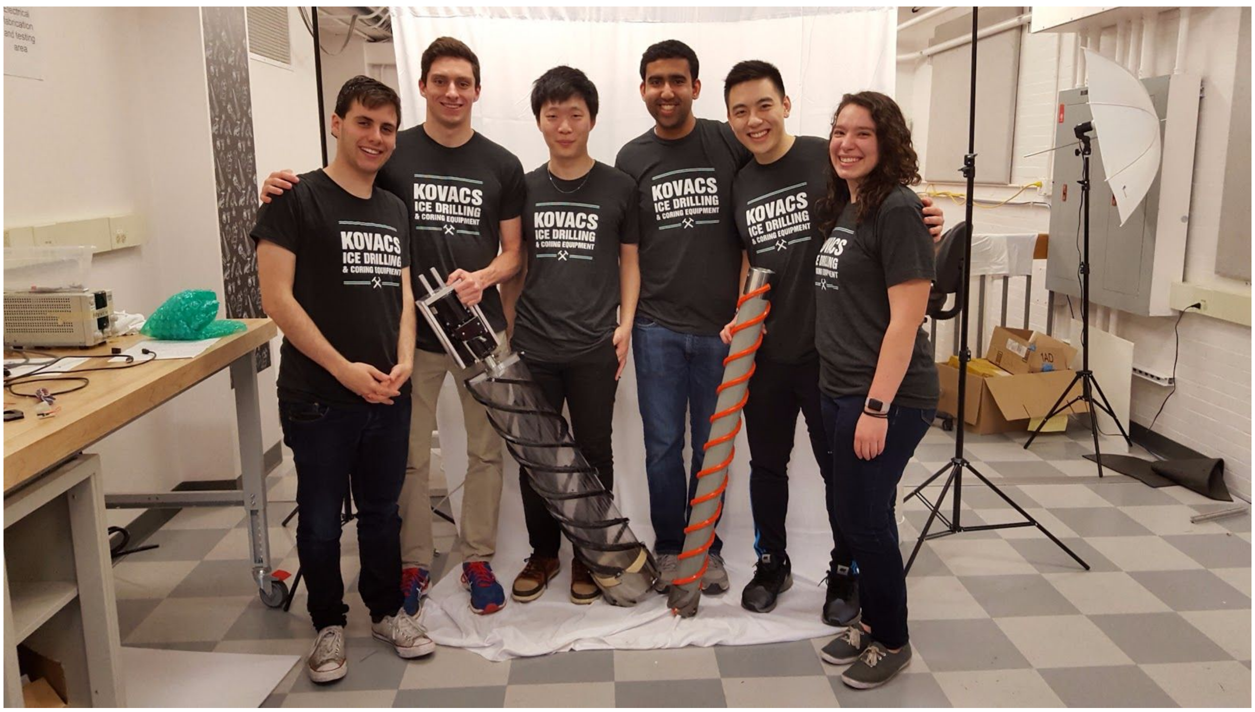
MWH

MARS WATER HORIZONS

Mars Water Horizons: *A Robotic Extraction System for Subsurface Ice on Mars*



Left to Right: Michael Gromis, Robert Thomas, Taeho Lee, Gautam Nagaraj, Thomas Eng, Wanda Lipps

University of Pennsylvania

Advisors -

Dr. Jennifer Lukes: jrlukes@seas.upenn.edu

Dr. David Goldsby: dgoldsby@sas.upenn.edu

Grant Boeckmann:grant.boeckmann@ssec.wisc.edu

Sid Deliwala: deliwala@ee.upenn.edu

Peter Rockett: prockett@seas.upenn.edu

Introduction

NASA and many other aerospace companies have their sights set on sending humans to Mars in the near future. However, sending people and materials to Mars is incredibly expensive. It takes 226 kg of fuel to send 1 kg of payload from Earth to Mars. This means that to send enough fuel to Mars for a return journey, five additional launches of NASA's Space Launch System (SLS) would be required. This translates to an additional $2.5 billion just to transport fuel. Being able to produce fuel on Mars would make missions to Mars more economically viable.

Fortunately, NASA has recently discovered subsurface water ice deposits on the Mars. If this ice can be extracted and melted, the water could be reacted with the CO_2 in the atmosphere through the electrolysis and Sabatier process to create methane which can be used as rocket fuel. The process is illustrated in Figure 1.

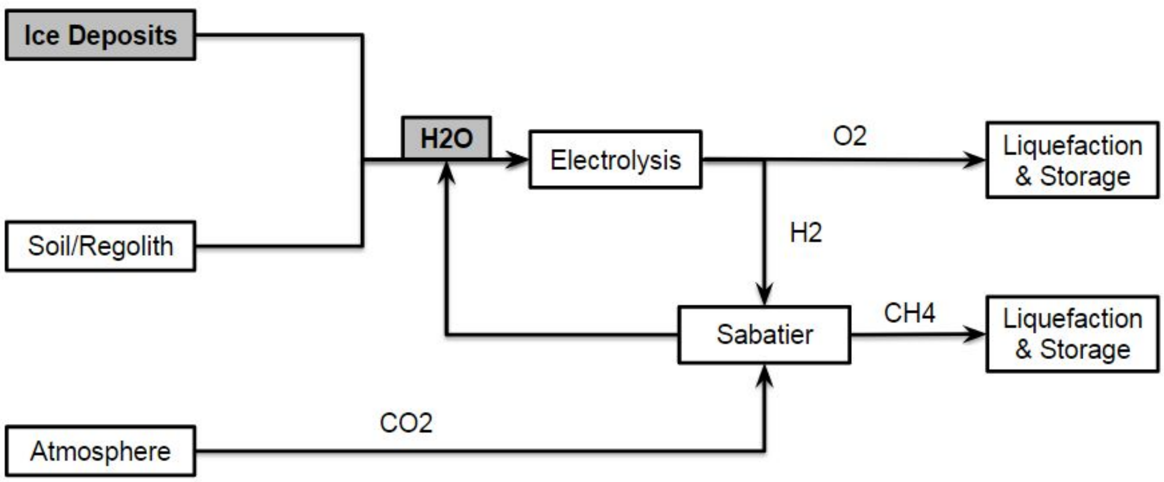


Figure 1: Electrolysis and Sabatier Processes for Fuel Production

The implemented solution is a movable coring drill that was fabricated completely in-house by the team to drill and extract multiple cores from the Martian surface. These cores are then melted in a controlled and insulated environment above ground with adjustable heating input. The drill is actuated using stepper motors and linear actuators. Control for the system is provided by an Arduino microcontroller to which commands are sent via a laptop computer connected to the serial port. The system will be able to operate for a minimum of 5.5 hours without human aid, though it can be teleoperated. Over the 5.5-hour test period, we expect to be able to extract and melt 2 cores of ice which translates to approximately 20 liters.

