NASA RASC-AL

2021 Moon to Mars Ice and Prospecting Challenge, Project Plan

Sub-lunar Tap Yielding eXplorer (STYX)
&
Surface Telemetry Operations and Next-generation Excavation System (STONES)

Team Members

All student members are undergraduates studying mechanical engineering at the California Polytechnic State University, San Luis Obispo. This team is composed of two sub teams and was formed on 9/14/2020.

Mechanical Team

Michelle Leclere
- *Mechanical Team Lead*

Bradley Behrens
- *Water Processing Lead*

Dominic Duran
- *Structures Design Lead*

Alex Martinez
- *Excavation Design Lead*

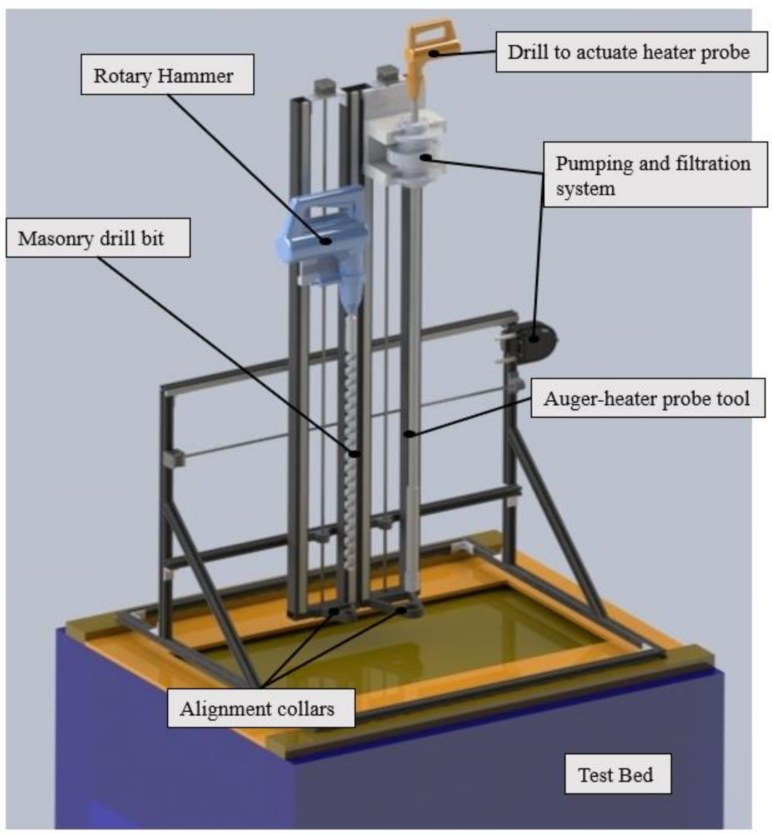
Mechatronics Team

Schuyler Ryan
- *Mechatronics Team Lead*

Rebecca Rodriguez
- *Telemetry Systems Lead*

Jacob Everest
- *Programming Lead*

Tyler Guffey
- *Electrical Design Lead*



Peter Schuster

- *Faculty Adviser*

CAL POLY

I. INTRODUCTION

STYX & STONES is this team's proposed design for the 2021 NASA RASC-AL Moon to Mars Ice & Prospecting challenge. The name STYX & STONES was chosen as a homage to last year's Cal Poly team members who were unable to participate in an on-site technical demonstration due to COVID-19. The name also refers to the comeback "sticks and stones may break my bones" as this year's team intends to make a strong comeback considering the many challenges faced throughout 2020.

Design efforts toward the project have been focused on ideation, preliminary calculations, thorough CAD modeling, and concept model testing to ensure design feasibility. The results of these efforts are innovative and yield a conceptually proven design direction unique from other proposals.

Some novel design features this team will implement are an auger-heater probe hybrid tool, hot water-jet recirculation system, and durable tool mounting carriage. The team's excavation system will translate on two axes, use a rotary hammer and masonry drill bit to bore holes, and deliver water via a peristaltic pump and a two-stage filtration system. Each of these functions are explained further in the upcoming sections.

