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Technical Paper

Tartan Ice Drilling System (TIDS)

Carnegie Mellon University

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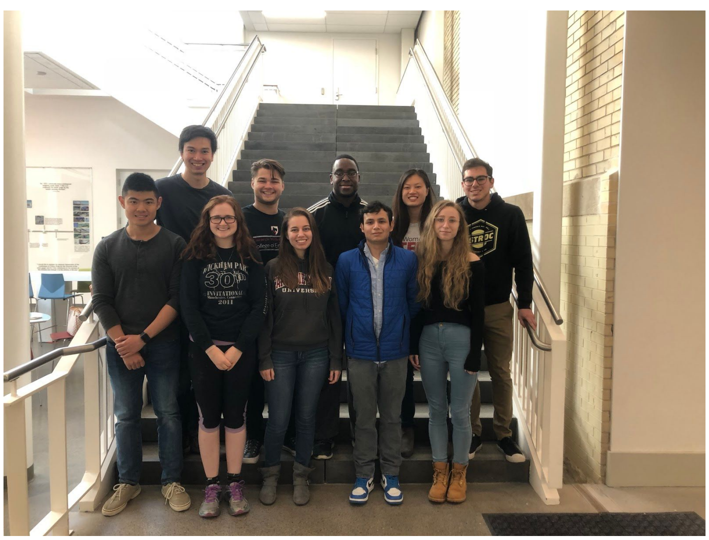

1 Introduction

The Tartan Ice Drilling System (TIDS), developed by students at Carnegie Mellon University, represents a bold and innovative design for a Martian water extraction system and for the future of spaceflight. This overall design iteration is driven by advancements in key subsystems. The adaptation of ice core drilling processes for the Martian environment allows for the application of effective and reliable Earth-based solutions. The implementation of an induction distillation process presents an opportunity to generate highly-pure water samples at low time and energy cost. The design of the control system was intended to mimic production spacecraft operations from the start, leading to more practical outcomes for future development. Altogether, TIDS combines many novel and innovative components into a single system, all of which yield interesting takeaways for NASA research.

2 System Description

2.1 Mounting System

The mounting system for the robot consists of having through-holes drilled through the bottom of the frame in order to bolt the chassis to the 2” x 4” wooden beams provided. We decided to use wing nuts on the bolts in order to more easily manually move the frame along the wooden beams. This way, we only had to actuate our system in the X and Z-axis direction, and we can manually move the robot in the Y-axis direction (along the beams). This ease of mobility has helped in significantly reducing weight and monetary expenditures since we do not need to have a Y-axis direction actuation.

2.2 System Excavation Operations

Our coring drill is driven down into the ground by a lead screw-gantry system attached to a NEMA 23 stepper motor, and is rotated by a motor that provides enough torque in order to dig through the overburden and effectively penetrate the subsurface ice. In order to extract cores, the 890 mm, drill barrel is made of a UHMW pipe and is able to cut through the clay and ice using a steel drill bit. Steel cutters shave through ice, clay, and gravel in a helical motion due to the barrel’s rotation and z-axis motion. Debris passes up the drill barrel with the aid of LDPE flights mounted on the outside of the barrel. The drill head cuts an annulus around a core of overburden between 300 mm - 600 mm tall and an ice core 240 - 260 mm tall. Reversing the direction of the drill once it has reached depth will actuate core dogs that are operated by torsional springs. These press into the sides of the core and propagate a crack through the ice, breaking it from the ground. Once the core is removed, the drill is lifted approximately 500 mm above the frame’s base in order to clear the height of the water purification system. Once it has been lifted, it is moved along the “X” axis using a second lead screw/motor actuated system toward the heating chamber. Induction sensors are placed at the end of each lead screw, in order to sense when the system is about to reach its maximum distance capability. We use these sensors as a contingency break in case there’s inaccuracy with the stepper motors. Once above the heating chamber, the stepper motor drives the drill, pressing down on a carbon fiber collar that allows for the core dogs to be pushed back up into their original position within the drill bit. Contact with the collar can be inferred from a spike in weight on bit data and expected z-positioning. Once the core dogs are up, the ice falls past the collar into a cylindrical chamber to be melted and purified into liquid water.

Due to the high accuracy required by the system with depositing the core into the water extraction system, the X-Axis utilized a 5-Phase NEMA 24 stepper motor in order to provide greater accuracy and reduce vibration.

2.3 Water Extraction System/Technique - Drill

Ice extraction is carried out utilizing a coring drill that removes cylindrical ice cores along with an upper layer of overburden. The custom aluminum drill head, machined on a 4-axis CNC Mill, was mounted with three ice cutters and three core dogs, allowing the drill to cut through regolith and ice. The core dogs are made of carbon steel while the ice cutters are made of high-speed steel.

