Northeastern University

Prospecting Underground Distilling Liquid Extractor

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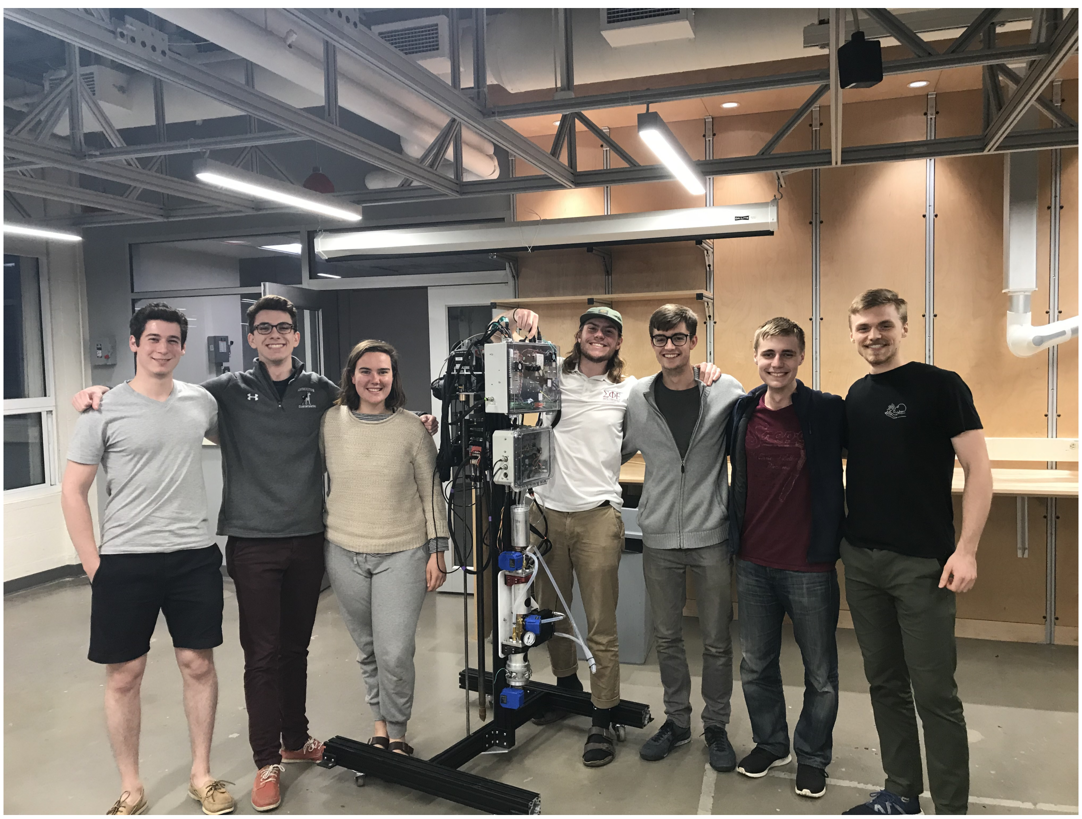


Contents

1 Design

1.1 Design Overview

The Northeastern University Prospecting Underground Distilling Liquid Extractor (PUDLE) is a robot which extracts subsurface water and evaluates regolith layer properties on extraterrestrial bodies, shown in Figure 1. This system is engineered to meet the requirements of the NASA's 2019 RASC-AL Special Edition: Moon to Mars Ice and Prospecting Challenge and it incorporates the lessons learned from the Planetary Articulating Water Extraction System (PAWES), Northeastern University's entry in the 2018 Mars Ice Challenge [1].

PUDLE is designed as two separate systems which work in tandem to assess regolith composition and extract clean water. These two systems are the Jackhammer Extraction Tool (JET), a combination prospecting and water extraction jackhammer, and the multiple-effect distillation system capable of providing purified water. The system uses a jackhammer outfitted with load cells to penetrate and analyze overburden. The tip of the jackhammer is heated and lowered via cables to melt ice and extract water. The water is cleaned in a multiple-effect distillation system. The system weighs 58 kg with an operational volume of 0.95 x 0.95 x 1.7 m. The JET shaft of the jackhammer is 0.87 m long, capable of applying a weight on bit (WOB) of 150 N at an expected average penetration speed of 3.33 mm/s. The system is powered by a 120 VAC wall outlet, controlled via a Robot Operating System (ROS) software suite, and operated remotely. A Hidden Markov Model (HMM) applied to system telemetry aids the operator in producing a digital core. The resulting system is a robust solution for subsurface water extraction on Mars and determining regolith composition on the moon.

1.2 Jackhammer Extraction Tool

The JET is composed of a Bosch DH507 jackhammer, a coupler, a shaft, an an actuated heated tip, driven via a tension cabling system and secured via a clamp, shown in Figure 2. The tip acts as both the jackhammer bit and the ice melting element. The tip is connected via a cable, which contains power and sensor wiring, an endoscopic camera, water tubing, and two steel tensioning cables. Two NEMA 23 stepper motors drive the cable, allowing the tip to separate from the shaft, descend through the ice deposit, and melt ice deeper than the length of the jackhammer shaft. The only change made to the JET since the midpoint review is the addition of a second stepper motor to aid in driving the tip downward. The depth of accessible ice is limited only by the length of the cable. Before jackhammering, the tip is drawn into the shaft and the steel tensioning cables are clamped in place using a bike shifter cable tensioned via a linear actuator with a 250 N maximum static force. The tip contains two Tutco 150 W cartridge heaters, a hermetically sealed thermocouple, and two water inlet ports. The inlet ports are covered by the shaft while jackhammering and are only exposed when the tip is released into the ice block. This geometry greatly mitigates the risk of developing a clog while jackhammering.

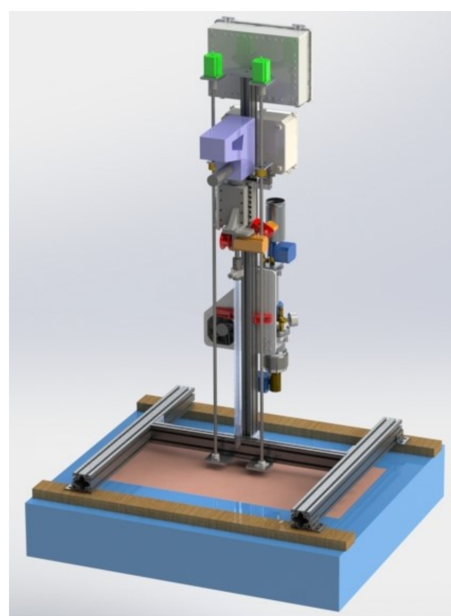


Figure 1: *An overview of the complete system design*

The shaft is a high carbon steel tube: 1.125 in. OD, 0.875 in. ID, and 0.87 m long. The tension cables, wires, and water tubing from the tip are routed through the shaft and out via holes in the coupler, which attaches the JET shaft to the jackhammer. The shaft is inserted into the coupler and held in via a 0.44 in. diameter quick release pin. A Bosch DH507 demolition hammer was chosen for its compact size, 11 x 18 x 4 in., and weight, 5.62 kg, capable of penetrating stone and concrete. Springs attached between the jackhammer mount and the coupler preload the jackhammer by approximately 200 N, which allows the percussion mechanism to activate with minimal WOB. This allows percussive hammering in low density materials and provides damping to reduce noise without losing accuracy in WOB data.

