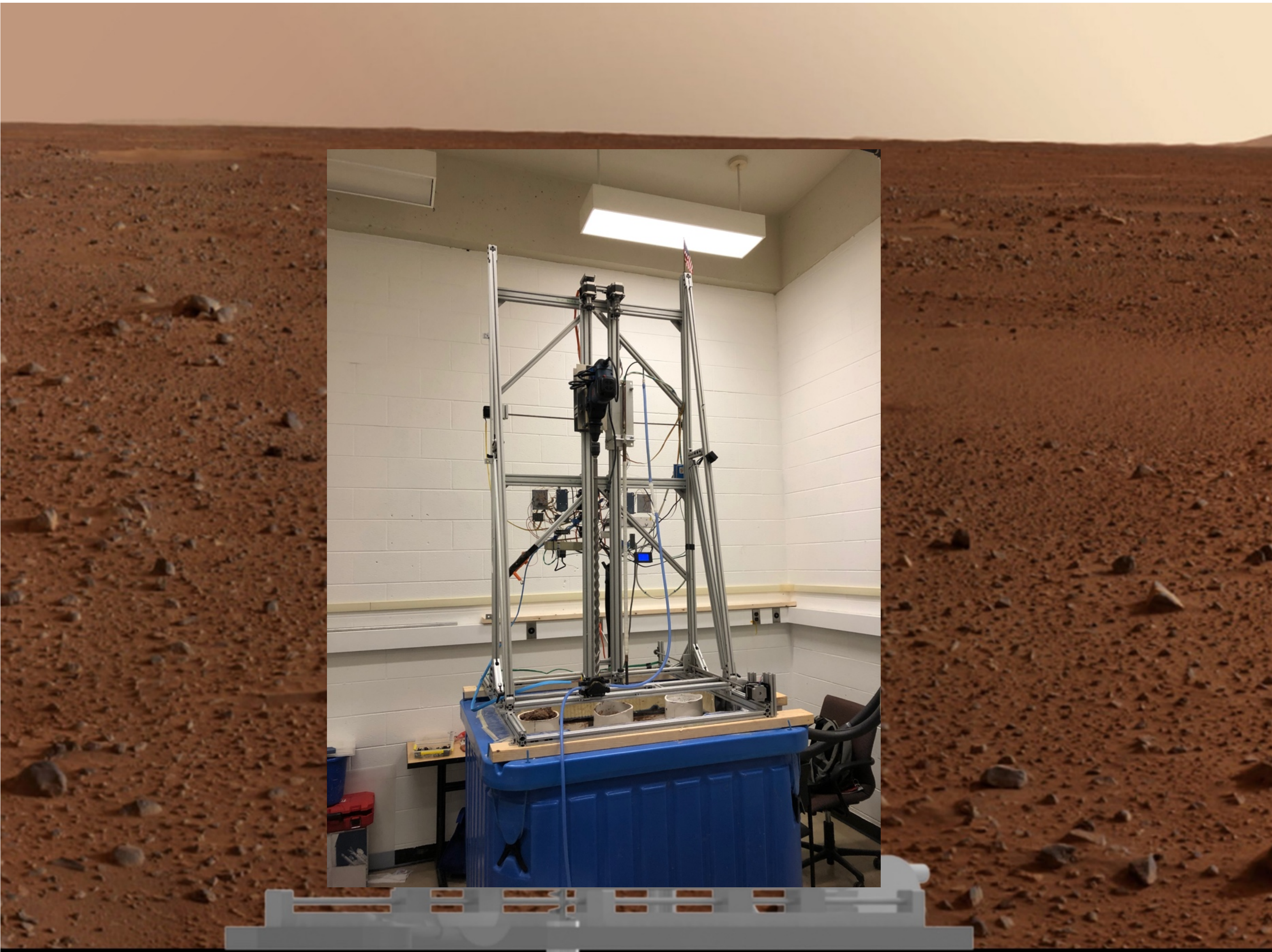

2019 RASC-AL Special Edition

Moon to Mars Ice & Prospecting Challenge

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HYDRATION

High Yield Dihydrogen-monoxide Retrieval And Terrain Identification On New worlds

Massachusetts Institute of Technology

Introduction

We have developed a water extraction and digital core prospecting system consistent with the goals of NASA's Moon to Mars Ice and Prospecting Challenge: our design and prototype, **HYDRATION** (**H**igh **Y**ield **D**ihydrogen-monoxide **R**etrieval **A**nd **T**errain **I**dentification **O**n **N**ew worlds) is an auger-based mechanism to access and then melt subsurface ice deposits *in situ*, pump out the water using a peristaltic pump with a regenerative filtration system, and reconstruct a digital profile of the overburden layers using multi-sensor data fusion to eventually train a neural network. Leveraging our HYDRA system and Bonar box testbed from last year's entry [1], we have completed the construction of an integrated prototype and have commenced testing under competition-like conditions. This report details the design, construction, integration and testing of HYDRATION as well as its two paths to flight for the Moon and Mars.

HYDRATION System Description

The major elements of the HYDRATION system include an auger apparatus, the down-hole heating system, a peristaltic pump and tubing, the filtration system, the sensors providing data for the digital core system, as well as various motors, control and power systems to enable remote operations. Note that the digital core system sensors have a dual use as part of the auger system, however it should be considered discrete from a functional standpoint. The system also includes cameras and ground microphones for monitoring and is designed to be run completely hands-off remotely from a distance, though not autonomously.

