Design and Experimental Validation of a Martian Water Extraction System

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Figure 1. Rendered preliminary CAD design (left), final system at the challenge (right)

Abstract— **This paper discusses the design and realization of a robotic water extraction system used to harvest subsurface ice from a simulated Martian environment. The Mars Reconnaissance Orbiter has discovered ice buried approximately 1-2 m below the surface at the mid-latitudes of Mars. Access to this vital resource could greatly contribute to the success of a human mission to Mars. Our research and development effort into the in-situ procurement of water on Mars was guided by the 2018 NASA Revolutionary Aerospace System Concepts Academic Linkages (RASC-AL) Mars Ice Challenge. The focus of the challenge was to validate design concepts that maximize water collected from a simulated Martian test-bed using a robotic system. The steering committee provided the team with a design framework including functional, operational, and physical requirements. For this challenge, the team developed the Planetary Articulating Water Extraction System (PAWES). PAWES uses an auger based drilling system in combination with an articulating water extraction tool to collect water from subsurface ice deposits. In this paper, we present potential solutions to ice extraction on Mars, an overview of the PAWES system, and experimental results of prototype testing in terrestrial conditions. Additionally, we will discuss lessons learned from the implementation and validation of PAWES to guide further development of Martian water extraction systems.**

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1. INTRODUCTION

Successfully executing a manned mission to Mars is a major milestone in humanity's exploration of the Solar System. Though unmanned systems have successfully landed on Mars seven times, there are many challenges that impede human exploration of Mars [1]. Maintaining a habitable living environment, providing sustenance, and returning a vehicle to Earth are all challenges that we have yet to face.

Water is a crucial resource for a manned mission. From uses as simple as consumption and crop irrigation to more involved applications like the synthesis of plastics, a continuous supply of water would greatly assist in establishing and sustaining a human presence on Mars. Furthermore, hydrogen extracted from electrolyzed water could be employed in the Sabatier reaction to generate methane, a major component of some rocket fuels [2].

Recent research using the High Resolution Imaging Experiment (HiRISE) instrument on the Mars Reconnaissance Orbiter (MRO) have revealed mid-latitude ice deposits buried 1-2 m below the surface and extending to depths of 100 m [3]. Once accessed, these ice deposits could provide astronauts with an ample supply of water to sustain surface operations and create return fuel for a number of missions. It costs approximately $10,000 to send one pound of payload into Earth orbit [4]. Sending a small payload of equipment to manufacture propellant on Mars as opposed to the thousands of pounds of fuel required to leave the Martian surface could substantially reduce the cost of a manned mission. This use of in situ resources could provide the means of decreasing mission costs and supporting astronauts while on Mars. On future missions, it will be imperative that in-situ resource utilization (ISRU) techniques are employed to successfully support a manned expedition to Mars.

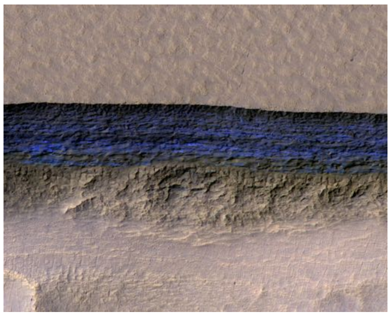

Figure 2. Enhanced color image of Mars taken by HiRISE showing a cross-section of the subsurface ice in a scarp

In this paper, we discuss the operating environment of a Martian water extraction system and the design considerations that the Martian environment imposes. We then provide an overview of a prototype water extraction system and, by subsystem, discuss the results of and lessons learned from its operational performance.

2. The Challenge

The National Institute of Aerospace, in coordination with NASA, administers the Revolutionary Aerospace System Concepts - Academic Linkages (RASC-AL) Mars Ice Challenge. This initiative tasks 10 collegiate teams to develop robotic systems to remotely collect water from subsurface ice. Northeastern University's solution to this challenge is the Planetary Articulating Water Extraction System (PAWES).

Competition Parameters

A technical committee assembled by RASC-AL designed a Martian surface test-bed: a modified ice chest filled with a half meter of ice covered by a half meter of pitcher's mound clay and gravel, used as simulated Martian overburden. The chest was lined with dry ice to imitate Martian temperature conditions. The apparatus was cooled to a minimum temperature of -10°C. A diagram of this test-bed is found in Figure 3 [5]. The challenge provided the team with a design framework including functional, operational, and physical requirements. These requirements are summarized in Table 1 [5].