System Description

Our design utilizes a coring drill (7 in ID / 8 in OD) that can be moved in all three Cartesian axes. This allows us to drill multiple holes with the frame mounted in a fixed location, thus increasing our maximum possible water output. After the drill reaches its maximum depth of approximately one meter, it will be raised extracting a core of ice and clay with it. The drill will then move horizontally to position itself above the melting chamber where it will deposit the ice portion of the clay for melting. The melting chamber is powered by four heating elements rated for up to 250 W each giving us a maximum heating power of 1000 W. While the ice is melting, the drill will release the clay portion of the core off to the side of the machine and will begin drilling a new hole. The drilling and melting operations are timed to take approximately the same amount of time to avoid any backlogs.

Mounting System

Our mounting system will use the supplied carriage bolts mounted to the top of the testbed. We have drilled holes in the base rails of our system that line up with these bolts, and the frame will be secured using nuts. This mounting system has proven secure as we have not had issues with our system becoming disconnected from the boards despite significant torsion and axial loads applied to the frame. See Figure 2 for an image of our mounting system.

Figure 2: Illustration of one of four mounting points

System Excavation Operations

The coring drill is the centerpiece of our excavation system. The drill will run at a speed of 90 rpm during the excavation process. The expected rates of penetration are 1.2 meters per hour for clay and 0.7 meters per hour for ice leading to a drilling time of 67 minutes per hole. This means our system will be capable of drilling two complete holes during the test period.

The drill was designed based on an ice coring drill with the help of Kovacs Ice Drilling and Coring Equipment, Inc. This drill has an outer diameter of 8 inches and an inner diameter of 7 inches and is just under 3 feet long. It has a polycarbonate tube with Low Density Polyethylene (LDPE) flutes running helically up the outside of the drill, with a drill bit head machined out of A2 Tool Steel. The LDPE flutes are screwed into the sides of the polycarbonate tube and serve to distribute the excess clay and ice out and away from the core hole. The flutes are lined with PTFE tape to prevent clay particles from clogging the drill, which in turn reduces the torque required for drilling.

The drill head was manufactured using 4-axis machining on a HAAS Minimill although it possesses 5-axis features. The head has 4 slots for cutting teeth that actively dig into the clay and ice to cut out a cylindrical core. The head also possesses 4 pockets for core dogs, which propagate cracks through the ice to break the core off from the ground. Finally, the drill head has helical flights at a 40° which was determined based on the rate of penetration and the RPM.

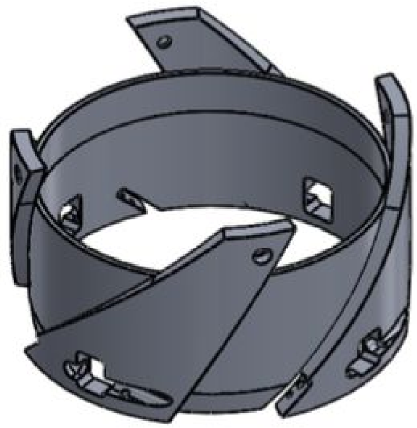


Figure 3: 3D rendering of drill bit

The core dogs are an integral part of all ice coring drills. They are mounted in the sidewall of the drill head and cut inward toward the center axis of the drill when actuated. Springs actuate the core dogs, and the stiffness of the spring controls the actuation force. When the drill is moving downward during the excavation process, the material inside the drill pushes the core dogs back into the sidewall of the drill. Raising the drill allows the core dogs to actuate which propagates cracks through the ice at the bottom of the core. This weakens the ice sufficiently such that the core can be broken off from the surrounding ice.

The drill is powered by an AC gear motor that was selected for its ability to operate continuously for extended periods of time without overheating. The motor has a nameplate RPM of 90 and a maximum torque of 67.3in-lb (7.6Nm). Ice coring experts indicated that a range of 60-100 RPM is optimal and that our drill design would require about 0.5 Nm of torque per cutting tooth to drill through ice.

Water Extraction System

The extracted ice will be melted in an insulated chamber above ground. The drill will deposit the ice core in the melting chamber. This will be achieved using a ring on top of the melting chamber to disengage the core dogs allowing the ice core to slide out. The main structure of the melting chamber is made of ⅛” carbon fiber plates that are connected via press fits and epoxy. The bottom of the melting chamber is made of ⅛” aluminum plates to which the heating elements are mounted. The inside walls of the melting chamber are lined with a combination of fiberglass and ceramic blanket insulation. The insulation prevents heat loss from the melting chamber ensuring the maximum amount of heat is transferred to the ice. Fiberglass insulation was chosen due to its low thermal conductivity of 0.04 W/m*K. A ¼” layer of fiberglass insulation was applied around the inside walls of the melting chamber. However, during testing the heating elements reached higher temperatures than expected (maxed out IR thermometer rated to 700℉). This caused the insulation closest to the heating elements to burn. Thus, the insulation around the bottom of the melting chamber near the heating elements was replaced with ½” thick ceramic blanket. This ceramic blanket is rated to over 2000℉ and has proved effective during testing. Only necessary areas were replaced with ceramic blanket due to its increased weight compared to the fiberglass.

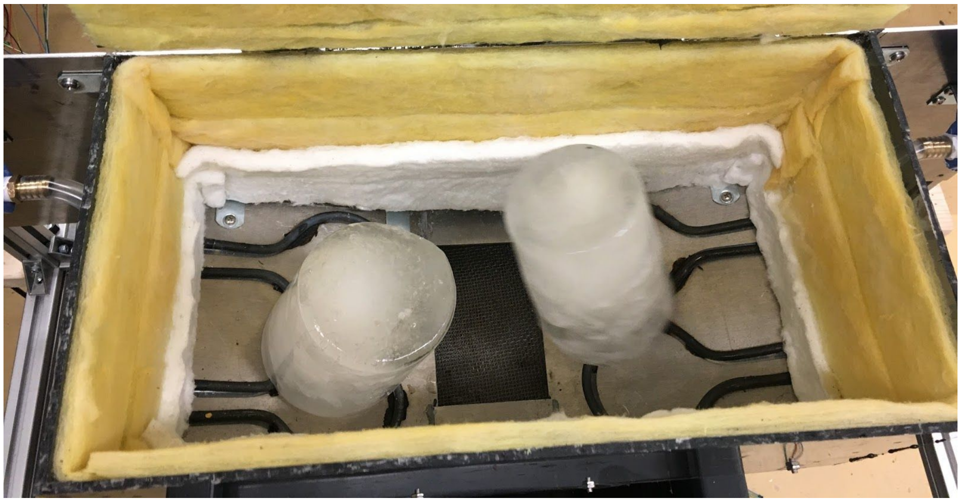


Figure 4: Melting chamber with test ice cores

Filtration and Water Collection

The filtration system consists of two stages. A metal sieve with increasingly fine mesh sizes is the first stage. This removes any large clay particles or pieces of gravel. The second stage is a five-micron carbon filter that removes finer clay particles. The sieve is positioned below the melting chamber, so gravity drives the flow through the sieve. The five-micron carbon filters are mounted on either side of the melting chamber. A peristaltic pump pumps the water from the sieve through the carbon filters. A peristaltic pump was chosen for this application due to its ability to pump air and water. This was necessary since the melting rate of the ice was low; as such, the flow of water into and through the tube will not be constant.

