2018 RASC-AL MARS ICE CHALLENGE

Technical Report

In-Situ Ice Chip Extractor

West Virginia University

Statler College of Engineering and Mineral Resources

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Introduction

Robotics have played an incredibly important role in the exploration of our solar system, and will continue to do so, as they are not restricted to the many limitations of the human body. Though as humans seek to travel to Mars and beyond, robotics can play a new role, in supporting human life off Earth. As the cost of bringing supplies to Mars (or anywhere off Earth) is extremely high, it makes logical sense to utilize the surrounding natural resources. This is known as in-situ resource utilization (ISRU), and is a perfect candidate for robotic solutions, as these processes can be physically demanding, time consuming, and dangerous for astronauts.

The In-Situ Ice Chip Extractor or IS-ICE, is a robotic system designed to support human activities on the Martian surface by providing a method of extracting sub-surface water ice, vital to life support and fuel production. IS-ICE utilizes an Archimedes screw inspired drill to bore through regolith and into subsurface ice. As the drill cuts through the ice, the cuttings created are transported up an auger enclosed in an aluminum housing. When the drill reaches maximum depth the auger and housing will be full of ice cuttings and regolith, and the drill is retracted out of the bore hole, transported to the melting/ water extraction chamber and the drill is reversed to dump the cuttings to be melted and filtered. IS-ICE's primary control system is a low power computer and micro-controller, and is designed to be teleoperated, though has hard/soft coded limitations to help mitigate operator errors.

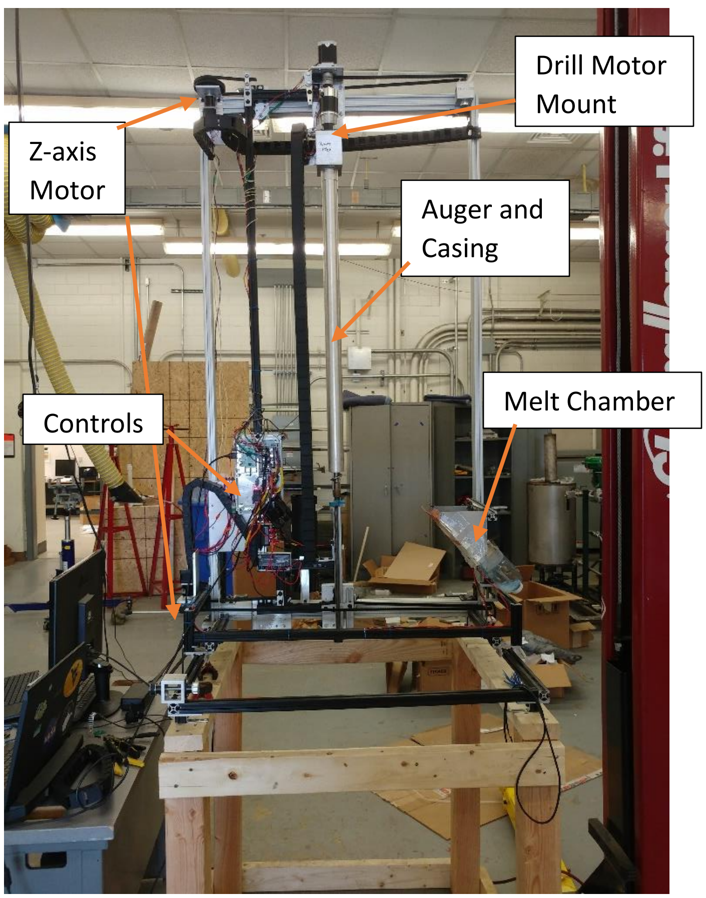

Figure 1: IS-ICE front view

System Description

IS-ICE is capable of extracting water ice from any point in a 1 m by 0.5 m(X-Axis and Z-Axis) area at a depth of up to 76 cm(Y-Axis) thanks to its CNC Mill inspired design. The estimated maximum ideal water ice yield, as calculated by finding of the volume of the cylindrical bore into ice, per bore hole is 709 ml (roughly 695 grams), which translates to 695 ml of liquid water per bore hole, assuming no loss from evaporation, spillage or in the filter water retention. Each bore hole is 50.8 mm in diameter (2"), with at-least 100 mm spacing between bore hole centers a maximum of 45 bore holes may be made, resulting in an estimated maximum of ~31.3 liters of liquid water to be extracted from the entire work area. Within a 6-hour work period however, a maximum of 18 holes can be made, at a rate of 1 bore per 20 minutes. Thus, the estimated ideal maximum water to be collected during the competition is 25 liters.

