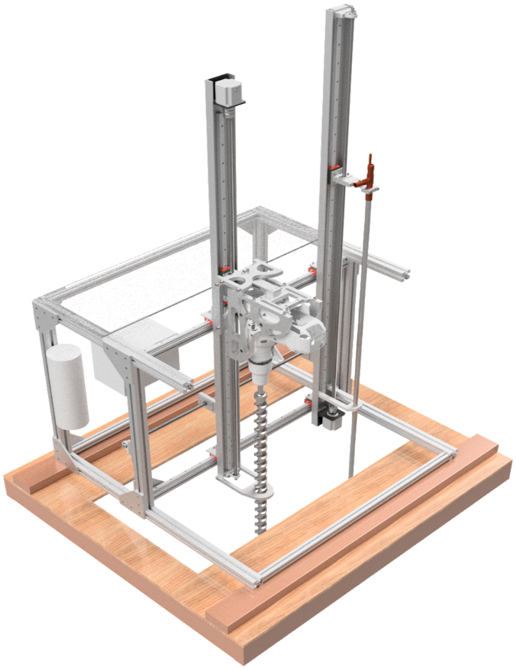
NASA RASC-AL Special Edition

Moon to Mars Ice and Prospecting Challenge

Technical Paper

DEIMOS

Drill-based Extraction of Ice-water and Martian Overburden System



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Introduction

With the ever increasing capacity for space travel, it is important to be able to sustain unmanned missions to unsettled planets such as Mars. To have a deep space habitat, it is imperative to have a method of purifying martian ice and turning it into usable water. The extracted water could be used for drinking and growing plants. This also presents the possibility of splitting the water into hydrogen and oxygen to have a source of rocket fuel. For these objectives to be possible, a drilling apparatus that can be used on Mars to extract and purify the ice into usable water is required. The Drill-based Extraction of Ice and Martian Overburden System (DEIMOS) system looks to achieve the aforementioned objectives to enable further space exploration.

System Description

The DEIMOS design is split into five subsystems: mounting, drilling, extraction, filtration, and digital core. The full CAD model is shown below in Figure 1. The subsystems are supported by a frame made up of 10 and 15 series aluminum. The horizontal and vertical motion for the drill and extractors is done through the use of guide rails along lead screws and stepper motors. Multiple pumps are used within the system to extract the ice from the simulated test bed, as well as routing the water through the filtration system and out to the collection container.

All of the subsystems are designed for Earth-based operation, and adhere to 1x1x2m volumetric, 60 kg mass, 120VAC voltage, 9A current, and 150N Weight-on-bit (WOB) pressure constraints. The system also maintains the viability to adjust the system for path-to-flight needs so that the system could be used on the Moon or on Mars.

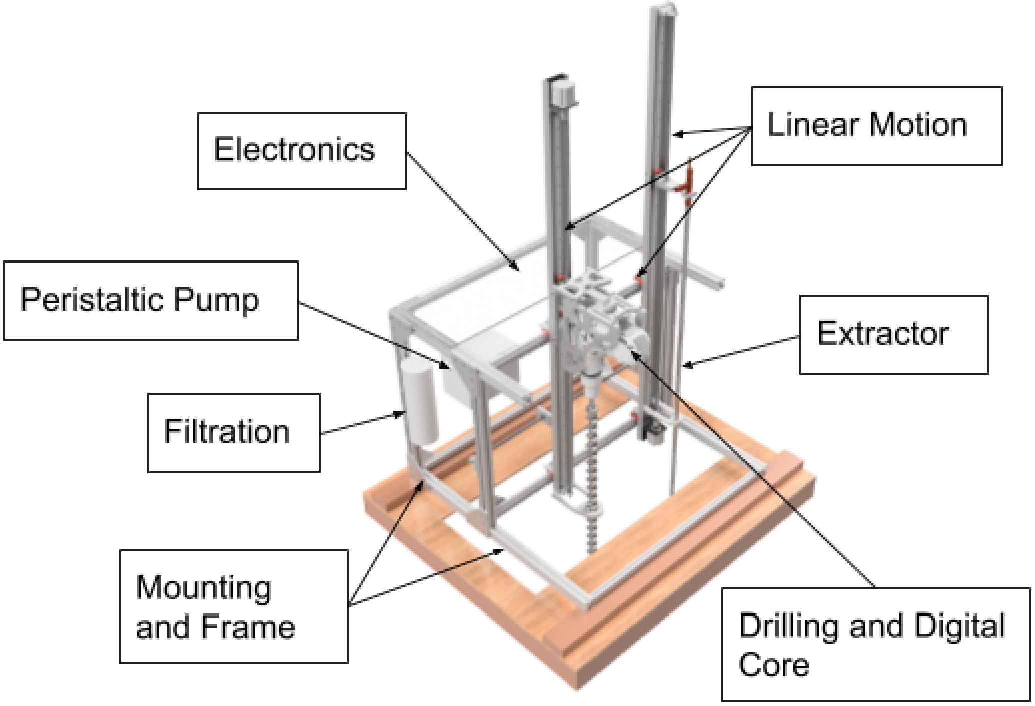
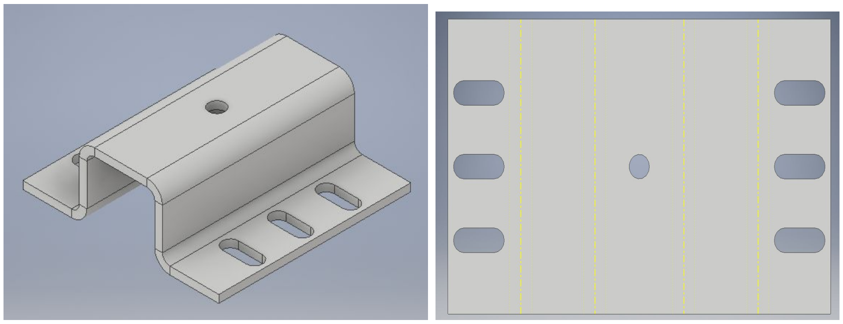


