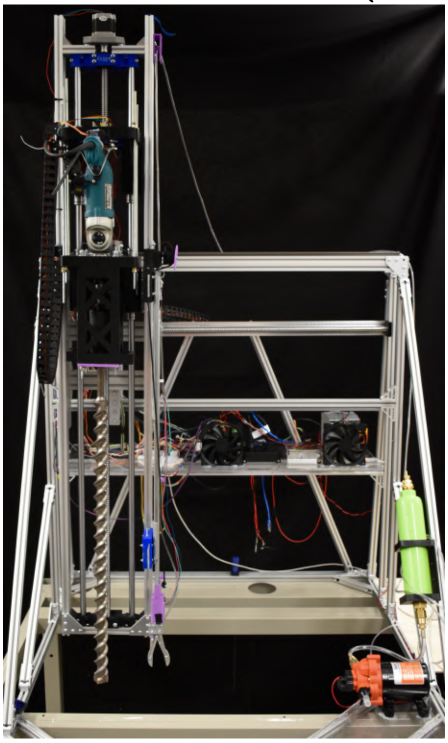
Overburden Layer Ice-to-Vapor Extracting Robot (OLIVER)



Matthew Anderson
Liam Chapin
Joshua Moser
Maria Wass

Jack Carden
Matias Marquez
Michael McCampbell

Tanner Catron
Cullen Downey
Kelly Normyle
Nathan Walkenhorst

Advisor: Dr. Erik Komendera
Advisor: Dr. Kevin Shinpaugh

Virginia Polytechnic Institute and State University

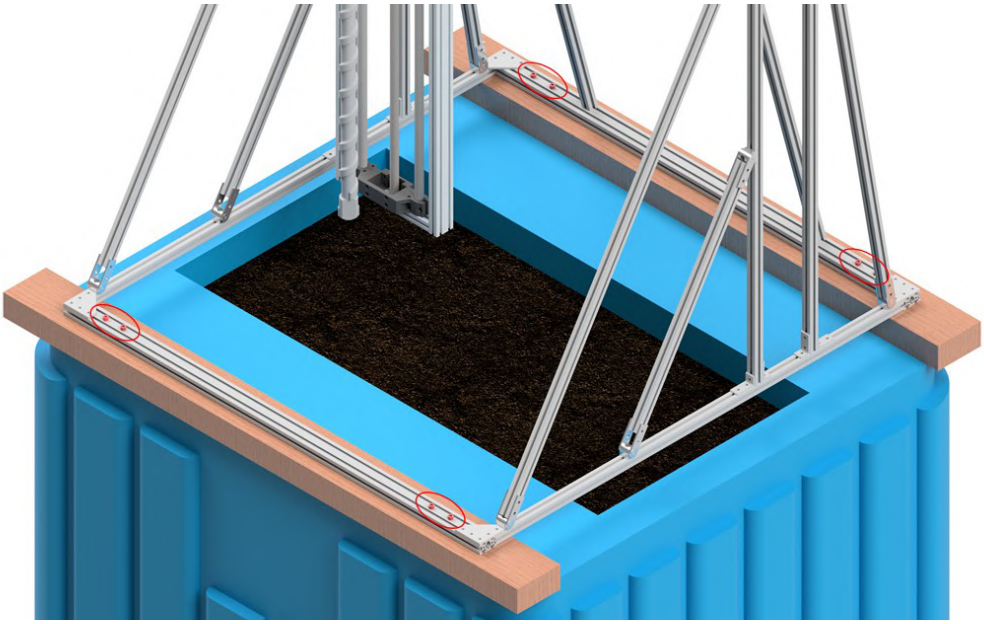


Figure 1: System to mount OLIVER to overburden & ice container

1 Introduction

A future persistent presence in space is dependent on the ability to extract and utilize all potential resources in an environment. Water is the most crucial resource: once extracted, it can undergo electrolysis to produce hydrogen and oxygen fuel, be used as an ad-hoc radiation shelter, or simply be consumed for sustenance. The challenge is to extract water from subsurface ice in an environment where the lack of an atmosphere prevents the existence of a liquid state. The Field and Space Experimental Robotics (FASER) Laboratory presents the Overburden Layer Ice-to-Vapor Extracting Robot (OLIVER), a robotic resource extraction system that will excavate the ice, convert it into liquid, filter it and capture it in a reservoir.

2 System Description

The systems on OLIVER can be grouped into different subsystems. The mounting system to attach the robot to the mining surface, the mining system to bore the hole to the ice, the extraction system that melts the ice into water and pulls it from the bored hole and finally, the filtering system to purify the extracted liquid.

2.1 Mounting System

OLIVER will be mounted to the top of the overburden container with bolts through the front and back foot elements on the robotic system. As shown in Figure 1, the robot will be mounted so that the horizontal actuation will be in parallel with the longer dimension of the rectangular opening. The frame was specifically designed to allow the drill and extraction systems to be positioned in a way that centered them over the opening and thereby allowing access to the maximum drilling real estate.

2.2 System Excavation Operation

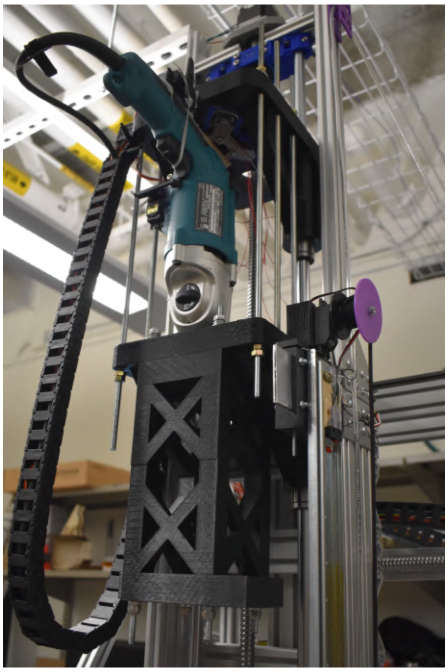
The operation to extract and filter water can be broken down into 6 operational steps listed below. These different steps will be described in more detail in the following sections.

