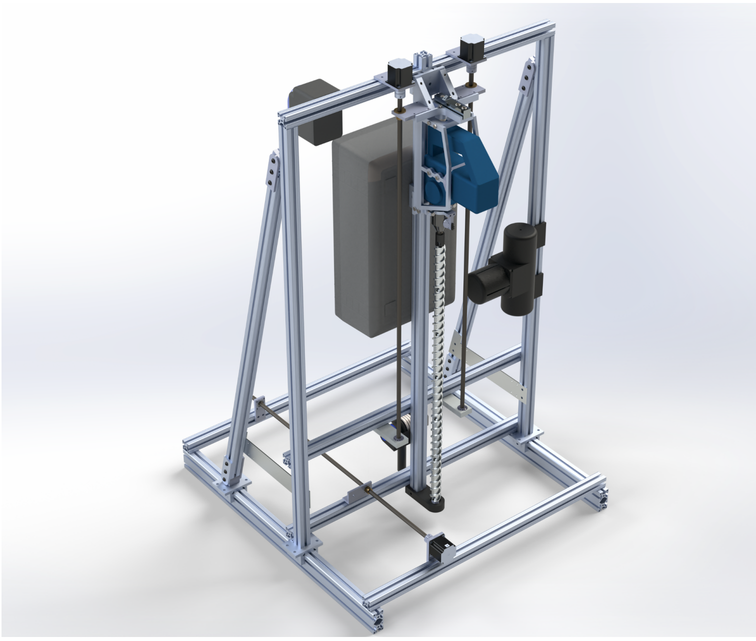
2021 NASA RASC-AL Special Edition

*Moon to Mars Ice Prospecting Challenge***:** *Technical Paper*

Aztec in-situ Resource Extraction System (ARES)

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Executive Summary

The Aztec in-situ Resource Extraction System (ARES) is a remote user-controlled drilling, prospecting, and water extraction system. ARES is designed to have a path to flight for water extraction on Mars and prospecting for a digital core on the Moon. ARES performs the following functions:

Drilling Through Layers

ARES uses a rotary-hammer drill actuated by dual stepper motor-driven lead screws to breach overburden and ice. The drill bit is comprised of aluminum sections welded together with a steel cutting tip insert. Drilling is performed at a fixed plunge rate and RPM. To limit weight on bit to less than 150 N, ARES automatically begins pecking (alternately raising and lowering the bit) when it experiences a high weight on bit. Our dry run proved capability to drill through several layers of sand, gravel, cement blocks, drywall, and ice to establish our extraction tube.

Prospecting for a Digital Core

Drill RPM, plunge rate, weight on bit, and current draw are captured and displayed in Labview. After drilling is complete, these data arrays are exported to Excel and finally post-processed in Matlab, relative hardness is calculated, and the results are displayed in independent data graphs for the team to analyze and determine the number, depth, and relative hardness of the overburden layers.

Extracting Water

After reaching the desired plunge depth, the bit retracts, the system moves horizontally to place the heater directly over the hole, and a reel lowers the heater assembly down to the ice. The heater melts ice with infrared radiation, and water is continuously pumped out of the hole through a tube in the center of the hollow sleeve heater. A peristaltic pump flows water out of the hole and through a filter.

Filtering Water

Water is pumped through a two-stage 3D printed filter before collection. The first stage is a 5 micron steel mesh that catches most debris in the water. This stage is automatically regenerable by actuation of a purge valve when pressure rises in the filter. The second stage is a layer of activated carbon that further filters the water.

Hardware Control

ARES is governed by two Arduino 2560 controllers working in parallel, and all data is sent over two USB cables to COM ports on the operator's laptop. A LabView interface displays live data from the sensors and serves as the remote user control interface. High power elements are controlled by the arduinos through stepper drivers, solid state relays, and a phase fired controller. Control and data collection is split between the two arduinos using 5 synchronous timers each.

1 System Description

The Aztec in-situ Resource Extraction System (ARES) is a two-stage drilling and water extraction system. ARES uses rotary percussive drilling to breach overburden to gain access to underground ice deposits. Once a hole is drilled, it uses a reel to lower its heater assembly to the ice. The heater generates infrared radiation to melt ice, and water is continuously drawn out of the hole with a peristaltic pump, flowed through a regenerable filter, and collected. Radiative heating allows ARES to deliver heat directly to the ice walls, generating water quickly and remaining effective as the melt-hole grows. The peristaltic pump and regenerable filter allow the system to process large quantities of fouled water. The system is controlled by two Arduino 2560s, which connect to a LabVIEW user interface for remote control on a laptop computer. Weight on bit, RPM, drill current, and plunge rate data are collected and plotted in MATLAB for analysis of the overburden layers. Figure 1 shows ARES's mode of operations, which consists of six steps. The process times shown below are estimates.