Figure 1: Full CAD Model of DEIMOS

Mounting System

For the mounting system, the team is using a custom sheet metal clamp that fastens to the bottom portion of the frame to the 2”x4” boards, as seen in Figures 2.1 and 2.2 These clamps include slotted holes to allow for any uncertainty in the location of the boards as per the NASA competition guidelines. These mounting clamps have been attached to the frame and the test bed setup. Figure 3 below shows the mounts installed on the frame.



Figures 2.1 (left) and 2.2 (right): Mounting Clamps.

The frame of DEIMOS is built from aluminum 80/20 stock. Ball bearing sliders have been chosen to serve as the means of traversing in the horizontal and vertical members. The horizontal slider rails are backed by a 1”x1” piece of 80/20 for added support. These rails are also positioned such that the sliders are not traversing on their side and are able to take advantage of their 900lbs static yield rating, as well as the 23 ft-lb roll capacity. This load is distributed between two carriages, further reducing load on individual carriages. In order to back the vertical members, U-channel is used. Within these U-channels, a rail is placed so that the linear sliders can traverse up and down. This is the case for the drill setup as well as the extractor setup. U-channel was chosen specifically for added rigidity. On the drilling vertical assembly, the stepper motor is mounted at the bottom for clearance purposes. On the extractors, the stepper is mounted on the bottom so the structure is not top heavy. All stepper motors will be wrapped in a covering to prevent dust and debris from damaging them during drilling.

Figure 3: DEIMOS Mounts on Frame

Drilling System

The team is using a DeWALT SDS MAX Hammer drill with a 1.5 inch diameter drill bit. The drill is mounted to the frame using the mount, CNC machined by Protolabs, shown in Figure 4. This mount allows the drill to move horizontally and vertically. The drill is mounted to the lead screw carriage. In order to excavate into the overburden the drill is positioned horizontally over the test bed. Then the drill is turned on and lowered into the overburden. When the drill bit contacts the regolith, the drill is pushed upward relative to the subframe and apply force to the load cell. Layers within the digital core are assessed by use of a load cell and predetermined weights of the drill, the drill bit and the supporting frame. Drilling is conducted until the drill bit reaches a depth of 2 inches into the ice. This is achieved by a calibration in water ice which has already been programmed into the weight-on-bit system.

Figure 4: Drill mounted with Protolabs Drill Mount

Extraction System

The extraction subsystem utilizes the recirculation of heated water to enhance the melting of the ice. The extraction tip is shown in Figure 5 below. This tip is constructed of copper, and uses a sealed 500 Watt cartridge heater. Surrounding the heater are 12 small copper tubes that serve as the pathways for the extracted water. The stem of the extractor is constructed of stainless steel pipe so that heat is concentrated near the tip. Once the extractor is inserted into the drilled hole, the heater turns on and will begin to melt the ice. While the ice is melted, a peristaltic pump is used to draw in the water. The pump will then be stalled and reversed, so that heated water is fed into the borehole. The convection effect of the heated water will continue the melting process of the ice. The water is cycled in and out of the extractor yielding more and more melted water. The reversing control of the peristaltic pump enhances the melting of the ice.

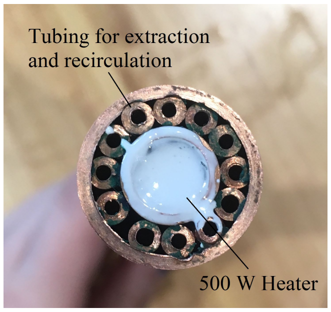


Figure 5: Bottom view of extractor tip.

