NASA RASC-AL Special Edition: Moon to Mars Ice & Prospecting Challenge

Planetary Ice Extractor

Autonomous Prototype Solution for Lunar or Martian Extraction
09/05/2018 – 05/19/2019

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Project Sponsored By: NASA, Cosine Additive, Control Flow Inc, Anko Products

1. Introduction

This report details the completed work towards the NASA RASC-AL Special Edition Competition from project initiation up to 05/19/2019, as per requirements of the NASA RASC-AL Special Edition Challenge. Representing the University of Houston are, Joseph Pauwels, Sharlyn Tijerina, Andrew Advani, and Jacob Frady, under the guidance of Dr. Ralph Metcalfe and Dr. Christiana Chang.

Creating a sustainable Mars colony has become a prominent topic in today's aerospace community. One of the main constraints limiting interplanetary travel is carrying enough fuel for a round-trip flight, which would be exorbitantly expensive taking into consideration it costs $10,000 to send one pound of payload from the Earth to space [4]. While this problem can be reduced by increasing efficiency of orbital maneuvers or propulsion systems, these methods are not effective enough to create a viable, long-term solution to a sustainable Mars colony.

Recently, NASA discovered large ice deposits on the surface of Mars which triggered a revolutionary solution to the aforementioned problem: harvest the water, split it into H_2 and 0_2 atoms, and use these for fuel [5]. This is an intricate process because the ice contains isotropic poisons and perchlorates and is covered by a layer called overburden that can range in microstructure from sand to hard stone. Another difficulty is that most of the atmosphere of Mars has a pressure below the Armstrong limit, meaning when exposed to the atmosphere, ice will sublimate into a gas.

To better understand the process of subsurface ice mining and to spur innovation, NASA created the NASA Revolutionary Aerospace Systems Concepts - Academic Linkages challenge. To answer this challenge, the University of Houston team has designed and fabricated the Planetary Ice Extractor (PIE), where this device will create a digital core of the simulated Martian surface at competition by monitoring the weight of the bit, drill through various overburden layers using a masonry bit, melt the ice using a resistance heater, extract and filter the water through a process called electrocoagulation where the coagulated particles will be filtered through a 15 micron stainless steel back washable mesh filter.

2. System Description

2.1 Water Extraction Capabilities

The heating element of the water extractor was shown to be able to melt ice at a rate of 7.5 mL/min at 1.5 A and 30 mL/min at 4.5 A. The relation of amperage draw to melt rate is non-linear, and the team expects a melting rate higher than 7.5 mL/min as both the heater and the control relay are rated for 3 A (approximately 360 watts) of output. The peristaltic pump used for the extraction is commercially available and rated for a flow rate of 50 mL/min which is enough to meet the team's goal of 7.5 mL/min of water extraction.

2.2 Capability to Prospect for a Digital Core

The ability of the PIE to prospect for a digital core is based on the ability of the ACS motion control hardware to detect changes in the downward pressure of the drill via the amperage draw of the vertical axis of the drill. This data (along with the rate of penetration) will be plotted with respect to the depth of the drill. This data can then be exported and interpreted by the operators of the device to determine the locations of the overburden layer boundaries and relative hardnesses of each layer. Further development could lead to more accurate estimates of the unconfined compressive strength of each layer of material.

2.3 Mounting System

The mounting solution for PIE was accomplished by counterboring 10 holes in each of the x-axes rails. Each of these holes is ⅛" with a ⅜" counterbore ¼" deep. A 1.00" flanged, wood screw will be used to secure the rails to the platforms. A mock-up platform was constructed as seen in Fig. 1 and Fig. 2 to verify the mounting solution.

Fig. 1. PIE on Test Mount

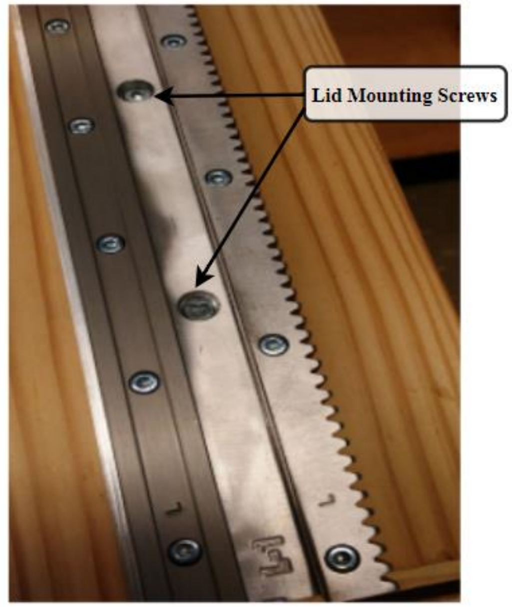

Fig. 2. Lid Mounting Solution

2.4 System Excavation Operations

Excavation for the PIE begins by moving the drill over the desired hole location. Moving the drill into location is made possible by using the X-axis motors that translate forwards and backward motion along the PIE mounting rails. Once the drill is in the target location the Z-axis motor controlling the vertical motion begins rotating the ball screw slowing descending the drill at 10 mm/s to the overburden surface until it touches the surface causing compression on the drill which translates to a current spike on the Z-axis motor that tells the system to stop descending and retract 10mm. The frame of the PIE can be seen in Fig. 3.

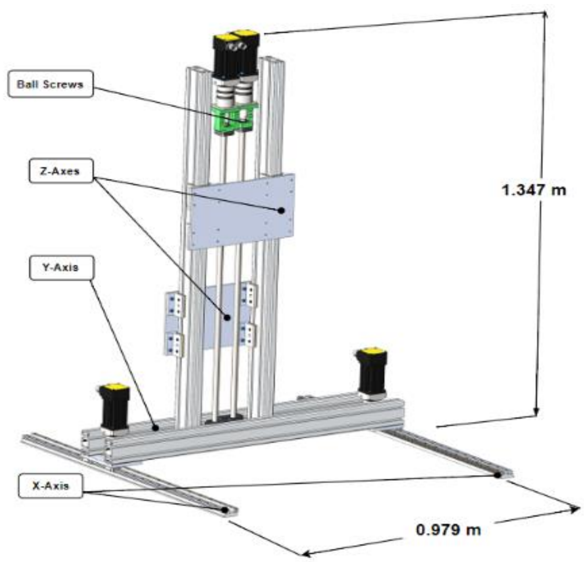

Fig. 3. Frame of PIE

Upon reaching the overburden, the drill rotation motor is engaged, and a drilling cycle begins. Drilling through the overburden to the ice interface will be accomplished by rotating the drill at a constant 300 rpm and using a pecking cycle which will descend 50mm each peck and retract 10mm to elevate pressure on the bit and allow regolith to be brought to the surface. The pecking cycle will help increase the life cycle of the drill and help to produce a well-defined borehole for water extraction. Once the pecking cycle has reached the maximum depth, roughly 25.4mm past the overburden layer the drill will be retracted and the X-axis will be engaged forward to begin water melting, extraction and filtration. Once the hole is completely evacuated the PIE moves to its next location and the cycle is repeated.