1. Drill through the overburden layers

2. Remove drill and deposit sheath

3. Lower heated agitator into sheath
4. Melt ice into water and pump the water out of the hole
5. Pump water through filter
6. Capture purified water into storage container

2.3 Solution to Mine through Overburden


(a) Drill assembly on linear actuator

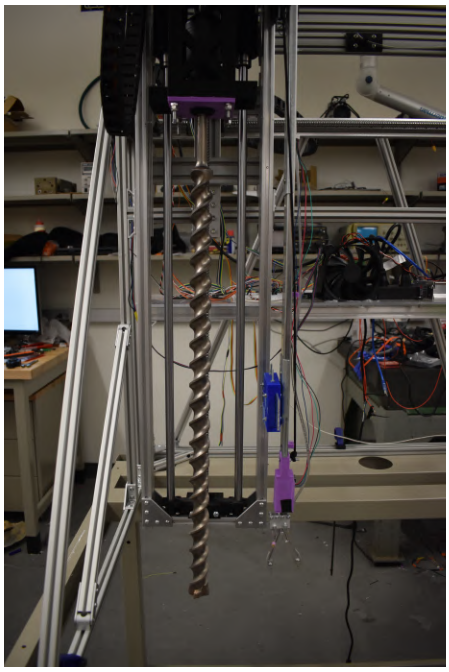
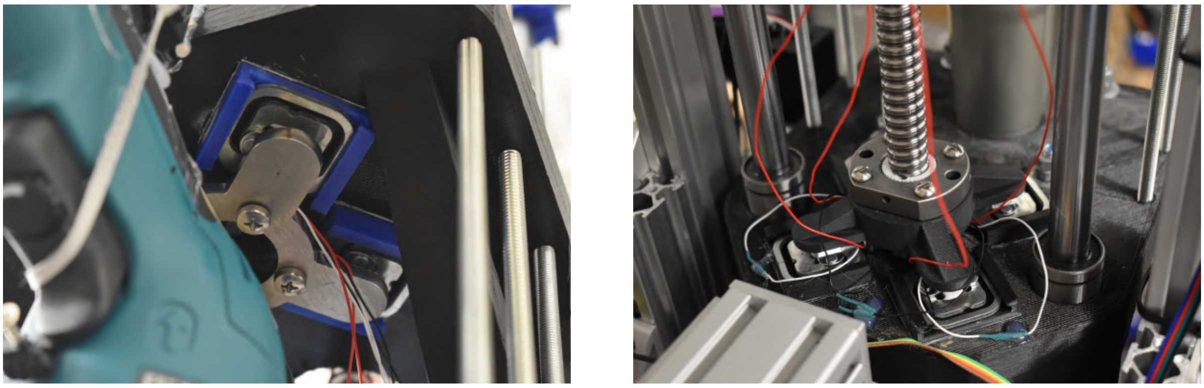

(b) Drill bit in drill assembly

Figure 2: Drilling assembly

To mine through the overburden layers to access the ice, a Makita HP 2050 rotary hammer drill was chosen to utilize both rotary and percussive forces, allowing it to drill through more consolidated layers. The Makita was used in conjunction with a SDS Max drill bit connected through a modified adapter that allowed it to fit into the drill chuck. This bit features auger flanges and a carbide cutting tip. The drill assembly is actuated with a linear ball screw actuator that lowers and raises the entire drill assembly (figure 2). A sheath is left in the hole after the ice layer is reached to preserve the hole integrity. The release and grasping mechanism for the sheath enables the the sheath to be deployed after drilling and retrieved after the extraction process to allow for another hole to be excavated.

2.4 System & Technique for Extracting Digital Core

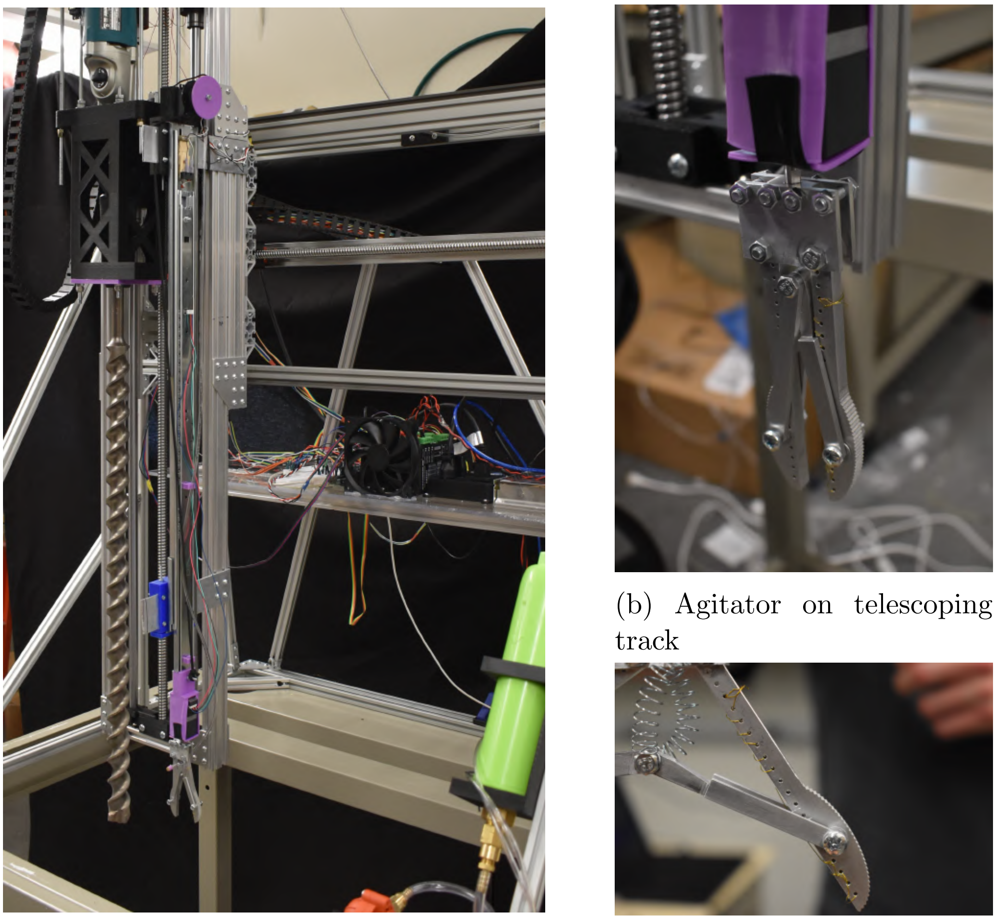
The digital core will be determined by measuring the force applied inline with the bit and to the linear actuator responsible for the vertical motion of the drill assembly. These forces are measured by two separate Wheatstone bridges consisting of four load cells each. One Wheatstone bridge is placed directly behind the drill inline with the drill bit and the other is attached around the ball screw rod in between the slide and the drill carriage (subfigures 3a & 3b respectively). Knowing these forces along with the current usage and the vertical velocity of the drill's descent the different layers will be detected and recorded.