Filtration System

To filter the collected water, a two step system is used. The first step in the system is a small piece of mesh on the end of the extractor tip. This will prevent large pieces of debris from clogging the extractor and tubing. The second step is a gravity filter that is primed with sand. The filter housing is a section of 4 inch PVC tube that is fitted with end caps. The top end cap has a threaded top that be screwed in and out for maintenance, and connections for ⅜" tubing. The bottom end cap also has connections for ⅜" tubing. At the bottom of the filtration canister has a 50 micron polishing pad at the bottom, and then sand above that. A CAD model of this filtration system can be seen in Figures 6.1 and 6.2. In the cross sectional view (Figure 6.2) the green section represents the filtration foam while the yellow section represents the sand. As water is pumped in, the sand and foam act as a gravity filter to purify the water. The peristaltic pump pushes water into the filter, while a secondary pump pulls water through the other end.

Figures 6.1 (left) and 6.2 (right): CAD models of filtration system

Digital Core

The digital core subsystem is the final subsystem in the design. This subsystem focuses on fulfilling the requirement of sensing and acquiring the readout of the drill's weight on bit during the drilling process. To do this the team plans to utilize a load cell and load cell amplifier. The beam load cell is mounted as shown below (Figure 7). It will rest on the drill mount and the beam will deflect as the drill pushes down into the overburden.

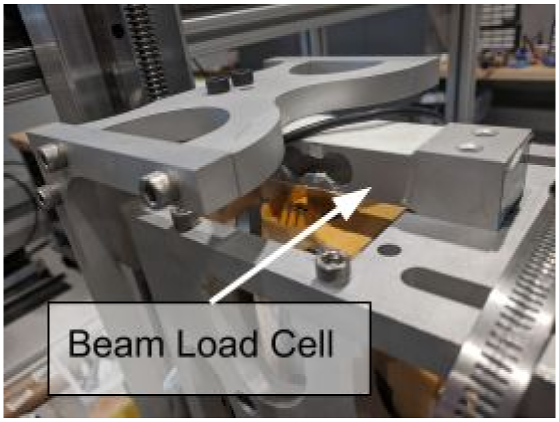


Figure 7: Drill mount with load cell

A lead screw is used to move the drill and is connected to the drill by a lead screw carriage and the drill mount as seen in Figure 8.

Figure 8: Side View of Drill Mount - Showing Lead Screw Connection

The force on the drillbit is measured by a connecting plate from the drill mount to the load cell. The load cell is wired to a load cell amplifier. The amplifier has a visual readout that allows data to be seen instantaneously and exported out to a datalogger. The BLH load cell shown in Figure 9 is used for digital core applications.

Figure 9: BLH PS2010-T Load Cell Amplifier

Control, Communications, and Datalogging

The entire DEIMOS system is controlled by a single Arduino Mega 2560 communicating with a PC over USB. A wired USB connection was chosen over wireless communication due to the unknown RF noise environment at the testing facility; the wired connection offers the simplest, cheapest, and most reliable solution. The Arduino acts like a DAQ (Data Acquisition System) in as it does not have any control logic or routines programmed into its memory; all data collected by the sensors connected to the Arduino are sent to the connected PC where processing and logging occurs. The data is processed in Simulink, which in turns sends commands to the appropriate Arduino I/O to perform the necessary action. Sending raw data to the PC allows for faster and simpler processing. Raw data can be logged immediately, while ADC signals read from the Arduino can be processed in Simulink. This also allows future development to be ported to different software if desired without much hassle.

To prevent linear motion elements from colliding with parts of the frame, limit switches with hinge actuators are used. The limit switches double to perform a homing sequence to ensure the drill and extractor are up and out of any overburden before making any horizontal motion. Additionally a horizontal limit switch also serves to calibrate the home position along the x-axis.

One auxiliary limit switch is used on the extractor to detect when the extractor tip contacts the ice. The extractor is designed to have some vertical play in its clamping mechanism; as the extractor is pushed into ice, the extractor moves up relative to its clamping mechanism and actuates the limit switch. This signals the extractor stepper to turn off momentarily until more ice is melted. Once more ice is melted, the extractor will slide down along the clamp and release the limit switch, signalling the extractor stepper motor to resume motion.

The vertical motion for the drill relies on the weight on bit reading to control the speed, or penetration rate. This is controlled through a PID loop with a weight on bit setpoint of 100N to prevent any spikes from overshooting the 150N limit. If the weight on bit reading overshoots the setpoint, the vertical travel speed is decreased to reduce the weight on bit.

Multiple current sensors are in use in the DEIMOS electrical system; a current sensor is inline with the 9A fusing for the system to monitor total current draw for the entire system. An additional current sensor is used with the drill motor. The current drawn by the motor is used to interpolate the torque on the drill. This torque value is used in the Mechanical Specific Energy equation to determine hardness (Prasad):

$$MSE = \frac{WoB}{A_C} + \frac{T \cdot RPM}{A_c \cdot RoP}$$

where MSE is Mechanical Specific Energy, WoB is weight on bit measured by the load cell, T is torque derived from the current reading, RPM is rotational speed of the drill measured by a hall effect sensor built into the drill, Ac is the cross sectional area of the drill head, and RoP is the rate of penetration according to the speed that the stepper motor is being driven at.