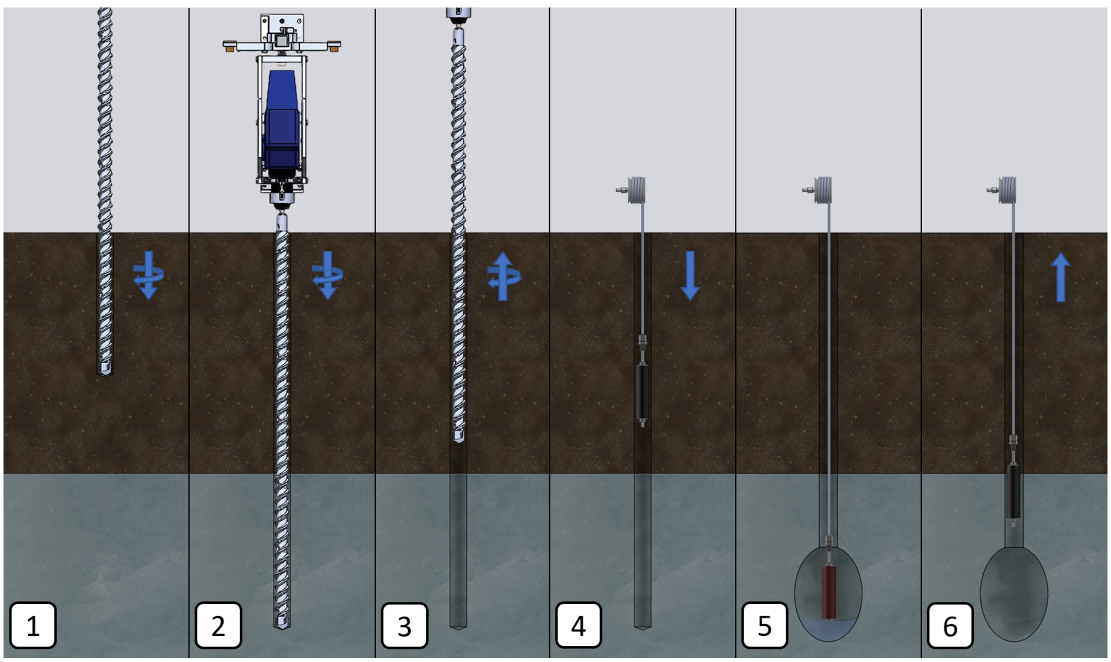

Figure 1. ARES mode of operations

(1) The rotary-hammer drill plunges down (*1 hr.*)
(2) The drill reaches final depth
(3) The drill is removed from the ice (*10 min*)
(4) The heater is lowered *(5 min)*
(5) The heater begins melting ice. Water is pumped out, filtered, and collected (*4 hr 40 min*)
(6) At the end of the competition day, the heater is removed from the hole *(5 min)*

1.1 Mounting system

The system is mounted to the test stand via an 8020 aluminum frame. The frame is designed as a supportive subsystem that caters to the needs of the drilling, melting, extraction, and electrical subsystems. It is constructed of 38mm (1.5") hollow aluminum T-Slotted extrusions joined with standard brackets and hinges. The frame is mounted to the test station via angle brackets that secure the aluminum extrusions of the frame to the provided 2x4s with wood screws every 0.25m. The frame's extruded aluminum construction and geometry provide high strength and stiffness at a light weight, and its versatile mounting solutions allow for design iteration. A horizontal power screw controls one dimensional lateral system movement within the 1x0.5m drilling area.

1.2 Drilling System

The ARES drilling system combines the use of a rotary hammer drill with an auger-style drill bit to drill through overburden and ice. ARES operates the drill in rotary-percussive mode, meaning that it spins the bit while hammering it down into the drilling medium. This allows the drill to carve through softer materials and break up the hardest materials. The drill's ample flutes allow for the extraction of cuttings.

The drill is a Bosch RH328VC rotary hammer. The bit is made up of six AL-6061 flute sections welded together, tipped with a high speed steel cutting insert. This design increases the lifespan of the bit by requiring only small inserts to be replaced rather than requiring multiple drill bits or a much heavier all-steel bit. The aluminum construction of the body of the drill bit is lightweight and durable enough for the direct and abrasive forces it encounters. Drilling operations are paused periodically to prevent heat buildup from damaging the bit or drill

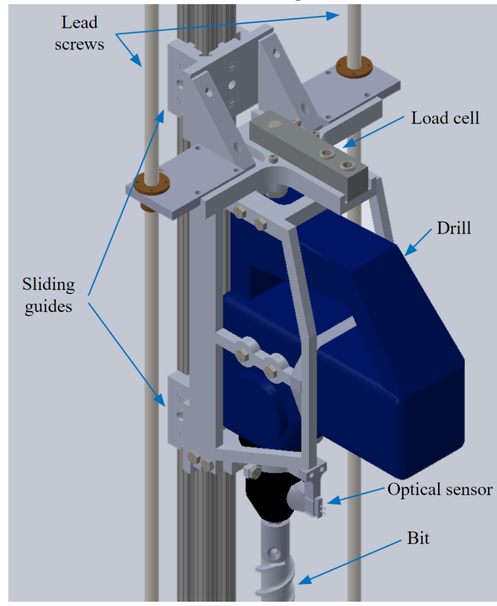

Figure 2. *Drill assembly CAD model*

Drilling telemetry is collected from a bar load cell, an optical RPM sensor, a Hall effect current sensor, and a LIDAR sensor. To ensure the drill does not exceed the 150N weight on bit (WOB) limit, the drill automatically conducts a pecking operation, raising the drill bit a short distance and lowering it at a lower plunge rate when it encounters a WOB greater than 130N. The pecking operation and continuously spinning the drill bit will help to reduce the chance of the bit seizing in ice.

1.3 Ice Melting System

ARES uses infrared radiation to melt ice downhole. This technique holds a number of advantages over more traditional conductive and convective methods. The conventional Rodriguez wells (or rodwells) used in the Arctic use a water-steam recirculation system to produce a pool of water downhole that is used to conduct heat to the ice (Lunardini et al.). In comparison to the equipment on ARES, this requires the addition of a steam generator, a second downhole pipeline for steam, and a downhole pump. This additional hardware would make the system heavier, potentially less reliable, and would stretch the limits of the drilling system by requiring it to drill a larger hole with the same limited power. These functional problems aside, this method is less energy-efficient than radiative heating, as it loses heat to the surrounding environment along the length of the steam pipe. As the melt-hole grows in size and the source of heat gets further from the ice, heat transfer to the ice would be slowed more and more by passing through the intermediate water. Alternatively, any method that relies on air as a transmission medium would face the even slower process of atmospheric convection. Methods that rely on direct conduction from a heating element to the ice would be limited in time-wise and total water production by the need to place the heater's surface in direct contact with the ice being melted. By using infrared radiation, ARES applies heat directly to the ice even as the melt-hole grows, avoiding these problems.

Unlike a traditional conduction rodwell, an infrared well like ARES is fail-safe in the case of a loss of power. A traditional rodwell relies on a downhole pump submerged in a pool of water. In a loss of power scenario, the water pool would freeze, potentially trapping the pump meters underground and very likely damaging it due to water freezing in the pump chamber. This could leave it totally unable to extract itself, let alone resume water production. ARES avoids this problem by locating the pump outside the hole, locating the heat source inside the hole, and by not relying on submersion in a pool of water to transfer heat to the ice. If power is cut off to ARES, it can be immediately retracted as soon as power is restored with no damage and no danger of becoming trapped. In the worst-case scenario, the heater will need to be turned on for a few minutes to melt the frozen pool of water that may form around the tip of the water extraction tube.

