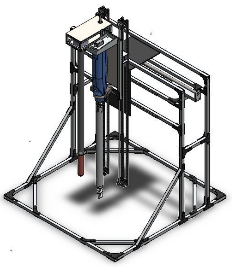
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
TWO-PROBE AUTOMATED REGOLITH UPHEAVAL SYSTEM



Advisor: Dr. Kevin Shinpaugh

Seniors: Michel Bopp[1], David Fehrle[1], Mark Norton[1], Anaya Acharya[2], Shlok Agarwal[2], Sam Bethge[3], Julian Cohen[5], Rohan Desai[2], Tony DiGregorio[1], Justin Hartman[4], Natalie Kakish[3], Aman Kothari[3], Jack Michaud[2],Varun Modak[2], Yash Patil[5], Tanushree Shinde[1], Jackson Underwood[2], Tom Varner[4], Dakota Yannibelli[5]

1. Aerospace Engineering, 2. Electrical and Computer Engineering, 3. Computer Science,
4. Mining Engineering, 5. Mechanical Engineering

Executive Summary

TAURUS is designed to extract ice from a simulated Martian environment using a mounted drill and probe system to tunnel deep into the ice layer. Extraction begins with the drill bit penetrating the primary overburden layer. Regolith is broken down and removed through the sleeve to the surface. Drilling continues until the ice layer is successfully penetrated. The drill bit is then manually detached from the sleeve and removed from the overburden layer, while the sleeve is left down hole to aid stability. The probe is then inserted down the sleeve to melt through the ice layer. Heat is then transferred using a conductive tip and convective recirculation cycle.

After a threshold of water has been extracted, it is diverted to a collection point with the help of an alternate solenoid path. Siphoned water will pass through a ceramic filtration system consisting of candle filters and fine sieve mesh. A junction of the pores and carbon core removes large particles such as organic matter and harmful contaminants and toxins.

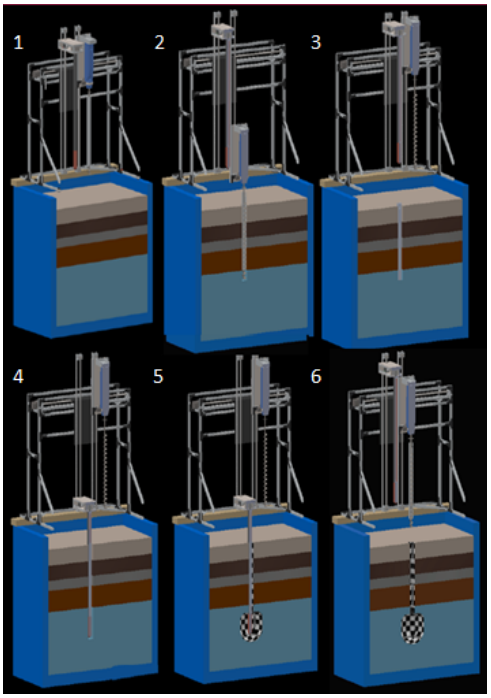


Figure 1: Concept of Operations

The electrical and software systems used to maneuver TAURUS will be implemented using three Raspberry Pis with HTTP servers that will allow for communication between these microcontrollers while they lead the tasks of drilling, heating, extraction, and filtration. HTTP requests allow for messages to be sent between Pis and the graphical user interface (GUI). Stepper motors connected to motor drivers will be utilized to achieve two-dimensional motion. Data is logged every second and sent back to a client GUI. The communication system is key as it provides data consistency and ensures direct communication between the motors and microcontrollers.

A digital core would be determined from the data that would be collected throughout a successful system operation. Mechanical specific energy, which is a way to measure the hardness of a material, would be calculated for the periods when the drilling takes place. Python scripts will be able to effectively determine the boundaries between different layers.

Table of Contents

1. System Description

TAURUS is a Rodwell-based drilling system using two separate probes: one for drilling through the overburden layers and the other for heating and extraction of water drilling through the overburden layers. The drilling probe first digs into the surface, and then the other probe melts the ice into water to then extract and recirculate hot water to dissipate heat to a larger area of ice to collect a greater amount of water.

1.1 Mounting System

Attached to the frame is a horizontal traverse system, which holds the drill and probe platform. Thus the frame is supported and free to move on ball-bearing carriages and guide rails with a total length of 600 mm and width of 12 mm. A hollow linear positioning motor is used to move the platform on a lead screw with a length of 960 mm and a diameter of 9.53 mm. The horizontal traverse system, Figure 2, consists of a stationary motor and rotating lead screw which drives the sub-platform.

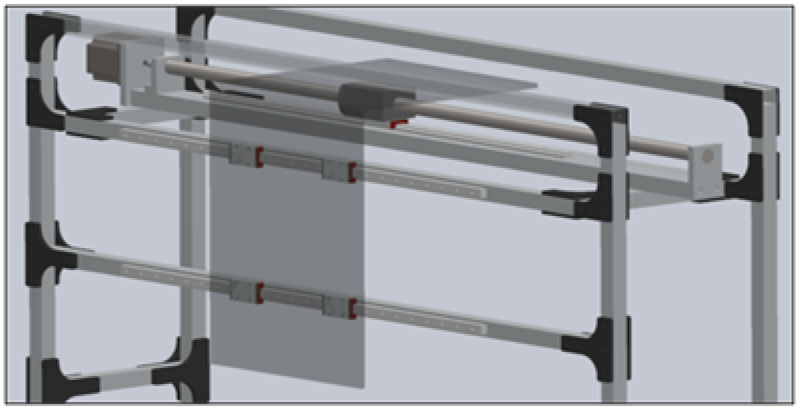


Figure 2: TAURUS Horizontal Traverse

Visual representation of the horizontal traverse components mounted onto the Chassis. Note, the transparent shape in the center of the figure is the sub-platform on TAURUS that holds the drill and probe.

The TAURUS sub-platform contains both drill and probe and operates on the horizontal traverse system. With two separate vertical traverse systems, independent operation of the drill and the probe is possible. The two vertical traverse systems, shown in Figure 3a, feature a stationary lead screw and free-moving motors. Attached to each motor are unique mounting systems, dedicated to the probe and the drill. The drill mount, shown in Figure 4, is made of a solid metal backing plate, supported by an "H" frame of 20 mm square aluminum tubing to provide lightweight structural rigidity. The base of the drill is clamped to the horizontal beam of the drill mount and is held vertical by a top horizontal plate. The metal backing plate is connected to a NEMA 23 stepper motor through a triaxial load cell, used to accurately measure all forces acting on the drill.