2.5 Water Extraction System/Technique

Extracting water from beneath the overburden requires a separate tool head as seen in Fig 4. This tool head is equipped with a peristaltic pump, ¼" tubing, and a commercially available resistance heater with an integrated thermocouple which will be lowered into the borehole created by the drill tool head. Once the heater is lowered into the hole, the ice will be melted via radiation and/or conduction, depending on the amount of contact the heater is in with the ice, until water surrounds the cartridge heater. The water will convectively cool the cartridge heater while simultaneously moving the heat towards the ice surrounding the heater until the heater temperature reaches an equilibrium above the melting point of ice. Water will then be pumped out of the borehole using a top-mounted peristaltic pump at a rate of 50 mL/min directly into the electrocoagulation system. Once the electrocoagulation system is filled with water, the pumping stops but melting continues as the electrocoagulation process begins. Once the water in the electrocoagulation box is filtered out, the cycle of melting, pumping, and electrocoagulation repeats until the borehole is entirely excavated of water. This will be determined by reading the temperature of the thermocouple inside of the cartridge heater. Once the equilibrium temperature of the water changes, and no more water can be extracted from the hole, the PIE will begin drilling a new hole.

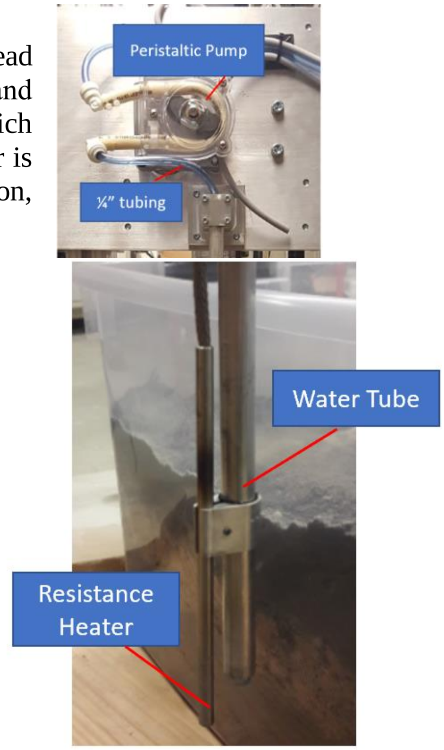

Fig. 4. Water Extraction Tool Head

2.6 Prospecting for a Digital Core

To prospect for a digital core, the WOB will be monitored during the pecking cycle of the drill. As the drill meets the surface of the overburden (or a new layer of overburden), the WOB will be dynamically adjusted to where the rate of penetration is slightly above zero such that the threshold WOB can be determined. As the drill proceeds downwards, the rate of penetration will change once the drill reaches a layer boundary as the material will be harder or softer with a different threshold WOB required for penetration. This location of the layer boundary will be recorded and the new threshold WOB will be calculated. The threshold WOB can then be used, with equation (1), to approximate the unconfined compressive strength of the material [1].

$$WOB_{threshold} \approx UCS * Area_{cutter} \quad (1)$$

2.7 Filtration and Water Collection

The filtration system consists of a 4.2" x 4.2" x 1.7" electrocoagulation chamber containing six evenly spaced 2024 aluminum plates. The electrocoagulation system holds about 500mL of water which is connected to a 15-micron stainless steel mesh filter chamber as seen in Fig. 5. 2024 aluminum plates were chosen for the process due to its high corrosivity, which will aid in the electrocoagulation process.

Water from the water extraction will pass through the electrocoagulation chamber initially where the process will run for 15 minutes maintaining a constant amperage. The PIE's software will change the polarity of the plates once the software reads the threshold of 24V by using a water level sensor to avoid the blockage of particles on the positively charged plates. After 15 minutes, the coagulated particles will be captured using a 15-micron stainless steel mesh filter where the purified water will remain. After three filtration cycles, the filter will be back flushed by using 200mL of unfiltered water from the borehole. The fluid network of the filtration system can be seen in Fig. 6. below. The filtration system can filter 1500 mL per hour.

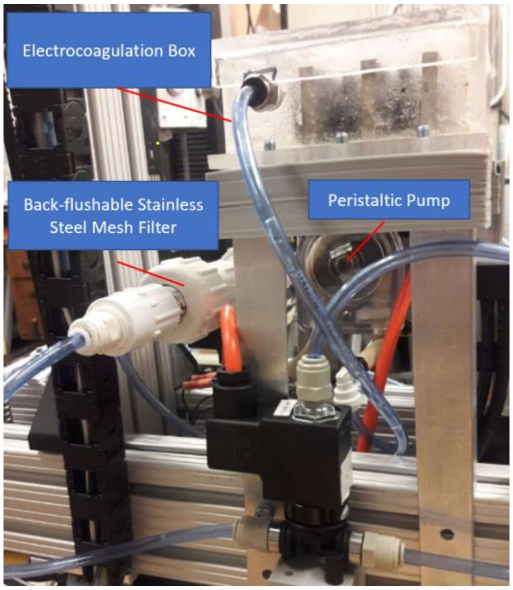

Fig. 5. Electrocoagulation System

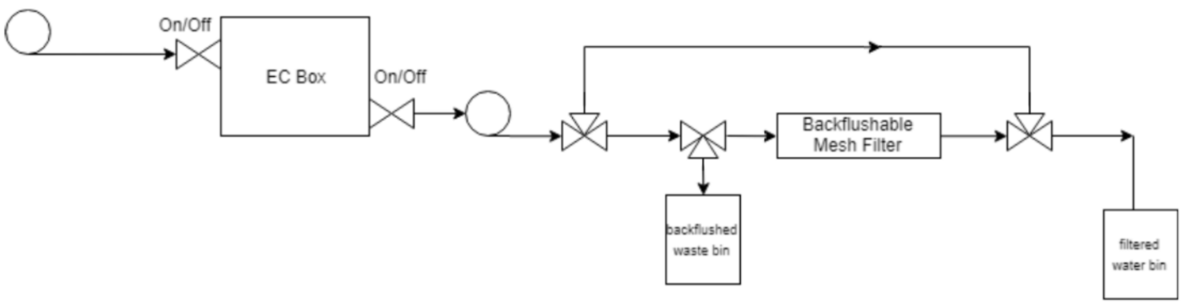

Fig. 6. Fluid Network of Filtration System

2.8 Mining Through Overburden Layers

When evaluating the possible overburden layers presented, the clear choice, because of the concrete and rock, was to choose a quad head masonry bit. While clay and dirt will be present among the layers, a quad head masonry bit will increase drilling time through concrete by 25% over a standard bit and the carbide insert as shown in Fig 7 will increase the life of the drill bit as it is capable of drilling multiple hole before becoming dull.

