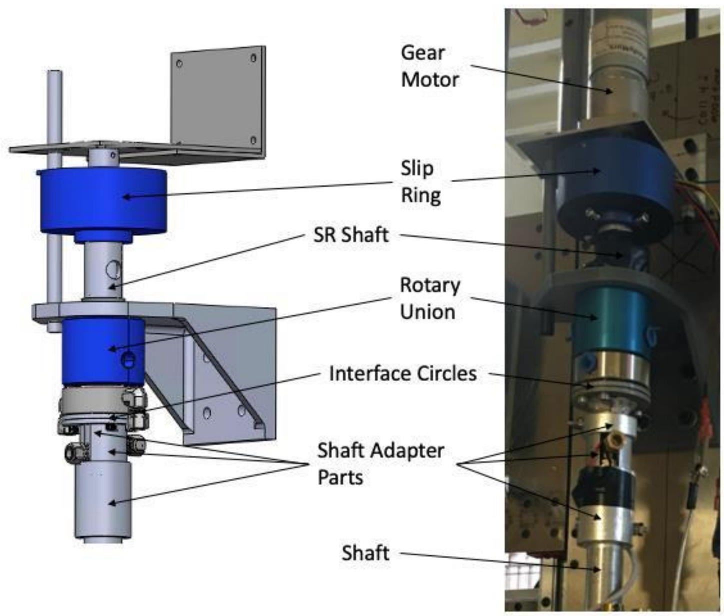


Figure 6*. Rotary joint CAD model (left) and manufactured subsystem (right)*

Control and Communication System: The STYX & STONES prototype is controlled by a TI MSP432 microcontroller that has been programmed to control all subsystems. All code has been written in C and uploaded to the microcontroller via USB. Each subsystem has one or more associated header files, which define which pins are associated with each function, and source files, which define what the functions are. Both file types can be created and used independently, allowing them to be run and thoroughly debugged before full-system testing. As shown in Figure 7, the code was verified one subsystem at a time by attaching the microcontroller to LEDs demonstrating that the program sent signals to the proper pins at the right times.

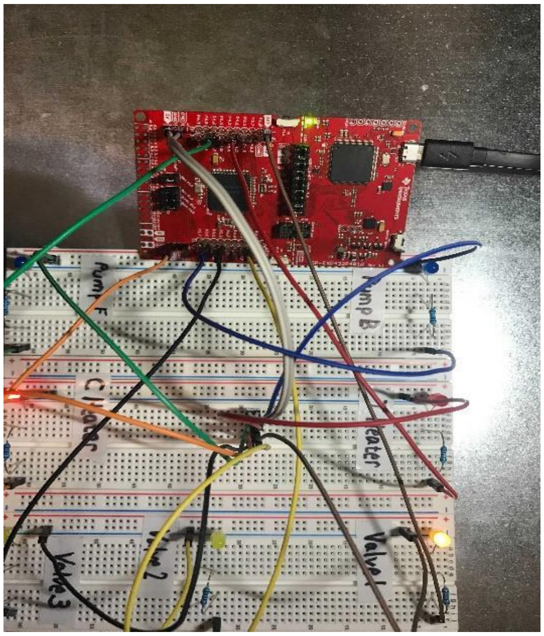


Figure 7. *LED and Breadboard setup to test signals and timing from Microcontroller*

Limit switches are included at each end of the X- and Z- axis rails, which stop all motion when depressed by the carriages or tools. To test this function, the limit switches were connected to the microcontroller and a motor not yet mounted to the prototype. When the switch was depressed, the motor was stopped successfully. The microcontroller also communicates with relays and motor drivers; the relays areused to control the valves of the water collection system, rotary hammer drill, and cartridge heater, while the motor drivers are used to control the motors and peristaltic pump.Finally, the temperature of the heated auger is constantly monitored by a thermocouple inside its tip. As a safety precaution, the cartridge heater is shut off if the thermocouple senses temperature more than 300°C. To verify this safety feature, the end of the thermocouple was placed over a flame to simulate a heater, and the LED representing the cartridge heater successfully went out.