(a) Load cells inline with drill bit

(b) Load cells inline with drill actuator

Figure 3: Load cells used to generate digital core during drilling

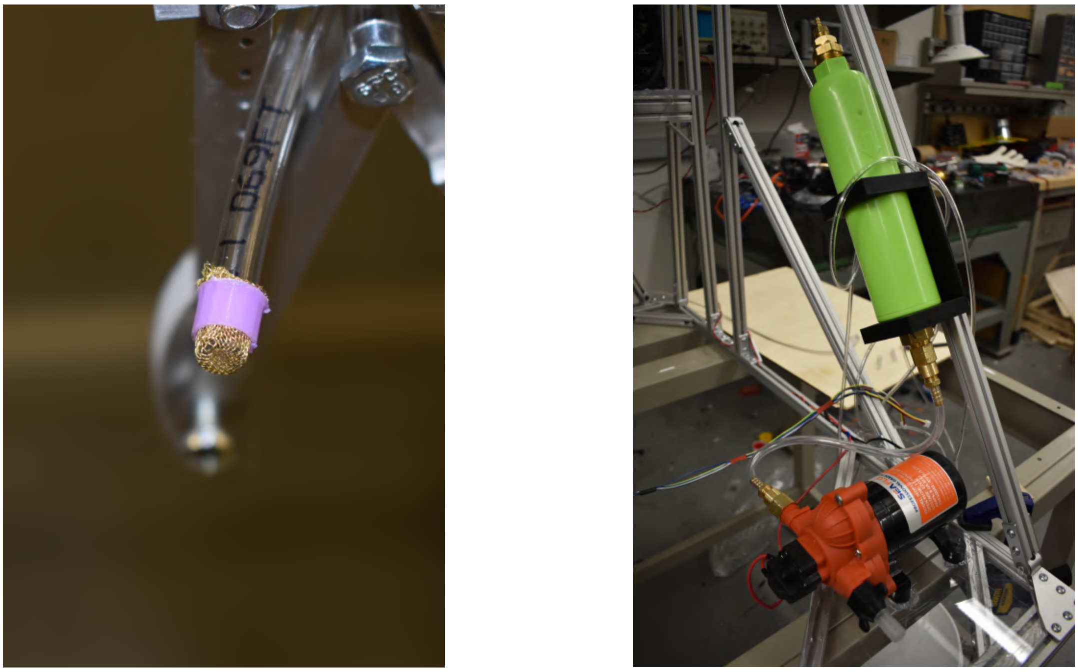


(a) Telescoping track to melt and remove ice

(b) Agitator on telescoping track

(c) Nichrome wire on agitator

Figure 4: Water Extraction System



(a) Hose at the end of extraction system (b) Filter and pump

Figure 5: Water filtration system

2.5 Water Extraction System & Filtration

After the drill has bored down to the ice layer and deposited the sheath, the drill is retracted and the extraction system (subfigure 4a) is deposited into the sheath down to the ice layer where the agitator, heated by insulated nichrome wire, is spun to scrape the ice into a slurry.

As the ice is melted into water by the spinning heated agitator, a pump draws the liquid out of the hole and pulls it through a filter to purify the water (subfigure 5b). One end of the hose is attached at the agitator where a small filter protects the opening from particulate matter (subfigure 5a). The other end runs through the filter and pump system, then deposits water in a collection container. To prevent tangling while the telescoping track changes length, the hose runs through a series of guides.