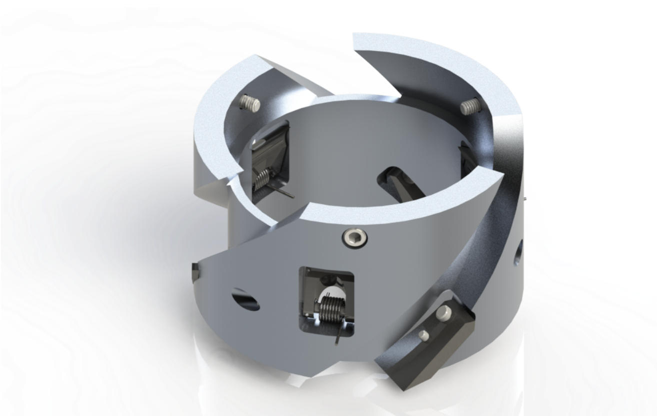

Figure 1: Drill head assembly with steel cutters and core dogs

The 860 mm UHMW barrel with an inner diameter of 70 mm and outer diameter of 80 mm will produce ice cores around 240 mm in height. Clay, gravel, and ice shavings will be lifted out of the cutting region using ~13 mm thick LDPE flights, preventing the drill from getting stuck in the hole. We will rotate the drill using a 394 W DC motor mounted to our z-positioning system. Reversing the drill out of the hole will cause the core dogs to actuate with the help of music-wire steel torsional springs that will bite into the ice with a maximum torque of .12 N-m. This will allow sites for crack propagation so that when the z-motion is reversed to pull the barrel out of the hole, the ice core will break in tension. The broken ice core will then be transferred and deposited in the water heating system. After discussing ice coring techniques with mechanical engineers from the Ice Drilling Design and Operations (IDDO), we decided that ice shavings around 1 mm in thickness would be optimal for our purposes. This is important to ensure that the drill does not get stuck, because both large shavings (> 5 mm) and smaller shavings (< 1mm) can lead to drill bit freezing and inefficient drilling. WOB measurements are measured with a 50 kg button load cell placed between the main barrel and motor assembly. Signals from the load cell are transferred to our control system utilizing a custom 3D printed slip ring. The slip ring assembly consists of spring loaded carbon brushes that maintain contact with copper rings while the drill barrel is rotating.

Our drill will run at a constant 64 RPM, with a z-penetration of 1 mm per revolution. The motor can provide a maximum continuous torque of 31 N-m, but we do not expect to encounter more than 15 N-m under normal drilling conditions. However, because it is difficult to predict the torque needed for coring operations in dirt and gravel, and also because ice coring drills are notorious for being inefficient in rocky environments, we selected a relatively powerful motor that should eliminate the possibility of the drill getting stuck. It is also worth noting that industrial ice coring drills with larger diameters typically use motors with continuous torque values in the 50 N-m to 90 N-m range.[1]

2.4 Filtration and Water Collection - Water

The water is filtered using thermal distillation: vaporization and re-condensation of the ice into pure water. The first part of the system involves the evaporation chamber, which is heated through induction. The drill deposits the ice core through a circular opening at the top of the compartment and into a 76 mm diameter steel tube. A current of 10 amps is passed through a 6 mm copper tube encircling the tube and induces a current in the shell of the tube, producing heat and raising the temperature of the steel tube by 1 degree per second. The generated water vapor passes through an attached 12.7 mm copper tube and into the condensation chamber. Based on the design of a jacketed condenser, the condensation chamber consists of 607 mm long copper coil with a 30 gauge galvanized steel pipe shell. A centrifugal pump pushes ambient air through the shell at 670 cfm to condense the water vapor in the tubing into liquid water. The pure, condensed water then flows through the attached hose to be collected.

2.5 Solution to Deal with Overburden and Preventing Drill Bit Freezing

To prevent the drill bit from freezing underground, we wanted to minimize the melting of ice into water that may refreeze downhole, and then also create as many hydrophobic surfaces as possible on the drill. The first task was carried out by researching rates of penetration and the speed at which to run the drill for our geometry of the drill head.[2] Coating the drill head and the majority of the barrel surfaces with Teflon will increase the likelihood of material moving out of the cutting region while decreasing the likelihood of any refreezing near the drill bit. Additionally, UHMW has a very low coefficient of friction. This makes it difficult for material to stick to the barrel that would in turn increase the torque on the motor. This could potentially lead to the motor stalling and the drill becoming stuck. We also constructed the water collection system to have the top of the ice core come close to the top of the carbon fiber collar that retracts the core dogs. This has the advantage of preventing large amounts of overburden from entering the water filtration system, which can then be easily sealed during the evaporation process.
Excess overburden that builds ups inside of the water collection system will be removed from the bottom of the system by removing a steel clamped plate with an EPDM 90 mm diameter O-ring that is rated for high temperature steam. EPDM is chemically inert and has a large heat tolerance and would be useful in creating tight seals for our water system in both Earth and Martian conditions.