Water extraction capabilities: a rotary-percussive drill with a 1" carbide-tipped steel drill bit excavates a hole through the overburden and into the ice layer. Once the ice layer is breached, the meltwater and cuttings mix together to produce mud which lines and helps stabilize the hole walls as the drill bit travels up and down inside. The drill bit is removed from the hole and the heater and water inlet assembly is lowered through the hole and into the ice. A 500W radiator glowing at 600 deg C immediately causes ice melt in the 1" hole around it, and the peristaltic pump brings the water to the surface for filtration and collection.

***Digital Core prospecting capabilities*:** The HYDRATION concept utilizes the data streams from multiple sensors to infer the makeup of a digital core with the planned use of a neural network. For the Lunar path to flight, additional resources will be required to build up a data set sufficient to train a neural network to infer the makeup of the digital core. For the competition, the data fusion and inference functions will be performed by the human operator based on the experience gained during pre-competition integrated testing, as detailed in the relevant section below.

Mounting system: The structure of the HYDRATION system is made of aluminum for its high strength to weight ratio. The Earth prototype is made of 80/20 T-slot aluminum framing members because of its ease of assembly and low cost. The system features multiple translating carriers which allow for four degrees of freedom (see Fig. 1 below). The base of these carriers will be screwed directly into the wooden beams on top of the bin. The structure is designed to handle loading due to Earth's gravity, weight on bit, and the dynamic loads of operation with a suitable factor of safety. HYDRATION has been mounted on the Bonar box in the same manner as the previous year's HYDRA project. The lightweight aluminum structure has been screwed directly to the wooden 2x4 structure mounted to the top of the box using four 1" 80/20 corner brackets.

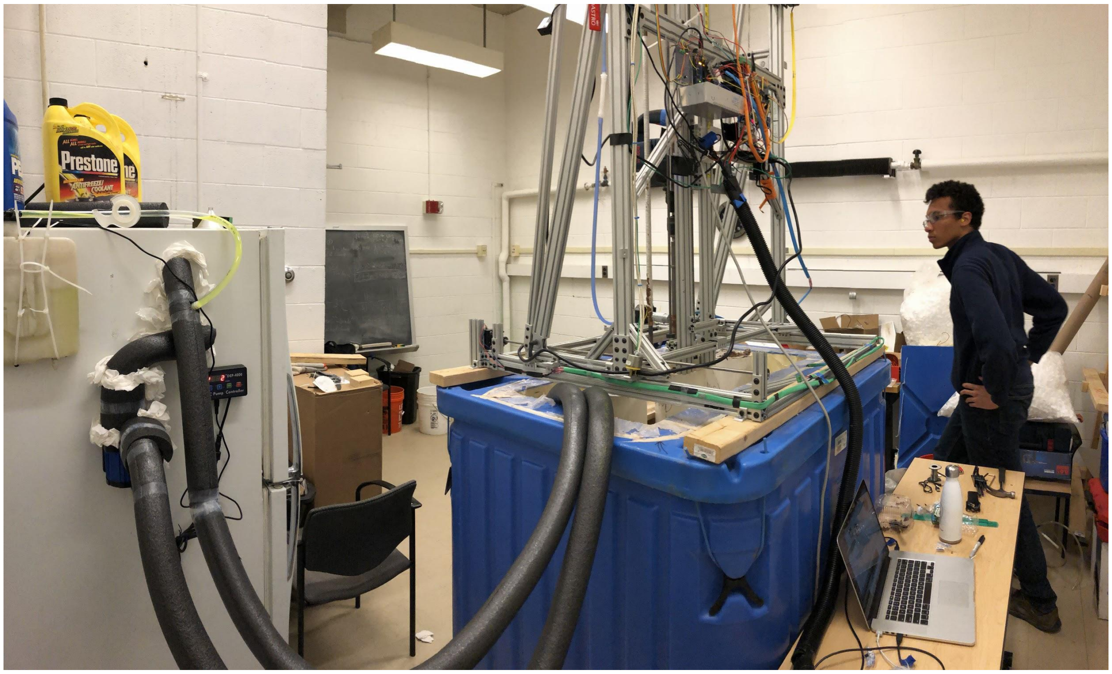

Figure 1: The HYDRATION system mounted on the 2” x 4”’s on the MIT Bonar box, showing adjacent workstation and our new refrigeration system to keep ice blocks frozen without the use of dry ice.

System Excavation Operations: In what follows, the numbers in double brackets refer to Fig. 2 below which depicts the graphical CONOPS for our system. Based on previous experience, research, and development testing, the baseline design for penetrating the overburden is a rotary hammer drill bit and auger, inspired by methods developed for the PVEx planetary volatiles extractor concept [2].

