Final Report For The In-Situ Resource Extraction System

 

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Introduction

The In-Situ Resource Extraction System, or In-RES, was developed with the intent to bring mining engineering perspectives to the field of in situ resource utilization. Based on concepts from the mining and petroleum industries, In-RES uses heated sunflower oil to artificially create a water reservoir in a borehole. This oil and the resulting meltwater are then pumped out of the borehole and into a separation tank. The liquids differentiate in this tank based on density and are then either drained into a water collection tank or recirculated back into the oil reservoir. In-RES is designed for a human operator to physically deploy the system in a target area and control it with a laptop computer. Modifications to the drill's operating code could further allow the drill to be teleoperated once a human operator deploys the drill to its operational location. This flexibility makes In-RES a utilitarian design that can be modified to meet the requirements of a mission to Mars.

System Description

The In-RES drill rig has the freedom of movement to extract water from any point in a 1 m by 0.5 m area at a depth of up to 76 cm. During proof-of-concept testing, variations in injected oil temperatures and residence times generated varying amounts of extracted water. Final borehole design of the drilling and extraction system estimate that 687 mL of water can be extracted from a borehole. Extrapolating this behavior to a 1.5 hole per hour drilling rate to account for drill movement between hole locations, the In-RES drill rig is projected to produce 6.2 L of water during the competition.

Technical Specifications

The In-RES drilling system has an overall mass of 25.9 kg. The drill has a length of 0.95 cm, a width of 0.95 cm, and a height of 1.37 m. The drill stem has a length of 91.44 cm and a diameter of 3.81 cm, while the drill bit has a length of 5 cm and a diameter of 3.81 cm. The drill moves in the x- and y-directions at a speed of 96 cm/min., while it moves in the z-direction at a speed of 0.02 cm/min. into the borehole and 0.3 cm/min. out of the borehole. The drill uses a weight-on-bit (WOB) of 50 N and a speed of 437 RPM, while its stall torque is 22 kgf-cm. In-RES uses a Raspberry Pi 3 Model B V1.2 as its on-board computer. This Raspberry Pi controls each of the x-, y-, and z-directional motors using an Arduino Mega for each motor. A human operator controls the movement, drilling action, and pumping of the drill system using the Raspberry Pi terminal on a laptop as the user interface. A Midwest Motion PS-450 power supply provides all of the power required in DC from a provided 120V AC, 10 A outlet.

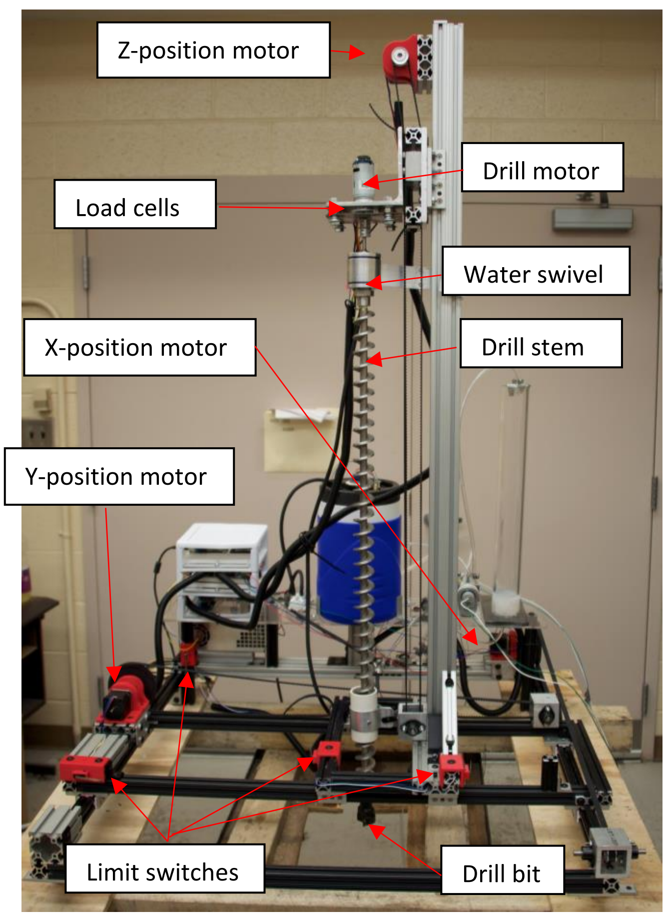
Mounting System

The drill rig attaches to the mounting platform using four angled pieces of aluminum. Each piece of angled aluminum is bolted to a support strut that rests on the mounting platform. Wood screws drilled through holes in the angled aluminum anchor the drill rig to the mounting platform. This system has thus far successfully secured the rig during drilling operations.

System Excavation and Overburden Removal Operations

The drill rig excavates regolith from a drilling site using an 91.44 cm long drill stem with a 3.81 diameter at a rotational speed of 437 RPM. During drilling operations, the operator first inputs the distances that a drill should move in the x-, y-, and z-directions, as well as the drill's rotational speed. The drill will then move the desired distances in the x- and y-directions and begin drilling in the z-direction. Entering the z-direction drilling depth in small increments allows the operator to control the drill's descent as it approaches the overburden-ice interface. When the load cells peak above the average of 50 N WOB for regolith, the drill is assumed to have reached the ice. At this point, the drill stem spins without drilling further into the ice in order to convey all of the regolith cuttings out of the borehole.