Full-system operation begins by flashing code onto the TI MSP432 from a laptop connected with a micro-USB cable as shown in Figure 8. The microcontroller is then detached from the laptop and connected to the main power strip, and the STYX & STONES system runs through its excavation and water collection sequences autonomously.

Datalogging: A Pmod microSD adapter is connected to the microcontroller to collect data from the load cells and Z-axis encoders in real time and load them onto an SD card. After operations, the data on the SD card can be transferred to a laptop using a USB card reader and visualized in Microsoft Excel. The WOB data can be monitored in real-time during operation on a laptop computer, but early use of real-time data display proved to alter important timing of interrupt handling giving erroneous data. For testing purposes and to verify the function of the sensors, printing data to the console is sufficient.

Figure 8. *Microcontroller connected to laptop with micro-USB*

Design Changes and Improvements

Since the Mid-Project Review (MPR) in March 2021, we have made minor design changes to the drill assembly, electrical configuration, and heated auger. During MPR testing, we observed oscillatory deflection in the masonry drill bit due to the looseness of the SDS drill chuck and shank. To mitigate this, several 3D printed collars were modeled, fabricated, and tested. Due to limited space for mounting and the violent motion of the drill bit, several collars failed during testing. Ultimately, a collar fixed to the bottom of the drill plate and contacting the shank of the drill bit was implemented and has significantly reduced the bit deflection, leading to more precisely drilled holes that reduce concerns surrounding auger entry. Throughout the project, the electrical design remained flexible to allow for convenient troubleshooting, so the containment unit was constantly under development. The plastic box we used was repeatedly reorganized and modified to determine the most functional arrangement. In late July, the final configuration was moved into a portable metal container and all connections that were originally hard-wired were reconfigured to a disconnect system, as shown in Figure 9B, to keep transport and testing safe. The final electrical configuration is shown in Figure 9A. Outside of the central containment box, dangling cables and wires were bundled together and wrapped in a cable sleeve, to keep them from tangling in any moving parts. These changes were a dramatic improvement to the system and safety of the testing environment.