Overburden Management

The overburden is not expected to be an issue during the excavation process. During initial tests, the overburden tended to stick to the drill clogging the flutes. However, the flutes of the drill have been coated with teflon which significantly reduced sticking and improved drilling performance. After the ice is deposited in the melting chamber, the core barrel will still contain 30 kg of overburden. This overburden will be deposited on the side of the test environment opposite the melting chamber. The system will have framework in that location to contain the overburden.

Figure 5: Teflon coating on the drill head

Temperature Management
Due to the low rotational speed and material ablation of our drill, significant heat is not generated during the drilling process. This is critical to the ice drilling operations as it prevents melting of the ice during drilling. We have not encountered any issues with ice melting and refreezing on the drill during testing. The teflon coating will also help prevent ice from sticking to the drill.

Control and Communication System
The actuation for the X and Y axes is provided by linear rails driven by lead screws (see Figure 6 for axes definition). The lead screws are powered by Nema 23 stepper motors (1.9Nm holding torque) and have a thread pitch of 0.123 threads per mm. This, combined with the motor resolution of 50,000 steps per revolution, gives the drill very fine positional accuracy. The lead screws also provide the advantage of being non-back drivable meaning that torque from the motors is not required to hold the drill in position during drilling operations. This saves power for use in other applications and reduces wear on the motors. When the drill is operating, it will exert a torque on the XY actuation table. If the linear rails could be back driven easily, the stepper motors would have to hold the drill in position during drilling. This would require larger and heavier stepper motors and would add to the power requirements while drilling.

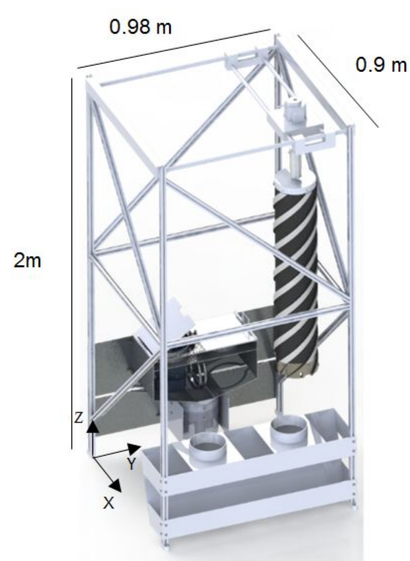


Figure 6: System axes definition

The Z axis is actuated using the Rigibelt actuator. This actuator meshes flexible members together creating a rigid rod in tension and compression. This actuator is ideal for this application due to its long stroke length (over 2 meters) and compact size when fully retracted. Rigibelt is also rated for 224 daN (225lbf). Compact size of the Z actuation system was critical to meeting the size constraint. The Rigibelt is driven by a Nema 34 stepper motor rated for 8Nm of holding torque. This motor was chosen to ensure the Z actuation system can provide enough force to lift the fully laden core out of the ground as well as hold its position as it moves in the XY plane.

The stepper motors for all three axes use motor drivers that receive input commands from an

Arduino microcontroller. Positions and velocities for all three axes can be easily commanded via a laptop connected to the Arduino serial port. The Arduino also provides control inputs for the drill motor. The drill motor uses an on/off switch that can be actuated by a signal from the Arduino. The power regulation to the melting chamber is also controlled by the Arduino. The Arduino provides a signal to the SCR controller that supplies power to the heating elements.

Data Logging
The Arduino serial monitor can display the commanded input signals for position, speed, and power. This data can be exported from the serial monitor to Excel where it can be processed and graphed or logged into an SD card.

Technical Specifications

Specification	System Value
Overall Mass	50 kg
Overall Volume	2 m^3
Length of Drill Bit	0.889 m
WOB	100 N
Rated Load	114 lb
Max Drilling Speed	90 RPM
Drill Torque	7.6 Nm
On Board Computer	Arduino Mega
Communications Interface	Arduino Command Serial
Software	Arduino 1.8.1
Power	907.95 W

Design Changes/Improvements
XY Table
This change was made due to the issues that were encountered with drill stability. The solution is also elaborated on in the Challenges and Solutions section.

Coating for Drill
Due to clay liquefaction and clumping on the drill head, a coating was deemed necessary for the drill head. After reviewing capable hydrophobic lubricants that would not be readily absorbed by clay, a physical teflon coating was deemed to be best suited. The physical coating is unlikely to show significant wear and, in early tests, has shown to repel clay extremely efficiently.

Removal of filter for weight savings
In the original design, the filtration system had 2 filters running in parallel; this allowed for an extra level of safety in the case where one filter became clogged. However, after calculating the weight of our system in early May, one of the filters was removed to ensure that the system would be under the weight restrictions given by NASA. The mass of one such filter with its case is approximately 1.5 pounds.

New Materials for MC for weight savings
Another change stemming from our beginning of May weight analysis was the changing of the wall materials of the melting chamber. Previously chosen as acrylic due to high availability and ease of manufacturing, the acrylic walls and door were determined to be too heavy in their current form. Without a significant redesign, the only way to cut a significant portion of weight was to change materials. As such, foam core carbon fiber laminate was chosen as the replacement material. Although carbon fiber does becomes brittle under cold conditions, like Mars, we believe that an adequate replacement material could be found by NASA given time and money. Due to the monetary restrictions and the fast approaching competition date, the carbon fiber laminate will be used in the competition demo.

New Drill for more torque
In recent drill tests, the old motor was damaged and was therefore unable to be used safely moving forward. As such, and due to the excessive strain on the motor that was seen during these tests, a motor with more torque was deemed necessary. Based on this, a new drill motor was ordered and selected to offer more torque for the drilling process. This additional torque will be able to overcome the required drilling torque while providing a large enough safety factor in performance. This will also improve the lifespan of the motor.

Challenges and Solutions
Drill Stabilization
During initial drill testing, our vertical actuation system driven by the Rigibelt experienced more torsional displacement and bending than we anticipated. Due to this, we redesigned our z actuation subsystem. Instead of a guideless system, the Rigibelt is mounted in a fixed location at the top of the frame, and it will drive the x,y actuation table up and down. The drill is rigidly mounted to the bottom of the x,y actuation table. The table is guided by wheels that interface with the vertical beams of the frame. This puts the torque from the drilling operation into the frame which will provide much more torsional stability than the Rigibelt alone.

Clogged Drill Head/Stalling Motor
When drilling through the overburden, the overburden tends to stick to the drill head, particularly in the flutes. This clogged the drill and prevented cuttings from being raised to the surface. Due to this, the torque required to turn the drill greatly increased and the drill motor stalled when the drill was approximately 4 inches deep. By coating the flutes in PTFE tape, the overburden does not stick and travels up the flutes as designed, and it does not remain on the drill head when extracted.