Per challenge guidelines, the system had to be designed to operate in a test-bed under Earth conditions. It was, however, expected that minimal design changes would be required to allow the system to operate on Mars. Therefore limitations imposed by the Martian environment were strongly considered during the design process.

Table 1. Challenge design specifications

Constraint Type	Design Limit	PAWES Value
System Volume	1m x 1m x 2m	1m x 1m x 1.28m
System Mass	60kg	48kg
Power Supply	120VAC, 10A	120VAC, 5A Peak
Weight on Bit(WOB)	150N Avg.	33.816N Avg.
Drill Length	39in	32in

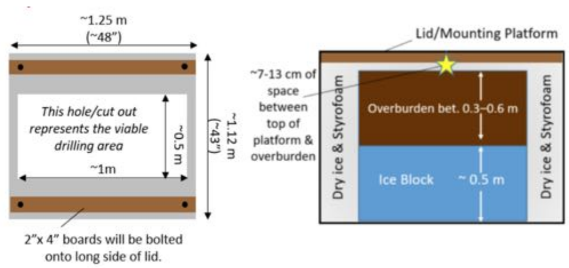

Figure 3. Diagram of the Mars simulation test-bed used at the Mars Ice Challenge

The challenge objective was to maximize total water collected by the system in two six-hour trials. PAWES was evaluated in three separate categories: a technical paper describing the methodology and justification for the design, a poster presentation detailing the collection process, and system performance. The challenge was held in June 2018 at NASA's Langley Research Center. PAWES collected 3209 mL of water: 1370 mL during the first day and 1839 mL during the second day. This was the most water collected at the challenge, 3 times more than any other system.

Figure 4. PAWES mounted to the test-bed at NASA Langley Research Center in June 2018

3. The Martian Environment

Martian overburden composition is relatively unknown. All in situ measurements made by robotic missions have not extended past the the depth of the Curiosity rover's drill, approximately 6 cm [6]. The Mars Pathfinder mission estimated that Martian soil is comparable to moderately dense soils found on Earth [7]. Topsoil surface analysis, however, found that regolith properties vary greatly over small areas, from highly compressed soils to loose soft soils [7]. This variance suggests that the system be able to handle regolith of differing density and composition.

Due to Mars' weak magnetic field and thin atmosphere, the system will be subject to high levels of radiation [8]. Therefore, any electronics must be capable of operating reliably in high radiation for extended periods of time. Additionally, Mars's reduced gravity limits the amount of downwards force an unsecured system can apply without lifting itself off the ground.

A consideration in the system design is its inherent inaccessibility for maintenance; it must be capable of reliable, independent operation with a low risk of critical faults for the duration of its unmanned service. Any consumable components such as filters or drill bits must either be long-lasting, automatically replaceable, or avoided in the design.

Finally, Martian atmospheric conditions effect the phase state of the extracted material. Mars' average surface pressure is 6.9 mbar and the surface temperature ranges anywhere from 183 K to 295 K [9] [10]. This places Mars' surface conditions around the triple point of water. Thus, depending upon weather, time of day, season, latitude, and altitude, slight variations in temperature and pressure will lead to sublimation and vaporization of ice and water. Under typical conditions liquid water cannot exist on the surface and solid ice will slowly sublimate.

4. Extraction Concepts

Taking into account the limitations imposed by the Martian environment, we considered two forms of water extraction: solid and liquid. Gaseous extraction was disregarded for the purposes of competition because of the temperature and pressure management it would require under Earth conditions. However, it could prove viable on Mars due to the atmospheric conditions.

Solid extraction is advantageous in terms of atmospheric conditions. Solid ice can temporarily exist on the Martian surface while liquid water would require pressurization. Furthermore, solid extraction ice cleaning could use mechanical methods such as shaking or sweeping debris from the surface of the ice. This would result in cleaner water, mitigating the complications caused by handling high turbidity fluid. Solid extraction allows for more efficient melting of the removed ice, as it can be brought into a controlled environment post-extraction. Additionally, solid core extraction has been validated in Martian analog on Earth [11].

Liquid extraction, however, is advantageous in terms of transporting deposits to the surface. Solid extraction requires that regolith is removed in proportion to the amount of ice being extracted; i.e. a large hole is needed to remove a large piece of ice. In liquid extraction water can be pumped to the surface through a hole of any size. Solid deposits could be crushed in order to aid transportation, but the increased surface area would expedite the sublimation process.