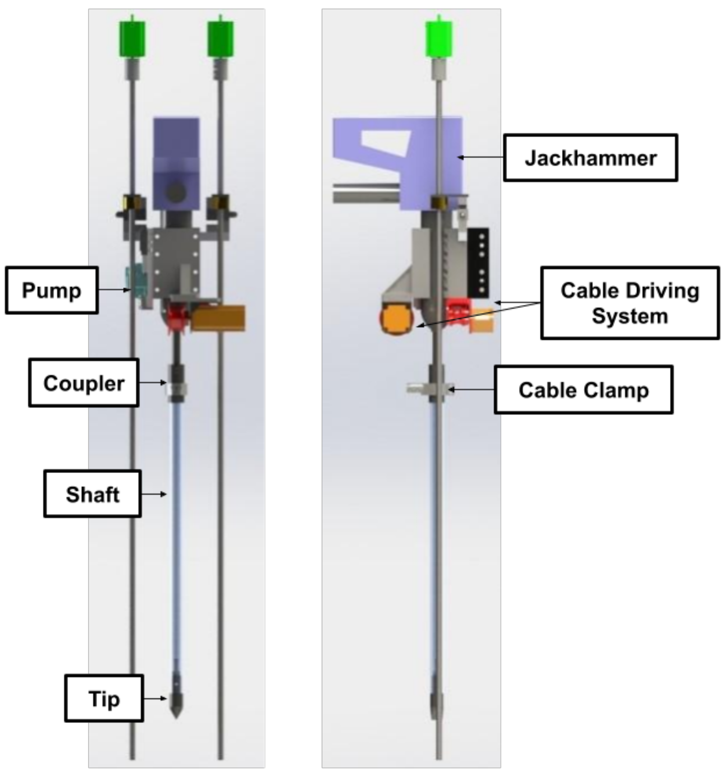


Figure 2: *Jackhammer Extraction Tool*

PUDLE's water extraction approach uses the Rodwell method, which submerges a heater into a pool of water and transfers heat to surrounding ice [2]. The Rodwell method is implemented by unspooling the tensioning cables and lowering the heated tip into the ice, creating a pool of meltwater which gradually grows as it is heated. The only limitation of the accessible depth for this method is the length of cable on the spool.

1.3 Distillation System

PUDLE uses a distillation system to process water extracted by the JET. Distillation is an effective way to remove impurities and sediment from water, but it is energy-intensive. To alleviate power concerns, PUDLE implements a multiple-effect distillation process in which vapor from the primary distillation tank flows in a helically coiled tube through a secondary heat exchange tank before it enters the radiator. This heat exchanger has two benefits: the water in the heat exchange tank cools the helical tube, causing some of the vapor to condense and reduce the load on the radiator and fan, and the energy released by this condensation pre-heats the water in the heat exchange tank before it enters the primary distillation tank. Some of the water in the heat exchange tank will also evaporate, as the temperature will be raised to 100° C by the helical heat exchange coil. The combination of these features results in a more power-efficient distillation system.

The isolated distillation system is shown in Figure 3. Incoming water from the JET enters the collection tank, which is a reservoir to allow the JET to continue collecting water while the distillation system is operating and closed. An actuated ball valve connects the collection tank to the heat exchange tank, and another connects the heat exchange tank to the distillation tank. While the distillation system is active, a 650 W band heater boils water inside the distillation tank. The water vapor passes through a FEP tube to the heat exchange coil, where it is partially condensed, after which it reaches the air-cooled radiator. When the distillation tank finishes boiling a batch of water, the heat exchange tank empties into it to provide the next batch. The distillation tank re-seals, and the heat exchange tank is filled from the collection tank, at which point the distillation process starts again. A valve at the bottom of the distillation tank allows any accumulated sediment to be purged once several distillation cycles have been conducted. A bypass valve allows meltwater to be separated based on its turbidity, to allow the distillation system to prioritize processing the dirtiest water while clean water is diverted. Water diversion is controlled by the operator monitoring incoming water through the onboard cameras.

Eight thermistors and two water-presence monitor the distillation system state. Thermistors are mounted on the distillation tank heater, distillation tank body, distillation vapor outlet, heat exchange tank body, radiator inlet, and radiator outlet. Water-presence sensors are located at the tops of the distillation tank and heat exchange tank.

Since the midpoint review, it was discovered that it is not necessary to pressure-seal the distillation system for optimal performance. This allowed the storage tank to be removed, with condensed water instead running directly to the collection bucket.