Overall Competition Strategy
As discussed in our project proposal paper, we selected the coring drill/solid extraction method since it was the best combination of maximizing water extraction while also mitigating risk. For a system of this type, drilling time was determined to be the limiting factor in the amount of water

that could be extracted. Drilling time was estimated based on ROPs from “Considerations, constraints and strategies for drilling on Mars” by Zacney and Cooper [13]. In order to maximize water output, we needed to maximize the amount of water extracted each time a hole was drilled. However, if too much ice was extracted from each hole, the melting chamber would not be able to keep up with the drilling process due to power constraints and a backlog would form there. Therefore, melting times were calculated for different diameter drills, and the drill size with the closest match between melting and drilling times was selected. This resulted in our 7 inch ID core drill. Based on the size of our drill, a maximum of 8 holes could be drilled in the Martian testbed. However, during the test period, we expect to be able to drill and extract 2 holes.

Integration and Testing
The melting chamber was tested over a range of input powers ranging from 150 to 950 W. Melting tests were conducted at 7 different points on this interval. The time required to melt a measured quantity of ice was recorded, and the efficiency for the heat transfer into the ice was calculated. The efficiency decreased as the input power increased. Using the power input and the efficiency, the time required to melt one core of ice was calculated. From this 630 W was determined to be the optimal input power as it provided the best balance between melting time and efficiency.

The drill and actuation systems were initially tested together. With the drill powered off, the actuation system was successfully able to move the drill in both directions in all three axes, and positional accuracy proved to be repeatable. The speed of the actuators was easily changed via the control code. The Z axis speed was initially set to 1 meter/hour which corresponded with the expected drill rate of penetration. The maximum speed of the X and Y axes was set at approximately 0.2 meters/second. Once the drill was powered on, it induced vibrations in the actuation system that disrupted the positional accuracy. The Rigibelt was the most severely affected as it behaves as a cantilevered beam. This is corrected with a drill stabilization system. In this stabilization system, the Rigibelt remains stationary while its moves the Cartesian drilling platform in the z-direction. Drilling by hand, the team was able to achieve rates of penetration of 1.2 meters/hour through clay and 0.7 meters/hour through ice. This translates to an estimated 25 minutes to drill through the overburden and 42 minutes to drill through the ice for a total of 67 minutes. An ice core was also successfully extracted using the core dogs.

Contingencies and Redundancies
Drilling Operations
During the drilling operations, there are multiple issues that could occur. If the drill head becomes clogged and the drill cannot make anymore progress through a hole, the drill will be extracted from the hole and moved to the drill cleaning station. The drill will be turned against a brush with stiff bristles to remove buildup on the drill head. The drill will then return to the hole and begin drilling again. If the drill gets stuck again, it will be extracted and cleaned, and a new hole location will be chosen.

Another issue that could be encountered is the core dogs not engaging properly to fracture the ice. The load sensor will be monitored during extraction. If a high enough extraction load is not recorded, meaning the core dogs have not engaged, the drill will be lowered back into the hole. In order to ensure the core dogs engage, the x,y actuation table will rock the drill back and forth. This will not only engage the core dogs, but also apply a bending moment to the ice core. This will further propagate cracks making it easier to extract. If the core still cannot be extracted at this point, the drill will be powered on with the core dogs engaged. This will reduce the cross sectional area of the core at the fracture point making it easier to break.

Melting Operations
During the melting operation, a heating element could potentially fail. However, because we will not be using the full power capabilities of the heating elements, we will be able to make up for the loss of a heating element by diverting power to the other three remaining heating elements.

Further, in the case that the annular lip does not disengage with the annular lips, the drill will rest above the melting chamber and the exposed ice will begin to melt from the melting chamber heat. Since the drill will not be able to drill another hole, more power can be diverted to heating elements to ensure maximum heat to contents of the barrel. Although this compromises how much ice the system can extract, it ensures that the system will extract some water successfully. A potential risk with this plan includes damage to the polyethylene strips due to the heat. As a result, the drill will need time to cool before returning to drilling as to not exert stress upon the strips while they are excessively heated.

Project Timeline

Month	Accomplishments
October and November	Brainstorming and iteration of design; draft of initial project plan
December	Creation of initial prototypes for melting chamber and drill; testing of different filtration methods
January	Sourcing of major equipment (Rigibelt, xy actuation); design review of coring drill
February	Manufacturing & assembly of second melting chamber and frame; material sourcing for drill
March	Manufacturing of drill bit; manual tests for drilling; individual subsystem tests for melting chamber
April	Redesign of xy table for drill stabilization; testing of drill bit coatings
May and June	Final assembly of last components and integration of subsystems; testing of final system

Safety Plan
Currently there are no hazardous materials or chemicals in our system. During operation of the system, the will be some hazards associated with the drill moving and spinning. The cutting teeth are sharp, and the drill is heavy. While the system is running, the team members will

maintain a safe distance away from the machine. However, if the system must be approached during operation, the team member approaching the system will wear a hard hat and safety glasses. Care should also be taken when near the melting chamber as the heating elements and conducting plates reach temperatures that could easily burn skin.

Path-to-Flight

In designing the proposed system, employability on Mars has been a strong consideration; we have tried to minimize the differences required in system fabrication and design to ensure that the path to Mars will be as short as possible. The robotic ice extraction system falls at the end penultimate stage of the journey to mars, the lander phase, or the last stage, the manned mission. The system can either be mounted on a rover for semi-autonomous use on Mars prior to manned involvement or on a manned rover. The system is key to the return journey from Mars, a vital part of the mission that is often overlooked.

In terms of materials selection, there are only a couple of parts that need to be replaced. Due to weight constraints, we were forced to fabricate the melting chamber out of carbon fiber. Carbon fiber is known not to perform well under extreme cold conditions and therefore would need to be replaced when built for Mars. Secondly, for monetary and manufacturability reasons, the frame of the system is aluminum; if NASA implements our solution on Mars, we would suggest that an aluminum-titanium alloy be used as it can be made much stronger. Also, we believe that a tungsten alloy can be used to replace the heavier steel parts, such as the fasteners and mounting plates that we have incorporated into our design.

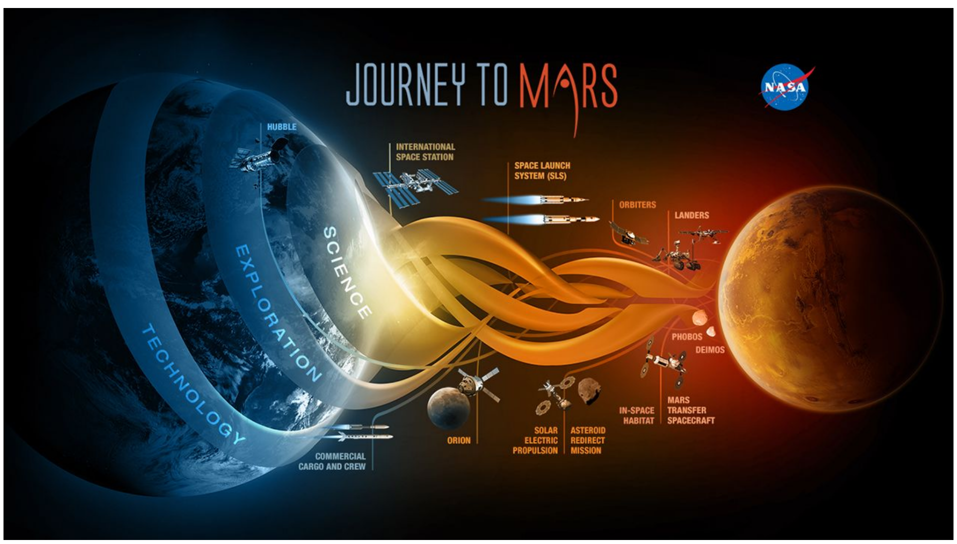


Figure 7: The different stages of a journey to Mars. [12]