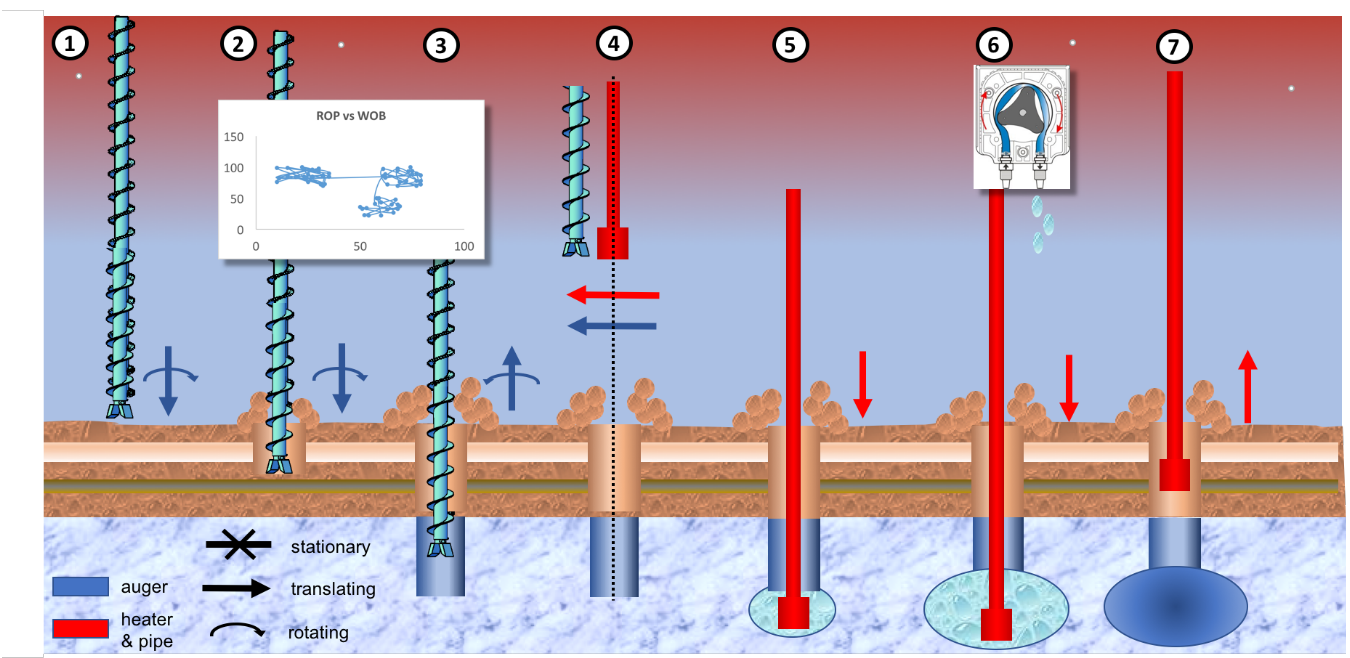

Figure 2: Concept of Operations for HYDRATION on the Moon (1-3) and Mars (1-7)

The auger is placed over the site and lowered to the regolith ((1)). During excavation of the overburden layers, the various sensors will provide information to the experienced remote operator to enable layer identification and reconstruction of the digital core ((2)). The excavation will be considered complete when the auger is at least 12 inches into the ice, an experimentally determined depth which assures that the neck of the ice cavity will not melt and expand before we have finished collecting all the water and moved on to a new hole. At this point, the operator may elect to ream the hole at high vertical speed ((2)) and when the hole is deemed ready to accept the heater and inlet assembly, the auger will be withdrawn from the hole ((3)) and the Y-axis will translate by the right distance to position the heater over the hole ((4)). The heating element and inlet tube will be lowered into the hole ((5)). In the event that the heating element load cell detects resistance, a new hole will be prepared while the mud solidifies in the first hole ((1)) - ((3)), and then the auger will return to the first hole to ream it with a fast ROP / slow RPM one more time ((1)) - ((3)) and then try again to lower the heating element steps ((4)) - ((5)). The 500W heater will be activated to melt the ice in place and extract liquid water, while a peristaltic pump fit at the tube outlet above ground with a fine mesh filter will pump clean liquid water out of the hole and the operator will continuously lower the heater to the bottom of the ice cavity ((6)). The coarse and fine mesh filters screening contaminant from the liquid water are regenerable – running the pump in reverse will provide airflow or water which can clean out the filters. Upon completion the heating element and tube will be removed from the hole ((7)), and the assembly will be moved to a new location to repeat the operations and produce more water.

Water Extraction System / Technique: The HYDRATION mounting system, power supply and electronics are heritage from HYDRA [1], and supporting the new water extraction system which is based on the concept of high temperature radiative heating and continuous water extraction. On the Z1 axis, the drill stack features an 8A, 1 ⅛” rated Bosch rotary-percussive drill driving a 1” uncoated carbide-tipped steel drill bit with a spiral flute, multi-point design optimized for hammer and rotary drilling through masonry and concrete. The drill mounts to the stack with two large U-bolts and is adjusted using shims while the drill bit passes through a 1” bushing, enabling accurate vertical alignment. The down-hole 500W radiative heater with integrated water inlet is structurally supported and protected by a grounded, insulated ½” copper pipe which has been mounted on the Z2 axis. The parallel Z2 and Z1 axes are fastened together at three hard points and are driven together over three parallel rails. The mounting plate for the heater and inlet assembly has alignment screws enabling precise three-axis collimation of heater-and-inlet assembly with drill bit.