Mounting System

IS-ICE mounts to the attachment platform using four pieces of 90-degree angle aluminum, each piece is screwed to the mounting platform with woodscrews, and bolted to support struts on IS-ICE that will rest on the mounting platform. This system has proven successful during all drill tests.

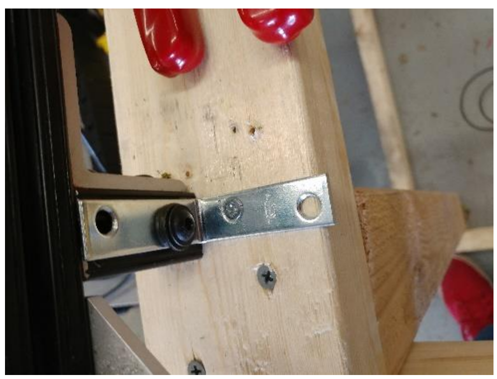

Figure 2: IS-ICE mounting hardware

System Excavation and Overburden Removal Operations

IS-ICE excavates regolith and ice using a 91.44 cm long, 3.81 cm outer diameter, auger at 253 rpm, plus a cutting bit. The system is given the command to perform a drilling operation, which will then ask for a position in the available work area. Once provided the position, IS-ICE will translate the drill to the appropriate position and begin to lower the drill. When contact with the regolith is detected by the load cells, the drill will begin to rotate at its full speed of 253 rpm. The drill will continue downwards at a rate of 1.14 mm per second, until it has reached its maximum depth as signaled by a limit switch. While drilling, IS-ICE monitors its weight on bit, and will stop the descent when a threshold of 45 Newtons is sensed by the loadcells, resuming when below the threshold. Regolith is expelled out of the overburden escape slots in the auger casing, preventing the casing from clogging. The casing prevents collapse of the overburden while drilling, and as the drill only enters a bore hole once during nominal operation, bore hole collapse, post operation, is not necessary to prevent. Post extraction, IS-ICE positions its bore cap tool over the hole and releases a cap, which covers the bore hole to help reduce sublimation into the Martian atmosphere, and marking the location for future utility.

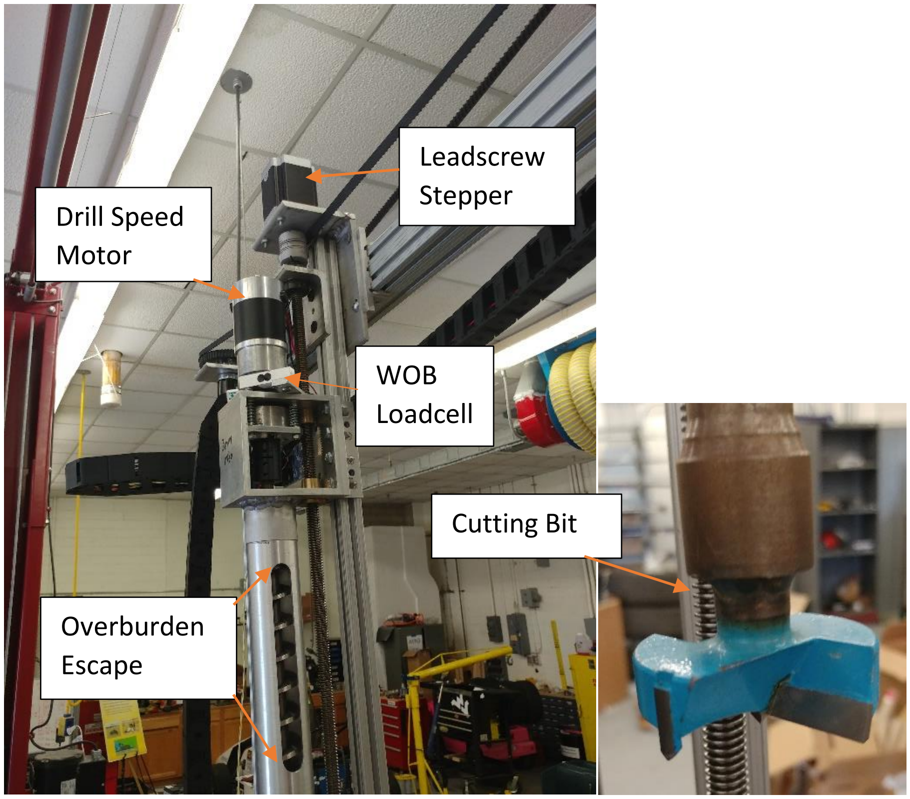

Figure 3:Drill motor mounting, load cells, overburden escape, cutting bit, and Y-axis motor

