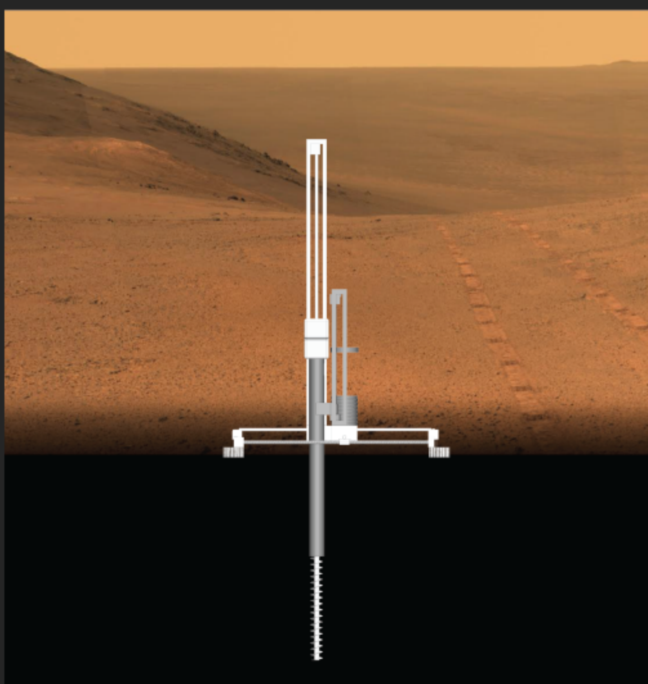
RASC-AL Special Edition Mars Ice Challenge
May 2018 | Final Report

HYDRA

(**H**igh **Y**ield **D**ihydrogen-monoxide **R**etrieval **A**ssembly)



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1.0 Introduction

The HYDRA (High-Yield Dihydrogen-monoxide Retrieval Assembly) system was designed with the objective of maximizing the rate of filtered water production from a source of subsurface ice on Mars. In the decision making process, the team needed to balance the design constraints to effectively perform a variety of required functions, such as drilling, extracting, melting, pumping, and filtering. The design constraints for the competition article included the following: total system mass less than 60 kg, power draw less than 10 A at 120 VAC, stowed volume less than 1 m x 1 m x 2 m, and weight on bit less than 150 N. Throughout the design process, the team took care to design for performance under competition conditions, while still maintaining a viable path to flight for a Mars-based system modeled after this Earth-based system. For example, under competition conditions, the ice is known to be located in a 0.5 m x 1 m area beneath 0.3 to 0.6 m of overburden. However, on Mars the potential location of subsurface ice will be much more variable and uncertain. This report will summarize and discuss the design, development, assembly, testing and integration of HYDRA with particular emphasis given to explaining the mechanical and operational principles of the system and its extensibility to a Mars-ready system.

2.0 System Description

Based on the above considerations, the final HYDRA design consists of an outer hollow auger to drill through regolith, a concentric inner auger to drill through ice, three stepper motors with lead screws to enable 3-axis motion of the auger, an aluminum structure to withstand drilling loads and limit deflections, an oven to melt ice, a guide to funnel ice chips into the oven, and a pump to transport water through filters to the collection reservoir. The details of this design are presented below.

2.1 Water Extraction Capabilities

2.1.1 Mounting System

The majority of the HYDRA system structure is built using 1" width, T-slotted, aluminum 80-20 framing. A central carriage consists of a vertical frame on which the drilling sub-assembly is mounted. This carriage is in turn mounted to a 1 m x 1 m base frame of the same material. The carriage is translated forward and aft (the X-direction) over the base by means of a lead-screw and stepper motor in order to access multiple hole locations in one degree of motion. The second degree of planar motion (in the Y-direction) is achieved on the vertical frame itself with a similar lead screw and stepper motor that translate only the vertical movable drill rail left and right to access additional hole locations. The drilling sub-assembly is affixed to the vertical movable drill rail by means of a mounting structure made of two thin steel plates; between the two plates is a block with a threaded hole through which a third lead screw travels to allow for Z-direction translation of the drilling rig. The water collection, melting, filtering and pumping sub-assemblies rest at the base of the X-translating carriage. The electronics bed sits on the opposite end of the carriage to avoid water or regolith damage/contamination. The arrangement of the axes is shown in Figure 1 below.

The base frame, which supports the X-translation carriage, is the primary interface between HYDRA and the competition setup (i.e. the Bonar box and the wood 2x4's). Attaching HYDRA to the wood is done in a simple and sturdy manner. Elbow brackets join the T-slotted base frame to the wood by means of a bolt and slot nut on the 80-20 side and wood screws on the 2x4 side. Three elbow brackets are used to affix HYDRA to each of the 2x4's.

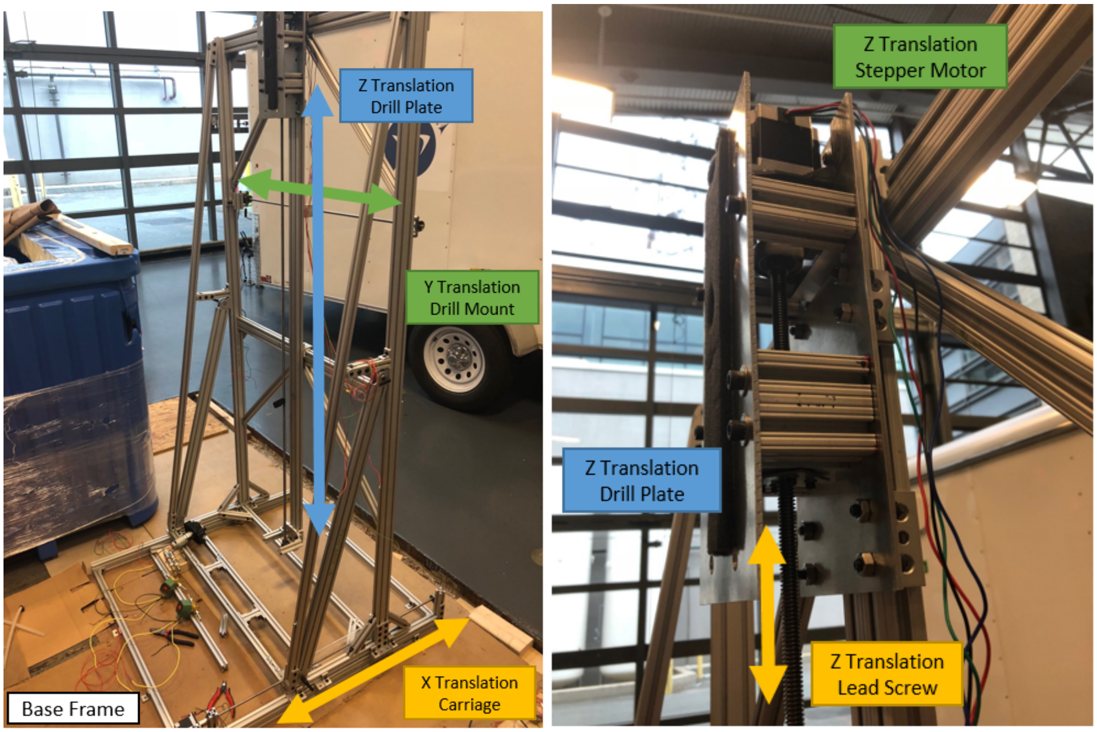


Figure 1. HYDRA mounting system.

Beyond the functional mounting material as described above, structural analysis determined the need for supports to prevent buckling of the vertical members under the weight of the drilling assembly (this is briefly presented in the following paragraphs). This support was included as two diagonal members running from the base of the HYDRA frame up the vertical member. The longer diagonal extends to the top of the vertical member at a height of 2 m. The second extends about half-way up. Both diagonals originate from the same side of HYDRA such that the final shape resembles two nested right triangles as shown in the image above. This entire setup is what translates along the base frame in the X-direction. Lastly the two horizontal members which carry the drilling sub-assembly and its lead screw/stepper motor and guide rail mount are supported by means of 45 degree diagonals attached to the vertical member.

The overall HYDRA mounting structure has been designed parametrically in Rhinoceros and Grasshopper in order to evaluate in real-time different design solutions and load conditions. All the solutions have been compared through the results of Finite Element analysis, performed in Karamba. The final design was chosen for its ease of construction and optimized for minimizing its mass and preventing resonance between the natural frequency of the structure and the vibrations caused by the drill. The structural system is predicted to be stiff enough such that its maximum displacement at top of the structure is on the order of hundredths of millimeters on Earth and one third of that on Mars where the force of gravity is at 38%. The figure below summarizes the findings of the analysis for the Earth version. As the utilization of the members is only at 30% for the Earth system, the Mars system can be redesigned with more slender elements resulting in a saving of mass which can be applied elsewhere; for example to add thermal inertia to the interior of the reactor, a larger primary drill motor and/or a second drill motor for the outer auger.

The modal analysis, graphically depicted in Appendix B, shows the regular and symmetrical behavior of the structure as the first 2 modal shapes are translational while the third one is rotational.