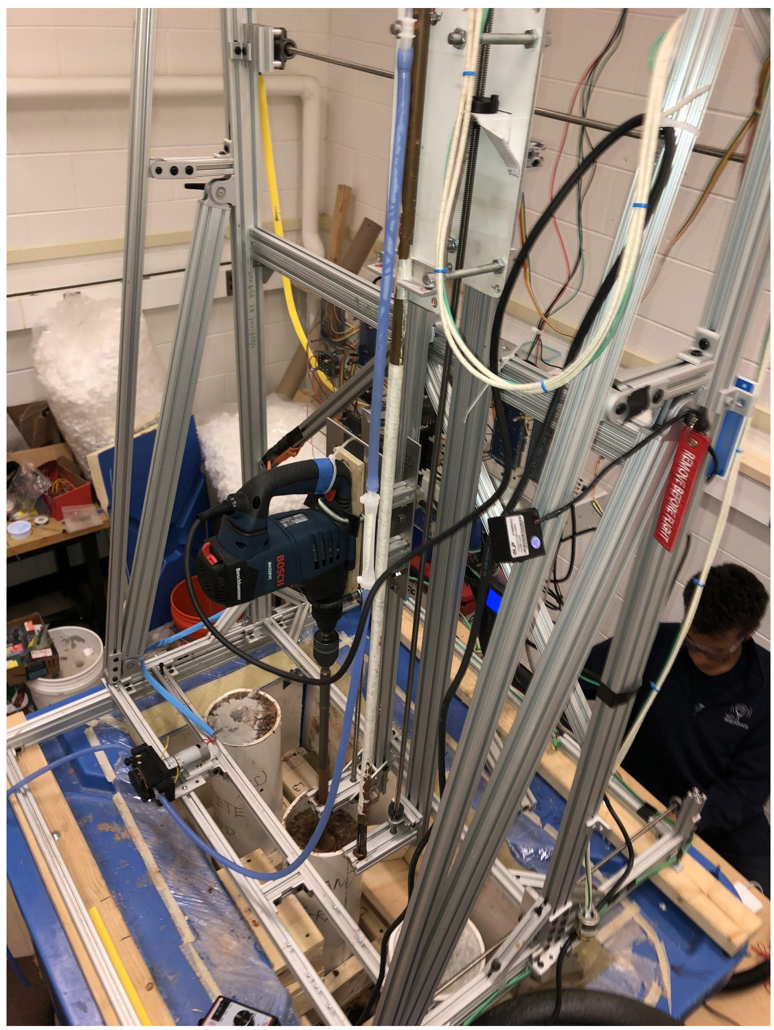

Figure 3(a): Mounting plate for heater and water inlet assembly, **3(b):** Restraining bushings for drill bit and heater assembly, **3(c):** Spherical 1.4 liter ice cavity melted by radiative heater and filled with dirty water.

A variable speed, reversible peristaltic pump lifts water from the hole, through the regenerative filter system and into the collection bin. Our integrated testing demonstrated that HYDRATION can drill through the overburden and into the ice in ~30 minutes; lower the heater-and-inlet assembly through the hole and into the ice in ~5 minutes; and extract 1.4 litres of water in 30 minutes by continuous pumping. The continuous pumping of cold water kept the heating element hotter and the structural copper pipe cool. As we had reported previously [cite our midterm report], this strategy resulted in efficiency gains relative to prior year attempts by other teams to maintain a pool of liquid water. The relatively cool copper pipe helped maintain the 1” neck above the ice cavity, mitigating the risk of cave-ins from above.

Our decision to pump water constantly was driven by experimentation. A test was performed using a 500W cylindrical cartridge heater at full power for 10 minutes in a predrilled hole in ice. At the beginning of the test, the heater was centered in the hole and not in contact with the ice except for the bottom tip of the heater. During the test, the heater gradually heated to 600C in areas where it was not in contact with water. The resulting hole shape was bulged at the top, showing that this heater could expand the hole more quickly using radiative heating than with conductive heating. The pump pickup for this test was a silicon hose that we had next to, but not touching, the heating element. Our next 500W heater test used constant pumping to keep the hole free of water and the heating element hotter for faster hole expansion. The pump pickup for this test was a 1 meter long, 3mm diameter steel line clamped to and supporting the heating element. This process resulted in an average of 32mL/min[1] for 35 minutes of heating. Significant losses were measured from heating the steel pickup pipe and the water, and the overall efficiency estimate was lower than an earlier 70W heating test (35% compared to 45%). However, the rate of water acquisition was promising, and as a result the team adopted the radiative operation of the heater with continuous pumping.

System/technique utilized for prospecting for a digital core: A data-driven approach to layer characterization was applied to create the digital core, inspired by the approach of Gui, et. al. (2002), where non-dimensional parameters for velocity and force were measured and evaluated for different layer materials. We will measure power consumption, WOB, rotation rate and z-axis vertical velocity during our drilling process, in addition to audio-visual inputs - a high frame-rate camera observing the drill site from above, and a ground microphone inspired by the Mars InSight lander seismographic experiment. To translate this data into thickness and hardness of the different layers, we have taken advantage of integrated testing to build up operator knowledge of layer type

[1] similar to what we obtained by radiatively melting in the full-size ice block during our integrated test

indicators by drilling into materials of different uniformity and different compressive strengths prior to the competition, and recording our observations from experiments as shown in Table 1 below. For the path to flight to the Moon, data from a large number of similar experiments can be used to pre-train a neural network and enable it to make predictions on the hardness of the materials in real time.