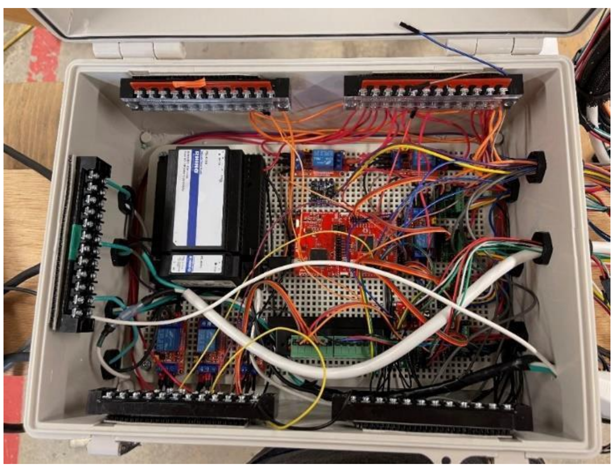


Figure 9A. *Secure containment of electrical hardware*

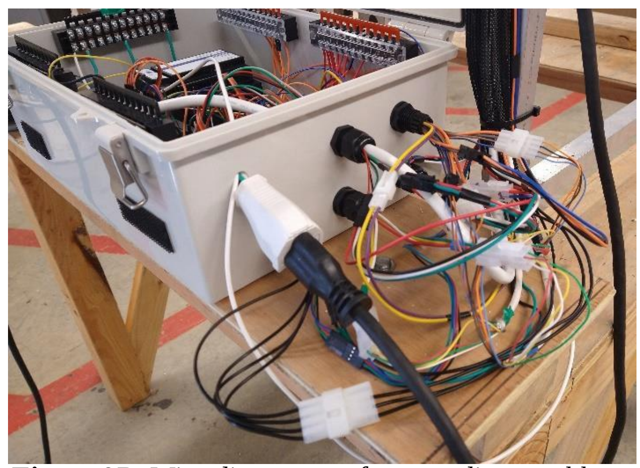


Figure 9B. *Wire disconnects for easy disassembly and transportation*

Finally, the heated auger geometry and control were slightly modified due to late-stage revelations. The auger geometry was first tested using 3D printed prototypes and a 1.5" diameter hole with loose debris inside. In general, we found that overburden tended to compact under the tip of the auger instead of getting pulled up through the flutes. Thus, we modified the auger shape so that the flutes extend to the bottom of the tool, and the core tapers to a smaller diameter. These changes proved to be a tedious manufacturing process, but the copper prototype was successful at reaching the ice surface beneath the overburden. The cartridge heater housed inside the copper auger proved to heat up much faster and more intensely than expected. This posed concerns about overheating electrical components or boiling the liquid water, which could cause irreversible damage to the water collection system. To avoid these issues, we augmented the heated auger with a thermocouple in its tip to ensure it heats up appropriately and an emergency shut off routine was added to the software to avoid overheating.

Summary of Integration and Test Plan

STYX & STONES testing began in February 2021, initially with subsystem tests for each of the following: rotary hammer and drill bit penetration through ~7 in of concrete, primary and secondary filtration, pump tests, water-jet concept prototype tests, stepper motor tests (X- and Y- axes), load cell calibration and data logging. We progressed to integrated tests of pairs or groups of related subsystems, such as the Z-axis motor, rotary hammer, load cells, or the water inlet mesh, filters, and pump. Finally, wemoved on to full-system autonomous testing in June 2021.

During full-system testing, the excavation process occurred without issue. The rotary hammer was powered on at the correct height above the overburden and plunged into the overburden without exceeding WOB constraints. By powering off the rotary hammer prior to removing the bit, there were minor amounts of debris left in the hole. Following the removal of the bit, the prototype correctly positioned the heated auger directly over the drilled hole. The heated auger was then lowered, while rotating, into the hole burrowing itself past the debris. During the test, the heated auger stopped translating into the hole because the Z-axis motor shaft dislodged from its pulley. We quickly designed aset-pin to hold the motor shaft onto the pulley to avoid future dislodging. This did not impact the effectiveness of the auger tool during this test, as the hole maintained its structural integrity well and didnot collapse sand back in on itself.

The melting and water extraction state successfully started operating after the tool reached its planned depth. The extraction system was set to cycle between the water jet, water recirculation, and water extraction using even time increments. This was to verify functionality of each state, but the time increments have been adjusted to reflect a more realistic timeframe for each state to run during actual operation. Everything went smoothly during the melting and water extraction process until a fluid buildupbegan to form at the outlet of the pump and the test was called off to protect the hardware and electronics.The error was determined to be caused by a dysfunctional valve, which was promptly replaced and tested,and will be re-tested as part of further full-system testing prior to the competition.

An important note about the full-system tests to date is that the digital core has not been verified during a dry run of the system. The digital core has been independently verified, but as mentioned previously, data was printed to the console before being copied to Excel for analysis. This poses serious problems with the use of interrupts for vital data readings, so we have invested in external memory to load data onto, to circumvent the limited memory space available to the microcontroller. We plan to run at least one more full-system test to prove that we can successfully extract this data before the competition.

The water collection system proved successful in the full-system tests performed. Sediment-free water was successfully extracted from a basin of dirty water at a rate of roughly 250 mL/min. Accounting forice melting, we expect to produce about 15 quarts of water at the competition. Finally, the maximum power draw of the system never exceeded 9A, peaking at 6.3 A, and averaging 0.5 A over a full-system test.

Overall Strategy for the Competition

The two key aspects of system performance are layer depth determination (prospecting) and maximizing water extraction. Our strategies for these are as follows.

Layer depths will be determined by the values of the Z-axis encoders corresponding to clusters of load cell data. Layer hardness will be determined by the values provided by the load cells and if two layers have the same average hardness, they can be visually differentiated by howmuch the data deviates from the average reading for that layer. With experience, our mechatronics and telemetry leads will be able to recognize these patterns associated with different layers. For off-Earth autonomous operation, a Markov Model will ideally replace an operator, and categorize the data automatically.