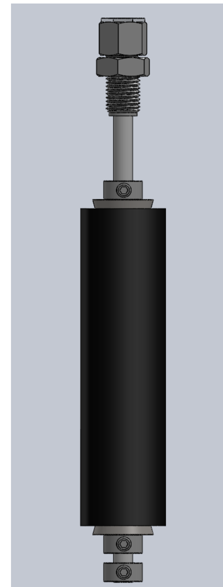

Figure 3. *Heater assembly CAD*

ARES uses a hollow cylindrical resistive heater to produce infrared radiation. The heater is powered by a maximum of 720W of 120VAC modulated by a phase-fired controller based on readings from the heater's on-board thermocouple. The heater is coated on the exterior face with a high emissivity coating provided by Emisshield ($\varepsilon \sim= 0.95$), and on all other faces with a ceramic anti-corrosion coating.

An Inconel water extraction tube is located in the center of the heater, where it is insulated from the heater with a Macor ceramic tube. The assembly is held together with shaft collars and washers, and a fitting is attached to the top of the Inconel tube with a ceramic adhesive. On the other end, the fitting attaches to a silicone tube, which, along with the heater and thermocouple leads, is contained in a braided stainless steel sleeve. This sleeve supports the heater assembly via a threaded clamping connection with the fitting. All materials in the heater assembly were chosen for their ability to handle the high temperatures they are exposed to.

1.4 Water Filtration and Collection System

Water accumulated by melting ice downhole is extracted through the tube located in the center of the heater. This arrangement allows the heater to have the greatest possible surface area facing the ice to deliver infrared radiation, while still allowing water to be collected from the small pool that forms below the heater. Water is extracted continuously while the heater runs. A peristaltic pump creates the pressure head that sucks water out of the hole and pushes it through a filter. The pump draws only 9W, allowing it to operate simultaneously with the heater and control systems. The peristaltic pump works by using a motor to rotate rollers to squeeze a flexible tube from the outside. Since the pumping mechanism never touches the water directly, it can flow fouled water without any risk of damaging itself . It produces an 80 psi pressure differential to flow water through the filter.

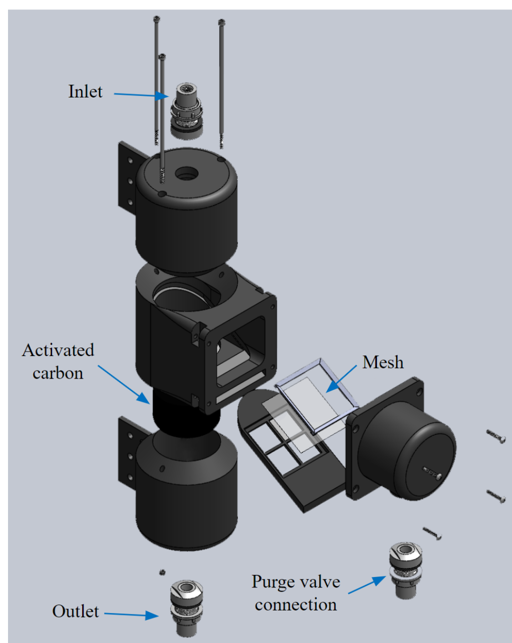

Figure 4. *Filter CAD, exploded*

Water is filtered through a two-stage 3D printed filter with a sintered steel 5 micron mesh and activated carbon stage to further remove particulate matter. The filter is able to regenerate itself by use of a purge valve integrated with the sediment trap on the filter. As sediment builds up in the trap, a pressure switch monitors the pressure in the housing. When sediment build-up causes the pressure to reach a threshold, the purge valve is triggered, which causes water to flow back across the mesh, flushing the built-up sediment in the trap.

1.5 Power Distribution System

The power distribution system begins with the 120VAC single phase from the outlet through our system switch and 9 Amp Fast Blow Fuse. The 120VAC line is fed to a small 120/24 VAC transformer that is used for timing of the phased fired controller, which modulates power to the heater. The 120V bus also feeds a 12VDC power supply for the Arduino 2560 controllers and a 48VDC power supply that provides power to the stepper motors and driver modules. 5VDC logic level power for most peripheral equipment comes from the Arduinos via their shields and a custom PCB breakout board. One copper ground bar is used for AC ground, and the major DC elements share independent grounds separated by voltage rating. Table 1 shows a power consumption breakdown, and figure 5 shows a diagram of the power distribution system. All wire and lugs were sized according to the NFPA-70 2020 for ampacity and are able to operate safely at between -26°C and 30°C.

Table 1. *Power Consumption Breakdown*

Individual Power Consumption by Subsystem				
Subsystem	**Component**	**Rating**	**Amperage (A)**	**Power (W)**
Drilling	Microcontroller	5V, 3.3V, 1.1V	1A	5W
	Drill	8 A	6A	700W (120Vac)
	Opamp	5.5V, 3V	0.75mA	2.25mW
	Load Cell	12V	33.33mA	400mW
	RPM Sensor	3V	100mA	200mW
	Current Sensor	5.5V	6mA	33mW
Linear Control	Z-Axis Stepper Drill	24V	2A	48W
	Z-Axis Stepper Heater/Extraction	24V	2A	48W
	X-Axis Stepper	24V	2A	48W
Heater	Opamp	5.5V, 3V	0.75mA	2.25mW
	Current Sensor	5.5V	6mA	33mW
	Heating Element	120Vac	4.17A	700W
Extraction	Peristaltic Pump	120V single phase	500mA	6.1W
	Current Sensor	5.5V	6mA	33mW
Digital Core	Central Board	3V	40mA	120mW
	Nodal MCU's	3V	7.8mA	23.4mW