Table 1: Summary of learnings from HYDRATION digital core development campaign

	Indicative of sand or uncompacted fines	**Indicative of compacted clays - medium strength**	**Indicative of compacted clays mixed with gravel**	**Indicative of concrete - hardest material**	**Indicative of drilling in pure water ice**
Current sensor (Amperes)	~4.5A - 5A	~5A - 6.5A	~5A - 7A with irregular brief spikes	~7.9A	Very regular pattern ~5.4A (rotary) to ~6A (hammer)
WOB load cell sensor (N)	Steady, ~0N	Relatively steady <100N	Varies 50N - 130N	Relatively steady >100N	Steady (while in rotary mode)
RPM Hall effect sensor	Increase in RPM at transition	Up/down change in RPM at transition	Transients in RPM data	Decrease in RPM at transition	Steady RPM during drilling
Visual (camera)	Sand or fines mixed in with other materials at surface	Dry, dark mound at surface	Gravel appears at surface	Lighter cuttings overlying darker cuttings	Appearance of mud at surface shortly after entering ice
Ground microphone	Sounds similar to free-spinning drill bit	Deeper sounds with gradual changes	Irregular sounds	Loudest sounds	Steady sound pattern

Filtration and water collection: A peristaltic pump will pull water through a fine mesh filter with nominal 200 micron openings for filtration of meltwater particulate. The tradeoff between pressure drop, water quality, and clogging risk drove the selection of the actual filter size. When filter regeneration is needed, the pump can run in reverse to push air through the filter and send particles into the hole, thereby discarding any accumulated regolith. A risk with this design which will likely require hands-on time during the competition is mud accumulation at the downhole water inlet that the pump might not completely clear. However, for the path to flight to Mars this risk is mitigated as we collect water vapor through large openings above the heater which should not come into contact with mud.

Solution to mine through the overburden layers: The mining solution concept is driven by our need to prepare a 12” hole in the ice before inserting our cartridge heater and water inlet assembly. The Z1 axis, governing the vertical velocity of the drill bit and the WOB, will be managed by the operator to keep WOB within the set limit of < 150N. Different vertical speed settings will be used for different layers, relying on the skills of the operators which are being developed during integrated testing and pre-competition practice on our Bonar ice box testbed at MIT. Once the ice interface is identified and an initial ~6” - 8” of ice is drilled, the hole will be reamed 2-3 times at high vertical velocity, cutting into new ice each time until the depth of the hole in the ice block is ~12”. At that point the hole should be relatively clear and cased with mud produced from the meltwater (see picture on the right) and the drill bit will be removed to prepare for lowering the heater and water inlet assembly.

Control and communication system: The control system is similar to last year's HYDRA system [1], as shown in the picture on the right. HYDRATION is controlled through a laptop connected over USB to two Arduinos and a camera. One Arduino is dedicated to actuating the motors and pump and the other Arduino is dedicated to sensing. A MATLAB script controls the commands, and features a safe mode function that shuts down all systems. All stepper motors additionally have hard-wired switches to cut power if necessary. The heater drop mechanism has been accommodated by adding a fourth stepper motor for rigid actuation of the heater and water inlet assembly.

***Datalogger*:** A laptop running MATLAB records and displays data on power consumption and WOB in real time, via a serial interface to the sensor Arduino Mega. We are also adding the ability to log RPM data using a Hall effect sensor.

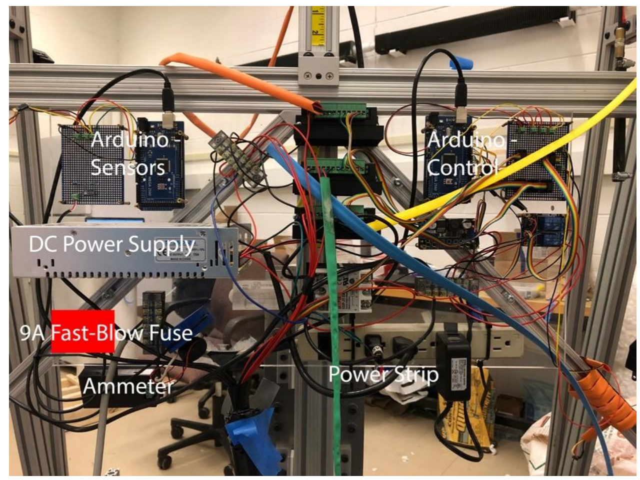

Figure 4: HYDRATION's control system is heritage from HYDRA [1]

Table 2: Technical Specifications for HYDRATION

Overall Mass	59 kg	**Max drilling speed**	900RPM
Overall Volume	$2m^3$	**Torque**	2.4 lb-ft
Length of Drill bit	0.997m (hard stop)	**On-board computer**	2x Arduino Mega 2560
WOB / Drill force	150N	**Communications interface**	Arduino Serial
Rated load	9A	**Software**	Arduino IDE and MATLAB
Power	<1200W	**Heater Power**	500W

Design Changes/Improvements: in the period since our project proposal in November 2018 and the midterm review in March 2019, our team has made the following changes to the design.

Table 3: Design changes log for HYDRATION

Change	**Reason**
Removed sleeve	Incompatible with heater design; experimentation indicated that meltwater from drilling into ice will produce mud which will help stabilize the sides of the hole.
Copper pipe casing for heater wires and pump inlet	For rigidity of the heater and inlet assembly during operations when it is being lowered into the hole.
Added Hall effect RPM sensor	Improve multi-sensor fusion capabilities, taking advantage of the built-in clutch of our Bosch drill, which progressively disengages under excess load, to capture data on involuntary RPM changes
Added heat resistant wiring and grounding for heater	For safety, in case the heater cartridge is flooded, to reduce the risk of short and electric shock.
De-scoped neural net for layer detection	The full neural net has not been implemented for the competition version due to a lack of resources to develop sufficient training data.
Removed downhole thermometer	This was done for simplicity. Frozen bits can be prevented with an appropriate operational concept (OPSCON) of “never stop moving”.
Removed second Y axis (see Fig. 1)	For reduction in mass, complexity and cost, and to achieve better alignment between drill bit and heater and inlet assembly
Replaced ¾” drill bit with a 1” drill bit	Although the ¾” drill bit was very effective at cutting through concrete, we replaced it with a 1” drill bit because the hole was too narrow for the tolerances we could achieve in lowering the heater and water inlet boom.