Regolith cuttings conveyed out of the borehole are deposited by the auger drill stem on the surface of the test bed around the borehole. Based on a borehole diameter of 3.8 cm and an estimated overburden depth of 50.8 cm, each borehole will remove roughly 2,305 cm^3 of overburden. Boreholes are therefore drilled in a grid pattern with a center-to-center spacing of 12.5 cm to maximize water extraction from each borehole while minimizing the potential for cuttings to fall back into a borehole. Because the drill never leaves the borehole until drilling and ice extraction is complete, the drill stem acts as a casing for the borehole during water extraction. Collapse of the borehole or regolith cutting contamination from the surface spoil piles, therefore, will be mitigated by the drill stem's presence during extraction operations.



In-RES drill system layout

Control System and Datalogger

The control system consists of two Arduino Mega 2560s and a Raspberry Pi 3. The Arduinos are programmed specifically for the operations they will handle, and are broken down into a drill control Arduino and a relay control Arduino. The Raspberry Pi acts as the master controller, relaying inputs from the operator, to the Arduino, while also displaying sensor information and operational status to the remote display. The Raspberry Pi also acts as a data logger for the system by logging the WOB for later review as a .txt file. The motor control Arduino provides commands to three Pololu A4988 Stepper Drivers and a Pololu Simple High Power Motor Controller, which in turn directly control the motors. The Arduino also reads the encoder information from the drill motor, the data from the load cells mounted on the drill platform, and the states of the position limit switches. On startup, the steppers will pull the drill towards the "home" position where they will stop once the position limit switches are activated. Upon receiving coordinates input by the user into the Pi, the Arduino will activate the stepper drivers and count the steps to determine when the final position is reached. The Arduino will drive the drill z-position stepper upon reaching the drill position and run the drill motor at the rotational speed determined by the operator. Once drilling is complete, the Arduino is ready to move to a new position. The drill will not move in x- or y-directions, however, unless the z-direction upper limit switch is pressed to ensure the drill stem is above the ground.

The z-direction travel speed is regulated as a function of the drill RPM and the WOB. As the encoder relays data that the drill's RPM has been slowing while drilling, the drill z-direction stepper motor will slow down. If necessary, the stepper will even come to a halt until the drill has cut enough of the surrounding regolith or ice to continue advancing down the borehole. The WOB is measured using two load cells mounted on the drill platform. As the drill pushes down onto the ground, the reaction force pushes back on the platform. This platform, in turn, pushes against the load cells mounted to the rigid column, and so provides a force reading for the WOB.

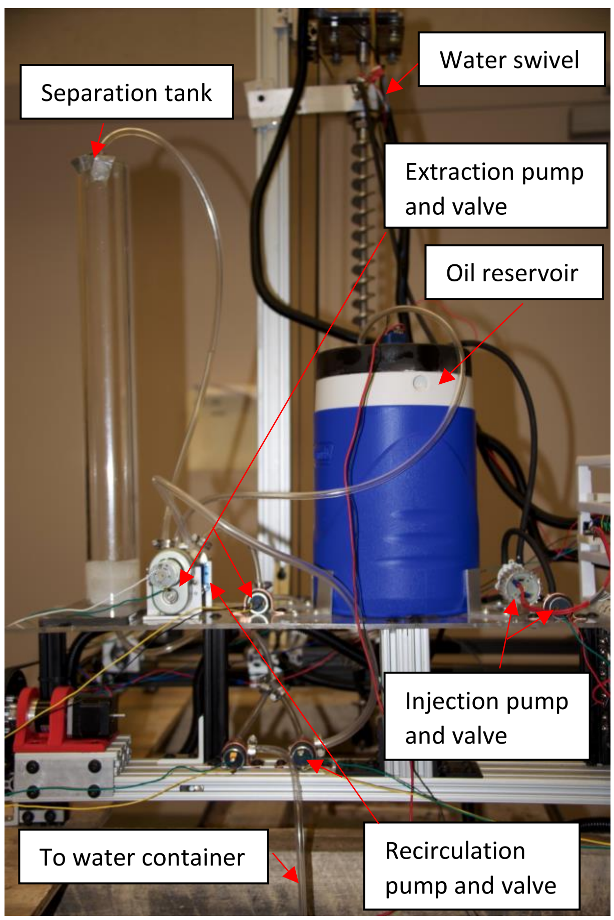
The relay control Arduino operates a series of single pole double throw (SPDT) relays which activate the pumps, and open/close valves. These valves and pumps are turned on and off through the use of an "injection/extraction protocol" that stipulates the order and length of time for which each component is energized. This Arduino also controls the heated oil reservoir. A high temperature, waterproof DS18B20 digital temperature sensor and a proportional, integral, derivative (PID) control scheme are used to control the operation of an immersion heater. This control ensures a constant reservoir temperature of 85°C and allows the heater to turn on or off as necessary to regulate the temperature.

Water Extraction, Filtration, and Collection System

Following the removal of regolith cuttings out of the borehole, the drill again begins to drill downwards in the ice until it has traveled an input depth of 7.5 cm in the z-direction. The drill rotates in ice at a speed of 437 RPM during this drilling operation to prevent the drill from freezing to the ice. Once the drill has reached the 7.5 cm depth, the drill is moved to the regolith-ice interface in preparation for heated oil injection. The injection system pumps 145 mL of oil at 85°C through the open injection valve, the water swivel, the hollow drill stem, and into the borehole. This oil will reside in the borehole ice for 3 minutes to maximize the melted volume of ice while minimizing the potential for the water to re-freeze.