Table 1: Control and Data logger Specifications

Sensor/Actuator	***Purpose***	***Critical Specs***
5V Relay Modules	Turn on and off high voltages with	250VAC 10A/30VDC 10A rated

	logic level voltage	15-20mA current draw
SPDT Micro Limit Switch	Detect end of travel for linear motion	Long straight hinge lever actuator
100K Thermistor	Monitor the temperature of the extractor tip	100KΩ with ± 1% accuracy
12VDC Switching Power Supply	Supply 12V and 24V in series for DEIMOS electrical system	12VDC with pot adjustment, 30A max continuous draw
Water flow sensor	Detect flow of water from extractor and filter	1.2MPa rating, 0.15-1.5 L/min
NEMA 23 Stepper	Provide vertical and horizontal motion	600 RPM max, 2.5A rating, 1.8° increments, 140in-oz starting torque, 17in-oz continuous torque
Beam Load Cell	Measure weight on bit	50kg rating, combined error <0.03%RO, temperature effect <0.003 (%RO/℃)
BLH PS2010-T	Load Cell Amplifier	4-20mA output, onboard display, zero/span calibration, Newton units
ACS712 Current Sensor	Measure current drawn by system and by drill motor	20A rating, total error ±1.5%
DM542T Stepper Motor Driver	Drive stepper motors using two logic level signals	1/128 step resolution, 20-50VDC, 1.0-4.2A
4-20mA to 0-5V converter	Take 4-20mA output signal of load cell into Arduino ADC	0-20mA or 4-20mA signals
Voltage Detector	Determine if critical circuits are being powered	25V Max, 0.00489V resolution

Technical Specifications

Table 2: Technical Specifications

Overall Mass	55kg	***Max Drilling Speed***	540 RPM
Overall Volume	1.63m x 0.90m x 0.92m	***Torque***	16.4 ft-lbs
Drill Bit Length	0.9144m	***On Board Computer***	Arduino Mega 2560
Drill Force	140N	***Comms Interface***	USB
Rated Load	9A	***Software***	Simulink
Power Usage	1000W	***System Telemetry***	YZC-1B Beam Load Cell, BLH PS-2010T

Design Changes and Challenges

Since the submitted midpoint review, the team has decided to forego the concept of sleeves from DEIMOS. The team encountered more pressing challenges with other subsystems and did not arrive at an adequate solution as of this report. The risk of the drilled hole collapsing was decided to be a secondary failure. Ensuring all subsystems working together was a higher priority.

Another design modification was the lowering the number of extractors on DEIMOS from two to one. The team saw the use of two extractors as unnecessarily difficult. One difficulty was that pumping from two extractors would require more elaborate pumping actuation and would limit the pumping power per extractor. Additionally the plumbing logic would be increased and without a guarantee of improved extraction. Lastly the power constraints for the extractor heaters, pumps would not allow parallel use of power.

The team also updated their linear motion concept. The original design consisted of a rectangular aluminum tube that slid over a 33 inch beam of 80/20 aluminum extrusion as seen in Figure 10. Ultimately this design was changed as the rectangular slider exhibited significant friction and was found to limit motion control. The team has since moved to a more streamlined design in which two parallel linear slider rails are positioned at the top and bottom of the frame along two beams of 80/20. Along these rails, carriages are able to move freely with minimal friction.

Figure 10: Original Linear Motion Setup

Challenges were also experienced during the design and testing phase for the extractor. The previous extractor was limited by having one hole for extraction and one hole for recirculation. This was deemed as a potential failure point. Additionally the original extractor did not have adequate conduction from the cartridge heater to the exterior of the extractor. To address both of these concerns, the team redesigned the extractor with 12 copper tubes that serve as distinct pathways for flow and additionally increase the conduction of heat from the cartridge heater to the exterior of the extractor. This change has increased the melt rate significantly over the original extractor.

Competition Strategy

The overall strategy of the team involves several innovative concepts working together to minimize drill time and maximize extraction rate. As an example, the team determined that it would be most efficient to use the digital core while drilling into the overburden. Given that there is only 12 hours to extract the most amount of water, this multitasking saves significant time. This was accomplished by using a beam load cell, described above, so that the act of drilling would not be interrupted. From there, the team uses the heated extractor tip to pull water from the hole. The pumps are reversible so that water can be recirculated back into the hole with two added benefits. First, this reciprocation enhances the melt rate, helping to melt the ice faster. Secondly this reversing of flow serves to keep the the pump tubing free of debris and can be run in reverse for longer if a clog in the pipe is detected. In order to ensure clean separation of water from debris, the extracted water is pumped through a through a sand filter prior to the collection bucket.

Integration and Test Plan

The team was able to conduct multiple test runs leading up to the competition. First, the team was able to test the linear motion on the robot. The team was able to use some simple code to move the drill and extractor along the horizontal axis as well as the vertical axis.