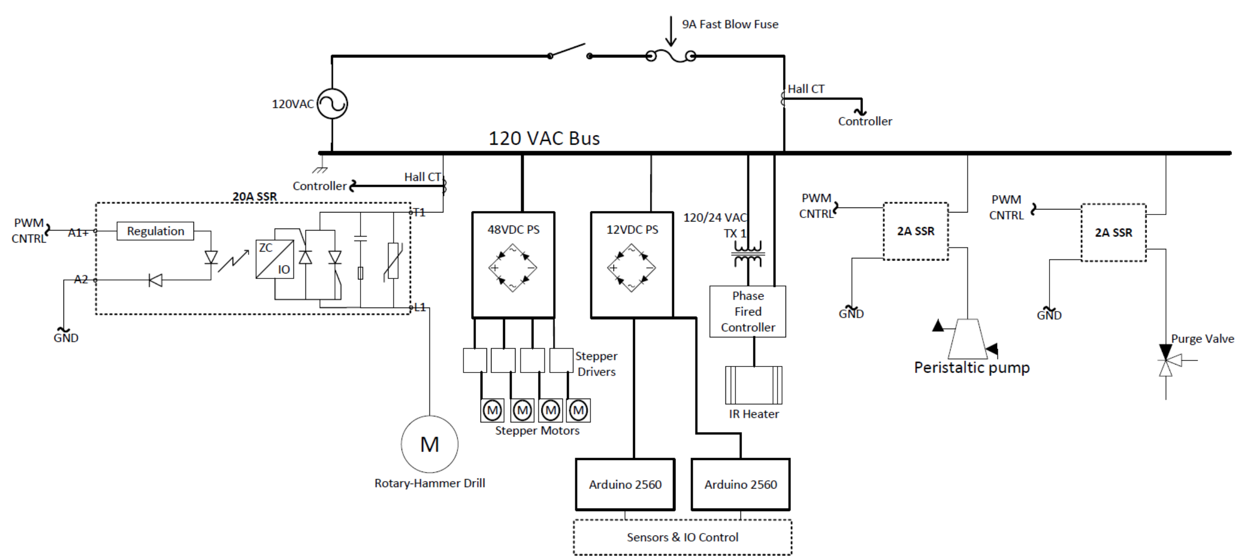

Figure 5. *Diagram of ARES's power distribution system*

1.6 Control and Communication System

The main component of the ARES control system is two Arduino 2560 microcontrollers. Sensory equipment and controlled loads are divided between the two controllers to distribute the computational load during each phase of operation. Controlled and monitored circuits of the same type are kept on the same controller to reduce the memory usage for each controller. In order to get so many disparate pieces of equipment to work together, Interrupt Service Routine (ISR) programming and 5 separate clocks on each board were used to time our controls and outputs. A USB-B to USB-A cable extends from each controller out to the operator's laptop where data is collected and visualized over the COM ports in a LabView interface. Our interface also has remote control capabilities to manually control and emergency stop our equipment.

The Arduinos report system current at 338Hz and weight on bit at 650Hz. The software uses weight on bit data to retract and perform pecking operations if a weight in excess of 140N is detected. Figure 6 shows the continuous reporting of all data in our LabView environment.

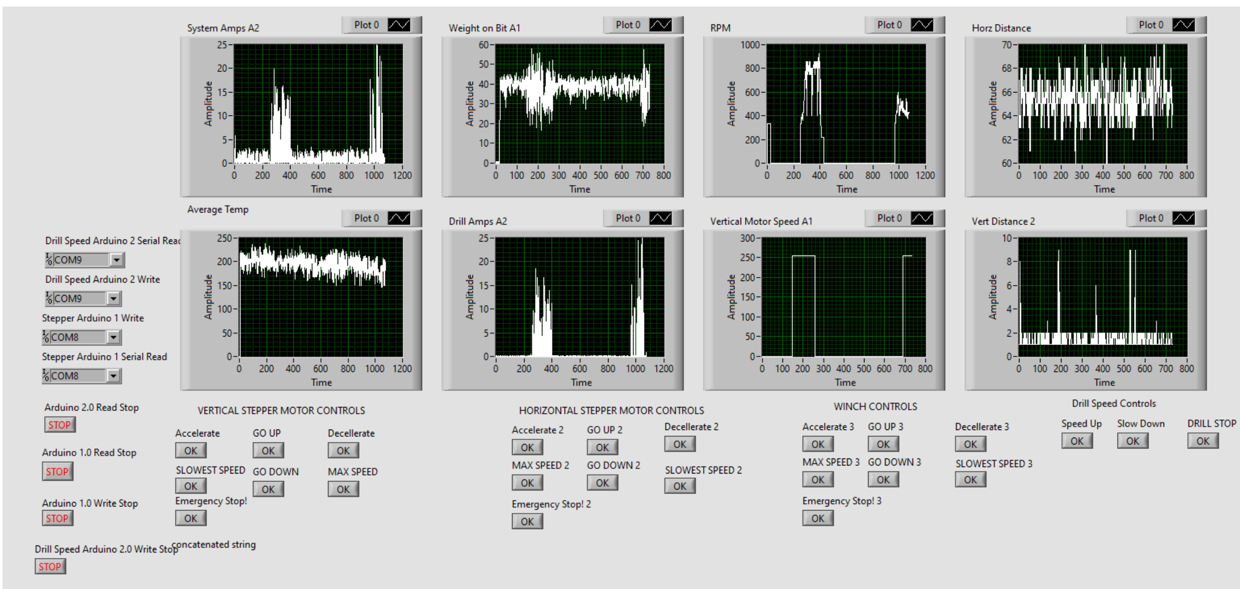

Figure 6. *Screenshot of LabView control and monitoring system*

1.7 Digital Core

Drilling telemetry is collected from a Hall effect current sensor, optical RPM sensor, bar load cell, and lidar rangefinder. These data on drill current draw, RPM, weight on bit, and plunge rate/depth are used to develop a digital core. To produce consistent, useful data, some of these variables are held constant and others are allowed to vary. While drilling we hold the desired RPM control value at a set high speed and our plunge rate at a set low speed. We implemented a pecking operation for when the weight on bit exceeds 140N and operate the drill in rotary + hammered mode so the hammering operation will take over at high loads. We understand that our hardest materials will be observed when this happens and currently cannot differentiate ice from cement as hammering operations make our algorithm described below irrelevant. However we know that the ice we are drilling for is near half a meter plunge depth and will be looking for that at competition.

Our digital core takes advantage of the Mechanical Specific Energy (MSE) equation, as follows

$$MSE(psi) = \frac{WOB}{Ac} + \frac{2\pi * RPM * I_{load} * Kt}{Ac * ROP}$$ (Hamrick).

WOB - Weight on bit | Ac - Cross sectional Area of the bit | ROP - Rate of penetration
Kt - torque constant of the drill motor | RPM - Rotations per minute of the drill bit

We will estimate the torque constant for our drill to determine relative hardness of each layer. The digital core is post-processed in Matlab using the above equation and data received and stored by LabView.

2 Technical Specifications

ARES weighs 51 kg and measures 0.98x0.98x1.49m with the drill in the retracted position. The drill bit has a diameter of 1-⅜” and measures 100 cm (39.4”) from the tip to the drill adapter, and when installed on the drill, it is physically limited from reaching more than 94 cm (37”) past the 2x4 interface on the bottom rail of the frame. The weight on bit is automatically limited to 150 N by the controller. Two Arduino 2560s serve as the onboard computers. They communicate with a laptop computer running a LabVIEW interface via a usb cord. A 9 amp fast-blow fuse limits power to the system. The sensors used in the drilling system include a set of two LIDAR modules for distance and position, a beam load cell measuring the weight on bit, a hall effect sensor recording the revolutions per minute (RPM); for power a custom PCB current sensor is used, as well as a custom power distribution board,

3 Design Changes

The following design changes occurred since the mid-project review.

