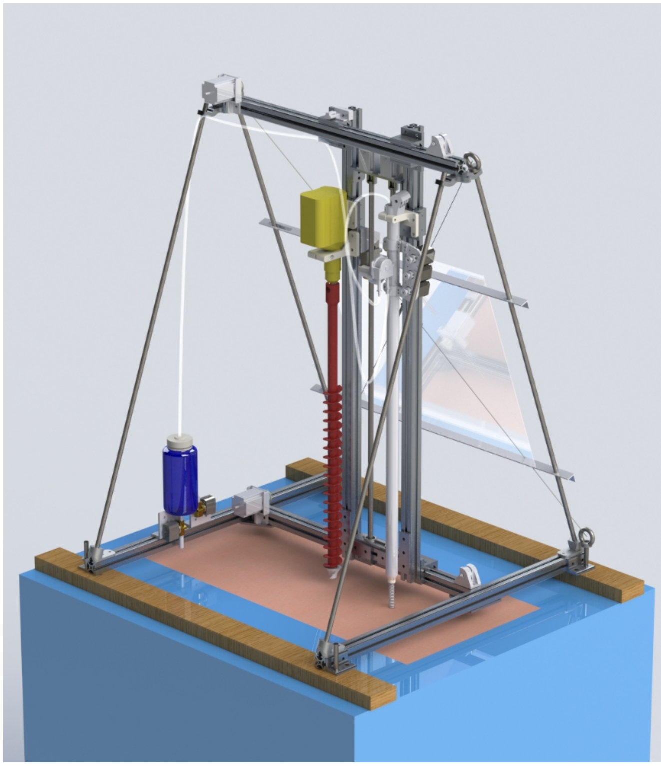
NU: PAWES

Proposal for Autonomous Extraction of Water from the Martian Surface

Elisa Danthinne (EE '21), Emmy Kelly (ME '20), Rashad Khan (CE '21),

Daniel McGann (CE/CS '20), Patrick Moore (EE '21), Andrew Panasyuk (ME'20),

Grace Peck (Phys '20), Fizzah Shaikh (EE '21), Tucker Spencer-Wallace (ME '21), Ben Zinser (ME'21)

Advisor: Dr. Taskin Padir

May 2018

Table of Contents

Introduction

Successfully executing a manned mission to Mars is the next major milestone in humanity's exploration of the Solar System. Though we have successfully reached Mars over 20 times, there are many challenges specific to human habitation on Mars which stand in the way of accomplishing this monumental goal. A number of these challenges could be greatly mitigated by having the ability to sustainably collect on site Martian water. From uses as simple as consumption and crop irrigation, to more involved applications using electrolization and complex chemistry, a continuous supply of water would greatly assist in establishing a sustainable human presence on Mars.

Perhaps most intriguing is the possibility of using water to produce return rocket propellant on Mars. It would be highly expensive to transport fuel to Mars. At current technological capabilities, it costs approximately $10,000 to send a pound of payload into Earth's orbit [8]. The fuel used to launch the Space Shuttle weighed a total of 1.6 billions pounds [11]. This rough estimate puts the cost of transporting return fuel at well over one billion dollars. A manned mission to Mars would be far more economically viable if, rather than sending return fuel, a few hundred pounds of a machinery were sent to Mars to produce the propellant there. This is made possible through the Sabatier reaction, which uses hydrogen, created through electrolyzing collected water, and carbon dioxide, found abundantly in the Martian atmosphere, to produce water and methane, which can be used as a rocket propellant.

It is for these reasons that Revolutionary Aerospace Systems Concepts – Academic Linkages (RASC-AL) has created the Mars Ice Challenge, which puts collegiate robotics teams to the task of creating a system capable of collecting, melting, and filtering subsurface Martian ice. This report details Northeastern University's response to this challenge through the Planetary Articulating Water Extraction System (PAWES), a lightweight remotely controlled robotic system outfitted with an auger, a 360° articulating heated water extracting nozzle, and an electroflocculation driven filtration system.

System Description

System Overview

PAWES works in three different phases of operation. It begins with the **drilling phase**. The process first positions the drilling subsystem over the desired extraction site and lowers the auger to create a hole through the overburden until it reaches the ice. The auger heater is then engaged. This melts a thin top layer of ice, creating just enough water to transform the overburden into mud, which adheres to the walls of the hole to provide support. This allows the system to better clear the ice in preparation for the **extraction phase**. The auger is then retracted and the position system orients the extraction subsystem over the hole. The extractor is then lowered onto the ice and melts while maintaining physical contact with the ice to doing so by using its ability to fully articulate. The pump is intermittently turned on during extraction to move the melted water into the filtration chamber. The **filtration phase**, which removes particles in the water through electroflocculation, is engaged when the chamber is filled. When the system has removed the maximum amount of water from a single hole, the extractor is withdrawn and the system is repositioned to a new extraction site.

Water Extraction Capabilities

During a full-scale test simulating competition conditions, PAWES extracted approximately 450mL of water in one hour. From this estimate, the expected rate of water extraction is approximately 7.5ml/min during the extraction phase. Factoring in drilling time, the expected water extraction rate is 6.25mL/min, yielding 13.47L of water per 0.5m deep hole at a articulation angle of 45°.

Mounting and Movement System

The mounting system is based on a standard triangular truss, chosen to improve stability while minimizing weight. The structure of the top, base, auger, and extraction system, are composed of 80/20 extruded aluminum beams. Four steel threaded rods provide support at the sides and tension cables mounted diagonally stabilize the frame. A variety of 3D printed parts act as supporting brackets and mounts. These parts have been thoroughly assessed under the deadload of the frame and the maximum peak upwards load of 150N WOB. The dimensions of the frame are 38x38x50in, meeting the size constraints. The system can be mounted to the testbed frame using 0.5in threaded bolts. At each of the mounting bolts, an external 80/20 fastener is clamped down, and is adjustable in multiple directions depending on test station tolerances. The electrical bay is mounted on an acrylic board which is secured to the system using two aluminum brackets. The right side of the brackets have been slotted to accommodate for test station tolerances.

