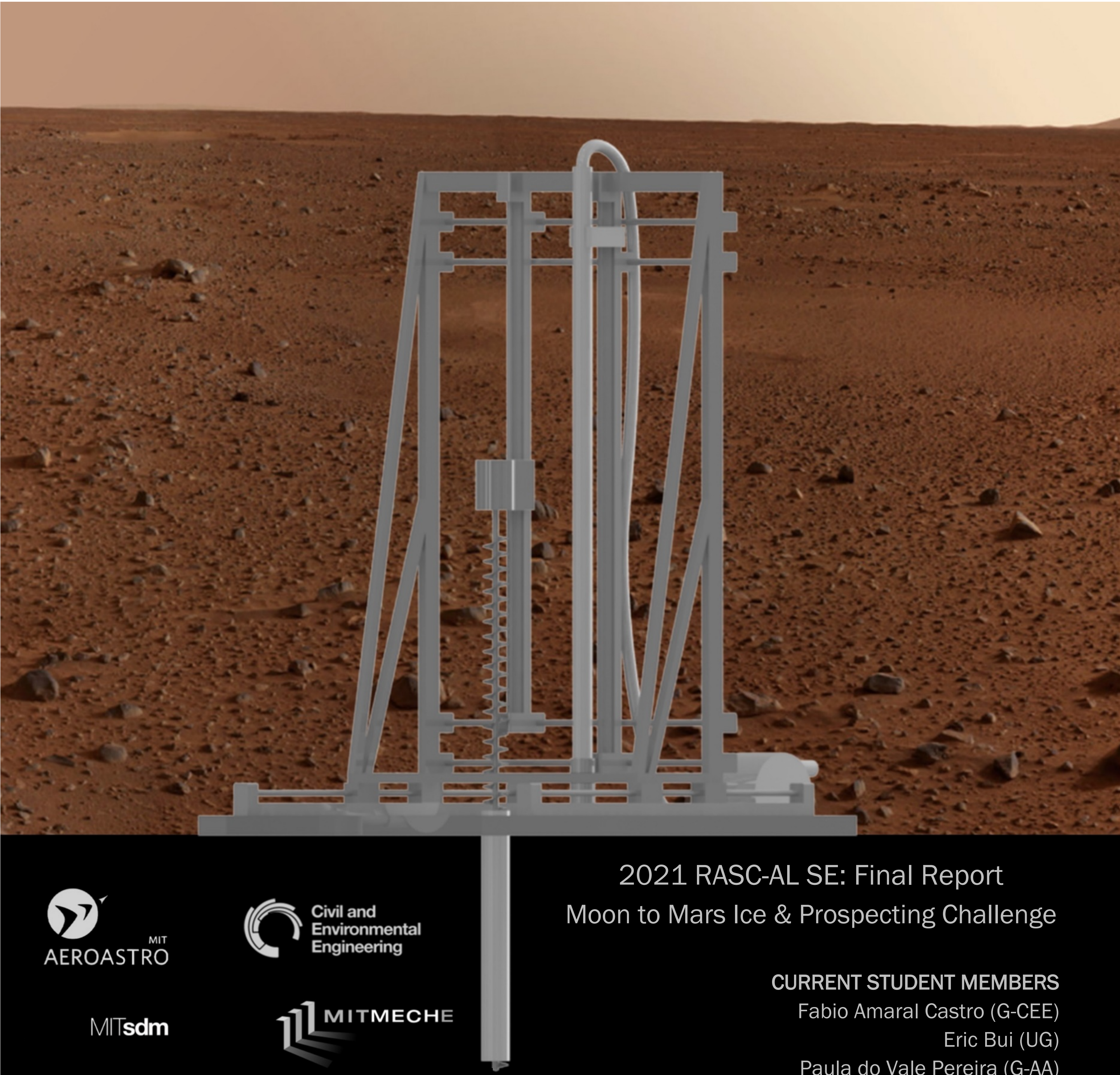

2021 RASC-AL SE: Final Report

Moon to Mars Ice & Prospecting Challenge

MIT Space Resources Workshop

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HYDRATION III

Massachusetts Institute of Technology

High **Y**ield **D**ihydrogen-monoxide **R**etrieval **A**nd **T**errain **I**dentification **O**n **N**ew worlds **III**

1 Executive Summary

NASA is returning to the Moon with the Artemis project, this time to stay and to develop technologies for the exploration of Mars. Sustainably staying on the Moon and Mars requires technology development to utilize water that is bound up in subsurface ice. MIT's HYDRATION III is an Earth-conditions proof of concept for a semi-autonomous water ice mining system for Mars which also serves as a prospecting system to classify layers of underlying rock or regolith on the Moon using an artificial neural network.

The remotely-controlled HYDRATION III system drills a self-casing borehole through the simulated overburden layers and into the simulated ice sheet. It then retracts the drill bit, translates by a fixed distance and lowers a cylindrical 700W radiative heater into the ice sheet with a regenerative filter and intake to melt and collect the water. In addition, high-resolution data is collected during drilling by sensors including power, weight on bit, accelerometer and torque on lead screw. The time-stamped sensor data stream is fed into a pre-trained neural net to automate the remote identification of the overburden layers, yielding a "digital core".

Our goals with HYDRATION III were to improve system reliability, develop a remote operability capability and improve system efficiency and performance. Since the March 2021 midterm report, we have performed 11 integrated tests, of which 8 involved a full system tests. These tests uncovered weaknesses in our design and production and allowed us the opportunity to iterate both the design and the execution to get closer to our project goals. The last two integrated tests on August 21st and August 28th delivered the success we were looking for: full validation of the drilling assembly and hands-off production of water. This report describes our system and our final development efforts.

We are grateful to NIA / NASA for the funding support, MIT's Department of Aeronautics and Astronautics and MassRobotics for providing us with workspaces, to our undergraduate friends at EPFL who contributed their ideas, sub-assemblies and analyses and to the analog astronauts of the ASCLEPIOS mission who served as beta testers of HYDRATION III on July 19th. Thank you!

2 System Description

2.1 System Overview

The major elements of the HYDRATION III system, shown in Fig. 1 below, include an auger apparatus, the down-hole heating system, a peristaltic pump and tubing, the filtration system, the sensors providing data for the mission control and digital core systems, as well as various motors, control, communications and power systems supporting remotely controlled semi-autonomous operations.