Mechanical Team Lead: Michelle Leclere works as an assistant for Cal Poly's hand-drafting and SolidWorks labs, giving her experience with solid modeling and GD&T. She also has experience directing Cal Poly SWE's Team Tech team. These experiences show understanding of design for manufacturability and strong project management skills. Her work experience in Boeing's manufacturing and structural design teams will provide context for reliable and lightweight design.

Water Processing Lead: Bradley Behrens is focusing on a career in design and analysis of aerospace propulsion systems. Through Cal Poly's labs and design projects, he has experience designing for manufacturability using CAD and GD&T. By interning within the HVAC industry, he gained hands-on experience with component fabrication. Using his skills and passion for design, he is committed to delivering a water collection system with high mission assurance.

Structures Design Lead: Dominic Duran works as a lab assistant for Cal Poly's hand-drafting and SolidWorks labs. Paired with his manufacturing and structural design experience at Northrop Grumman and Cal Poly Racing, he is confident that he can design a reliable frame to support each subsystem.

Excavation Lead: Alex Martinez has completed numerous engineering design courses through his major, providing him with the skills he needs to analyze and create the drilling system for this project. His passion for engineering combined with his design skills will allow him to produce an excavation system optimized for speed and reliability.

Mechatronics Team Lead: Schuyler Ryan has been involved with several robotics projects including building autonomous SUMO fight bots, making a light-following mouse-bot, and being involved with Cal Poly's Robordentia competition. With his extensive experience and skills working with mechanical systems, he is confident in the team's ability to fully automate the system.

Telemetry Systems Lead: Rebecca Rodriguez's focus is on mechatronics. Her strengths come from working with her dad where she gets to learn the real-world application of engineering concepts. She has experience wiring solenoids for an air bag suspension, as well as installing a fuel level sensor for a gas tank. She will ensure that the telemetry system will perform as required to determine the digital core.

Programming Lead: Jacob Everest has engaged in many projects such as designing, building, and programing a miniature autonomous greenhouse to water, warm, and expose his lemon tree to sunlight. His experiences include working with the Cal Poly Hyperloop team, interning at L3Harris Technologies, and working at The Home Depot during the school year. Next year he hopes to get his Master of Engineering.

Electrical Design Lead: Tyler Guffey has had the opportunity to experience many interesting, hands-on projects, ranging from car restoration to wrought iron fences. His experience in creating his own designs and researching components independently will aid in increasing the integrity of this project, and being an excellent teammate.

II. MECHANICAL DESIGN

A. Linear Motion

The team decided to proceed with a two-axis leadscrew design to limit design complexity and retain the necessary strength for drilling operations. Leadscrews can be self-locking and provide significant mechanical advantage as well as the desired stiffness for the application [1]. The most significant modification that was made to last year's design is the addition of a third leadscrew to support vertical motion of the heater probe unit. While the expansion of the carriage reduces the drillable envelope for this year's prototype, the two z-axis leadscrews eliminate the need to use a rotary tool changer which proved to be a challenge for last year's team. This design will still be capable of translating .45m horizontally across the test bed with the two-tool design depicted on the cover page above. For background on last year's STYX design, refer to Appendix A.

17HS15-1504S-X1 stepper motors were selected to aid the movement of the leadscrew system in both the horizontal and vertical directions. These motors were chosen due to their proven excellence on related projects with their controllability and cost. The motor's resolution, torque capacity, and power consumption were also considered as important factors. The motor's specification sheet can be found in Appendix B.

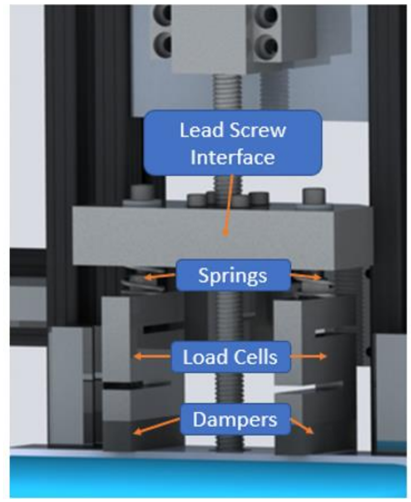


Figure 1. Load Cell Integration

The team is using the spring-damper load cell interface shown in Figure 1. Load cell data will provide closed-loop feedback to ensure that the 150N force on bit requirement is not exceeded. The integrated damper material will serve to reduce noise in the load cell data and vibratory loads 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 if the drill were to suddenly transition from a soft to a hard material.