- **Drill bit revision:** The drill bit design was finalized to the design described in section 1.2, and a final solution for the drill bit wobble was created in the form of a 3D printed bit stabilizer at the bottom of the frame.
- **Drilling method:** Testing showed that rotary percussive was the most effective drilling method and would not interfere in data collection, since percussive action only becomes dominant in materials close to our WOB limit. Therefore, the drill will run exclusively in this mode.
- **Heater insulation:** The heater assembly was finalized with macor ceramic insulation. Unlike the ceramic fiber alternative considered, it has no danger of becoming waterlogged and losing some of its insulating power. The ceramic fiber insulation will be retained as a backup part.
- **Heater & pump simultaneous operation:** Testing showed that the heater and pump can be run simultaneously without causing problems with in-tube boiling.
- **Inlet mesh:** The 25 micron mesh on the water extraction tube inlet was swapped for a 1mm mesh. This larger mesh still prevents the ingress of large particles that could stop up the tube, but has less danger of filling up with small particles and clogging itself.
- **Purchased electronics enclosure:** After considering a 3D printed electronics enclosure for weight savings, the team opted for the more robust option of a pelican air case, which seals the electronics against water and dust and can be used to ship them without disassembly.
- **Revised breakout board**: After a trace run too close to the ground plane short circuited and problems with our intended rpm sensor circuit, the PCB hosting components that require biasing and/or amplification has been revised and reordered with a more simplified footprint that addresses those problems.

4 Challenges

Along with the project itself, the unique circumstances of the last year and a half posed a number of challenges to the team. The electrical and drilling systems faced challenges and setbacks that slowed completion of the system, and price increases and shipping delays caused by the pandemic slowed the assembly and testing of the system.

- **Electrical Troubleshooting:** Heater leads shorting from lacking insulation. A PCB trace put too close to the ground plane caused another short and forced a redesign. Poor quality quick connectors had pins pushed back multiple times causing sensors to fail. Incorrect op-amp biasing provided faulty load cell data. Wire strands not fully contained in the screw terminal shorting together in multiple cases.
- **Arduino Control System:** Source code for the LIDAR sensors was not ISR driven, therefore could not directly integrate without the arduino entering waiting loops that interrupted other equipment. Code for the LIDAR sensor and various others had to be reimagined in an ISR format.
- **Drill Bit Failures:** long-run testing revealed greater-than-anticipated problems with the six-piece drill bit. The original attachment mechanism of screws failed after high heat from continuous drilling broke the loctite applied to them and vibration from rotary-percussive drilling in ice began to shake them loose. This problem was solved by removing the screws and instead welding together the six flute sections.
- **Parts Procurement:** COVID-19 caused delays in manufacturing and shipping at some of our suppliers. The team was forced to pay higher prices and large shipping fees on some parts to expedite their arrival. This problem was minimized by using a bill of materials and schedule to ensure parts were selected and ordered as quickly as possible. The effects of the extra cost and slower build were mitigated by supplementary grants from SDSU's Student Success Fee fund and Research Foundation travel fund and the postponement of the competition to September.
- **Team Availability:** All members of our team were senior undergraduates at SDSU at the time we joined the competition, and we have all since graduated and moved on to full-time work. This resulted in decreased availability and participation from some of our team members, which slowed down the process of putting the finishing touches on the system. Thanks to the continued commitment of key team members, we have nevertheless completed a fully functional rig, and will be able to field a full team of five participants and at the on-site competition.

5 Competition Strategy

5.1 Digital Core Creation

Ares' telemetry is continuously logged and displayed in real time in LabView during the penetration phase of operation. Once our desired depth is reached, the operator will export the data to an Excel file. From there, the data will be copied and dropped into a pre-built Matlab file to be visualized and analyzed. Trends and changes in individual data points including weight on bit and drill current will be used along with calculations of the mechanical specific energy equation to determine the number and relative hardness of overburden layers. Layer depth will be determined from LIDAR data. For the hardest materials, the percussive function of the drill will become more dominant, creating large fluctuations in the weight on bit. This introduces noise in the data, but since it will only occur in the hardest materials, it will not prevent the determination of their relative hardness.

5.2 Water Collection

ARES produces liquid water by melting ice with infrared radiation. Radiative heating allows the system to apply heat energy directly to the ice without relying on an intermediate medium. This gives it the ability to produce large amounts of water quickly and efficiently. The utility of radiative heating is most apparent after a significant amount of ice has been melted and the melt hole grows in size. This is the point at which traditional methods struggle most to apply heat to the ice, but radiative heating allows ARES to continue to apply large amounts of heat energy directly to the ice surface. This allows the system to make the most out of every hole. As such, we will aim to drill a single hole on each day, spending as little time on drilling as possible to maximize time spent melting and extracting the ice. As it is melted, water is continuously drawn up through a tube in the center of the heater. The extraction system has robust protections against clogging. A 1mm wire mesh on the inlet prevents the incursion of large particles, and water is pumped with a peristaltic pump. Unlike traditional positive displacement pumps, peristaltic pumps are unhindered by particulate matter in the pumped fluid. The pump sends water through a filter containing a 5 micron mesh and activated carbon before collection in the competition bucket. In case of particulate saturation, the filter is regenerable by actuation of a purge valve that clears the mesh of debris by flushing it with water.

Figure 7. *Infrared heater in ice*

6 Integration and Test Plan

ARES was assembled and tested first in individual subsystems, then in greater degrees of integration, culminating in a fully integrated competition simulation dry run. In the first stage of testing, purchased and self-manufactured components were checked for compliance with our requirements and for their ability to interface with each other. These tests led to a number of reworked parts, including the heater, which was updated to a design that produced a more uniform temperature across its whole face, the drill bit, which was modified to withstand the heat and forces of drilling with a welded aluminum construction, and a few 3D printed parts whose design was refined to fit their purpose better.