Then, the team was able to test the extractor tip in a bucket with a 5 inch layer of ice at the bottom. The extractor tip performed as expected and water was able to be melted and pumped out of the hole as the extractor moved further downwards.

For a fully integrated test run, the team froze a bucket of water and then poured simulated regolith over the ice. The drill was then used to drill into the overburden and into the top of the ice layer. The drill was then moved out of the hole and the extractor was moved into position. The extractor was able to move into the hole and past the small amounts of debris that had been left from the drilling inside the hole, and make contact with the ice. Water was then collected in a beaker after pumping it out of the hole.

The next step for the team is to continue this same testing, but with more of an overburden layer as well as a thicker ice layer. The team is also be finalizing the plumbing systems on the robot so that the filter can be integrated with our water collection route.

Tactical Plan

In order to be prepared for the competition, the team made a list of possible points of failure, the probability that the event would occur, the impact the event would have, and how the event can be mitigated as seen Table 3 below.

Table 3: Risk and mitigation table.

Risk	***Probability***	***Impact***	***Mitigation***
The load cell doesn't pick up the different layers due to bending of the drill mount frame	2	3	The drill mount frame has been secured and reinforced along the body of the drill
The pump gets clogged and the flow cannot be reversed	2	5	Using a peristaltic pump minimizes the amount of clogs going through the piping and a mesh filter is attached to the end of the extractor
Drill bit breaks	1	5	The factor of safety for the bit that the team purchased is high enough that this highly unlikely
Heater burns out from overheating	2	3	There is a thermocouple at the tip in conjunction with a throttle control
Lead screw failure	3	5	The team has reduced the weight on the lead screws to minimize the stress

Power shut off/ electronic failure	1	3	There is an emergency cut off switch in the worst case scenario
Gravity Filter clogs from buildup of sediment overnight between competition days.	3	5	The team has prepared an extra filtration canister to bring to competition and replace in the system.

Project Timeline

Outlined in Table 4 below is the project timeline the team has adhered to during this project.

Table 4: Project Timeline with major tasks.

Month	***Deliverables***
September - November	● Pump calculations, heat transfer ● Path to flight research ● NASA application
December	● Accepted into the competition ● Overall system design
January - February	● Frame construction ● Subsystem testing
March	● Received Protolabs service grant ● Midpoint review
April	● Prototype fully assembled ● Testing of subsystems
May	● Integration of subsystems ● Optimizing system ● Full run through of system operations

Safety Plan

Safety is of utmost concern for the team, and therefore a safety plan has been put in place. While performing certain testing and construction, team members wear protective safety glasses and gloves. Safety glasses are to protect team members from any debris that may fly while cutting into overburden, and also while cutting pieces of metal for the frame, mounting brackets, and other components. Protective gloves are used while cutting material for DEIMOS, and also while handling any elements of the extraction system that may have heated up during testing. Since DEIMOS utilizes a hammer drill, the team plans to use hearing protection for any member close to the system during extensive testing. While testing the isolated extraction system, the team also takes caution to ensure no water leaks from the system to the electronics. This is done by checking for any leaks before running each iteration, and keeping the electronics away from the water flow. DEIMOS will also be equipped with an emergency stop in the unlikely event of a system malfunction.

Paths to Flight

Water Extraction on Mars

The main differences in operating conditions between Earth and Mars are its atmospheric conditions. The temperature on Mars ranges from -120 degrees Celsius to 27 degrees Celsius (at the equator) (Zacny), while the atmospheric pressure ranges from 0.1 kPa to 1.5 kPa (Zacny). DEIMOS must be constructed from materials that can withstand these conditions. Also, its subsystems, specifically extraction and filtration, must be adjusted to fit these conditions. Another aspect that will greatly affect DEIMOS is the mission itself. Right now, DEIMOS is only operable in a simulated test environment that does not move outside the test bed. DEIMOS will require housing, and other changes to accommodate itself to life on Mars. These factors include forces and shock from launch and landing, being dormant while traveling, and being able to withstand the longevity of its mission on Mars.

Drill Bit

The drill bit would be changed to a hybrid of a diamond-impregnated drill bit and a discrete-cutter bit. This bit would be advantageous to use since the composition of the Martian soil varies. The diamond-impregnated part of the bit would aid in cutting through the soft parts of the soil, while the discrete-cutter parts would cut through the hard materials. This design should be self sharpening, since each part of it would wear away and expose the other when the material of the soil changes, as shown in Figure 11 below (Zacny). This drill bit would be composed of polycrystalline diamond compacts (PDC).