B. Drilling Unit

For overburden excavation, the team has decided to perform hammer drilling with a multi-function Bosch RH432VCQ rotary hammer. A rotary hammer will provide the axial force needed to penetrate concrete and combines this with rotational motion to create a hole as clean as in traditional drilling. The team has decided to use a 32" masonry drill bit to get through the overburden, and an auger-heater probe hybrid tool to melt ice and collect water. The sizes and functions of the masonry drill bit and additional heater probe tool are outlined in Table 1.

This year's team will be retaining the same rotary hammer and masonry drill bit used in last year's prototype. In addition, the preliminary testing in Appendix C from last year has provided this year's team with relevant data to determine maximum drill diameter, ideal weight on bit, chip clearance methods, and starting and continuous current for the rotary hammer.

Table 1. Tooling Components

Component	Size	Function
Masonry Drill	1.5" OD	Create hole through overburden and 4" deep into ice.
Heater Probe	1" OD,	Melt ice and collect water.
Heater Probe Shaft	.75" OD	Circulate water to melt additional ice.
Auger Tip	35mm (~1.4") OD	Lead heater probe through debris in hole.

C. Heater Probe Unit

After the drilling process is complete, the masonry drill bit will be carefully extracted leaving a 1.5" diameter hole in the overburden with a 4" deep pilot hole in the ice. At this point, the team is anticipating the hole partially filling up with softened debris including small rocky inclusions. Thus, the team has designed a heater probe with an auger tip that will rotate down through the softened debris in the hole. The goal of this mechanism is to obtain direct contact between the heated probe and the ice surface for effective conductive heat transfer. Based on a preliminary test using the auger from last year's STYX prototype, the team discovered that the auger successfully actuates the shaft down into the debris-filled hole. Information on this test can be found in Appendix D.

The heater probe design includes a 1" diameter copper housing with an internal 1/4" diameter, 300 W cartridge heater and a 2' long, 156 W coil heater. Additionally, a water jet connected to a recirculation loop is included to expand the probe's melt capability per hole using convection heat transfer. Figure 2 shows a labeled schematic of the heater probe with the recirculating water jet assembly. Note that there will be a mesh at the suction port and a filter before the pump as well.

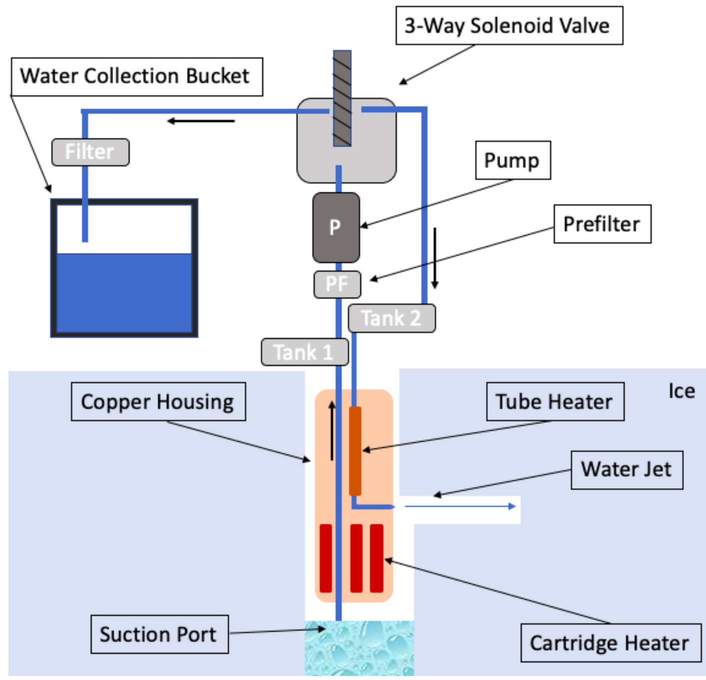


Figure 2. Labeled schematic of water collection system.