Water Extraction, filtering, and collection

When the drill has reached max depth, the auger casing will contain the ice chips created by the cutting bit, and will begin to retract out of the drill hole immediately to prevent freezing. While retracting, the auger will no longer spin to prevent ice loss. The drill will retract to its maximum height, signaled by a limit switch, and will then translate horizontally to the melt chamber. The drill is signaled by a limit switch that it is over the melt chamber and will begin to rotate in the reverse direction than drilling to convey the ice chips into the melt chamber. The melt chamber than activates a silicone heat pad, which will heat to 50 degrees Celsius (as measured by imbedded thermocouple) to quickly melt the ice. The liquid water then passes through a steel mesh to remove large particles, into a secondary 1-micron filter. After passing through the secondary filter, the water flows out of the IS-ICE melt chamber and into the collection tank. The melt chamber requires no pumps, relying on gravity to move the water.

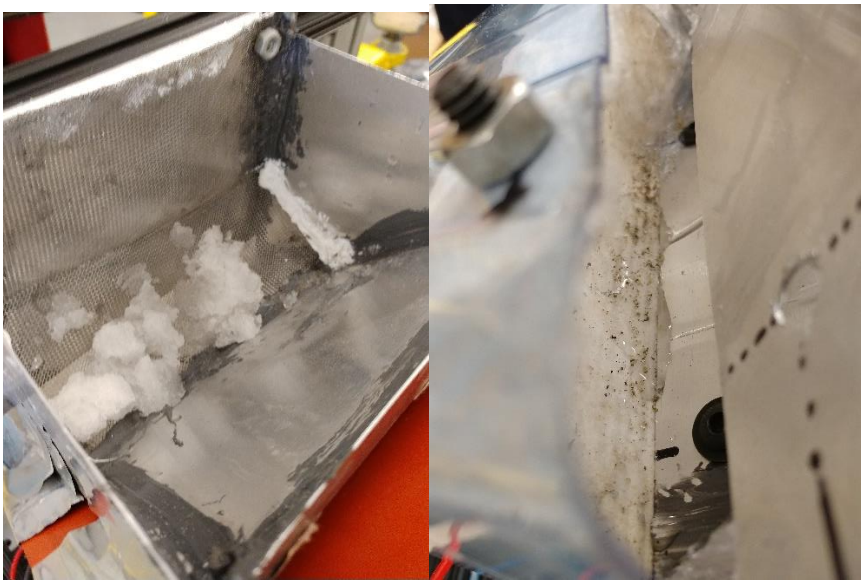

Figure 4: IS-ICE Melt Chamber during systems integration test with ice only, and water filtering through 1-micron filter

Control Systems and Datalogger

IS-ICE is teleoperated by a user interfacing with a Raspberry Pi 3, which relays commands to an Arduino Mega 2560 via USB serial communication. The Arduino reads and executes commands from the Pi, while simultaneously monitoring IS-ICE to prevent failure. The Arduino has an attached RAMPS 1.4 board, which acts as the interface between the Arduino, 3 stepper controllers for positioning, drill motor controller, servo, heater, loadcells, limit switches, and current sensor.

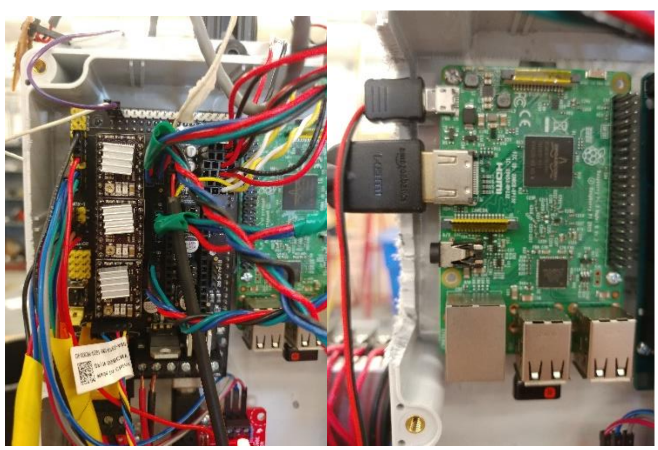

Figure 5: Arduino with attached RAMPS 1.4 board and attached Pololu Stepper Drivers, and the Raspberry Pi 3

The drill motor controller allows the motor to be directly interfaced with the 12V supply (preventing damage to the Arduino), and uses an analog input from the Arduino, to control the speed with a signal of 0V being a full stop and 5V being top speed. A switching relay is used to reverse the drill motor, as commanded by the Arduino.