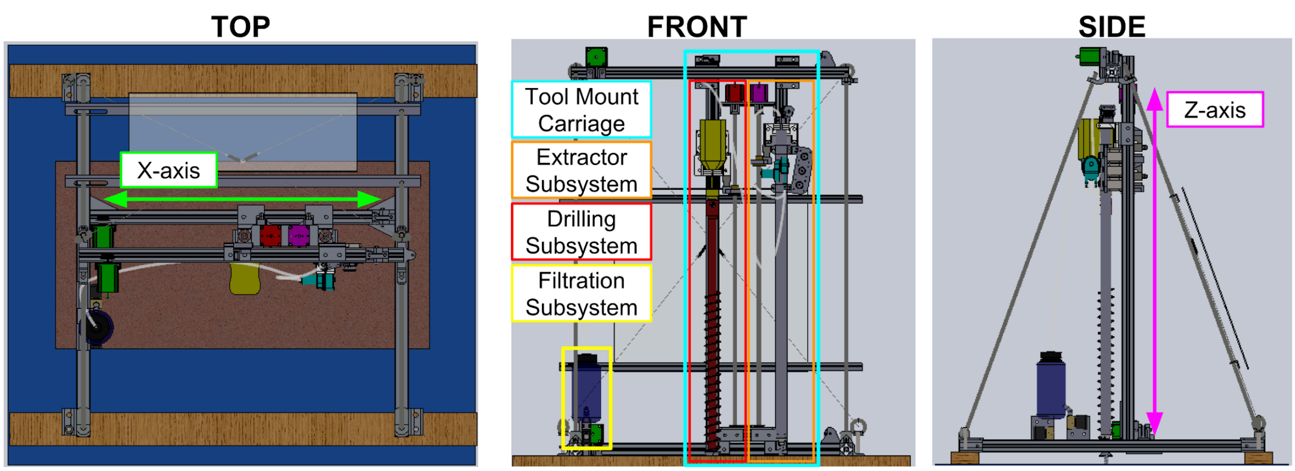


Figure 1: PAWES Mounting and Movement System

The PAWES position system moves in two directions; vertically on the Z-axis, and horizontally on the X-axis. The team determined that these two axes of movement make the system adequately versatile in the context of the challenge time constraints. The X-axis movement is driven by two NEMA 23 stepper motors positioned at the top and bottom of the system. They both use a simple pulley system supported by 3D printed parts. The Z-axis movement is also controlled by two NEMA 23 stepper motors, one driving the auger and the other the extractor. The motors rotate two lead screws which drive the auger and extractor subsystems through their mounts to a lead screw nut.

Drilling and Overburden

The drilling subsystem is a 32in long 2in diameter steel auger powered by a conventional drill motor taken from a corded universal hand drill. The auger drills into the overburden as the Z-axis stepper lowers it. The speed of the drill is monitored and adjusted manually depending upon the drilling conditions. The auger is lowered into the hole, steadily moving downwards in accordance with the weight on bit requirements. When it reaches the ice, a 60W PTC (positive temperature coefficient) heater mounted within the bit is engaged. This allows a small amount of ice to be melted during drilling, which is absorbed by the overburden making it a malleable material which will stick to the walls of the hole, preventing the overburden from caving in at the ice-overburden interface.

Temperature Management

The auger is not designed to be in contact with the ice for extended periods of the time, therefore freezing to the ice is an unlikely issue. Additionally, the PTC heating element inside the auger tip will be activated for the duration of the drilling section. The resistance of the ceramic heater element increases with temperature, with a temperature limit of about 200 degrees Celsius. Should the auger get stuck in the ice, the PTC heater could melt any ice to free the auger.

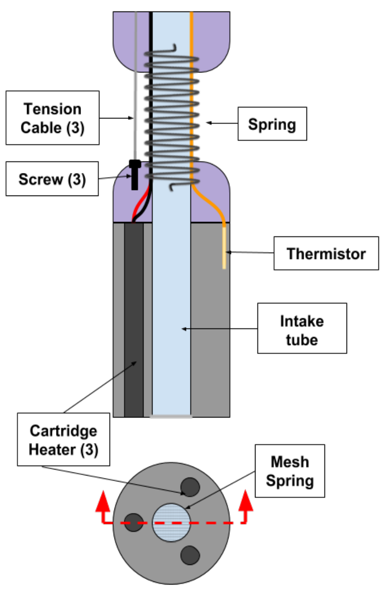


Figure 2: Extractor Diagram

Extraction System

In the melting phase, a custom-made extractor with a heated aluminum nozzle is lowered through the hole drilled by the auger (Figure 2). When the nozzle makes contact with the top surface of the ice, the three 200W cartridge heaters embedded in the nozzle receive power. Once the nozzle has melted an initial pilot hole, articulation begins. The nozzle is mounted on a spring. Three cables, each driven by a NEMA 17 stepper motor, are attached at equidistant locations around the perimeter of the nozzle. These cables can be extended or retracted to cause the spring to bend, allowing the nozzle to be articulated outward radially, and around in a full 360° motion. The nozzle moves in a corkscrew motion down into the ice, melting a hole larger than that initially drilled by the auger. A peristaltic pump mounted on the top of the system is powered intermittently as the nozzle melts through the ice to draw water through a tube located in the nozzle head. A mesh barrier is fixed to the end of the extraction nozzle, preventing any large clumps from entering the tubing. The collected water is then deposited into the filtration chamber.

Filtration and Water Collection

The PAWES filtration system functions via electroflocculation. The filtration chamber features two aluminum mesh screens positioned at top and bottom of the chamber. Given a 12V potential difference, these screens act as an anode and a cathode which cause the ionized particles in the water to clump and then fall to the bottom due to their increased mass. There are two outlet valves in the chamber, a bottom valve to remove the sediment, and a side valve to remove the filtered water (Figure 3).

Due to the design of the extraction system, which has minimal contact with the overburden, initial mesh on the extraction nozzle, and the small size of the extraction tube, only minimal sediment is expected to enter the filtration chamber.