In terms of the extraction process, we believe that there are only a couple of modifications necessary to implement our solution on Mars. We would suggest an optical sensor or electrical resistivity sensor on the bottom of the drill to determine where the ice meets the overburden. The purpose of this sensor is to guide the drill on how far to drill into the ice before breaking off segments for later melting. Furthermore, in the cases where the layer of ice is not of uniform depth, this optical sensor will allow for modifications to the depth of drilling. As the sensor detects a sharp change in composition, the drill will be engaged to initiate the first cut.

Our system does not need to worry about sublimation to the atmosphere as the ice is exposed to the environment for minimal time. Sublimation is only a top concern within the melting chamber. Since the chamber is currently open to the atmosphere, if the system were to be transferred to low-pressure Martian atmosphere, there is a chance the ice would sublimate when the heating elements are activated. For this reason, the melting chamber would need to be airtight with a small compressor to bring the pressure above the triple point of water and prevent sublimation. Further, the current melting chamber design is not air-tight, thus any implementation must be properly sealed. The fluid management system would be designed to analyze and set the temperature and pressure needed to prevent sublimation. Further, in the event of power reduction, certain heating coils would have the ability to be shut off to limit the amount of power used by the melting chamber. While this would slow down the melting process, it would ultimately save power without compromising overall operations. The use of a dynamic power allocation system could also be used to scale back the power usage of the entire system in the case of a power loss or drop on Mars.

Vibrations on liftoff could cause a lot of trouble with our prototype. Many of the fasteners holding the frame and z actuation system in place are screws and bolts. Sustained vibrations could potentially unhinge these joints. In order to counteract this, each joint should be sealed in place prior to use. For the purposes of the competition, this will not be possible, as we need to transport it from a large distance away and possibly troubleshoot during the competition. Going to Mars, the bolts and screws that were used could be replaced by welds, as there is no assembly that can be performed on the surface of Mars. In addition, the system currently uses many different types of adhesives (for carbon fiber, ceramic blankets, etc); for a Martian mission, it would better to standardize these adhesives and epoxies. Furthermore, the temperature ranges for the adhesives need to be more thoroughly investigated before use on Mars.

The current prototype drill utilizes PTFE (Teflon) strips to prevent accumulation on the head. This is currently being used because of moisture in the clay, which allows it to more quickly liquify onto the drill head. Under Martian conditions, we believe that there will not be much moisture in the soil as it has probably evaporated or sublimated in the last couple million years. As such, the need for such a coating may be unnecessary. However, if removed, another coating should be applied for drilling through ice. The core dogs and teeth are liable to freeze over due to the environment residing near the triple point of water. In this case, a hydrophobic coating should be applied for use on Mars. During tests on earth, even PAM cooking spray proved to be useful in preventing icing of the core dogs and cutting teeth. While on Earth, however, temperatures are quite warm; on Mars, the temperatures could be much lower. As such, cold-rated lubricants are needed for use on Mars. According to Kleuber Lubrication Munich, the coating optimal for the environment down to -30 C is a synthesized PAO (polyalphaolefin)[11]. This base oil on aluminum is typically operated in temperatures in the Arctic and should be functional in the Martian environment range.

During operations on Mars, extending the life of consumable elements such as the filter cartridges will be critical to minimizing operational costs of the system. Replacing such items on Mars not only requires astronauts present to carry out the maintenance, but also requires shipping the parts from Earth. During normal operation, the filter cartridges should last approximately 3 months before requiring replacement. If any kind of malfunction occurs, a large amount of clay could be released into the melting chamber, likely fully clogging the filters. In order to prevent this, we recommend that a secondary release valve be installed in the melting chamber that simply allows the clay and ice to be released from the melting chamber. While losing the ice is not ideal, protecting the filters is more important. We believe an optical sensor inside the chamber that could determine the opacity of the water in the chamber would be able to detect if clay levels are too high.

All four motors on our system (X, Y, Z, drill) are all mission critical. In the current design, if a motor fails, neither the excavation nor extraction process can be performed. Operating on Earth where maintenance and troubleshooting of the system are fairly straightforward, a motor failure is not the same catastrophic event it would be on Mars. Diagnosing and repairing the system on the surface of Mars would be a tremendous challenge. As such, for a system operating on Mars, we recommend building in at least one layer of redundancy into the motors. We would also recommend the inclusion of self-diagnostic software for all the electronic components of the system as this would greatly help the troubleshooting process on Mars. Further, the motor that drives the Rigibelt was sized to lift and hold the fully loaded core. Since the gravitational force on Mars is approximately one-third of Earth's, the fully loaded core would be lighter. Therefore, this motor would not need to be as powerful. This motor is one of the main weight drivers of the system. Reducing the torque of this motor would decrease the weight of the system as a whole.

Another consideration for Mars implementation is the dust that may damage and clog system components. The current machine works in a controlled environment where minimal dust can clog the openings, therefore the designed system is open to surroundings. In an unpredictable Martian environment, the drilling area and electronics and mechanisms should be encased so that they do not get damaged by the elements. One possible solution is covering the sides with a geosynthetic liner.

The filtration system is another area where improvements could be made for use on Mars. Currently, the system utilizes one carbon mesh filter sealed inside of a casing; this was chosen for its ease of use, removal, and availability. On Mars, however, removing the seal, replacing the cartridge filter, and then re-sealing the filter could be difficult and time consuming. As such, an integrated filter and casing that could be swapped out as a whole by just disconnecting the tubing on either end would probably be better suited for a Martian mission.
Size is an area where modifications could be made prior to a Martian mission. Currently, the system occupies the entire 1 m x 1 m x 2 m volume limit. Contrarily, the majority of the volume actually empty space. Space on launch vehicles and on a Martian mission would be very expensive and valuable; as such, a system that is predominantly empty space, may not be cost effective. If the height of the system was reduced, however, it could become much more compact and viable for Mars. The entire two meters in required for the height of the system to ensure that close to a 1 meter core can be extracted. The stroke length for the z axis actuation system is the main inhibitor to reducing the vertical size of the system. The Rigibelt system currently employs decreases the expected stroke length from a typical drill. However, the body of the Rigibelt occupies about 0.2 m in height. Further reductions in the height of a zipper mechanism like the Rigibelt system, could help make the entire system smaller and more compact.