The system will maximize the water acquired with our custom heated auger tool by employing the slowly rotating hot water jet. We will use the high temperature heater in the tool tip to create an initial water pool, allowing enough water to be collected such that it can recirculate and be ejected from the water jet for an extended range of melting. The heater is maintained at a high temperature for the entire duration of the water extraction process, which takes most of the system operation time. We expect the water jet to create a 10” diameter cavity in the ice that is 13” deep over the course of several hours, which provides about 15 quarts of water per hole assuming up to a quart of water is lost since it can sit below the suction holes or during backflushing.

Another important strategy we considered was how to best ship STYX & STONES from San Luis Obispo, CA to Hampton, VA without catastrophic damage. The prototype will be broken down to fit in packaging with maximum overall dimensions of 1 ft x 2 ft x 7 ft. The Z-axis assembly will be removed, allowing the remaining eight members of the frame to be completely disassembled. While the masonry drill bit can easily be removed, the auger cannot. While it is convenient that the most complex assembly will be ready out-of-the-box, extra safety wrapping will be used for the auger to ensure it is not damaged on the way to the competition. Once on-site, we expect to complete full assembly within 2 hours, allowing extra time to repair any minor damage that may occur during shipping or re-assembly.

Tactical Plan for Contingencies and Redundancies

For all mechanical components and electrical hardware, the STYX & STONES team’s plan for contingencies consists of purchasing and acquiring backup equipment in the case of failure. Our project budget will allow for the purchase of backup electronics, drilling hardware, and pump/filtration systems. A team member’s personal 3D printer will also be brought along to aid in any other unforeseen issues. In addition, the system software can be overridden in the case of serious program malfunction, so the system can be teleoperated from a connected laptop on the command line. Finally, an emergency stop state is included in the software in case the machine is at risk of damaging itself or encounters unexpected problems. The stop state will have a protocol to attempt to overcome the error and continue, or in the worst case, start the operation over.

Challenges and Final Project Timeline

Taking on a project of this magnitude was bound to have several challenges. One major challenge was the limited computer science expertise on the team. Since the team is entirely composed of senior Mechanical Engineering students, we had to rely heavily on one student for all computing endeavors. This was a high-risk decision leaving us with only one member well-equipped to operate the system in the competition environment.

Many manufacturing obstacles had to be overcome as well. The heated auger was originally planned to be manufactured with Cal Poly’s CNC lathe, but the job fell through days before it was scheduled due to a high volume of CNC requests from other senior design groups. The team’s water processing lead had to continue with the copper flute manufacturing on a manual lathe which added approximately 3 weeks to the original manufacturing plan and delayed the start of full system testing until June. In addition, Cal Poly’s COVID-19 restrictions required us to strategically separate our time in the workroom and the machine shop into 2-hour blocks. This obstacle did not initially disrupt our integration deadline, but when unforeseen challenges arose, it was difficult to get time with the prototype to resolve issues.

Table 2 shows the final timeline to complete the STYX & STONES project. As this project extended beyond the school year, many of the group members had either graduated or were working full-time internships over summer. While the remaining group members were eager to demonstrate a functional prototype, work capacity was limited to approximately 20 hours/week to complete full-systemtesting.

Table 2. Project Timeline

Concept Design	Finalized Design	Manufacturing	Integration	Testing
Sep 2020 – Feb 2021	Feb 2021 – Apr 2021	Feb 2021 – May 2021	May 2021 – Jun 2021	Jun 2021 – Aug 2021

Safety Plan

No chemicals or hazardous materials are used on or around the system at any time. A set of hazards specific to STYX & STONES operations were compiled into a safety plan. These hazards and their relative severities were assessed using FMEA and DesignSafe risk assessment software. The resulting safety plan is shown in Table 3 below. PPE requirements include safety glasses, face masks, andhearing protection to be worn during operation.