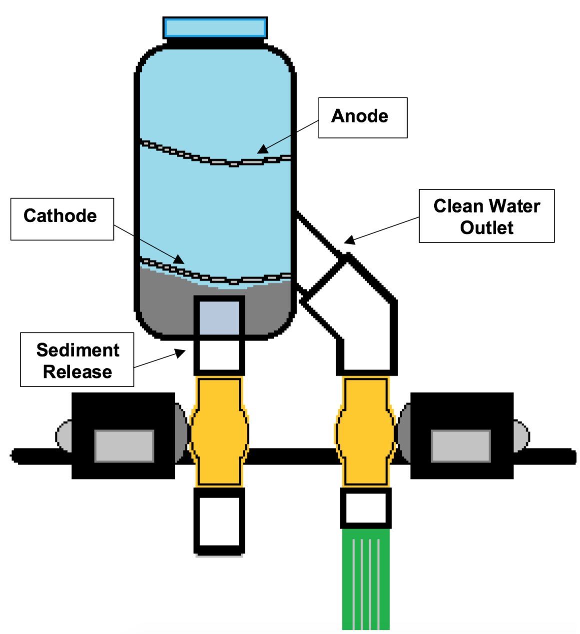


Figure 3: Flocculation Chamber Diagram

Furthermore, any overburden which does enter the chamber will enter at the beginning of each melting phase. Once the nozzle has penetrated deeper into the ice, it is unlikely that additional overburden will continue to flow into the system.

Control and Communication System

<u>Power Distribution</u>

The electrical control is powered from a 120VAC power outlet and is designed to stay within the 10A current constraint for each phase of operation. The total system power usage is constantly monitored by the current sensor. At any given time, the system is solely in one of its three phases, and only the electrical components needed for that phase are supplied power. From the power source, a single cable enters a manual kill-switch, reboot relay, and current sensor before power is split by a series of converters supplying 5VDC, 24VDC with a 12V step-down, and 60VDC. Power is controlled by relays leading to each functional electrical component: the drill motor, stepper motors for positioning, pump, filtration valves, and melting heaters. A Raspberry Pi leading to two Arduino Megas comprise on-board control that interfaces between sensors and relays, and remote computer (control station) connected via ethernet. The computer, microcontrollers, and sensors, as fundamental components to system operation, are allocated their own 5VDC power converter that is powered directly by the 120VAC power source. The heating phase draws the most power, turning on the heaters and steppers in the articulating head and pump. In testing, the current draw at this time was never recorded to exceed 10A.

<u>Control</u>

The control system for PAWES was implemented using the ROS (Robot Operating System) Framework. The framework facilitates communication between the five distributed software nodes that run across the system's various tasks and processors. Each Arduino runs its own dedicated node, one interfacing with the active action components, and the other reading and reporting sensor information to the system. The onboard processor (Raspberry Pi 3) runs three nodes, two corresponding to the serial communication with the nodes running on the Arduino Megas, and one running on board the system that operates and reports data from the system's user camera. The control station computer is connected to the Raspberry Pi over a local network via ethernet due to its increased reliability over a wireless solution. It contains the system's user interface, safety monitor, and data logger. The distributed nature of the system allowed for the system to be tested and debugged much more effectively due to the ability of each node to run independently of the other nodes. This system is visualized in Figure 4.

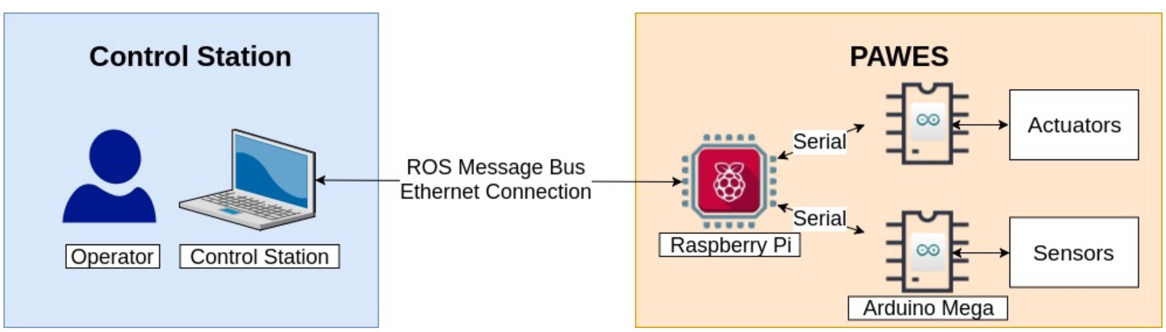


Figure 4: PAWES Network Diagram

This user controls the system through an interface consists of various widgets separated by their functions, including widgets allowing for control of the movement system (**Fig 5 - 3**), drilling system (**Fig 5 - 2**), power system (**Fig 5 - 4**), melting system (**Fig 5 - 1**), extraction system (**Fig 5 - 1**), and filtration system (**Fig 5 - 4**). All system position and sensor data is displayed for the user to view, with mission critical data such as weight on bit and system power consumption in their own independent widgets (**Fig 5 - 5, 6**). Finally the user interface provides the operator the system camera feed (**Fig XX** - 7).