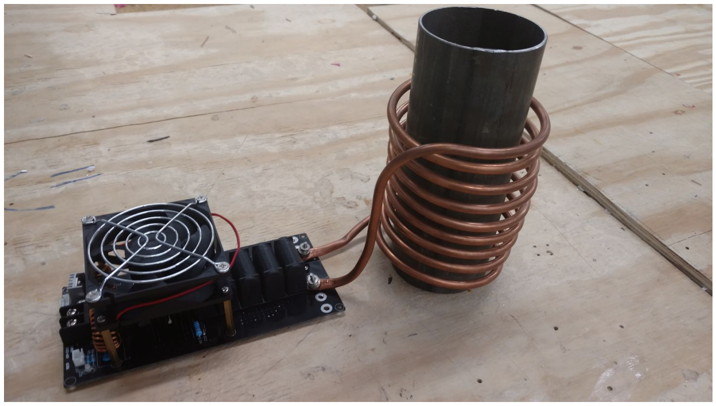

Figure 2: Induction Heater with Steel Ice Collection Tube

2.6 Control and Communication System - Controls

As the brains of the drilling system, the control and communication system is designed to maximize autonomous operation and seamless function of all hardware components. Although it would be infeasible within the budget and timeframe to develop a system to work without adaptation for a spacecraft, significant effort was put into designing control and communication system that resembles true hardware and software for a NASA Mars mission. The best comparison for an active mission on the \Martian surface is the Curiosity rover. The planned Mars 2020 rover is based on the Curiosity system architecture.[4] Curiosity uses two 200MHz BAE RAD750 computers with 256 kB of EEPROM, 256 MB of DRAM, and 2 GB of flash memory.[4] The software is embedded C code running on top of Wind River Systems' VxWorks real-time operating system (RTOS). Our computing selection mimics this design using a Beaglebone Black Wireless development board with a 1GHz ARM Cortex-A8 processor, 512 MB of DRAM, and 4 GB of flash memory.[5] Our software is embedded C++ code running on top of an IoT distribution of the Debian 9.3 Linux kernel with RTOS support.[6] Thus, our computing hardware and software is built as a proof-of-concept for a true Mars mission.

The Beaglebone was selected for its ability to mimic production spaceflight hardware as well as its versatility for controlling external hardware components through 65 GPIO pins, 8 PWM pins, 7 ADC inputs, 2 SPI buses, and 2 I^2C buses. This allows us to use a variety of sensors and actuators for near-autonomous operation. The control system can be divided into five subgroups: power control, positioning, drilling, heating, and chilling. In the power control subgroup, an 8 channel relay controls power to all other components and a current sensor allows power consumption logging for the entire system. In the positioning subgroup, stepper motors control movement on the X and Z axis, aided by inductive proximity sensors at the ends of each axis for homing. In the drilling subgroup, a 90V DC motor runs the drill, and an encoder, current sensor, and weight on bit sensor allow for dynamic speed adjustment to remain below stall torque. In the heating subgroup, an induction controller runs the heating process, monitored by an infrared temperature sensor, and the melting chamber cover is sealed by a servo motor. In the chilling subgroup, an air blower is controlled through the relay. The full set of components in the control system is detailed in the table below:

Table 1: Components and Control

Function	Component and Datasheet	Control
Main current sensor	Phidgets i-Snail-VC-10	ADC
Power control relay	8 Channel Relay	GPIO (8)
Axis proximity sensors (3)	LJ12A3-4-Z/BY	GPIO
X-Axis stepper motor	Oriental PKP569FMN24A + CVD524-K driver	GPIO (6)
Z-Axis stepper motor	NEMA 23-HS16-0884S + TB6600 driver	GPIO (3)
Drill motor	MMP D33-655J-90V GP81-035	PWM
Drill encoder	MMP EU series optical encoder	GPIO (3)
Drill current sensor	LEM LTS 6-NP	ADC
Drill weight on bit sensor	CZL204E 50kg load cell + HX711 amplifier	GPIO (2)
Heater induction controller	1000W ZVS Induction Heating Board	GPIO
Heater temperature sensor	Melexis MLX90614	I^2C
Heater cover servo motor	DS3218	PWM
Chilling system	Zoom 450W Air Blower	GPIO

As the different components have varying power requirements, we constructed a robust power system that takes a single 120VAC input and outputs 120 VAC, 90VDC, 36VDC, 24VDC, 5VDC, and 3.3VDC. This is achieved with a switching power supply, three buck converters, and one boost converter. The dynamic component of the power system is an 8 channel relay, which allows the computer to selectively supply power to each component, thereby reducing the overall power consumption at any time. Additionally, current sensors monitor the power draw for the entire system and the drill motor. A map of the entire power system is included below:

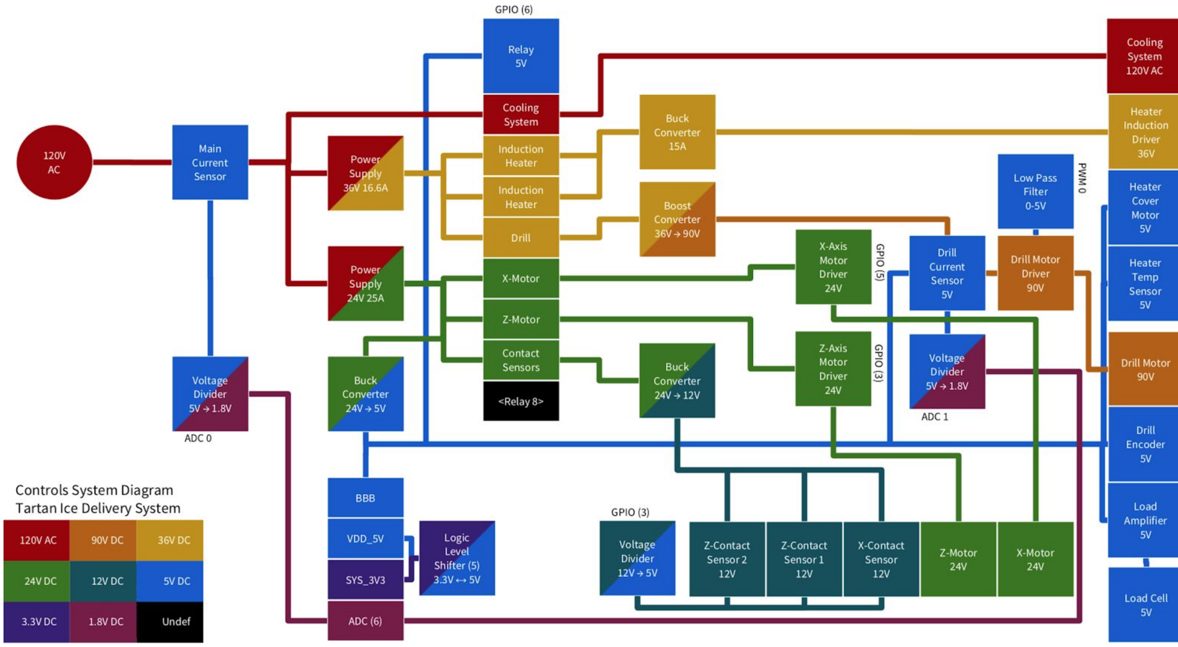

Figure 3: Power control system

The power control system is encapsulated within a strong plastic container to centralize the voltage converters, cooling fans, and to isolate potentially-hazardous internal wiring.

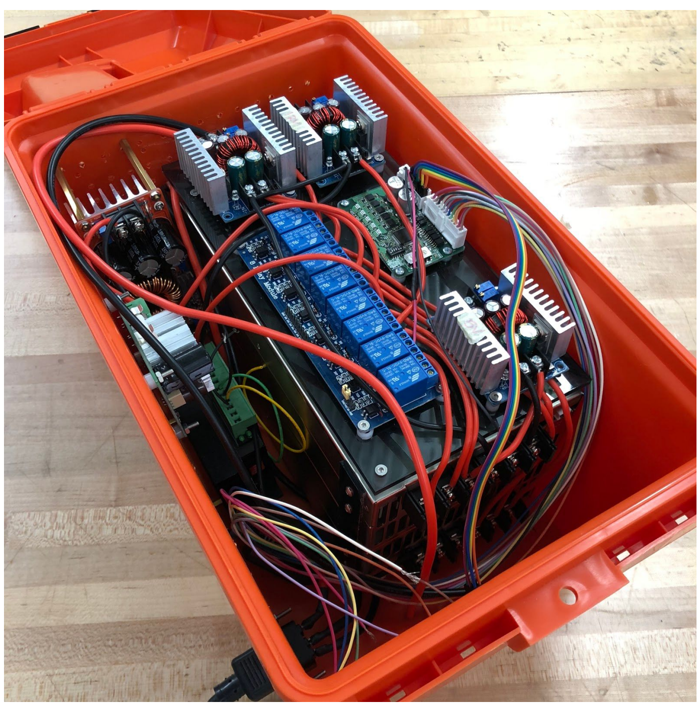

Figure 4: Control box containing hardware

All software is custom designed for the Beaglebone and to support the various hardware components. The software is divided into two repositories: BBBKit and tids-control. BBBKit[7] is a custom library we developed to abstract the I/O functions of the Beaglebone. Due to the rapid growth and continued development of the Beaglebone kernel, no existing library supports all I/O operations on the newest kernel. The development of BBBKit even led to some novel research into the relatively-undocumented kernel. The tids-control[8] software, built on top of BBBKit, controls the autonomous operation and communication and contains drivers for interfacing with each hardware component.

The communication subsystem was also designed to mimic production spaceflight systems. Rovers such as Curiosity are wirelessly managed by controllers on Earth, but communication lag and throughput mean that most high-level commands may be transmitted manually, but the underlying operations would be executed by the system semi-autonomously. To mimic and even improve upon this process, the communication software was designed to use only start, stop, and reset commands, with all other operations controlled autonomously by the computer. Commands and telemetry are transmitted wirelessly over Wi-Fi Direct, meaning that the system operates with no physical connection to the external computer, just like a traditional spacecraft.