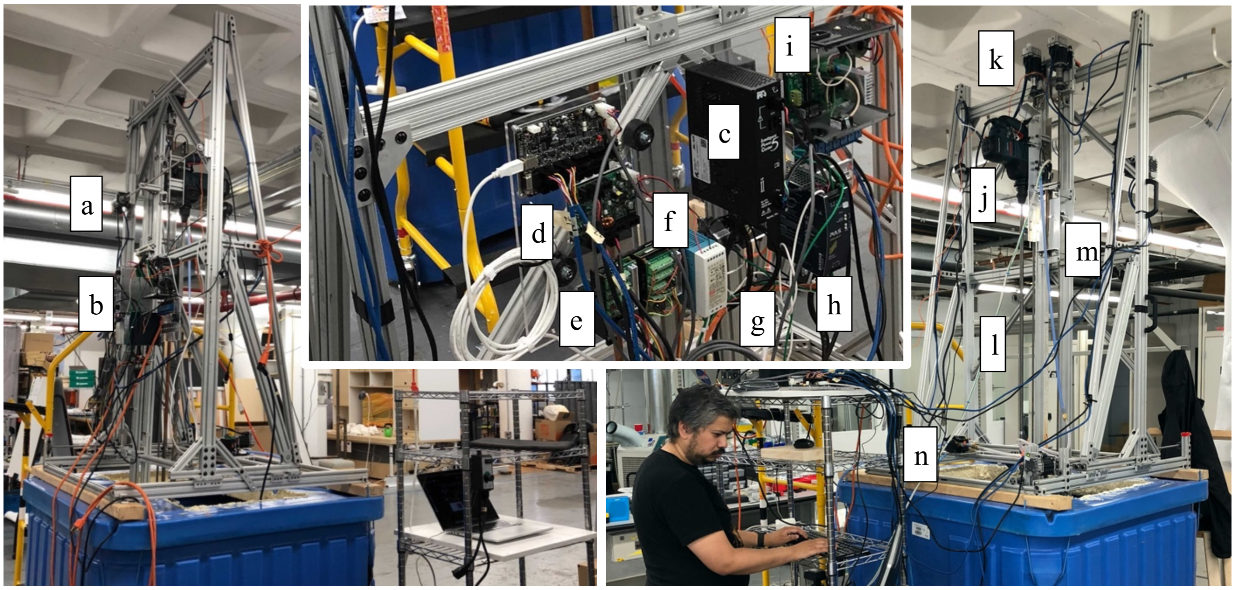


Figure 1 HYDRATION III mounted on MIT test station. Key subsystems: (a) Y-axis servo motor and lead screw (b) e-panel mounted on structural frame using anti-vibration dampers (c) 75VDC power supply for servos (d) servo control hub and PDU (e) two RaspberryPi computers (f) 5V PSU for computers (g) power meter (h) 24V PSU for pump and control boards (i) triac controller for drill and heater setpoint control (j) 8A rotary hammer drill motor (k) Z1 and Z2 axis servos and lead screws with in-line S-shape load cells (l) 1" carbide-tipped concrete drill bit (m) heater, water pickup and regenerative filter stack and (n) peristaltic water pump

2.2 Concept of Operations

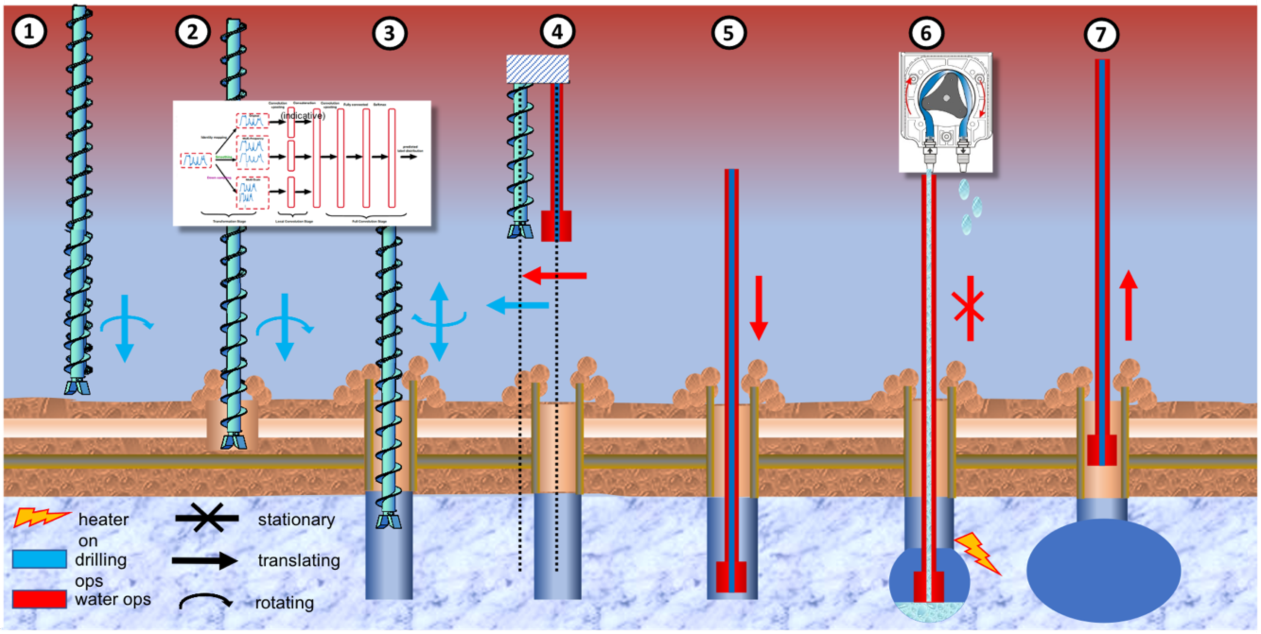
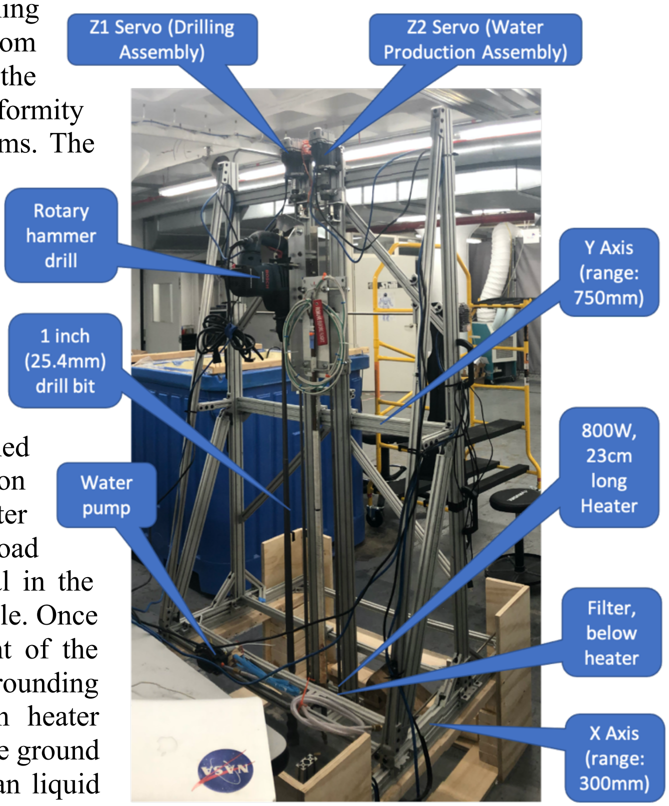


Figure 2 Concept of Operations for HYDRATION III: (1) position drill bit and set the zero level (2) drill through overburden while collecting sensor data (3) continue drilling through ice, build mud casing and extract drill bit (4) translate heater stack over borehole (5) lower heater stack into ice layer (6) activate 700W heater and peristaltic pump, collect water while regenerating the downhole filter as needed (7) extract heater stack from empty borehole and move to a new location