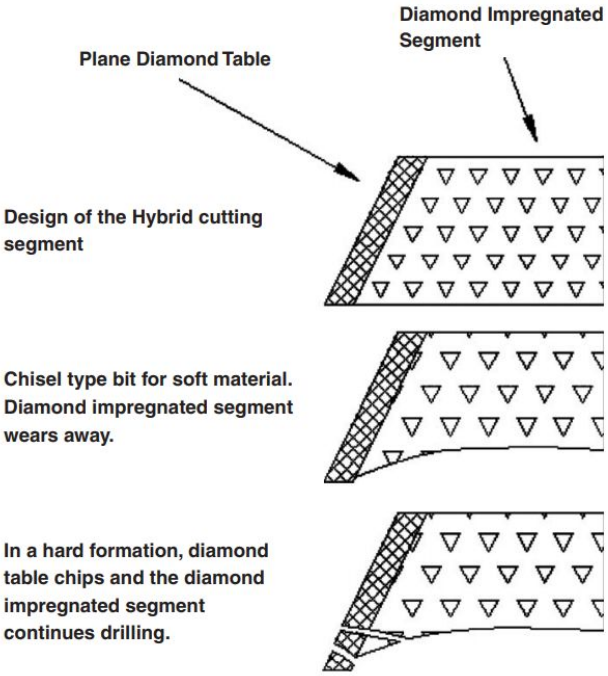


*Figure 11: Schematic for hybrid drill bit (*Zacny*)*

Mounting

The current material for the frame and lead screws are aluminum and steel components. Although these materials are durable enough to last for DEIMOS's mission, further analysis and optimization are required. As an intermediate design step, areas of the frame that exhibit the largest stresses will be made out of titanium. For example areas including the drill supports and linear slide connections.

Extraction and Filtration

The extraction and filtration subsystems will likely need the most significant changes. The largest difference between Earth and Mars operating systems is the ambient environment. Mars is much colder than Earth, as discussed earlier, and also has almost no atmosphere. The pressure and temperature differences would cause the ice to sublimate as it is exposed. This presents issues such as refreezing while extracting and losing collected water. These conditions on the phase diagram of water are shown below in Figure 12.

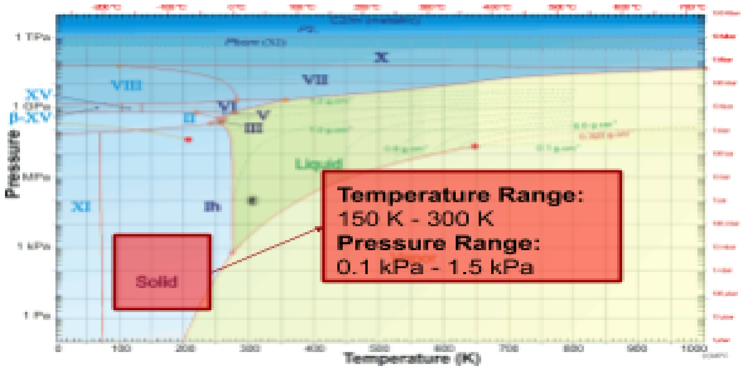


Figure 12: Phase Diagram of Water showing atmospheric conditions on Mars. (Zacny*)*

Because of this, recirculation as a way of melting the ice and the use of a gravity filter are not viable. The extractor would be modified to a sleeved auger that would enter the borehole after the drill is removed. This auger will transfer ice chips into the collection chamber. The sleeve around the auger will help protect the extracted ice from being exposed to the environment. The initial collection chamber will then act as a transfer tank that is completely sealed and pressurized turn the ice into water vapor. The vapor will move through a valve that will condense the vapor back into water for collection. The valve will lead into the final collection chamber, which is sealed and insulated to ensure the water does not refreeze. The initial collection chamber will have a slanted floor that can open once the extraction and filtering processes are complete. When opened, this floor will dump all overburden particles that are filtered out of the collected water.

An added benefit of this system is that condensing the water filters it. Not only does it filter out visible particles from the overburden, but also percolates that are in Martian soil. Also, excess heat generated by this system can be transferred to an RTG (Radioactive Thermionic Generator). Changing the filtration and extraction system also allows for the removal of some tubing and the peristaltic pumps, reducing the system's mass.

Housing

In order to land and traverse the martian environment, DEIMOS would need to be housed and mounted inside a contained structure. This structure would be made of tungsten and will consist of a door at the bottom that will open to allow for the drill and extractors to be used. All subsystems will be mounted inside this housing. The housing will also have six wheels, three on each side, in order to travel around Mars and its terrain. The wheel legs would be made of titanium tubing, and the wheels would be made of aluminum. These wheels utilize a similar design and materials from Curiosity (Bell). DEIMOS will be equipped with six anchoring legs, that will stay tucked into the ridges on the side of the housing when not in use. When excavating operations must occur. The system will stop moving, and the legs will protrude out and pierce into the overburden to steady DEIMOS while drilling. These legs would be made of titanium. The top of the housing will have low gain and high antenna for communications. This model can be seen in Figure 13 below.