Once entire substems could be tested, the team was able to gather key data about the system's water extraction capabilities. ARES's first generation heaters, which will be used as backup units at the on-site competition, melt ice at a rate of about 2.6 L per hour for the first two hours of operation. Contingency testing showed that the heater copes well with overburden ingress into the ice-hole. ARES's pump can extract water at up to 5 L/hr, and it was shown to be able to pump in conditions of highly fouled water. In fully integrated dry runs, the drill was confirmed to be able to penetrate all overburden types expected at the competition. Drilling and digital core creation were tested by drilling into a stratified material sample. Team members blind to the sample's actual composition then developed an interpretation of the data generated to determine the number, depth and relative hardnesses of the layers.

7 Tactical Plan

The primary risks involved in the operation of ARES are hole collapse and drill or heater failure. Each of these risks has been evaluated and mitigation strategies are in place. If the hole collapses while the heater assembly is not lowered in, the drill can simply be reinserted into the hole and used to excavate the collapsed overburden. If this does not succeed, ARES would move on to drill a new hole in a location adjacent to the failed hole. In the case of hole collapse during the water extraction operation, the heater would be turned off and given 5 minutes to cool down. Then, ARES would attempt to extract the heater assembly from the hole with the winch. If this fails, crew members would manually pull on the heater umbilical to extract it. In the worst case scenario where the heater cannot be manually extracted, the umbilical would be cut and a backup heater would be installed.

Previous iterations of the drill bit have failed in long run tests. We believe that the most recent version of the bit effectively mitigates these problems by replacing temporary screwed connections with welded connections. However, in the event of a mechanical failure of the drill bit, the team has backup flute segments that can be used to assemble a new drill bit. The team also has two backup heaters, which will be used in case of irretrievable hole collapse or electrical failure of the primary heater.

8 Safety Plan

ARES team members and observers will keep their entire bodies, including their hands, outside the footprint of the system while the drill is spinning. ARES also includes a heater that reaches an extremely high temperature to produce infrared radiation. The heater will only be activated downhole. An infrared thermometer and/or the internal thermocouple are used to verify the temperature of the heater before handling it after it has been turned on.

The power distribution elements pose a dangerous risk of shock. All wires were sized for ampacity using NEC code, wiring diagrams have been made for all circuits, wires are wrapped together and routed cleanly to reduce the risk of short circuits, and low current control elements have been separated from higher current elements in the enclosure. A Pelican air case and cable glands are also used to prevent exposure to dust and moisture. A single switch can be thrown to disconnect the entire system from power in the event of an emergency, and stop buttons have been added to the user interface for remote deactivation of various operations as well.

9 Paths to Flight

9.1 Martian Water Extraction

Manned missions to Mars will require significant quantities of liquid water to provide life support, produce ascent vehicle fuel, do laundry, and supply chemical and agricultural experiments. A 2016 NASA assessment indicates a one year mission with a crew size of 5 would require over 40 tons of water to provide these needs (Hoffman et. al). To produce this much water from in-situ water ice deposits, a long term well would need to be established on a large ice deposit. A path-to-flight version of ARES would be suitable for the establishment of such a well. Because it uses infrared radiation to melt ice, ARES continues to apply a high level of heat to the ice even as the melt-hole grows in size, making it an ideal candidate for the creation of large, long-term wells.

Any method that relies on a pool of water to conduct heat would face issues in Mars's low pressure atmosphere. Without sealing and pressurizing the hole, the ambient pressure (being on average just below the triple point of water) would prevent a water pool from forming. In a hole pressurized to just a few kPa above the triple point of water, as would be seen in the path-to-flight version of ARES, water would begin boiling at as little as 30 ºC, making a water pool an infeasible means for heat transfer. Alternatively, any method that relies on air as a transmission medium would face the slow process of extremely slow to non-existent convection in the low-to-no-atmosphere environments of the Moon and Mars. Radiative heating avoids these problems by applying heat energy directly to ice regardless of melthole size.

Creating an ARES well on Mars would begin by drilling the hole, which could be accomplished by an autonomous rover-mounted drill or a stationary drilling rig. After drilling is complete, a long-term water extraction rig would be installed. This structure would be firmly affixed to the Martian surface, which could be achieved with pins driven into the surface at an angle through holes at the base of the structure at each of three or four positions equally spaced around its perimeter. The structure would contain the reel from which the heater and water extraction tubes are sent downhole, and would also contain the pump, filter, water collection tank, and compressor for the apparatus described below.

A rover-based drill has the clear advantage of allowing a well to be drilled and a water supply to be established before humans land on Mars. However, drilling a hole and installing a long term water extraction structure would be a challenging feat for an autonomous rover to accomplish. A drill on a stationary frame and a long term water extraction structure could be set up and monitored by astronauts much more easily and at a much lower weight and cost. More information on the ice deposits targeted would need to be known to choose between these options.

Given the low atmospheric pressure on Mars, the current rotary hammer drill that is used will not be suitable as it relies on a piston mechanism to compress air and create the rotary percussive action. Though the drill itself will need to change, the use of rotary percussive drilling is not new and has been proven successful during previous Apollo missions. The low pressure atmosphere also means particles of dust and cuttings are able to move much more freely as they are not slowed down by the atmosphere. To prevent excessive debris from being kicked up from the drilling operations, a sheet metal shroud would be placed over the hole before drilling.

The water extraction and filtration system would also require modification for a mission to extract water on Mars. With the exception of the inlet mesh, filtration would be separated from the system entirely. ARES would pump water directly into collection tanks, where it would freeze. Once full, collection tanks would be transported closer to their base via rover, where the ice collected in the tank could be re-melted and filtered. This reduces the complexity of the water extraction system and reduces the severity of the risk of filter failure, as water collection can continue unabated, and astronauts are on hand to immediately fix any problem. A filtration system located near the base of operations could also be better integrated into a water recycling system. Recycling water used for drinking, laundry, and other non-consumptive needs would significantly reduce the mission's water needs.

The fundamentals of the filtration system could remain largely the same with a regenerable mesh filter. Because of the atmosphere's inability to support liquid water, the purge valve regeneration system would need to be modified to a wholly internal backwash system with a removable sediment trap that could be cleaned after a set number of cycles. An additional filtration step would need to be added for removing perchlorates.

To produce the amount of water needed to supply a manned mission, the heater would need to be scaled up. The drill would be scaled to accommodate this larger heater, and increased in length as needed based on information about the specific ice deposits targeted for extraction operations.