In the below, the numbers in double parentheses refer to the 7 stages in Fig. 2 above, the graphical CONOPS for our system. From left to right, ((1)) the drill bit is activated and lowered over the selected site, where we set the zero level relative to the top of the overburden. At ((2)), the Z1 servo drives the spinning drill bit into the overburden, but some material might still fall into the hole either before or while the clay mud wall is being formed. The instantaneous power, weight on bit, torque on bit and vibration-induced accelerations are logged for later analysis and also fed back to the experienced operator, who monitors operations and issues updated commands to the controller of the Z1-axis servo motor with a view to maintaining maximum ROP subject to not breaching WOB limits. The transition into clean ice - going from ((2)) to ((3)) – is marked by the appearance of water at the top of the borehole and by a distinct shift to stable uniformity and regularity in the patterns of all sensor data streams. The excavation of the borehole will be considered complete once the auger has penetrated approximately 400mm into the ice, allowing for an intact ice neck to remain in place above the radiative heater during the melting phase. At the end of ((3)), once the mud wall lining and the ice borehole have been constructed, the auger will be withdrawn, followed by ((4)) where the entire Z1-Z2 axis assembly will be translated by a fixed, predetermined distance of 132mm so as to position the water production stack directly over the borehole. In ((5)) the water production stack is lowered into the hole, with a Z2 load cell providing feedback on any contact with material in the sides or at or near the anticipated bottom of the borehole. Once the heater is in position fully inside the ice segment of the borehole, in ((6)) the heater is activated to melt the surrounding ice and produce liquid water. Simultaneously with heater activation, a peristaltic pump fit at the tube outlet above ground with a fine mesh filter is also activated to pump clean liquid water out of the hole. The fine mesh filter screening contaminant from the liquid water is regenerable – running the pump in reverse will provide airflow which can clean out the mesh. This stage lasts for 20 – 30 minutes and results in a cavity of a few inches in diameter as well as high-yield production of cold water. Finally at ((7)), when water flow rate has slowed significantly, this signals that the ice cavern is too large and that meltwater production rate is falling while refreezing rate is rising. At the point where net water production slows to a trickle or suddenly stops without a vacuum forming in the inlet silicone tube, the water production stack will be removed from the hole and the system will be ready to drill another hole at a new location.



2.3 Mounting System

HYDRATION III has been mounted on the Bonar box in the same manner as the previous years' HYDRA [1] and HYDRATION [2, 3] projects, with some changes to the structure to reduce vibrations, reduce mass and improve system reliability. Specifically, we have shortened the structural frame by 22cm and we have reduced the degrees of freedom of the translating carriers from four to three by removing the

X-axis servo, without surrendering path-to-flight realism / relevance. As in previous years, the base of these carriers will be screwed directly into the two wooden beams on top of the bin at four points using 1” 80/20 corner brackets. The structure is made of aluminum for its high strength to weight ratio and 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.

2.4 Mining through Overburden Layers

Based on previous research and experience acquired through testing, the baseline subsystem for penetrating the overburden is a rotary hammer drill bit and auger, inspired by the PVEx planetary volatiles extractor concept [4]. The drill stack features a ClearPath CPM-SCHP-2341S-ELNB servo motor with integrated driver and controller, and an 8A, 1 ⅛” rated Bosch RH328VC 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. A S-gauge in-line load cell, shown as installed between the fixed frame and the floating lead-screw bearing in the picture inset, delivers reliable weight on bit data which has been calibrated and validated. The HYDRATION III drilling assembly can reliably produce a stable mud lining along the borehole walls using a small amount of meltwater produced by the drill bit together with remotely commanded operations where we vary: the rate of penetration (RPM of Z1 servo); the speed of the drill motor (RPM of the drill bit); and the direction of vertical movement of the drill bit. A careful choreography of steps before and after penetrating the ice layer results in a stable borehole mud lining which is essential for water production.

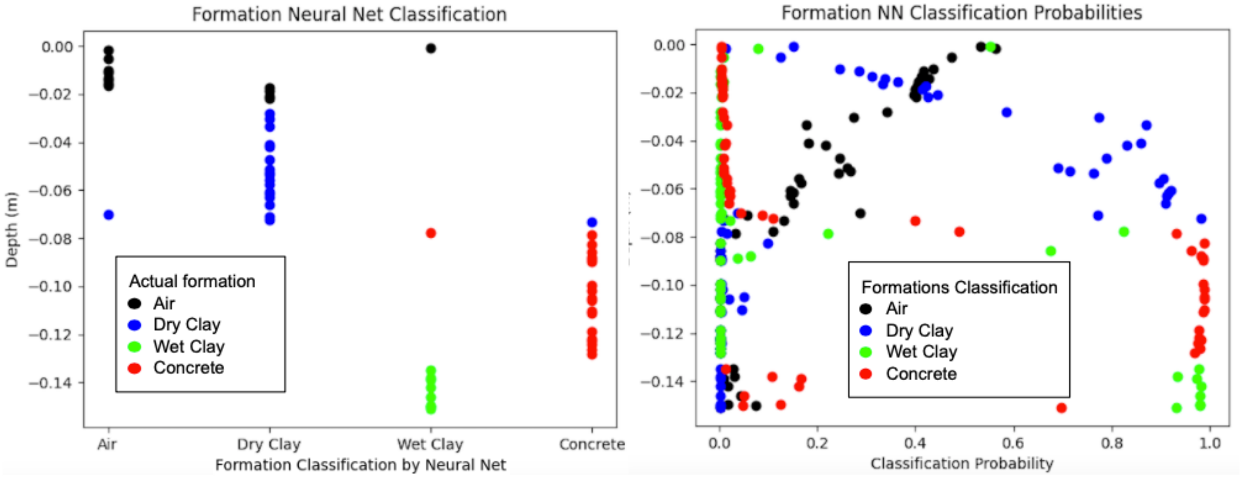
2.5 Drilling Telemetry for Digital Core

Torque on Bit (NEW)	Drill bit vertical position (NEW)	Rate of penetration (NEW)	Commanded Z1 servo RPM (signed integer)
Weight on Bit	Total current draw	Drilling vibrations	Commanded drilling power (% of max)

A data-driven approach to layer characterization will be applied to create the digital core. This year we have three new sensors and all sensors have been upgraded using higher quality equipment, such as the power meter shown on the right, the S-gauge load cells, and the built-in encoders and torque measurements reported by our ClearPath servo motors. Time-stamped data from all sensors, collected at 10Hz during integrated testing, is being used to train a machine learning model to identify transitions and differences between the varying layer materials. All sensor outputs are converted to 0 - 3.3V/5V/12V signals and fed to the analog inputs to be stored as time-lapse data on the Pi. Statistical features of these sets, including mean, median (using bins), standard deviation and range / variance, will be calculated using the moving average method. These statistical features as well as the raw datasets will be the inputs to our machine learning (ML) classifier to predict the composition and layer thickness (i.e. the depths of transitions between layers) of the simulated regolith. During operational drilling at the forum or by a flight article, sensor data streams as well as command inputs will be logged and time-stamped and the data will be fed to a pre-trained machine learning algorithm to estimate the relative hardness and thickness of the ground layers. As a backup and/or validation of the ML classifier output, the raw data will also be

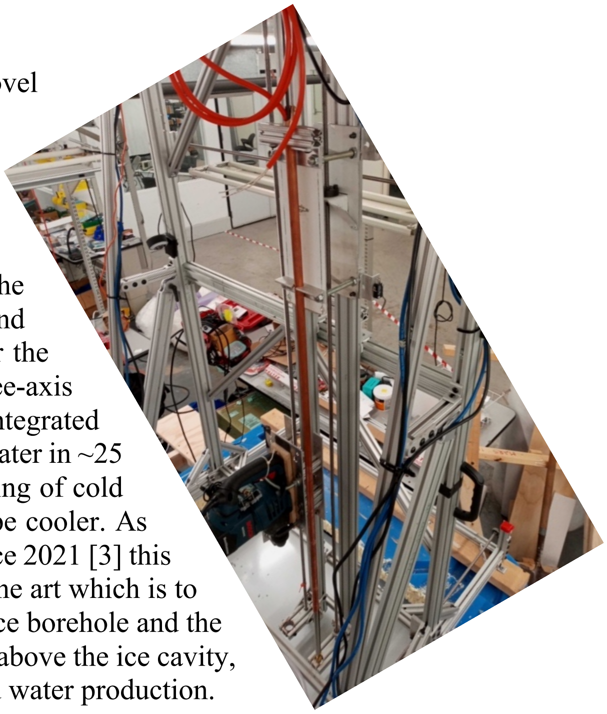
visualized on charts where vertical distance is on one axis and normalized sensor data streams on the other axis, supporting the operator to make a determination regarding layer transitions and hardness.