The probe mount has a modified construction, consisting of a 10 mm square aluminum tube frame that encloses the probe system. On one side of the frame's rectangular footprint is a NEMA 23 stepper motor that drives the probe traverse. On the other half of the frame's base, a servo motor is mounted to drive the rotation of the probe itself. Attached to the top and bottom of the probe mount frame are thin aluminum plates to improve rigidity. Between the top plate and the probe motor is a load cell used to measure any forces acting on the probe.

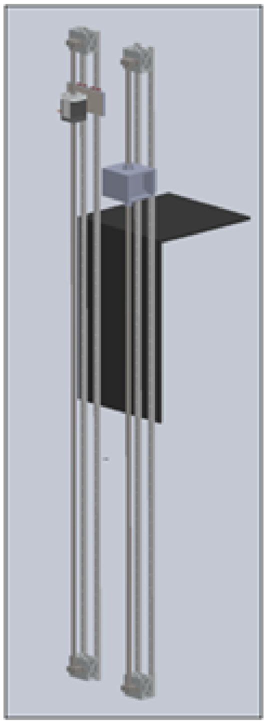


Figure 3a: TAURUS Vertical Traverses. Visual representation of the vertical traverse components mounted onto the sub-platform. The sub-platform is then mounted onto the horizontal traverse system.
Figure 3b: TAURUS Drill Mount. Bosch SDS Plus drill mounted onto the vertical traverse. The vertical traverse is connected to the horizontal traverse. The drill, drill mount, and both traverse systems are operational.

1.2 System Excavation Operations and Solution to Mine Through Overburden Layers

To access reserve ice beneath the surface overburden layers, TAURUS utilizes a DIABLO, 1.5 by 36-inch, Carbide-Tipped Rebar Demon SDS-Max 4-Cutter Hammer Bit. This drill bit is designed with a four-pronged, male attachment in the center of the shank length. The purpose of the attachment is to allow the bit to be removed from the sleeve after the desired drill hole length has been achieved and the team is ready to move to the probe heating phase of extraction.

MSAT's choice of a masonry drill bit was due to its known ability to penetrate aerated concrete more effectively than other commercial bit options. In particular, the 1.5-inch diameter auger bit features four cutting flutes on the downhole face of the carbide-tipped bit. Utilizing four flutes allows this bit to dissipate heat more efficiently than a standard two-flute design, thereby reducing the risk of breakage during competitive use.

For the DIABLO auger bit to be compatible with the SDS Max drill, three alterations were required. These are depicted in Figure 4. All drill bit and sleeve alterations were outsourced to the AOE Machine Shop for fabrication. First, the full 18 mm shank length was removed along with an extra two inches to account for the inner auger attachment length. The decision to not increase the length of the auger was based on reducing overall mass, to stay within WOB requirements. With the shank removed, the fabricated inner auger connection was welded in its place and on center. Finally, a 10 mm SDS Plus shank was attached atop the inner auger connect, also on center.

Starting at the top, the 10 mm shank allows the bit to be used with an SDS Plus drill. In the middle of the shank is the inner auger connect, which allows the bit to attach to the sleeve, and subsequently be removed from the test environment when the team is ready to proceed to the next phase of extraction. Below this connection point is the workload of the auger, which culminates in a four fluted carbide hammer tip.

The drill extraction system consists of two members: the auger and the outer casing sleeve. The sleeve's function is to reinforce drill hole stability while first assisting in the removal of overburden by the auger bit, and later to assist in the probe heating of reserve ice layers. To attach to the drill extraction system, the sleeve is fabricated with four L-shaped inserts, which allow for the inner auger to connect to the slide and lock in place. This process is shown in Figure 5. Once the desired drill hole length has been achieved, the team will disconnect the auger bit, effectively leaving the sleeve in the test environment.

The mechanical connection between the auger and the casing sleeve. The sleeve was updated from Aluminum 6101-T61 to ASTM-A513 (Type-5) mechanical grade metal to achieve minimal wall thickness. Shown: a) connected for drilling and b) separating as the auger traverses upwards. The connection occurs mechanically and is locked when the auger and sleeve are rotated clockwise and unlocked when the auger is rotated counterclockwise and then vertically traversed.

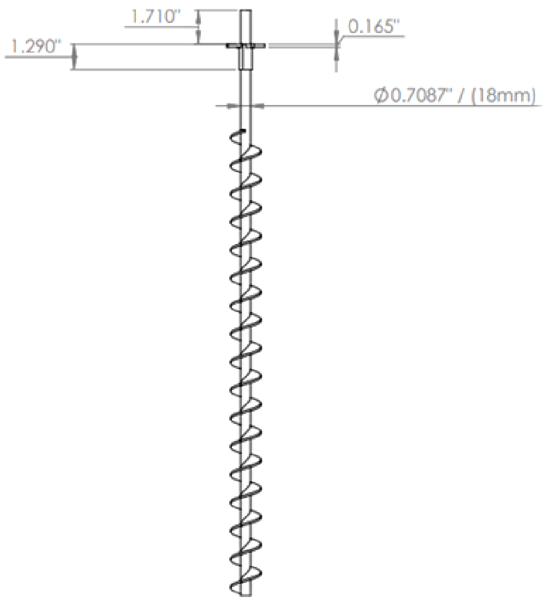


Figure 4: Auger drill bit with alterations.

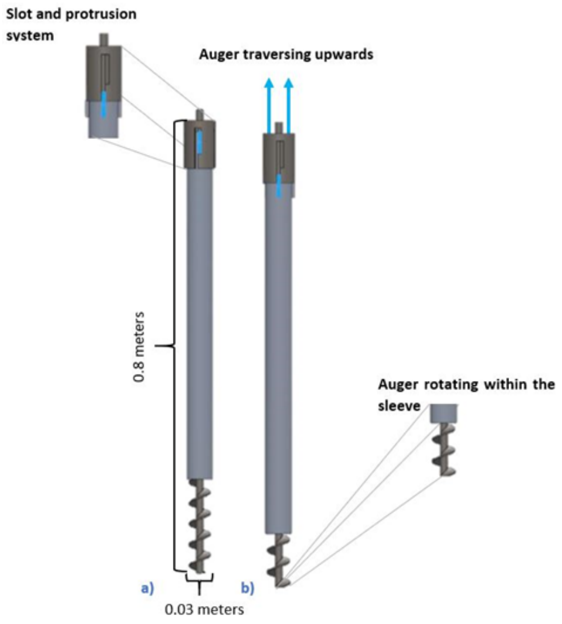


Figure 5: Auger sleeve connection.

1.3 Water Extraction System

The TAURUS recirculation system consists of the components that serve to melt and extract water from the ice layer in the testbed. The major components of the design include the probe and probe tip, the pump, the heating cartridges, the pre-heat container, and the sediment filter. A flow diagram of the recirculation system is shown in Figure 6.