Table 3. Design Hazards Corrective Actions

Description of Hazard	Planned Corrective Action
Rotating Drill Bit	- Do not stand within 3 feet of drill during operation. - Tie back loose hair and do not wear loose clothing. - Allow drill bit to cool before handling.
Electrocution	- Prevent access to exposed electrical parts. - Ensure frame is grounded to common ground terminal. - Wear insulated gloves and clothing when handling electronics. - Do not make changes to circuit while it is powered. - Do not handle live wires.
System Misuse	- Only members with the appropriate training may run the system. - Operator must never run the system without the presence of at leastone accompanying group member.
Close Range Hazards (Pinch Points & Dust)	- The operator must give a 3-second warning call before running theprogram to allow all bystanders to move to a safe distance (3ft+) from the system. - Safety glasses and dust masks must be worn by ALL attendees during regolith penetration.
Hazardous Noise Levels and Air Particulate	- Earplugs, dust masks, and eye protection will be onsite.

Final Project Budget

The prototype was completed with a budget of over $10,000 remaining. Much of this success is owed to last year's Cal Poly STYX team, who left a legacy of $8,800 for this year's effort. Additionally, Capstan Inc. sponsoredthe Cal Poly effort last year by providing them with two cylindrical, 5 micron sintered bronze water filters, which our team reused. Capstan was excited to hear about Cal Poly's continued participation in this project, as they have previously supplied filters to NASA for use on the Curiosity Rover. Materials purchased for making preliminary prototypes to narrow down design choices, and final prototyping are included by subsystem in the design/build section of Table 4 below. Testing materials were reused from last year's effort with no expense to the current team.

Table 4. Final Project Expenditures

	Item	Amount (USD)
Budget	Senior Design Materials Budget	$1,000.00
	NASA RASC-AL Stipend	$10,000.00
	Remaining Funds from Last Year's Team	$7,800.00
	Total Starting Budget	**$18,800.00**
Expenditures	Design/Build Expenses by Subsystem	
	Frame	$1,211.17
	Drilling Subsystem	$722.16
	Heated Auger Subsystem	$2,930.83
	Water Processing	$300.32
	Telemetry, Electrical, and Controls	$2,096.32
	Total Prototype Expenses	$7,170.80
	Projected Transportation Costs	
	UPS Ground Transport to Hampton, VA	$346.50
	UPS Ground Transport from Hampton, VA	$346.50
	Total Project Expenditures	**$7,863.80**

Path-to-Flight

The culminating challenge of this project was to design and build an Earth-based analog to a water extraction and prospecting system intended for use on the Moon and Mars. Throughout our design process, we revisited the most effective ways to minimize differences between our Earth-based system, and a modified version suitable for Lunar and Martian environments. However, many of the systems presented in this design must be modified for the best functionality on the Moon and Mars. If the STYX & STONES system is modified as proposed, it will be capable of remotely generating digital cores of different regolith layers on the Moon and extracting clean liquid water from the subsurface of Mars.

Path-to-Flight for Water Extraction on Mars

Environmental challenges, design complexity, and material compatibilities are all sources of complication with the current STYX & STONES design. The two primary environmental challenges for STYX & STONES are extremely low temperature, and the Martian atmospheric pressure. Heated auger complexity and lack of water purification are major design limitations. Specific mitigation for each is discussed below.

Essential Design Modifications for Low Temperature: The low ambient temperatures on Mars (-275°F - 85°F) could pose several challenges to the STYX & STONES prototype.

First, extreme cold may compromise the ductility of metal/plastic parts such as the frame, drill bit, auger shaft, and microcontroller, and the elasticity of rubber tubing and seals. While aluminum alloys are frequently used in spacecraft structures, high cycling of thermal expansion and contraction will decrease the life of most of our metal and plastic components [1]. The Mars system would require us to carefully select plastics and rubbers that maintain flexibility at near cryogenic operating temperatures. To avoid cracking of metal components, the primary structure could be augmented with vibration isolators at high noise locations like the frame joints and testbed attachment points. The controls system could also be re-configured to include higher accuracy limit switches to avoid impact. As part of the re-design process, in-depth modal and fatigue analyses utilizing low temperature material properties would need to be done to determine the most effective concept.

Second, it is imperative that the load cells used to measure WOB be re-calibrated for the Mars temperature range to ensure the WOB datalogging is accurate. Large surface temperature fluctuations that take place on Mars would be enough to severely throw off strain gauge measurements, allowing the drilling rig to exceed 150N WOB and risk tipping the rig over or damaging on-board components [2].