Challenges: The most important challenge we faced was with the detailed design of the sleeve. It seemed to be expensive engineering-wise, and its operations could not easily be reconciled with our concept which required a separate heater and water inlet. Upon subsystem testing (drilling through overburden and ice directly below it) we noticed that meltwater from the drilling would produce mud which would then case and stabilize the hole, even for layers which were relatively uncompacted and prone to collapse. So we mitigated the challenge of the sleeve by abandoning it and developing more involved drilling and hole reaming operations.

Another challenge was designing the WOB sensor to get an accurate reading with the drill’s hammer action. On last year’s HYDRA, the WOB sensor was placed between the bit and the drill motor. This year, the hammer action in the drill motor requires that the WOB sensor be placed in the load path between the drill motor and HYDRATION’s structure. Since the WOB load is transferred through the drill to the Z1-axis lead screw, the WOB sensor has been located between the lead screw motor and the structure. Although this is far removed from the bit itself, we have verified the weight on bit load by pressing the bit into a scale up to 150 N and calibrating our MATLAB interface so that the WOB sensor reads the same load.

Overall Strategy for the Competition: To improve the accuracy of our digital core, we have characterized a number of independent potential indicators of the layer that the bit is traversing. These indicators include power draw, WOB, visual images, sound and the rotation rate of the drill bit. With experience, our operators will be able to recognize the patterns associated with the different layers. For the path to flight to the Moon, a neural net will be able to reliably do the same. To maximize the water recovery, after experimentation we have settled on a high-temperature radiative heating concept with constant water pumping, exploiting the $Q = \varepsilon\sigma A T^4$ relationship and the geometry of the hole in the ice to achieve efficient heat transfer from the radiative heater to the exposed ice surfaces resulting in constant production of cold water. The low energy losses are evident in the cold temperature of the extracted water, which also has the beneficial side effect of keeping our inlet tube cool and reducing transfer of heat to the neck of the ice cavity which supports all the overburden above the heater and water inlet.

Summary of Integration and Test Plan: our testing plan started in January, initially with subsystem tests of each of the following: drill and drill bit test through 20cm of concrete, heater test, pump test, stepper motor tests (X, Y, Z1 and Z2 axes), load cell and current draw calibration, load cell and current draw data logging. Subsequently, we progressed to integrated tests of pairs or groups of related subsystems, such as the Z1 motor, the drill, the load cell and the current draw meter, or the heater, water inlet, filtration system and the pump. We have completed six hours of continuous integrated testing, simulating one full day at the competition. During these tests, we have drilled five holes through all types of overburden, of which one hole was through overburden and ice and another was a hole drilled directly into the ice to characterize heater operation under ideal conditions. We report that drilling a hole takes ~30 minutes, aligning and lowering the heater takes ~10 minutes, and melting 1.4 liters of water takes ~30 minutes. For these full-system-level integrated tests, the completed HYDRATION system has been mounted on our Bonar Polar Ice box which was inherited from last year's HYDRA [1]. To support the testing, we have designed and built the following two test items (1) a coolant loop to maintain the ice blocks frozen throughout our testing period, and (2) a low-mass simulation of various configurations of anticipated overburden layers, laid down inside 20" x 6" PVC pipes which are secured by wooden framing and which are placed directly on the ice block.

Figure 5: We created three different layered cores for use during integration testing, in order to assist with the development of digital indicators for the interpretation of layers at the competition. The cores are easy to lift and remove / replace and give access to the ice below in order to allow "post mortem" examination of each drilling experiment.

Tactical Plan for Contingencies/Redundancies: During drilling, HYDRATION uses a "low speed" setting of about 2.5cm/minute. A "high speed" mode moves the drill by ~12.5cm/minute and can be used in ice. The drill speed is currently controlled by hand using a plug-in speed controller, and the heater is controlled via the laptop, but can also be unplugged from the standard socket by hand if necessary. In the event of a damaged drill motor, we have purchased a second, identical drill motor which we will carry to the competition as a spare. All stepper motors and stepper motor controllers are identical, and we will carry one spare of each to the competition. As they are identical, we can use any of the controllers with any of the steppers, meaning we can instantly recover from a burnt controller contingency. A burnt stepper motor contingency will require a replacement which will take longer, and for this we will have the necessary tools and spares on hand. In the event of a blocked downhole water inlet, we will use the downhole heater and the water pump in reverse to attempt to clear it. The heater will warm and expand the metal brake line inlet, and the water pump will create pressure to expel the blocking material from the inlet. We will have spare mesh to replace the coarse mesh before the inlet if needed. In the event of a burnt Arduino controller, we will have two spares already flashed with the correct programs. Also, we will have two laptops with the same Matlab script already loaded and tested.

Project Timeline: Concept generation and project proposal took place in November 2018. Concept selection followed in December. Detailed design of the drill stack and heater subsystem followed in January 2019, together with procurement and modifications of the existing HYDRA [1] to accommodate the new subsystems. In February we iterated on both the drill bit size (from ¾" to 1") and on the heater power (from 70W to 500W). By March we had completed extensive testing at the subsystem level, and through extensive experimentation identified our preferred strategy of continuous pumping to minimize the time needed to collect all the water from a hole before moving on. In April we completed substantial mechanical works to integrate the new subsystems on the old HYDRA structure, and in parallel we completed the modifications to the MATLAB code. In early May we constructed the facilities for integrated testing, completed integration and started integrated testing with HYDRATION mounted on the Bonar box under competition-like conditions.