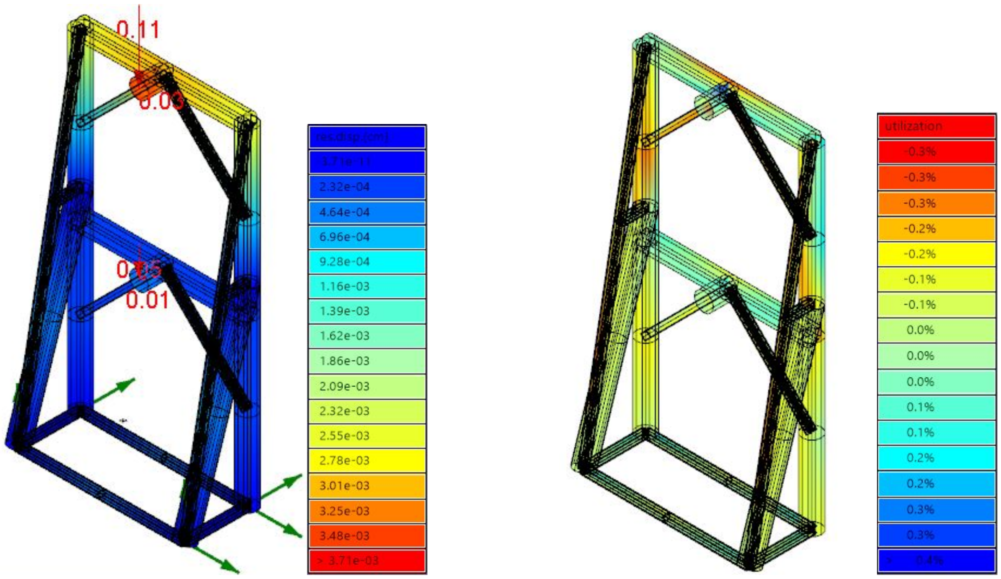


Figure 2. HYDRA structural displacements and utilization (blue is tension and red compression).

Moreover, as the auger will have a maximum rotation rate equal to 1600 RPM, which corresponds to a period of 0.03759 s, its vibrations will not enter in resonance with the HYDRA structure, which has a fundamental period of vibration equal to 0.021337 s. The periods for the Mars system remain the same because the distribution of mass is the same.

2.1.2 Dealing with the Overburden

The method chosen to access the ice is a concentric, two-auger system with counter-rotating flights and a novel locking mechanism such that only one drill motor is needed to conduct two phases of operation - drilling through overburden and drilling through ice.

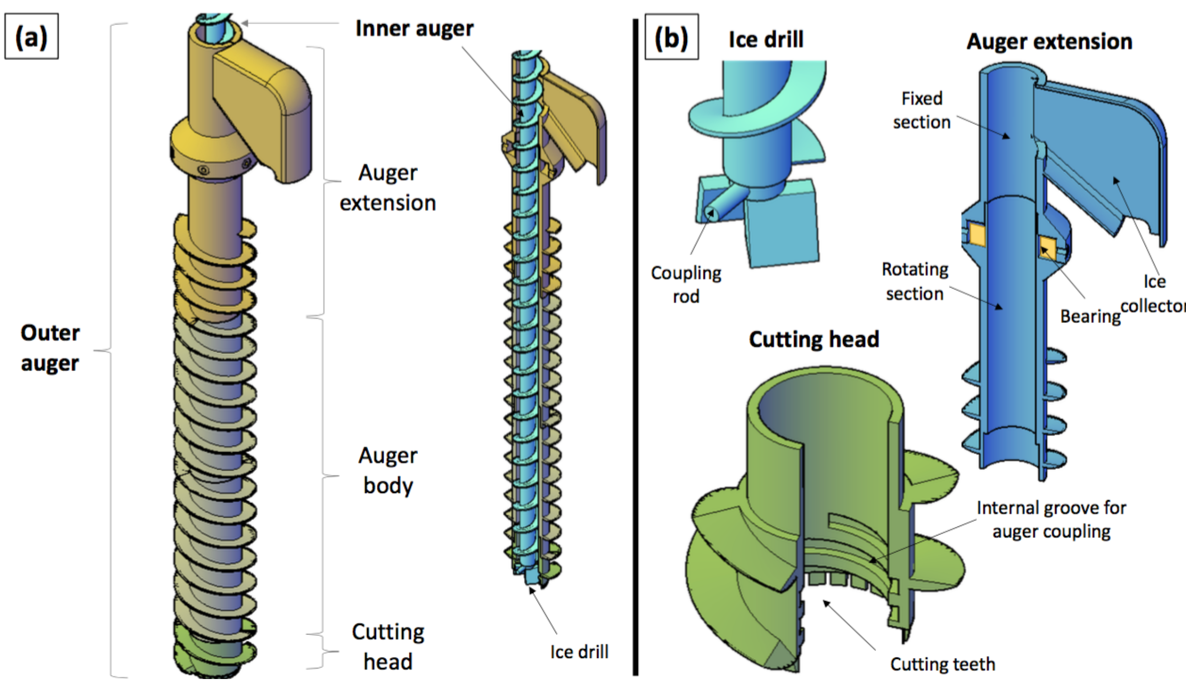


Figure 3 - Drilling system. **(a)** Two auger system with counter-rotating flights. **(b)** Details.

The drilling system is shown in Figure 3a and consists on an (hollow) outer auger designed to excavate through the clay while hosting an inner auger which is specialized in ice drilling. The outer external auger is composed of (1) the cutting head with a locking mechanism, (2) the main auger body, and (3) the auger extension. The cutting head (Figure 3b) contains an internal groove that allows for rotation-coupling with the inner auger. This is done through a transversal rod located at the top of the ice drill as shown in Figure 3b. When the drill motor rotates counter-clockwise, the horizontal rod makes contact inside the groove and forces the rotation of the outer auger. In order to decouple, the drill motor direction is reversed and both augers disengage. Note that the flights of the inner- and outer- augers run in opposite directions, so they only drill when the drill motor rotates in the appropriate direction - counter-clockwise to drill through the overburden with the outer auger, and clockwise to drill through ice with the inner auger. The reverse Archimedes screw action of the inner auger keeps the inside of the casing free of overburden as the augers descend through clay.

The upper end of the outer auger (i.e. the auger extension) consists of a rotating and a fixed section connected using a tapered roller bearing (Figure 3b). The functions of this extension are to provide a constraint for the drill string, thereby preventing bit whirl, and to collect the ice during drilling operations and to redirect it to the oven. Section 2.1.3 describes a high-level concept of operations of the excavation process.

2.1.3 System Excavation Operations

Excavation begins by positioning the drill head over the desired hole location. This is accomplished by using the X and Y translation capabilities which have been designed into the HYDRA mounting system. Once the drill sub-assembly is aligned with the hole location, the Z translation motor is commanded to begin descent of the drill (Step 1 @ Figure 4). Shortly thereafter, the drill motor begins spinning such that the regolith is extracted by the outer auger once contact is made (Step 2 @ Figure 4). The pin locking mechanism ensures that the inner auger (whose flutes counter-rotate with the outer auger) is not extracting regolith through its flutes - ensuring a clean path for eventual ice extraction.

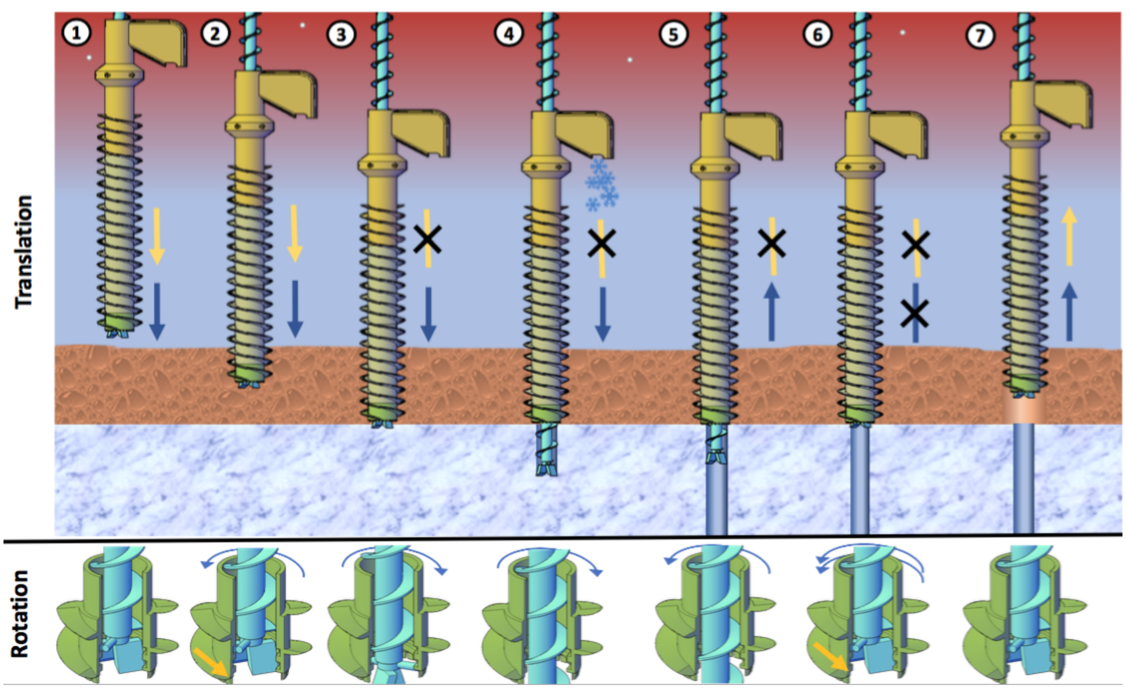


Figure 4 - CONOPS of HYDRA showing translation and rotation movements during drilling operations. Blue and yellow arrows refer to inner- and outer- augers movement, respectively.