5. Planetary Articulating Water Extraction System (PAWES)

PAWES, shown in Figure 4, is a remote controlled robotic system. It is comprised of three subsystems, shown in Figure 5: an auger, a 360°C articulating heated water extractor, and an electroflocculation filtration system. It works by transitioning through four different operational phases.

1. The process begins with the drilling phase. The system targets a desired extraction site and drills a borehole to the ice layer. A heater in the auger tip is engaged for the duration of drilling. When the auger reaches the interface between the overburden and the ice, the heating causes a small amount of melted ice to mix with the overburden, creating a clay-like mixture which maintains the structure of the borehole base. This provides the system with access to clear ice in preparation for the melting phase.

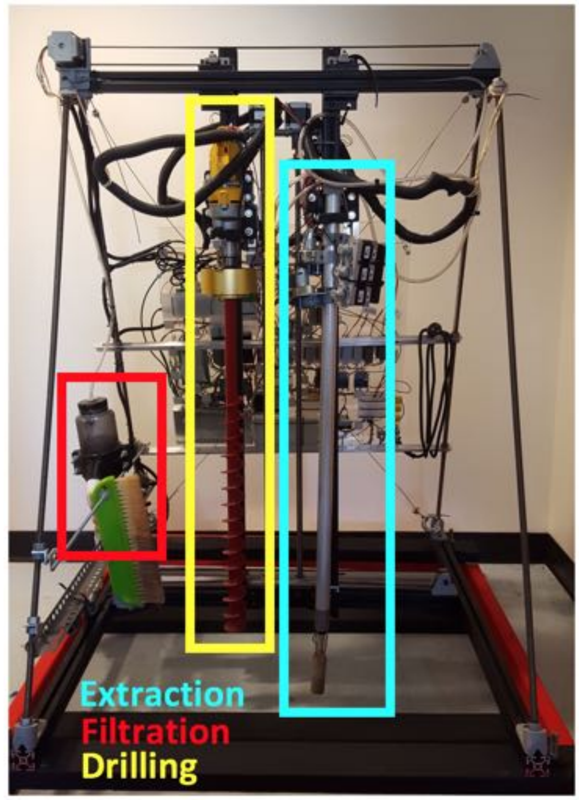

Figure 5. Location of the drilling, extraction, and filtration subsystems on PAWES

2. The extractor is lowered into the hole until the heated articulating nozzle contacts the ice. The articulation of the nozzle allows it to maintain contact with the ice during the melting phase.

3. The extraction phase occurs intermittently with the melting phase. The pump is engaged to move the melt-water into the filtration chamber.

4. The filtration phase separates particles in the water through electroflocculation (EF) assisted gravity separation. Filtration is engaged when the chamber is filled and can process water in parallel with other phases. These operation phases are cycled through until the desired amount of water has been extracted.

PAWES underwent system-level testing during the month before the challenge at Langley in June. Throughout testing and challenge operations the PAWES team monitored each subsystem's performance. The following sections are comprised of system methodology, results, and insight gained from these operations. Results from pre-challenge testing will be referred to as "preliminary testing". Testing during the competition will be referenced in terms of "Day 1" and