Once the 3-minute oil residence time has passed, the drill stem is lowered in the z-direction until the load cell reports a load, thereby indicating that the stem has reached the bottom of the borehole. Oil and water are then pumped out of the borehole and through the drill stem using the extraction pump. These fluids pass through the open extraction valve to the filtration and separation tank. The filtration screen, located at the top of the separation tank, removes all particles larger than 125 µm and allows the oil/water mixture to flow down to the separation tank. In the separation tank, the oil/water mixture separates over a period of successive injections and extractions to maximize the volume of collected water. This larger volume then ensures fewer water bubbles are entrained within the oil. The water collection valve is then opened and the water allowed to gravimetrically drain into a collection tank. As the last of the water is drained, the water collection valve is closed and the oil recirculation valve is opened. The oil recirculation pump then pumps the oil back into the oil heating reservoir for reheating.

Each borehole is subjected to multiple oil injections and extractions. After the initial injection and extraction operation, 145 mL of oil is again injected into the borehole for 3 minutes. This volume can be further increased depending on the volume of water extracted from the previous extraction operation. The drill stem is again lowered to the bottom of the hole and the oil/water mixture pumped out of the borehole. This process repeats until the drill stem has reached its maximum total depth of 76 cm. Once the drill reaches its maximum depth and all fluids have been extracted from the borehole, the drill stem is raised out of the borehole. The drill then moves to the next target location identified in the drilling pattern by its distance in the x- and y-directions from the previous borehole.



Water extraction system

Challenges and Design Changes/Improvements

A primary design challenge since the mid-project review focused on the type of water swivel used on the drill rig. The initial water swivel was based on an existing swivel design used in rock coring drills. A spindle, or the rotating part of the swivel that connects the motor shaft and drill stem, was machined in-house from brass to minimize the water swivel's weight. During implementation, however, the water swivel housing was prone to moving along the length of the spindle, rather than maintain a fixed position relative to the spindle. An attempt to correct this movement resulted in the swivel housing moving off of the spindle during drilling, shredding its seals in the process. The brass spindle subsequently could not generate a seal so that oil and meltwater could be pumped from the borehole.

This series of events led to the procurement of a new, custom-designed water swivel fabricated for this specific application from an equipment vendor. This new swivel uses a ¼" shank that is connected to the ¼" drill motor shaft using a ¼" coupler. The water swivel rotates at a maximum speed of 450 RPMs and is rated for 130°C temperatures. Additionally, the new swivel threads directly onto the drill stem. The new swivel's smaller size and robust design have allowed it to generate the required seal and permit both the injection and extraction of oil and meltwater.

Another challenge encountered since the mid-project report has been the drill bit design. The original bit design utilized a bolt that was split in half so that two cutting heads were created on the bolt shaft. While this bit cut through both ice and soil around the borehole perimeter, the cutting heads did not cut material at the center of the borehole due to their orientation. This created a "coring" effect in the regolith that the auger was unable to convey out of the hole.

A second bit was therefore designed to cut all of the material in the borehole based on a spade bit typically used with a handheld drill. This bit was able to cut through both regolith and ice while generating a more circular borehole. However, the 3 in. length of the spade bit meant that there would be 3 in. of ice cuttings/meltwater that could never be extracted since the oil/water extraction inlet was located where the bit threaded onto the drill stem. As a result, a third drill bit was designed with a low profile, the ability to filter particles larger than 3.2 mm from entering the drill stem, and the ability to easily cut through frozen regolith. This third bit is a modified bit from a mine roof bolter and has a tungsten carbide tip that can nominally cut through sandstones and other hard rock. This bit has thus far drilled through frozen regolith, damp regolith, and ice.

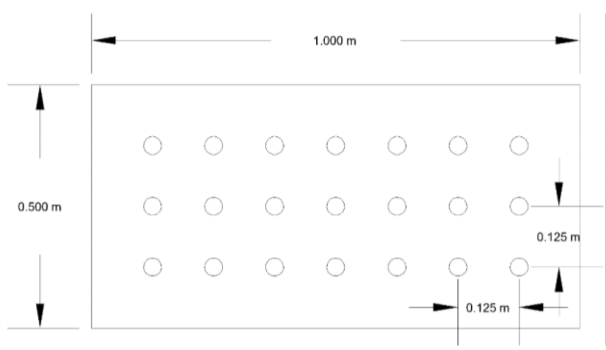
The final challenge encountered has been creating a watertight seal at the base of the oil reservoir. The heating element for the oil was installed at the bottom of the reservoir to maximize the volume of oil in which the element is submerged. Installing this element at the bottom of the reservoir created numerous leaks through the bottom of the oil reservoir whose sources were not easily identifiable. Pipe fittings and joint compound sealed the leaks occurring along the heating element, while leaks from the inside of the reservoir were sealed with silicone caulk. After sealing the components with several layers of silicone, the reservoir still leaked. As a result, a new reservoir was purchased in order to heat the oil from the top of the reservoir, thereby negating any potential problem with leaks. Further development of a custom-fabricated oil reservoir is being pursued in order to provide a final satisfactory product.

Overall Strategy for the Competition

The drill will move through the regolith layer at a rate of 0.02 cm/s until it reaches a depth of 11.4 cm, at which point the drill will be raised by 2 cm to relieve the confining stresses on the drill stem from the surrounding regolith. The drill will lower to the bottom of the borehole and resume drilling for another 11.4 cm or until the drill begins to stall in the borehole. This process will continue until the drill reaches the ice layer.