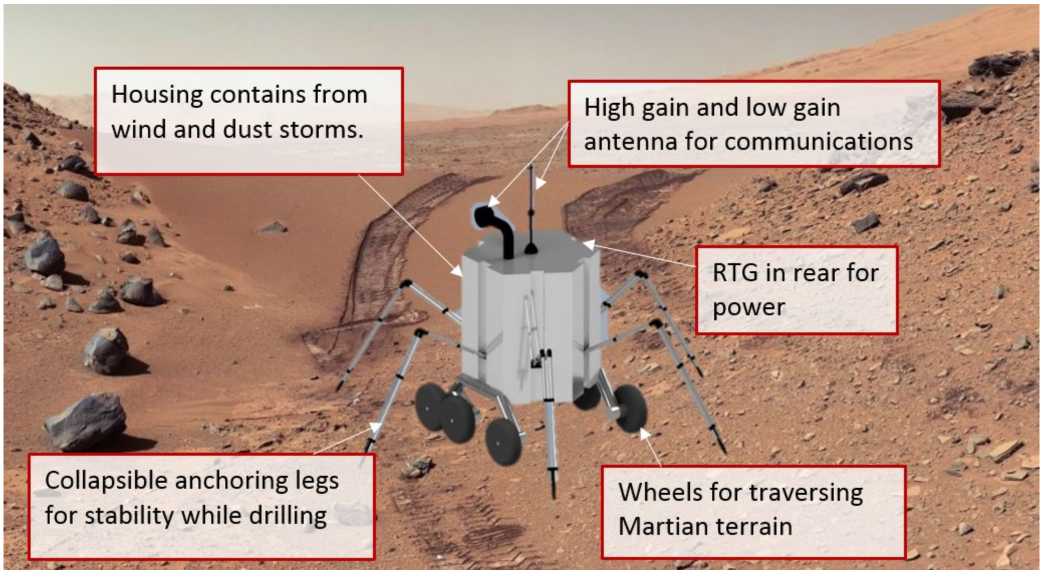


Figure 13: Model of housing structure for DEIMOS on Mars

Power

In order to power DEIMOS while on Mars, a radioisotope thermoelectric generator will be utilized. This technology has been used on previous rovers on Mars and is more adaptable to the martian environment than a solar array is. Solar panels are dependant on the rover's location and the position of the Sun. RTG's can provide power for drilling and extraction regardless of the rover's location. (Zacny)

Programming

When communicating with DEIMOS while on Mars, a time delay will be experienced. This delay can be up to 24 minutes long ("Time Delay between Mars and Earth."). This means that DEIMOS's programming code would have to be completely autonomous, and also have time built in to account for this delay, especially if errors are encountered.

Weather

The weather on Mars includes frequent dust storms. These storms cause potential harm if DEIMOS is not properly protected. Its housing will protect most of the inner subsystems, but some parts are still at risk when the bottom door opens for drilling and extraction. In order to protect the electronics and control systems inside, they will be covered by a shielding made of aluminum. This shielding will protect any sensitive systems from being clogged with dust and any debris.

Lunar Prospecting

The largest operating differences between Earth and the Moon is the atmosphere and gravity. The Moon is much cooler, with an average temperature range of -178 degrees Celsius to 117 degrees Celsius (Williams). The Moon also has very little atmosphere, which means there is no protection from radiation. Major adaptations to DEIMOS for Lunar prospecting are material upgrades, the addition of housing and a means to traverse Lunar terrain, and updates to the drilling and digital core subsystem. Because of the moon's low gravity (⅙ of earth) mechanisms to hold DEIMOS to the surface while drilling will need to be employed. Since only the drilling and digital core subsystems are needed for lunar prospecting, the extraction and filtration subsystems will be removed. This will significantly reduce the system's mass.

Drill Bit

The drill bit used on the on-Earth DEIMOS would need to be updated to a bit that can withstand the temperature on the Moon and longevity of its mission. Because of the similarities between Martian and Lunar overburden, the updated hybrid drill bit discussed earlier will be used for prospecting on the Moon.

Load Cell

The current load cell used does not need any modifications for digital prospecting on the moon. The only concern is how to calibrate this load cell. The new housing for DEIMOS will have an internal frame in which the load cell will be fastened above the drill. This will serve as the basis for calibration while constructing the digital core.

Housing

For Lunar prospecting, DEIMOS will need a mobile protective housing. The same housing, wheels, and materials discussed earlier for adaptations for extracting water on Mars will be applied. Since Lunar prospecting requires the use of a drill and the effective gravity is much lower than Mars, anchoring legs will be required. The biggest difference in the housing is the need to protect front the extreme radiation experienced on the Moon. To do so, the housing will be wrapped in multi-layer insulation (MLI) blanket. Although MLI will add weight to the system, the removal of extraction and filtration will allow for this. A model of this system can be found in Figure 14 below.