Finally, it is possible that ice deposits could accumulate on STYX & STONES if there is enough moisture in the Martian atmosphere. To avoid this, we recommend covering the entire system in thermal blankets when not in use or relocating it to an indoor facility during the coldest hours of the day. Operators could also be instructed to check the ambient temperature before running the program, and warning labels could be added to advise against use if the ambient temperature is below 0°C.

Essential Design Modifications for Atmospheric Pressure: In addition to extremely low temperature, another significant obstacle for STYX & STONES is the Martian atmospheric pressure. The surface pressure on Mars (roughly 650 Pa) is extremely close to the triple point pressure of water (612 Pa), making it likely that any exposed ice will sublimate into water vapor instead of melting to liquid [3]. Additionally, the current water collection method relies on pulling a vacuum with our peristaltic pump. Pulling vacuum will be difficult to accomplish with our current equipment on Mars where the ambient pressure is less than 1% of that on Earth.

To mitigate these challenges, we propose a “pressurized hole” solution. Figure 10 shows a schematic of an upgraded heated-auger tool with an added sealing apron to seal off the hole. After drilling, the auger will enter the hole in the same manner as the competition prototype. When the auger reaches the ice level, the sealing apron will get pressed against the top surface of the overburden. The dynamic seals between the spinning shaft and the sealing apron allow the shaft to continue rotating while the apron remains stationary. As the heated auger continues to melt downward, the forces from the springs will further push the apron into the overburden creating a reliable seal. To pressurize the hole, the pump will be reversed while only V2 (the valve attached to the collection line) remains open. This will push the Martian atmosphere gasses into the hole via the plumbing used for normal operation. Once the apron seals the hole and the pump pressure rises to 100 kPa, the pressure in the hole will be close to the levels near Earth's atmospheric pressure (101.3 kPa). Note that the current pump design can pump gases with a maximum pressure rise of about 140 kPa. During the melting process, this allows the ice inside the hole to go from a solid phase to a liquid phase. Additionally, by pressurizing the hole, the pump will be capable of pulling a vacuum to transport water from the auger suction ports to the suction lines. It is likely that the pump would have to undergo a pulsing type of operation where it would briefly reverse to pressurize the hole (blowing gas into the hole) and then go forward again to collect water.