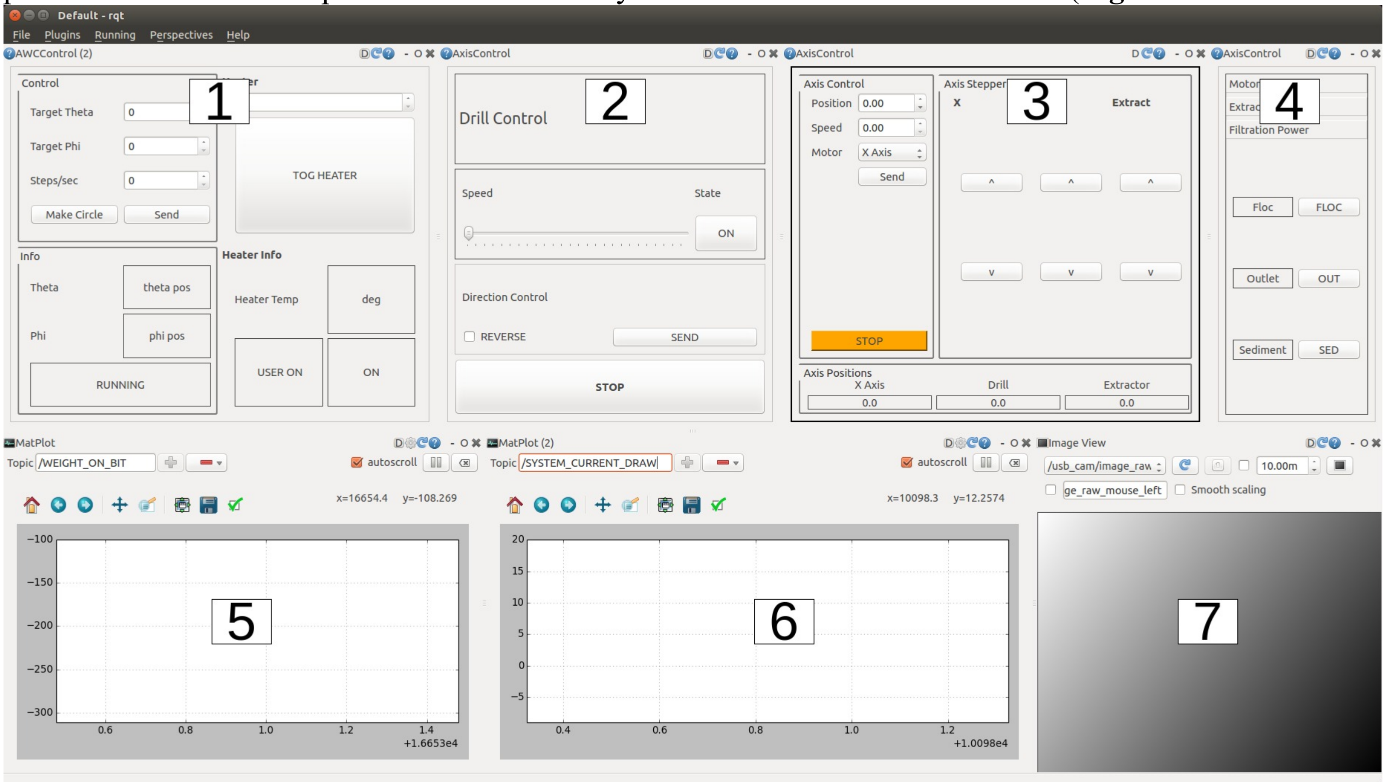


Figure 5: PAWES User Interface

PAWES relies on open loop user input to control most components in PAWES. For example, drilling requires the operator to vary rotational speed of the auger depending on the realtime resistance of the overburden on the bit. PAWES otherwise lacks a method of sensing the torque experienced by the auger. There are two processes which are exceptions to this open-ended method of control. First, the movement system is calibrated by three limit switches located at the movement system's home positions, and the system is programmed against being commanded to move beyond its physical limits. Second, the heating element also uses system feedback from the thermistor sensor to regulate the temperature of the heater tip so that it stays within an adjustable range of temperatures.

PAWES comes equipped with three dedicated sensors to monitor mission critical information. Weight on bit is measured using a TAS501 S-Type load cell positioned between the lead screw driving the drill's motion and the auger mount. This force has the same magnitude that the system auger tip is importing on the test bed. The extraction subsystem is also monitored by a load cell to view data on the force between the tip of the extractor and the ice which it is melting. Finally, an ACS712 AC current sensor measures the total power consumption of the system. PAWES also includes sensors to measure the temperature of the extractor head, the limits of the movement system, and the view down the extraction hole. Cartridge heaters in the nozzle have the ability to overheat. Thus, a thermistor temperature sensor embedded within the heater head measures the temperature of the cartridges to automatically cycle power to the heaters to maintain safe operating temperatures. A set of limit switches signal when the system has reached its home positions for system calibration and safety. Finally, a USB camera is mounted on the moving carriage in order for the operator to have a clear view of the hole being drilled and extracted from in the test bed. A summary of the technical specifications of the sensors on board can be found below in Table 1.

Table 1: PAWES Sensor Specifications		
Sensor	Purpose	Specifications/Limits
TAS501 S-Type Load Cell	Weight on Bit	200 kg Capacity 0.03 kg Error
TAS501 S-Type Load Cell	Weight on Extractor	200 kg Capacity 0.03 kg Error
ASC712	System Current Draw	30 Amps Capacity
Hinge Roller Switch	Movement System Limit Sensor	
10K Ohm Thermistor	Heater Temperature	-55 to 125 Deg. C
USB Camera	User Observation View	1080p Resolution

Datalogging

All sensors output information in real time to be viewed by the system operator. This data is also logged by the control station in two ways. Two separate nodes run continuously throughout system operation to log data. The first subscribes to system data messages and writes the data at a rate of 2Hz directly to a file in CSV format. The second is a built-in ROS node called "ROS Bag" that similarly subscribes to important data and saves every output value over the course of operation. Two nodes were used because while ROS Bag is known for reliability, its output data format is not user friendly for later processing in other programs.

Technical Specifications

Table 2: System Specifications

Overall Mass	42.6kg
Overall Volume	38inx38inx50in
Length of Drill bit	32in
Weight on bit/drill force	50-100N
Rated load	500N
Maximum Drilling Speed	500rpm
Torque	5ft-lbs
On Board Computer System	Raspberry Pi 3, two Arduino Megas
Communications Interface	QT GUI (Python)
Software	Robot Operating System (C++)
Max power	960W

Design changes since Mid-Project Review:

Auger System

The most major design change since the mid-point review is the addition of a heated auger tip. This was implemented to eliminate issues with properly removing the overburden from the hole. This solution is thoroughly described in the "Challenge" section below. Additionally, a brush was added on the system to clean dirt off of the auger between drills.

Remote and Autonomous Control

Testing showed the unpredictable variables which the system faces, many of which cannot be detected by its current sensor suite. This complexity was too much for the existing autonomous algorithms to handle without significant development and testing. Thus, the team decided to abandon autonomous operation of the system in favor of perfecting the existing remote operation interface. This decision was made due to time constraints in the competition timeline, increased risk that would result from insufficient testing, and lack of overall benefit given the system could be controlled suitably from the remote operation interface.