2.6 Control and Communication System

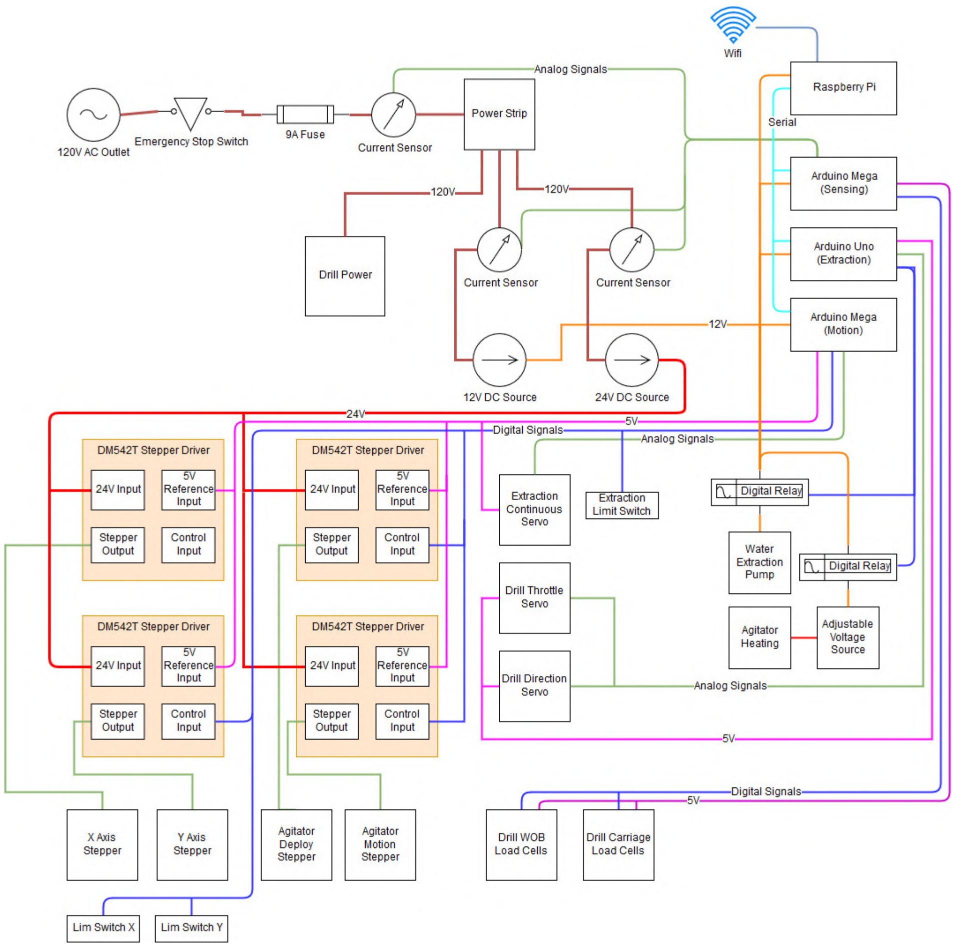


Figure 6: Diagram of control system and communication system

The OLIVER Robot is controlled by a Raspberry Pi microcomputer which in turn controls a series of Arduino microcontrollers. Each Arduino is responsible for a different subsection of the machine.

1. Motion - An Arduino Mega is responsible for moving the robot about its axes, controlling four stepper motors (the X and Y table motors and two agitator motors) and a continuous servomotor responsible for raising and lowering the extraction mechanism. The motion controller also has sensory input from three limit switches installed on the robot which allow it to home itself when powered, or when requested from the Raspberry Pi unit.

2. Excavation - An Arduino Uno is responsible for actuating the Drill (both controlling the speed and direction), and enabling/disabling the pump mechanism.

3. Data gathering - An Arduino Mega is responsible for collecting and returning data from on-board load cells and current sensors.

Communication between the Raspberry Pi unit and the Arduino units takes the form of standard serial over USB, with a baud rate of 9600. Communication between the Raspberry Pi unit and the remote control computer is accomplished via UDP over a local Wi-Fi network.

2.7 Datalogger

In order to extract data from the OLIVER robot, the Raspberry Pi control unit polls the Arduino Mega responsible for data collection from load cells and current sensors. This data will be returned from the pi via UDP to a remote python server which stores the data in a text file.

The robot uses ACS712ELC current sensors with a 20A capacity, connected to the primary power supply, the 12V source, and the 24V source. Reading from the primary power supply current sensor allows room for active control on the drill to prevent over current draw that would risk blowing the fuse. The scale factor of the chosen module is 100mV per Amp.

The load cells used for the robot are simple strain gauge type, wired in Wheatstone bridges above the drill, and at the attachment point of the drill carriage system. These bridge circuits are fed through one HX711 24 bit load cell amplifier each, which is in turn measured and reported back by the Arduino.

3 Technical Specifications

The technical specifications for OLIVER are shown in Table 1. A drill bit length of 0.914 meters ensured that the thickest amount of overburden could be drilled through. The rated load is limited by the carrying capacity of the horizontal lead screw actuator. Maximum drill speed and torque were determined by the specifications of the drill. Weight on bit is limited through programming, as the vertical lead screw actuator is capable of exceeding allowable force. Current is limited to 8 amps, to allow for a buffer from blowing a fuse.

Table 1: Technical Specifications

Specs	Value	Units
Overall Mass	56.05	kg
Overall Volume	1.601	m^3
Bit Length	0.914	m
Rated Load	294.3	N
Max Drill Speed	2,900	rpm
Max Torque	45.9	Nm
WOB	120	N
Max Power	960	W
On-board Computer System	Raspberry Pi	–
Communications Interface	Wi-Fi & Serial	–
Software	Linux, Python, & Ardiuno	–

4 Design Changes & Improvements from Mid-project Review

4.1 Drill System

The original design for the drilling system utilized a steel bit that was smooth along the shaft and came to a point with a 45^o slope an inch from the end. The design relied on the weight to pound through the overburden through the use of a hammer drill. This type of drill would also allow for a compression to take place in the the material of the hole wall thereby lowering the chance for the whole to cave in after the drill was extracted. However, it was determined that the weight of the bit would punch past some of the layers making it hard to determine the digital core. It was also determined that friction from the hole walls made drilling down to the needed depth was more difficult. To mitigate these issues a new bit was chosen that had flutes along the shaft to extract the dirt. It also had cutting edges on the bit to help it remove the overburden material. Since was made out of aluminum it was much lighter. This allowed for easier control of the boring rate.