A change in the WOB will serve as an indicator for when the drill reaches the ice layer. After drilling an initial depth of 7.5 cm into the ice, the drill will be raised to a depth of 2.5 cm below the regolith-ice interface and the extraction process will begin. Oil will be pumped into the borehole until reaches the drill bit. After the oil resides in the ice for 3 minutes, the mixture of oil and water will be extracted. Oil will then be pumped into the ice once again to an ice depth of 2.5 cm and the extraction process will continue until a maximum drill depth of 76 cm has been reached, the ice fractures, or the separation column is filled with fluid. If the separation column is filled before maximum drill depth is reached, extraction operations will cease until the separation process is completed. When the max drill depth is reached or if the ice fractures, the drill will move out of the borehole and to the next location.

Since the oil will widen the borehole within the ice to an unknown diameter, the spacing of boreholes from each other will be 12.5 cm in order to provide enough space for the regolith cuttings. The adjacent boreholes have to avoid drilling into the cavities produced in the ice and maintain the structural integrity of the ice so that no fractures link two boreholes together. Such an occurrence could otherwise lead to oil losses in the ice block. This same spacing will also be used from the edges of the viable drilling area. The resulting drilling pattern will be a 7 x 3 grid of boreholes in the designated drilling area. In order to optimize time, the drill will not begin drilling a second borehole until all injection and extraction operations for its current hole have been completed.



Drilling pattern for ice excavation boreholes

Summary of Integration and Test Plan

Testing to date has thus far focused on synchronizing the drill stem's advancement rate and rotational speed to improve its drilling and regolith conveying abilities. The drill has thus far succeeded in drilling 8.9 cm in frozen regolith and 11.4 cm in wet regolith before the drill motor stalls. No stalling occurred in ice, where the drill was able to reach a depth of 8.9 cm. During these drilling tests, the z-direction motion belt repeatedly skipped its rotations and deformed. This phenomenon did not occur during previous drilling operations, and so it is thought that the belt fatigues quickly during drilling operations.

The low weight on bit of the system of 50 N, meanwhile, is thought to originate less as a failing of the stepper motor to “drive” the drill and more as a result of the mass of the drill stem, drill bit, water swivel, and drill motor. As a result, alternatives to this belt design that increase the WOB and eliminate the skipping problem are currently being pursued. Specifically, a metal roller chain design is currently being considered to replace the z-direction belt assembly. Additionally, two motors are being purchased to allow for further experimentation with drill torque and speed to improve the drill’s cutting ability. The first motor has a rotational speed of 1,621 RPMs and a stall torque of 7 kgf-cm, while the second motor has a rotational speed of 165 RPMs and a stall torque of 680.5 kgf-cm. The testing scheme below will identify which motor and operating condition will convey the most amount of regolith out of the borehole, thereby improving overall drill performance. Additionally, these tests will identify the time required to drill in the regolith to the ice so that a more accurate estimate of drilling time per borehole can be calculated.

165 RPM motor	437 RPM motor	1621 RPM motor
Half speed	Half speed	Half speed
Full speed	Full speed	Full speed

Drill test in moist regolith

Drill test in ice

The injection and extraction system has thus far been tested for operability and to identify points for improvement in the system layout. One round of injection and extraction operations found that all valves and pumps operate as planned within the system. Oil with a temperature of 65°C was successfully pumped from the oil reservoir down the drill stem into an icy borehole. This oil was then successfully pumped out of the borehole, into the separation tank, and successfully recirculated into the oil reservoir. During this test, the oil a) was much cooler than desired for injection, and b) resided in the icy borehole for too long (5 minutes vs. the desired 3 minutes), leading to a further decrease in oil temperature and the potential for freezeback. As a result, water was not extracted from this operation.

Future ice tests are planned to test the amount of water extracted at 85°C after 3 min. and 5 min. of residence time to identify the length of time necessary to melt the ice at this temperature. Additionally, it was found during ice drilling that drilling in the presence of some oil greatly improves the drill's ability to cut the ice. As a result, a test is also planned to examine what effect, if any, injection during drilling operations will have on the volume of extracted water.

Tactical Plan for Contingencies/Redundancies:

Several potential failure points exist in In-RES that could lead to inferior drill performance or failure. These failure points include extraction system clogs; a loss of oil to the test site; a stalled drill stem; failure to drill through regolith; and a miscount of the motor steps. Clogs may occur when large particles become lodged at the drill bit inlet, near valve inlets, and within the drill stem or tubing. These particles will likely be smaller than 3.2 mm when inside the drill stem due to the small drill bit inlet size. Additionally, all particles will be filtered out prior to entering the separation tank. Blockages that occur near valve or in the tubing/drill stem, therefore, are the primary concern. These blockages will be mitigated by opening the water drainage and extraction valves and purging the lines of blockages by pumping the extraction pump in reverse. Hose clamps around each inlet/outlet will prevent hoses from blowing loose during these purges.

Downhole oil loss to cracks in the ice is another concern since the oil is a finite resource. The key indicator for oil loss during injection and extraction operations will be the failure to extract the meltwater and injected oil from the borehole. If this occurs, the drilling operation for that borehole will be terminated and the drill will be extracted from the borehole. The drill will then move to the opposite side of the testing area and drill a new borehole.