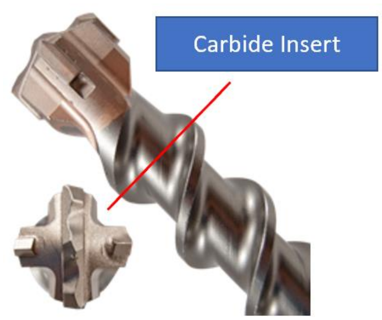

Fig. 7. Carbide Insert on Drill

2.9 Managing Temperature to Prevent Drill from Freezing in Ice

Once the drill has started penetrating the ice, a reduction in RPM's will be used to reduce heat generation downhole. Additionally, the use of the previously mentioned peaking cycle will limit the heat generation and freezing in the ice. The strategy of the PIE is not to penetrate to the bottom of the container but to start a bore hole in the ice for the heater to melt the ice for extraction. Because of this strategy, freezing on the drill will be negated.

2.10 Control and Communication System

Control of the PIE will primarily be performed through the custom-made software dashboard that communicates with the device over TCP/IP on a single CAT5e cable. The dashboard contains all necessary jog controls, telemetry, autonomous execution profiles, machine settings, etc. that will be required during remote crew and autonomous operation. The dashboard contains no logic to control the device, the dashboard simply relays commands from the operator to the device and telemetry from the device back to the operator. Therefore, in the event of a failure on the operator's machine, the device will continue to operate autonomously. The dashboard will simply need to re-establish a network connection to the device. The dashboard interface is shown in Appendix B. Instructions for obtaining and compiling the source code can be found in Appendix B.

The commands sent from the dashboard to the device are handled by the ACSPL+ device software running on the PIE. This device software is responsible for the motion control of all the axes and the actuation of all solenoids, valves, pumps, heater, and the electrocoagulation system. In addition, the device software includes subroutines for the various drilling profiles, jog controls, water extraction and processing, and all subroutines required for remote crew and autonomous operation. Instructions for obtaining the source code can be found in Appendix B.

The hardware used to control the PIE is based on the ACS motion control platform utilizing an ACS SpiiPlusEC as the main processor, an ACS UDMpm for high fidelity motion control and monitoring of two axes, Leadshine ACS306 motor drivers for the 3 additional axes, and several Beckhoff EtherCAT I/O modules for additional digital and analog inputs and outputs. The top-level electrical schematic for this control hardware is shown in Fig. 8.

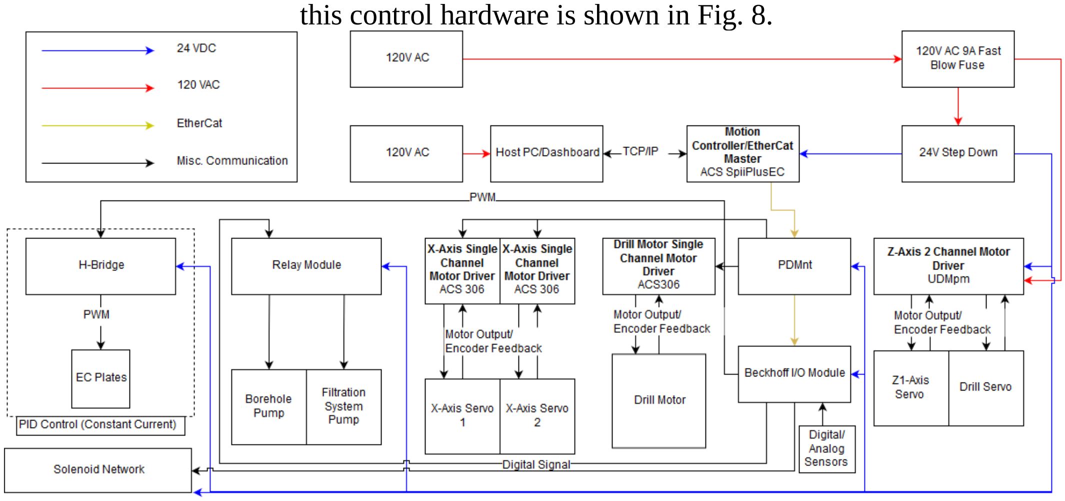

Fig. 8. Electrical Schematic for Control Hardware

2.11 Datalogger

A wide array of data will be collected such as the amperage draw from the drill motor and the vertical axis moving the drill, the water level in the electrocoagulation box, the amperage and voltage of the electrocoagulation process, the rate of penetration (ROP) of the drill, the WOB of the drill, the heater temperature, etc. This data will be displayed and logged in various forms. Data that is required for further processing (such as the WOB and ROP for digital coring) will be displayed on a real-time cartesian plot and can be exported to a CSV file for further processing in excel or MATLAB. Additional system telemetry (such as the electrocoagulation amperage, the heater temperature, WOB, etc.) will always be displayed on the dashboard for the operator's knowledge. These values will only be processed by the system in operation and will not be logged for further processing.

3. Technical Specifications

Table 1 shows the technical specifications for the overall system, drilling, and the electrical and software components of the system.