Upon reaching the regolith-ice interface, descent and rotation are briefly paused. The drill motor is then spun up in the reverse direction and the descent motor re-engages (Step 3 @ Figure 4). As the inner auger begins cutting into the ice, the locking mechanism disengages (Step 4 @ Figure 4). The outer auger then stays in place and prevents regolith from entering the ice path while the inner auger continues descending. This continues until the inner auger has excavated to its design depth while the ice is extracted by the flutes of the inner auger. The process continues with extraction of the drill and repositioning over a new hole location, taking care to engage the locking mechanism once the outer auger is near the surface of the clay (Steps 5-7 @ Figure 4). Operations (and power supply) then shift to the water melting, filtering and transporting system. Once the melting process is complete, the drill descends towards the clay to commence drilling a new hole.

2.1.4 Water Extraction System / Technique

The water extraction system consists of a hollow stem auger, a reactor or oven and a filtration system with backwash capabilities. The outer, left-handed auger penetrates through the clay to the ice interface, and the inner, right-handed steel auger cuts and transports the ice for delivery to the oven via the custom designed ice collector in the fixed upper part of the outer auger. The ice is melted in the oven and the water is pumped out to the collection tank using the peristaltic pump, both under operator control. This water extraction technique will be modified to take advantage of sublimation for the Mars based system, as described below. For the Mars system, sensors can be added and existing sensors queried to detect and infer the state of the extraction system, enabling an autonomous system to take appropriate action.

2.1.5 Oven, Filtration and Water Collection

Oven System

In order to produce clean, liquid water, the snow ice must first be melted. During each drilling segment, the ice is transported up the auger shaft and directed towards the oven with a custom 3D printed part as shown below. For the Mars-based system, the enclosed casing of the outer auger will mitigate sublimation of the fine ice cuttings. It may be necessary to extend the path and lead it directly into the ice/water reactor (oven), trading off productivity for mass.

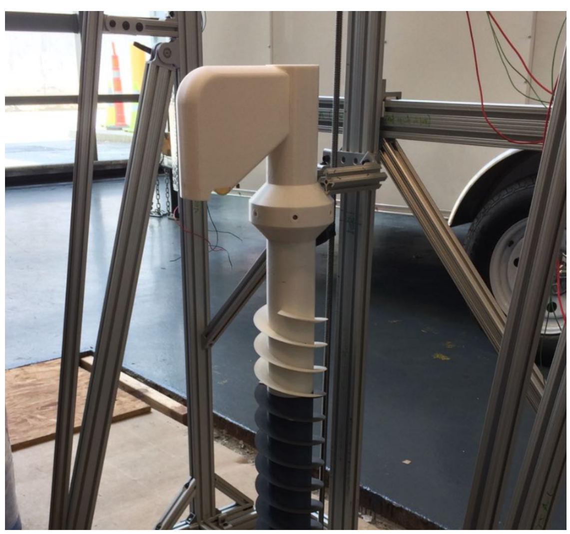


Figure 5 - Water collection system.

This piece directs the ice cuttings down towards the oven, which sits behind the auger near the base of the structure. It should be noted that while the duo-auger design has been built to minimize the amount of overburden that is transported up the auger shaft, it is still expected that a small amount will make it through. In order to prevent this overburden from entering the oven and contaminating the water supply, the oven includes an actuated, hinged lid. At the beginning of each hole that is drilled into the ice, the lid will remain closed while a mixture of overburden and snow ice falls out of the head. When the team determines that relatively pure snow ice is being transported up the auger, the lid will be opened. It opens away from the auger and stops at a 120 degree angle relative to the base of the drilling structure. This gives it the additional use of acting as a backstop to ensure the falling snow ice makes it into the oven and does not miss.

The oven itself was made from a copper window box planter, originally designed for gardening. It has a useful shape and size for the HYDRA design and is made of copper, which is one of the most thermally conductive materials available. The box planter measures 5.25” x 22” x 6.75” and is shown below. Copper has a high melting point of 1,085 degrees Celsius, meaning that the team does not need to worry about the oven melting under high heating conditions. Additionally, it is relatively easy to machine, making this box planter an ideal choice for the oven.

To heat the oven, extreme temperature resistive strip heaters were utilized as shown below in an image of the underside of the oven.These heaters are commonly wrapped around industrial pipes that need to maintain high temperatures, especially in colder regions of the United States. Two heaters were used, each of which pulls 624 W at full power[1]. The strip heaters are wired to a power controller that allows their power level to be manipulated to meet competition requirements. The heater strips are held in place with aluminum cross braces. The cross braces themselves are held onto the oven with a nut and bolt. High temperature epoxy was used to seal the holes and make the oven waterproof.

The oven will be wrapped in alternating layers of aluminum foil and fiberglass insulation in order to minimize radiative heat loss (not shown in image above). This worked well in the prototype, as the outside layer of aluminum foil was only slightly warm to the touch. It is important to minimize heat losses in a system that will go to Mars, as heating is power-intensive and power is a critical resource. Therefore, for a system on Mars, it is advised that a similar multi-layer insulation approach be utilized around any heating elements. Heat exchangers are also a useful tool to improve the thermal efficiency of the system.

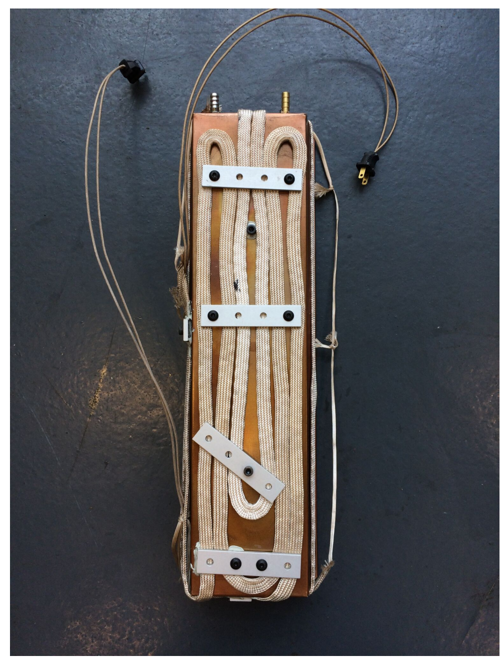


Figure 6 - The oven of HYDRA; **Figure 7** - the heating system.

Filtration System

A triple-redundant filtration system is used to ensure that the collected water meets NASA purification specifications. Being two- or three-fault redundant is important for space systems, as a single failure on a piece of equipment without redundancy could be mission ending. The first level of redundancy is with the lid mechanism that was described earlier. Any overburden that makes it up the auger shaft and attempts to find its way into the oven should be blocked by the lid, which is only opened when the team is sure that pure snow ice is coming out. However, in the event that this is not enough, the inlet and outlet tubes that transport water to and from the oven are covered in a coarse, 1000 micron mesh. This will prevent any rocks or larger particles from making it into the tubing system. In the event that smaller particles find their way into the oven and through the coarse filters, the

1 https://www.mcmaster.com/#4550t143/=1bnbbtw

tubing system incorporates two 90 micron inline filters. These will prevent any particles larger than 90 microns from making it into the water collection system. This system is shown schematically below.

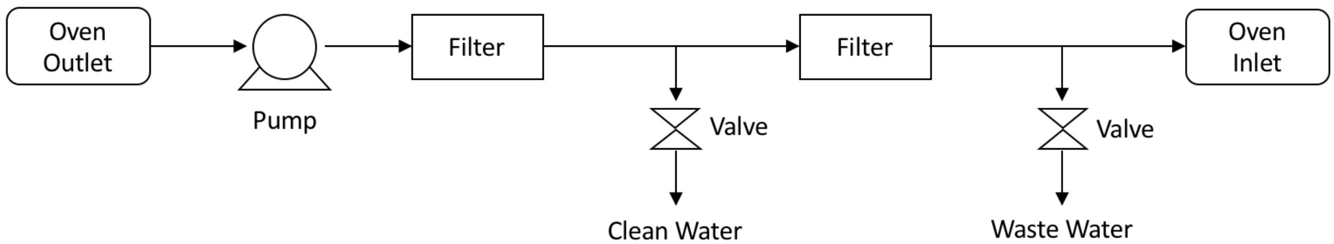


Figure 8 - HYDRA filtration system.

In addition to the inline filters, a peristaltic pump is used to move the liquid through the filtration cycle. This was chosen because it can operate with or without air bubbles present and can also run in both directions without any damage to the pump. In the event that clean water is to be collected, the clean water valve will be commanded open and the pump turned on. This pulls water from the oven, through a filter, and out of the clean water line.