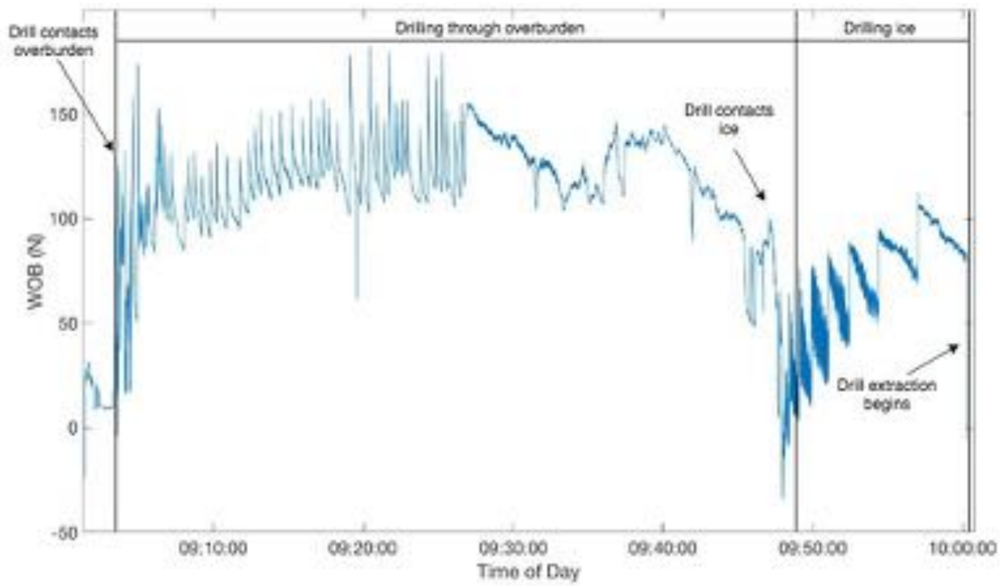

Figure 6. **Day 1 WOB vs. Time Data**

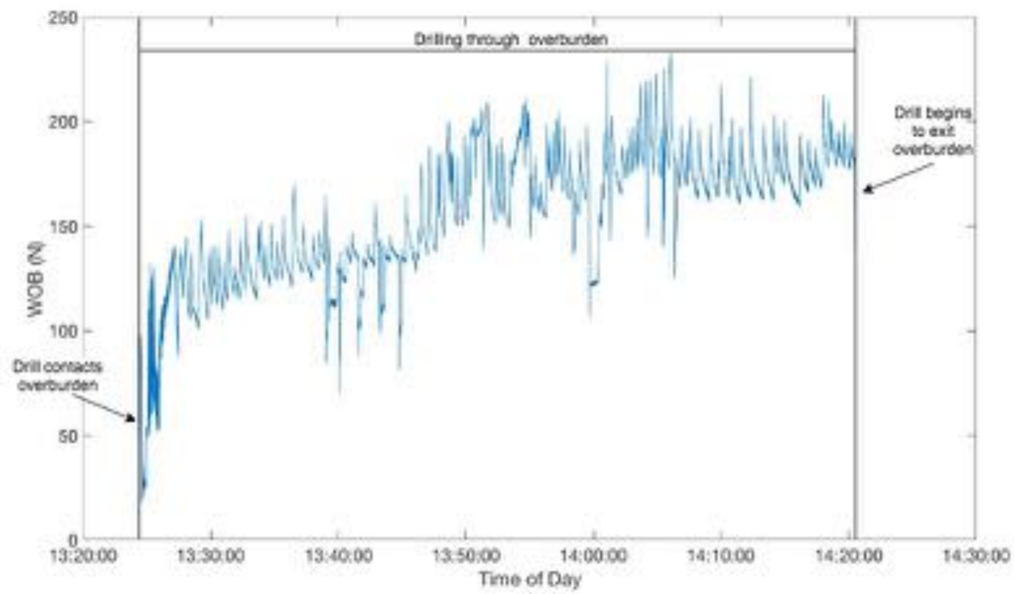

Figure 7. **Day 2 WOB vs. Time Data**

”Day 2” operations.

Drilling and Overburden

The drilling subsystem is comprised of a 32 in long, 2 in diameter steel auger, powered by a universal motor. The rotational drill speed and weight on bit (WOB) are individually monitored and manually adjusted during the drilling process, allowing the team to respond to excessive system vibration, changing regolith density/composition, and comply with the 150 N challenge WOB limit. The tip of the auger contains a 60W heater, which loosens the frozen overburden during the drilling process.

The drilling process on Day 1 was controlled in a manual feedback loop based on WOB, seen in Figure 6. From 9:03 am, when the drill initially contacted the overburden, until 9:28 am, the system forced the auger into the regolith until a 150 N WOB was measured. The auger then remained stationary until the load reduced to 100 N. These cycles repeated approximately every 42 seconds. As the auger reached the middle of the regolith layer, the overburden became cooler, more densely packed, and harder to drill through. This phase, from 9:28 am to 9:48 am, is characterized by a steady, slow changing WOB. The rate of penetration subsequently decreased, as the auger spent longer clearing overburden. The last region, from 9:48 am to 10:00 am, is where the auger made contact with the ice. This phase is characterized by cyclic variations in the WOB. These high-rate cycles were due to the uneven ice surface, which pushed the auger up and down. This oscillation continued until the ice surface was flattened by the auger.

Figure 7 shows the WOB vs time during Day 2. Drilling was not successful because the auger heater was not functional during this day. The auger was operated at a much higher WOB to compensate for the failed heater but was only able to bore to a depth of 10 cm.

From Figure 6 we can identify the time of initial contact with both the regolith and ice layers. From this we know that the 50 cm of regolith was penetrated in 59 minutes 20 seconds, and required an average WOB of 102.05 N. On Day 2 the auger heater failed and a drilling sequence was attempted with an unheated bit. During this process 10 cm of overburden were bored as shown in Figure 8. This operation took a total of 56 minutes 3 seconds.