2.7 Datalogger - Controls

As discussed in the previous section, various sensors can measure current, load, drill speed, and melting chamber temperature during system operation, and this telemetry can be wirelessly communicated back to the external computer. Main current data is measured by a split core current transformed clamped around the main AC line and communicated to the computer through an ADC. Weight on bit data is measured by a load cell on the drill motor, converted to a digital signal through an external amplifier, and communicated to the computer using GPIO. This sensor data can then be wirelessly communicated and updated live in the terminal during system operation. Additionally, the data can be saved to files on-device or externally for observation and analysis at a later point.

3 Design Changes/Improvements

When simulating the drill's motion on our CAD model, we came to notice that the torque experienced by the Z axis was too large for the dual steel-shaft and lead screw system we originally had in place, which sought to emulate the X-axis design. Several FEA tests produced excessive deflections of the Z-axis lead screw and guide shafts, which would have cause the axis to seize. As a result, we opted to use a profiled linear rail in tandem to the lead screw. This way, the rail is less prone to torsion and prevents the lead screw from deflecting. The single rail also provided extra stiffness to the Z-axis.

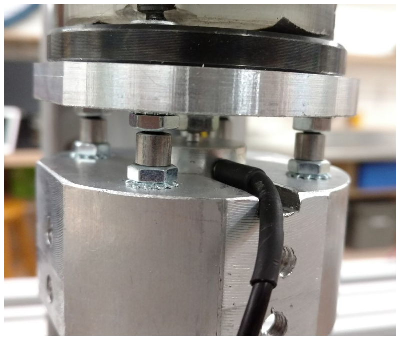

Figure 5: a) Load cell assembly b) Carbon fiber collar attached to water system

Changing the mounting of the button load cell to be mounted beneath the motor allowed us to get both reliable measurements for WOB while maintaining a secure attachment to the z-positioning system. This would be otherwise difficult unless we characterized the torque-speed curve for the z-axis stepper motor. A carbon fiber collar with teeth at the entrance of the water system was used to retract the core dogs and remove the ice core from the drill. This was a simple and robust way of releasing the ice core where before we were looking at complicated moving assemblies within the drill bit itself that might damage either the drill bit or the ice core.

The original design for the condensing chamber incorporated a heat exchanger utilizing a liquid cooling fluid. Though using a liquid as a cooling fluid has advantages, such as significantly higher heat transfer coefficients, providing the availability of the liquid would pose several challenges. Whether creating a source of cooling water by adding an initial slow condensing step through separate means or transporting a refrigerant from Earth, the process of obtaining the cooling liquid would add unnecessary complexity and weight to the system. Thus, the system was adapted to utilize ambient air as the cooling fluid, made possible by a high volumetric flow rate and increased length of tubing in the condensing chamber.

4 Challenges

The largest structural challenge faced in the design of the system was having to deal with such a great amount of torque being exerted on the moving gantry systems. There were a few ways to deal with this issue: change the motor such that the stall torque would not cause the systems to deflect, or change the design of the moving systems such that they would be able to withstand the stall torque of the drill motor. In order to ensure drilling capability, we decided (as stated above) to change the “Z” axis system to a profiled rail coupled by a lead screw in order to withstand a higher torque.

Wobbling of the drill became evident with the initial drill assembly due to how the drill barrel moved relative to the motor as a result of the load cell assembly. The assembly was changed to move the entire barrel relative to the motor as opposed to moving pieces of the barrel assembly relative to itself. Removing the ice core was a particular concern as most ice cores utilized in Antarctic or Arctic drilling remove cores out of the top of the barrel by laying the full barrel on its side. This was something we deemed are system incapable of doing within the constraints of the competition. However the stiff collar design for releasing the core dogs is a simple way of accomplishing this task, with the exception that it requires precise knowledge of the location of our drill head relative to the water system.

Developing methods of vaporizing and condensing the water with time and energy efficiency was the greatest challenge to designing the water filtration system. Resistive heating for vaporization was heavily considered. However, process of melting and evaporating the full ice core using a heating element would take an estimated 15-18 minutes, even longer with overburden contamination. With the power constraint preventing the drill from operating concurrently with the water filtration system, the resulting rate of water production would have been far from sufficient for producing a water source. Induction heating, on the other hand, operates much more efficiently and can produce the same results at 5x the rate. Similarly, most of the methods of condensing water vapor in industry incorporate pressurization or at least liquid coolant. Due to both the given power constraints and expected challenge of pressurizing a condensing chamber on Mars with a much less dense atmosphere, simply compressing the vapor to liquid did not appear feasible for this prototype. Though slightly more possible, using a liquid coolant fluid for the condenser also posed challenges, as described above. Thus, a custom designed and fabricated jacketed condenser was created to fit within the competition restrictions while still performing the function. Both parts of the system went through several iterations before finally reaching the design current prototype.

As previously discussed, control system challenges included handling new and relatively-undocumented changes within the Beaglebone kernel, which required us to create a custom I/O library (BBBKit) instead of using existing software. However, the ability to own and optimize all levels of the software stack has proven beneficial, and the Beaglebone has allowed us to better simulate the control systems of production spacecraft.