Additionally, since the Midpoint Review a USB webcam was added to assist in the control of the system. This was done due to the shift to remote system operation. The camera gives the operator a view angle of the drilled hole, inaccessible during hands off operation, and thus allows for improved ease of operation.

Electrical Bank Design

The electrical system was slightly modified by adding a DC Motor Controller and an H-Bridge to allow for drill speed control as well as direction, giving significantly more control of auger motion.

Challenges:

Auger Heater and Overburden

Testing revealed a major issue with the drilling procedure. When the overburden was dry, small pebbles of overburden would form than fall back into the hole. This resulted in a 1-2in pile of overburden on the bottom of the hole, no matter its depth. To resolve this issue, a heating element was added to the auger. This allows the auger to melt a thin layer of ice. The water combines with the overburden to create a wet mud. As the auger runs, the mud adheres to the wall of the hole, creating a stable hole that does not cave back in. The heater is unnecessary if the overburden at the drilling site is already moist. However, heating is still beneficial to encourage the mud to become more malleable. Figure 6 illustrates that a distinct layer of overburden remains in the bottom of the hole made without the auger heater, but the hole made with the auger heater has a mixture of dirt and water that can be easily melted into.

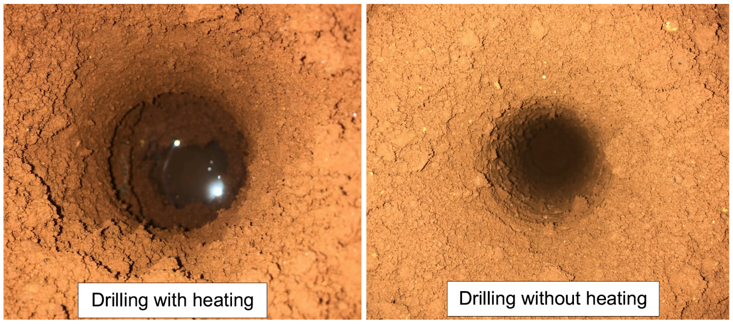


Figure 6: Heated Auger Comparison


Figure 7: Melted Extractor

Extractor Heater Failure

Both final extractor designs encountered issues with over-temperature failures. While the heaters were properly bonded to the aluminum heatsink body of the extractor, both failures were due to nearby components. In one case, the PVC pumping tube was bonded to the extractor too closely to the resistor bodies; the tube melted and prevented the pump from drawing water up the extractor. The failure in the other design resulted from exceeding the operating temperature of the sealing epoxy and thermal paste, causing minor vaporization of the paste.

Overall Strategy for Competition:

The competition procedure was developed and verified through testing. The first phase of system operation is the drilling phase. At the beginning of the competition, the system will align the tool carriage at the most positive position along the frame, and the drill will be powered to rotate at an initial speed of ~60rpm. The auger will then descend into the overburden, maintaining a speed between 100 to 200rpm, and the weight on bit between 50 and 100N. When the auger reaches the interface between the ice and the overburden, heat will be supplied to the auger, and it will rotate in the same position for 15 minutes. The auger will then be pulled out of the hole to reveal a clean hole. The x-axis will move the auger to a brush, where the auger will rotate pressed into the brush to clean any dirt from the threads.

Next, the system will transition into the extraction phase, where it will reposition then lower the extractor into the hole, through the overburden, and into the ice, powering the extractor heaters and melting while controlling weight on bit between 50 and 100N. The pump will be intermittently activated to extract water before the hole melts too widely, risking overburden falling in. Once the extractor reaches a depth of 6in below the interface, it will begin articulating by positioning at an angle of 15° with the vertical and turning radially 360°. The extractor will then lower 0.20in, change its angle to 35°, and articulate a full 360° again. The process of lowering and rotating 360° will then continue to repeat at varying rates, determined by how quickly the heat transfers from the extractor to the ice and the weight on bit, until the extractor has reached its lowest z-axis position. Once the extractor is at its lowest position, the extractor is retracted, and the auger is moved above the overburden to drill a new hole 8in away from the previous hole. The process of drilling and extracting repeats until the time runs out.

The filtration subsystem will run parallel to extraction, and the filtration and melting phases will alternate as needed. Once the tank is filled with enough liquid to completely submerge both flocculation meshes, voltage will be provided to the mesh, clumping sediment. Once sediment settles, the release valve will be opened to drain clean water. Once the clean water has drained, the sediment valve will be opened to release the dirty water. Both valves will close, and the process will repeat once the tank is full again.

Based on previous testing results, the melting phase takes the longest amount of time, specifically the heater melting the ice. As such, the team aims maximize the amount of water taken from a single hole and drill and extract from 1-2 holes for the duration of the competition.

Summary of Integration and Test Plan (and test results):

Drill

The drill was tested with a lab power supply to determine the needed DC voltage supply. In 10 minutes of drilling at 100.3W, the auger drilled through all overburden and reached a depth of approximately 1.5cm into the ice, sufficient for competition purposes and within power constraints. Further qualitative testing of the drill was done regularly to determine to the optimal drilling procedure.

Extractor

Three extractor nozzle designs were created each with different internal geometries to accommodate different types of heating elements: 90W flexible sheet heaters, 200W cartridge heaters, and 100W resistor heaters. These heaters were selected due to their differing advantages in terms of ease of use and efficiency. The resistor nozzle was damaged beyond repair before formal testing could be done. This was due to a malfunctioning thermocouple, which allowed the resistors to become hot enough to melt the outtake tube. This failure highlighted the importance of a having a well calibrated temperature sensor to properly regulate the temperature of the nozzle.

The flexible heater and cartridge nozzle were both formally tested. Each was connected to a 120V AC power supply. The room-temperature heaters were set on a block of ice and heated to approximately 60C. For the next 10 minutes power to the heaters was cycled in order to retain a temperature of 55±5C. The test set up was highly conservative as no force was applied on the melting surface and the heaters were not moved to retain contact with the melting surface. The flexible sheet nozzle transferred heat at approximately 90% efficiency, melted at a rate of 6.4ml/min, and drew a total of 21.8KJ. The cartridge nozzle transferred heat at approximately 86% efficiency, melted at a rate of 10.3ml/min, and drew a total of 36.5KJ. Before testing it was unclear which heater would produce a higher melting rate, as the cartridge nozzle had a higher wattage but the the flexible sheet nozzle allowed for thinner walls and more surface contact. The test results showed the the cartridge heater produces a significantly higher melting rate. Thus it was chosen for the full system.