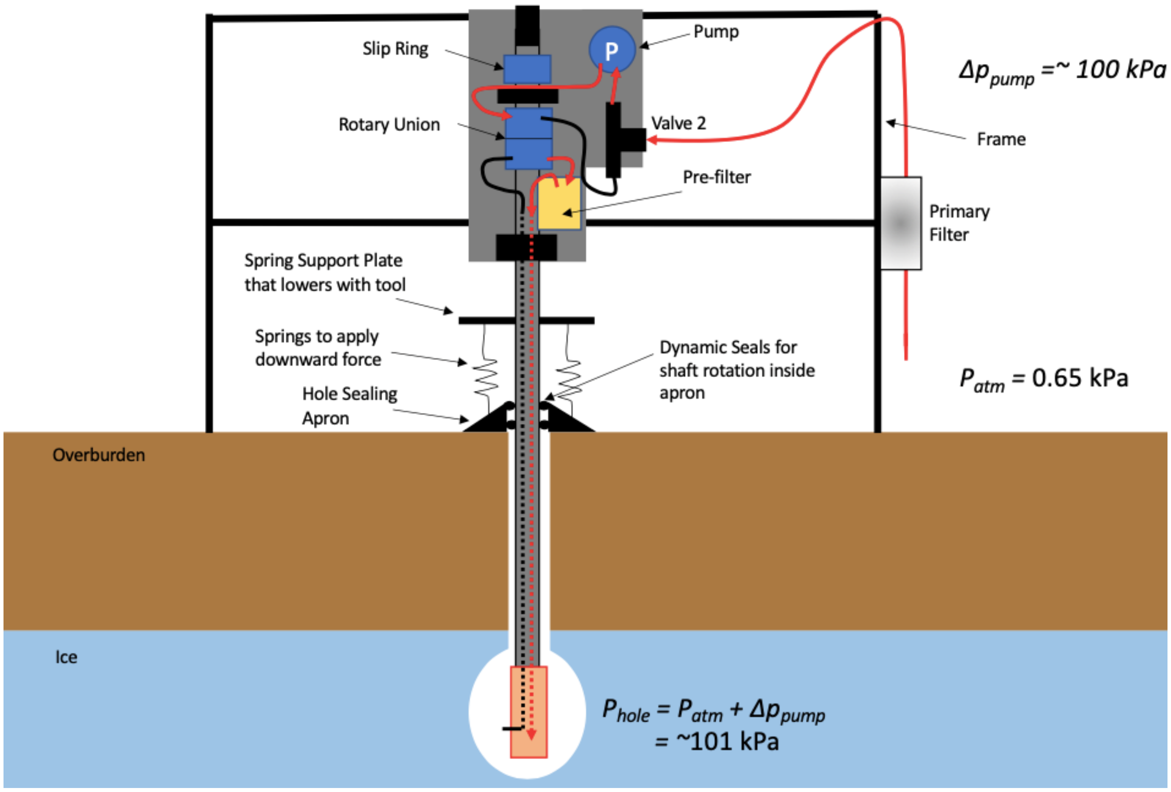


Figure 10. *Schematic of Hole Pressurization Design Solution*

As an alternative recommendation, a second pump could be implemented to push atmospheric gases into the hole while the suction pump pulls out water after a significant amount has been melted. To confirm one way flow for this design option, check valves could be placed in the lines. Both options offer creative solutions to the challenge of a low atmospheric pressure on Mars, but extensive testing and analysis would need to be conducted to evaluate the feasibility of each.

Essential Design Modifications for Tool Complexity: Another significant challenge to operation on Mars is the complexity of the heated auger tool. While the hybrid tool has proven effective on Earth, it may have pitfalls in practice on Mars. First, the heating element must be very closely monitored such that it does not overheat and damage the copper auger, so a thermocouple is in place to keep track of the temperature. During manufacturing we found it very difficult to leak test the welded connections in and around the copper auger and its tip without damaging the thermocouple already housed inside. We recommend adding a second thermocouple or water-proof casing to protect the thermocouple if it fails or a leak occurs during operation.

Additionally, the rest of the tool may prove challenging to repair or maintain. The tube and wire routing through the tool shaft, filtration system, and rotary joint must be more condensed to avoid accidental internal disconnects from vibration or momentary pressure increases from clogging. Using rotary electrical contacts and rotating seals will help prevent this from happening. In general, making the heated auger tool in pieces that are easily fastened together would drastically improve the ability to both assemble and maintain it. The auger itself will benefit from being machined out of a material with higher yield strength. The copper was chosen to maximize heat transfer, but the capability of the cartridge heater proved to be far beyond original expectations, so there is much more flexibility in auger material selection and geometry. With the extremely cold temperatures on Mars, it is very likely that once the regolith layers have been pulverized and exposed to the atmosphere, the loose regolith will become ice-laden and behave like dense beach sand [3]. The current auger material and geometry can remove moderate amounts of packed sand and soil from a drilled hole, but this would not be enough to deal with the quantity and density of ice-laden soil found in Martian holes. As such, a less ductile material would be needed to reach the ice, and the auger should also be outfitted with wider flutes to increase the overburden carrying capacity of the tool. Adding additional steps to the operational plan such as repeatedly lifting the auger out of the overburden, jogging away from the hole, and spinning to release the removed overburden, would help mitigate this issue as well.

Essential Design Modifications for Water Purification: Finally, a major challenge to the STYX & STONES prototype is that the current filtration system relies entirely on mechanical filtration. Perchlorates present in the Martian regolith are hazardous to human health and any contaminants in the water would reduce the usefulness of this limited resource [4]. An additional chemical treatment or distillation step must be added to avoid water contamination from Martian soil.

Overall Impact to Operation: As a result of recommended adaptations, we expect the followingimpacts on overall Martian performance as compared to Earth-based operations shown in Table 5.