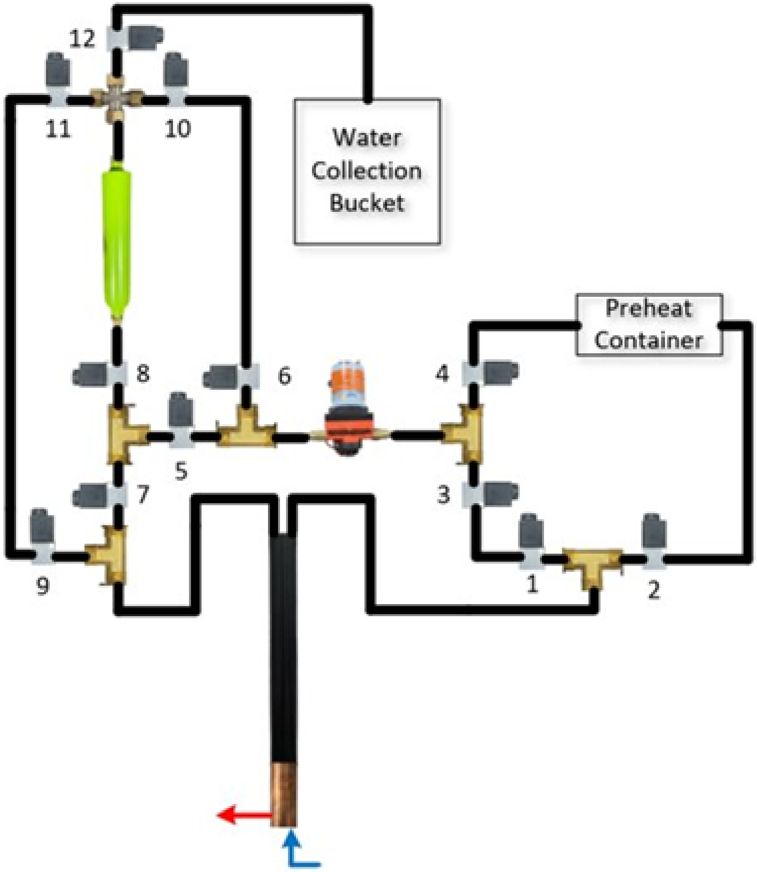


Figure 6: TAURUS Full Recirculation System.

Figure 6 shows the pump completing the recirculation loop necessary to create a Rodwell. This is achieved by utilizing a series of solenoids and relays to control the circulation of water. In discussing the functionality of the recirculation system, the system is designed such that it can melt the ice layer through the formation of a Rodwell, using both conductive and convective heating techniques. The recirculation system begins as the probe is positioned over the sleeve that has been set into the overburden and penetrates the ice layer. Water carried aboard TAURUS at the beginning of the operation is preheated using a cartridge heater in a small water tank for the recirculation process where heated water will be able to convectively melt the ice as it is driven back into the Rodwell. The pump will pull water from the Rodwell, through the inlet of the probe tip, into the preheat container, and back in the Rodwell. Additionally, thermal epoxy is used in some locations of the system to secure tubing. Once the desired amount of water is collected, water is directed through the filter and into the collection bin.

As depicted in Table 1, the recirculation system has been modified to incorporate a series of 12 relays and solenoids to form multiple paths for water to flow through. This allows the recirculation system to operate in desired modes. This table describes the 4 operating modes that consist of opening specific solenoids that allow water to be pumped through selective paths that complete the purpose of their respective operating modes.

Table 1: Operating modes of the TAURUS recirculation system

Item	Preheated Water Circulation Phase	Recirculation Phase	Refilling and Collection Phase	Filter Cleaning Phase
1		OPEN	OPEN	OPEN
2	OPEN			
3		OPEN	OPEN	OPEN
4	OPEN			
5	OPEN	OPEN		OPEN
6			OPEN	
7	OPEN		OPEN	
8		OPEN	OPEN	OPEN
9				OPEN
10			OPEN	
11				OPEN
12		OPEN		

The probe, shown in Figure 7, is made from a thin-walled carbon fiber tube 0.65 m long and with an outer diameter of 0.032 m. There is a copper cylinder tip with an additional length of 0.15 m. The probe tip has a hole drilled through the center for housing a 500 W heating cartridge. The probe design was constrained by the choice of a heating cartridge that would maximize the amount of water TAURUS could extract, while additionally remaining within the WOB limitations.

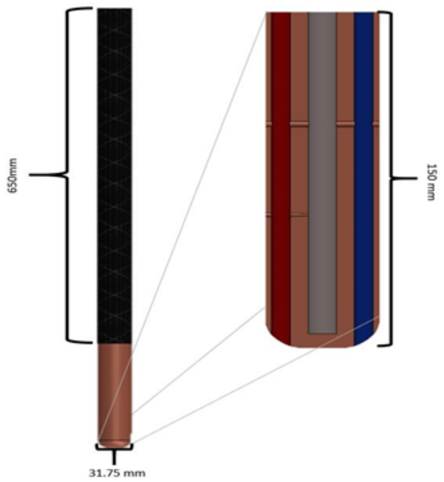


Figure 7: TAURUS Probe Tip. Drawing indicating water flow through the tip of the probe. The red component indicates the channel for hot water to travel down, and the blue component indicates cooler water to travel up. The grey component indicates the housing for the cartridge heater responsible for raising the temperature of the water.

TAURUS utilizes a SEAFLO 42 Series Variable Flow pump. This variable flow pump has a max flow rate of 3.00 GPM and a mass of 2.50 kg. The input and output ports on the pump have a 1.27 cm diameter, which is adapted to fit 0.635 cm Tygon tubing that attaches the pump to the sleeve and the filtration system.

The heating cartridge used in the preheat container and probe are both rated for 12.5 V however the preheat container heater has power rating of 300 W and the probe heater has a power rating of 500 W. Both heating cartridges have an embedded temperature sensor that shows live temperature readings on the GUI.

1.4 Filtration and Water Collection

To clean the water, TAURUS uses a carbon block filtration system made by CLEAR2O®. The filter casing contains a single solid carbon block that filters sediment as small as 1 micron. Its performance will be able to filter out nearly all sediment that may enter the water in the recirculation system during the extraction process. A recent modification of the recirculation allows for the filter to be cleaned using a backflow process. This mode of the recirculation system was previously mentioned in Table 5.

1.5 Managing Temperature Changes

The TAURUS sleeve houses two cartridge heaters, which are the primary heating source on the drill. The drillbit used in the design of TAURUS preheats before reaching the ice as it drills through the overburden layers. A pool of water will be created in the cold layer, which will be reheated and recirculated. The recirculation of the water will both regulate the temperature of the system and help in melting more ice, thereby reducing power consumption.