The functional neural net, with 3 layers of respective 8, 12 and 8 nodes, takes as inputs the sensor measurements for electrical current, electrical power, rotations per minute, vibrations in x, y and z directions, weight on bit and rate of penetration. It predicts the probability of the sampled layer to belong to each type of formation. The neural net training parameters (layers, number of iterations and learning rate) will be will then be set in order to maximize prediction accuracy in testing sets. The charts below show test results after training and testing the neural net into random training and testing sets of the same hole.



2.6 Water Extraction System

The HYDRATION III water extraction system is a novel “R**a**dwell” concept, relying on high temperature radiative heating and continuous water extraction from an initially mechanically-excavated 1” borehole. The downhole 700W, 50mm x 270mm cylindrical radiative heater with integrated water inlet and 1/8” downhole filter 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 the heater-and-inlet assembly with the drill bit. Our integrated testing demonstrated that HYDRATION III can extract ~2 litres of water in ~25 minutes of continuous melting and pumping. The continuous pumping of cold water keeps the heating element hotter and the structural copper pipe cooler. As we had reported previously at the 2019 forum [2] and at Earth & Space 2021 [3] this strategy resulted in efficiency gains relative to the Rodwell state of the art which is to maintain a pool of liquid water [5]. The initial 400mm depth of the ice borehole and the relatively cool copper pipe contribute to maintaining the 1” ice neck above the ice cavity, mitigating the risk of cave-ins from above which would abruptly end water production.



2.7 Water Filtration and Collection

A 300rpm reversible peristaltic pump pulls water through a fine mesh downhole filter with nominal 200 micron openings for filtration of meltwater particulate. In HYDRATION III this ‘filter’ is in fact a bronze air muffler, a commercial off the shelf (COTS) automobile part. The tradeoff between pressure drop, water quality, and clogging risk drove the selection of the actual filter size and material. When filter regeneration is needed, the pump can be run in reverse to push air through the filter and send particles into the hole, temporarily stopped to flood the hole, restarted and reversed several times, thereby diluting and discarding some of the accumulated mud coating. 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.

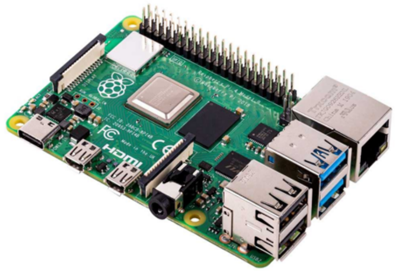
2.8 Managing Temperature Changes to Prevent Drill from Freezing

The techniques to prevent the drill bit from freezing in the hole are based on operational protocol supported by our hardware capabilities. The last line of defense from freezing is that, while in ice, the drill will be kept spinning under all circumstances. The first line of defense is to avoid producing excessive meltwater. Thus, drill RPM and Z1 servo RPM will be controlled to produce only the necessary and sufficient meltwater for the construction of the mud wall borehole casing. Once the mud wall forms and firms up, the drill bit will be fully raised out of the borehole to the zero level of the bushing to snap off any accumulated ice from the flutes. Then, with a cleaner drill bit, the remainder of the 400mm borehole segment will be drilled through the ice using a relatively higher Z1 servo RPM (45-60) and a relatively lower drill power level (70% - 80%). In our experience during testing, this still maintains WOB near the allowed limits, but it also triggers the rotary hammer's percussion function, leading to reduced total downhole energy transfer and thereby to less meltwater production and more ice shavings being excavated and removed.

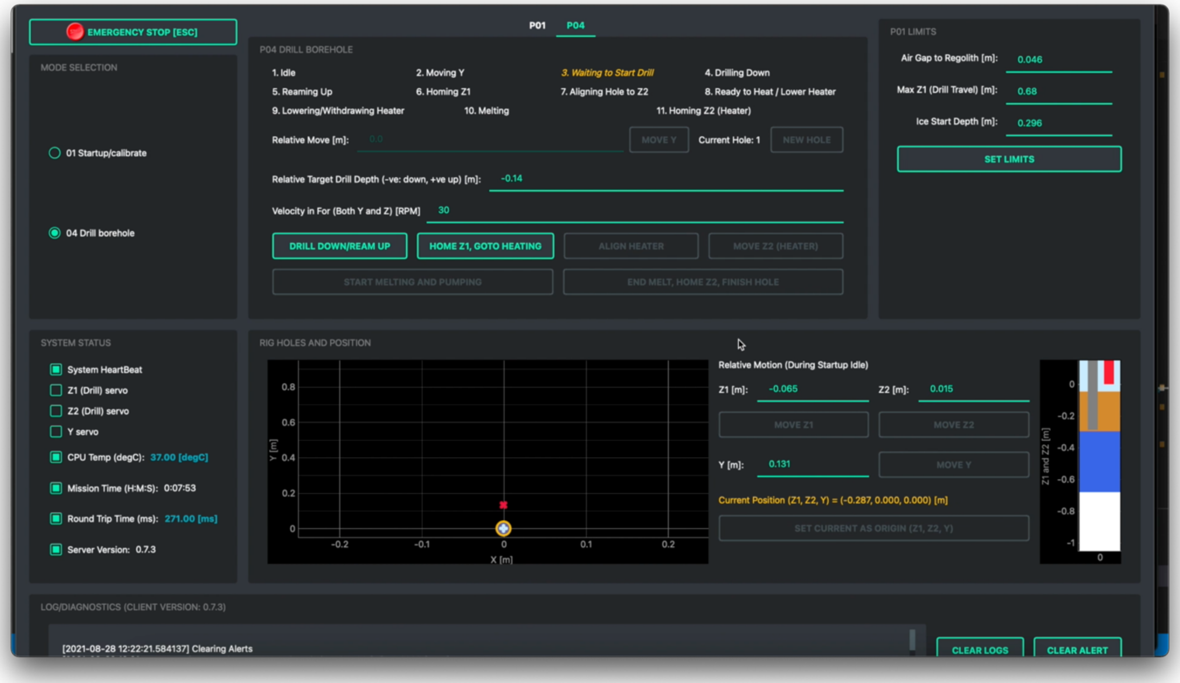
2.9 Datalogger for Current and Weight on Bit

A Raspberry Pi continuously records total system current and weight on bit and logs them in timestamped files which are exported every 5 minutes and visualized for the operator's reference.

2.10 Control and Communication System



Two Raspberry Pi 4 embedded controllers installed on our e-panel run our custom Mission Control server thread and communicate wirelessly via SSH over 802.11ac to client laptop computers which run our custom client Mission Control software. The first Raspberry Pi communicates with the Z1, Z2 and Y servo motors via the ClearPath hub using its high-speed USB 3.0 port and also interacts with the operator, translating operator commands to actuator instructions. It also controls the drill motor and heater via a triac, and the pump through a stepper motor driver. The Mission Control software, screenshot in Fig. 3 below, is structured to lead the operator through a sequence of nominal operations steps and provides emergency stop of the servos and various remote operations capabilities for use in contingencies including sensor readouts, movement of any axis and actuation of different systems.