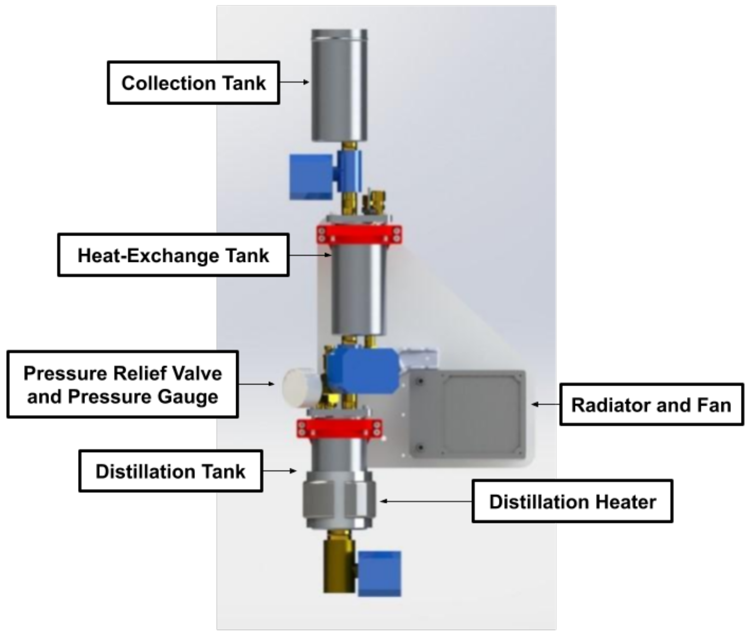


Figure 3: *Distillation System*

1.4 Structural Mounting

The JET is mounted on a single z-axis powered movement system, driven with lead screws by two NEMA 23 stepper motors. To prevent unnecessary torsion on the frame, the JET is aligned between the two lead screws so the force applied by the jackhammer is evenly distributed. PUDLE is adjustable in the x-y plane, but is not powered. For the challenge, the tower will be adjusted manually by loosening the 8 screws holding the z-axis in place, sliding the assembly, and re-securing it in the new position. A non-powered movement system in the y-axis reduces system weight, power draw, and prototyping cost. Use of the Rodwell method means the system can remain at the same extraction hole for a long duration. PUDLE's structure and movement system functions exclusively to showcase the JET for the RASC-AL testbed. Additional benefits are discussed further in the Path to Flight section.

The CAD model is shown in Figure 1. The frame is mounted to the testbed with wood screws fixing standard 80/20 corner brackets onto the 2x4 wood beams. An H-structure made of 80/20 extruded aluminum acts as the main frame. In the middle of the H cross beam, a vertical 80/20 beam is mounted with two lead screws to allow for Z-axis movement.

1.5 Electrical System

The electrical system of PUDLE is split into two parts: the JET electrical box and the distillation electrical box. The boxes are connectorized and use custom cable harnesses to be as modular as possible for ease of transportation. PUDLE is powered by a 120 VAC source from a wall outlet that plugs into the JET electrical box. The maximum system current draw is limited by the required 9 A fuse as well as an 8.5 A circuit breaker that acts as the manual kill switch of the system. The fast-blow fuse and circuit breaker ensure that the system is protected from any electrical shorts. The power is distributed to 24 VDC, 12 VDC and 5 VDC terminal blocks within the JET electrical box, and the distillation electrical box receives 120 VAC and 24 VDC to power its components. Because the distribution of power takes place in the isolated, grounded electrical boxes, the team is not at risk of an electrical accident.

The ground station interfaces with the JET electrical box via Ethernet that plugs into a bulkhead jack. The Ethernet cable is routed to a Raspberry Pi 3 that serves as the onboard computer for the system. The Pi interfaces with a USB hub that aggregates signals from the three system cameras and three system Arduino Mega microcontrollers. Two of the Megas are housed in the JET electrical box and are responsible for the control of the pump, z-axis movement system, WOB sensors, jackhammer control, cable driving motors, current sensing for the JET assembly, JET thermistors, and heater control. The layout of the JET electrical box is shown in Figure 4. The JET control box features thermistor and limit switch through-hole breakout boards. The distillation electrical box houses the controls of the filtration system including a single Arduino Mega responsible for valve control, fan control, heater control, and sensor I/O. The box includes custom thermistor and valve control signal through-hole breakout boards. The distillation electrical box, shown in Figure 5, is modular and can be completely disassembled for challenge transport.

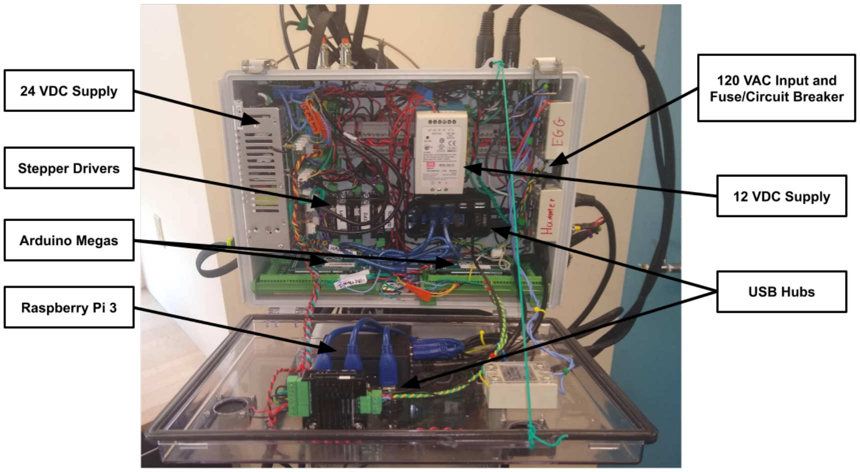


Figure 4: *JET Electrical Box*

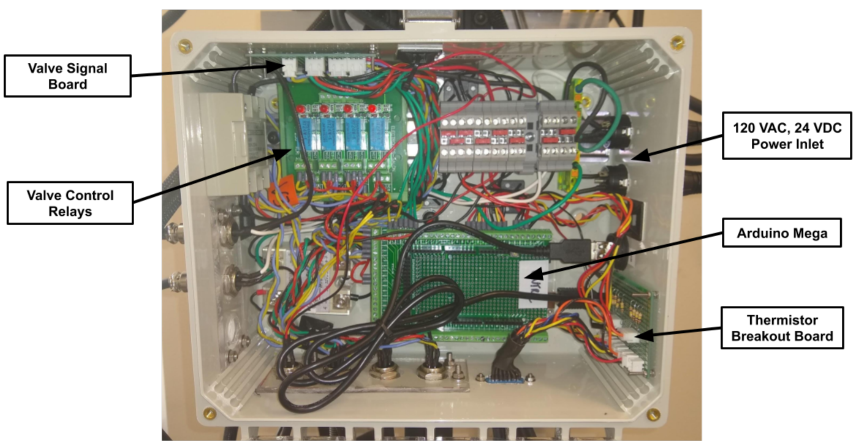


Figure 5: *Distillation Electrical Box*

1.6 Software and Controls

The software and controls on PUDLE use the ROS framework. The controls system is distributed across two processors and three microcontroller AVR chips. The AVR microcontrollers are responsible for handling all hardware interactions and control loops. The onboard computer (OBC) is responsible for managing the interactions between the three microcontrollers and handling image collection from three onboard cameras. The ground station computer (GSC) is tasked with data logging, displaying system telemetry, and accepting user input. Communication between each processor is handled by the ROS backend and allows for serial communication to and from the AVR chips as well a higher data rate Ethernet communication between the GSC and OBC.

PUDLE is operated through user input from a custom Qt-based GUI, shown in Figure 6. This interface is designed to enable the operator to issue macro-style commands which initiate different phases of operation such as initiating a JET drilling sequence or a JET ice melting sequence. Control of PUDLE's distillation system is similar but will start only once and operate in the background, monitoring system behavior to determine what actions to perform. In addition to these high level controls, all low-level functionality of PUDLE is exposed to allow the operator to perform localized actions such as actuating individual valves or adjusting the position of the JET.