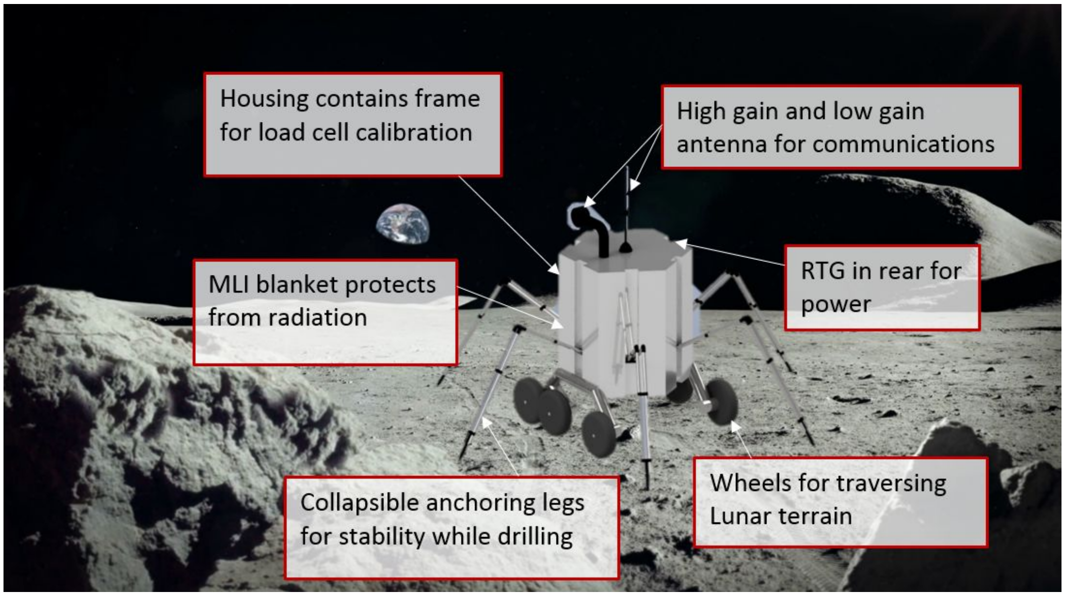


Figure 14: Model of housing structure for DEIMOS on the Moon.

Power

The Lunar adaptation of DEIMOS will also use an RTG, like in the Mars adaptation discussed earlier. This will allow for digital prospecting on any location on the Moon, regardless of the Sun's position.

Programming

Since the time delay between Earth and the Moon is 1.3 seconds, the code used on DEIMOS be completely autonomous and will adjust as needed for any communication delays.

Budget

The entire D.E.I.M.O.S. system cost a total of $9,531.43. This was possible due to several donors, Stevens Institute of Technology Mechanical Engineering Department, NASA, and Protolabs. In March, the team applied and was given a service grant to Protolabs for $5,972.30 to be used for their various services. The team primarily used the services of Protolabs to produce the drill mount, the extractor tip, and some of the digital core fasteners. The Mechanical Engineering Department at Stevens provided the team with a total of $2.700.00 to help relieve some of the burden from the registration fee and travel to the competition. A breakdown of the various system budgets and grant totals can be seen below in Table 5.

Table 5: Categorized Budget

Costs	***Amount***	***Grants***	***Amount***
Testing/Frame	$1,024.59	Stevens Senior Design	$700.00
Electrical	$359.42	NASA	$10,000.00
Drilling	$789.64	Stevens ME Grant	$2,000.00
Linear Motion	$1,488.21	Cleanup	$875.00
Extracting	$679.80		
Filtration	$666.95		
Travel/Housing	$2,872.82		
Registration	$1,650.00		
Total Spent	**$9,531.43**	**Total Budget**	**$13,575.00**
Budget Remaining	**$4,043.57**		

Acknowledgements

The DEIMOS team would like to thank Mechanical Engineering Advisor - Professor Eric Williams, Bruce Fraser, Thomas Cook, Salvatore Pellicone, and the Mechanical Engineering Department at Stevens Institute of Technology for their assistance with the DEIMOS project.

References

Bell, Terence. “Metals on the Mars Rover Curiosity.” *The Balance Careers*, The Balance, 2 Aug. 2018, www.thebalancecareers.com/metals-on-the-mars-rover-curiosity-2340049.

“Communication Delay.” *Communication Delay*, www.spaceacademy.net.au/spacelink/commdly.htm.

“Time Delay between Mars and Earth.” *Mars Express*, 5 Aug. 2012, blogs.esa.int/mex/2012/08/05/time-delay-between-mars-and-earth/.

Prasad, Umesh. “Mechanical Specific Energy (MSE) in Coring: A Tool to Understand the Drilling Mechanism and Coring Parameters Optimization for Improved Core Recovery.” Datapages, 31 Dec. 2018.

Williams, David R. “Moon Fact Sheet.” *NASA*, NASA, 3 July 2017, nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html.

Zacny, K., and G. Cooper. “Considerations, Constraints and Strategies for Drilling on Mars.” *Planetary and Space Science*, vol. 54, no. 4, 2006, pp. 345–356., doi:10.1016/j.pss.2005.12.003.