1.6 Control and Communication Systems

The electrical and software systems used to control TAURUS will be implemented using three different Raspberry Pi 4 Model B's. The three Raspberry Pi 4's send data back and forth to the client. On the receiving end, a Graphical User Interface (GUI) is set up to allow engineers to control the system components remotely. The GUI features different pages to control the different subsystems such as horizontal traverse, digital core, vertical traverse, water recirculation, and filtration & heating systems. For quick access, there is an emergency stop button that puts a stop to all the tasks being conducted by all the systems by cutting their power supply.

To move the drill over the drilling area, the team plans to use two traverse systems controlled by NEMA 23. There will be two vertical traverses, one for the drill and the other for the probe, along with a horizontal traverse to move the drill and the probe simultaneously on the horizontal axis. To control the power going to the heaters, for-loop statements are written to check if the temperature of the heaters exceeds a certain threshold. If the current exceeds a given value, all the systems and operations are immediately terminated using an interrupt routine. After the problem is fixed, the system will restart all the operations from the point that they were terminated.

The team plans on utilizing load cells to monitor the weight-on-bit. Torque will be calculated using the power drawn by the drill and its rotations per minute (RPM). The rate of penetration (ROP) will be measured by the vertical axis traverse system. The RPM sensors on the drill read the RPM of the drill in short intervals of time and send it back to the Raspberry Pis. The vertical axis motor will send the readings for the ROP to the microcontroller. Data from each sensor is stored in an SQLite relational database on the same computer as the GUI. After drilling has concluded, this data will be analyzed using Python data analysis libraries, including Pandas, Matplotlib, and Scikit Learn.

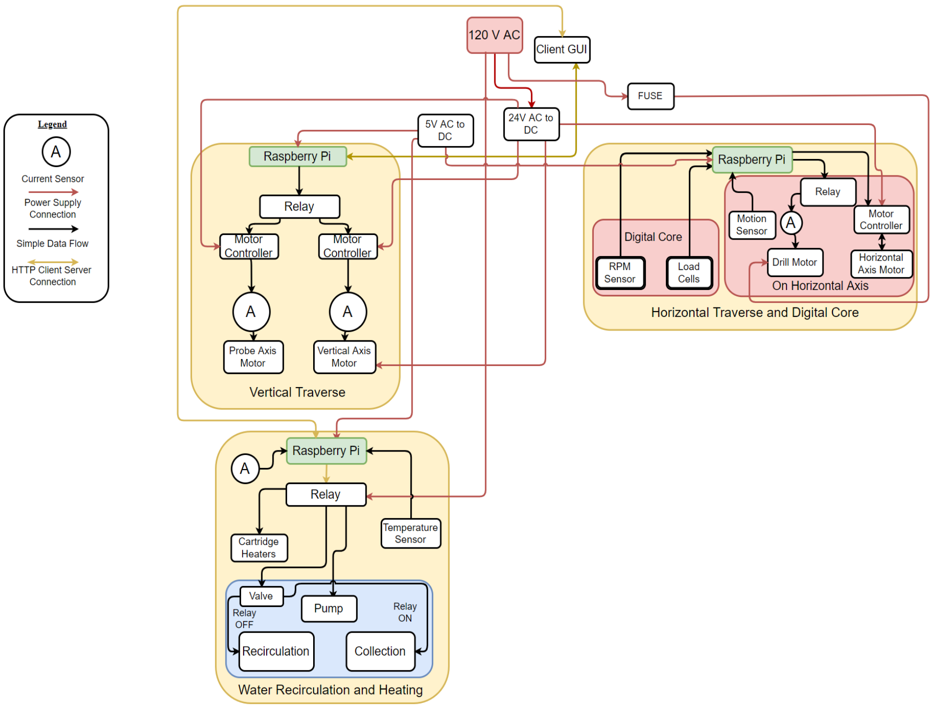


Figure 8: TAURUS Control System Diagram

1.6.1 Traverse and Drilling System

The traverse system connects together the functionality of the drill and probe. The drilling system provides smooth horizontal and vertical movements that allow for the drill to autonomously move over the site. Both traverse axes are controlled using the GUI. The traverse and the drilling systems are primarily semi autonomous systems; it has features to stop in case of emergency, to cover a specified distance, and to change speeds. By analyzing readings from the motion sensors, load cells, and RPM sensors, the system can conduct motion and drilling tasks semi-autonomously. The accuracy and precision of movement is decided by the stepper motors. The user can also switch to manual control using the GUI. When the system is in manual override mode, the user is in complete control of the stepper motors that control both traverse axes. The axes no longer move by a specific distance, and the user has to manually stop and start the motion of the drill. Unlike in semi-autonomous mode, the drill would not trigger an emergency stop or try to regulate the system if certain thresholds are exceeded. Instead, the user would have complete control.

In semi-autonomous mode, the traverse axes can move by the user specified distances. If the system encounters any problem while moving, motion will stop by commanding it to terminate. The laser measures the distance from the sensor to the handle, allowing for a precise location of the drill to be calculated.

1.7 Data Logger

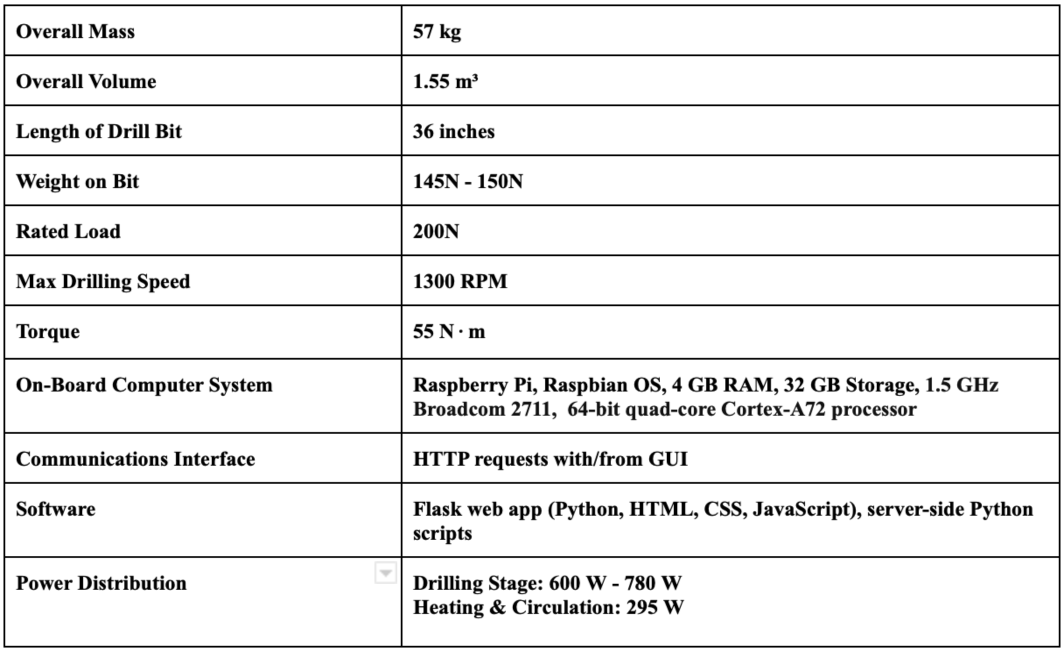
The data from each sensor will be stored into a MySQL database. This data will be stored in multiple tables and include values for probe temperature, surface hardness, torque, drill pressure, time, etc. Flask will be used to implement the GUI and will implement multithreading using Celery and RabbitMQ in order to run multiple processes at the same time, such as running the motor and calculating sensor data simultaneously. After sensor data is received by the main Flask application, it will be pushed to the database. The main library the team will use for database work is SQLAlchemy. Rough estimates of layer hardness will be calculated during drilling but finalized graphs will be calculated from datasets after drilling has completed.