To facilitate this operation, the GUI displays all measured system information for the operator. Additionally, the operator has constant video streams from three cameras on PUDLE showing the target drilling area, a downwards view from the top of the system and an endoscopic camera showing the tip from 15 cm above. In addition to displaying this information, telemetry is recorded on the GSC to .csv files. This includes total system current draw as measured by a Hall Effect current sensor and system WOB as measured by two S-type load cells. This data is the main source of information used to perform post analysis for digital core determinations.

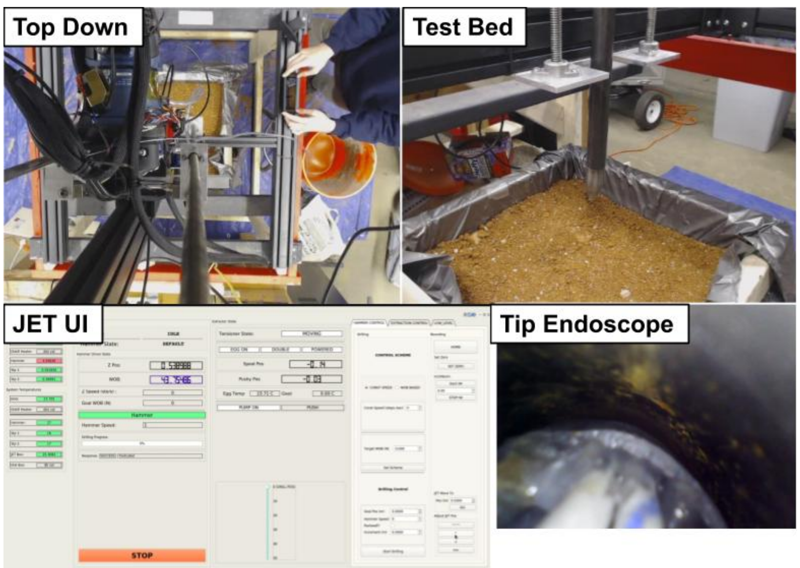


Figure 6: *PUDLE UI and System Camera Views*

1.7 Digital Core Analysis

Creation of a digital core is completed through manual inspection of WOB data collected throughout the drilling phase, aided by an unsupervised learning algorithm to identify layer boundaries. Clustering of WOB data enables differentiation between materials in the overburden with respect to hardness. However, this alone does not utilize position data and risks overestimating the number of layers by misclassifying outliers within a layer. To benefit from materials commonly being contiguous in position, a Hidden Markov Model (HMM) is used with depth as the time axis [3]. In this model, there exists a set of states (materials), and a set of observable behaviors (WOB). For a pair of states (A, B), there exists a transition probability that a system in state A at time t will transition to state B at time $t + 1$ [3]. This allows the model to prioritize staying in the same state, or material, over transitioning to a new state. Additionally, for each state A there exists a set of emission probabilities that describe the distribution of that state over the set of observable behaviors [3]. Given a sequence of measurements from a drilling cycle, the model can infer a sequence of layers that most accurately reflects the observed telemetry. The analysis employs a simple model using a single behavior of WOB to infer the hidden states. Pandas, NumPy and Scikit-learn software packages were used to build a framework to ingest the data logged through the controls system and run this model.

In order to achieve good results from the model, data cleaning post-collection is performed prior to running the HMM. These methods include filtering such as removing periods where drilling was paused or in the ice layer, as well as noise reduction in WOB. Data processing methods are automated using Pandas and explored through an interactive GUI. Data smoothing parameters are determined through both manual inspection and optimization of the log probability of the smoothed data under the model. Number of layers and layer boundaries can be explored and validated through an interactive GUI that allows for manual adjustment of these parameters.

2 Testing and Validation

2.1 Full System Integration Testing

Full system integration testing was conducted throughout the month of May and is detailed in the following sections. Testing included jackhammering through multiple layers of varied overburden and ice melting. Extensive notes were taken during each test allowing strategic improvement of any underperforming sub-systems. In this period, PUDLE drilled 27 holes through three different configurations of overburden layers. Many of these drill trials were used to test overburden drilling and refine strategies for digital core analysis. The final four holes were used to test an integrated drill-melt operation. While these holes validated the ability of PUDLE to drill and melt continuously, a software bug prevented extraction of any water from these melt holes.

Extraction integration testing was performed after software fixes had been implemented. A small ice block was covered with a layer of loose clay to simulate a potential overburden-ice interface. PUDLE then performed an extraction operation deploying the JET heated tip ∼3 in. from the end of the JET shaft. In this test 0.5 L of water was collected over a testing time of ∼30 mins. After measuring, the collected dirty water was re-pumped through the JET and into the distillation system. A full distillation run with user control successfully converted the collected water into pure clear water in ∼50 mins.

PUDLE underwent full system operation for a total of 13 hours. Throughout this period, each extraction sub-process was tested, and integrated process transitions were validated. Testing will continue up until the competition, during which the team will work to hone processes and collect more data for digital core creation.

2.2 Distillation Testing

The distillation system was tested in stages throughout the development process. Initial testing focused on leak-proofing and heater performance. During integration testing, 0.5 L of sediment-laden water extracted by the JET in a previous test was pumped into the collection tank to initiate a standard distillation cycle. 0.45 L of water was distilled in 50 minutes, giving a flow rate of 0.54 L/hr with the duty cycle of the 650 W distillation tank heater at 100% until the end of testing. Testing was concluded once the heater duty cycle dropped to approximately 25%, indicating that no further water was inside the tank to absorb energy.