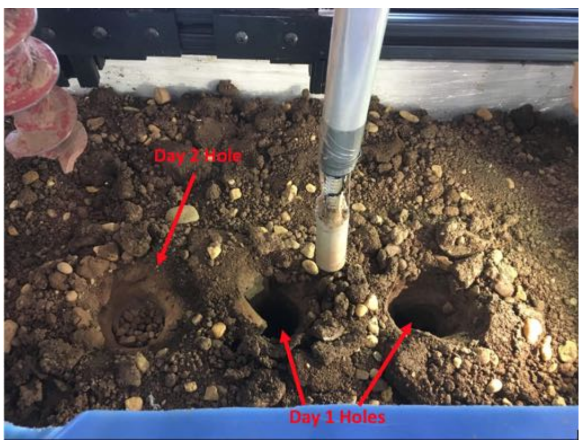

Figure 8. Holes drilled during competitions: to the left is the 10 cm depth hole drilled without heater functionality on Day 2 and to the middle and right are the holes drilled through to the ice on Day 1

These results show that heating of the bit significantly improved performance of the PAWES drilling subsystem. The rate of penetration on Day 1 and Day 2 were 0.140 mm/s and 0.03 mm/s respectively. On Day 1, with the heater running, the drilling subsystem was able to penetrate the regolith 267% faster while only using 66% of the force required on Day 2. Any performance differences can be attributed to changes in the drilling subsystem, as the drilling method and ground composition were identical. Therefore, the change in rate of penetration suggests that any drilling into cold regolith should have a heated tool to improve drilling performance.

Melting

The melting subsystem consists of an aluminum heated nozzle containing three 200 W cartridge heaters as shown in Figure 9. The heated nozzle can be articulated using a "marionette-style" drive system. To articulate, three stepper motors spool three tension cables that are evenly spaced around the circumference of the nozzle. This drive scheme allows the 3 in long nozzle to reach angles of up to 45° from the horizontal as shown in Figure 10, thus enabling access to 15 times more volume than a non-articulating nozzle of the same size. Furthermore, the articulation provides direct contact with the ice at all times, taking advantage of conductive heat transfer to rapidly melt the ice.

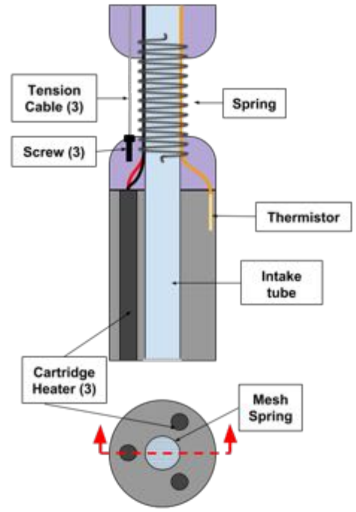

Figure 9. Cross section showing the nozzle's internal components

PAWES extracted 1370 mL of water during Day 1 of the challenge and 1839 mL during Day 2. The ice was heated for two hours on Day 1 and three and a half hours on Day 2. While active, the heaters were intermittently turned on to maintain a temperature near 60°C. The nozzle was constrained to a maximum operating temperature of 60°C due to the temperature limits of extractor components. The melt rates for Day 1 and Day 2 of the challenge were 11.4 mL/min and 8.8 mL/min respectively.

Table 2. Successful water extraction techniques

Team	University	Technique
PAWES	Northeastern University	Liquid
HYDRA	MIT	Crushed Solid
MINERS	Colorado School of Mines	Liquid
MIDAS II	West Virginia University	Liquid
TINAD	University of Tennessee	Liquid

The results of the challenge showed that liquid extraction is more feasible than solid extraction. During the challenge, 5 of the 10 teams were able to collect water. A summary of team extraction techniques can be seen in Table 2. All five teams that were unable to harvest water used solid extraction techniques while the top three performing teams used liquid extraction techniques.