5. Overall Strategy for Competition

The Tartan Ice Drilling System will perform favorably in the competition by following the below procedure:

1. Drill moves to first site centered ~100 mm from evaporation chamber on the x-axis
2. Drill moves down z-axis and drills to provide an ice core of 240mm.
    a. Depending on the height of the overburden (600 mm - 400 mm), the drill will reach a maximum depth of 840mm and minimum depth of 640 mm
    b. The system will recognize the approximate depth of overburden based on WOB data
3. Drill cuts core and lifts above the surface and moves along the x-axis to the evaporation chamber
4. Drill moves down the z-axis to the top of the evaporation chamber, interacting with the carbon fiber collar to release the core into the chamber
5. Drill lifts 50 mm and moves along the x-axis to discard the overburden
6. Cover drops over the collar on the top of the evaporation chamber
7. The induction heater and pump turn on
8. The ice core is vaporized and re-condensed
9. The cover over the collar opens
10. The drill moves 40 mm from previous hole on the x-axis
11. Repeat steps 2-10

Due to the two-axial design, only 6 cores can be collected in each row on the x-axis. Thus, after every 6th core the system frame should be moved at least 40 mm along the y-plane. Though power constraints prevent the water filtration system from operating at the same time as the drilling system, the efficiency of both processes should allow for the collection of at least 12 ice cores a day, or a total of 22.2 L of water of the two day period.

6. Integration and Test Plan

Before system integration, each of the subsystems were tested individually with the controls to ensure proper performance. **Table 2** below summarizes the testing results.

Table 2: Subsystem Testing Results

System Tested	Method of Testing	Results
Induction Heater Performance	Optimization of heating rate based on power input. The system should take no longer than 3 minutes to reach 120℃ and remain within power requirements.	Using 30V with 10A, the temperature rises 1℃ every 1-1.5 s. Thus, to reach required temperature, the induction heater will take ~2 minutes.
Air Pump Performance	Control system successfully connects to and controls the air pump.	The control system was capable of turning on the air pump to the appropriate cfm.
Load Cell	Perform correct calibration on load cell to ensure proper WOB data collected. Using open source code for an Arduino, the calibration factor can be determined for the load cell and integrated into the code to product accurate WOB data.	The determined calibration factor for the load cell was -56500.
Drill Motor	Has an encoder that gives straight forward data and a current sensor and through the voltage, can determine how much torque you're getting Keep torque 13 N-m	Have to measure the signal and at what point you receive the signal
X/Z-axis Driver	Using magnetic field detectors to determine where the axis is	Magnetic sensor tested to detect if motion sensing was capable
Inductive Proximity Sensors (Homing Mechanism)	Used a piece of aluminum to understand the range (determine	The sensor was calibrated properly and ready to attach to

	sensitivity); calibrating the system to sensor	the main system.

The system was integrated together in parts. To start, both the X and Z positioning systems were bolted and attached to the main frame. Additional rails were also attached at the frame base to support the components of the controls and water systems. Next, the drill motor was attached the z-directional positioning system. The drill motor was attached to the drill barrel using two aluminum clamps. The evaporation chamber was built around the induction controller and steel tube. The collar for core release and the cover was attached to an elevator motor were attached to the top of the compartment. The evaporation chamber attaches to the condenser chamber through an extension of the copper tube in the condenser shell. The condenser shell rests on a PVC fitting connected to the pump. Lastly, the Beaglebone, power adapters, and power supply are consolidated in one main control box with extruding wires to connect to all the electronics in the system and an outlet.

Due to unforeseen integration challenges and shipment delays, the dry-run was not performed before writing this report. However, upon completion of the system construction, full testing is expected to be performed in the next week and certainly before the competition. To accurately perform a full system evaluation, a testing ice block (38 mm x 38 mm x 64 mm) was created. The block will be secured to the ground and the full drilling system will be tested following the procedure outlined above.

7. Tactical Plan for Contingencies/Redundancies

Due to the large power draw from all individual systems on the robot, we would not be able to simultaneously extract ice cores and turn on the heating system. That being said, our whole project works on a serial-based system of operations. With this sequential system, time becomes an issue, and we would like to be able to extract 10-12 cores per day, if not more. Because of this, we have designed for a induction heating system that can heat the ice very quickly and that can be easily controlled. In a case in which we are pressed for time, we can increase the amount of current passing through the induction coil and therefore melt the ice quicker. In the case that the stepper motor begins desynchronizing and losing steps due to unforeseen loading on the system, the stepping mode can be changed in order to obtain more available torque at the cost of increased power consumption. From testing, we can determine desynchronization from calculating the distance required to move the axis given the pitch of the lead screw and rpm of the stepper motor.

8 Updated Timeline

Table 3: Timeline

Month	Progress
December	Research of Earth-based excavation systems and brainstorming of project plan
January	Recruitment of team members

February and March	Designing and modeling project, further research of water filtration systems and drilling systems
April	Sourcing and manufacturing of major parts and equipment, drilling system iterative prototyping.
May and June	Assembly of all subgroups and components, integration of system, final testing.