Table 1. Technical Specifications of PIE

System Specifications	**Overall Mass (kg)**	**60**
	Overall Volume (m^3)	**1**
Drill Specifications	**Length (cm)**	**91.44 (36 in)**
	WOB (N)	**0-150 (dynamic loading)**
	Rated Load (N)	**3594 N**
	Max Drilling RPM (RPM)	**600**
	Torque (Nm)	**2.86**
Electrical and Software Specifications	**Computer**	**ACS SpiiPlusEC EtherCAT Master**
	Communication Interface	**TCP/IP over Ethernet**
	Software	**C# Dashboard & ACSPL+ Motion Control**
	Power	**120 VAC with 9 A fast blow glass fuse**
	Telemetry	**WOB, Power, Sensors**

4. Design Changes/Improvements

Since the mid-project review submitted on March 14th, 2019, the team chose to remove the on/off valves which were attached to the electrocoagulation system which served to close off the electrocoagulation system while it underwent its process. The valves which were being used proved to be low quality and frequently leaked and heated up too quickly for the duration the valves were being used. To mitigate any chance of burning out during competition, these valves will be removed and the halting of the two pumps will be used to prevent any water from further entering into the filtration system while electrocoagulation is in process. In addition, the electrical box was mounted vertically on the gantry to eliminate excess cable chains and to clear out additional space for drilling and water extraction as seen in Fig 9.

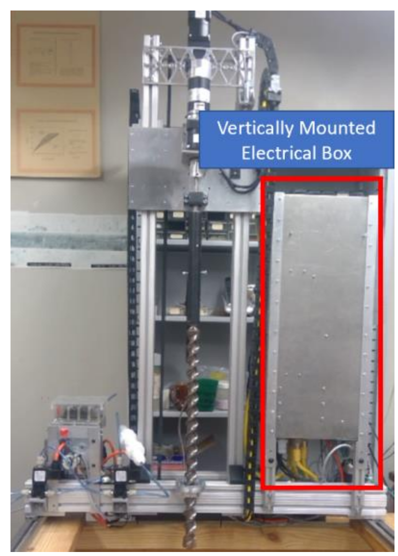

Fig. 9. Updated Configuration of Mounted Electrical Box

5 Challenges

The greatest challenges the team had to overcome were component lead-times, scheduling conflicts, and delays in acquiring components for the ACS control system from our sponsors.

Lead time on major components for the project such as ball screws and associated hardware pushed back the early fabrication process. The team was able to mitigate the effects of this delay by building sub-assemblies and checking component fits in the interim time.

Coordinating each member's schedule caused issues in production as well. All the team members work full or part time, lead student organizations, have a full course load of classes.

Therefore, coordinating everyone together to build has proved a difficult. Therefore, the team acquired a lab space in the engineering building early February, which has made it easier for each member to work on the project in their own time. Likewise, each member was assigned a subsystem for the project which each team member has been working on independently.

Lastly, the largest setback was the sponsoring company being unable to donate the equipment until less than a week before the mid-project review deadline. Although the circumstances could not have been mitigated, in the meantime, the team was working on elements of the software, such as the dashboard design, and familiarizing themselves with the control architecture. Ultimately, the team was able to work through the delay and achieve the goal of a partly functional system by the mid-project review.

6. Overall Strategy for the Competition

The PIE will be primarily operated autonomously and therefore will generally follow the concept of operations shown in Fig. 10. Additional considerations such as back flushing, melting and pumping timings will depend on sensor feedback from the water level sensor. Back flushing will occur once the water level sensor detects that the rate of water draining from the electrocoagulation box slows indicating a clogged filter. Additionally, the extractor pump will stop once the electrocoagulation box is filled with water, whereas the heater will constantly operate as not to freeze but will enter a reduced power mode once the desired volume of water is predicted to be at the base of the borehole. The digital core will be generated manually after the device autonomously collects and logs the required data for generating the digital core during a modified drilling cycle. During normal drilling operation, the device will use a pecking cycle to reduce loading on the device while drilling through the overburden as fast as is reasonable.

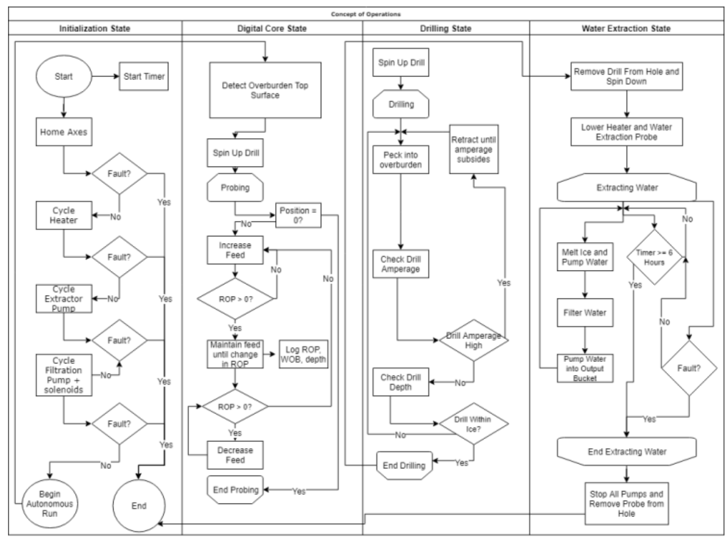

Fig. 10. PIE ConOps

7. Summary of Integration and Test Plan

While integrating subsystems, working in parallel, a testing platform was constructed as in Fig 11. The testing platform was made to resemble the drilling conditions at competition as best known. Specifically, this setup consisted of several different layer of soft soils, small stones, large rocks, and a layer of sandstone. The average thickness of each of these layers was roughly three to four inches. To prevent the re-construction of this platform with every test, the ice was placed into a separate container for most of the preliminary individual and integrated tests.

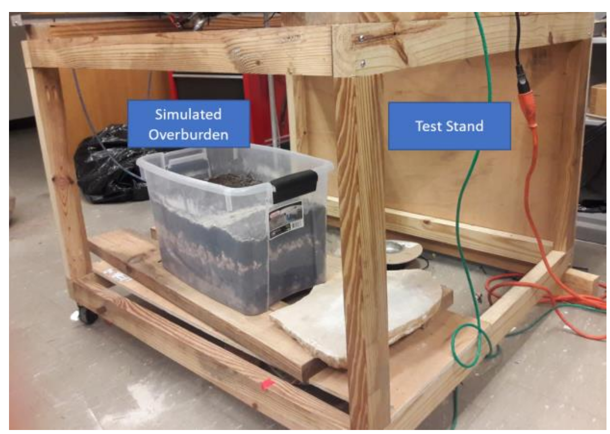

Fig. 11. Constructed Test Stand for PIE

After the integration of the subsystems, two separate verifications were conducted: individual verification and grouped verification. The individual verification was conducted as an intermediary set of tests to quickly assess whether each of the subsystems - who have undergone slight modifications - would perform as they did during the initial testing-and-design phase, without being slowed by any unforeseen complications in the autonomous software. This process was successful, and the summary of the results are broken down by subsystem and listed in Table 2. The only subsystem to have not been completed successfully was the digital coring. During the digital-coring process, the control system is monitoring the current applied to the motor and comparing that to the rate-of-change of the rotary encoder. Comparing the encoder with the amperage input, the WOB can be calculated, which is critical in determining the compressive strength of the drilled materials. The motion control system can read the amperage to a minuscule degree, but there is still an excessive amount of noise in this data making it difficult to accurately sense the loose soils or sands. Several approaches have been tried to attenuate the noise. The best performing of the attenuation methods was by using moving averages, and although this solution has not been perfected at this time, it shows significant improvement and will be continually tuned up until the competition.