Relative Move [m]: 0.0

Current Hole: 1

Relative Target Drill Depth (-ve: down, +ve up) [m]: -0.14

Velocity in For (Both Y and Z) [RPM] 30

Air Gap to Regolith [m]: 0.046

Max Z1 (Drill Travel) [m]: 0.68

Ice Start Depth [m]: 0.296

☑ System HeartBeat
☐ Z1 (Drill) servo
☐ Z2 (Drill) servo
☐ Y servo
☑ CPU Temp (degC): 37.00 [degC]
☑ Mission Time (H:M:S): 0:07:53
☑ Round Trip Time (ms): 271.00 [ms]
☑ Server Version: 0.7.3

Relative Motion (During Startup Idle)

Z1 [m]: -0.065

Z2 [m]: 0.015

Y [m]: 0.131

Current Position (Z1, Z2, Y) = (-0.287, 0.000, 0.000) [m]

```
[2021-08-28 12:22:21.584137] Clearing Alerts
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Figure 3 A snapshot from our custom Mission Control user interface.

2.11 Technical Specifications

Overall Mass	59.3 kg	**Maximum drilling speed and typical drilling current**	900RPM (5A)
Overall Volume and dimensions	1.9m^3 (1m x 1m x 1.9m)	**Z1 Servo Peak and Cont. (RMS) Torque @75VDC**	5.8 N-m (peak) 1.2 N-m (cont)
Length of Drill bit	0.997m (hard stop)	**On-board computer**	2x RaspBerry Pi 4
WOB / Drill force	<150N	**Communications interface**	Wireless, via WiFi and long distance LTE
Rated load @ 115VAC	9A	**Software**	Our own client/server using PyQT and ClearPath C++ libraries
Maximum vertical speed at cont. torque	0.053 m s^{-1} (1600 RPM on Z1)	**Maximum Heater Power**	700W

3 System Development, Integration and Testing

3.1 Design Changes and Improvements

We have made the following system design changes since the mid-project review:

Change	Rationale	Benefits of change	Costs of change	Costs mitigated by
Removed drill tachometer	Redundant, not essential for main functions	Reduced mass, coding load & complexity	None apparent	
Removed pump flow meter	Not necessary for competition	Reduced mass, coding load & complexity	Impacts true remote operability	Overhead video provides indication of water flow
Removed X-axis motor, bearings and lead screw	Not necessary on Moon, Mars nor at the competition	Reduced mass (-2.1kg), eliminated vibrations during drilling	Will have to drill in a straight line at competition (one line per day)	Can still slide the base over by hand and lock it to a new position
Replaced Z1 servo with a more powerful model	More margin to help pull the drill bit out of tough situations	60% more torque, reduced risk of stalling, tolerance to unexpected friction in system	More mass (+0.6kg), no longer identical with others so no spare if it fails	Since it's still a NEMA23 mount, if it fails we can replace with our smaller spare
Shortened the structural frame by 22cm	Needed to cut mass to pay for higher mass of servos and new e-panel	Reduced system mass (-1.4kg); contributed to reducing vibrations	Drilling (Z1) and water assembly (Z2) stacks hang below zero level of system, closer to top of overburden	If Z1, Z2 are too close to overburden, we can mount them higher up
Simplified Mission Control software	Best use of limited software dev resources	Essential features for competition have been more thoroughly tested	Some of the initially planned features will not be available	Workarounds exist for the unavailable features

3.2 Production Challenges and How Addressed

The most significant production challenge this year was Covid-related capacity limits to use our lab at MIT (37-084), which was also being used by our BIG Idea Lunar Tower team. Moreover our recently graduated members could not enter. This was solved by moving the HYDRATION III project to space provided free of charge to our team by the non-profit MassRobotics, at Boston's Seaport District.

The next most significant production challenge was to keep the mass budget under control. Our overarching goal this year - to improve reliability, performance and remote operability - came with a substantial mass cost in better servos with their associated harnesses, better/more/heavier power supply units, more sensors, limit switches etc. This required mass optimization initiatives, as detailed above.

The third production challenge was the need to support a four-month integrated testing program while also keeping the testbed as realistic and as safe as possible. Since our space at MassRobotics is indoors, we did not want to use dry ice. Instead, we installed a chest freezer inside the Bonar box, and built a smaller version of the competition testbed with 530mm L X 400mm W x 400mm D of ice overlaid by 250mm D of six layers of clay, concrete, stone, sand, pebbles etc. overburden. A cross-section of the overburden layers is shown in Fig X below. Between tests, we replace the chest freezer cover to keep our testbed frozen, as shown in Fig X below, in the rightmost frame.

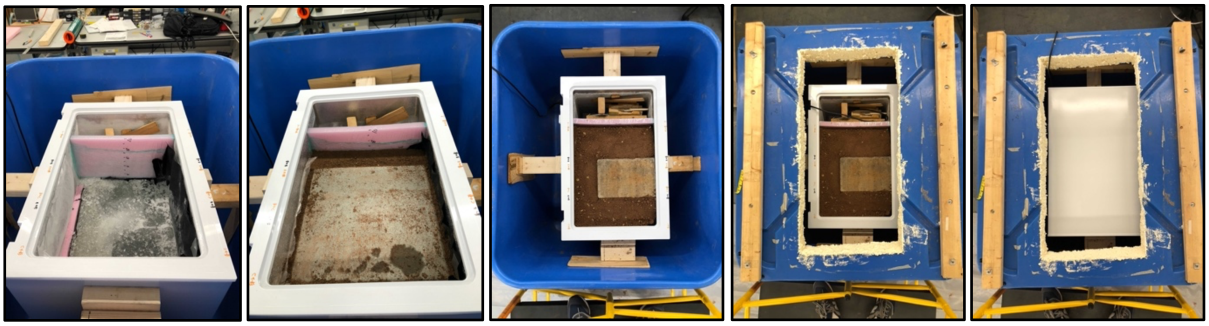


Figure 4 Development of a long-lived test station inside a chest freezer to support four months of integrated testing. Ice block dimensions 530mm X 400 mm X 400mm depth. Overburden dimensions 530mm X 400mm X 250mm depth.

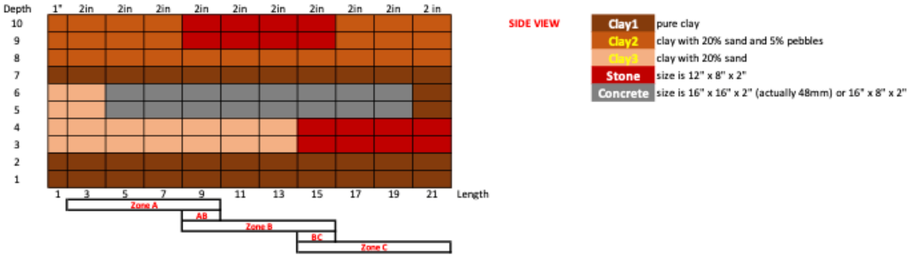