2.3 Rodwell Testing

Testing of the ice melting using the Rodwell method was conducted periodically throughout the development of PUDLE. Testing results guided the design of three JET tip iterations, shown in Figure 8. The first Rodwell testing was done by holding the first iteration of the heated tip against an ice block, shown in Figure 7. This test suggested that heat was not effectively reaching the bottom point of the tip, which

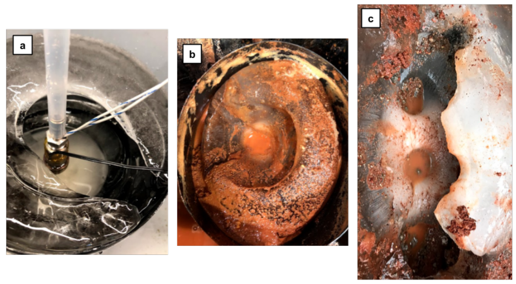


Figure 7: *Three tip iterations with accompanying thermal gradients, assuming 1 in. submerged in water and no heat transfer through the bottom face of the heater*

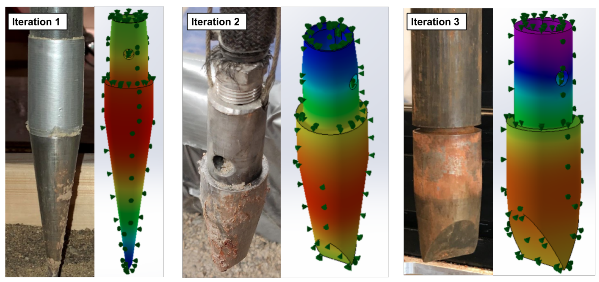


Figure 8: *a,b,c) JET Tip Design Iterations*

restricted its ability to melt in the z-axis and move downward. Follow-up thermal simulations substantiated this finding. It was determined that there was not enough cross-sectional area for sufficient thermal conduction to the bottom of the tip. To compensate for poor heat transfer, thermal analysis showed that the tip should be cut off at two 30° angles, creating a chisel rather than a point as shown in Figure 8. After this change, the new iteration melted at a rate of 1.5 L/hr.

The first two iterations of the tip contained only one 150 W cartridge heater. The third iteration was designed to fit two 150 W heaters. With this change, the final iteration was used in integration testing to collect water from under overburden at a rate of 1.2 L/hr. The reduction of 0.3 L/hr does not represent a slower melt rate. The initial value of 1.5 L/hr comes from total water melted, whereas the 1.2 L/hr is from liquid melted and extracted.

2.4 Overburden Penetration Testing

Overburden penetration testing demonstrated PUDLE's ability to both penetrate high strength materials, such as concrete, and identify the properties of the regolith. A wooden test frame was constructed to support stacking multiple layers, seen in Figure 11. During testing, PID control for the jackhammer was adjusted to achieve efficient penetration with interpretable prospecting data.

The original approach for prospecting was to drill continuously while collecting data on WOB and speed supplemented by intermittent pseudo-Rockwell testing. Preliminary tests discovered that the system could not maintain a WOB range where the maximum was attainable in both the softest and hardest materials due to the large disparity in hardness between materials like sand and concrete. This disparity resulted in the system penetrating full layers in the span of a single Rockwell test. The Rockwell method also has a very small sampling rate and disrupted the continuous WOB measurements that proved crucial to the final analysis. Due to these obstacles, a continuous-movement control scheme was selected over Rockwell-based data collection.

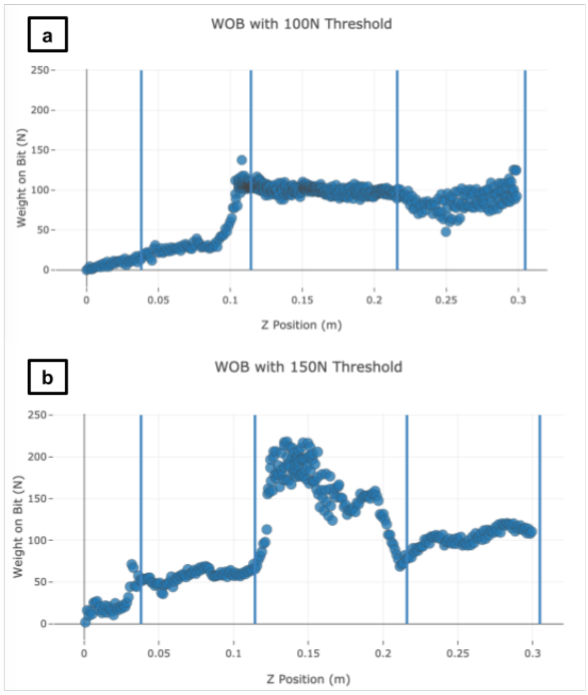


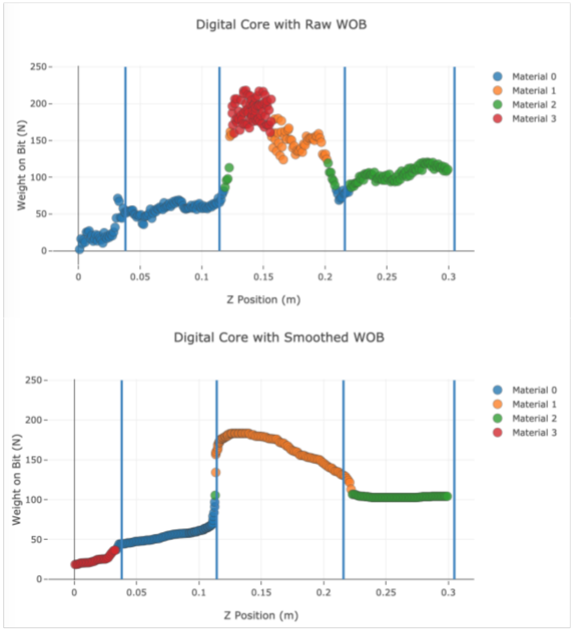
Figure 9: *a) Raw WOB data at a 100 N threshold b) Raw WOB data at a 150 N threshold*

Additional rounds of testing were conducted to select optimal parameters for the PID-based operation. This entailed selecting an upper threshold for WOB used by the PID loop to adjust drilling speed. Tests were performed by drilling through a full simulated test bed with four layers consisting of sand, clay, concrete and a final layer of clay. Beginning at low thresholds, tests showed that WOB limits below 100 N struggle to efficiently penetrate the concrete layer. Figure 9 shows the raw WOB measurements for two drilling cycles conducted at 100 N and 150 N. Both cycles were able to efficiently penetrate the test bed, with the 100 N and 150 N thresholds traveling on average 1.67 mm/s and 3.33 mm/s respectively. The vertical lines in the figure signify the layer boundaries of the test bed. Using the 100 N threshold, readings at the top of the threshold are observed for the bottom two layers while a notable distinction exists in the 150 N trial. This indicates that the low ceiling of 100 N is not flexible enough to account for the hardness of all materials used in drill testing. Maintaining a threshold WOB of 150 N allowed for proper stratification of the WOB data.