4.2 Extraction & Filtration System

The original plan for the filtration and extraction system was to utilize a low pressure environment to easily heat the ice to a point where it would convert to a water vapor state. This added complexity while testing since a pump and a sealed borehole would be needed to achieve the required pressure drop on Earth. After testing, it was determined that the necessary seal and pressure drop could not be achieved on this system. Because of this, the extraction and filtration system was substituted to pump out the liquid after the ice melted and pass it through a filter. Despite having to make this change for this system, this team still recommends the vaporization design for actual deployment. Since pressure will be sufficiently low on the Moon or on Mars, the seal and pump system will not be needed.

4.3 Agitator & Heating

The original design for the agitator and heating unit was to have two agitators spinning around a central heating unit, in order to mix the water creating a uniform temperature, and to run along the edge of the ice, pulling pieces from the walls creating a slurry to heat up for extraction. This was changed to making the scrapers themselves the heating element, to create direct contact between the ice and the heating element, while still creating an even temperature within the ice hole. The heating agitator design utilized nichrome wire coiled through the length of the aluminum agitator, as nichrome is commonly used for heating elements.

5 Challenges & Mitigations

5.1 Physical Challenges

The mounting of the drill to the drill carriage proved a challenge due to the contour on the back of the drill. The original mount allowed the drill to slip forward, changing the angle of the drill bit, as well as losing accuracy in the load cells on the back end of the drill. The mount for the drill was corrected by contouring and layering slices of 1/4" plywood to match the back of the drill and provide an interface with the load cell plate. Further problems with the drill arose when a commercial drill bit that fit our specifications didn't fit inside the Makita drill chuck. An attempt was made to solve this problem by finding an adapter that could interface the SDS Max Drill bit with our standard sized drill, but no such adapter exists or is easily available. Ultimately, this issue was mitigated by buying an auxiliary SDS Max drill chuck and grinding it to the correct size to work with our drill.

5.2 Electronics Challenges

5.2.1 Load Cells

As for electronics, one of the first issues encountered was inaccurate readings from the load cell on the back of the drill, which was due to part of the force being dispersed perpendicular to the load intended for the cell. This was partially mitigated by reworking the drill mount to deter slippage and keep it upright. There was also a second load cell array added to the base of the drill carriage in an attempt to increase accuracy.

5.2.2 Actuating the Robot

The primary four stepper motors on the robot are driven by StepperOnline DM542T stepping drivers. When first installed on the robot and loaded with the intended code, the stepper motors presented issues where they could only be driven in one direction. The manifestation of this issue was that the "absolute value" of directed velocity was used, instead of the *directional* velocity. This problem was resolved by removing the enable/disable connections on the DM542T drivers, and permanently setting a HIGH (5v) reference on the direction standard, which allowed for the direction to be easily changed.

5.3 Extraction Challenges

5.3.1 Pump Selection

Several pumps were evaluated to determine the correct pump to use to extract the water and send it through the filter. The first couple chosen did not have the correct pressure differential, they would either push the water through the filter too violently or they would not have the ability to draw the water through the filter. This was mitigated by choosing a pump specifically designed for drawing water through a filtration system.

5.3.2 Filtering

As indicated earlier the original design incorporated an evaporation system that would purify the water by changing the physical state to gas and back to liquid. However, after it was determined that the correct pressure could not be reached the design was revised to utilize inline water filters. Through several model iterations a filter was found that sufficiently cleaned the water without retaining a portion of it internally after the filter processes was completed.

5.3.3 Agitator

The original design for the heated agitators intended on the use of aluminum agitators and insulated nichrome wire. Problems arose fixing the nichrome wire to the aluminum agitator. The coating on the nichrome wire does not have strong adhesive properties. This made it very susceptible to the loss of isolation when the wire encountered the hard edges of the agitator. To mitigate this, the method and location of attachment for the nichrome wire was modified, in addition to the acquisition of alternative nichrome wire that has better insulation adhesion.

6 Summary of Integration and Test Plan

Each of OLIVER's subsystems were developed and tested individually. While complete integration is ongoing, most subsystems are functioning in conjunction with the rest of the robot under operational constraints. Ongoing issues are discussed below.

6.1 Drill Assembly

OLIVER's drill assembly was the first of OLIVER's subsystems to be built and tested. Initially, the drill and lead screw that actuates it were placed on a purpose built wooden test stand used to evaluate the capability of several tested bits to drill through overburden and ice. The chosen Makita HP 2050 drill is actuated by a pair of Tower Hobby 180 degree servos, one of which controls the velocity of the drill by squeezing the trigger, and the other controls the direction by flipping the drill's direction lever. The stand on which the drill assembly was mounted was positioned such that a trash can filled with overburden, ice, or some combination of the above could be placed below it for testing.

6.2 Filtration

OLIVER's filtration system was developed and tested in parallel with the development of the extraction system. While OLIVER's initial design called for a vacuum extraction system using a ground sealed fume hood, evaluation of this system revealed that it was not capable of extracting a sufficient amount of water to be considered effective, despite evaluating a range of vacuum pumps for this capability.

Ultimately, the decision was made to transition from using a vacuum pump to using a standard water pump, with the caveat that the water pump must be capable of "running dry" so tit does not become overheated in the absence of a constant high volume water flow. The current pump, a SEAFLO 33 series, is capable of moving 11.6 liters a minute, and is capable of running dry.

In order to filter the collected water, a two stage process is used. At the front of the water extraction tube, in the borehole, the tube is covered by a fine metal mesh, which prevents large sediments and chunks of overburden from entering and clogging the pipe. A carbon block filter (CLEAR$_2$O) is responsible for removing the smaller particulates missed by the initial mesh.

6.3 Extraction

The extraction system is composed of the telescoping track, the headed agitator mechanism, fixture points for attaching the extraction hose as well as the servos to operate it. During testing the Tower Hobby continuous servo raised and lowered the telescoping track through the entire displacement range. Additional testing will tune the system to remove instances where the agitator does not smoothly enter the sheath to travel down to the ice in the bore hole.