At an average of 610 Pa, Mars's atmospheric pressure lies just below the triple point of water (Haberle). This is the most important and challenging environmental characteristic to overcome in the collection of liquid water from ice on Mars. ARES would overcome this challenge by sealing the hole near the top of the ice deposit and pressurizing the resulting chamber to produce liquid water downhole. Pressurizing the hole above the triple point of water would require only 1 Pa gauge pressure, however, this would leave the liquid water highly unstable, with a small increase in temperature causing it to boil off. By raising the pressure by as little as 6.4 kPa (less than 1 psi) to 7 kPa, the boiling point of water would increase to more than 38 C. This would provide a comfortable operating environment for ice to be melted into water and sucked into the extraction tube without significant boil-off.

A 7 kPa pressurized hole could be accomplished with the mechanism shown in figure 8. This mechanism, located on the heater assembly umbilical, would consist of an air tube, valve, and inflatable silicone tube. The air tube, which would be attached to a compressor on the other end, would be used to inflate the silicone tube to seal the hole. Once the hole is sealed, the valve would be actuated, and air from the supply tube would be used to pressurize the hole. A pressure sensor inside the chamber would be used to monitor the pressure through extraction operations and the compressor would be used to maintain pressure by continuously pumping air into the hole as it expands in size. This assembly would be attached to the umbilical with a bushing, allowing the heater assembly to freely slide further down the hole once the hole-sealing tube is inflated and secured in place.

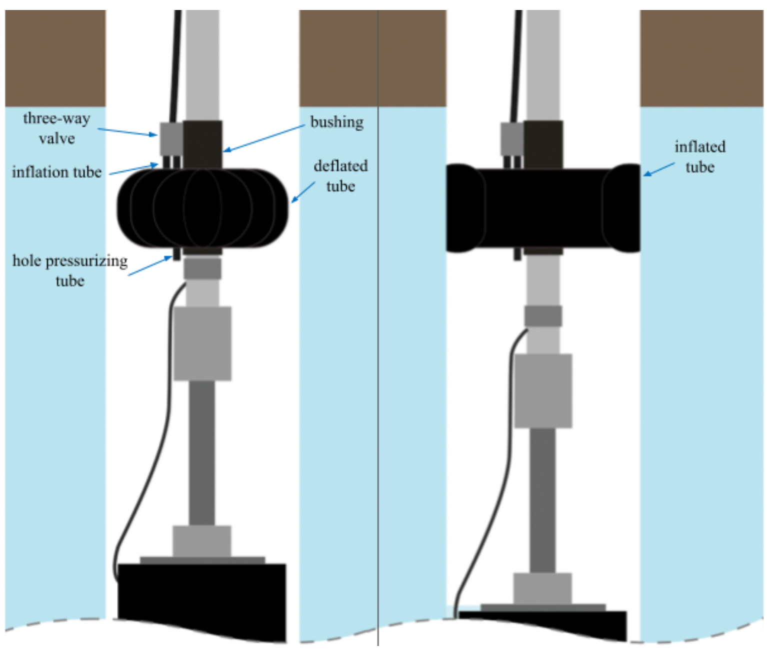

Figure 8. *Proposed hole pressurization apparatus*

In addition to this sealing and pressurization mechanism, the heater assembly would need to be modified by thickening and improving the insulation between the heater body and the extraction tube. The bottom section of the umbilical that passes through the bushing on the hole pressurization apparatus would need to be treated with a heat resistant resin or replaced with a more rigid structure, as the current sleeve is flexible enough to potentially bunch up and jam on the bushing.

The Martian environment's other unique properties, including intense temperatures, low gravity, high irradiation, and fine dust would impact the design of a path-to-flight version of ARES. To combat low and widely varying day-to-night temperatures, a version of ARES sent to Mars would need to be designed and toleranced for the thermal cycling it would experience. Sensitive electronics would need to have nearby heaters to protect them from damage caused by low temperatures. The water extraction system, including the tubing, and pump would also need integrated heating to keep water liquid and melt ice deposits to allow the system to restart in the case of power failure. Power and control electronics would need to be shielded from solar irradiation with robust housings. The water extraction system structure would need to hold the winch, pump, and compressor in a weather-tight enclosure to minimize dust ingress over the long periods over which it would operate on the Martian surface. In addition to protection from general environmental dust, dust from the hole site could also damage the moving parts of the water extraction system, so the winch, compressor, and pump would be sealed off from the hole with the exception of a hole for the heater/water-tube umbilical.

9.2 Lunar Prospecting

Prospecting for a digital core on the moon would require a number of significant modifications to ARES. If producing a digital core is the sole goal of the mission, the entire water extraction system, including the heater, pump, and filter could be discarded. For a prospecting mission, the system would be mounted on a rover to allow collection of cores at a wide variety of sites of interest. A ground-penetrating radar (GPR) would be added to ARES's arsenal, allowing the rover to choose drilling sites of the most interest to scientists.

In this case, the heater assembly would be replaced by a sensor suite. The sensor assembly would include a lighting and photography system. A concept sketch of this is pictured in figure 9. For the camera, a number of miniature camera modules with different lens types would be paired with a set of filters similar to the ones used to gather geological data from Curiosity and Perseverance mast-cams. Unlike the circular arrangement on the Mars rovers, on ARES these filters would be arranged on a flexible film tape on rollers, which would be driven by a miniature stepper motor. In addition, the sensor suite would contain one or more miniature spectrometer probe ends to measure visible, ultraviolet, alpha rays, and/or x-rays. An electrode with flexible metallic strips would also be included on this assembly to collect conductivity data on the materials in the hole wall.

To enable the system to gather as many digital cores as possible, the drill bit would be upgraded to a hardened steel with a carbide coating. Additional heat sinking or an active cooling system would need to be added to the drill to account for the lack of atmospheric convective cooling.