Filtration

The Filtration system underwent initial testing for proof of concept purposes for the team's 2017 proposal. The system was visibly highly effective at clearing sediment. Further testing of this filtration have been done a yielded similar results.

Figure 8: Flocculation Test Results

Full-Scale Testing and System Integration

The full system was informally tested multiple times in order to properly integrate subsystems and understand test conditions. These tests provided invaluable knowledge which informed the design changes since Mid-Project Review.

Figure 9: Full System Integration

PAWES has successfully collected approximately 450ml of water in a full-scale test, done with the goal of accurately replicating competition conditions. The test was executed according to the procedure, as described above, with little deviation. The steps of the drilling phase can be clearly observed in the WOB data, shown in Figure 10. Once the ice was cleared, the extractor was lowered into the hole and began melting. The heater was engaged for approximately one hour. It melted 4in down before articulating was engaged. The nozzle went through two full rotations at the same height, the first at 15° and the second at 20°. The test yielded a 7.5ml/min melt rate.

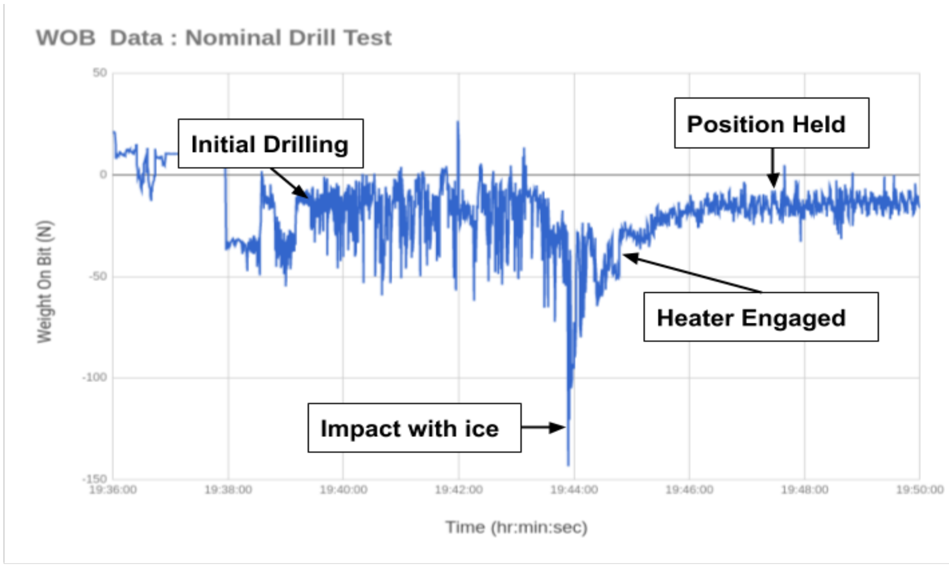


Figure 10: WOB during drilling.

Tactical Plan for Contingencies/Redundancies:

Additional components of all subsystems will be brought to the competition to replace any parts that may malfunction or break, including: a Raspberry Pi, an Arduino, a NEMA 17 motor and driver, all fasteners, and 3D printed parts under critical load. Furthermore, a mobile 3D printer will be brought to competition, allowing the team to assess damage and print replacements on site.

Project Timeline:

Below in Table 3 are the outlined milestones we made for our team at the midpoint review. The entire system was completed, and a full functioning test was run prior to this paper submission.

Table 3: Competition Timeline

	Milestones
January	All parts were purchased and initial construction began.
February	Frame for system was built, axis movement was programmed, movement system was wired independently, and initial filtration system was built.
March	Initial testing for the filtration system and extractor system was run. The motor to drive the auger was wired along with the filtration and extractor systems. In software, the algorithm for extractor movement was begun, and the overall system state flow was completed. The midpoint design review was also written.
April	By the end of April, the filtration, drill, movement, and software were fully integrated.
May	The extractor was integrated into the system, and 4 full scale tests were run prior to May 20th. Additionally, small improvements were added to the system based on testing data.

Safety Plan:

The electrical system integrates multiple safety measures in powering the system, both to protect PAWES and people working with it. There are two overall ‘kill’ switches to turn the system off, one manual switch that can be triggered at any time and one relay that opens when current draw exceeds 13Amps a threshold decided based on competition guidelines to assume potential error of 30% in critical data. Because subsystems provided power through relays, when subsystems are not in use they receive no power. Additionally, all high-current capable circuits are fused to prevent damage in the event of electrical shorts. Finally, in the case of electrical fire, the competition fire extinguishers will be located before the system is turned on. During system testing, team members follow safety protocol by wearing closed-toe shoes and safety glasses.

Path-to-Flight

While PAWES will have to undergo a variety of modifications and upgrades in order to function on Mars, the system’s lightweight minimalist design allows for a modularity and ease of use that will be ideal for implementation. This section will first lay out the modifications necessary for use on Mars and explain the various advantages PAWES offers.

Transport

If PAWES is launched fully assembled and ready for use upon landing, the mounting subsystem must account for vibrations and trauma during transit. Currently, the structure is supported by bolts and screws, which could loosen or detach. Each fastener will require a locking feature which is not dependent on a preload, as required by NASA [3].

Materials and Components

On Mars, PAWES will be experience temperatures ranging from -125℃ to 20℃ [5], an average pressure of 6.36mbar, and dust storms with winds as high as 30m/s [5]. The PAWES prototype currently uses aluminum, steel, and 3D printed plastic components in the interest of cost and machinability. To prevent significant wear in the current structural materials as well as increase the strength of PAWES, these materials will be replaced with a similarly lightweight material like titanium, as used on the Curiosity rover. In addition, the axis movement system belt will be a material compatible with Martian temperatures, such as Teflon [1].