1.7.1 User Interface and Communications

The GUI is set up on the Flask Python framework that allows users to see and control it as a local web page on any browser. This GUI features different pages to control the different subsystems such as horizontal traverse, digital core, vertical traverse, water recirculation, and filtration and heating. For quick access, on each page, there is an emergency stop button that halts all actions from all subsystems. Communication to subsystems is done through HTTP requests on the local network where the Raspberry Pis are also connected. Each Raspberry Pi will be responsible for multiple tasks at once.

1.8 Technical Specifications

Table 2: Technical specifications for TAURUS



Overall Mass	**57 kg**
Overall Volume	**$1.55\ m^3$**
Length of Drill Bit	**36 inches**
Weight on Bit	**145N - 150N**
Rated Load	**200N**
Max Drilling Speed	**1300 RPM**
Torque	**55 N · m**
On-Board Computer System	**Raspberry Pi, Raspbian OS, 4 GB RAM, 32 GB Storage, 1.5 GHz Broadcom 2711, 64-bit quad-core Cortex-A72 processor**
Communications Interface	**HTTP requests with/from GUI**
Software	**Flask web app (Python, HTML, CSS, JavaScript), server-side Python scripts**
Power Distribution	**Drilling Stage: 600 W - 780 W Heating & Circulation: 295 W**

2. Design Changes and Improvements

The latest software development cycles allowed us to update the GUI with small changes to simplify the usability. The web endpoints for the Raspberry Pis are now flexible enough to be deployed online on such a system like AWS. Amazon Web services will be a future research opportunity now for our system to be hosted on. The probe connection went through several iterations since the midpoint review. The use of a double U-joint connection allows the alignment between the sleeve and the probe to be slightly off concentricity. A new connection between the probe and the probe motor had to be fabricated to accommodate the double U-joint.

3. Challenges

Structurally, the biggest issue was performing a complete chassis rebuild. This was necessary because the original chassis was damaged during transportation. In terms of embedded systems, there were certain sensors and relays that ended up being defective causing delays in system testing and integration. Further research was needed to find replacement sensors that could perform optimally. Looking at data, software frameworks were incompatible with the windows platform. The team had to switch entirely to linux to rectify this issue.

Beyond technical challenges, our team had to adapt to the challenge of working together during the ongoing COVID-19 pandemic. Limited access to lab spaces and multiple team members working remotely added to the time delays. This led to struggles with communication and collaboration, as our meetings continued to take place through video conferencing. So, the team members had to balance their commitments to the project, their respective summer internships and work.

4. Overall Strategy Planned for Competition

During the competition, the system will record information from various sensors to develop an accurate digital core. This information includes depth traveled, weight-on-bit, RPM, and all other drill information. Mechanical Specific Energy (MSE) is defined as the energy required to remove a unit volume of rock [19]. MSE is expressed in units of energy input divided by volume removed and can be expressed mathematically in terms of weight-on-bit, torque, ROP, RPM, and the cross-sectional area of drilling. Each of these values can be calculated and collected through various control systems used in the design. Mechanical Specific Energy will be calculated from the following formula:

$$MSE = \frac{WOB}{A} + \frac{2\pi \cdot RPM \cdot T}{A \cdot ROP}, T = 9,548 \cdot \frac{Power}{Speed}$$

where: WOB -- weight on bit [N], A -- area of bit $[M^2]$, RPM -- rotations per minute,
ROP -- rate of penetration [M/s]

By recording the depth traveled every 3 seconds, we will be able to go back and calculate mechanical specific energy for every depth. MSE can be used as a unit of measuring the hardness of a surface; the harder the surface, the more energy would be needed. The result of this equation will be converted into pascals (Pa). With k-means clustering we will cluster the hardness values vs depth traveled to determine the depth of each layer and the average hardness of each level. These scripts for hardness and clustering will be tested during preliminary tests with a unique layering of materials of known hardness level.

5. Tactical Plan for Contingencies/Redundancies

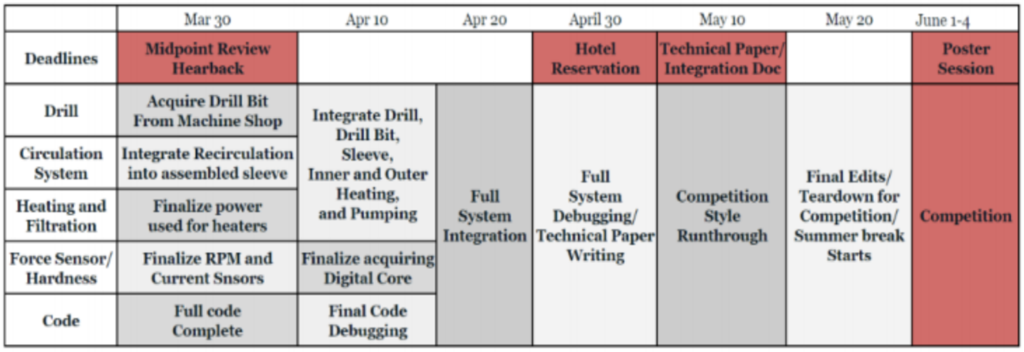
Data/Operational Contingencies: For malfunctioning current sensors, we propose a 9 AC/DC Relay to cut off over-current which automatically resets itself on correction. For malfunctioning temperature sensors, the given depth of ice in the simulated system will be used to predict when the ice is reached. In case the data from either the load cells or torque is skewed, results for the digital core are logged based on the other source. In case some of the systems malfunction the user can take complete manual control to prevent any impending accidents.