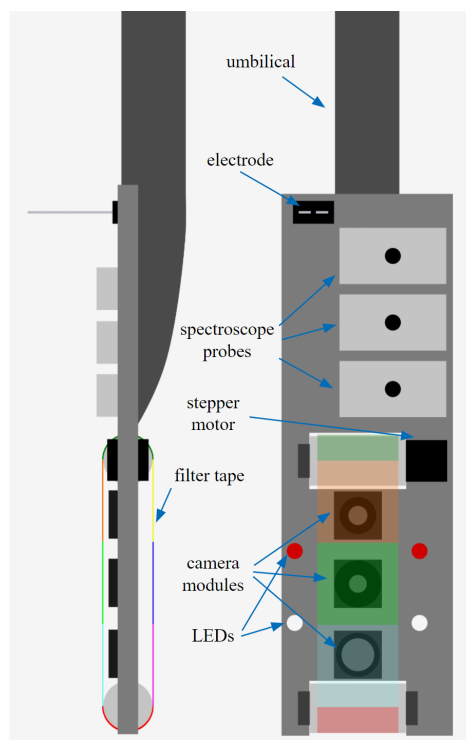

Fig 9. *Concept down-hole sensor suite*

In many ways, the environmental challenges faced on the Moon are more extreme versions of the challenges faced on Mars. Instead of having a thin atmosphere, the Moon has no substantial atmosphere. The surface temperature of the Moon reaches much higher and lower extremes than the temperature on Mars. Moon dust is finer, sharper, and able to spread further than that on Mars. To survive this challenging environment, equipment sent to the moon must be designed and toleranced for high temperature variations. Moving components must be sealed against dust ingress to the greatest degree possible.

If water production is to be attempted, a water extraction structure and hole-pressurization apparatus similar to the one described for the mission to Mars would be used. Given the total lack of atmosphere on the Moon, the initial air supply to pressurize the hole will need to be flown in. After water has been produced, additional air would be supplied by hydrolysis of a small portion of the water collected.

The temperature swings on the moon from roughly -175℃ to 175℃. These extremes pose the greatest obstacle to establishing a lunar base. A rover mounted drill would have to plan its missions around lunar dawn. Using on board sensors the unmanned rover can travel places an astronaut could not and have extended hours of operation in a given day. The lunar base itself would need to be well insulated, perhaps excavating and establishing a subsurface structure with insulating and reflective material above it to reduce the daily fluctuations. The drill-rover would have to retreat to such a base as the temperature dips too low or rises above it’s designed operating temperature range.

For a water extraction mission, fine water filtration would be moved to the base of operations to reduce points of failure on the drill. A sediment filter would suffice to protect most drill components, and fine filter cartridges could be safely maintained from an operator at the base.

9.3 Additional Alterations For Path to Flight

For either of the above mentioned missions, the prototype would also need the following design changes:

Longevity- Given the cost of moving materials from earth to space, it is prudent to select equipment for its ability to last as long as possible and to be durable in extreme environments. The deployable version of Ares would replace its commercial hammer drill with a brushless dc stepper motor with a planetary gear stage, and either simulate a hammering operation with stepper pulsing, by a final mechanical hammer stage, or a piezoelectric actuator similar to that of the Auto-Gopher II (Badescu et al.).

Reliability- While the Earth based model is capable of prospecting with its two vertical stepper motors aligned, they will eventually drift out of phase and require manual re-alignment. The deployable actuation would be facilitated by using a chain and gear to drive the vertical axis in step with one motor, or with a singular drive screw and a guide rod.

Efficiency- The use of two Arduino 2560’s has been successful as a replacement solution for a flawed early design. However, it is not the most effective or efficient way to accomplish the task. A refined version of Ares would use a Field Programmable Array (FPGA) as its main controller.

Power- The current design is powered by 120VAC single phase power. We recommend that a path-to-flight version be powered by a radioisotope thermoelectric generator (RTG). The continuous, predictable power provided by an RTG would allow ARES to produce water continuously through the day and night. A solar array and battery storage could also be used to provide the system with constant power. In either case, the input to ARES would be a DC source. To accommodate this, DC to DC converters or linear step-down regulators would be used to provide appropriate voltages to each component, and the AC heater would be replaced with a DC heater.

10 Project Timeline

An outline of the timeline of the design, construction, and testing of ARES is shown below in table 2.

Table 2. ARES development timeline

Phase & Task #	Task Title	Date	Phase & Task #	Task Title	Date
A.1	Project task defined	9/11/2020	**D.1**	Primary parts manufacturing complete	2/26/2021
A.2	System requirements defined	9/18/2020	**D.2**	**Mid-Project Status Review**	**3/18/2021**
A.3	Project Management Plan implemented	9/18/2020	**D.3**	Initial subsystem level testing complete	3/30/2021
A.4	**Notice of Intent filed**	**10/1/2020**	**D.4**	**Finalist Selection**	**4/2/2021**
B.1	Background research compiled	10/2/2020	**D.5**	Major systems (drill, heater, pump filter) integrated testing complete	4/27/2021
B.2	System level trade studies completed	10/12/2020	**N/A**	End of Semester & Graduation	5/26/2021
B.3	Subsystem level trade studies completed	10/24/2020	**D.6**	Reworked mechanical parts completed	7/23/2021
B.4	Preliminary Design Review	11/2/2020	**D.7**	Full electrical integration completed	8/27/2021
C.1	**Project Plan Submitted**	**11/24/2020**	**D.8**	Fully integrated dry run completed	8/27/2021
C.2	Critical Design Review	12/7/2020	**D.8**	**Technical Paper, Poster, Integration Video Submitted**	**8/31/2021**
C.3	**Semi-Finalist Selection**	**12/14/2020**	**D.10**	**On-site Competition**	**9/22/2021**

11 Budget

For a summary of the project funding and costs please refer to Table 3 below.

Sponsorship for this project includes NASA, San Diego State University ($12,189), a gifted Emisshield application for the IR heater ($400 value), and team member sourced funds ($2,189). Pandemic shortages coupled with the Chinese new year forced multiple design changes and more expensive US product purchases to meet project milestones. Competition registration fees were not originally factored into the team budget as well as many bulk materials the team purchased as the project progressed. Many of these bulk materials will be available for future competing classes and will reduce their overhead.

In total the cost to build the project in parts alone was $17,628.82, project testing included purchase of ice blocks, gravel, repairs of parts etc. and totals $500, and shipping our drill to competition is estimated to be $470. The team used open source software and student software licenses to complete the work.

Table 3. Budget sources and expenses (excludes team member travel expenses)

Sponsorship	Totals	Expenses	Totals
NASA Grant	$10,000.00	Design	$0.00
SDSU Student Success Fee Fund	$8,389.00	Drill Construction	$17,628.82
		Testing	$324.00
SDSU College of Engineering Fund	$3,800.00	Shipping (estimate)	$470.00
		NASA Fee	$1,800
Funded by the Team	$2,043.00	Travel	$3,691.20
Grand Total	**$24,232.00**	**Grand Total**	**$23,914.02**

A1 Appendix: References

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