Two key failure points during drilling operations are the potential for the drill to stall in ice or fail to drill through material. The latter case is a highly unlikely scenario. However, should it occur, drilling operations for that borehole will be terminated and the drill will move to a different location to drill a new borehole. A stalled drill stem is likely to be caused by aggregate particles lodged in the side of the borehole that cannot be conveyed out of the borehole. Alternatively, the auger can become choked if the rate of penetration is too high for the auger to convey all of the material out of the borehole. Finally, stalling could also occur if the drill operates at a high speed in the ice. A stalled auger will be overcome first by attempting to rotate the drill in the reverse direction and moving the stem out of the borehole. In the event that the drill is stalled in the ice, hot oil will be pumped into the drill stem to melt the ice surrounding the trapped bit. The drill speed will then be lowered to increase the drill's torque and drilling/injection operations will continue.

The final failure point, a slippage of the belt across the motor hub that is not counted among the motor steps, is less severe than other failures. If the belt appears to be slipping, or if the drill rig/stem are not moving the proscribed distances entered into the computer, the drill stem and rig will be moved by manually entering distances until they reach the "home" position, i.e. the x+, y+, and z+ limit switches are all triggered. The drill will then move a test distance in each direction and compared to markers along the axes of movement to identify the amount of slippage. This slippage will then be included in future movement calculations so that drilling operations can continue.

Project Timeline

The remaining days until the competition will be used to implement the possible changes to the z-motor belt system as well as tests for the optimum motor condition and residence time. These tests are scheduled on the Gantt chart below:

Testing Schedule	5/31 – 6/5	6/6 – 6/11
Oil residence time		
Z-direction belt replacement		
Motor operation testing		

Safety Plan

Safety considerations for In-RES can be broken down into three categories: chemical, mechanical, and burn/shock. The primary chemical consideration is the heated oil used to melt and extract meltwater. The oil used for this application, sunflower oil, is a vegetable oil selected for its low pour point. As a vegetable oil, this chemical is generally nontoxic to humans. While sunflower oil has a smoke point of 125°C, the heating element will only heat the oil to a temperature of 85°C and will shut off at a temperature of 100°C. As a result, the oil will never approach the temperature required for ignition. Because vegetable oil is regulated under the same conditions as petroleum products, a secondary containment system will be installed around the testing area. This will prevent any potential contamination into the surrounding environment.

Burn and shock hazards exist due to the presence of the heating element and the energized drill rig. Mechanical risks, meanwhile, consist of pinch points along moving components such as belts, hubs, shafts, the drill stem, motors, and mobile sections of the drill rig structure. De-energizing the drill rig prior to performing any necessary maintenance or corrections will prevent most of these hazards. Using thermally insulated gloves around the oil reservoir and injection equipment, meanwhile, will prevent any burns that might occur. The heating element is always submerged in oil inside the oil reservoir, and so no direct contact will ever occur with this component. To fight any potential fire, the drill rig will first be de-energized to shut down the source of the fire (if electrical/heating element). A fire extinguisher will then be used as necessary to put out the fire.

In addition to these measures, limit switches backed by physical stops are incorporated in the drill rig's design to prevent any motion beyond the intended working area. An emergency stop has also been installed to immediately shut down the drill if a catastrophic failure with any of the components occurs. This will protect all personnel from physical harm while also mitigating any physical damage done to the drill.

The Path-To-Flight for the In-Situ Resource Extraction System

The In-RES system is based on concepts derived from the mining and petroleum industries. It combines the use of a hollow drill stem and water swivel with the use of a working fluid to enhance production in a target formation. These two ideas came together to inspire the overall design for a Martian drill that uses a heated fluid to melt and extract ice. Independent of this design process, reviewer comments from the initial In-RES proposal brought the concept of a Rodriguez well, or Rodwell, to the team's attention. Subsequent review of Schmitt and Rodriguez (1962) and Haehnel and Knuth (2010) revealed the potential variation in meltwater reservoirs shapes depending on the level of heat flow into the ice. Additionally, these works identified freeze-back as a potential result of employing a Rodwell design at the scale at which In-RES operates. Subsequent testing of different configurations of oil temperature and residence time in ice found that a long residence time can lead to the fluids re-freezing, resulting in decreased water extraction. This phenomenon, in turn, led to the initial selection of a 5 min. residence time for the oil.

The In-RES concept provides numerous avenues for future development in order to customize the drill rig to meet the specific demands of a mission to Mars. The current configuration is arranged for a full-sized or scaled-up drilling rig to be deployed with a human operator on-site to control the drill. In a Mars mission where teleoperation from Earth or a fully automated drill rig is desired, the drill's programming would be further developed to incorporate this control scheme. A general operating protocol would first be developed to identify a "home" position; the default spacing between boreholes; the appropriate drilling speeds for regolith and ice; and the pump and valve sequences required for oil injection and extraction. This reconfiguration would require the inclusion of a pH sensor at the bottom of the separation tank. The pH sensor would then identify if all of the water in the separation tank had been drained from the tank based on the surrounding liquid's pH. Additional sensors, such as a force-torque sensor on the drill's motor shaft, would record the drill's performance independently of the load cells. These two streams of information would then provide feedback to the drill on the drilling medium and if it had entered ice, for instance, or was simply stalled against an entrained piece of aggregate. Further protocols would require development to address contingencies such as mitigation of a stalled/choked drill stem, the loss of oil in ice cracks, and clogging within the injection system. One challenge that would be difficult to overcome in an automated In-RES design is the filtration system. Currently, the 125 µm mesh is cleaned when necessary by the drill operator. Since this would not necessarily be an option in an autonomous setting, an alternative method of cleaning the particles from the screen will be required. This could involve a rotating brush that scrubs the particles into a collection bin that periodically empties onto the Martian surface.