Furthermore, extracting a shorter core could also help reduce the size of the system. Currently, the core length is approximately one meter. This ensures that each hole needs to be drilled only once; this prevents the need for a very accurate motor actuation that would be needed if the same hole needed to be visited several times. A Martian mission would theoretically have a much larger budget than we have; as such, more expensive and accurate motors could be purchased for actuation in the XY plane. These would allow multiple visits to the same hole in the ground. A such, a smaller core could be extracted multiple times. This would have a two fold effect on the height of the system. Firstly, the reduced core height would reduce the height of the melting chamber; with smaller cores, the need for a taller melting chamber is eliminated. A decreased melting chamber height would allow decrease the height needed for the core drill to move up before depositing ice cores. These reductions compounded would help make the entire system shorter and more compact.

Another modification needed for Martian deployment is the re-manufacturing of the drill head. The current drill head prototype that is being used for the competition was made using 4-axis machining equipment; this was the most complex equipment available to us at the University of Pennsylvania. While this provided sufficient dexterity for a simplified drill head, the theoretical design that we had initially suggested required 6-axis machining capabilities. As such, a Martian drill head would need to be manufactured using 6-axis fabrication tools to ensure that the core dogs, flutes, and components of the drill head would be optimal for performance on Mars.

Currently, our system relies heavily on teleoperation. We can send the system commands as we watch it run in real time. As this is not feasible in a space environment due to lag in communications, the system would need a higher level of automation. With a higher level of automation, comes the need for increased number of sensors and computing power. However, since our system moves in a relatively similar pattern in space, the complexity of the automation may be reduced. The most complex operation would be drilling. Without human monitoring in real time, the system would need the ability to detect problems and resolve them. Inclusion of an IMU would help the system ensure the drill is stable as it descends as well as detect when the drill may stall. The system would need to process this data on-board. Although many scenarios and reactions could be implemented into the system, it would be better if the machine could take advantage of developments in machine learning and use a database of ice coring records that were manually conducted to make decisions.

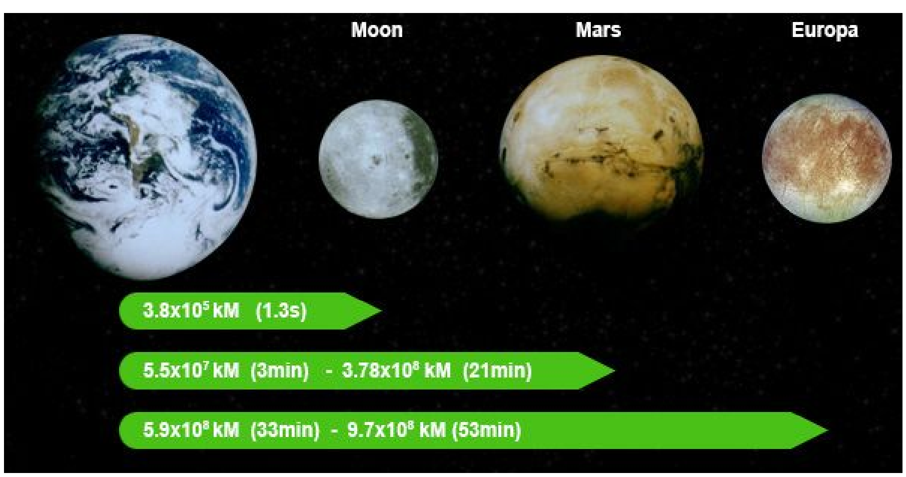


Figure 8: Distances to planets and moons with time delays for communication
http://spaceskills.org/wp-content/uploads/2013/05/CommunicationDistancesBlk.jpg

Budget

Our project received funding from two sources as well as some discounts and sponsorship. We received $2400 from the University of Pennsylvania Mechanical Engineering and Applied Mechanics department as per the senior capstone project allocation. We received an initial $5000 from NASA for our participation in the NASA RASC-AL Mars Ice Challenge. We received an additional $6200 from NASA in early April after we passed the Midpoint Project Review. Kovacs Enterprise helped with the design of our drill by allowing us to borrow their One Mark III ice coring drill valued at $6,500, cutting teeth valued at $155, and a set of coring dogs valued at $150 free of charge. Serapid Technology provided us with a Rigibelt for the price of $500, a generous discount from the original price of $2,100. Table 1 breaks down the most up-to-date costs of the producing the system. This chart does not include costs incurred from purchases that did not contribute to the final system, but does include costs incurred from earlier prototyping.

Category	Expenses
Travel	$ 4,399.09
Drill	$ 2,369.51
Melting Chamber	$ 832.69
Z Actuation	$ 749.95
Electronics	$ 557.37
Frame	$ 564.52
XY Actuation	$ 446.58
Testing	$ 423.72
Filter	$ 348.09
Tools	$ 154.26
Total	**$10,845.78**

Table 1. Expenses for materials needed for current system. Note that travel is the most expensive part of project.

References

[1] N. Stockton, "Review: Google Pixel," in *Science*, WIRED, 2016. [Online]. Available: https://www.wired.com/2016/09/elon-musk-colonize-mars/. Accessed: Oct. 20, 2016.

[2] J. Wilson, "Journey to mars overview," NASA, 2016. [Online]. Available: http://www.nasa.gov/content/journey-to-mars-overview. Accessed: Oct. 20, 2016

[3] K. R. Sridhar, J. E. Finn, and M. H. Kliss, “In-situ resource utilization technologies for Mars life support systems.,” *Adv. Space Res.*, vol. 25, no. 2, pp. 249–255, 2000.

[4] M. Wall, "NASA’s huge new rocket may cost $500 Million per launch," in *Space.com*, Space.com. [Online]. Available: http://www.space.com/17556-giant-nasarocket-space-launch-cost.html. Accessed: Oct. 20, 2016.

[5] I. Smith. Geoscience Colloquium, “What’s Stored in the Pola Caps of Mars?: A Record of Recent climate and Flowing CO2 Glaciers.” University of Pennsylvania, 14 October 2016.

[6] G. B. Sanders and W. E. Larson, “Progress made in lunar in situ resource utilization under NASA’s exploration technology and development program,” *Journal of Aerospace Engineering*, vol. 26, no. 1, pp. 5-17, Jan. 2013

[7] G. Sanders, "Comparison of Lunar and Mars In-Situ Resource Utilization for Future Robotic and Human Missions," in *AIAA Aerospace Sciences Meeting*, Orlando, Florida: AIAA, 2011. [Online]. Available: http://enu.kz/repository/2011/ AIAA-2011-120.pdf. Accessed: Oct. 20, 2016.

[8] S. Siceloff, "Engineers building hard-working mining robot," Brian Dunbar, 2013. [Online]. Available: http://www.nasa.gov/topics/technology/features/RASSOR.html. Accessed: Oct. 20, 2016.

[9] G. B. Sanders, "Mars ISRU: State-of-the-Art and System Level Considerations," 2016. [Online]. Available: http://kiss.caltech.edu/new_website/workshops/isru/ presentations/Sanders.pdf. Accessed: Oct. 20, 2016.