One of the primary reasons for the success of liquid extraction over solid ice extraction was overburden management. Teams using solid extraction spent more time drilling and processing overburden, whereas teams using liquid extraction dedicated the time to melting and extracting. Another benefit of liquid extraction is that it can make use of previously melted water as a heat transfer medium, commonly known as the Rodwell extraction method [12]. The Rodwell method takes advantage of heat transfer through water, and melts out a volume from the ice as shown in Figure 11 [12]. In addition to melting by direct contact with the articulating extractor nozzle, PAWES was able to leave the heated tip in the melted water and use the Rodwell method. While the Rodwell method is slower than direct contact, it allowed access to the volume of ice

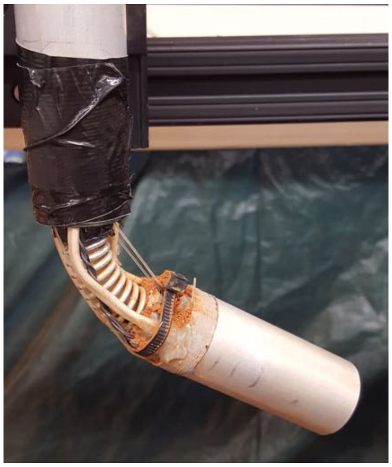

Figure 10. **Nozzle prototype during articulation**

that could not be contacted with the nozzle. Using this method reduces the number of boreholes necessary and saves the time required to drill them. All teams found that liquid extraction methods allowed for more time devoted to melting, and therefore more successful extraction processes. Given this evidence, liquid extraction techniques are likely the most efficient extraction method to collect subsurface ice.

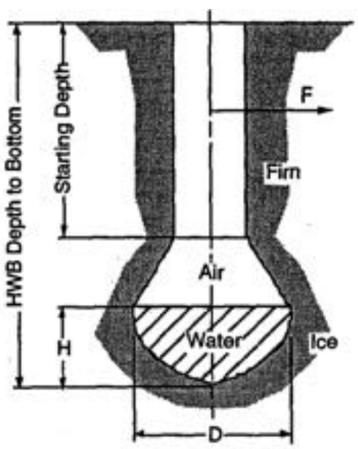

Figure 11. **Shape of the ice melting profile caused by use of the Rodwell method**

Single Tool Integration

Inherently, the carriage containing the extraction and drilling systems had to transition from auger to extractor. This process left the hole open and allowed loose regolith to fall in and cover the ice, becoming a clogging risk and preventing full heater contact. Condensing the drilling and melting subsystems into a single tool would eliminate the need for a transition and streamline the process of shielding ice and melt-water from the Martian atmosphere. Additionally, a single tool would aid in maintaining the integrity of the walls of a bored hole and reduce the risk of collapse.

Extraction

After melting, the water is removed from the hole through 3/16 in flexible tubing using two peristaltic pumps in series. Each pump is self-priming and capable of pumping sediment-heavy water up to 25 psi at 300 ml/min.

In preliminary testing, it was found that as the system melted ice and drew up dirty water, sediment in the water could aggregate into a clog as shown in Figure 12. A procedure was developed to lower the risk of a blockage:

1. Every 90 seconds stop downward extractor motion and pump up liquid water.
2. Continue pumping until either the flow stops or air begins rising up the tube.
3. Reverse the pumping direction and purge as much liquid as possible back through the extractor into the hole. Ensure the system never has still liquid in the internal tubing.
4. Once the extractor has reached the bottom travel limit of the Z axis, pump again, then remove it from the hole.

Pumping cycles of 90 seconds were found to be the most effective method of melting downwards in preliminary testing. As the heated bit descended into the ice these pumping intervals expanded the walls of the ice cavity to the full diameter of the auger. A hole at the overburden-ice interface any larger than the auger would create an overhang and expose unsupported overburden, which would serve as a clogging hazard if it fell into the hole.

Figure 12. **Sediment slurry forming a clog in extraction tubing during preliminary testing**

An additional objective of pump cycling was to prevent liquid from collecting within the tubes. When liquid filled the tubes and stagnated, sediment settled into clogs. While the procedure was an improvement over pumping in a single direction, it did not prevent stagnation due to the accidental intake of waterlogged sediment settled at the bottom of the hole. Beyond this strategy, there was no explicit subsystem designed to prevent or manage clogs. Additionally, the water intake was located at the bottom of the hole, where it created a clogging risk when the extractor was lowered. Any silt or collapsed overburden settled at the bottom of the hole could be forced into the nozzle inlet and cause a clog.

During Day 1 the system experienced clogging problems. Between Day 1 and Day 2, the 3/16 in internal diameter tubing within the extractor was replaced with 1/4 in tubing in order to lower the risk of developing a clog. Nonetheless, a blockage developed. While this issue was resolved remotely, it highlighted the lack of a dedicated clog management system.