One of the major benefits of the design shown above is that it is a **regenerative system**. If the filter gets clogged by use over time, both valves are closed and the pump is simply run in reverse. This forces water through the lines the opposite direction, cleaning out whatever was blocking the first inline filter in the diagram. The dirt is then forced back into the oven and sucked out of the oven by the "Oven Inlet" line. By opening the Waste Water valve, this dirt can then be deposited into a waste bucket and therefore removed from the system. The reason a second filter is included is in case some of the dirt skips over the Waste Water line and attempts to move towards the clean water valve region. The second filter will block this from happening. In the event that this happens enough and the second filter gets blocked, the dirt can be removed simply by running the pump in the primary direction and closing the clean water valve, which will force the dirt out of the second filter and into the waste water line again. The key takeaway is that this pumping system is three-fault redundant and completely regenerative. In order to be conscious of the path-to-flight, it was also designed with minimal mass; only two inline filters and two valves are required in order to run the system. It took several design iterations to reduce both of these numbers to two, but for a flight system, this reduction in mass would be well worth the effort, if NASA elects to keep a pump and filters system in addition to the sublimation system..

2.1.6 Managing temperature changes to prevent drill from freezing in the ice

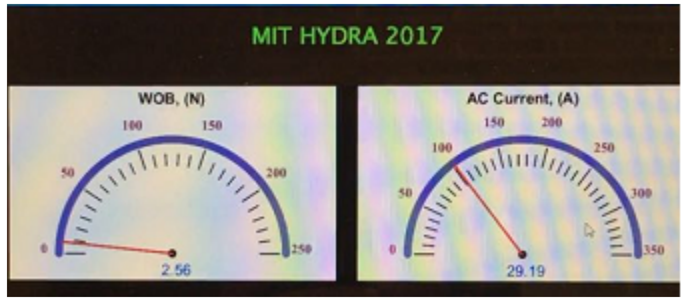
When drilling in ice, we will maintain low enough RPM to reduce the downhole generation of heat. Upon reaching the maximum drilling depth we will start Z translation upwards and increase RPM to lift all remaining cuttings up the auger and into the oven. RPM will be reduced when the ice auger is about to engage with the outer auger.

2.1.7 Control and Communication System

The central control and communication system hardware used on HYDRA is Arduino Mega 2560, PC and wired remote controllers. The code shown in Appendices E1 and E2 is burned into the Arduino Mega, establishing a graphical user interface running on the PC using Processing. The systems controlled by central control and communication system are grouped into four categories: 1. XYZ motion; 2. oven system; 3. water filtration system; 4. Data display.

XYZ motion of the drill mount is controlled by three 24V DC stepper motors. The speed or RPM of each motor is controlled in real time by the remote controller that talks to Arduino hardware.

Oven system melting safety cut-off is programmed into a PID controller via a temperature setpoint. The central system only controls the initialization and termination of the melting process. The operator has visual feedback on the melting conditions via the overhead USB camera.



Water filtration system: the pumping system is controlled by a remote controller and two drain valves (one for clean water and one for wastewater) by central control system through mechanical relays.

Data display: During drilling, WOB and current consumption are displayed on PC as feedback to an operator for making adjustment of the speed of Z motion and speed of the drill motor, so that the system is operating under the limits of WOB and power consumption.

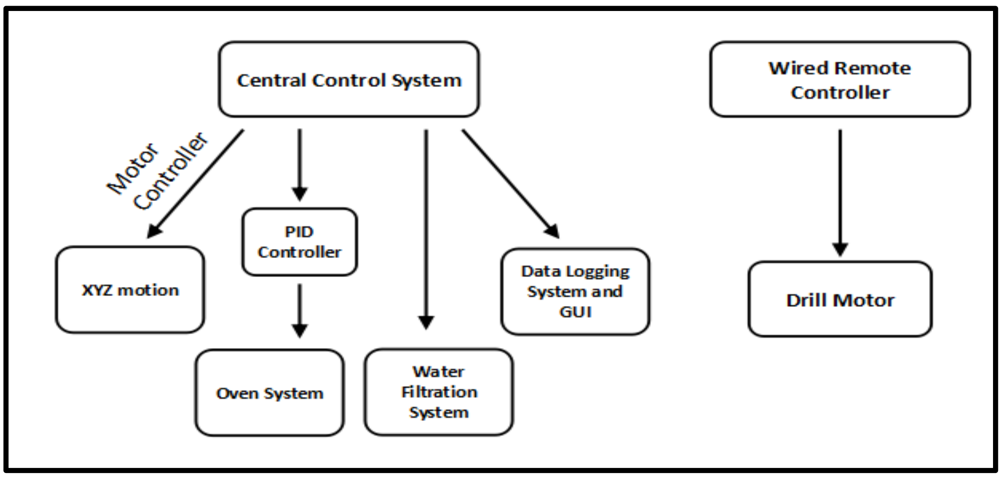


Figure 9 - HYDRA Control System.

2.1.8 Datalogger

Sensor voltages, including WOB in N and AC current in Amp, are recorded by Arduino, then transmitted to PC through serial communication. The GUI refreshes every second and stores information about WOB, AC current and time every ten seconds. Data are stored in the PC RAM, then in hard drive of a PC after the test.

3.0 Technical Specifications

Overall Mass	57 kg	**Max drilling speed**	1600RPM
Overall Volume	$2m^3$	**Torque**	2.1 lb-ft
Length of Drill bit	0.997m (hard stop)	**On-board computer**	Arduino Mega 2560
WOB / Drill force	150N	**Communications interface**	Arduino Serial
Rated load	10A	**Software**	Arduino IDE and “Processing” software
Power	1200W		

4.0 Design Changes and Improvements

The Competition Article incorporates the following design changes relative to the Original Design and the Prototype:

Change	Relative to	Rationale
Replaced guy wires with rigid diagonals	Prototype	Improved structural performance (FEM)
Added bracket and bearing to top of outer auger to control bit whirl	Prototype	Based on midterm judges' feedback
Replaced 'donut' and ice ramp with an enclosed ice collector, taking advantage of newly-fixed upper part of outer auger	Original Design	Better control of ice path into oven
Redesigned structure using 1" 80/20 instead of 1 ½" 80/20	Prototype	Reduce structure mass to enable three-axis control
Replaced moving, cylindrical oven with fixed, oblong design	Original design	No need to move oven; increased contact area between ice cuttings and heated surfaces
Replaced drop-in casing with hollow-stem left-handed outer auger design (note: the inner, concentric ice auger is right-handed)	Original design	To keep ice path free of clay and protect sharp ice auger blades while drilling through clay, which contains quartz.

5.0 Challenges

Preventing Bit Whirl: Early testing indicated bit whirl when a long drill string was suspended below the drill. This fact was also pointed out by the judges. It was addressed by redesigning the auger extension segment of the outer auger to have two parts, a fixed upper part and a rotating lower part connected by a roller bearing. The upper part of the outer auger was then secured onto an 80/20 slider bearing which slides on the vertical z-axis 2" wide member (drill rail) below the drill plate. This constrains the outer auger preventing it from moving in the X and Y axes relative to the drill rail, thereby constraining the inner ice auger to remain directly below the drill at all times.

Securing the Ice Path: Early pre-midterm testing indicated that ice cuttings would emerge from the top of the outer auger with the consistency of snow. For this reason we could not rely on the donut and ramp arrangement previously envisaged. We looked for a way to guide the ice so that it would emerge from only one side of the outer auger. This was facilitated by the decision above to make the upper part of the outer auger fixed and non-rotating. This made it possible to design a window and an enclosed ramp directly into the top part of the auger extension, and to constrain the end of that ramp to always be vertically above the lateral centerline of the oven as the drill rail moves along the Y axis.

Digital speed and direction control of AC drill: Attempts had been made to digitally control a single phase AC drill motor with a combination of solid state relay and Arduino Mega, but these were unsuccessful. The speed and direction of drill motor will therefore be controlled by an analog remote controller for the competition phase. For the path to flight, a DC drill motor is indicated for ease of digital control. Cost and schedule considerations (mainly lock-in due to the design of drill plate) led us to decide against the switch to a DC motor when the difficulty became apparent.

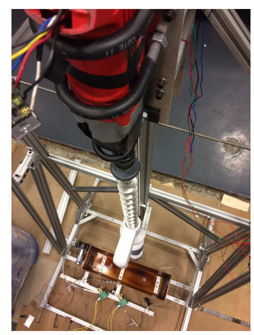
6.0 Overall Strategy

HYDRA consists on an integral design that aims to be flexible in order to reach every part of the ground and underground ice with its driller to take full advantage of the potential ice to be extracted and at the same time to have enough strength to handle the strong vibrations produced by the drilling process. Three-axis movement allows access to the entire ice block, and we selected a COTS auger and drill bit from Kovacs Enterprises which is already optimized for drilling holes in ice, as recommended by a member of the British Antarctic Survey. This drill allows us to gain high efficiency in the ice drilling process, extracting small cuttings which are easier to melt. The ice drill hole diameter is only 2” in order to avoid overloading the drill.

A hollow auger allows us to penetrate the clay layer, as described in 2.1.3, isolating the inner auger from the clay layer, creating a clear path to bring clean ice from the underground to the top and, through the integrated ice collector in the fixed upper part of the outer auger, deposited directly into the oven. The need to secure the path of the ice from the hole to the oven drove many of our detailed design decisions, especially regarding the detailed design of the drill rail, the outer auger, and the positioning and dimensions of the oven.