Mechanical Contingencies: During operations at the competition, some parts or components might break. Therefore, spares of critical 3D printed parts will be used to replace the broken parts. The custom auger will experience copious down hole friction forces. The lack of control over true alignment where the four pronged connection meets the auger can lead to a wobble effect down hole and increased strain on the connecting components. A spare custom auger has been made with attention paid to previous shortcomings. A few pieces of chassis aluminum, fiberglass brackets, and several types of bolts, screws, washers, and nuts will be brought to the competition to replace as needed. As concerns recirculation, the event of water loss, spare tubing and fittings will be brought to fix leaks if they present themselves. A mesh has been installed on the bottom of the probe to minimize the size of particles that can enter the recirculation system. In the event debris does build in the system, each section of the recirculation system will be cut off one-by-one to determine the location of the blockage and where to focus water flow to help clear the system.

6. Project Timeline

Initial: The initial timeline was proposed to build and test the complete system before the previously scheduled competition date. The first three weeks were reserved to build and test individual components. The next two weeks involved the integration of the system and the last full month was reserved for exhaustive testing and identifying redundancies in various scenarios.

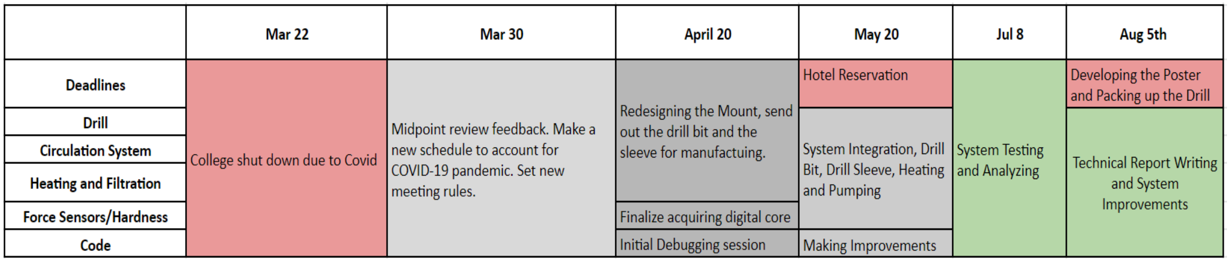
Table 3: Initial timeline for TAURUS



	Mar 30	Apr 10	Apr 20	April 30	May 10	May 20	June 1-4
Deadlines	**Midpoint Review Hearback**			**Hotel Reservation**	**Technical Paper/ Integration Doc**		**Poster Session**
Drill	**Acquire Drill Bit From Machine Shop**	**Integrate Drill, Drill Bit, Sleeve, Inner and Outer Heating, and Pumping**	**Full System Integration**	**Full System Debugging/ Technical Paper Writing**	**Competition Style Runthrough**	**Final Edits/ Teardown for Competition/ Summer break Starts**	**Competition**
Circulation System	**Integrate Recirculation into assembled sleeve**						
Heating and Filtration	**Finalize power used for heaters**						
Force Sensor/ Hardness	**Finalize RPM and Current Snsors**	**Finalize acquiring Digital Core**					
Code	**Full code Complete**	**Final Code Debugging**					

Reformed: The initial timeline was drastically reformed due to the unforeseen COVID-19 and resultant shut down of the campus. The reformed timeline accounts for time lost. It then reserves two months for design changes and system integration. Further, it reserves another month for system testing and analyzing alongside writing the technical report and further improvements.

Table 4: Revised timeline for TAURUS



	Mar 22	**Mar 30**	**April 20**	**May 20**	**Jul 8**	**Aug 5th**
Deadlines	College shut down due to Covid	Midpoint review feedback. Make a new schedule to account for COVID-19 pandemic. Set new meeting rules.	Redesigning the Mount, send out the drill bit and the sleeve for manufactuing.	Hotel Reservation	System Testing and Analyzing	Developing the Poster and Packing up the Drill
Drill				System Integration, Drill Bit, Drill Sleeve, Heating and Pumping		Technical Report Writing and System Improvements
Circulation System						
Heating and Filtration						
Force Sensors/Hardness			Finalize acquiring digital core			
Code			Initial Debugging session	Making Improvements		

7. Safety Plan

Many safety measures will need to be taken while operating TAURUS. Safety gloves and glasses will be worn anytime a team member works on electrical or mechanical systems on TAURUS. Ear protection will be added during drilling since this is the only time that loud noises are prevalent. No hazardous liquids besides lead-free solder and epoxy adhesives are expected. Load and current sensors are being used throughout the system to prevent overheating of electronics and overloading of the system. New safety precautions to combat the spread of COVID-19 involve wearing masks, routine sanitization, virtual meetings, and limited capacity within workspaces.

8. Path to Flight

8.1 Water Extraction on Mars

To extract and process water on Mars, a sufficient power system must be developed. The power supply can either be from a radioisotope thermoelectric generator, from solar panels, or from Kilopower Reactor Using Stirling Technology (KRUSTY). Due to the dust conditions on Mars, a panel cleaning system should be considered if solar panels are selected. Solar panels limit operations based on the cyclic nature of surface sunlight and impose other restrictions based on the geometry and weather conditions. A radioisotope thermoelectric generator on the other hand would have to be exceptionally large to completely meet the peak power demand of the system. The competition guideline states that teams will be provided with 120 V AC with a current limit of 9 Amps. This sets the maximum power available on Earth during operations to 1080 W. For perspective, a single Multi Mission Radioisotope Thermoelectric Generator (MMRTG), weighs 45 kg and can provide 100 W of power. This system would require multiple RTG's to operate at an acceptable rate. As a third option, KRUSTY could supply plenty of power to operate TAURUS and provide much higher watts/kg than any of the other methods. An MMRTG and polar panels will require additional mass in batteries for operation at peak power demands while the KRUSTY could solely rely on its constant power output level. In the near future, ISRU systems will become more functional around the same time as KRUSTY systems mature enough to be used as a reliable and main power source.

The Martian surface atmospheric conditions place exposed ice at significant risk of sublimation. The triple point of ice is situated right at the ambient conditions on the surface of Mars. Sublimation in an ice harvesting system would lead to some loss of water within the system. To mitigate this, the team brainstormed ways to isolate the ice from the atmosphere. The alteration required for such a quarantine is simply the addition of an inflatable balloon which is attached to the probe around a midpoint location. The balloon would be inflated and a seal formed between the probe and the sleeve. The balloon could serve two functions. First, the pressure inside the well could then be slightly increased to reduce the rate of sublimation of the ice. Also, the balloon would contain any water vapor from the sublimated ice produced and thus, once a water vapor partial pressure equilibrium is achieved, sublimation would cease. This simple adaptation would eliminate the minor loss due to sublimation on the small scale of the TAURUS platform, and reduce larger losses resulting from the implementation of this design on a larger scale. The gas which fills the balloon could be Martian surface atmosphere and the pressure to fill the balloon could be supplied by a small compressor.