Electrical

For the electrical system to function properly on Mars it must be fully shielded from the harsh environment. Cold temperatures run the risk of damaging components and rendering them inoperable [2]. The Martian atmosphere, with a density of only ~0.020 kg/m^3, increases the difficulty of dissipating heat generated by electrical components, especially in confined spaces [5]. Furthermore, Mars’ weak magnetic field causes the surface to be subject to high levels of radiation, which can interfere with and easily damage electrical components [12]. Therefore, the electrical components will be need to be radiation hardened. In order to properly protect the electrical components from these environmental dangers, they will be stored in a radiation shielded electronics box kept at a constant pressure and temperature.

Control

Control software will need to be modified to enable robust autonomy, especially because of the lengthy delay that will result during long-range communication with PAWES from on Earth. Communication with the system may be as little as three exchanges per day [1]. Even if the system is controlled from Mars, autonomy is ideal in order for PAWES to run unattended, like other life-support systems. This will be achieved by implementing the autonomous code to run operations completely independent of human intervention. Additionally, this would also necessitate the inclusion of additional sensors to allow for the autonomous code to create an accurate model of its environment, allowing it to better plan trajectories given the dynamic conditions of the Martian environment.

Drill

The drill design should be equipped to handle a variety of materials. The current bit is suitable for competition purposes in which overburden composition, conditions and depth are predictable. Unlike the competition, Mars has many variations of soil makeup, and will require an auger capable of handling a variety of situations. Additionally, due to manufacturing deficiencies, the current bit is slightly warped, preventing it from running at high speeds due to the resulting vibration of the system. For use on a Mars, manufacture will need to be more precise, and a different lighter weight material, like titanium, will be used. Drill designs like the Ice Breaker drill could be a viable replacement for use on Mars rather than the Earth friendly bit proposed in the PAWES prototype [10]. The percussive motion allows a wider range of materials to be drilled through, with a more predictable weight-on-bit and therefore a simpler, more reliable mechanical design. Additionally, for the system to feasibly produce a significant amount of water for sustenance, the drill would have to be larger to access the needed amount of ice.

The average Martian atmospheric pressure is 6mbar [5]. This happens to be the triple point pressure of water. Therefore, slight variations in temperature and pressure around the triple point, 6mbar and 0℃, will lead to sublimation and vaporization of the ice and water. Liquid water is critical to successful drilling as it stabilizes the walls of the hole. Therefore, the hole must be pressurized. Current procedure requires the drill to be removed from the hole and replaced with the extractor, which would expose the hole to the atmosphere. In order to prevent this, an integrated auger-extractor design in which the extractor is housed within a hollow auger must be implemented. Allowing for the extraction system to enter the ice without removal of the auger from the target hole and maintaining separation from the atmosphere throughout the entire operational cycle. The maximum temperature of Mars' surface is approximately 20℃ [5]. The hole would have to be pressurized to approximately 40mbar in order to raise the vaporization temperature to 30℃, which will never occur on Mars.

Extraction

The extraction will be carried out exactly as it is on Earth. A larger nozzle or more powerful heaters could be implemented in order to maximize the melt rate. As aforementioned, the Martian atmosphere requires an integrated auger-extractor design in order to properly pressurize the hole. This will also protect the water and ice during extraction.

The existing pumping system would need minor modification for operation on Mars. The use of a peristaltic pump is still feasible, but the pump would either need to be able to create a stronger vacuum or be located closer to the nozzle. While the lower gravity on Mars allows water to rise higher under a vacuum, the lower atmospheric pressure reduces the pressure differential acting upon the water. The net result is that water cannot rise as high in the tube, and may not reach the pump. This problem can be resolved by moving the pump into the extractor itself. The lowered pump will be able to prime itself with water, at which point it begins to push the water upwards with positive pressure - a much more effective method of raising water than suction.

Filtration

The electroflocculation-based filtration system should function on Mars with a few modifications. It is ideal for removing the fine Martian dust even the classical filters cannot. Electroflocculation creates a potential difference in a liquid in order to clump debris, and thus filter effectively. The chamber will be pressurized to 40mbar so water stays in liquid phase. Furthermore, filtration operation will need to be optimized under Mars' 1/3g gravity and modified for long-term use [5]. The competition design does not take into account long term buildup of debris at the bottom of the filtration chamber. An optical sensor will detect when level of debris has passed a certain threshold. When clean water is gone, the exit valve will then be opened to clean the system while minimizing water loss. A pumped will also be implemented in order to allow the filter to be backwashed and cleaned.

Overall

The design of PAWES is ideal for implementation on Mars because of its simple lightweight nature. The straightforward assembly and motion of the system means it can be easily disassembled and robotically reassembled on Mars, which will drastically save space during transportation. Therefore, with the improved reliability and robustness of the system from the modifications listed above, PAWES in its current design, could be used effectively for a manned mission on Mars.

The system is also constrained to certain competition requirements which may not be beneficial for use on a actual mission to Mars. The team envisions PAWES as a modular system which can be applied in the following ways to improve its effectiveness for a manned mission to Mars.

Advancements

One way that PAWES could be greatly improved for implementation on Mars is by mounting the system's water extraction, melting, and filtration systems on a mobile platform. The technology PAWES is built around could be implemented onto a dedicated rover, or as a set of tools on a rover with a larger operational scope. While the development of the mobile base would be intensive, it is a process which has been completed multiple times with great success on Mars, for example the Opportunity and Curiosity rovers. The mobility of the rover itself will be used to position the auger and the extractor in the Y-axis, the direction in which PAWES is currently constrained. Additionally, with the inclusion of the rover base, the control system for the rover will need to be implemented for autonomous functionality of the rover and PAWES. This implementation of PAWES would allow for a large area of operation, increasing potential extraction site and therefore increase the amount of water collect. This method is ideal for a long-term sustainable source of water on Mars.

Another advantage of implementing PAWES on a mobile platform is that the system could be launched to Mars years before the arrival of mission astronauts, because of the mobility provided by the rover base, the rover implementation will be able to perform automated setup and positioning, allowing it to collect larger quantities of water than could be collected in the duration of the manned mission. This is ideal if the water collected is to be converted into return propellent, as it will take time to collect and react enough water to fuel a return trip.