Safety Plan: No chemicals or hazardous materials are used on or around the prospecting robot, including that we do not use dry ice. No hazardous or flammable chemicals are used or stored in the project room to protect against fires and air quality issues. No alcohol is allowed in the room and no one is allowed in the room while impaired. In case of medical issues MIT Campus police will be informed and the injured party will be taken to MIT's campus medical facility, about 1200' distant, or to one of the many excellent local hospitals within 2 miles of the workroom for further treatment. We are explicitly not keeping a first aid kit in the room, as is campus policy, due to the close proximity of free, professional help.

We have outfitted the room with personal ear protection, personal eye protection, thermal gloves, and each team member carries a cell phone until the university installs a land line in case we need to call for help. The HYDRATION team agrees that any operational testing involving the heater or the drill requires that at least two team members are present. Team members handling portions of the heating system while in use or shortly after use must wear thermally-protective gloves. A bucket of water is kept nearby to quench the heater after use. All team members working with or near the drill must wear safety glasses and earplugs during operation. When working on the drill, it must stay unplugged until it is safe to use. The electrical system must be unplugged when not in use and when being serviced or modified. All wires are insulated or shrink-wrapped to prevent shorts. Currently the frame is not grounded (the drill is double-insulated, unmodified, and UL approved; all other electronics are low voltage) but the copper tube which supports the line voltage heater (120VAC) and water inlet is grounded.

We have a domestic refrigerator, two old car radiators and a pump which have been converted into a heat exchanger so that we can maintain frozen ice blocks in the Bonar Box indefinitely, in our small, enclosed lab, mitigating the suffocation danger inherent in the use of dry ice. This system uses pumped antifreeze to extract heat from the Bonar box and reject it into the freezer cabinet where one of our two car radiators has been located. We did not disassemble the refrigerator, merely drilled holes in its side to pass through the inlet and outlet pipes. The floor is covered with vinyl composite tile, which is electrically insulating but a slipping concern should water spill. The room has a wet/dry shop vac and paper towels for spill cleanup.

All electrical outlets, which wrap three sides of the room, are grounded. Extension cord use is very limited because of the convenience of the outlets, which reduces both tripping hazards and the potential for the cord to get damaged as it could be walked on or have equipment dragged over it if it were left out.

The most important safety consideration is the mindset of the team. Before starting an experiment, we ask what failure modes exist and ensure that these risks are mitigated, which is more valuable than all the rules and equipment we can buy.

Path to Flight

This project poses a unique challenge: build an Earth-based analog that will be an effective demonstration of a water extraction and prospecting system which will ultimately be used on the Moon and Mars. In our design process we were simultaneously thinking of (i) a concept for efficient and robust extraction of water from buried ice sheets on Mars, (ii) a concept for reliably obtaining data on the layers of rock on the Moon (iii) an Earth-based analog concept for testing purposes, and (iv) minimizing the differences between the Earth analog, the Moon and the Mars systems. The HYDRATION system, if modified for flight as proposed, will be able to generate digital cores of different regolith layers on the Moon and carry out water extraction on Mars under the remote control or supervision of crew.

Path to Flight for Mars Water Extraction: A relatively small number of changes to HYDRATION, most of them reducing the part count, system complexity or system risk, can convert the Earth-conditions prototype into a system that is capable of flight to Mars. Changes to the CONOPS (Figure 2 above) have been discussed already in the system description above, and are also highlighted in Table 4 below, where the sublimation is considered as an alternative to melting, and a cold trap and scroll compressor will replace the peristaltic pump and filtration system. These changes to the CONOPS will allow us to reach our goal of retrieving liquid water under Mars conditions.

Table 4. CONOPS changes for Mars version of HYDRATION

Component of CONOPS	Changes for Mars System
Auger in Regolith	The Mars system will be built to handle a variety of regolith substrates and clays. No major changes anticipated.
Begin Drilling Ice	Some sublimation will occur before HYDRATION can seal the hole. However, according to literature, it will not occur at a rate that causes significant loss of water to our system. In addition the volumetric expansion of the gas in sublimation in the low ambient pressure of Mars will entrain particulates and assist with clearing the hole, as per the literature (Zacny)
Melt/Sublimate Ice	The Mars system will sublimate the water ice, collect the water vapor and condense it in a cold trap, rather than melt it. This has the added benefit of purifying the water and reducing operational risk, as the vapor inlets can be all along the rod above the heater, rather than below the heater where there is risk of mud clogging the coarse filters.
Water Collection	The peristaltic pump and filter will be removed. Instead, vapors will travel through a scroll compressor to pressurize the water vapor, and then into a cold trap to cool the vapors into a liquid. The purified liquid water will be gravity-fed to a collection tank. To prevent loss of water vapor to the atmosphere, pressure from the scroll compressor will be used to inflate a choke around the rod housing the downhole equipment, thereby sealing the hole. Extensive testing will be required.