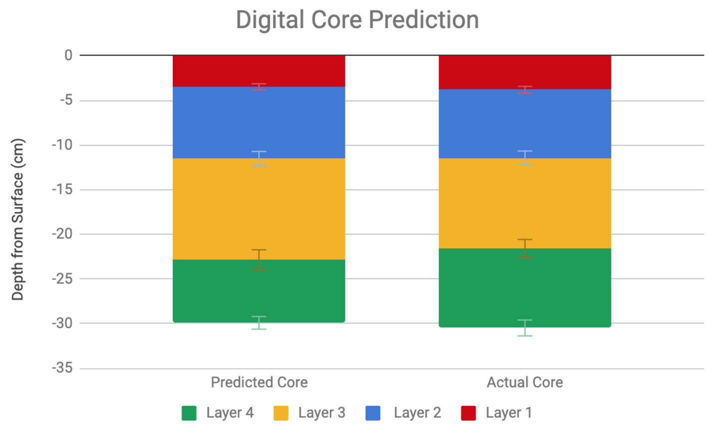
Although the higher threshold allowed for variability of the WOB between layers, the variance was too noisy to extract a confident prediction of the core. Smoothing with a rolling median across the WOB data was used to draw out periods of relative flatness separated by near-vertical spikes indicating layer boundaries. The size of the window was selected by iteratively running the HMM and maximizing the model's log probability, the confidence of the labels assigned to the data [4]. The contrast between the raw WOB and the adjusted data is seen in Figure 10a. The smoothed data was able to condense periods of transition where the JET tip was embedded between two layers, resulting in highly accurate estimation of layer thicknesses. This collapse of the transition periods resulted in an constant shift of the smoothed data that was corrected to align with the shape of the original WOB. This process was paired with a manual inspection of the model when looking for a varying number of layers to arrive at a final prediction of the core.

The final prediction of the layer boundaries from analysis in Figure 10a can be seen in Figure 10b, along with the corresponding location estimates and error in Figure 10c. The error margin on all predicted layer boundaries is below the accepted margin of error for the competition of 1.5 cm.

It is worth noting that in this model, a material is fully characterized by the WOB it takes for PUDLE to penetrate it. Thus, layers with different composition but similar hardness would be labeled as the same material. This raises the question of whether it is possible to equate two layers of originally the



(a) *Raw WOB Data vs WOB Data Smoothed with a Rolling Median Filter*



(b) *Digital Core Layer Boundary Predictions - Graphic*

Layer Boundary	Predicted (cm)	Actual (cm)	Error (cm)
1 - 2	3.38	3.81	0.43
2 - 3	11.36	11.43	0.07
3 - 4	22.31	21.59	0.72
4 - ice	29.91	30.48	0.57

(c) *Digital Core Layer Boundary Predictions - Table*

Figure 10: *Final Digital Core Prediction*

same material prior to construction of the overburden. For example, in Figure 10, both layers 1 and 4 were made from the same clay. However, the bottom layer of clay was significantly compressed under the weight of the additional layers. PUDLE then measured a much higher WOB for the bottom layer of clay compared to the top. This indicates that comparison of what might originally have been the same material becomes less well defined in the context of its position in the overburden. However, the measured WOB still provides useful information about the requirements necessary to penetrate the material.

3 Tactical Plan

The plan for system operation was developed through operation analysis of each system test and has been condensed to the following:

1. Setup: The JET is aligned above a target location, software is booted, system checkout is performed, and the data logger is started.
2. Drilling: The system is lowered to the surface of the regolith, using the test-bed camera to identify the exact point of contact between the heated tip and the regolith. The operator configures a control scheme, setting a target WOB and a goal depth. On execution, PUDLE automatically jackhammers to the target depth. The operator supervises for any unexpected behavior and stops if necessary.
3. Drilling Data Export: After prospecting, the logged data is exported to a separate computer for digital core analysis, which occurs in parallel with the following steps of system operation.
4. Downwards Melt: Upon reaching the ice, the JET melts down by applying a downward force with the heater on. When the ice melts, the system reads a WOB reduction and automatically presses

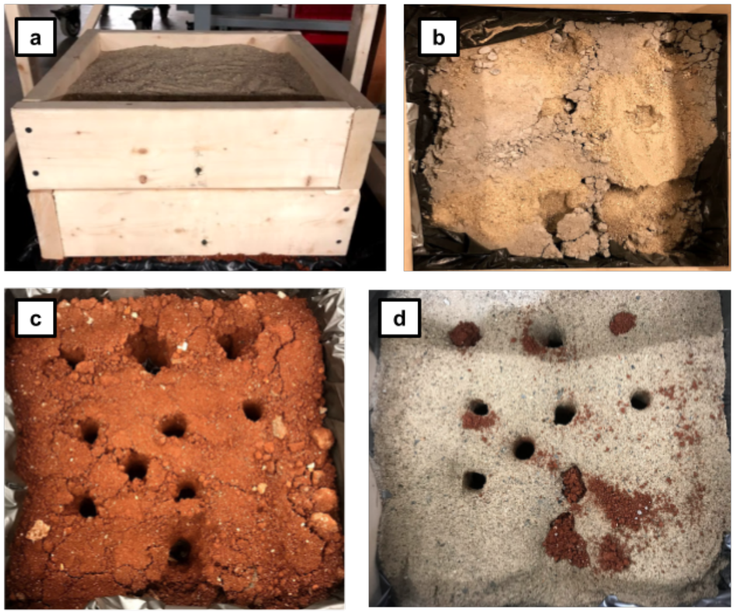


Figure 11: *Overburden penetration test setup (a) jackhammer holes in concrete (b), clay (c) and sand (d)*

down further to reestablish the weight on bit. This process is repeated until the tip is ∼15 cm into the ice.

5. Heated Tip Deployment: The tip stops moving downwards and begins to melt outward via the Rodwell method. The tip tensioner is disengaged to allow the heated tip to fall from the end of the JET, exposing the water inlet ports.

6. Rodwell and Extraction: The operator allows Rodwell melting to continue for ∼15 mins before engaging the pump to extract melt water. The heated tip is lowered to the bottom of the cavity such that it melts another Rodwell cavity lower than the previous. This is repeated until the bottom of the ice block is reached.

7. Additional Notes: The distillation system automatically engages when enough water is collected to fill the distillation tank, and runs in cycles automatically, during the Rodwell and extraction phase.

4 Safety Plan

To ensure the system runs continuously without posing dangers to itself or the operators, a number of safety precautions have been taken. Potential sources of danger include the jackhammer, high temperature components, and pressure vessels. To ensure all operators are safe, hearing protection is worn during jackhammer operation and safety glasses are worn when in the operating zone of the system. To ensure that no member is burned on a hot component, high temperature indication stickers are on all hot elements of the distillation system and the heated tip of the jackhammer has a temperature readout on the user interface. While the distillation system has an uninterruptible connection to atmosphere, a pressure relief valve and pressure gauge provide safety against dynamic pressure effects.