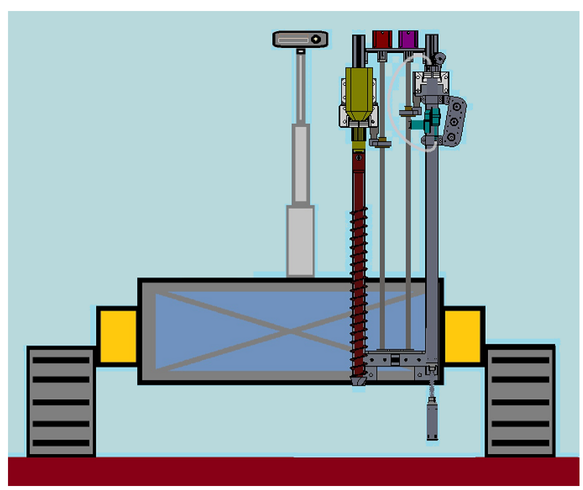


Figure 11: Rover and System Mount

An important consideration of this implementation is the physical dynamics of the system. Due to the height required for the Z movement the mobile rover base will have to be robust enough to endure storms and winds on the surface of Mars. The rover base will therefore need to have a large footprint to achieve this stability. This size constraint could reduce the total ice bearing areas that are accessible by the platform. These areas may be the desired landing site for scientific missions. Therefore under these circumstances, the original PAWES stationary design could be implemented and utilized.

Additionally, to sustain this level of autonomy, the wall outlet power supply will be replaced with a dedicated power generator. One consideration is the use of nuclear power generation through plutonium. This method is used on the Curiosity rover and is capable of providing 110W of power [4]. This is more reliable than solar energy, which may be compromised by buildup of Martian dust. The system will have an additional backup solar power source in the case of any power anomalies.

There are circumstances in which PAWES as implemented on a stationary or rover platform fall short for the necessities of the mission's astronauts. Scientific expeditions to sites a distance from landing could easily be beyond the range of a rover. Similarly, a mission to Mars' mountainous terrain could be impossible for a rover to navigate. Finally, in the case of an emergency or equipment failure astronauts will desperately need a backup method to gather water for survival. For cases like these, the PAWES systems could be stripped down into a portable tool. Without need for a movement system, all required functionality from PAWES to extract water could be reduced into a easily storable, and portable format while still maintaining all critical functionality.

This version of PAWES will consist of the drilling, and extraction system into one contained case. This will be accomplished via the integrated extractor drill design has detailed above allowing for a smaller overall footprint and eliminates the need for any movement in the X-Axis. Vertical movement will be accomplished via a track driven system on the sides of the case or via lead screw similar to the current design. For stability, the system would also utilize a set of anchors at its base that attach the system into the Martian surface. The electrical bay would be contained within the same case. Flocculation could occur separately after water has been extract or within the case. Power to the system would be provided by a combination of batteries and foldable solar cells to allow for the system to function independently and maintain its portable form factor. Operation of this tool will consist of manual placement and anchoring of the system by a mission astronaut followed by autonomous operation until all water has been extracted. During this time, the system could be left alone by mission astronauts.

While this implementation of PAWES requires much more intervention from humans, by removing the movement system, the total footprint and weight is greatly reduced. A reduced size and weight will make the system drastically more portable and could, therefore, be used as a backup system to the full system as described above, as a supplemental supply to the main water collection system, in cases where mobility is challenged by rough or mountainous terrain, or in emergencies where a easily accessible water extraction is required.

Finally, to achieve this potential and successfully execute a Mars mission, the system must be properly tested and maintained. This is especially important if PAWES is to be a mission-critical tool. The device design should be thoroughly tested in a Mars-like environment before being sent to Mars. Replacement parts should be available for components that may experience wear over time. These include replacement drill tips, as well as electronic components that might not withstand the harsh environment. These suggestions are analogous to testing and redundancies implemented on previous Mars rovers.

Budget:

The following table describes the cost breakdown for the creation of PAWES has broken down by subsystem, has well has costs for team travel to competition.

Table 4: System Cost Breakdown

Purpose	**Cost ($)**
Travel	3200
Hardware	400
Structure and Movement Subsystem	2000
Extractor Subsystem	700
Drill Subsystem	400
Electrical Components	2900
Total:	9700

Acknowledgments:

The NU PAWES team would like to give acknowledgment to Chris Kenyon, Michael Janov, Lindsey Wright, Kurt Braun, Mohammad Taslim, Carol Livermore, Murphy Wonsick, and Sebastien Danthinne, all of whom greatly contributed to the success of this project.

We would also like to Moflon Technology Co. for their generous contribution to this project.

References:

1. Conveyor System Design for Extreme Temperature Applications. *Belt Technologies* (2016). Available at: https://www.belttechnologies.com/conveyor-system-design-extreme-high-low-temperature-applications/.

2. Patterson, R. L. H. Evaluation of COTS Electronic Parts for Extreme Temperature Use in NASA Missions. in (2008).

3. Barrett, R. T. Fastern Design Manuel. (1990). Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19900009424.pdf

4. Garner, R. How to Protect Astronauts from Space Radiation on Mars. *NASA* (2015). Available at: http://www.nasa.gov/feature/goddard/real-martians-how-to-protect-astronauts-from-space-radiation-on-mars.

5. mars.nasa.gov. Mars Facts | Mars Exploration Program. Available at: https://mars.nasa.gov/allaboutmars/facts/.

6. Hassler, D. M. *et al.* Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover. *Science* **343,** 1244797 (2014).

7. Multi-Mission Radioisotope Thermoelectric Generator. *nuclear.gov* (2008).

8. NASA - Advanced Space Transportation Program fact sheet. Available at: https://www.nasa.gov/centers/marshall/news/background/facts/astp.html.

9. NASA - Amazing Facts: Space Shuttle External Tank. Available at: https://www.nasa.gov/centers/marshall/about/star/et_11.html.

10. Zacny, K. *et al.* Reaching 1 m Deep on Mars: The Icebreaker Drill. *Astrobiology* **13,** 1166–1198 (2013).

11. Space Shuttle. Available at: http://abyss.uoregon.edu/~js/space/lectures/lec23.html.

12. Howard, J. W. & Hardage, D. M. Spacecraft Environments Interactions: Space Radiation and Its Effects on Electronic Systens. (1999).