The key to the operation of In-RES is its utilization of a hollow drill stem and heated working fluid to extract subsurface ice. This configuration avoids the need for increased design complexity to rotate a drilling system out of the borehole and the melting system into the borehole. The injection oil is the system's lone potentially consumable component, and therefore should be further investigated for potential in-situ substitutions. A heated, briny water, for instance, might perform a similar role while having the benefit of existing in-situ on Mars. Ambient Martian atmosphere condensed and heated in a storage tank similar to the In-RES oil reservoir could likewise provide the heated working fluid for extracting ice from the Martin subsurface.

Further development for flight would require optimization the drill stem's design in order to create a low-friction surface while identifying the proper flight pitch, thickness, and width to most efficiently convey regolith out of the borehole. Modifications to this design would then require alterations to the drill's operational RPMs in order to ensure the minimum speed required to convey particles has been met (Zacny and Cooper, 2007). Additionally, the drill bit should undergo further modification to minimize the distance between the cutting tip and the first auger flight in order to improve the efficiency of conveying regolith cuttings. An optimum design could rely on the 0.64 cm- thick tungsten carbide cutting bit welded directly to the drill stem, rather than the entire 5 cm drill bit that threads onto the drill stem.

Mars will be an operating environment with a unique set of challenges for a robot developed on Earth. Perhaps one of the greatest challenges that a water extraction mission would face is the potential sublimation of water ice exposed to Mars' surface atmosphere and temperature. Water has vaporization pressure of 600 Pa at 0 °C, while Mars' atmosphere is at a pressure of 600 Pa and a temperature range of -195°C to 20 °C with an average temperature of -60°C (Engineers Edge, 2017; Sharp, 2012). As a result, water ice exposed to these conditions would directly sublimate into water vapor and would be lost during extraction. The In-RES system addresses this loss through its use of heated sunflower oil. While very little information currently exists on the triple points of vegetable oils, what information can be garnered has identified the vaporization pressure of these oils as being low enough to effectively approach 0 kPa (Engineers Edge, 2017). During water extraction operations, the heated injection oil floats on top of any liquid water generated while filling the icy section of the borehole. This, in effect, creates a "cap" that will insulate the ice from the atmospheric conditions and prevent sublimation. The oil level in the icy borehole, however, can lower in elevation as the oil melts deeper into the ice and the generated meltwater shrinks in volume from its previous size as ice. Ensuring the icy section of the borehole is completely submerged in oil during the continuous injection and extraction operations for that borehole will minimize the amount of time that the sides of the borehole are exposed to the atmosphere. Once the drill moves to another location, this borehole can then be allowed to sublimate into the atmosphere. Alternatively, further development of a pipeline system could direct the sublimated ice exiting this borehole to a central collection tank as part of a passive water extraction system using Mars' own atmosphere and temperature in its favor.

While temperature plays a role in the process of ice sublimation, it can also directly affect the performance of the In-RES system. Because of Mars' extreme temperature range, the drill rig will need to be constructed of metals and plastics that will not experience brittle failure from operating at these temperatures or from the thermal stresses induced by the changes in temperature in the drill rig. Aluminum's resistance to low temperature effects mean that most of the drill's structure can be fabricated from this metal. Sensitive components, such as the motors, sensors, motor controllers/Arduinos, Raspberry Pi, and the computer used to control drilling operations will all require encapsulation/insulation to protect them from the low temperatures of Mars. The separation tank will similarly require insulation in order to prevent meltwater from freezing at the bottom of the tank.

All injection/extraction tubing and pumps will require the use of a tubing material (potentially Norprene) rated for the low temperatures of Mars to prevent freezing in the lines. This material will also be required to withstand the high temperatures at which In-RES will be operating. One solution to this challenge is to use a heat-resistant tubing for all injection lines since the heated oil will prevent those lines from reaching ambient temperatures. A low temperature-resistant material could then be used in all extraction applications since the oil will have cooled in the ice. Additionally, the water swivel system relies on two seals to ensure that the spindle connected to the drilling motor and the drill stem can rotate freely while preventing leaks of oil and water. These seals are currently rated for use in temperatures exceeding 130 °C. However, the lowest operating temperature of the seals is currently unknown. These seals will require confirmation of their applicability for use in the low temperatures of Mars or replacement with a more resilient seal material.

Another potential hazard that could affect In-RES' performance is the effect of fine particles suspended in the air. Claudin and Andreotti (2006) discuss how most particles smaller than 100 µm can be suspended in the air with a wind speed of 150 km/h., while NASA has previously stated that the highest wind velocities experienced on Mars are roughly 60 mph (Mersmann, 2015). Using this speed and the model from Claudin and Andreotti (2006), one finds that particles of 50 µm or smaller can be suspended by this wind. This suspension of particles and the particles' electrostatic nature mean that any drilling system used on Mars will become covered in a thin layer of dust. This dust could cause problems with the drill's motion system by jamming the rail system along which the drill's linear bearings translate, thereby preventing motion. While the linear bearings currently in use are designed to be operable with dirt and water present in the rail system, these bearings should be tested under vacuum conditions in a dusty environment in order to confirm their usability on Mars.