Once the heater probe is submerged in the ice layer and the pilot hole is filled with water and debris, the pump will be turned on while the solenoid valve is in recirculation mode. When the cavity has a significant amount of water, the solenoid valve will be flipped to collect water. During the melting process, the solenoid valve will constantly be changing modes to maintain a balance of water in the on-site well. Figure 3 shows a CAD model of the heater probe design. Note that the whole auger, probe, and shaft rotate together, and the auger tip is hollow with an internal 300 W cartridge heater.

For preliminary testing, the team created a concept prototype with copper pipe fittings as shown in Appendix E. Based on this design, the team is concerned with debris build-up above the auger flutes causing the suction port to be clogged. The initial test showed that the overburden does in fact build up above the flutes. To further examine this concern, the team is setting up a test to actuate the concept heater probe into the hole with the auger attached on the end. This test will also examine the effectiveness of augering into the hole multiple times to remove loose debris. Additionally, the team is considering design alternatives including a custom heater housing with a water jet and suction ports that are incorporated as part of the auger flutes. Finally, the team is examining alternative materials while keeping in mind galvanic corrosion and thermally induced stress at the joint due to dissimilar metals.

To account for the rotation of internal pipes and wires, the team designed a sealed tank assembly as shown in Figure 4. The shaft rotates inside the tank assembly where the shaft has two holes in it for the suction and discharge water flow. When the pump is turned on, Tank 1 will become a partial vacuum that will pull water up from the suction port on the heater probe below. Once Tank 1 is filled, water will flow through the prefilter, pump, and solenoid valve before dumping into Tank 2 (only when the solenoid valve is in recirculation mode).

Subsequently, the water in Tank 2 will enter the shaft suction hole and flow down to the water jet. For the electrical wires, they will remain inside the shaft until they are above the tank mount. Then slip-rings will be used to transfer the electric signal from the wires to external wires.

Preliminary analysis of the hydrostatic tank pressure showed that the selected pump will be successful at drawing water up 1.2 m in standard gravity (Appendix F). The team conducted preliminary testing using the concept heater probe, last year's peristaltic pump, and a filter tank with a volume of approximately 12.5 in^3 (Appendix G). The test results agreed with the preliminary analysis showing that the pump can successfully create enough vacuum pressure to draw water. Next, the team will examine how to effectively seal the tanks so they can maintain the required pressure. To accomplish this, the team is in contact with engineers from multiple shaft seal and bearing manufacturers to verify this requirement. To seal the drilled hole during water extraction and prevent ice sublimation in the Mars environment, a similar housing using a shaft seal and bearing is being considered.