Table 2. Individual Testing-System Verification

Experiment	Independent Variables	Dependent Variable	Expected Results	Achieved
Drilling Penetration Rate	Drill RPM and WOB	Hole Depth	Reach 0.8m depth in 15 minutes	Yes ☑
Ice Melting Rate (Cartridge Heater)	Power Consumption	Volume of melted water	7.5 mL of water melted per minute @ 180 watts	Yes ☑
Digital Coring	Drill rpm & WOB	Penetration Rate	Relative Variations in Material Compressive Strength	No ☒
Electrocoagulation	Current & Time	Water Clarity	Match pristine clarity of tap water clarity	Yes ☑

8. Tactical Plan for Contingencies/Redundancies

The team has considered contingencies for each subsystem which include drilling, digital core, heating, water extraction, and filtration.

Table 3. Contingency Plan Table

Subsystem	Cause of Failure	Contingency
Drilling	Wear on the bit	Have a backup drill bit
Digital Core	Insufficient/inadequate date collection	Manual layer probing with the drill
Water Extraction	Clogged tubing	Manual or automated reversal of the pump direction
Electrocoagulation System	Wear on aluminum plates or clogging of plates from debris	Have backup aluminum plates
Filtration System	Tubing gets clogged	Manual or automated reversal of the pump direction

9. Project Timeline

The project was initiated in early September of 2018 and followed through to completion in the Summer of 2019. The team expects to be completed with final debugging and tweaking prior to the competition during the week of June 3rd - June 7th, 2019. The timeline is shown in the Gantt chart in Fig. 12.

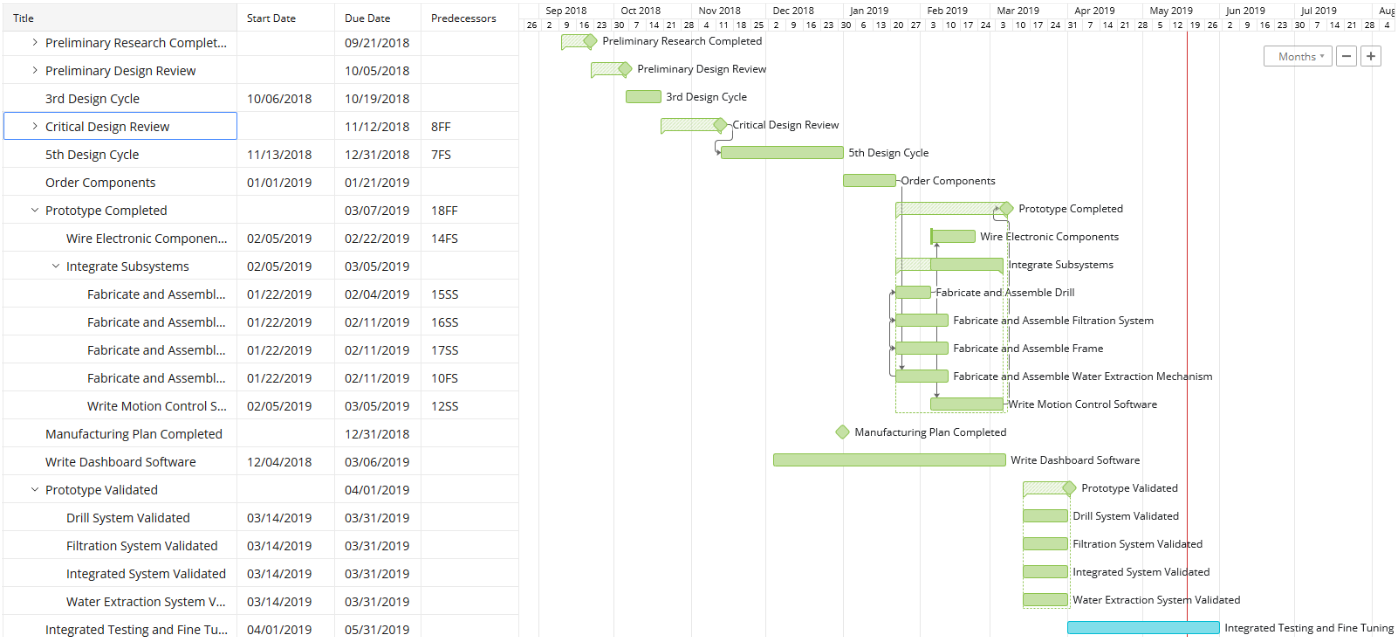

Fig. 12. Project Gantt Chart

10. Safety Plan

Table 3 shows a risk matrix for the PIE and the likelihood of each hazard to occur with its corresponding severity.

Table 4. Risk Matrix

		Consequence				
		Insignificant	Minor	Moderate	Major	Critical
Probability	Rare		7	5, 6	1	3
	Unlikely				4	
	Possible		2			
	Likely					

The hazards shown in the risk matrix correspond to the hazards enumerated below with their corresponding risk mitigation strategy.

1. Dust and Debris from drill thrown out of the test station into an individual's eyes.

    a. Safety glasses will be worn to prevent injury to eyes while device in operation.
2. Sharp edges on the device or drill may cut an individual
    a. Gloves will be used when moving or handling the device.
3. Drill may cause severe injury during operation.
    a. The device must not be handled while powered on or in operation.
4. Cartridge heater could cause severe burns if handled while in operation
    a. The device must not be handled while powered on or in operation.
5. Loose clothing could be caught in belt drive or rack and pinion drives.
    a. The device must not be handled while powered on or in operation.
    b. Individuals should remain at least 1 foot away from the device and test station while the device is in operation.
    c. Individuals should refrain from wearing baggy clothes, wear long hair, etc... that may get caught in the device.
    d. E-Stop switch (software or hardware) must be pressed if this occurs
6. Large sections of the device could fall and cause injury during assembly or transportation
    a. Individuals should wear closed toed shoes while assembling or transporting the device.
    b. At least two people are required to lift or move large sections of the device during assembly and operation.
7. High voltage power could cause electric shock
    a. The electrical box must not be opened while the device is in operation.
    b. Work on the electrical components must only be handled by UH team members.
    c. The electrical box should not be handled unless the system is disconnected from the wall.