[10] K. Zacny, P. Chu, G. Paulsen, A. Avanesyan, J. Craft, and L. Osborne, “Mobile In-Situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In Situ Resource Utilization,” *AIAA Sp. 2012 Conf. Expo.*, no. September, p. 5168, 2012.

[11] "Lubricant Challenges In Extreme Cold Environments". *KLUSA* 14.08 n. pag. Web. 30 May 2017.

[12] G. Daines, “NASA's Journey to Mars,” *NASA*, 13-Feb-2015. [Online]. Available: https://www.nasa.gov/content/nasas-journey-to-mars/. [Accessed: 30-May-2017].

[13] K. Zacny and G. Cooper, “Considerations, constraints and strategies for drilling on Mars,” *Planet. Space Sci.*, vol. 54, no. 4, pp. 345–356, 2006.

Appendices

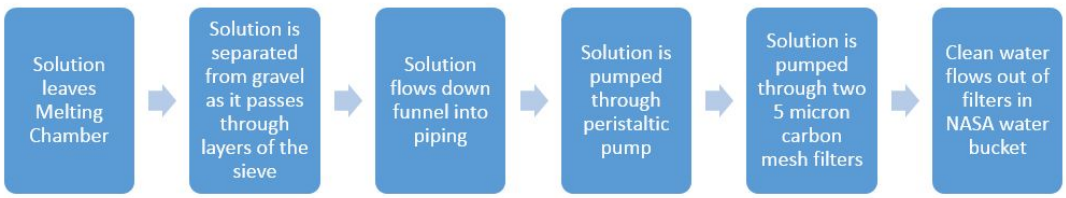


Figure A.1: Detailed flow explanation of water through the filtration system

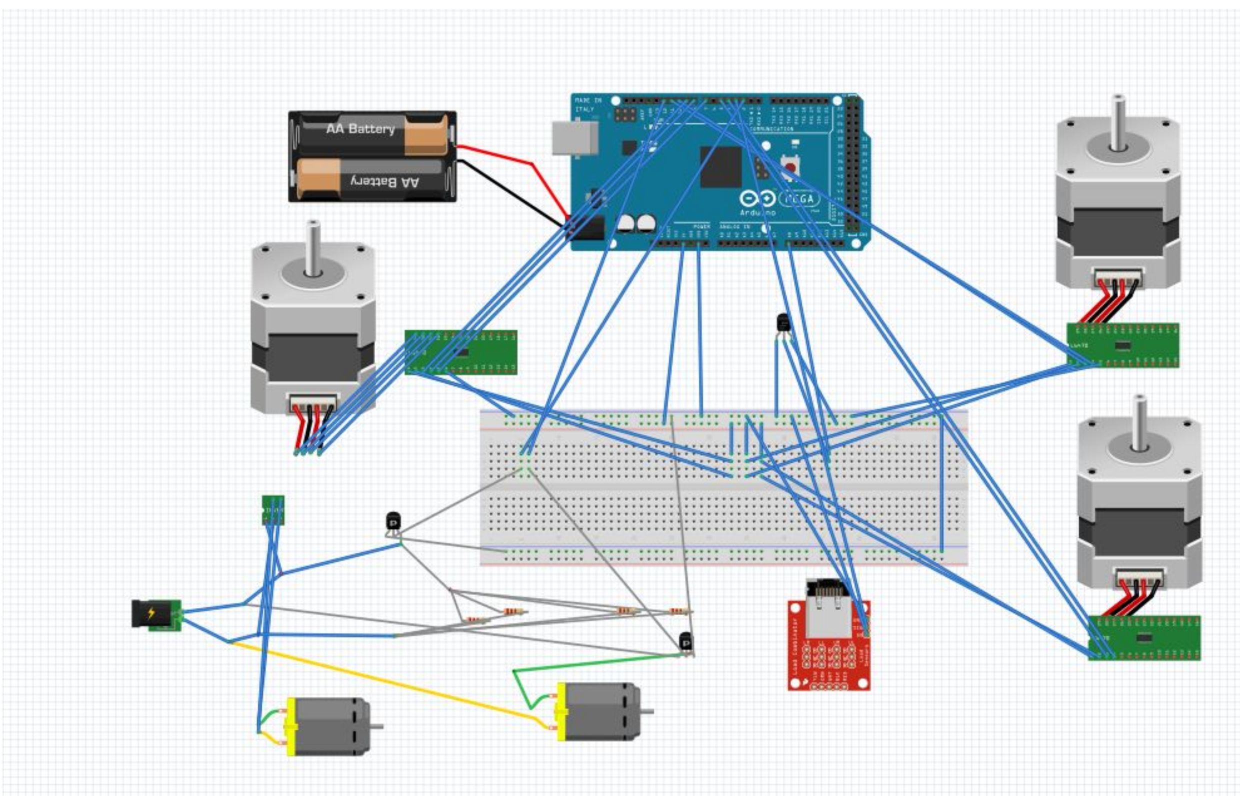


Figure A.2: Electronics drawing showing connections to breadboard

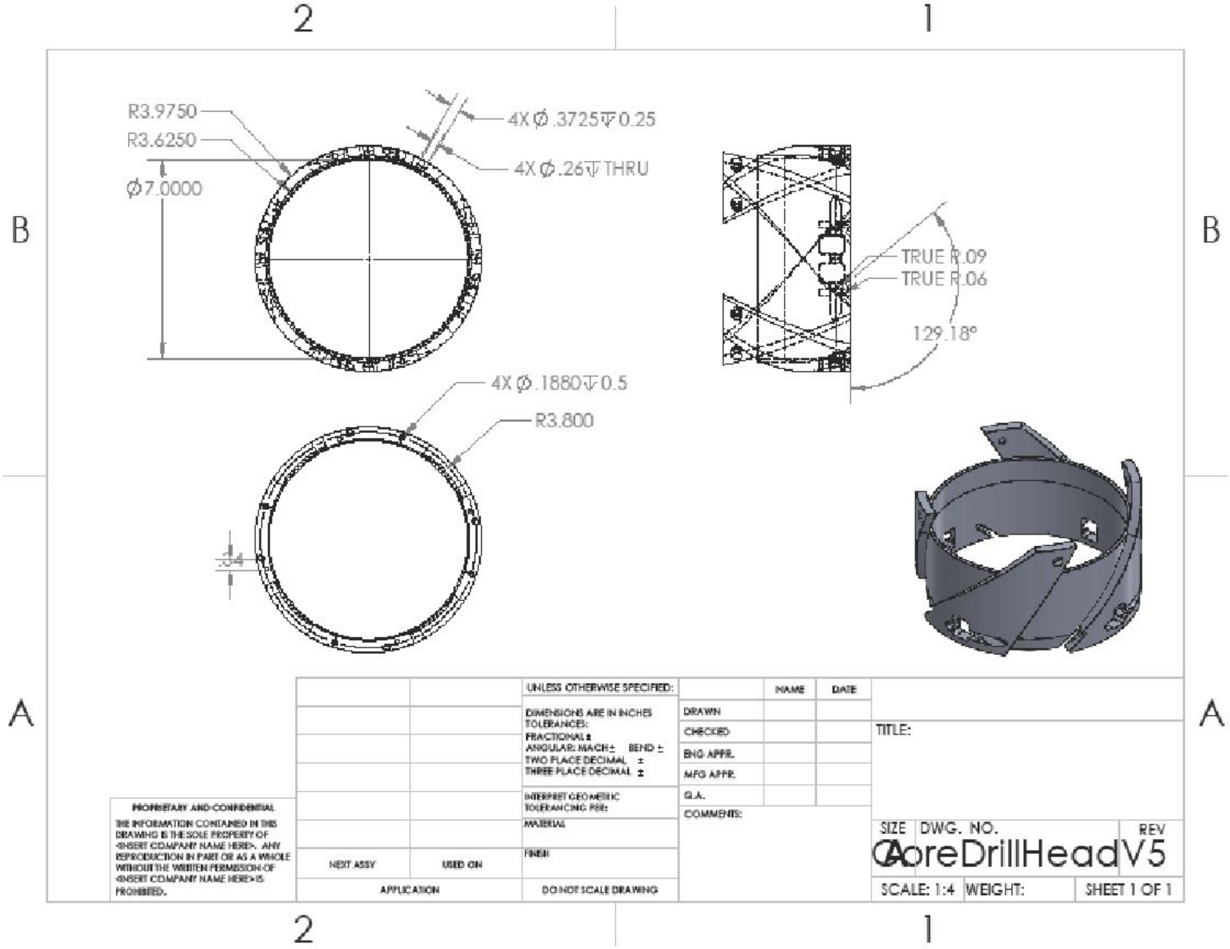


Figure A.3: Drill Head Engineering Drawing

```
#include <AccelStepper.h>
#include <elapsedMillis.h>
#include <math.h>
int pulseXPin = 9;
int dirXPin = 8;
int enableXPin = 7;
int pulseYPin = 10;
int dirYPin = 11;
int enableYPin = 12;
int pulseZPin = 5;
int dirZPin = 4;
int powerPin = 13;
int limitX = 2; //x-axis limit switch pin - interrupt pin 2
int readingX; //checks whether x-limit is reached
int limitY = 1; //y-axis limit switch pin
int resolutionx = 400; //steps per revolution
```

```
int resolutiony = 400; //steps per revolution
int resolutionz = 1600; //steps per revolution
double distPerRevx = 8.077; //millimeter per revolution
double distPerRevy = 8.077;
double distPerRevz = 81.64; //mm per rev
int maxX; //maximum position (mm) to travel in x-direction
int maxY; //maximum position (mm) to travel in y-direction
int xDrillPos[] = {
  1, 2, 3}; //mm
int yDrillPos[] = {
  1,2,3}; //mm
int drillPosCount = 0;
int xMeltPos[2] = {
  1,2}; //mm
int yMeltPos[2] = {
  1,2}; //mm
int xSlide; //mm
int ySlide; //mm
int phase = 1;
int meltpin = 7;
int meltOnMilli = 10000;
int meltOffMilli = 10000;
int pumpPin;
int beastPin;
int counter_xpressed = 0;
boolean xLocalized = false;

unsigned long last_click = 0;
int button_delay = 200;

char inputString[200] = "";         // a string to hold incoming data
boolean stringComplete = false;

AccelStepper stepperX(1, pulseXPin, dirXPin);
AccelStepper stepperY(1, pulseYPin, dirYPin);
AccelStepper stepperZ(1, pulseZPin, dirZPin);

void setup() {
  Serial.begin(9600);
  pinMode(powerPin, OUTPUT);
  digitalWrite(powerPin, HIGH);
  pinMode(meltpin, OUTPUT);
  pinMode(limitX, INPUT_PULLUP);
  stepperX.setMaxSpeed(100000);
  stepperX.setAcceleration(40000);
  stepperX.setEnablePin(enableXPin);
  stepperX.setPinsInverted(false, false, true);
```

```
  stepperX.enableOutputs();