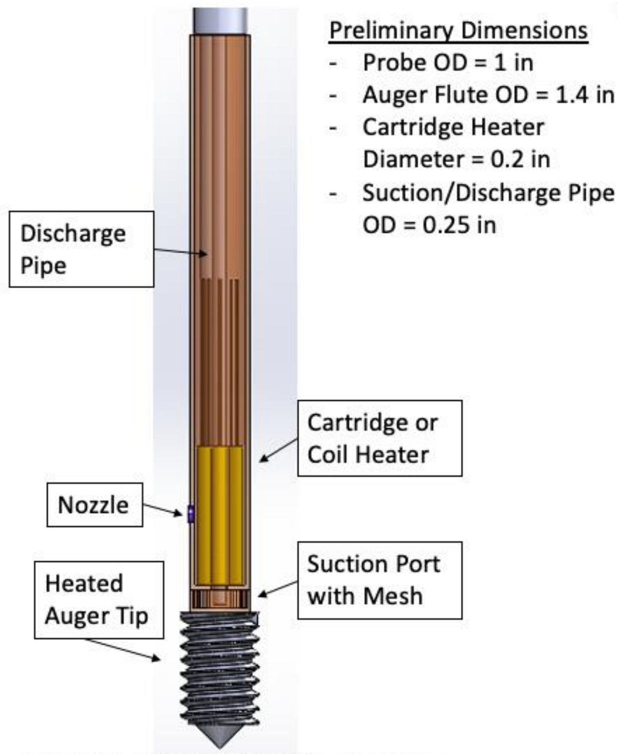


Figure 3. CAD Model of Heater Probe

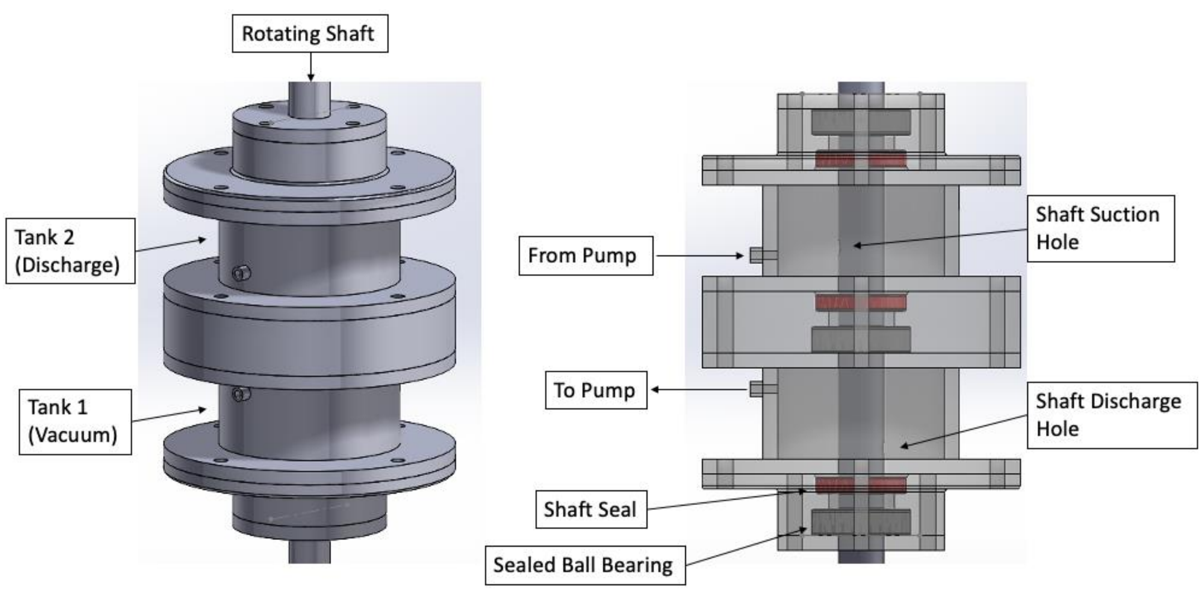


Figure 4. Closeup CAD of preliminary mount assembly.

Figure 5 depicts the heater probe assembly attachment to the carriage. A C-shaped extruded mount will be bolted to a 6.75"x10" aluminum plate that will translate vertically along the carriage rails via leadscrew, and the sealed tank flanges will be bolted to the extruded mount. A 2.86 lb. Ryobi D43K corded hand drill will be mounted above the tanks to the plate in the same fashion as the rotary hammer.

The heater probe assembly will be detailed to fit the 3/8" chuck of the auxiliary drill, and the hand drill will provide the rotary motion required for the heater probe to auger into the loosened overburden.

The Ryobi D43K hand drill was selected because it is extremely lightweight while retaining a powerful 5.5 A motor [2]. This design will allow for the tanks to remain stationary against the extruded mount and the heater probe will be free to spin concentrically on the sealed bearings. Finally, to minimize runout of the heater probe, an alignment collar will be rigidly attached to the carriage to constrain the tool as it is plunged into the overburden.

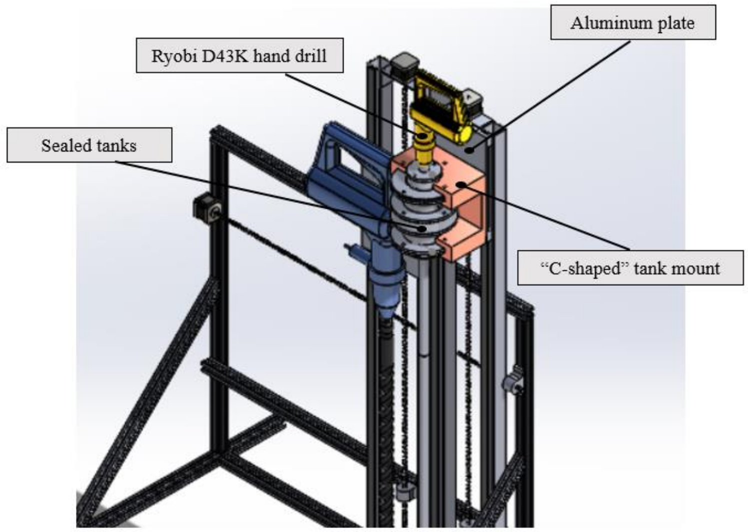


Figure 5. Heater probe assembly mounted to carriage.