Each phase of the process has been analyzed and designed in order to maximize as much as possible the amount of ice extracted and transported into the oven avoiding contamination with the overburden. The selection of a long, fixed oven was guided by simplicity (no moving oven) and by the efficiency benefit of increasing the efficiency of exchange of heat between the ice, the oven surfaces and the meltwater. Finally, the water obtained from the ice extracted is conducted into a filtering system employing a pump that makes possible to repeat the process as many times as required to obtain clean water from the system.

7.0 Integration and Test Plan



The following subsystems of the competition article were tested individually: burn test, leak test and heat load test of the new oven; Z-motor actuation, XY-motion actuation, drilling, filter regeneration for the new filters, and data logging of current load. The load cell data logging and the peristaltic pump had already been tested previously.

As of the writing of this report, all integration work has been completed, with the exception of the water handling subsystem which is currently being connected and mounted. Water melting tests were run at the subsystem level, simulating the production of ice from three holes in a row. With no insulation, no lid and running at half heating power, the time to complete the melting was 25 min, 18 min and 14 min respectively. Water quality tests were run and checked against the nut milk bags leaving no residue that could not be rinsed through the mesh.

The test plan for the period 21 - 31 May starts with testing of Z-axis actuation and drilling together, and calibration of WOB; the oven and pump together, and calibration of the current meter; and with verification that all remote control actuators are operational. Following the successful completion of the first two days’ integration checks and tests, the Bonar Box will be prepared with ice, dry ice and clay on May 23rd and HYDRA will be mounted to the lid. Six hours of testing under competition conditions will take place on May 24th, 25th and 26th. Any adjustments required will be effected using MIT facilities and supplies between May 24th and June 3rd. The objective is to verify that the integrated system is working as designed and to give an opportunity to the operators to develop their tactics and technique.

8.0 Tactical Plan for Contingencies and Redundancies

Throughout the course of development and design for HYDRA, various potential failure modes and hazards were identified which could prevent objectives from being met. They are generally associated with components being run at or near design limits and/or beyond their rated lifetime. In addition, some operational hazards - that is, hazards arising from imperfect design caused by uncertainty in operational conditions - are identified dealing mainly with the ice extraction process and the novel inner/outer auger assembly. These are shown below as categorized by expected likelihood of occurrence and the consequence to the system. As much as possible, the team prioritized buying down the highest likelihood, highest consequence risks first.

Nature of Contingency	Likelihood	Consequence	Response Plan
Burned out translation motor	Medium	Low	Two spare NEMA 23's will be on hand. Also, can sacrifice X or Y actuation and still access new hole locations
Burned out heater strips or patch	Medium	Medium	Spare heater strip; can be shaped to suit in case of contingency
Mechanical jamming of Z actuation	Low	High	Manual intervention on 1st day; extensive testing; quality tracks & lead screw; excess torque margin.
Mechanical jamming of X or Y actuation	Medium	Medium	Sacrifice the narrower actuation path (repurpose parts to protect longer path)
Drill motor damage	Low	High	High quality drill motor; testing under competition conditions beforehand; one spare drill will be on hand.
Ice does not make it to oven	High	High	Manually unblock path; retract inner auger flights past the brushes; or wait until ice melts.
Disengaging of outer auger	Medium	High	Properly engage, extract and attempt again. If broken, second set of outer auger and cutter head on hand to replace the broken part
Clogging of filters	High	Medium	Advance testing with same clay as competition. On day of competition, operator uses flexibility of pump, valves to clear.
Pump failure	Low	High	Peristaltic pump - spare tubing on hand; gravity drain;

9.0 Project Timeline

The detailed timeline of past work is shown in Appendix D. The project started in October 2017 with conceptual design, moving on to proposal stage in mid-November and early experiments with drilling in December. Detailed design was carried out in January 2018, and assembly and testing of the Prototype took place during February and early March. Following the mid-term review, a new structural design with three-axis capability was created in late March for the Competition Article and implemented in April, while development continued on the control system. A new upper part for the outer auger and associated interfaces to the rotating lower part, the drill rail and the oven were designed and produced between late April and mid-May. The new oven was constructed in early May. System integration began in mid-May and has been completed as of the writing of this report with the exception of the water system. The period from 21 May - 31 May will see the completion of the integration of the water system, and the execution of a three-day integrated test plan under competition conditions.

10.0 Safety Plan

Source of Hazard	Nature of Hazard	Mitigation
Rotary Drill operation	Projectile	Testing ramp; safety glasses
Rotary Drill attachment, removal and handling	Hand injury (cut)	Grip gloves; Unpowered when handled
Rotary Drill extended	Electrical risk	Safety gloves, proper grounding and extensive tape

trigger control		insulation for prototype. Will be replaced by a telecommand system in the competition article.
Oven operation	Fire risk	Non-flammable materials used; stress tested in controlled environment
Oven operation	Burn risk	Handled with gloves during testing/operations
Oven operation	Electrical risk	Unpowered when handled
Hazardous materials: Dry Ice in Bonar box	Cold touch; respiratory risk	Hangar doors will be opened & room ventilated to outside; operators safety trained by MIT
Hazardous materials: Fiber glass used in oven insulation	Respiratory and skin irritant	Masks, latex gloves, safety goggles when installing; enclosed in layers of aluminum foil. To be replaced with a safer insulation system in competition article
Elevated loads: drill assembly mounted on Bonar Box	Drill assembly collapses onto operators or bystanders	In prototype, operate on floor with subscale demo. When building & testing the competition article, hard hats; safety chain from wall to top of drill; stand back 10 feet while drill is operating.
Electronics	Leaked or spilled water in contact with electronics	In Competition Article, relocate electrical components.

11.0 Path to Flight

This project presents a unique challenge: build an Earth-based analog that will be an effective demonstration of a water extraction system that will ultimately be used on Mars. In our design process we were simultaneously concerned with designing an architecture that efficiently and robustly works for the competition on Earth but that could also be extended to a Mars mission with minimal modifications and loss in performance.

From an ice extraction standpoint, literature suggests that only coring, augering or other rotary drilling methods would be capable of breaking hard materials under the expected Mars surface conditions (Zacny, Luczek et al, 2015). Down-hole melting designs were discounted given the high thermal conductivity of ice, the sublimation and refreezing risks as well as last year's competition experiences. Therefore, we suggest maintaining the dual auger system used in HYDRA. Only one major change to the design architecture in this area is required in order to be implementable for Mars. Rather than melting the ice, we suggest sublimating it. This is necessary based on the phase diagram for water at Mars pressure[2]. The risks due to melting and refreezing pointed out in (Zacny, Marinova et al, 2013) suggested to us that the most effective approach for Mars is a modular design where the extraction and liquefaction stages are separated. In order to change the design to accommodate this, the oven can still be used in its current configuration but will be better sealed and will have an outlet line in its lid to capture water vapor. Additionally, a scroll compressor will be added above the lid to pressurize the water vapor above the triple point of water to allow it to condense in a cold trap. Although this is implemented because it is necessary, it also has several benefits. The first is that the cold trap will capture any ice that would have escaped the oven via sublimation in the current architecture, improving capture efficiency. The second is that sublimation is an excellent way to remove dirt from the water; as the dirt will not sublimate, only the water vapor will be left. In a similar vein, this system purifies the water from other mission-critical contaminants like perchlorates, which will be discussed later in this section.

From a high-level concept of operations standpoint, a couple of changes - some already mentioned - will be made. The table below describes specific path to flight changes that would be made on a stage-by-stage basis of our architecture:

2 http://www1.lsbu.ac.uk/water/water_phase_diagram.html

Stage of Operation	Changes for Mars System
Penetrate regolith layer with auger	The HYDRA concept has been built and tested under a wide variety of substrates. No major changes are anticipated on this end. However, the depth of regolith is fixed in the competition, whereas on Mars it will be variable. A load sensor would be added to the Mars system that would detect when ice is first contacted, signaling the outer auger to stop rotating and the inner auger to begin descending into the ice.
Begin drilling ice	The auger is built to handle a range of ice hardnesses. No major changes expected.
Seal oven and melt ice	The Mars system would be designed to sublimate the ice rather than melt it. The oven would be built in the same manner as the current system. Sublimation has the added benefit of purifying the water.
Pump and capture water	On Mars, the peristaltic pump and filter will be removed. Instead, water vapor that is produced in the oven will travel through an opening in the top of the oven, pass through a scroll compressor to pressurize the water vapor, and fall into a cold trap to cool the vapors into a liquid. It must be pressurized in order to allow for liquefaction. The purified liquid water will then be gravity-fed to a collection tank for storage.

From a materials standpoint, only a few changes should be considered. First, the majority of the frame is made of aluminum. While aluminum can withstand Mars conditions, if budget allows, we would recommend making some of the critical structural components out of titanium for increased strength. Second, the outer auger is made from 3D printed Acrylonitrile Butadiene Styrene (ABS). This worked for the purpose of the competition, because the drill only had to drill a small number of regolith holes. However, the team recommends 3D printing it from aluminum to increase its lifetime on Mars. It will add a small amount of mass but will be worth the increased performance.