Blockages were difficult to detect because they were evaluated qualitatively based on the observation of liquid flow in the pump. Quantitative indicators of clogs, such as an array of pressure and flow sensors, would expedite the detection process. Once blockages are detected, a number of potential solutions could be implemented to remove them from the transportation tubing. These include the use of a resonating wire that travels along the interior of the tube, the agitation of the entire transportation tubing to dislodge sediment blockages, or the use of a high pressure back flow to break apart the blockage. These systems may be able to remove any sediment blockages in the transportation tubing, preventing total system failure.

Filtration

To remove sediment from collected water, PAWES uses a filterless electroflocculation assisted gravity separation system, depicted in Figure 14. Electroflocculation subjects sediment-heavy water to an electrical potential. When exposed to this potential difference the clay particles from the regolith are electrically attracted to each other due to their electrochemical properties. This causes the particles to clump and settle faster than they would in unassisted gravity filtration [13] [14] [15]. After sediment separation, filtered water is released, leaving a sludge that can be purged from the filtration system. This filtration technique is advantageous because it does not require a replaceable filter and thus has a greater lifetime than traditional filtering techniques. This is especially relevant for an in situ Mars application.

During preliminary testing, the flocculation system was more effective than gravitation separation alone. Separation results from preliminary testing of EF using a voltage of 12 V for 20 minutes are shown in Figure 13.

Figure 13. Gravity separation (left) vs electroflocculation assisted gravity separation (right)

Observation and system performance analysis determined that stagnant water is a requirement of electroflocculation. Any disturbances, such as frame vibrations or splashing from unfiltered water entering the filtration chamber, are sources of flow which agitate separated particles in the water causing filtration to fail. During operation of PAWES, the filtration chamber experienced significant vibrations that agitated the slurry. The entry point for collected water was at the top of the chamber, so unfiltered water caused disturbances each extraction cycle. An additional consideration is that gravity separation would take longer in the Martian environment than on Earth, due to the weaker gravity.

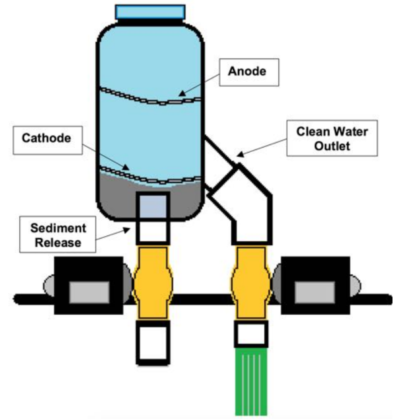

Figure 14. Diagram of the filtration subsystem showing location of the clean water outlet and the sediment release outlet

To make electroflocculation a more viable filtration option, several precautions would need to be taken to lower the impact of water-disturbing conditions. A damping system would assist in reducing frame vibrations. Furthermore, the filtration system could be separated from the main system body and deployed on the ground in a location isolated from drilling vibrations.

In the next iteration of PAWES, we intend to use a distillation filtration system. Distillation is a more robust method, providing pure water. While distillation avoids the problems caused by vibration and would effectively remove more water from a slurry, a challenge it faces is heat exchange. Any vapor must be cooled to condense. Typically condensation through heat exchange with the air would be unpractical on Mars given the thin atmosphere. An option is using Mars itself as a heat sink, and burying a heat exchanger underground. Heat pipes would allow good conduction between the distillation condenser and ground. Additionally, an efficient distillation technique such as multiple-effect distillation could be used [16], allowing any collected slurry to exchange heat with distillation vapor. This process requires less energy and increases distillation rate.

6. SENSING AND CONTROLS

PAWES was developed to operate as a remote system. Per the competition rules, a human operator was allowed direct control from a ground station. This was chosen over a semi-autonomous operator in the loop or fully autonomous scheme due to time and financial constraints during the development of the prototype.

PAWES uses a current sensor and a drill load cell, both of which were required by the challenge design criteria. In addition to these required sensors, PAWES monitors the temperature of the heated extractor, the force on the extractor subsystem, and uses a camera stream of the drilling and extraction target area. These were added in order to ensure safe operation of the heated extractor and to provide the operator with sufficient information to run PAWES though its extraction procedure from the control station.

To enable this control scheme, two microcontrollers are located on board to output system control signals and handle sensor data. To pass control messages via serial to these controllers PAWES has an on-board processor. This processor also controls the test-bed camera stream. The processor connects via Ethernet to a laptop at the control station, which provides the user interface, data logging of sensor information, and kinematics calculations for the articulating extractor.