6.4 Frame

The frame was designed to accommodate the existing filtration and drill assembly components. It features a highly stable 8020 aluminum structure with an integrated horizontal lead screw counterpart to the vertical lead screw present on the drill assembly. The drill assembly is mounted to the frame and horizontal lead screw via a 8020 aluminum carriage. This carriage is mounted to two guide rails parallel to the horizontal lead screw above and below.

6.5 Command and Control

Following completion of the frame elements and integration of the drill, filtration, and extraction sub-assemblies onto the frame, development of the overarching command and control system began in earnest. The first task was to integrate code developed for subsystem testing to reduce the need for additional Arduino microcontrollers, and to also move from using desktop programmable power supplies to the static 12V and 24V supplies serving as OLIVER's backbone power bus.

The second and most pressing task is external control with digital core. While subsystems, including load cells and current meters, had been tested on their own, the integration process presented its own tasks, due to oversights inherent in testing in a vacuum, such as not accounting for the power consumed by the device that is measuring the power consumed. The digital core system, integrating both the current sensors mounted on the complete power bus, presents a continuing challenge as new components are added to the robot and code is modified for efficiency.

6.6 Final Integration Progress

The current integration progress of OLIVER is approximately 85-90% to completion. Major unresolved issues are verification of digital core against test-substrate with full frame assembly, locking and unlocking the drill sheath, and mitigating damage to the nichrome wire insulation. Now that the physical robot has been constructed and integrated, resolving these outstanding issues is the team's primary focus. Additionally, with all major components in place on the robot frame, testing and debugging software has accelerated dramatically.

7 Tactical Plan for Contingencies & Redundancies

The primary plan in place to ensure OLIVER reliability during during the competition is modularity. The frame and drill system, having been separately designed and tested, consist mostly of 3D printed and stock aluminum parts, for which there are spares, and are easily replaced. The electronics system was designed so that most of the components are easily replaceable, or even hot-swappable (limit switches, load cell amplifiers, stepper drivers, and relays). Cabling onboard the robot was done with quick disconnect JST (Japan Solderless Terminal) connections on either end so that any device can be swapped without rebuilding the robot.

In the event of an electrical failure, such as over-current, the 9A fast-blow fuse is located in an easily accessible 3d printed cartridge, which allows for easy swapping. Upon a system reset, the robot would re-home itself to regain positional certainty, and then receive desired state instruction from the remote host computer.

The largest risk for failure of a physical component is fracturing a load bearing 3d printed component. As an effort to mitigate this, all critical 3D printed components feature a high infill percentage with a cubic subdivision internal structure. In the event that a 3D printed component is fractured, the team has prepared spares which can be replaced for any given component without excessive difficulty.

A significant risk is a sediment jam on the fine mesh at the end of the water extraction tube. In the event of this jam, the robot can be commanded to shut off the pump, and partially retract the agitator mechanism from the borehole, at which point, water running down from the tube attachment point at the top of the drill frame will clear any chunks of sediment affixed to the end of the extraction pipe.

8 Project Timeline

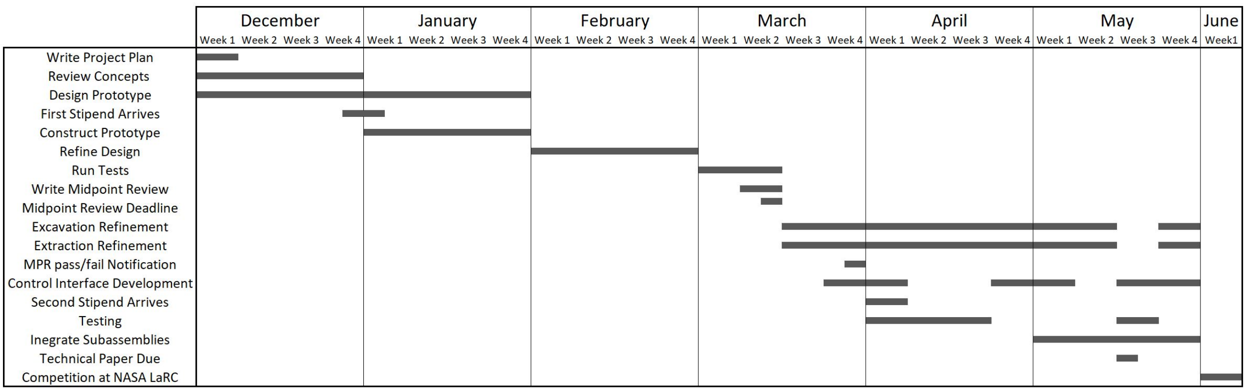


Figure 7: Project Timeline

9 Safety Plan

9.1 Operational Safety

Because the OLIVER robot will employ heavy machinery, its operation could pose numerous safety concerns if precautions are not diligently taken. Many of these precautions are effective at mitigating hazards and are easily implemented. For instance, all persons (including non-operators) occupying the same relative space as the robot will be required to wear safety glasses in case of debris ejections and ear protection to mitigate the potential effect of the drill's loudness on hearing. Additionally, a perimeter will be maintained around the robot in which no persons or objects will be permitted to enter in case OLIVER tips or the drill is dislodged from the frame. To further promote safety, load and current sensors will be used to detect off-nominal loading conditions (e.g. non-axial loads on the drill bit) and unexpected current draws (e.g. high current draws during idling) respectively. In these cases, the software will automatically shut down the robot. Additionally, the requisite fuse system will prevent over-current from damaging the robot.

9.2 Hazardous Materials

Below are the chemicals and hazardous materials that are used on this robot.

- Gorilla Epoxy-Resin
- Super Glue
- Hot Glue

PPE for these materials were only needed during application. When applied they were done in a large open room and under filtration system vent. The lab space where these chemicals were applied also had safety glasses, gloves and masks for when they were needed.