Dust poses a second hazard to In-RES' pumps. The peristaltic and geared pumps used on In-RES are generally enclosed by an outer shell. There are, however, several small openings on each pump used to vent heat generated during the operation of the pump. These openings, however, are also pathways through which dust could enter the pumps and clog the rotation of the pump's rotors and gears. These openings will therefore require shielding to prevent any particle infiltration.

Power limitations on Mars provide a dynamic set of challenges to the operation of any robot. In-RES incorporates 12VDC throughout the drill layout in order to streamline its power distribution system. This voltage, however, generates temperatures approaching 37°C around the Arduino and motor controllers. These components will also require radiation hardening to protect them from the effects of solar radiation. One benefit to working on Mars, therefore, could be using Mars' low temperatures to provide a low-energy method of cooling the electronics. The creation of an enclosed area for the electronics, motors, and pumps that is surrounded by a thermally conductive metal could provide a low-energy method cool these devices by using the external Martian atmosphere as a heat sink. This metal casing could then act as a shield against UV rays in addition to the steps taken to harden the electrical components against radiation.

A final, more general step that will be required on In-RES' path to flight is the standardization of components and units across the drill system. Due to the nature of using off-the-shelf motors and components for the construction of In-RES, some subsystems utilize the Imperial system of measurement while other utilize the metric system. Development of In-RES for flight must include the replacement of all Imperial system-based components and hardware with their approximate metric equivalents. This would affect the construction of the drill bit, drill stem, water swivel, and drill motor in particular since these components use the Imperial system in the In-RES prototype.

Budget

This project has been sponsored and supported by the West Virginia Robotic Technology Center at West Virginia University. The In-RES team has operated within the Mars Ice Challenge Development Award's allotment of $10,000, and so has not required any external funding. JENNMAR, a mine roof and ground control company, donated six drill bits each valued at $20. The Benjamin M. Statler College of Engineering and Mineral Resources donated the workshop space required for fabricating the drill, as well as aluminum sheet metal, ¼" bolts and nuts, and two 5-gal. buckets, and a bag of marble chips.

Drill Design and Construction Budget				
Manufacturer	**Model No.**	**Component**	**Quantity**	**Unit Price**
Pololu	2487	Pololu Basic 2-Channel SPDT Relay Carrier with 12VDC Relays (Assembled)	3	$8.25
Pololu	2482	Pololu Basic SPDT Relay Carrier with 12VDC Relay (Assembled)	3	$4.95
Simply Pumps	GM2012	GM2012 12 V Self-priming gear pump	1	$87.00
Dernord	605155	Submersible Water Heater Element Stainless Steel w/ 1 in. NPT Flange 12v 150 W	1	$22.99
Coleman	1403	1 Gallon Jug, Red	1	$6.92
Phidgets	RB-Phi-267	12V, 1.7A, 667oz-in NEMA-17 Bipolar Stepper Motor	3	$48.00
Pololu	RB-Pol-176	Pololu 8-35V 2A Single Bipolar Stepper Motor Driver A4988	3	$5.95
ServoCity	638330	437 RPM HD Premium Planetary Gear Motor w/Encoder	1	$59.99
ServoCity	605062	18v25 Simple Motor Controller	1	$54.99
Adafruit	191	Arduino Mega 2560 R3	3	$45.00
Adafruit	3055	Raspberry Pi 3 Model B	1	$40.00
American Science and Surplus	BCBI6683	12 V Normally Closed Solenoid Valve	6	$3.75
Simply Pumps	FT316	Clear PVC tubing, 3/16 ID, 5/16 OD	5 m	$1/ft.
Adafruit	1311	Hook-up Wire Spool Set - 22AWG Solid Core - 6 x 25 ft	2	$15.95
Adafruit	642	High Temp Waterproof DS18B20 Digital temperature sensor + extras	1	$14.95
Simply Pumps	TS200N	Norprene Industrial Tubing 3/16" ID 10 Feet Long	1	$13.95
ServoCity	545624	1.5"-0.770" Pattern Adaptor	4	$4.99
ServoCity	545388	Face Tapped Clamping Hubs, 0.770" Pattern with 8mm bore	4	$5.99
ServoCity	615394	Timing Hub Pulley	4	$7.99
UKAM Industrial Superhard Tools		Water swivel adapter, ¼" strait shank with thread: ½"-13 TPI female; 212 °F temperature rating	1	$469.70
Auger Fabrication, Inc.	SK-12988	1-1/2" OD, ¼" ID, 1" pitch, 36" long Auger, tac welded with end threads: ½"-13 TPI male	1	$458.00
ServoCity	607066	PH Series JST 6-pin connector (2mm Pitch)	5	$0.79
ServoCity	605155	Screw Terminal Block	10	$0.99
Pololu	1403	Snap-Action Switch with 50mm Lever: 3-Pin, SPDT, 5A	10	$0.95
Pololu	2198	ACS711LC Current Sensor Carrier -25A to +25A	1	$3.95
Pololu	2452	ACS711EX Current Sensor Carrier -15.5A to +15.5A	5	$3.95
Sparkfun	13331	Load Cell - 50kg, Disc (TAS606)	2	$56.95
Sparkfun	13879	SparkFun Load Cell Amplifier - HX711	2	$9.95
Midwest Motion	MMP PS450W-12V	450 W 12 VDC Power Supply	1	$196.00