11. Path to Flight
11.1 Path to Mars:

Introduction: Extracting water from the Martian surface offers a unique challenge due to a wide array of possible problems. These problems can arise from the atmospheric conditions, drilling through the crust, or in the extraction or purification of the extracted ice. Many of the difficulties in operating in the harsh atmospheric environment of Mars are due to the fine dust covering the surface and the ever-present solar radiation. The dust on the surface of Mars ranges in size but is largely between 1 and 50 micrometers - similar to talcum powder - and are likely electrified by triboelectrification and ultraviolet radiation [2]. The properties of this microscopic, electrified dust induce three major concerns: it will easy penetrate into bearings and electrical housings, it will induce electrostatic build-up to any electrically isolated equipment and can wreak havoc on electrical components. Other electro-mechanical considerations are associated with the unflagging radiation present at the Mars surface. This radiation increases the difficulty of maintaining electro-mechanical systems and has two distinct types: solar radiation which consist of low energy protons from the Sun and, the evermore heinous, Galactic Cosmic Rays (GCR) which are extrasolar, high-energy atomic nuclei [3]. Relatively, solar radiation is easy to mitigate, however, GCRs cannot be shielded against and can cause damage in both astronauts and electrical systems [3]. Fortunately, GCRs do not bombard the Martian surface evenly as can be seen below in Fig. XX. In Fig. XX, there is an apparent ideal mining zone (the large blue spot) in which contains a location knows as Hellas Planitia.

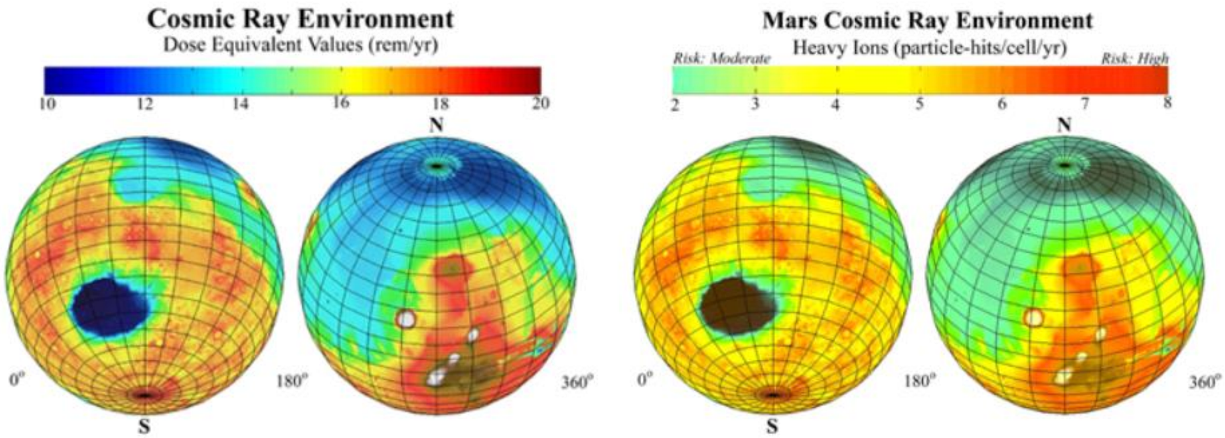

Fig. 13. Cosmic ray collision frequency on the Martian Surface [3]

The reason this area has relatively low levels of GCR is because this is a large impact crater and is topologically deeper than most of Mars. An added benefit of low elevation at this location is that the atmospheric pressure is above the triple point of water. While many of the challenges will arise due to do atmospheric phenomena, drilling, extracting, and filtering water will also have some unique obstacles to overcome. The drilling approach can vary depending on the operating location. To reach the ice, the drill could need to penetrate a wide range of overburden types, such as various shapes, sandstones, and volcanic basalt rock [6]. Each of these distinct formations have different hardness and thus require different drilling parameters or even a different drill bit geometry altogether. Each of the obstacles affects each of the subsystem designs differently.

Structure: The structure subsystem is comprised of all the mechanical components that serve as a central rigid body on which the drill, electronics, telemetry, and water extraction devices are mounted. Several susceptible features of the structure assembly are associated with the linear motion systems, which consists of a linear rails, bearings, and motors. The difficulty with many traditional metal-ball bearings are that they require grease to lubricate. Unfortunately, grease degrades in low pressure and high radiation environments [7]. To mitigate this problem, four possible solutions were surveyed: additive-doped greases, ceramic bearings, air bearings, and solid-state bearings. Additively-doped greases are expensive and still require complex distribution equipment to continually replenish the grease escaping the bearings. Ceramic bearings are relatively frictionless and therefore do not require grease at all. The drawback to ceramic bearings is that they are sensitive to intense vibrations which would certainly occur during the drilling phase. Air bearings are designed to use a thin layer of gas between two surfaces which allows the bearing to slide with very little friction. Air bearings could be a potential solution, but they need a steady supply of gas to operate, so this could be a potential weak point in the design if the machine ran out or was unable to capture the exiting gas for reuse. Finally, solid-state bearing was examined and selected for this project, and would be recommended for use on the Martian surface. These types of bearing are constructed out of a high-molecular-weight polymer. An example of this type of bearing can be seen in Fig. 13.

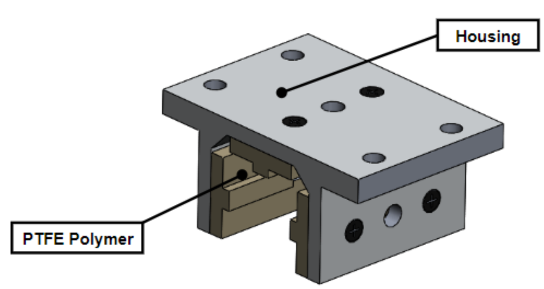

Fig. 14. Solid-State, PTFE bearing

Despite having higher friction, solid-polymer bearings where chosen due to their longevity in space environments and it stability under vibration. More specifically, a polytetrafluoroethylene (PTFE) bearing was chosen for this project because of availability, however, this should be changed to an ethylene-tetrafluoroethylene (ETFE), such as Dupont's Tefzel®, before being dispatched to Mars. Tefzel® was designed specifically to handle higher level of radiation and meets the 20,000-hour-criterion for constant radiation exposure [8]. Although polymer bearings are known for tremendous resistance to degradation in dirty environments, the microsized iron-oxide dust on Mars's surface is unique and a series of tested would need to be run to ensure that the bearing life would not decrease to less than the intended service life of the of the mining equipment. After finalizing the bearing, it is a relatively simple process to select the associated rail to minimize friction and decrease wear. Finally, the job of electric motor selection would be outsourced to Maxon Motor Company who developed brushless direct current (BLDC) motor for the previous Mars rovers: Sojourner, Spirit, and Opportunity. This company has extensive experience in radiation-hardened hall effect sensors used in the commutation of BLDCs.