Figure 5 Cross-section of overburden layers. By selecting a different Y coordinate in zones A, B or C, we can drill through various vertical profiles of varying difficulty, producing different labeled data sets with which to train our neural net.

The fourth production challenge was the persistent stalling of the Z1 servo motor which worsened as we progressed through the integrated testing between June and early August. After eliminating software causes, we looked for causes in mechanism friction and downhole friction. We took apart the Z1 drilling assembly for servicing and identified and addressed four separate sources of friction between the lead screw and other parts. These in turn were all caused by excessive vibrations and operator errors during recent integrated tests. We also Teflon-coated the drill bit to reduce downhole friction. As a result the Z1 servo stalling was completely eliminated. Regardless, following this experience we still replaced the Z1 servo motor with a 60% stronger model to provide added margin for any new sources of friction that might emerge during the competition (or on Mars), and traded the extra mass by removing the X-axis servo.

3.3 Summary of Integration and Testing Plan

The period following the midterm report was exclusively devoted to integration and testing. As discussed above, two key prerequisites supporting the high-fidelity phase of our integration and testing plan were: (1) the move to MassRobotics, so that we could congregate for long periods at an exclusive space for our team with no capacity limits and no exclusions for recent graduates and (2) the construction of a realistic, long-lived testbed with ice and overburden. The move to MassRobotics was completed on April 24th (after MIT's Office of Legal Counsel approved the pro bono agreement) and the chest freezer testbed was completed on June 5th, in time for our integrated testing program which started June 12th:

Date of integrated test	**Test objective**	**Test results**
June 12th	SI Iteration 3 - system testing for startup, XY, borehole, water collection, full sensor data collection	Drilled through overburden and ice. Built mud wall. Collected sensor data. Cave-in prevented water collection. Significant vibrations. Stalling Z1 motor. Server crashes.
June 28th	Client/server connection through a cellular service as part of our optional remote operations demo at Langley	Successful wireless / cellular connection via a tunneling service.
July 4th	Hardware in the loop test: client/server connection through cellular service, with hardware in the loop	Successfully controlled all actuators via wireless / cellular connection and tunneling service
July 8th	SI Iteration 4 - full remote system tests with remote team under tougher-than-competition conditions	Drilled through overburden and ice with remote team controlling the system. Repeated stalling of Z1 servo and crashing / restarting of server. WOB and power logging validated.
July 10th	ASCLEPIOS / HYDRATION III dress rehearsal: remote analog astronauts control the HYDRATION III system	Drilled through overburden and ice. Collected sensor data. Repeated stalling of Z1 servo and crashing/restarting of server. Hole caved in. No water collected.
July 19th	ASCLEPIOS / HYDRATION III mission: remote analog astronauts control the HYDRATION III system	Drilled through overburden and ice. Collected sensor data. Repeated stalling of Z1 servo and crashing/restarting of server. Stuck drill bit. No water collected.
Aug 6th	Limit-switch integration and limit-switch-based homing of servos	Completed limit switch integration and wired one limit switch for software integration purposes.
Aug 8th	SI Iteration 5 - repeat full remote system tests with remote team under tougher-than-competition conditions	Drilled through permafrosted overburden and ice. Collected data. Repeated stalling of Z1 servo. No water collected.
Aug 15th	SI Iteration 5 - repeat full remote system tests with remote team under tougher-than-competition conditions	Drilled through permafrosted overburden and ice. Repeated stalling, now accompanied by grinding noises. Ended test and decided to fully service the Z1 assembly.
Aug 21st	SI Iteration 5 - repeat full remote system tests with remote team under tougher-than-competition conditions	Service of Z1 axis a success. All vibrations gone. No Z1 stalls; max torque <50% with existing servo. Borehole was clean and had a solid mud wall. Tested heater and melting ice. Did not test the pump.
Aug 28th	SI Iteration 5 - repeat full remote system tests with remote team under tougher-than-competition conditions	Drilled through overburden and ice. Built mud wall. Collected data. Extracted bit, lowered heater. Tested heater. Tested pump. Collected 30ml of **hands-off** water. Validated entire system. But, damaged heater upon removal (filter got stuck downhole)

4 System Operations

4.1 Overall Strategy for the Competition