Comparison of Critical Figures of Merit (FOM) for path-to-flight to Mars: We anticipate the following impacts to critical FOM of our HYDRATION system as a result of path-to-flight adaptations for Mars, as shown in Table 5 below:

Table 5. Figures of Merit impacted by path-to-flight changes for Mars

Metric	Difference	Explanation
Mass & Volume	No change to mass or volume	Taking advantage of sublimation will allow us to remove the pump and filtering mechanism from the Earth system. However, a compressor will be added. Overall dimensions remain the same.
Power	Decrease	Sublimation on Mars may require less power than melting ice on Earth, and thermal losses may also be lower on Mars. An overall decrease in power is expected, but further analysis is required.
Reliability	Neutral	Sublimation on Mars requires no filter regeneration, giving the Mars system an advantage for reliability relative to the Earth prototype.
Water Production Rate	Neutral / Decrease	Time will be saved in the Mars system because filtration and cleaning of the filter are not required. However, sublimation will likely take longer than melting and pumping of the ice on Earth. Water production rate will be ~same, or less.
System Lifetime	Increase	Mars system will likely have longer lifetime because it has fewer moving parts, and because the productivity of water for each hole drilled is expected to be higher, as it will be easier to cause sublimation on Mars at a larger distance from the 500W radiator than it is to cause melting on Earth at the same distance.

Other Factors Considered - Mars: In addition to the challenges with sublimation arising from Mars ambient conditions, several path-to-flight factors were taken into consideration when designing and selecting the final architecture.

1. *Regolith*: The depth and hardness of regolith on Mars will be more variable than during the competition. By keeping the drill hole diameter to a minimum, our system can more easily be upgraded to a Mars-ready system that has the margin of power necessary to work under varying regolith conditions while still being able to lower a heater down to the ice.

2. *Simplicity*: In a remotely operated system, particularly one in a new and harsh environment like Mars, simplicity is key. We designed our solution to have the fewest number of moving parts possible while still completing its job. This decrease in system complexity ultimately increases our system reliability.
3. *Reduced Gravity:* Reduced gravity should not have significant effects on the system.
4. *Launch Environment*: The launch environment is harsh, and includes significant acoustic and vibrational loads. The Moon/Mars system will have to be built to withstand the rigors of the launch environment.
5. *Radiation Environment:*The radiation environment on Mars requires special hardware, particularly electronics. This consideration is factored in by limiting ourselves to similarly performing hardware, such as the Arduino, to run the control software.
6. *Dust:* Fine-grained dust on the surface presents a risk to moving parts in the drill and translation systems, as well as electronic components. For Mars, a HEPA filter could be used on component air intakes to protect these components from abrasive damage and clogging.
7. *Perchlorates*: Perchlorates detected in the Martian soil have the potential to poison any water supply generated by ISRU technology on Mars. Perchlorates can be successfully separated from water by distillation, so the distillation process proposed here will eliminate this problem. This gives the project a major extensibility advantage over proposals that do not consider this factor.
8. *Filtering*: When operating remotely on Mars, it is unacceptable for a clogged filter to halt water harvesting and end the mission. Our Mars system, however, does not require a filter, as the water is distilled.

Path to Flight for Lunar Digital Core / Prospecting: The prospecting portions of the HYDRATION system hardware include the mounting structure, translation, and drill functions, and exclude the heating element, pump, and filtration system. The latter set of components can simply be removed to leave a prospecting-capable system. For the CONOPS (Figure 1, above) this change removes steps 4 -7; no significant changes are otherwise expected. This modular system allows adaptability between the Moon and Mars. The data-driven approach to creating the digital core is robust to different types of layers, and can be applied to both the Moon and Mars.

***Thermal*:** On the Moon, there will be no atmosphere to convectively regulate heat generated from drilling or daily temperature changes. In addition, the system will spend long periods of time (>14 days) in or out of sunlight, depending on landing location. The Moon system will likely need an active thermal control system to keep itself within operating temperatures and a power source to keep going during the lunar night, or alternatively it can be landed near the Lunar South pole in a location with perpetual light.

Dust: Fine-grained dust on the surface presents a risk to moving parts in the drill and translation systems, as well as electronic components. For the Moon, an onboard dust purging system or additional dust coverings would be required.

Radiation Environment: The radiation environment on the Moon requires special hardware, particularly electronics. This consideration is factored in by limiting ourselves to similarly performing hardware, such as the Arduino, to run the control software.

Simplicity, Reduced Gravity and Launch environment: the same considerations applying for the Mars path to flight (above) apply also for the lunar path to flight.

Remote operation opportunities: given the short round-trip light travel time from Earth, the opportunities for a robotic, semi-autonomous, fully tele-operated system on the Moon are different than those on Mars. Operators on Earth can direct prospecting operations in near-real time. This is expected to significantly influence the design of the flight system for the Moon.

Budget:

	Cost		
Test station			
Test station support equipment	$ 1,792.51		
Refrigeration supplies	$ 160.00		
Ice	$ 220.00		
		$ 2,172.51	
HYDRATION system			
Structure	$ 3,200.00		
New drills, drill bit and heater	$ 810.00		
Power, sensors and controls	$ 970.00		
Other	$ 600.00		
		$ 5,580.00	
Logistics			
Shipping, travel and registration	$ 2,152.00		
		$ 2,152.00	
Grand total			**$ 9,904.51**

References

[1] Lordos, G., Arzuaga, I., Ge, C., Hinterman, E., Maupin, M., Moraguez, M., Sumini, V., Trujillo, A., Villamor, R., "HYDRA: High Yield Dihydrogen-monoxide Retrieval Assembly Final Report", RASC-AL Special Edition Mars Ice Challenge Forum, Hampton, VA, May 2018

[2] Zacny, K., Robotics, H., Indyk, S., Luczek, K., Paz, A., & LEAG, J. (2015). Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU). *Earth and Space*, 378.