Electronics: When designing electrical systems for the environment of Mars, very few atmospheric features cause a great deal of difficulties. Radiation, temperature, vibration and dust are the upfront concerns when selecting components. Radiation can cause wire insulation to degrade, scatter telemetry, cause software glitches, and reduce the functionality of transistors and other critical components. Radiation affects the electronics in different ways, depending on if the radiation is a continuous dosage, such as solar radiation, or a single event like those caused by GCRs as mentioned in the introduction to the "Path to Flight". A general overview to the types of damages corresponding to a single event or cumulative dosage can be seen in Fig. 14.

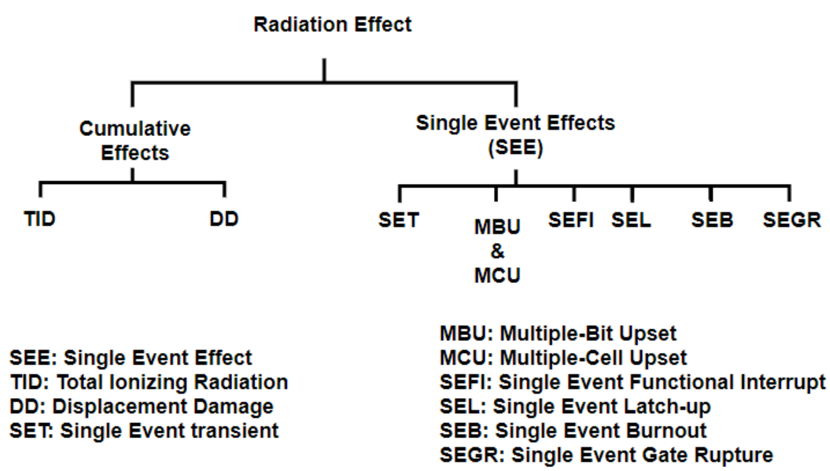

Fig. 15. Overview of types of failures and corresponding radiation type [9]

To mitigate these risks, all the hardware would be radiation hardened and shielded. To achieve this, all the microchips would be constructed on sapphire substrates to reduce the frequency of single event effects (SOS) caused by GCRs. To slow the degradation rate of the wiring insulation, all of the wire would be coated with a radiation resistant polymer such as Tefzel®. Additionally, the control cabinets and batteries would be heated with primarily with excess heat from the radioisotope thermoelectric generators that would be used to power the system during the first few weeks while this device is getting setup. After the solar arrays are setup and the radioactive fuel depletes, these heating systems would switch over to receiving their power from the arrays. The precautions affect the development of the electronics and are preemptively decided in a process known as radiation hardening by design (RHBD). Another way to radiation hardened is through the logic side. This logical radiation hardening would be implemented by installing redundant sensors and control computer that compare logic values in a comparator. This would add an additional safety net to catch any of the many types of possible corrupted data values.

Drilling: Drilling on Mars will be a difficult task. At first glance, drilling system used by oil and gas companies seem to be the way to go, where drilling is done through casing to help stabilize the downhole bore. However, Mars presents challenges with the cost of sending heavy casing to the surface which will be needed. A solution to this could be using a form of extruded tubing that is pulled down the hole while the drill penetrates the surface. This drilling could then be coupled with vacuum excavation to remove the drilled thought overburdened and make way for water extraction.

Water Extraction: Water extraction on Mars will need to be performed very carefully as the low atmospheric pressure is conducive to water boil off and sublimation. Due to the low atmospheric pressure, the location chosen was specifically targeted so that liquid water can exist within a certain temperature range. The maximum atmospheric pressure that can be seen at the base of the crater has been identified to be approximately 12.4 mbar during northern summer [10]. The phase diagram for water is shown in Fig. XX. shows that water can theoretically be stable in a liquid form at temperatures just above 0 ℃, however, there is a very small temperature window (at this pressure) that water can exist as a liquid. Therefore, the temperature at the base of the hole (and throughout the entire system must be carefully regulated to stay within these limits.

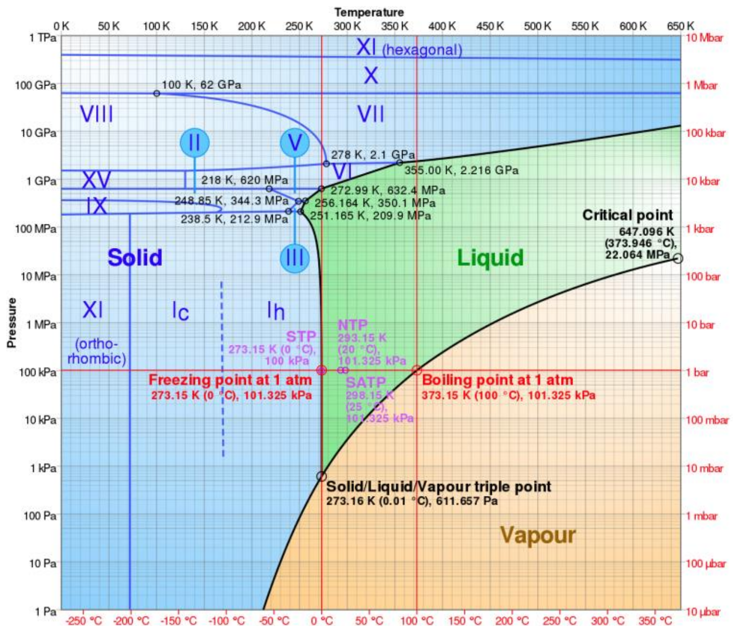

Fig. 16. Phase Diagram of Water [11]

Water Filtration:

Because the water on Mars contains perchlorates, electrocoagulation was chosen due to its ability to remove this toxicity in the water [5]. A consequence of the electrocoagulation system is that the system heats up a bit where some water boils off during the electrocoagulation process and, because the pressure on Mars is below the Armstrong limit, the electrocoagulation chamber will need to be pressurized to decrease the water vapor that boils off. Fortunately, during electrocoagulation, hydrogen and oxygen gas is created where a chamber could be created to capture these gases which could be re-used as fuel. Although electrocoagulation only serves to clump harmful toxins together, a separate back flushable filtration system must be installed to capture the coagulated particles. Should a mesh filter be used, over time, the mesh will have to be replaced.