D. Pumping and Filtration

The method of pumping and filtering the water is another design choice that this year's team chose to retain from the previous team's design. The STYX prototype utilized a self-cleanable, two-stage filtration system composed of a 600mL/min maximum peristaltic pump, sediment trap, 40-micron pre-filter, and a 5-micron sintered bronze filter (Appendix H). When this system was tested during the 2020 Mid-Point Review, it was highly successful at filtering out sand, dirt, and concrete powder caused by drilling, and the water came out clear [3]. Refer to the preliminary filter testing, documented in Appendix I. While last year's team included a sheath/auger setup that contributed to the delivery of clean water, this year's team plans to conduct robust endurance testing on the peristaltic pump to determine how effective it would be at backflushing the sintered bronze filter should that need to be done. The primary modification that will be made from last year's system is the integration of the two-tank system described in Section C above.

E. Frame and Lid Interface

To secure the proposed system to the provided 2x4's and test bed lid, the frame shown in Figure 1 will use ½" lag bolts at each corner. A damping material spanning the width of the frame will be included between the frame and the 2x4's to reduce vibrational loads. 1.5" square aluminum extrusions, both perforated and non-perforated, were selected for their variety of interfacing methods, modularity, and strength in non-terrestrially cold conditions. To maximize machine travel, the overall frame dimensions will be roughly .9m x 1m x 1.8m, which meets the packaging limits. The exact dimensions may be found in Appendix J. During on-site testing, the frame would be rotated 180 degrees in between uses to maximize the area available for water extraction and digital core development. With the frame and components discussed above, the team plans to design the full integrated system to be under the 60kg mass limit.

III. ELECTRICAL DESIGN

The electrical control system that will be implemented in this system will be composed of a primary digital logic system with back up analog overrides available for all major sub-systems such as the telemetry, drilling, and extraction systems. These will aid the team in the case of potential failure and provide an opportunity to easily test the subsystems. The system will be controlled by a primary microcontroller, Texas Instruments Model MSP432, which will use input from various sensors and components throughout the system to determine how it will activate other components. The microcontroller will activate and deactivate both AC and DC dependent components through solid state relays. The system's leadscrew motors will be operated with pulse-width modulated signals from the main microcontroller. The wiring will be properly connected to the system and all electrical components will be shielded so that there is no chance of shorting the system. Additionally, a 9 A fuse will be included on the primary power line to protect against damage to circuitry or components in the case of overloaded current.

A. AC/DC Components

The provided power source is 120 VAC, therefore, most of the chosen components run on 120 VAC; this design choice was made to curb any losses in converting the voltage. The rotary hammer is rated for 120 VAC at nominal 8.5 A, the heaters run on 120 VAC at nominal 2.5 A, and the auxiliary drill uses 120 VAC at 5.5 A. The DC components of the circuit will have varying power sources. The controls system will receive power from the alternate power source provided. The pump and stepper motors are not allowed to run on the alternate power supply provided, so they will receive power through full bridge rectifiers from the main power source provided to ensure that they receive DC voltage. Currently the team's chosen pump runs on 12 VDC with nominal 1.5 A.

B. Power Management

The main power supply will first pass through a current limiting circuit to ensure safe handling, placed before the 9 A fuse. It will then be diverted to the microcontroller and operational tool separately. Like most 32-bit MCUs, the TI MSP432 runs at 5 V with additional support for low-power operations and includes an onboard debug probe for energy measurements. Power will also be fed into a motor driver shield responsible for actuating the leadscrews. All additional power can be used by the pump system, heaters, and rotary hammer, which the team plans on never operating simultaneously. Using the simulated circuit in Appendix K, the heater probe operation draws a nominal 6.5 A without the auxiliary drill.