Following our first generation HYDRATION design (2019) [2,3], our system continues to evolve to improve the accuracy of prospecting for the digital core and maximizing the water acquired. For the prospecting capability, this year we have increased the number of independent sensor data sources that should all correlate with layer change. We are also collecting this data in accurately timestamped files alongside the precise time-stamped depth reported by the built-in encoder of our high-quality ClearPath Z1 servo motor. Finally, we have validated our prospecting system using the known overburden layers we have set up in our chest freezer.

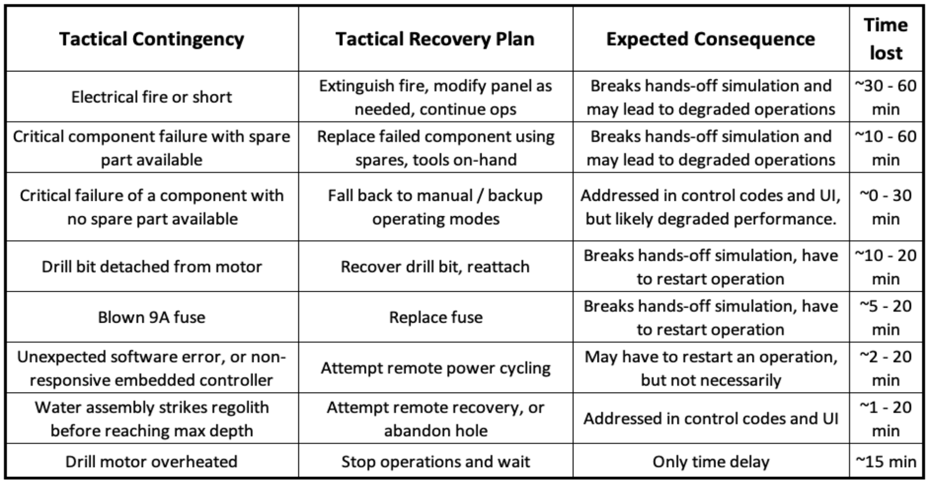
To maximize water production, we have integrated a higher-power heater and invested substantially in the increased reliability of the entire system, as well as in providing more remote control options to the operator for remote troubleshooting and recovery via our integrated Mission Control software which has been in development for 8 months. In addition to helping maximize water production, these capabilities make the system more realistic and flight-like.

For both prospecting and water production, we have invested in substantial integrated testing under competition-like conditions using our Bonar box and our new chest freezer which contains ice and known layers of overburden. This gave us the opportunity to discover and address many software and hardware issues that would have interfered with the productive use of the 12 hours we will have at the competition.

Given the late decision to remove the X-axis servo, at the competition we will drill along two lines at X=12.5cm on day one and X=37.5cm on day two. The sliding base on which the drilling frame is mounted will be moved to these positions at the start of the day's activities. On Mars, there is no "X axis" – this capability would be provided by a rover simply moving to a new location.

4.2 Tactical Plan for Contingencies and Redundancies

We have developed and are developing several protocols for remote recovery from contingencies where possible. One example, in the event of a blocked downhole water inlet, is as follows: the command sequence is: pump ON in reverse for TBD seconds, pump OFF for TBD seconds while heater is ON, pump ON in reverse for TBD seconds, pump OFF for TBD seconds, pump ON in pumping mode for TBD seconds. Repeating this sequence over TBD cycles is expected to push hot water at high pressure in the reverse direction, back-flushing and regenerating the downhole filter and restoring high-flow water production. In cases where remote recovery is not possible, our Langley field team will include at least one team member proficient in mechanical systems, electrical systems and the intricacies of our control software. We will also be carrying several spares with us to the competition, including: a second identical drill motor, a second long drill bit with shorter flutes, the proven but shorter drill bit from 2019, two spare servo motors, spare servo hub board and servo power board, power supplies, a heater, a Raspberry Pi with preloaded software, a second laptop with preloaded software, necessary tools and sundry small parts / sensor spares.



Tactical Contingency	Tactical Recovery Plan	Expected Consequence	Time lost
Electrical fire or short	Extinguish fire, modify panel as needed, continue ops	Breaks hands-off simulation and may lead to degraded operations	~30 - 60 min
Critical component failure with spare part available	Replace failed component using spares, tools on-hand	Breaks hands-off simulation and may lead to degraded operations	~10 - 60 min
Critical failure of a component with no spare part available	Fall back to manual / backup operating modes	Addressed in control codes and UI, but likely degraded performance.	~0 - 30 min
Drill bit detached from motor	Recover drill bit, reattach	Breaks hands-off simulation, have to restart operation	~10 - 20 min
Blown 9A fuse	Replace fuse	Breaks hands-off simulation, have to restart operation	~5 - 20 min
Unexpected software error, or non-responsive embedded controller	Attempt remote power cycling	May have to restart an operation, but not necessarily	~2 - 20 min
Water assembly strikes regolith before reaching max depth	Attempt remote recovery, or abandon hole	Addressed in control codes and UI	~1 - 20 min
Drill motor overheated	Stop operations and wait	Only time delay	~15 min

4.3 Safety Plan

No chemicals or significantly hazardous materials are used on or around the robot, including that we do not use dry ice. No hazardous or flammable chemicals are used or stored in the work area. No alcohol is allowed in the work area. The low-hazard chemicals WD-40 and LocTite are used, and members have been instructed on their safe handling and emergency procedures. Personal eye and ear protection, thermal gloves and face masks are available for all. Any operational testing involving the heater or the drill requires at least two team members present. Additionally, 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. The electrical system is unplugged when the drill is being serviced. All wires are insulated to prevent shorts. The frame is grounded to accommodate the line-voltage heater (120V). The drill is double-insulated, unmodified, and UL approved, and all other electronics that are not low voltage will be marked with orange markings. All 120VAC wires are insulated with an orange jacket to clearly indicate higher voltage wiring. In addition to the 9A fast blow fuse, the rig is equipped with an emergency stop button that disconnects all power. 