Many lessons about drilling into the lunar surface were learned during the Apollo missions. Important to note, similar drilling experiences occurred at all Apollo landing sites, therefore, lessons learned can be extrapolated to almost any location on the lunar surface [1]. One exception may be permanently shadowed craters near the lunar poles where water and other volatile molecules, in the form of frost, may change the regolith surface characteristics. Lunar surface characteristics are attributed to millions of years of impacts by micro-meteors that have disturbed and tamped the lunar regolith. The result being a heterogeneous regolith that is composed of lithic fragments, mineral fragments, and impact breccias, glasses, and agglutinates. These remnants are mostly angular shards and rounded melt fragments. With the median grain diameter being between 45 and 100 mm, particles less than 20 mm in diameter could cause problems in joints, seals, and other mechanical implements [1]. The lunar regolith densities are vastly different from typical terrestrial soil densities. Unlike Earth soil, the lunar regolith is 'fluffy' for the top few centimeters of the surface layer and quickly increases in density to the point of incompressibility below a depth of 10-20 cm. This is attributed to the cumulative effects of shock compaction from the repeated surface impacts. Earth should have similar surface densities as the lunar surface, however, the atmosphere has protected the Earth from the bombardment.

Due to reduced gravity on the Moon relative to Earth (0.166 g), the rover may lose its grip on the lunar surface while the drill is operating. Therefore, the rover may need to use anchors to assist the force of gravity in counteracting the upward forces generated from drilling. Research into anchoring technology is ongoing, but it has been demonstrated that an omni-directional anchoring mechanism can effectively anchor a mobile rover using micro-spine toe technology [2]. Mars' gravity is approximately thirty-eight percent of Earth's gravity. As a result, the probe would weigh less, causing a reduced force exerted by the drill bit. To address this, the drill would either need to be designed to dig through the overburden with less force or more force would need to be applied to the drill bit.

Another issue is the temperature variation on Mars. The surface temperature on Mars varies between –100 °C to 20 °C with an average of -65 °C [3]. Only some metals and alloys can handle these temperatures so other materials may need to be considered. Additionally, a radiating system and a heating system would need to be implemented to handle these temperature changes, especially to prevent the drill itself from freezing. Similarly, insulation will be required for a Lunar application to prevent the onboard water from freezing during the harsh lunar temperature swings. Temperature swings are not as drastic on Earth, therefore, the risk of water freezing during the lunar night is much greater. The use of internal heaters to heat the water and pump to circulate the water will be required. As a result, drill operations will cease during the lunar night in order to conserve energy. Reserve battery packs will be charged during the day using a system of solar panels.

The design would have to be modified to handle the charged particle density on Mars and the Moon. Mars' thin atmosphere combined with a weak magnetic field make it weak in defense from radiation bombardment. The charged particle flux on the surface of Mars is similar to that of Earth's upper atmosphere [4]. The lack of an atmosphere on the moon makes a Lunar design even more susceptible. Any electronics device would be exposed to single event effects and thus radiation hardened boards should be implemented to ensure mission lifetime operability. Externally, radiation shielding would need to be incorporated for use on Mars as well to protect all components.

Mechanical Systems: The mechanical systems on TAURUS require a thorough analysis on the limitations of the forces and vibration frequencies they can withstand as the rig is launched, landed, and operated on the Moon or Mars. The load paths through which these forces will be transmitted from the launch vehicle to the TAURUS, or its rover carrier, must be determined for all phases of the mission. Special attention must also be paid to the materials used in space to predict the lifetime, integrity, and longevity of components.

Chassis: The aluminum tubing which makes up the chassis of TAURUS is capable of withstanding the harsh space environment. It was designed to carry the loads of drilling and the weight of the system during operation. The fiberglass connection joints and the bolts which attach them would need to undergo vibration analysis to determine if any damage would be done to them during the flight, and extended impact drilling operation. Also, the composite fiberglass brackets must be made with a space grade resin which is not overly sensitive to ultraviolet light, extreme cold temperatures. Any vibration damping or lubricating polymers must be resistant to outgassing.

Traverse and Mounting System: The traverses on TAURUS would need to be enclosed in order to prevent dust from jamming or eroding the precisely machined threads. Also, the traverse motors would need to be insulated from the extreme cold in order to prevent freezing of the innards. The mounting system, namely the large fiberglass composite plates which attach the two vertical traverses to the horizontal traverse must follow the same testing and scrutiny as those for the chassis. Regular use and extreme circumstance loading and vibration testing of the fiberglass must be conducted as this component directly affects the alignment of the drill and probe. The materials which make up the mounting system must not be prone to warping from exposure to the climates expected.

Drill: The particular Bosch drill on the current prototype of TAURUS is certainly not a viable option for operation in the space environment. First off, the drill uses a highly viscous grease to lubricate the moving mechanical parts which operate the impact drive. This grease is likely not suitable for space and must be replaced. Also, the drill has lots of vents to prevent overheating during use which would be exposed to dust and potentially damage the brushless motor inside. A drill similar to NASA's Trident drill would be an excellent option to use for an ISRU system like TAURUS.

Drill Bit: The drill bit on TAURUS is well suited for use in a lunar or Martian application. The regolith types to be encountered on Mars in a real world application could have significant variation from what is expected and simulated in testing on Earth. However, the carbide tip and steel auger features of the drill bit on TAURUS should be strong enough to sort through some very tough layers.

Sleeve: The sleeve of TAURUS is made of aluminum which makes it an ideal strong but lightweight metal for use on the Moon or Mars. The issue with the prototype sleeve is the connection mechanism. It relies on being held in place by gravity and it is not mechanically clamped to the auger bit. For use in a real world application, a slip ring would likely be needed and an electromechanical fastening method would be used. The slight give and lax tolerances would result in unpredictable vibration patterns as the TAURUS was launched and landed on the Moon or Mars. The longevity of systems and the ability to predict normal wear is key to ensuring the worthiness of a space bound design.

Data Protection: Digital core measurement memory storage hardware must be radiation hardened. Additionally, the connections of all of the components required for the core hardness calculation must be secure to withstand the space environment and the trip to the destination. Finally, the data must be compressed to a minimum size before being transmitted to the data relay satellite and then back to Earth.

8.2 Lunar Prospecting

Regolith Properties: Many lessons about drilling into the lunar surface were learned during the Apollo missions. Important to note, similar drilling experiences occurred at all Apollo landing sites, therefore, lessons learned can be extrapolated to almost any location on the lunar surface [5]. One exception may be permanently shadowed craters near the lunar poles where water and other volatile molecules, in the form of frost, may change the regolith surface characteristics. Lunar surface characteristics are attributed to millions of years of impacts by micro-meteors that have disturbed and tamped the lunar regolith. The result is a heterogeneous regolith that is composed of lithic fragments, mineral fragments, and impact breccias, glasses, and agglutinates. These remnants are mostly angular shards and rounded melt fragments. With the median grain diameter being between 45 and 100 mm, particles less than 20 mm in diameter could cause problems in joints, seals, and other mechanical implements [5]. The lunar regolith densities are vastly different from typical terrestrial soil densities. Unlike Earth soil, the lunar regolith is 'fluffy' for the top few centimeters of the surface layer and quickly increases in density to the point of incompressibility below a depth of 10-20 cm. This is attributed to the cumulative effects of shock compaction from the repeated surface impacts. Earth should have similar surface densities as the lunar surface, however, weather and tectonic erosion on Earth has caused vast differences to occur.