IV. CONTROL SYSTEMS

The system is intended to be fully automated. This will mean sending signals to systems that will actuate and heat up, as well as receiving signals from pressure transducers, optical encoders and thermistors to ensure that the state of those systems is as expected. Namely, if the pump becomes clogged, tools become misaligned, tools freeze in the ice, or automatic control stops functioning, if a contingency procedure fails to solve the problem, manual control can be wrested. Feedback loops operating with PID control will be important to the implementation of the system and will be accessible through a user interface to determine if it is running correctly. This will allow the team to inspect for errors between the expected and actual performance parameters and correct as needed. Manual controls will be implemented in each system as a fail-safe if the system stops working correctly on its own.

A. Programming

The TI MSP432 microcontroller comes with a proprietary Integrated Development Environment (IDE), Code Composted Studio, which has a C compiler. C is the programming language of choice due to its widespread use in industrial robotics, and its analogies to assembly language - something all team members have experience working with. Libraries for motor control, sensor interfacing, and task management will be developed. The design strategy will be to manifest in finite-state-machine operation of said tasks to be reactive to acquired data while also running cooperatively. These tasks will include instructions for vertical actuation of the drill and heater assembly, horizontal actuation of the tool axis for hole relocating, power-flow logic, and data acquisition.

B. Telemetry

The telemetry system will monitor the weight on bit (WOB) of the rotary hammer drill in real-time and the resulting data will determine the digital core. Knowing that an increase in WOB correlates to a harder material will aid in identifying the overburden layers from softest to hardest. Additional sensors will be used to ensure that the other functions perform as necessary, such as power consumption. Data logging through a serial port will also record current consumption to ensure the 9 A fuse is not blown.

V. TIMELINE

Table 2 highlights critical design, manufacturing, and test/integration milestones. A detailed Gantt chart is available in Appendix L. The team's schedule was designed to leave approximately four weeks of margin between completion of full system testing and the competition's full integration deadline of May 18th, 2021. This margin will be available in case manufacturing or testing activities encounter issues.

Table 2. Project Milestones

Milestone	Date	Milestone	Date
Detail Design and Analysis Complete	12/20/20	Subsystem Testing Complete	3/16/21
Purchasing Complete	1/10/21	Full System Integration Complete	4/4/21
Subsystem Manufacturing Complete	2/21/21	Full System Testing Complete	4/20/21

VI. PATH TO FLIGHT

The team recognizes that the competition represents an idealized simulation of Martian and lunar environments. While many aspects of this design would operate effectively in an extraterrestrial environment, such as the low power requirements and autonomous operation, there are some other components that would not function as well. The following discussion aim to address these components and offer solutions to problems that arise from extraterrestrial operation.

A. Extracting Water on Mars

To extract water from Mars, the extraction system must be capable of withstanding extreme conditions. Mars has a thin atmosphere so the system will be exposed to high levels of radiation. Electrical components must be radiation-hardened to be protected from the radiation. Additional sensors may be implemented to ensure that autonomy runs smoothly. For example, an inertial measurement unit may be integrated to tram the drill before drilling takes place. In addition, ground penetrating radar like RIMFAX used on the Perseverance rover may be used to determine the possible overburden composition [4]. A long-term solution will also require a filtration system capable of regeneration.

Mars' low atmospheric pressure causes an assortment of additional issues. First, the low pressure and cold temperatures would cause water to sublimate rather than melt when introduced to heat. This project could use an air compressor and small housing near the base of the hole to pressurize the entire hole and well. Pressure required would not have to be as high as Earth's, but instead it would have to be high enough to force the ice to melt rather than sublimate. This would allow most functions to continue as expected on Earth. A second issue that could present a problem would be the large pressure difference between the Martian atmosphere and the positive pressure created in the upper tank of the heating probe. Such a pressure difference would increase forces on the seals and decrease life, but the team is confident that the seals can handle large pressure differences without failure. Furthermore, the team must conduct tests on the current pumping equipment to determine if it could be capable of drawing the water up to the bottom tank given the lower atmospheric pressure on Mars.

With the extremely cold temperatures (-284°F to 86°F) of the Martian environment, new problems arise with the removal of overburden [5]. It has been found that ice-laden soil and sediment act like beach sand when broken up and exposed to extraordinarily cold temperatures like those on Mars [6]. The current auger 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 stronger drill would be needed to create the torque necessary to clear out the hole.