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. In the unlikely case of a medical emergency, MIT Campus police will be informed and the injured party will be taken to one of the local hospitals within 2 miles of the work area for treatment. Per campus policy, we are not keeping a first aid kit with us, due to the close proximity of free, professional help. Due to COVID, with MIT permission, until April 2021 we had been operating out of members' yards where we apply the above safety policies as if we were in one of our labs, 37-084 at MIT (pre-Covid) or the 5th floor at MassRobotics, at the Boston Seaport District (post-Covid).

5 Paths to Flight to the Moon and Mars

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 III 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.

5.1 Path to Flight for Water Production on Mars

A relatively small number of changes to HYDRATION III, 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 the table 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.

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 III 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. This change will require the addition of an inflatable packer to the water stack to seal the borehole before melting starts.
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.

5.1.1 Comparison of Critical Figures of Merit (FOM) for path-to-flight to Mars

We anticipate the following impacts to critical FOM of our HYDRATION III system as a result of path-to-flight adaptations for Mars, as shown in the table below:

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	Probably Neutral	Sublimation on Mars requires no filter regeneration, giving the Mars system an advantage for reliability relative to the Earth prototype. This is offset by untested systems: the scroll compressor and packer will have to be tested in a relevant environment (i.e. TVAC) to troubleshoot and assess the impact to system reliability.
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.

5.1.2 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 Raspberry Pi, 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.

5.2 Path to Flight for Digital Core Prospecting on the Moon

The prospecting portions of the HYDRATION III 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 2, 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.

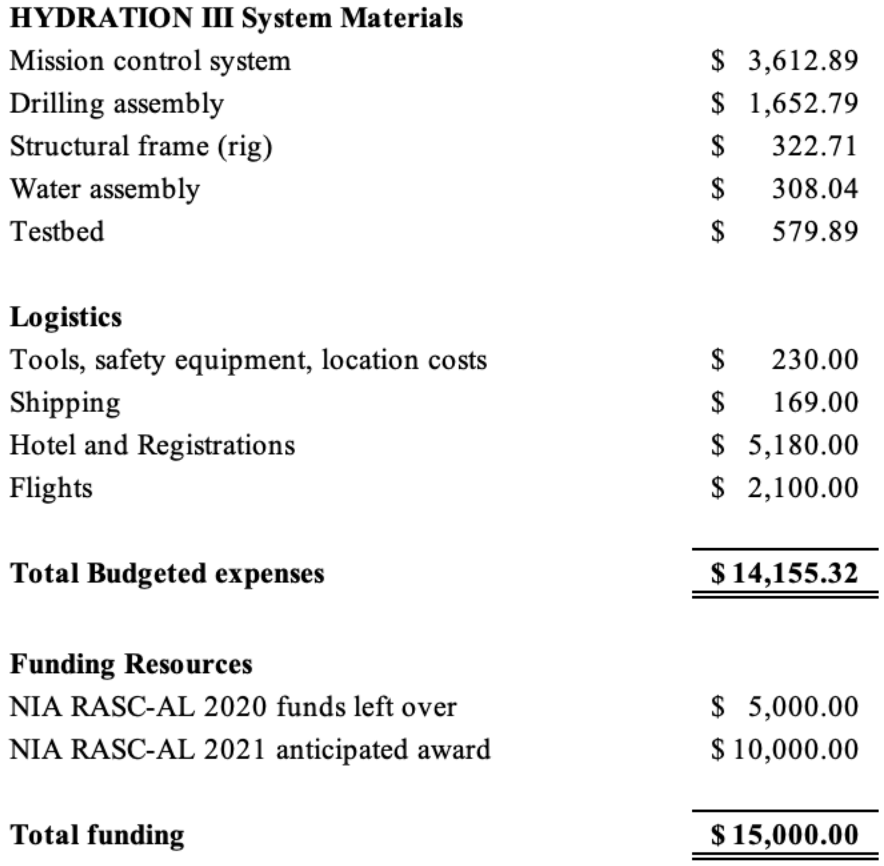
6 Project Cost – Time and Materials

6.1 Project Timeline

The HYDRATION III project started in summer 2020 and ends on September 30th, 2021 after the RASC-AL Special Edition Moon to Mars Ice and Prospecting Challenge which will take place in Hampton, VA between Sept 23-25, 2021.

6.2 Project Budget

The already-built HYDRATION II system, including some modifications made with the first $5,000 of the canceled 2019-2020 challenge, was the starting point for the below budget. We are grateful to Massachusetts Space Grant for sponsoring three of our team members to travel to Hampton, VA in September 2021.



HYDRATION III System Materials	
Mission control system	$ 3,612.89
Drilling assembly	$ 1,652.79
Structural frame (rig)	$ 322.71
Water assembly	$ 308.04
Testbed	$ 579.89
Logistics	
Tools, safety equipment, location costs	$ 230.00
Shipping	$ 169.00
Hotel and Registrations	$ 5,180.00
Flights	$ 2,100.00
Total Budgeted expenses	**$ 14,155.32**
Funding Resources	
NIA RASC-AL 2020 funds left over	$ 5,000.00
NIA RASC-AL 2021 anticipated award	$ 10,000.00
Total funding	**$ 15,000.00**

7 References

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[2] Adams, A., Alowayed, M., de Filippi, R., Takahashi, R., Vanderhout, A., "HYDRATION: High Yield Dihydrogen-monoxide Retrieval And Terrain Identification On New worlds", RASC-AL Special Edition Mars Ice Challenge Forum, Hampton, VA, May 2019

[3] Lordos, G., Vanderhout, A., Adams, A., Alowayed, M., de Filippi, R., Hoffman, J., de Weck, O., Takahashi, R., "HYDRATION: Mining Water Ice on the Moon and Mars Using Downhole Radiative Heating", 17th Biennial International Conference on Engineering, Science, Construction in Challenging Environments / Earth and Space 2021, April 2021

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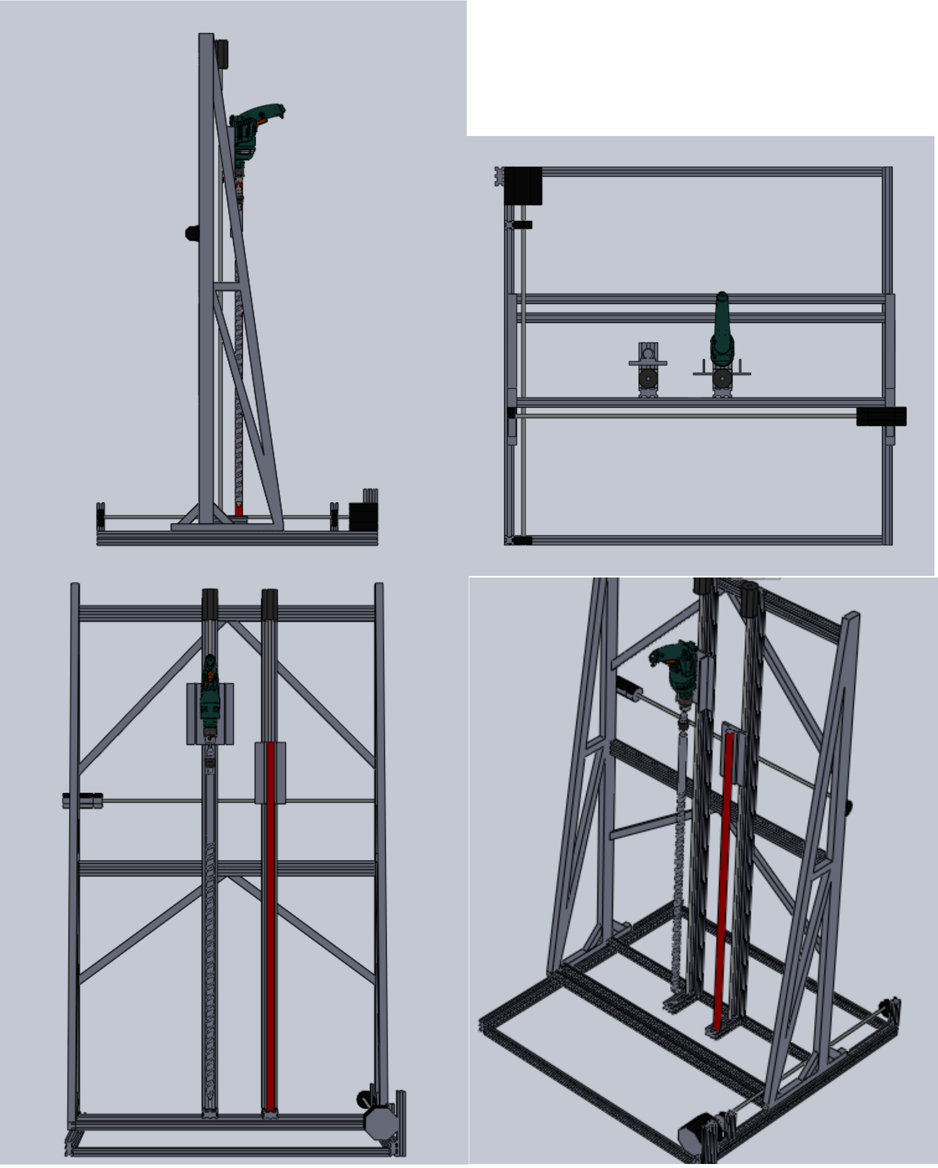
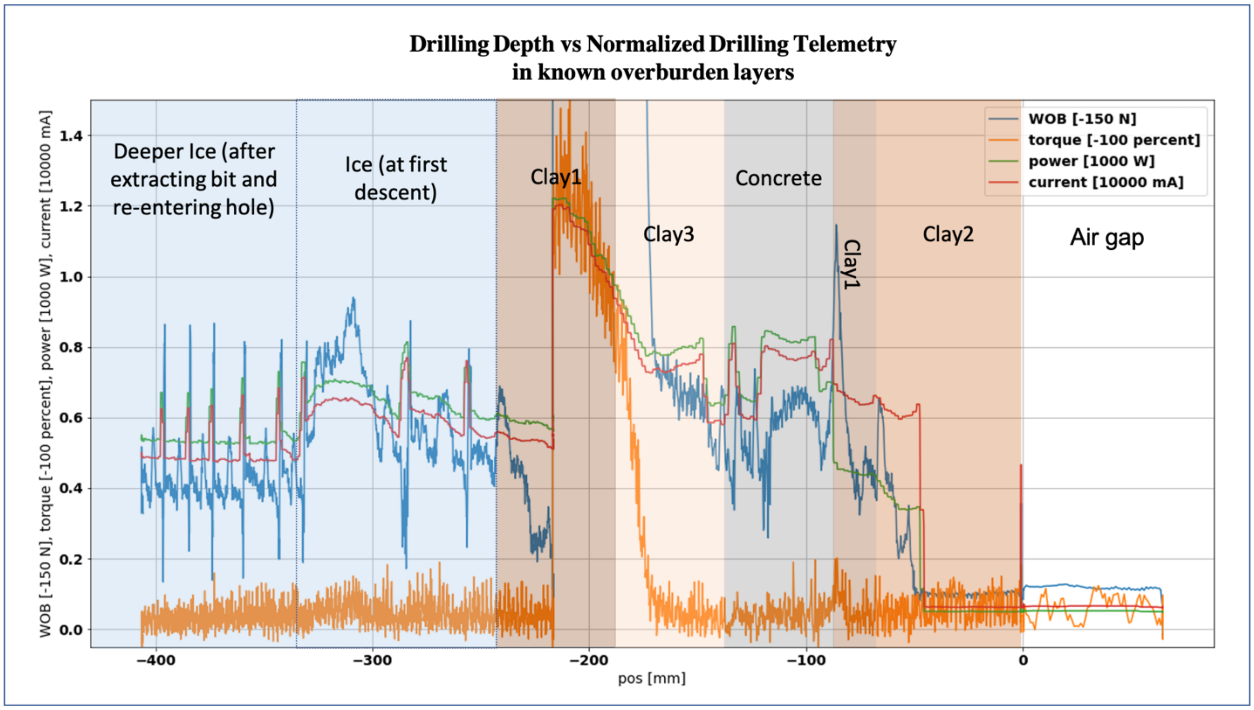
[5] Schmitt, R and Rodriguez, R (1963). "Glacier water supply and sewage disposal systems". In Symposium on Antarctic Logistics, 13–17 August 1962, Boulder, Colorado, USA. National Academy of Sciences–National Research Council, Washington, DC, 329–338

8 Appendices

8.1 Appendix 1 – CAD



8.2 Appendix 3 – Sample Sensor Data Analysis



Drilling Depth vs Normalized Drilling Telemetry
in known overburden layers