9 Safety Plan

The Z-directional positioning system is going to be resisting a majority of the torque being exerted by the drill. According to the FEA, the original design would not be able to withstand the torque, therefore the current design has been structurally reinforced in order to achieve a higher factor of safety. A potential hazard during drilling is projection of ice shavings, gravel or debris during excavation which will require all members to wear eye protection. Another area of caution is being able to safely remove the drill in the case it becomes stuck during excavation. The drill head has sharp cutters and core dogs capable of breaking skin so caution must be taken when handling the drill head. Under no circumstance should anyone stick their arms or limbs inside the barrel through the drill head as the core dogs are more than likely strong enough to cut into an individual's arm upon attempted removal. The induction heater reaches 120℃ in ~2 minutes. The evaporation chamber uses open siding to cool the tube more efficiently, however, the entire compartment will remain very hot and dangerous to the touch for at least 20 minutes. The main potential hazard for the control system is handling mains AC and high DC voltages as they are transformed and wired to various hardware components. The power system is never physically handled while active, and insulated high-gauge wires are used for power delivery to ensure high current spikes can be sustained without damage. Additionally, the use of a reinforced container to isolate the power supply and high-voltage components increases safety during system operation.

10 Path-to-Flight

The power source for the system would need to be adapted for the Martian environment, likely using solar panels or a radioisotope thermoelectric generator (RTG). We recommend an RTG, which would provide a higher-level and constant output of power. The MMRTG used by the Curiosity rover generates 9MJ per day, compared to 2.1MJ per day for the solar panels on the older Mars Exploration Rovers, and can be used at any latitude on Mars.[12] However, Curiosity's MMRTG still only outputs 110W of electricity, which is far from the 1200W maximum allowed for this competition.[13] Significant reductions in system power consumption will need to be achieved in order to run on a single RTG, if this is a requirement. An added benefit of RTG technology is that excess heat can be used to heat other hardware components, and in this case potentially bolster the ice melting system.

Although much of the control systems, including the computer and communication software, were designed to simulate the requirements of a production spacecraft, the underlying hardware and technologies would need to be upgraded to function on Mars. The computer should be replaced with a radiation-hardened system such as the BAE RAD5500 64-bit multi-core processor platform, the successor to the RAD750 computer used by Curiosity. As we designed our system with similar requirements, the C++ code could easily run on the RTOS of the RAD5500, although the I/O connections would need to be modified. The software should be updated to match the JPL Coding Standard.[14] Additionally, a two-computer system should be used to ensure redundancy in the case of a malfunction in one of the computers. To combat what can be extremely cold temperatures on the Martian surface, a new system must provide heat to the various hardware components. This could be accomplished by bundling components with small electrical heaters or by creating a comprehensive heat exchange system by cycling fluid from a heat source, such as an RTG, around the system.

As there is no Wifi on Mars,[15] the communications systems need to be upgraded to permit reliable communication. An X band radio could allow signal transmission and reception with Earth-based systems. However, low data throughput and high transmit power suggest that a more optimal solution would be communicating with an external Mars-based radio that relays communications to Earth as necessary. At scale, several drilling system units could simultaneously transmit to the relay at a lower power, decreasing saturation of the link to Earth. A UHF radio could be utilized, such as Curiosity's Electra-Lite software-defined radio. This relay could take the form of a designated station on the surface of Mars or existing satellites such as the Mars Odyssey Orbiter, Mars Reconnaissance Orbiter, and ESA's Mars Express Orbiter. Utilizing existing orbiters would lower cost, but their orbits would decrease the communication window. All communications should follow the international space data communication standards created by the Consultative Committee for Space Data Systems.[15]

Several changes will be made to the drilling system to ensure the reliability and longevity of the mechanical equipment meant for autonomous operation in space. One change that would be implemented is to utilize a rotary percussive drill, which has been shown to produce less bit wear than a rotary drag bit in dry environments like Mars.[16] The rotary percussive drill will be especially effective in dealing with the overburden, which is more likely to be rock with higher compressive strength then the overburden we are required to deal with for the competition. Similarly, it would be beneficial to consider a drill chuck design where the bit can be easily replaced after it has worn down.

Another change we would like to implement is a change in the core break-off mechanism. Instead of core dogs, we would use a mechanism similar to the offset tubes mechanism patented by Honeybee Robotics.[17] This mechanism would rely on offset tubes to shear the ice to failure during extraction. One study found that this method sheared and captured cores with a 94% success rate, with minimal core loss. One concern with this method is added weight to the system, as the additional tube and actuators can potentially add a large amount of weight to the drilling system. However, by implementing this mechanism, we believe we would have a more robust method for removing ice cores.

Material selection in terrestrial conditions must be altered to fit the environment on Mars. Simply put, we would want to replace the drill barrel made of UHMW and LDPE flights with aluminum composite and/or titanium alloys such as those used on the Curiosity rover.[18] UHMW and LDPE have lower specific strengths than composites made of these materials, poor thermal expansion coefficients,[19] and will decompose much quicker in the exposed Martian environment before their aluminum composite counterparts. Another benefit to creating the majority of the drill barrel from aluminum would be the capability of machining the entire drill body from a single stock on a 4-axis CNC mill without the need for attaching extra flights. Teflon could still be used to counter frictional losses and prevent the drill from freezing in the ground. Replacing the steel cutting teeth with silicon carbon - diamond cutting teeth would improve overall wear and corrosion resistance for greater longevity of the drill head.[20] The final consideration with the drills path to flight would be producing a custom made motor assembly that houses our load cell (WOB measurement), slip ring, and any other electronics to shield them from the elements as well as remove the need for any housing on the drill barrel itself for a more robust system.