Figure 6: Drill speed motor controller

Sensor data is relayed from the Arduino to the Pi, and is displayed for the operator to monitor the health and status of the system. The Raspberry Pi 3 records all data from the Arduino, and the command history, to a txt file for easy analysis. Currently the Pi requires a physical connection with a monitor to display information, but is controlled using a wireless keyboard and mouse.

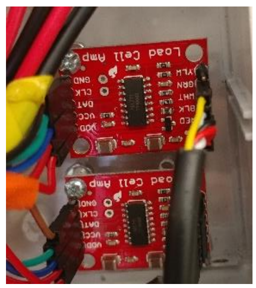

Figure 7: Load cell amplifiers

The Arduino has some safety features programed to prevent a damage to the system. When powered on IS-ICE automatically returns to a home position, signaled by the limit switches, and will output the current state of the machine. IS-ICE will only move in the X and Z axis when the Y axis upper limit switch is pressed, ensuring the drill is above any potential obstacles. When any limit switch is pressed, IS-ICE will not allow further travel in that direction, no matter the user input. When power consumption is found to be approaching the limit of 10 A at 120 VAC, IS-ICE will cut the power to the heater and to the drill speed motor, and immediately return to the home position to prevent over consumption. This is unlikely, as the DC power supply will outputs a maximum of 450W, meaning IS-ICE should draw at most 3.75 A at 120VAC.

Figure 8: Over the wire current sensor

Technical Specifications:

Mass	40.82 Kg
Volume	1.69 m^3 (1m Length, 0.93m Width, 1.82m Height)
Drill Length	91.44 cm
WOB Threshold	45 N
Drill Motor Rated Load(Continuous Torque)	1.81 N-m
Max Drill Speed	253
Max Drill Torque (Stall)	6.89 N-m
Stepper Holding Torque (X and Z Axis)	4.36 N-m
Stepper Holding Torque (Y Axis)	
On-Board Computer Systems	Raspberry Pi 3, Arduino Mega 2560 w/ RAMPS 1.4
Communication Interface (Human-Machine)	Keyboard, mouse, and monitor
Communication Interface (Pi-Arduino)	USB Serial
Software In Use (Pi)	Linux(Raspbian Pixel), Python (Ninja IDE)
Software in Use (Arduino)	Arduino
Power	120 VAC, 10 A, converted to 12VDC 450 Watt

Challenges, Design Changes, and Improvements

Design challenges faced since the mid semester report were primarily based around the fabrication and installation of brackets, manufacturing of the melt chamber, and figuring out a way to move the rails of the system in simultaneously in the X and Z directions without any binding.

The brackets were simple in design but execution of the fabrication process was difficult. The initial set of brackets, while they did align and mounted, were not very secure, nor did they allow for mounting more support structure. New brackets were made, but on three separate attempts the mill would not line the holes for the mounting plate in a straight line. The alignment of the bolt holes was critical to ensure there was very little flexing in the lead screw. Enlisting the help of more experience machinists helped solve this issue.

The melt chamber was originally to be cylindrical, and the sizing was originally supposed to allow the auger casing to fit tightly (<1mm of gap), but smoothly, heating the entire drill, and mitigating regolith in the water ice. However, these tight tolerances proved difficult to achieve with the teams current manufacturing capabilities, and a larger gap would have had a significant impact on the heat transfer properties of the system. The new solution was to build a container with very thin sheet aluminum, and reverse the auger to dump the ice chips into it. The container is sized to fit the silicone heater, and is so thin it heats near immediately.

To solve issues with binding of the slider bearings on the aluminum frame, support structure was added to the X and Z axes, reducing the available work area some, but with the added benefit of more smooth movement (less stepper slipping), increased rigidity, and better mounting for the controls system and melt chamber. On the Z axis, a second stepper motor is included to further improve smooth movement. Fortunately, the RAMPS 1.4 board has pins allowing the same signal to be sent to 2 separate stepper motors from only 1 stepper driver, making this a simple fix.