  stepperY.setMaxSpeed(100000);
  stepperY.setAcceleration(40000);
  stepperZ.setMaxSpeed(1000);
  stepperZ.setAcceleration(400);
  attachInterrupt(limitX, blink, FALLING);


}

void loop() {

  if(!xLocalized)
  {
    localize();
  }

  if (stringComplete) {
    Serial.println(inputString);
    String str = String(inputString);
    if(inputString[0] == 'x')
    {
      move('x', str.substring(1).toInt());
      Serial.println("Done Moving");
    }
    if(inputString[0] == 'y')
    {
      move('y', str.substring(1).toInt());
      Serial.println("Done Moving");
    }
    if(inputString[0] == 'z')
    {
      move('z', str.substring(1).toInt());
      Serial.println("Done Moving");
    }
    if(inputString[0] == 'm')
    {
      digitalWrite(meltpin, HIGH);

    }
    if(inputString[0] == 'o')
    {
      digitalWrite(meltpin, FALLING);

    }
    // clear the string:
    inputString[0] = '\0';
```

```
    stringComplete = false;
  }

long mm_to_steps(int resolution, double distPerRev, int mm) {
  long val = long(round(mm/distPerRev*resolution));
  return val;
}

void localize() {
  if (!xLocalized)
  {
  stepperX.move(mm_to_steps(resolutionx , distPerRevx, -2000));
  }
  while (!xLocalized) {
    readingX = digitalRead(limitX);
    Serial.println(readingX);
    stepperX.run();

    if (readingX == HIGH) {
      Serial.println(readingX);
      stepperX.disableOutputs();
      stepperX.setCurrentPosition(0);
      stepperX.enableOutputs();
      move('x', 0);
      xLocalized = true;
    }
  }

//  Y position localization with limit switches
    readingY = digitalRead(limitY);
    while (!yLocalized) {
      stepperY.run();
     //moves one step at a time may need to change this because super slow
      stepperY.move(-1);
      if (readingY = HIGH) {
        stepperY.setCurrentPosition(0);
        yLocalized = true;
      }
    }
}

void move(char coord, int mm) {

  if (coord == 'x')
  {
    int steps = mm;
    int steps = mm/distPerRev*resolutionx;
```

```
    stepperX.runToNewPosition(mm_to_steps(resolutionx, distPerRevx, mm));
  }
  if (coord == 'y'){
    stepperY.runToNewPosition(mm_to_steps(resolutiony, distPerRevy, mm));
  }
  if (coord == 'z')
  {
        stepperZ.runToNewPosition(mm_to_steps(resolutionz, distPerRevz, mm));
    }
}

void drill(boolean drillOn) {
}

void melt (boolean meltOn) {
  digitalWrite(meltpin, HIGH);
  delay(meltOnMilli);
  digitalWrite(meltpin, LOW);
  delay(meltOffMilli);
}

void serialEvent() {
  int inChar;
  while (Serial.available()) {
    // get the new byte:
    inChar = (char)Serial.readBytesUntil('\n', inputString, sizeof(inputString) - 1);
    // add it to the inputString:
    inputString[inChar] = '\0';
    stringComplete = true;
  }
}
```

Figure A.4: Arduino command code