The modifications to the HYDRA structure for a Mars version will require updating the design for launch loads (i.e. acceleration, vibrations, acoustics, shock), extended dormancy prior to operation (including the need to avoid cold welding), minimizing the stowed volume (creating a deployment mechanism to allow compact stowage), minimizing mass (replacing 80/20 structure with more mass efficient struts), and material compatibility with the Mars environment. To the last point, the structure will need to be built to accommodate the range of temperature swings that are present on Mars.

The drill itself will remain largely unchanged for a Mars version of HYDRA. However, significant testing should be conducted to determine operational life of the bit and assess performance in Mars-relevant pressure, temperature, and dust environments.

For the purposes of telemetry and control, several modifications will need to be made to allow remote operations on Mars. The current HYDRA system relies on hardwired telemetry and command, which will need to be replaced with wireless communication from Mars. This can easily be accommodated with the addition of an RF communications package. Another, more challenging, modification involves addressing the round-trip light-time delay for operations on Mars, which can vary from about 8.5 to 21 minutes. This new design environment necessitates autonomous operations, as opposed to the remote operations that can be performed using the Earth-based prototype. These new autonomous operations will require additional sensors, cameras, and coding to allow HYDRA to perform water extraction operations.

Comparison of Critical Metrics

It is necessary to note the effects on major metrics that the changes described above will have when moving from an Earth system to a Mars system. These are described in the table below.

Metric	Earth to Mars 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. A compressor and cold trap will be added. Net mass and overall dimensions remain the same.
Power	Decrease	Sublimation on Mars will likely require less power than melting ice on Earth. Provided the oven is well-insulated to minimize thermal losses, an overall decrease in power is expected.
Reliability	Decrease	Sublimation on Mars requires no filter regeneration, giving the Mars system an advantage for reliability. However, given the nature of autonomously operating a moving piece of equipment on another planet with a time delay and no chance at maintenance, it would be naive to state that the system reliability is the same on Mars as on Earth.
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 is therefore expected to stay the same or decrease on Mars.
System Lifetime	Increase	The Mars system will likely have a longer lifetime because it has fewer moving parts and therefore less chance to fail.

Other Factors Considered

In addition to the challenges with sublimation arising from Mars ambient conditions, several path-to-flight factors were taken into consideration when developing the final architecture. These include:

1. *Regolith*: The depth of regolith on Mars will be more variable than during the competition. Therefore, we designed our system to be upgraded to a Mars-ready system that has the flexibility necessary to work under varying regolith conditions. The hollow stem arrangement makes it feasible to incorporate a sensor on the bottom of the auger bit that detects when the regolith/ice interface is reached.
2. *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 perchlorate contamination.
3. *Filtering*: When operating remotely on Mars, it is unacceptable for a clogged filter to halt water harvesting and end the mission. Our Mars system does not require a filter, as the water is distilled.
4. *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 least number of moving parts possible while still completing its job. This decrease in system complexity ultimately increases our system reliability.

5. *Reduced Gravity:* Reduced gravity should not have significant effects on the system.
6. *Launch Environment*: The launch environment is harsh, and includes significant acoustic and vibrational loads. The Mars system will have to be built to withstand the launch environment.
7. *Dust:* A major challenge that NASA has faced when operating landers and rovers on the surface of Mars is dust. The combination of dry atmospheric conditions, presence of fine grain dust, and winds on the surface results in dust everywhere. If not accounted for, it would get into the bearings of the x-y-z translation system and the drill motor, among others. A clogging of any of these systems by dust could be mission ending. Therefore, the path-to-flight changes for a Mars system must heavily focus on the prevention of dust getting into the system. One of our team members has experience with Mars dust through his work on MOXIE, an instrument onboard NASA's Mars 2020 rover. MOXIE utilizes a scroll compressor and prevents dust from entering the compressor with a downwards-facing HEPA filter. A series of HEPA filters like this could be used to shield sensitive components of the drilling rig from dust. The vibrations from the drilling rig during operations would be sufficient to unclog the filters, thus making this a relatively reliable system.

12.0 Funding and Expenses

The total funding received was \$11,500, being \$10,000 from RASC-AL and \$1,500 from MIT via Space Grant fellowships to offset the travel costs of the three student members of the team to Virginia. The total expenses are projected to be \$11,448.06, of which \$1,650 are estimated traveling costs not yet billed or paid. The summary of the expenses broken down by category is shown in below. A more detailed summary and analysis of the expenses is shown in Appendix C. In-kind contributions were received from Kovacs Enterprises, who donated the ice auger and high strength cutting bit valued at \$770 and the MIT MechE department who donated three 3D-printed parts for the outer auger valued at \$300.

	Original Budget	Actual Spent
Test Station		
Bonar Box Test Station	$ 1,500.00	$ 1,792.51
	$ 1,500.00	**$ 1,792.51**
HYDRA System		
Structure	$ 3,000.00	$ 3,280.70
Drill and Augers		$ 1,063.03
Power Sensors and Controls	$ 2,500.00	$ 970.58
Water Processing	$ 500.00	$ 839.52
	$ 6,000.00	**$ 6,153.83**
Logistics		
Shipping Traveling and Registration	$ 4,300.00	$ 3,501.72
	$ 4,300.00	**$ 3,501.72**
Grand Total	**$ 11,800.00**	**$ 11,448.06**

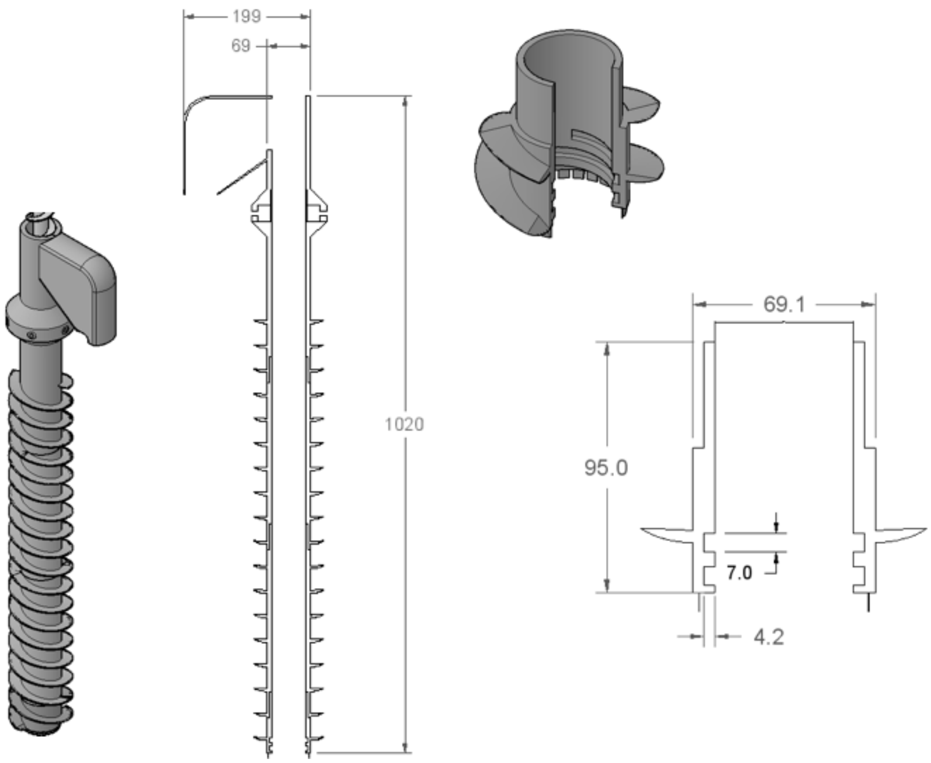
References

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.

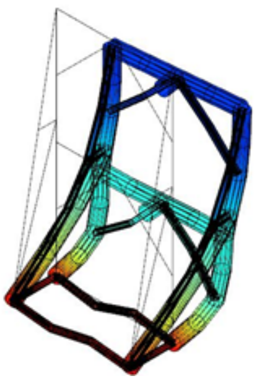
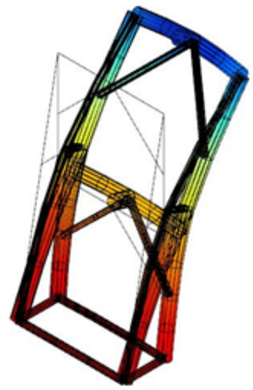
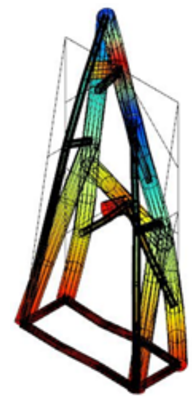
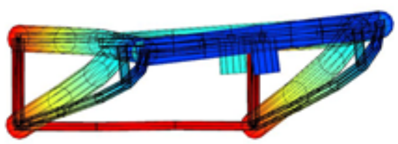
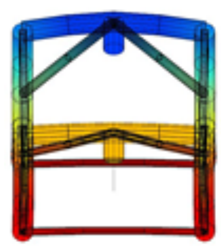
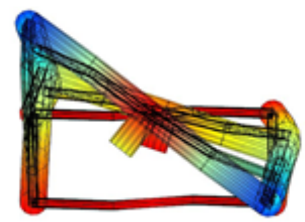
Zacny, K., Paulsen, G., McKay, C. P., Glass, B., Davé, A., Davila, A. F., ... & Cabrol, N. (2013). Reaching 1 m deep on Mars: the Icebreaker drill. *Astrobiology*, *13*(12), 1166-1198.