Some minor challenges have included the stepper drivers overheating, though easily remedied with attaching heatsinks and a small computer fan for cooling, as well as replacing 3D-printed stepper mounts with aluminum, to prevent them from breaking under tension.

Competition Strategy

To maximize water extraction during the competition, IS-ICE is expected to run for the entire work period. Starting at the farthest corner from the home position, IS-ICE will perform a drilling operation every 100 mm until the edge of the work area in the X axis is reached, where it will then move in the Z axis and repeat this order of operations until the work time has elapsed. A maximum of 18 holes is expected, assuming nominal operations, per day of the competition. Locations of drill sites will be recorded in a note book, as well as in the log file in the Pi for analysis and to prevent mistakenly drilling the same, or too close of a location. Operators will be switched on a 2-hour basis to prevent fatigue, and therefore mistakes. Those not operating will be on hand to make quick repairs, and to document the competition.

Contingency Plans

The following contingency plans have been made in the case of certain failure modes.

1. In the event of electronic component failure, spare components have been purchased and can be swapped in for the failed component with no consequence.
2. In the case of timing belt slippage, which can be audibly and visually identified, a return to the home position to zero the position state of IS-ICE will alleviate position errors.
3. Blockage of the auger may occur in the case of a rock getting jammed, or a particularly large chunk of ice or frozen regolith. In this case the auger may be switched between reverse and forward directions to free up the jam. If the problem persists the auger is removed to clear the blockage by hand.
4. In the case of the auger freezing in the bore hole, the auger can once again be switched between reverse and forward to free itself. If it remains stuck manual removal may be necessary.

Safety Plan

No PPE is seen as necessary for operation of IS-ICE during the competition. There are no hazardous materials that would require listing.

The following are critical safety procedures that must be followed while operating IS-ICE.

1. **No physical interaction with the robot shall be done while the robot is powered!**
    - A hands-off call will be made prior to powering the robot, to help prevent injuries.
2. Hazardous points (pinch, electric shock, high temperatures, sharp edges) will be clearly labeled to help prevent injuries for those ignoring procedure 1.
3. In case of fire, power will be cut immediately to remove potential sources of flames.

4. Limit switches prevent the drill from operating outside of its physical limitations
5. An emergency stop will prevent injuries and damage to the robot in the event of catastrophic failure.

Path to Flight

Mars will be an operating environment with a unique set of challenges for a robot developed on Earth. Multiple changes to the IS-ICE system will need to be made to prepare the system for Mars and overcome its unique challenges.

Some major design changes to IS-ICE would be to include a 4th axis of motion, being the angle of the drill, allowing the extraction of water ice from slopes and ridges, and avoiding potential obstacles such as large rocks by being able to drill into the desired area at an angle, increasing its potential work area. Another major design change, would to either incorporate IS-ICE into a rover design, or include a set of wheels that would allow a rover to easily transport IS-ICE, allowing the robot to be taken where needed. Another option would be to remove the CNC like positioning system and mount the drill to a rover directly, using the rovers motion systems to position the drill as needed.

IS-ICE will likely be constrained to within reach of power cables provided from a habitat, but could easily be modified to include batteries and solar arrays over top of the entire system. Having solar arrays and batteries would allow IS-ICE to be transported anywhere around the habitat and would not put a strain on habitat power systems. These batteries could extend operations in to the Martian night if needed as well. Using similar solar panels to those found on the Mars exploration rovers, Spirit and Opportunity, which produced at their prime 900 Watt-hours per Martian day, IS-ICE could operate at full capacity for at minimum 2 hours, though with strategic planning, likely be extended beyond that.

IS-ICE's 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. IS-ICE would also require wireless capabilities, to prevent the need to route data cables around a Martian habitat.

The control system for IS-ICE, is not currently radiation hardened, and would either need to develop new radiation hardened components. More likely, the systems would be modified to work with proven technology in use on current or planned missions (such as those on the upcoming Mars 2020 rover) and would include redundant components built in to prevent the need for maintenance. Wiring on the system would also need to be protected against radiation interference. This can be done with insulated conduit, which would help prevent some hazard of wires being broken due to unforeseen pinch points.

Inclusion of more sensing components such as conductivity(like those shown below) and force-torque sensors, would help IS-ICE identify drilling medium to ensure maximum water retrieval, and avoid drilling obstacles, such as large aggregate.