11.2 Path to Luna:

Prospecting for a digital core on the Moon has several unique challenges and several challenges that overlap with prospecting and mining for ice on Mars. Some of the overlap comes from the harsh environment of the Moon. The environment on the Moon is characterized by its very weak magnetic field, very rough and sharp lunar regolith, and extreme temperature fluctuations between the dark side and the light side of the moon. In addition, some of the more unique challenges that the Moon presents includes the very low surface gravity that makes drilling into the surface very difficult.

Similarly to how the device would need to be hardened against radiation on Mars, the prospecting device on the moon would need similar features to ensure that the lifespan of the device is maximized under extreme radiation fatigue. In addition, the device must be very dust tolerant and the device must have mechanisms to either prevent ingress of regolith into motion control hardware or electronics, or the device must be able to tolerate or eliminate any regolith that enters the device. Finally, the temperature of the device must be regulated such that the electrical system will operate nominally for extended periods of time. This can be accomplished by means like what was described for Mars, but it can also be accomplished by carefully choosing the landing site of the rover or lander. There exist several locations on the Moon that are either permanently lit or permanently dark (called PLA-permanently lit area or PSR-permanently shadowed regions) that are located at the poles of the moon [12]. By landing in either one of these locations, the temperature fluctuations throughout a lunar day are not as extreme and could make designing the lander or rover significantly easier for a smaller temperature window.

The very low surface gravity of the Moon drastically reduces the maximum weight on bit that is achievable by any rover or lander sent to the Moon. In fact, using equation (2), the maximum weight on bit can be calculated [13].

$$WOB \quad = f * 0.3 * M * g \qquad (1)$$

If all of the weight of the lander is above the drilling mechanism and assuming the acceleration due to gravity on the moon is 1.62 m/s^2, the maximum WOB of the device (weighing 60 kg) can be estimated as being 29 N. This WOB is drastically lower than what the device is capable of on Earth and will prove to be ineffective in drilling through any hardened materials. To achieve the 150 N WOB limit that was set as a constraint for the competition, a lander of no less than 309 kg would be required. By increasing the mass of the lander or rover to simply prospect for a digital core, the launch cost of the lander would become very expensive and not economically feasible or efficient.

A different solution to this problem would be for the lander to deploy several large mechanical anchors (similar to off the shelf concrete anchors) into the surrounding Moon rocks and surface. By deploying anchors that grip the surrounding rock, the WOB can be increased as the loading of the drill can be reacted against the Lunar surface.

12. Budget

Total funding received for this project was $10,000 which all came from RASC-AL which was used to purchase material and part, pay for shipping of the device and cover the cost of student travel and logging. A breakdown of the budget can be seen in Table 3 below. Total expenses are projected to be $9838.88 which is less than the funds received which was made possible by our generous donors. Cosine Additive donated, for use during competition, all the motors, drives and major electrical components at a cost of $6,000 to run all electrical systems. Control Flow Inc donated $325.00 in material which was used to make brackets and the drill extensions. Additionally, both peristaltic pumps were donated at a cost of $240 each for a total donation amount of $6565.00. A more detailed summary and itemized list of cost is shown in Appendix C.

Table 5. Budget Breakdown for PIE System by Subsystem

Subsystem	Original Budget	Actual Spent
Drill	$300.00	$556.88
Water Melting/Extraction	$800.00	$1275.46
Frame	$1,500.00	$1562.50
Filtration	$1,200.00	$1128.52
Electronics	$200.00	$635.00
Shipping, Travel and Registration	$4000.00	$4680.16
Total	$10,000.00	$9838.88

Appendix A: References

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Appendix B: Instructions to Obtain Software

Obtaining the Source Code:
Dashboard software for the Planetary Ice Extractor is open source and is licensed under the GNU General Public License V3 (GPL-3.0).

The source code for the dashboard software can be found at https://github.com/nasa-rasc-al-uh/PIE-HMI.

The source code can be downloaded directly from the website or cloned via HTTPS using git checkout with the url: https://github.com/nasa-rasc-al-uh/PIE-HMI.git.

Similarly, the motion control software for the Planetary Ice Extractor is open source and licensed under the GPL-3.0 and can be found at: https://github.com/nasa-rasc-al-uh/PIE-Motion-Control
HTTPS cloning: https://github.com/nasa-rasc-al-uh/PIE-Motion-Control.git

Compiling the Source Code
To compile the software, it is recommended to use Visual Studio 2017 Community edition (or higher) with the .NET framework version 4.6.1 (or higher). The LiveCharts add-in is required for the project to compile and that can be found using the Visual Studio package manager.

Additional Considerations
At the time of writing, the software is still in development and additional updates to the code base will be made up until the day of competition. Changes will be reflected to the github frequently and may not be the same as the code shown at the time of writing.

Due to the number of hardware and software dependencies of the motion control software, the instructions for compiling and executing the software will not be detailed. Instructions on setting up and configuring an ACS system can be found directly from ACS motion control.

Appendix C: Itemized Budget

Donated Amount	Vendor	Amount
$ 10,000.00	Amazon	$ 295.15
	McMaster-Carr	$1,730.15
	Grainger	$ 406.88
	Automation4Less	$ 204.09
	Automation Direct	$ 305.00
	Metal SuperMarket	$ 114.72
	McMaster-Carr	$ 163.85
	Amazon	$ 42.34
	Automation Direct	$ 165.50
	Utah Biodiesel Supply	$ 17.00
	McMaster-Carr	$ 51.94
	Automation Direct	$ 24.25
	Witonics	$ 17.97
	SF Cable	$ 48.83
	Automation Direct	$ 43.25
	McMaster-Carr	$ 591.05
	Mouser Electronic	$ 159.29
	Automation Direct	$ 135.00
	Anko	$ 29.58
	Utah Biodiesel Supply	$ 25.50
Registration	NASA RAS-CL	$1,100.00
Flights		$1,499.62
Hotel		$1,297.92
Shipment	Fedex (estimate)	$1,128.00
Car Rent	Avis (Mid-Size Suv)	$ 242.00
	Total:	$9,838.88