10 Paths-to-flight

OLIVER was originally designed to operate within a near-vacuum and requires modification to operate for demonstration within an atmosphere. These modifications would need to be removed from the prototype design for a flight-ready system.

10.1 General Modifications

There are numerous location-independent design modifications that must be implemented prior to achieving flight readiness for *any* ice extraction mission. These varied modifications will bolster the robot's structural integrity and the health of the electronics, promote mission efficiency, and protect against potential mission failures.

Any future version of OLIVER will require significantly more environmental protection than the current prototype concept affords. This protection would necessarily include an outer shell to prevent dust and regolith from interfering with drive mechanisms. Radiation will also be a significant complication for the prototype design, necessitating a change in electronics hardware. Replacement of the master Raspberry Pi controller will most likely use a flight-ready, tested, and evaluated computer. The Arduino microcontrollers can be replaced with AtmegaS128 space-qualified AVR boards [6]. Additionally, a new power bus would need to be developed in order to employ solar power, which may influence the selection of different motors and operating regimes.

10.2 Mars

OLIVER was conceptualized for Martian usage, so fewer modifications would be necessary (compared to lunar applications). Low pressure evaporation will be more energy efficient on the Martian surface compared to Earth, offsetting the decreased total power available. The following changes and considerations would be made for a Martian OLIVER variant.

10.2.1 Design Modifications

- Perchlorate Contaminants - Perchlorates (ClO_4^-) are present in Martian topsoil with concentrations between .5% and 1%. Ingesting just a few milligrams of perchlorates could potentially prove fatal to human explorers [4]. By using a low pressure evaporation extraction system, OLIVER stands to mitigate this issue, as contaminants would be left in the sediment and ice cavity. Collected water will be subjected to chemical purity tests, and may be additionally filtered as required.

- Mobility - While EDL (Entry, Descent, and Landing) technologies pertinent to Martian landings have improved since the deployments of the MSL (Mars Science Laboratory) rovers, landing is still not accurate to a sub-meter level. OLIVER must be able to transport itself to multiple drill sites over adverse terrain. Likely, the Martian OLIVER variant will use a rocker-boogie wheel system which has been flight proven on multiple Mars and Moon rovers. This would require the development of path planning algorithms/software and the implementation of computer vision techniques. However, it is of important note that the introduction of mobility into the system poses additional risks to the robot (e.g. incapacitation due to tipping) which could result in mission failure.

- Stabilization - Due to the low relative gravity on Mars, there will be significant unchecked reaction forces during drilling operations which could inspire unexpected motion (primarily in an upward direction normal to the surface). This would not only complicate drilling, but could also generate appreciable torques that may damage the drill bit if it is not perfectly perpendicular to the surface. In order to mitigate this issue, it is recommended that the flight version have deployable stabilizers to assist in anchoring the rover to the loose sediments. Furthermore, considerable instability exists due to the geometry of the frame. Since this geometry was majorly informed by the form factor of the competition's regolith/ice pit, it is highly recommended that the frame be redesigned for stability. This can be accomplished by:

    1. Aligning the drill assembly with the geometric center of the frame (rather than centering the drill bit)

    2. Lowering the robot's center of mass closer to the ground

    3. Providing a larger contact area between the drill assembly and the frame

    4. Incorporating an adaptive leveling system (e.g. via soft robots, hydraulics, etc.) that ensures the drill bit is perpendicular to the surface during drilling processes

- Power - Despite the distance of Mars from the sun, solar will likely be the best choice for power generation for the OLIVER rover. The rover may activate the drill in burst cycles in order to conserve power and maintain a high level of charge on the battery. In contrast to running a power hungry drill, the process of extracting water via low pressure evaporation will be more energy efficient.

- Autonomy - The delay in communication between Mars and Earth can be up to 20 minutes one way[9] causing up to a 40 minute delay between a command being sent through teleoperation and the results from that command being reported to the teleoperator. This is not a feasible time scale to respond to changing circumstances during the drilling operation. As a result full autonomy would be beneficial for the water extraction operation. This would require additional autonomy to be added that could recognize surface locations that were sufficient for drilling operations, navigate the system around obstacles and handle all elements of the normal drilling operation.

- Structural Integrity - It is imperative to ensure OLIVER's structural integrity by designing a sturdier, more durable frame to support the robot. The current prototype frame has been constructed from extruded aluminum and, although it can withstand the reaction forces encountered during drilling procedures, it is currently unclear whether or not it could survive the immense forces imposed by a launch or a Martian surface touchdown. The durability of the structure could be fortified with the addition of struts and drill frame supports at the expense of increased weight. As is customary, any OLIVER frame should be thoroughly shake tested and vibration tested prior to launch.

- Temperature and Humidity - Humidity is another environmental factor that needs to be accounted for. Unlike on the moon or in a controlled lab environment, the Martian atmosphere experiences fluctuating humidity levels that can even occasionally saturate the atmosphere [2]. This relatively high humidity could pose a risk to the health of OLIVER's electronics after long periods of exposure. Therefore, it would be necessary to add moisture protection to all external circuitry. Additionally, the temperature on Mars swings from -70 degrees C to 20 degrees [2]. This wide range of temperatures presents opportunities for thermal expansion, thermal strains, and potentially even thermal fatigue. It is unclear how how this thermal behavior will affect the commercial-off-the-shelf drill bit, the frame, and other OLIVER components. As such, it is critical that this behavior is either accounted for (by choosing more temperature resistant materials) or at least understood to ensure that thermal effects will not pose risks to the success of an OLIVER mission.

- Materials As discussed previously, the OLIVER prototype was constructed using adhesive materials (e.g. super glue, epoxy). Some adhesives exhibit brittle behaviors in the presence of radiation [3] which may allow for the weakening of joints in the martian environment where radiation can not sufficiently be scattered by a thin atmosphere. Therefore, it will be important to ensure all adhesives used in the final OLIVER design can withstand the high solar radiation levels characteristic of the martian environment.