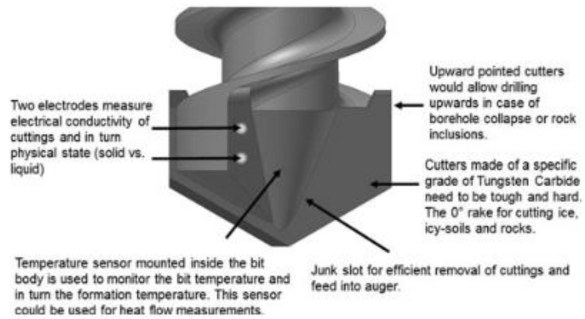

Figure 9: Example drill bit with conductivity sensors from Icebreaker drill.

Optimization of the drill stem 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. 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.

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°Cto 20 °C with an average temperature of -60°C. As a result, water ice exposed to these conditions would directly sublimate into water vapor and could be lost during extraction. The current borehole control system design, for instance, provides a proof-of-concept for development of a robust well-capping device. Ideally, this device would utilize a trap door with seals to allow a drill to enter the borehole and extract ice cuttings. Once the drill moves out of the well, the trap door could then close and seal the well against sublimation effects. The current melt chamber would need replaced to prevent sublimation as well. This could be done by reverting to the previous tight tolerance cylindrical chamber, which would have an automated cap prevent sublimation when the auger casing is not inserted.

The extremes of the Martian environment would also directly impact the performance of IS-ICE. Due to the extreme temperature ranges, the thermal stresses may induce brittle failure. This would require IS-ICE would need to be constructed from metal alloys, composites and plastics that have proven suitable for such an environment. The timing belts and pulleys used for translation on IS-ICE would require finding a composite replacement to prevent the constant need to replace them, or could be substituted for a timing chain constructed from a light-weight allow such as aluminum or titanium.

The dust on Mars poses a significant hazard to many components on IS-ICE, though some design considerations have already been considered in the current iteration. The slider bearing used for translation are superior to wheels when it comes to working in dusty environments, and are used in industry today, though will require testing in a vacuum environment. The leadscrew used for vertical motion would likely need to be sealed to prevent too much dust from accumulating and interrupting motion.

Standardization of all components on IS-ICE will be necessary for the Mars ready iteration of IS-ICE, as due to the nature of using commercial off the shelf components, both metric and imperial units are in use, causing some issues with design, and fitting. Also requiring many different bolts to purchased instead of have a simple set of only a few sizes.

Budget

This project has been sponsored and supported by the West Virginia Robotic Technology Center at West Virginia University. The IS-ICE team has operated within the Mars Ice Challenge Development Award's allotment of $10,000, and so has not required any external funding. IS-ICE utilizes many components from its predecessor In-Res, reducing costs significantly.

Purchased New Components	$2595
Estimated Cost of reused components	$2000
Gas for round trip to and from competition	$150
Estimated Total	$4645

Integration and Test Plan

Testing has consisted primarily of ensuring ice chips can be collected and transported to the melt chamber (in a timely manner), as IS-ICE advances through regolith simulant with no issue. Thanks to the leadscrew for vertical motion, rate of penetration is near constant, and slippage does not occur. However, a software defined solution was found to be required to prevent exceed the weight on bit requirements, as the leadscrew is capable of exerting well over 100 Newtons of thrust force.

A full systems integration test was done to ensure IS-ICE could translate to a specified location, collect ice chips and transport them to the melt chamber. Fortunately, the test was successful, though did not perform as well as hoped. A large portion of the ice chips were lost to the surface of the ice as they were pushed out of the way by the casing (see figures below). The melt chamber melted the ice within 5 minutes when heated to 70 degrees Celsius, slightly slower than hoped at a higher than planned operational temperature. There was also significant loss to the filter, suggesting that until the filter thoroughly soaked, some water will be lost to retention.

Figure 10:IS-ICE in final positioning over ice sample

Figure 11: IS-ICE entering the ice, as well as the lost ice chips on the surface of the sample.

Figure 12: Collected ice chips being melted

Project Timeline

The remaining time prior to competition will be spent working out bugs in the software, and making a short guide on how to operate IS-ICE so anyone can use it with little to no instruction. More tests will be conducted as well to see if it is possible to increase the vertical speed to try and increase the number of bore holes done in 6 hours.

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