Utilizing an induction heater on Mars has the benefit of being one of the most efficient designs for heating (REF) and has the capability of being formed into a variety of shapes to suit any kind of drill design, be it coring or auger designs. Another extremely useful benefit of the induction heater on Mars would be the utilization of overburden to our advantage when evaporating ice. Mars would consist of hematite and ferrite (REF) , both magnetic compounds that when situated in the alternating magnetic field of the induction heater would heat up. This material would be in direct contact with the ice allowing for more efficient heat transfer than the convection that occurs mostly in our current design. The coil design also potentially allows for an easier throughput of overburden and ice in our system without having to have direct contact with the heating system itself. This will pave the way for a regenerable, efficient ice evaporating system for the Martian surface.

Replacing the drill collar made of a carbon fiber layup would be one of the main priorities under the assumption we remained with a coring drill. The benefit of the stiffness of the carbon fiber with its low mass comes at the cost of the epoxy resin suitable for our operating temperature stability. The Aeropoxy Resin we have available has a maximum operating temperature nearing around 95 °C which makes it unsuitable to have direct contact with our steam.[21] To account for this we have utilized Kapton tape that is both a good thermal and electrical insulator to help prevent delamination of our carbon fiber. Suitable, long lasting alternatives would be use a higher temperature resistant lay-up resin or potentially coatings with aerogels that have been produced by NASA.[22]

Due to the difference between the atmosphere on Earth and Mars, both the heating and condensation chambers must be modified. Firstly, the heating chamber and drill interface would need to be built as to limit the ice core's time spent in an open atmosphere, as the ice may potentially sublimate considering Martian atmospheric conditions;[23] the triple point of water occurs at approximately 0 °C 612 Pa,[24] while the average temperature and pressure on Mars is - 63 °C and 636 Pa, respectively. When comparing these points on a water phase-diagram, Martian conditions are shown to be leftwards of the triple point, indicating that water would be solid at these conditions. However, temperatures on Mars can reach up to 20 °C depending on location and time of day, which would result in sublimation upon extraction of the core.[25] The current model allows for the ice to come into contact with Earth's atmosphere as it is being placed into the heating chamber; building an airtight seal around the drill and heating chamber interface would eliminate contact with the Martian atmosphere. Once inside the heating chamber, we can use sublimation to our advantage, and heat up the chamber as needed without worrying about the pressure.

As the steam is traveling from the heating chamber to the condenser, the pressure would again become relevant. In order to condense into liquid water, the temperature and atmospheric conditions must fall within a liquid region. Due to the water being used primarily for human astronaut use, the most logical conditions to use are Earth's: approximately 100 kPa and 20 °C. Thus, the condenser--and the tube of water running through it--must be pressurized appropriately by keeping these areas pumped to Earth atmosphere. Additionally, due to the lack of atmosphere on Mars, the cooling gas would need to be supplied elsewhere. Again, as condensation is attempting to bring the water to Earthly conditions, this cooling gas and pressurizing gas would simply be air stored from the astronaut base, however, it would need to be contained and recirculated. Using a traditional distillation setup could be more feasible, as cooling fluid can be recirculated in such setups.

Because lead screws are the primary mode of motion transmission for the X and Z axis, fatigue and wear are large concerns. Consistent use of a lead screw will cause the screw to wear over time, depending on environmental conditions and the physical condition on the screw. Additionally, there is a large possibility that dust and debris will clog the threads of the screw, hindering motion transmission of both axis and potentially rendering the entire mechanism immobile with attempting to extract a core. A telescoping bellow will be necessary in these cases in order to prevent debris from clogging the screw and nut, and thus extend the life of the motion transmission system. Bellows will also have to be placed on the guide shafts and Z-axis linear rail, to keep the mechanism as smooth as possible. An additional overall concern is to replace nuts and bolts with welded joints and rivets. Where bolts are necessary, they should be secured with an engineering adhesive to prevent loosening due to vibrations caused by the drilling system.

11 Budget

Our project's construction was made possible through funding from a few different resources, in addition to the given $10,000 from NASA. We received $1350 from Carnegie Mellon's College of Engineering in order to help cover our travel costs, and through additional team fundraising we earned over $700. Table 4 below breaks down the costs per major component of the robot, as well as predicted travel costs.

Table 4: Team Expenditures per project Category/ System

Category/System	**Expenses**
Travel/Hotel/Registration	$1,700
Structures/XZ Actuation	$2,700
Drill System	$1,100
Water Purification System	$980
Controls System	$1,780
General/Other	$250
Total Spent:	$8,510

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