Regarding electrical safety, most components are located in a protective box to prevent any water or debris from causing a short. All components outside of the box have been covered in heat shrink and cable casings. Additionally, all the components that could draw high current and reach a high temperature are connected to current and temperature sensors. Lastly, the overall system is wired with a current sensor and connected to a 9 A fuse and an 8.5 A circuit breaker between the wall and the system.

5 Contingency Plans

Systems which are critical to the operation of PUDLE will have redundant parts brought to competition. Potential points of failure are cartridge heaters, the JET cable clamp, and any critical brackets. To ensure these issues do not cause any major problems during the challenge, there is a fully assembled replacement JET tip. Similarly, there will be a second fully assembled clamp ready to change out if there is a failure. A 3D printer will be on hand to reprint any broken components.

Funding Sources	
MMIP Challenge Stipend	$10,000.00
MIC 2018 Award	$3,000.00
Tutco High Durability Cartridge Heaters (Received in Kind)	$433.44
Funding Total	$13,433.44
Expenses (Prototype)	
Mechanical Components (Structure, stock material, fasteners etc.)	$2,778.31
Electrical Components (Motors, processors, wiring, etc)	$3,504.74
Test Bed Materials (Overburden layers, framing wood)	$155.64
Prototype Expenses Total	$6,438.69
Expenses (Travel)	
Forum Registration Fees	$1,650.00
Hotel Reservation	$1,297.92
Flight Costs	$1,207.90
Rental Car	$350.95
Estimated Return Shipping	$200.00
Logistical Expenses For Forum (Gas, Tolls, Misc. Items)	$293.23
Travel Expenses Total	$5,000.00

Figure 12: *Challenge Budget Breakdown*

6 Budget

Figure 12 breaks down the team budget for the development of PUDLE. In total $13,433.44 was obtained in funding. Given the cost breakdown from prototype construction and travel for the 2018 challenge the team allocated $5000 of provided funds to travel costs, leaving $5000 of the 2019 stipend for prototype development. The team set aside all the award funding from the 2018 challenge for development of PUDLE. A generous donation was also received from Tutco, who supplied high durability cartridge heaters used in the JET heated tip.

7 Path to Flight

7.1 General Spaceflight Considerations

7.1.1 Mechanical

All aspects of PUDLE's mechanical system will need to be made more robust in order to operate in an extraterrestrial mission. PUDLE is primarily made of aluminum and steel. While aluminum is often used in spacecrafts, steel is too heavy and would likely be replaced with titanium. The existing system elements are secured by bolts, screws, and clamps. All fasteners would need an additional locking element to resist vibrations during launch and landing, as specified by NASA fastener requirements [5].

The design of PUDLE is highly modular. The system can easily be transitioned into a flat packed configuration by removing the JET, distillation system and support beam. On Mars or the moon, the system can be reassembled by humans or robots.

7.1.2 Electrical

All of PUDLE's electrical components would need to be replaced for a viable mission to Mars or the moon. Instead of a combination of COTS single board computers, microcontrollers, and breakout boards to interface with electrical system components, custom electrical boards would be needed for all processing, communication, and I/O. Doing so would greatly reduce the footprint of the electrical system and enable use of optimized electrical components.

Various environmental factors affect the design of a flight-ready electrical system. Electronic components can be damaged when exposed to extreme temperatures, so the flight-ready design would need insulation from the hot and cold temperatures that exist in extraterrestrial environments. For operation on either Mars or the moon, all electronics would need to be housed in a radiation-hardened container. Additionally, heat cycling will be a significant issue in both environments and active temperature regulation will be necessary [6]. PUDLE would also need a power source, likely a radioisotope thermoelectric generator (RTG) or a solar array.

7.1.3 Software

To achieve water extraction on Mars or prospecting on the moon the software would have to be rewritten to operate on a resource constrained CPU, as dictated by the need for a radiation hardened processor. This will involve implementing software in lower-level languages like C, or potentially C++, and developing for a real time operating system to avoid the large overhead of most operating systems. Additionally, as all hardware and actuators would be replaced for a flight-ready system, drivers would have to be written for all new components.

7.2 Martian Water Extraction

7.2.1 Mechanical

The JET system has been specifically design with Martian conditions in mind. The maximum depth of the challenge test bed is 1 m. Therefore, system design for the competition has no need to reach greater depths. However, the Mars Reconnaissance Orbiter (MRO) has found evidence of ice scarps on Mars, shown in Figure 13, estimated to have depths of 100 m or more [1]. These depths are accessible given the extraction system's tethered design. The only limitation to depth of water extraction for PUDLE is the length of the cabling and tubing attached to the JET tip. The JET could be modified for operation on

Mars to access these deep deposits by lengthening the cable and changing the pumping technique. Due to the low atmospheric pressure on Mars, a pump which works by creating a vacuum inside the tube is incapable of drawing a large head. Therefore, it may be necessary to pressurize the pumping hole or add a pump near the JET tip to push water up the tube. By heating the water in the Rodwell hole, it may be possible to create a high enough vapor pressure to force water up the tube. The interface between the JET shaft and overburden would need to be sealed, but this may occur naturally by water vapor condensing and freezing to seal any gaps. Deeper ice deposit access increases the system's overall water collection potential, and less time needs to be spent drilling through overburden and transporting the JET between extraction sites.

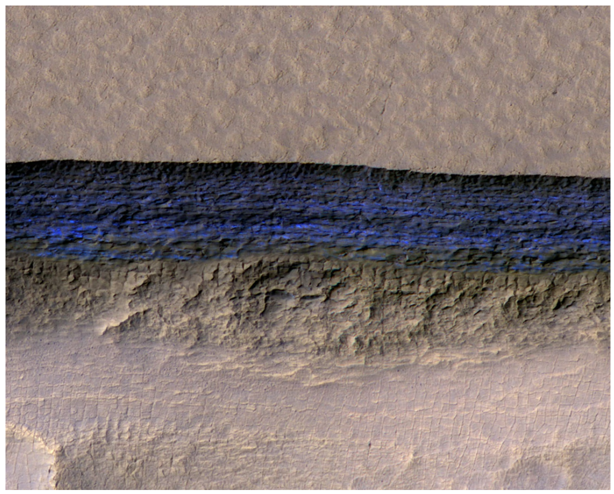


Figure 13: *False color image of Martian ice scarp taken by the HiRISE instrument on MRO [1]*

PUDLE was designed without an x-axis or y-axis movement system. This was done to reduce complexity for the purposes of the challenge, but also in anticipation of the system being mounted onto a mobile base. This makes the x-axis and y-axis movement irrelevant. If not mounted on a rover, the system can be picked up and moved to a different extraction location. Depending on the depth of the ice deposits, movement of PUDLE between extraction locations could be very infrequent.