Appendices

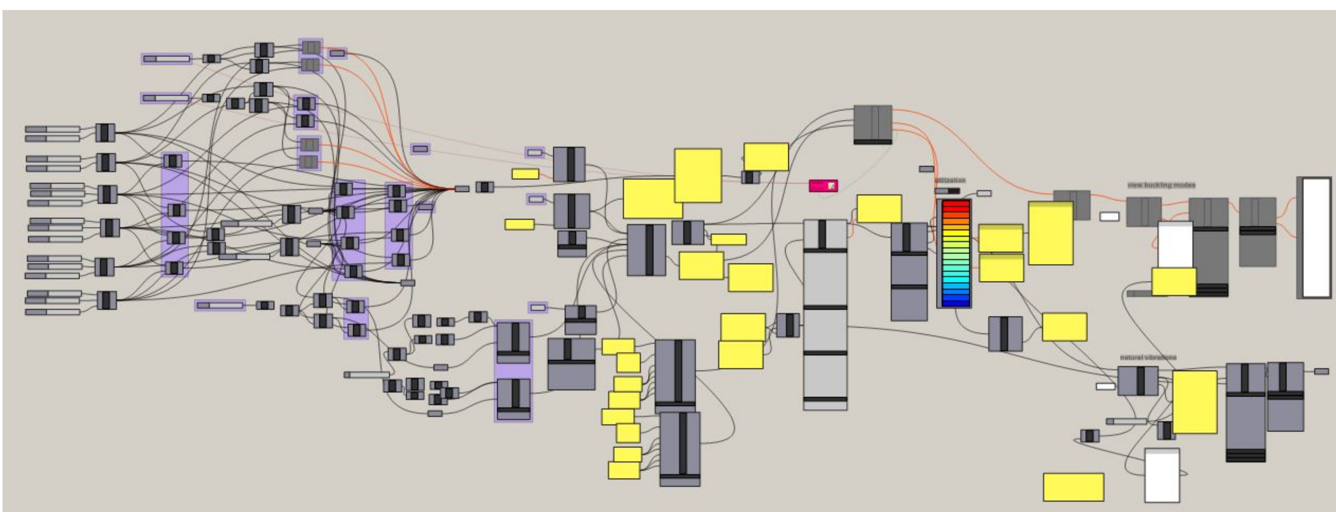
Appendix A: Technical Drawings



Appendix B: HYDRA Fundamental Periods of Vibration

1st Mode T=0.021337 s	**2nd Mode** T=0.016423 s	**3rd Mode** T=0.010652 s
		
		

Parametric model of the HYDRA structure in Grasshopper and Karamba



.

Appendix C: Summary and Analysis of Expenses by Category

<u>Bonar Box Test Station</u>		**$1,792.51**
Clay, sand, stones	SiteOne	$259.58
Bonar box	Polar	$760.31
Bonar lid	Polar	$332.64
Bathroom scale	Amazon	$28.22
Polystyrene	McMaster	$227.68
Cryo gloves, shovels, tarp, burlap bags, packing peanuts	Amazon	$184.08

<u>Structure</u>		**$3,280.70**
CNC shaft coupler	Amazon	$27.23
Extended straight, end brace, U-bolt	McMaster	$107.74
80/20 T-Slotted Framing components (various)	McMaster	$248.51
80/20 T-Slotted Framing components (various)	McMaster	$207.75
Wire lanyards, turnbuckles, bearings	McMaster	$276.70
Steel threaded rods, fasteners	McMaster	$83.35
Spacers, thread adapters, screws, washers, nuts	McMaster	$71.73
1" 80/20 components for new HYDRA	McMaster	$1,689.80
1" 80/20 components for new HYDRA	McMaster	$126.51
Inline pivots	McMaster	$71.66
Items returned to McMaster	McMaster	-$220.53
Lead screw with shaft coupling and mount support	Banggood	$43.94
Shaft couplings, stepper motors	Amazon	$141.55
1" 80/20 components for new HYDRA	McMaster	$315.59

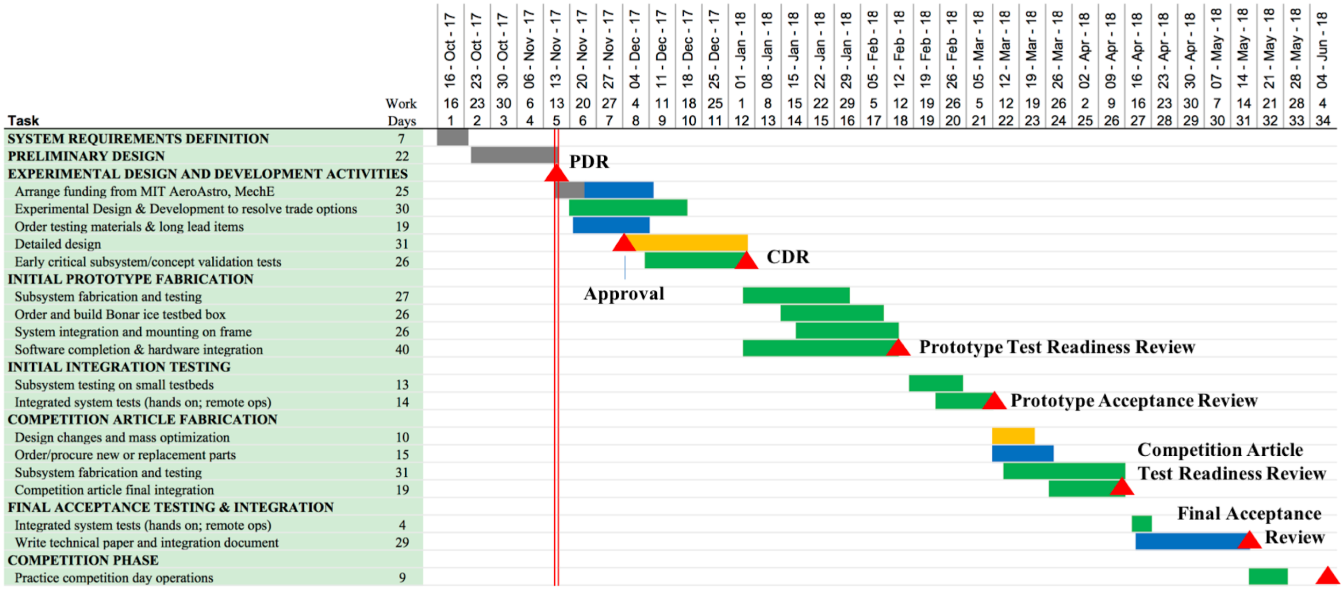
Bearing	Amazon	$25.85
Spacers, screws, fasteners, alum block	McMaster	$63.32
1" 80/20 components for new HYDRA	McMaster	$155.22
Refund	McMaster	-$155.22
<u>Power Sensors and Controls</u>		**$970.58**
Current sensor, power supply, stepper motor controller	Amazon	$83.58
PCB; Pin headers; thermocouple sensor; temp controller; NEMA 23 stepper	Amazon	$127.92
Current sensor; load cell sensor; programmable relay block	Digikey	$313.46
Pin headers	Amazon	$18.08
Ribbon cable, crimp connector, pin header, load cell amplifier	SparkFun	$53.95
USB-to-TTL, RS232 to terminal adapters	Amazon	$37.66
Heat shrink tubing, connectors, standoffs	Amazon	$77.49
Arduinos, MOSFETs, POT, Adapter	Digikey	$165.21
Power regulator 12V	Amazon	$15.54
Stepper controllers (2)	Amazon	$35.50
New current sensors	Digikey	$42.19
<u>Drill and Augers</u>		**$1,063.03**
3D printing	MakerWorks	$311.71
Spare drill	Home Depot	$180.00
Drill and other materials from home depot	Home Depot	$200.00
Aluminum tubing	TW Metals	$229.03
Drill lead screw and nut	McMaster	$119.29
Bearing	Amazon	$23.00

Water Processing		**$839.52**
Foam sealant	Grainger	$20.01
Fiber insulation blanket	Amazon	$66.64
Silicone tubing	Amazon	$37.98
Steel pot	Amazon	$41.23
Pipe T fittings, set of 2	Gamut	$16.73
Heat cable, power controller, heat sheet	McMaster	$205.59
Barb connector for tubing	Fawcett Boat Supplies	$2.77
Solenoid valves	Gamut	$125.12
Tubing clamps	McMaster	$14.77
Heat cable, new filters	McMaster	$120.06
Tubing, nut milk bags, camera, shovel	Amazon	$120.64
Liquid nails	Amazon	$13.99
Copper oven + bracket	Wayfair	$53.99