Table 5. Changes to STYX & STONES Performance with Mars System Adaptations

Metric	Difference	Explanation
Power Consumption	Increase	Both recommendations for hole pressurization add components to the system that will demand more energy for operation.
Reliability	Decrease	While added components protect the system from the Martian atmosphere, more parts correspond to more failure modes.
Mass & Volume	Increase	Most components would be upgraded by increasing their strength or adding parts will increase system mass.
Lifetime	Increase	Selecting materials with superior capabilities, adding thermal blankets, or limiting operation to optimal temperatures only will reduce potential for cracking and component failure.
Water Collection Rate	Increase	Pressurizing the hole will increase water yield.
Water Purity	Increase	Increasing auger efficiency will help decrease overburden collected with the water. And additional chemical/distillation step will remove remaining bacteria and perchlorates.

Path-to-Flight for Prospecting on the Moon

Like the Martian environment, prospecting for a digital core on the Moon will require consideration of the extreme range of temperatures (-280°F to 260°F) [5]. Issues with differential thermalexpansion and alteration of material properties will arise just as on Mars. Due to the design's tight tolerances any small changes in volume due to thermal expansion could lead to decreased life and possible failure depending on severity. For example, the rubber belts that drive the lead screws would become brittle or melt in response to the extreme temperatures. To mitigate these issues, the edge margins between adjacent parts in the assembly must be temperature compensated to avoid parts riding against each other when materials expand under high heat. Like on Mars, the load cells would need to be re- calibrated for the temperature range on the Moon as well.

The drill and motors will likely take much longer to cool after operations in the elevated temperature and lack of air to convection cool components. During drilling, a significant amount of heat is trapped in the hole by the cuttings which will heat up the drill bit and rotary hammer [6]. To avoid this,the bit will need to be removed from the hole more often to maximize opportunities to cool off convectively and prevent overheating. Other options include operating at lower cutting speeds than on Earth and adding operational instructions to not operate in extreme temperatures.

The moon is covered in fine, sharp dust particles that pose an issue to our onboard electronics and hardware [7]. This dust can damage the parts directly or coat them and increase risk of overheating. A modified design could include a thermal imager to monitor excess heating of components, and electrical redundancies if a component overheats. In addition, any piping components or electrical connections may be contained within dust tolerant connectors, such as the harsh environment protective housing patented by NASA [8]. Furthermore, if dust ingress occurs on the major axis bearings, lead screws, or motor gear boxes, the lifecycles of these components will be drastically reduced. To prevent this, a gasketed bearing solution could be implemented to prevent dust ingress for motors and bearings, while a flexible bag or CVCM approved fabric covers could be fitted over the lead screws, linear bearings, and rails to prevent dust from coating these surfaces [9].

Finally, much like the water extraction process for Mars, digital core prospecting must be suitable for extended periods of isolation. STYX & STONES was conceptually designed to be fully operational without human intervention, and from a software perspective, the current prototype is fully autonomous. However, the acquisition of a digital core has a few redundancies; if both load cells were to fail or have consistent measurement bias, the mission to collect a digital core would be forfeited. We recommend augmenting the load cells and mass-spring damper system with ground penetrating radar like RIMFAX used on the Perseverance rover to determine the possible overburden composition if the load cells fail, but also to consistently compare the digital core program results with the radar [10]. A change like this will ensure that enough information is collected to develop a digital core without routine maintenance if components malfunction. At the very least, it will help the system complete what is necessary until maintenance can be completed.

Conclusion

We are confident in our chosen design path, and we strongly believe that the proposed modifications will produce a valid Path-to-Flight for STYX & STONES. By re-evaluating our material selection, pressurizing the drilled hole, streamlining the heated auger design, and adding a water purification step, the lifetime and efficiency of STYX & STONES will be improved for use on Mars. Prospecting on the Moon can be improved by operating the rotary hammer at lower cutting speeds, protecting electronics, and moving parts from Lunar dust, and adding redundancies to the telemetry system.

We look forward to presenting our work at the competition and we thank NASA, NIA, and RASC-AL for providing the opportunity to engage in a meaningful senior project that gave us real engineering experience. We hope that our work can help to further your team's success in the future.

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