ServoCity	615428	Timing Belt Pulley for 8mm shaft, belt width<3/8", and 1/5" pitch	10	$8.99
ServoCity	615152	10mm width timing belt	32 ft	$3.59/ft
McMaster-Carr	47065T831	T-Slotted Framing, Corner Bracket for 1" High Single Rail, Black	10	$5.60
McMaster-Carr	47065T239	T-Slotted Framing, Extended Corner Bracket for 1" High Rail, Silver	10	$5.85
McMaster-Carr	47065T255	T-Slotted Framing, Straight Bracket for 1" High Single Rail, Silver	10	$6.75
McMaster-Carr	47065T259	T-Slotted Framing, Extended Straight Bracket for 1" High Rail, Silver	10	$6.74
McMaster-Carr	47065T186	T-Slotted Framing, Diagonal Brace for 1" High Single Rail, 6" Long	2	$15.67
McMaster-Carr	47065T218	T-Slotted Framing, Corner Brace for 2" High Double and Quad Rail, 2-5/8" Long	2	$19.51
McMaster-Carr	47065T501	T-Slotted Framing, Quad Rail, Silver, 2" High x 2" Wide, Solid, 6 ft. length	1	$59.37
McMaster-Carr	47065T107	T-Slotted Framing, Double Rail, Silver, 2" High x 1" Wide, Solid, 6 ft. length	1	$33.95
McMaster-Carr	47065T503	T-Slotted Framing, Single Rail, Black, 1" High x 1" Wide, Solid, 10 ft. length	6	$50.63
McMaster-Carr	47065T959	Bearing for 1" Width Rail, Base-Mount, 1-7/8" Length T-Slotted Framing	8	$46.16
McMaster-Carr	47065T964	Bearing for 2" Width Rail, Base-Mount, 1-7/8" Length T-Slotted Framing	2	$63.07
McMaster-Carr	47065T142	T-Slotted Framing, End-Feed Fastener, for 1" High Single Rail	30	$2.30
McMaster-Carr	47065T139	T-Slotted Framing, Compact End-Feed Fastener, for 1" High Single Rail	10	$1.85
McMaster-Carr	47065T147	T-Slotted Framing, Dual End-Feed Fastener, for 1" High Single Rail	10	$4.29
McMaster-Carr	8982K61	6061 Aluminum 90 Degree Angle, 1/4" Wall Thickness, 3" High x 3" Wide, 1 ft. length	1	$15.98
McMaster-Carr	8901K151	6061 Aluminum Sheet, 0.032" Thick, 2" x 24"	2	Donated ($4.99 ea.)
McMaster-Carr	8901K156	6061 Aluminum Sheet, 0.032" Thick, 8" x 8"	1	Donated ($6.24 ea.)
McMaster-Carr	91239A707	Hex Drive Rounded Head Screw, Black-Oxide Alloy Steel, M2 x 0.4 mm Thread, 12 mm Long	2	$6.37
McMaster-Carr	91239A117	Hex Drive Rounded Head Screw, Black-Oxide Alloy Steel, M3 x 0.5 mm Thread, 12 mm Long	1	$8.25
McMaster-Carr	91239A120	Hex Drive Rounded Head Screw, Black-Oxide Alloy Steel, M3 x 0.5 mm Thread, 16 mm Long	1	$9.47
McMaster-Carr	91239A148	Hex Drive Rounded Head Screw, Black-Oxide Alloy Steel, M4 x 0.7 mm Thread, 12 mm Long	1	$9.23
McMaster-Carr	91828A111	18-8 Stainless Steel Hex Nut, M2 x 0.4 mm Thread	1	$4.50
McMaster-Carr	91828A211	18-8 Stainless Steel Hex Nut, M3 x 0.5 mm Thread	1	$5.55
McMaster-Carr	91828A231	18-8 Stainless Steel Hex Nut, M4 x 0.7 mm Thread	1	$6.45
McMaster-Carr	92865A549	Medium-Strength Grade 5 Steel Hex Head Screw, Zinc-Plated, 1/4"-20 Thread Size, 2" Long, Fully Threaded	1	Donated ($7.70 per 100)

McMaster-Carr	92865A550	Medium-Strength Grade 5 Steel Hex Head Screw, Zinc-Plated, 1/4"-20 Thread Size, 2" Long, Partially Threaded	1	Donated ($7.70 per 100)
McMaster-Carr	95462A029	Medium-Strength Steel Hex Nut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size	1	Donated ($4.40 per 100)
JENNMAR	1-1/2DH	1-1/2” Roof Bolter Tungsten Carbide Drill Bit	6	Donated ($20 ea.)
			Subtotal	$3,864.72

Drill Testing Budget

Manufacturer	**Manufacturer**	**Manufacturer**	**Manufacturer**	**Manufacturer**
Turface	88972	Mound Clay, Red (50 lb. bag)	4	$24.80
Greensmix	383012	Bag of 1” marble chips	1	Donated ($4.98 ea.)
McMaster-Carr	4269T38	Polyethylene Plastic Pail with Snap-Lock Lid, Round, 5 Gallon Capacity	2	Donated ($9.73 ea.)
			Subtotal	$123.64

Drill Transportation Budget	
Gas for round-trip distance of 750 miles	$100
Flight for Sean to/from the competition	$422
U-Haul rental for drill	$94.75
Subtotal	$617

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