PAWES's software is implemented using the Robot Operating System (ROS) framework. ROS was chosen as it allows for the distributed processing and control required by the PAWES control scheme. Each element of the control system was implemented as a custom ROS node, including the embedded software on the micro-controllers, to allow for consistent passing of data between nodes. In operation this implementation provided the operator with an rqt based graphical user interface capable of direct control of all actuating components and live streams of data from the system's sensor suite. The user interface display can be seen in Figure 15.

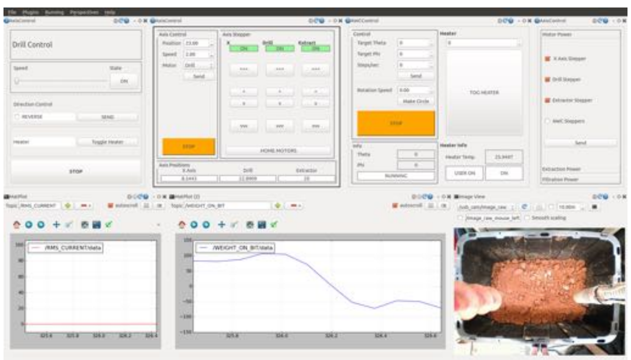

Figure 15. User interface for remote operation of PAWES

The control and sensing system functioned without error for the entirety of the 12 hours of the challenge. This system provided the operator with sufficient information to provide direct control. For example, live data streams from the drill weight-on-bit sensor enabled the operator to identify when the drilling system had impacted the ice, and the test-bed camera feed allowed for reliable positioning of each system above target locations.

While our control and sensing system provided a reliable method of operating PAWES over extended periods of time, it lacked sufficient state information to identify clogging of the system's slurry transport tubing or identify the state of the underground cavity melted by the system.

PAWES demonstrated that a robust reliable control scheme eases the challenges of controlling a water extraction system. Comprehensive internal and external state information is required to prevent critical failure of the system when in operation on Mars. In the case of PAWES, the system could have proven more robust if it had the ability to monitor the internal state of the transportation tubing to detect the formation of clogs.

To operate on Mars a water extraction system will need to be nearly autonomous. The performance of the PAWES sensor and control system supports the need for a sensor suite capable of identifying problems before they cause a critical failure to allow for complete autonomy. A water extraction system may encounter a variety of stresses across several components, many of which would be grounds for mission failure if they go undetected or have no built-in redundancy. PAWES's need for additional state knowledge regarding complex internal and external environments supports the theory that model based robust control system, such as that demonstrated by the DAME drill [17].

7. CONCLUSION

This paper discusses the design and testing of the Planetary Articulating Water Extraction System (PAWES), a remotely operated Martian water collection system. PAWES operates in four stages: drilling, extracting, melting, and filtration. These processes have been extensively tested and optimized in order to determine the best strategies for subsurface ice extraction. The result is a robust proof of concept of a system capable of collecting water on Mars.

From development and testing of this prototype, we highlight lessons learned regarding fundamental design choices for any Martian water collection system. Notably, this includes using liquid water extraction from subsurface ice deposits, a one tool drill-extractor design with a heated regolith drilling tip, a water transport system capable of sensing and self correcting clogs, distillation as a primary filtration method, and a sensory system for comprehensive state estimation including the subsurface environment. The authors believe that these aspects will improve the capability and reliability of a Martian water extraction system.

Development of an iterative design is currently underway. Future implementations of the system will use the takeaways from PAWES in order to create a higher efficiency water extraction system. The future system intends to be more robust and capable of handling diverse overburden materials that more accurately represent Martian regolith.

APPENDICES

A. EXTRACTION PROCEDURE

Drilling Phase

1. Move system to entry point
2. Power on auger and begin rotation
3. Lower auger into overburden until weight on bit (WOB) reaches 150 N
4. Lower system to when WOB is 100 N
5. When WOB spikes and does not drop, we will know the system has reached the ice
6. Rotate auger in position for 10 minutes maintaining a 100 N WOB
7. Remove the auger

Extraction Phase

9. Position the extractor over the extraction hole
10. Lower extractor until a WOB appears
11. Continue to heat and lower extractor until extractor has reached a depth of 4 inches into the ice
12. Articulate one loop at 25 degrees
13. Articulate one loop at 35 degrees
14. Lower the extractor until a WOB appeared again
15. Repeat prior 3 steps

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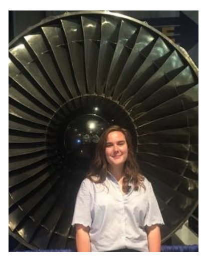

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