Gravity: Due to reduced gravity on the Moon relative to Earth (0.166g), the rover may lose its grip on the lunar surface while the drill is operating. Therefore, the rover may need to use anchors to assist the force of gravity in counteracting the upward forces generated from drilling. Research into anchoring technology is ongoing, but it has been demonstrated that an omni-directional anchoring mechanism can effectively anchor a mobile rover using micro-spine toe technology [6].

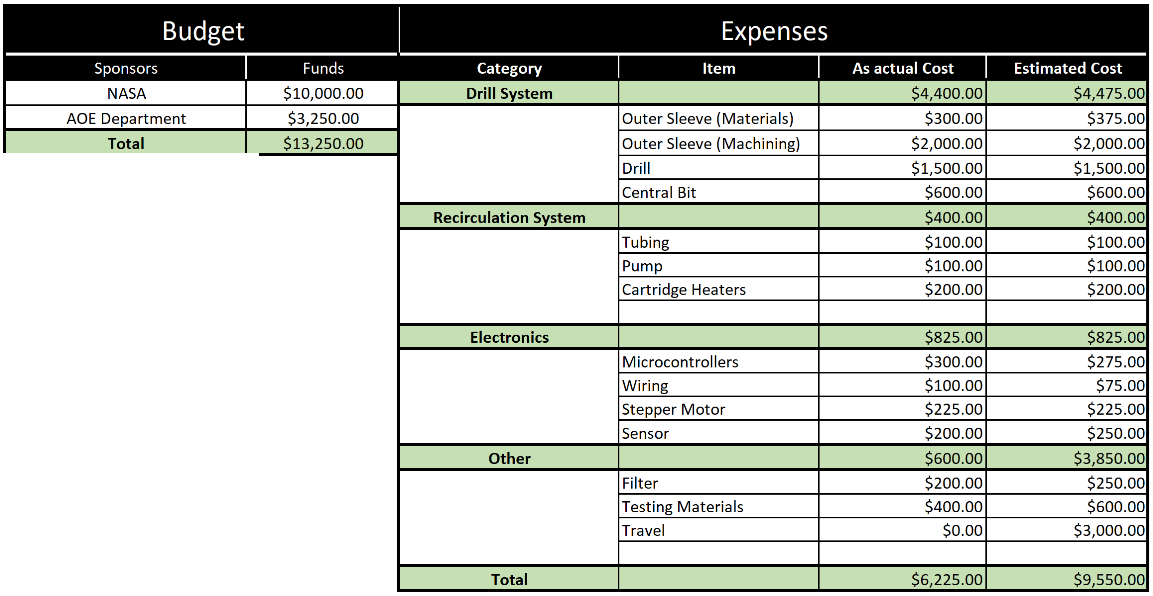
Thermal Environment: Insulation will be required to prevent the onboard water from freezing during the harsh lunar temperature swings. Temperature swings are not as drastic on Earth, therefore, the risk of water freezing during the lunar night is much greater. The use of internal heaters to heat the water and/or pump to circulate the water will be required. As a result, drill operations will cease during the lunar night in order to conserve energy. Reserve battery packs will be charged during the day using a system of solar panels.

9. Future Plans

Despite the limitations that were faced, we were able to complete tests on the heating system and horizontal movement of the traverse system. The components that have already been built are the frame and the traverse axes with drill, electrical, and software components planned and ready for building in the beginning of the semester. The system has gone through various changes since the midterm review, through research and troubleshooting. Given the circumstances, the team has been working diligently on the Internet of Things (IOT) devices, software and control systems, and the mounting system which are available to be worked on remotely. Most of the team members will be returning to work on the system this fall, and the labs will be opening up with revised rules which would give us a chance to test the systems that we have been working on throughout the summer. This will also allow us to complete the build and integration of various systems and test all of them together, which would give us a better understanding of the shortcomings faced by the designs and hence allow us to make improvements to the next year's design.

10. Budget

Table 5: Final TAURUS Budget



Budget		Expenses			
Sponsors	**Funds**	**Category**	**Item**	**As actual Cost**	**Estimated Cost**
NASA	$10,000.00	**Drill System**		$4,400.00	$4,475.00
AOE Department	$3,250.00		Outer Sleeve (Materials)	$300.00	$375.00
Total	$13,250.00		Outer Sleeve (Machining)	$2,000.00	$2,000.00
			Drill	$1,500.00	$1,500.00
			Central Bit	$600.00	$600.00
		Recirculation System		$400.00	$400.00
			Tubing	$100.00	$100.00
			Pump	$100.00	$100.00
			Cartridge Heaters	$200.00	$200.00
		Electronics		$825.00	$825.00
			Microcontrollers	$300.00	$275.00
			Wiring	$100.00	$75.00
			Stepper Motor	$225.00	$225.00
			Sensor	$200.00	$250.00
		Other		$600.00	$3,850.00
			Filter	$200.00	$250.00
			Testing Materials	$400.00	$600.00
			Travel	$0.00	$3,000.00
		Total		$6,225.00	$9,550.00

Appendix

[1] Bar-Cohen, Y., and Zacny, K., Drilling in extreme environments: penetration and sampling on Earth and other planets, Weinheim: Wiley-VCH, 2009.

[2] Parness. Anchoring foot mechanisms for sampling and mobility in microgravity. In 2011 IEEE International Conference of Robotics and Automation, 2011

[3] Cressler, J. D., and Mantooth, H. A., Extreme environment electronics, CRC Press, 2017.

[4] Ehresmann, B., Zeitlin, C., Hassler, D. M., Wimmer-Schweingruber, R. F., Böhm, E., Böttcher, S., Brinza, D. E., Burmeister, S., Guo, J., Köhler, J., and et al., "Charged particle spectra obtained with the Mars Science Laboratory Radiation Assessment Detector (MSL/RAD) on the surface of Mars," Journal of Geophysical Research: Planets, Vol. 119, No. 3, 2014, p. 468–479. doi:10.1002/2013je004547.

[5] Hall, L., "Overview: In-Situ Resource Utilization," NASA Available:https://www.nasa.gov/isru/overview.

[6] Wiliams, D., "Mars Fact Sheet," URL https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html.