PUDLE's distillation system is optimized for a transition to use on Mars. Atmospheric conditions affect the phase state of the extracted water. Mars' average surface pressure is 6.9 mbar and the surface temperature ranges from 183 K to 295 K [7]. This places Mars' surface atmospheric conditions near the triple point of water. Depending on weather, time of day, season, latitude, and altitude, slight variations in temperature and pressure will cause sublimation and vaporization of ice and water. Under typical conditions, liquid water cannot exist on the surface and solid ice will slowly sublimate. Thus, only a small amount of energy will be necessary to maintain a gaseous state on Mars, making the distillation system far more efficient. The ice deposits will likely be extracted as a water-vapor mix and the entire JET shaft will be heated to maintain this state. Depending upon performance of the system under these conditions it may be advantageous to forgo the distillation system entirely in favor of simple vapor extraction. Furthermore, distillation is a reliable form of filtration that will remove any potentially dangerous bacteria or viruses that may exist in Martian water after they have been thoroughly studied.

The multiple-effect distillation process provides additional benefits to reducing the power requirements of distillation, in the form of heat reclamation. This is important on Mars due to the difficulty of air cooling. The Martian atmosphere is very thin, so much higher flow rates are required for cooling performance similar to Earth. While the ideal case of a totally lossless system is thermodynamically impossible, it is plausible to significantly reduce the excess heat generated by designing a well-insulated multiple-effect distillery with several heat exchange stages.

7.2.2 Operations

In addition to these implementation changes, larger operational changes would have to be made for robust operation on Mars. Despite promising developments in robotic autonomy for IRSU, it is not realistic to implement full autonomy in the first water extraction system on Mars, primarily due to the lack of specific knowledge regarding Martian ice deposits [8] [9] [10]. The best implementation for an initial system would be a partially autonomous system that relies heavily on Earth-based analysis and planning to provide engineers and scientists opportunity to learn and characterize this unknown environment[11].

Implementation of an initial system like this should follow the same model of operation tested and validated on the MER and MSL missions [12]. This would consist of developing a command script style executor onboard the system to follow uplinked plans from Earth. This should be autonomous where possible to optimize the behavior of the system and allow for additional development of techniques for autonomous robots on Mars. Simulation software would need to be developed so mission planners can test and validate command plans before uplink to Mars. The simulation models would need to be constantly updated using digital core data from the system on Mars to pave the way for future systems with more autonomous functionality.

Additional water extraction systems would have to be implemented to obtain the amount of water necessary to sustain long-term Mars operations. With multiple water extraction systems operating simultaneously, and additional robotic agents transporting collected water, it is infeasible from human-power, time, and communications-bandwidth perspectives for operators to plan daily command scripts for every system. The system must instead be capable of operating with near-full independence. This should be accomplished through the optimization of the ground based modeling and simulation software. This software will have been validated and improved through the operations and data acquisition from the initial Martian flight system. On board running of these models will allow for the autonomous planning of system operations. In addition, the system must have a framework for communicating and optimizing its plans for the larger robotic team. Through these changes a multi-agent water extraction team will be capable of providing water for the support of human missions to Mars.

7.3 Lunar Prospecting

7.3.1 Mechanical

The largest concern in penetrating lunar regolith is properly constraining PUDLE. With a gravitational constant of 1.6 m/s^2, it would be far easier for the forces from the JET to dislodge the system [13]. A potential solution to this problem is to properly anchor PUDLE for stability during prospecting. Prospecting the lunar surface will also allow for simplifications of system complexity as components required for water extraction can be removed for a lunar deployment. Furthermore, the moon experiences extreme diurnal temperature changes, ranging from 95 K to 390 K. Materials must be robust to these changes and coefficients of thermal expansion would need to be considered [13].

7.3.2 Software

There are a number of advancements to data analysis that can be made for effective lunar prospecting. The Hidden Markov Model used for the purposes of this competition is intentionally unsupervised. Since the testbed composition is unknown, the goal is to explore and differentiate between layers of varying hardness. Using an unsupervised approach means the same data used to train the model is used to make a prediction. Through training, the model learns a set of emission probabilities, the function from a state to the measured WOB, and a matrix of transition probabilities, the likelihood of some material A to transition to another material B. In a supervised setting, the model is trained on a known sequence of material layers to learn these probabilities more accurately. By using a supervised approach, a more accurate lunar digital core can be inferred and substantiated by the current knowledge of the lunar surface.

To learn more accurate emission probabilities for the drilling telemetry of PUDLE, this model will be trained on a wide range lunar highland simulants to reflect materials present on the moon [14]. These emission probabilities will then be used to predict the subset of states present at a specific site on the moon. This provides evidence to which of the simulants exist at various locations and depths of the lunar surface.

Additional accuracy could be achieved through setting informed priors of the transition probabilities. Given no knowledge of the natural accumulation of sediment on the moon's surface, all transition probabilities are equal. However, if certain materials are known to appear together, higher transition probabilities can be assigned. More informed transition probabilities would allow the model to make smarter decisions at a layer boundary where it must assess whether a state change has occurred and into which state to transition. This would be particularly crucial in deciding between two materials of similar hardness that are not equally likely to appear beneath the previous layer.

While a supervised approach would yield very useful information about the lunar surface, the current model is still fairly limited. WOB serves as a good predictor of hardness, but that is the only feature for material classification. This model does not consider compositional variance that differentiates materials of similar hardness. Additional features that are independent of WOB would strengthen the model and allow classification of materials and layers beyond their hardness.

7.3.3 Operations

Operation of PUDLE for lunar prospecting requires much fewer changes than operations on Mars would require. This is mainly dictated by the relative closeness of Earth and the moon. With a much shorter communications delay between to the moon than to Mars, lunar prospecting can be closely controlled by Earth based operators. Additionally, lunar prospecting would require fewer systems to complete the mission, therefore allowing operation-based control with realistic human-power requirements.

8 Conclusion

This paper has detailed the design, testing, and validation of Northeastern University's Prospecting Underground Distilling Liquid Extractor, a robust solution to the 2019 RASC-AL Special Edition: Moon to Mars Ice & Prospecting Challenge. PUDLE's novel JET subsystem creates a single tool which can assess regolith layers, penetrate high strength materials, and ultimately melt and extract subsurface water. Use of Rodwell method allows this system to work efficiently for extended periods of time, ideal for supporting a long term mission. The distillation system is an efficient method for producing clean usable water and will be ideal in Martian atmospheric environments. These subsystems working in tandem creates, what this team believes to be, an ideal systems for Martian ice extraction and lunar regolith prospecting.

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