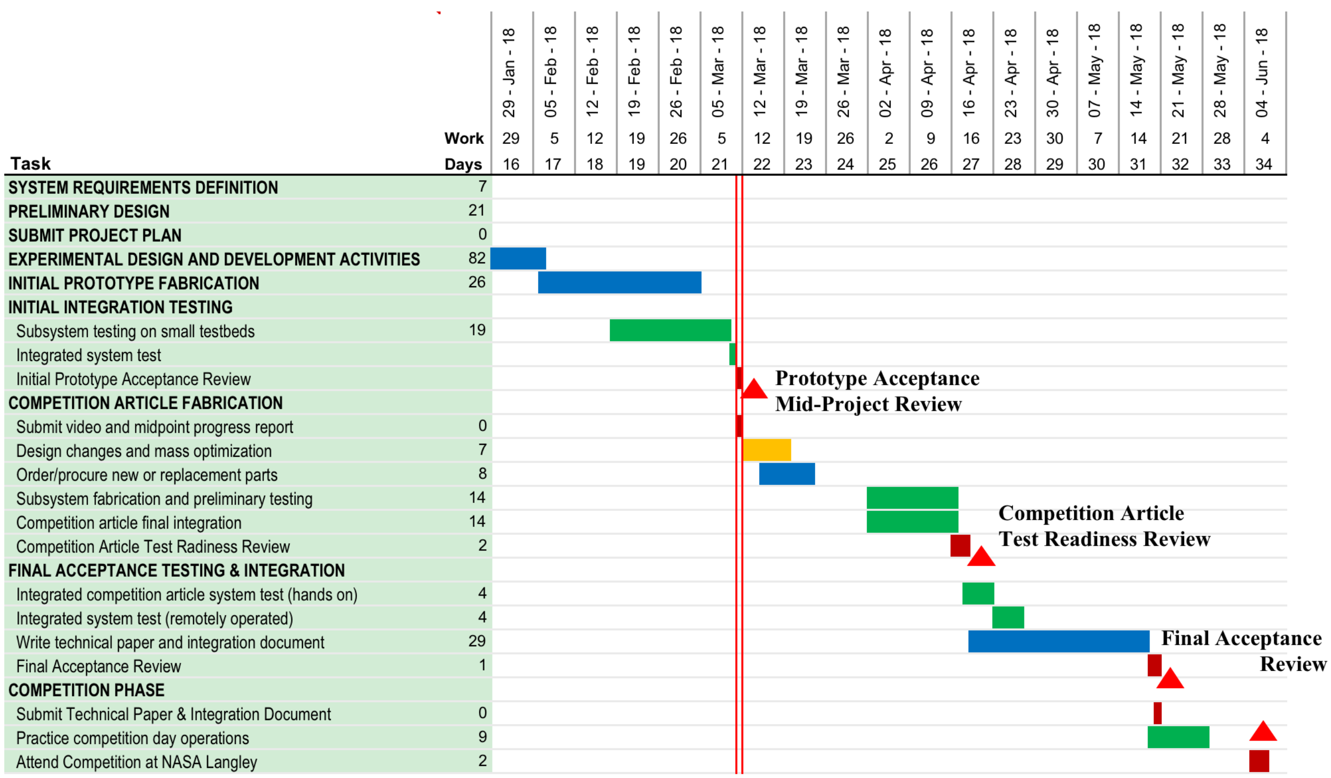
Shipping Traveling and Registration		**$3,501.72**
Flight for advisor		$372.00
Flights for students		$736.00
Van/truck	TBD	$500.00
Registration fees	RASC-AL	$1,100.00
Hotel room for students @ TownePlace Suites by Marriott	Marriott	$365.64
Hotel room for advisors @ Newport News Marriott City Center	Newport	$428.08

Appendix D: Project Timeline Charts

Original Plan as submitted with Project Proposal



Updated Plan as submitted for Midterm Review



Appendix E1: Arduino Code for Z motion Control

```
int PUL=7; //define Pulse pin
int DIR=6; //define Direction pin
int ENA=5; //define Enable Pin
int AIN = A0; //define analog input pin
int PulTime = 0; //define pulse time
int WOB_PIN = A1; // WOB weight on bits
int ACC_PIN = A2; //AC current reading
void setup() {
 Serial.begin(9600);
  //t.every(1000, takeReading, 5); // take a reading every second
  pinMode (PUL, OUTPUT);
  pinMode (DIR, OUTPUT);
  pinMode (ENA, OUTPUT);
  digitalWrite(DIR,LOW); // LOW is up, HIGH is down
  digitalWrite(ENA,HIGH); // LOW is free moving
}

void loop() {
  // t.update(); // must be in the loop
  int Pot = analogRead(AIN);
    int WOB = analogRead(WOB_PIN)/4;
      int ACC = analogRead(ACC_PIN)/4;
 PulTime= map(Pot, 500,1023, 10000, 500);
  //delay(PulTime); //delay 2 ms to let the ADC recover
  //Serial.println(Sensor1);
  //PulTime = speedUP();
  Serial.print(WOB);
  Serial.print(',');
  Serial.println(ACC);

  for(int x = 0; x < 300; x++)
  {
  digitalWrite(PUL,HIGH);
  delayMicroseconds(PulTime);
  digitalWrite(PUL,LOW);
  delayMicroseconds(PulTime);
  }
}
```

Appendix E2: Processing Code for Receiving Data from Arduino

```
import meter.*;
import processing.serial.*;

Serial myPort;  // Create object from Serial class
String val;     // Data received from the serial port

String filename;
Table table;
Meter m, m2;

void setup()
{
  size(950,400);
  background(0);

  fill(120, 50, 0);
  m = new Meter(this, 25, 100);
  // Adjust font color of meter value
  m.setTitleFontSize(20);
  m.setTitleFontName("Arial bold");
  m.setTitle("WOB, (N)");
  //m.setDisplayDigitalMeterValue(true);

  // Meter Scale
  //String[] scaleLabelsT = {"0", "10", "20", "30", "40", "50", "60", "70", "80"};
  String[] scaleLabelsT = {"0", "50", "100", "150", "200","250"};
  // !!!!
  m.setScaleLabels(scaleLabelsT);
  m.setScaleFontSize(18);
  m.setScaleFontName("Times New Roman bold");
  m.setScaleFontColor(color(200, 30, 70));
  m.setArcColor(color(141, 113, 178));
  m.setArcThickness(10);
  m.setMaxScaleValue(80);
  m.setNeedleThickness(3);
  m.setMinInputSignal(0);   // !!!!
  m.setMaxInputSignal(250);  // !!!!

  // A second meter for reference
  int mx = m.getMeterX();
  int my = m.getMeterY();
  int mw = m.getMeterWidth();

  m2 = new Meter(this, mx + mw + 20, my);
  m2.setTitleFontSize(20);
```

```
  m2.setTitleFontName("Arial bold");
  m2.setTitle("AC Current, (A)");
 // m2.setDisplayDigitalMeterValue(true);

  String[] scaleLabelsH = {"0", "50", "100", "150", "200","250","300","350"};
  //!!!!
  m2.setScaleLabels(scaleLabelsH);
  m2.setScaleFontSize(18);
  m2.setScaleFontName("Times New Roman bold");
  m2.setScaleFontColor(color(200, 30, 70));
  m2.setArcColor(color(141, 113, 178));
  m2.setArcThickness(10);
  m2.setMaxScaleValue(100);
  m2.setNeedleThickness(3);
  m2.setMinInputSignal(0); //!!!!
  m2.setMaxInputSignal(370); //!!!!


  // I know that the first port in the serial list on my mac
  // is Serial.list()[0].
  // On Windows machines, this generally opens COM1.
  // Open whatever port is the one you're using.
  String portName = Serial.list()[0]; //change the 0 to a 1 or 2 etc. to match your port
  myPort = new Serial(this, portName, 9600);

  table = new Table();
  //add a column header "Data" for the collected data
  table.addColumn("V1", Table.FLOAT);
  //add a column header "Time" and "Date" for a timestamp to each data entry
  table.addColumn("V2", Table.FLOAT);
  table.addColumn("Time", Table.STRING);
}

void draw()
{
  int h = hour();
  int min = minute();
  int s = second();
  int MOB = s % 10; // take reading very 10 seconds
  textSize(30);
  fill(0, 255, 0);
  text("MIT HYDRA 2017", 350, 50);

  if ( myPort.available() > 0)
  {  // If data is available,
   val = myPort.readStringUntil('\n');         // read it and store it in val
  }
```

```
  if(val !=null)
  {

    val = trim(val); //remove space
    int[] sensors = int(split(val, ',')); //split into individual number

        for (int sensorNum = 0; sensorNum < sensors.length; sensorNum++)
        {
          print("Sensor " + sensorNum + ": " + sensors[sensorNum] + "\t");
          int WOB = sensors[0];
          int AMP = sensors[1];
          m.updateMeter(WOB);
          m2.updateMeter(AMP);
       }
        // add a linefeed at the end:
        println();

    TableRow newRow = table.addRow();
      //place the new row and value under the "Data" column
    newRow.setFloat("V1", sensors[0]);
    newRow.setFloat("V2", sensors[1]);
    //place the new row and time under the "Time" column
    newRow.setString("Time", str(h) + ":" + str(min) + ":" + str(s));
  }
}

void keyPressed()
{
  //variables used for the filename timestamp
  int d = day();
  int m = month();
  int h = hour();
  int min = minute();
  int s = second();
  //variable as string under the data folder set as (mm-dd--hh-min-s.csv)
  filename = "data/" + str(m) + "-" + str(d) + "--" + str(h) + "-" + str(min) + "-" + str(s) + ".csv";
  //save as a table in csv format(data/table - data folder name table)
  saveTable(table, filename);
  exit();
}
```


RASC-AL SPECIAL EDITION MARS ICE CHALLENGE
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