- Task Specialization - In order to reduce cost and maximize the amount of water extracted for a mission–ready OLIVER, it may be more efficient to divorce the extraction system from the drilling system. Since the extraction process has a lower anticipated energy cost than does the drilling process, deploying multiple dedicated extraction units and one dedicated drilling unit would allow for water to be extracted from multiple shafts in parallel. Furthermore, if the drilling units left the sheathed shaft intact long-term, these holes could serve as self-contained water wells for future extraction attempts. This task specialization may also simplify the design of the robot's electronics since the robots would not need to accommodate tasks with differing voltage requirements.

10.2.2 Concept of Operations

- Launch Vehicle - Assuming that a hypothetical launch date occurs after the successful design, development, and testing of the Big Falcon Rocket (BFR), it has been determined that this launch vehicles would be the most appropriate for an OLIVER mission. This rockets was selected because it was primarily designed for the launch of astronauts and cargo to the martian surface [11]. As such, the lightweight and volume-limited OLIVER could be stowed on the BFR with other robots/pieces of equipment requisite to the development of infrastructure on Mars. Additionally, the Space Launch System (SLS) could serve as an alternate launch vehicle; however, it has been assumed that the BFR rocket will be the cheaper option [8].

- Landing site - In order to reduce OLIVER's potential travel times and reduce the risk for mobility-related failures, it is important that OLIVER lands within a region of known ice deposits. In 2008, radar evidence suggested that the Eastern Hellas region contained subsurface ice glaciers [5]. For these reason, this region seems be an appropriate landing site for early OLIVER missions.

10.3 Moon

The Moon presents a different set of challenges than that of Mars. The environment is drier and full of intrusive lunar regolith, as well as a more problematic geography for robots.

10.3.1 Design Modifications

- Temperature Swings of the Day/Night Cycle - Due to the temperature reliance of the robot's operation, it will require ample insulation to survive the harsh lunar temperature swings, and power will be devoted to internal heaters necessary to keep the rover operable. Drill operations will cease during the lunar night in order to conserve energy. Reserve battery packs will be charged during the day using a system of solar panels.

- Fineness of Lunar Regolith - The lunar regolith layer generally extends between 5 and 10 meters deep on the Moon, with a particle size of approximately 100 microns [7]. The fineness of the substrate presents a number of problems for OLIVER, including navigation, stabilization, and drill requirements. In order to prospect for resources on the Moon, OLIVER would need a replacement drill mechanism more typical of a deep coring drill than an auger. The MARTE drill system [12] developed by NASA Ames Research Center is capable of drilling 10 meters in its base configuration. A lunar adaptation of OLIVER may use a similar type of jointed auger in order to provide useful data over a wide depth range.

- Positional Instability - Due to the relatively low lunar gravity (0.166g), OLIVER may encounter situations in which the reaction forces encountered during coring operations cause the rover to lose its grip on the lunar surface. Therefore, it may be necessary to incorporate retractable 'anchors' that minimize the tendency for the robot to lose vertical stability. Research into this form and function of anchoring technology is ongoing, but it has been demonstrated that a variation of microspine toe technology can effectively anchor spacecraft omnidirectionally during coring processes in microgravity [10]. As OLIVER will benefit from more appreciable gravitational forces, this technology will produce more-than-sufficient anchoring forces for the proposed lunar coring operations.

- Materials - There are many materials used in the development of the OLIVER prototype that may not survive a lunar excavation mission. Due to the minimal ambient pressure on the moon, the potential for outgassing is present which renders some of the chemical adhesives employed for the prototype unsuitable.

10.3.2 Concept of Operations

- Launch Vehicle - Although the BFR could also be used for a lunar mission (as was suggested for a martian mission), it may not be necessary to employ that powerful of a rocket to travel only a fraction of the distance. However, it is recommended that whichever launch vehicle NASA decides upon for the 2024 and 2028 lunar missions is also used to transport OLIVER.

- Landing site In 2009, *Chandrayaan-1's* spectrometer discovered with high probability the existence of water near the Shackleton Crater located at the lunar south pole [1]. Due to the physical evidence of water ice, it is recommended that OLIVER lands near or inside this crater to commence drilling and extraction processes. Although this crater is an opportune landing site, any of the suspected ice-bearing craters on the lunar south pole would be appropriate.

11 Full Budget

The expense breakdown for this project can be seen in Figure 8. The two most expensive elements of OLIVER were the agitator assembly and the chassis. The agitator assembly had to be machined out of house by 3D Hubs. The required precision and the ability to have replacement parts increased the price. The chassis was constructed out of 80/20 for versatility.

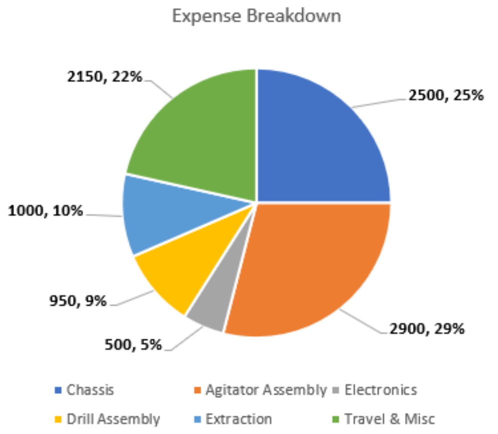


Figure 8: Project Budget Breakdown

12 Conclusion

The search for life on other worlds and the necessary support structure for human lives on other worlds follow the same theme - *follow the water*. The development of OLIVER is a necessary first step towards developing sustainable low-cost infrastructure on other worlds. This prototype Overburden Layer Ice-to-Vapor Extracting Robot lays the necessary foundation for a new phase of extraterrestrial exploration.

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