B. Prospecting on the Moon

Like the Martian environment, prospecting on the Moon will require consideration of the extreme range of temperatures possible (-280°F to 260°F) [7]. These large variations in temperature would cause issues with differential thermal expansion and alteration of material properties. 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 leadscrews would become brittle or melt in response to the extreme temperatures. Additionally, temperature fluctuations cause changes in material properties and would require recalibration of certain telemetry components such as load cells.

Electrostatically discharged moon dust poses an issue to onboard components. For example, it may cause overheating to electrical components if they become covered with dust [8]. The modified system can include a thermal imager to monitor excess heating of components. 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 [9]. Finally, the team will use components that will be compatible with an auxiliary power unit (APU) like that found on board a rover.

Additionally, the low pressure (near vacuum) of the moon means the effects of convection cooling are greatly reduced, possibly leading to problems with overheating electronics. Also, drill cuttings can trap 75-80% of heat generated during the drilling process, which would add further to the overheating problem [10]. To account for this, the design would likely require some alternative form of cooling for the motors and drills to prevent overheating during extended periods of operation.

C. Testbed Enhancements

Potential modifications to the team's individual testbed to create a more accurate analog for testing include vibration isolation, improved cooling and insulation, and solar radiation protection. For vibration isolation, the entire testbed could be placed in a hole in the ground that is lined with rubber or a soft plastic (similarly to high tolerance, heavy machinery). Given that the ground on the moon or Mars is not shifting or vibrating, the testbed ideally should not be either. For improved cooling and insulation to maintain the overburden layers at colder temperatures, cooling lines may be run around the sides of the testbed while a thin, insulating material covers the top of the overburden. This material would have to be soft enough to be easily drilled through and would not be included in the digital core. Solar radiation also becomes a concern given the lack of an atmosphere on the Moon and an atmosphere comprised of mostly carbon dioxide on Mars. To avoid potential damage, electrical control components could be housed in a Faraday cage that electromagnetic fields cannot penetrate.

VII. A Special Note from the Team

The team would like to thank NASA for giving us the opportunity to potentially participate in the RASC-AL competition. With the guidance of our enthusiastic faculty advisor, our team has created a unique design that we hope you find innovative and well-founded. We will use on-campus resources such as Cal Poly's Mustang 60 machine shop and labs that will give us access to mills, lathes, welding, 3D-printing, and CNC machines. We are proud of what we have accomplished and cannot wait to finalize, manufacture, test and demonstrate our design.

References

[1] Boone, Chris, et al. 2019, pp. 1–34, *2020 Moon to Mars Ice and Prospecting Challenge, Project Plan*.
[2] "Variable Speed Drill"| *Ryobi Power Tools*, https://www.ryobitools.com/power-tools/products/details/variable-speed-drill
[3] Boone, Chris, et al. pp. 1–18, *2020 Moon to Mars Ice and Prospecting Challenge, Technical Report*.
[4] "Radar Imager for Mars' Subsurface Exploration (RIMFAX)." *NASA*, NASA, mars.nasa.gov/mars2020/spacecraft/instruments/rimfax/.
[5] "Mars Facts." *NASA*, NASA, 13 Feb. 2020, mars.nasa.gov/all-about-mars/facts/.
[6] Zacny, Kris. (2018). *Drilling: How Do We Access the Subsurface on Mars?* [Recording].
[7] "In Depth." *NASA*, NASA, 3 Nov. 2020, solarsystem.nasa.gov/moons/earths-moon/in-depth/.
[8] "Apollo 17 Mission." *Apollo 17 Experiments - Soil Mechanics Investigation*, www.lpi.usra.edu/lunar/missions/apollo/apollo_17/experiments/smi/.
[9] "Patent Details." *NASA*, NASA, technology.nasa.gov/patent/KSC-TOPS-11.
[10] Kris, Zacny. 3rd ed., vol. 8, Mary Ann Liebert, Inc, 2008, *Drilling Systems for Extraterrestrial Subsurface Exploration*.

Appendices

[A] Background Research
[B] Stepper Motor Specifications Sheet
[C] STYX Preliminary Drill Testing
[D] Preliminary Auger Testing
[E] Heater Probe Concept Prototype
[F] Preliminary Analysis of Tank Vacuum Pressure
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