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FOLGRS

Facilitation of Outerspace Liquid and Gas Removal System

RASC-AL 2017
Special Edition: Mars Ice Challenge

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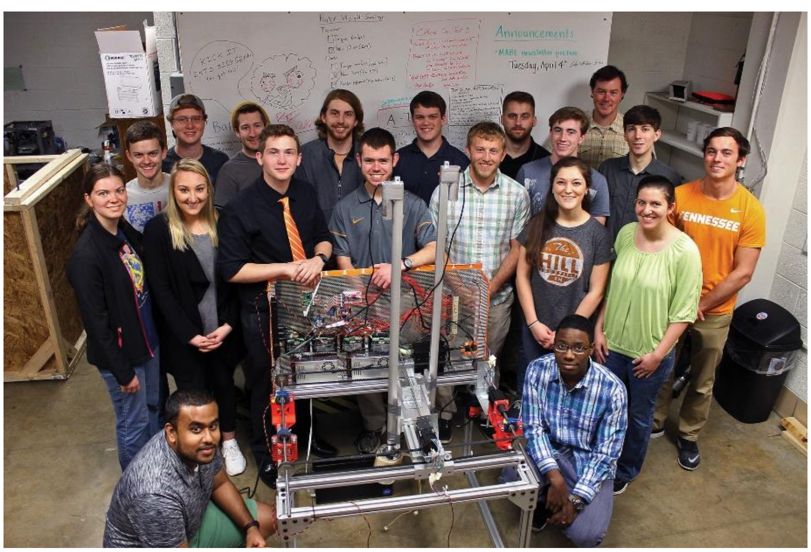

Introduction

The discovery of what are believed to be subsurface ice deposits on Mars has prompted experts to evaluate the viability of Martian exploration supported by in-situ water collection. The presence of usable water on Mars could allow for extended human exploration and potential colonization efforts without requiring resources such as agricultural products, polymer and propellants, oxygen, and drinking water from Earth. Access to usable water would greatly expand the potential of Martian exploration efforts, but these water deposits can only be utilized if technology to harvest liquid water from these subsurface ice deposits is developed. In response to a design challenge issued by NASA and the National Institute of Aerospace, a device was built under prescribed conditions and limitations in order to extract water from a simulated Martian ice deposit. Summarized below is the University of Tennessee, Knoxville's proposal for a Martian ice extraction system and explanation of the operation of that device in the simulated environment.

2. System Description

The prototype is modeled after a standard 3-axis gantry system which moves two individual tool heads in the X-Y plane as shown in **Figure 1**, and linear actuators move tool heads independently in the Z direction. This chassis is bolted to the simulated test bed via holes in each corner of the frame, and rests on the lip of the test bed.

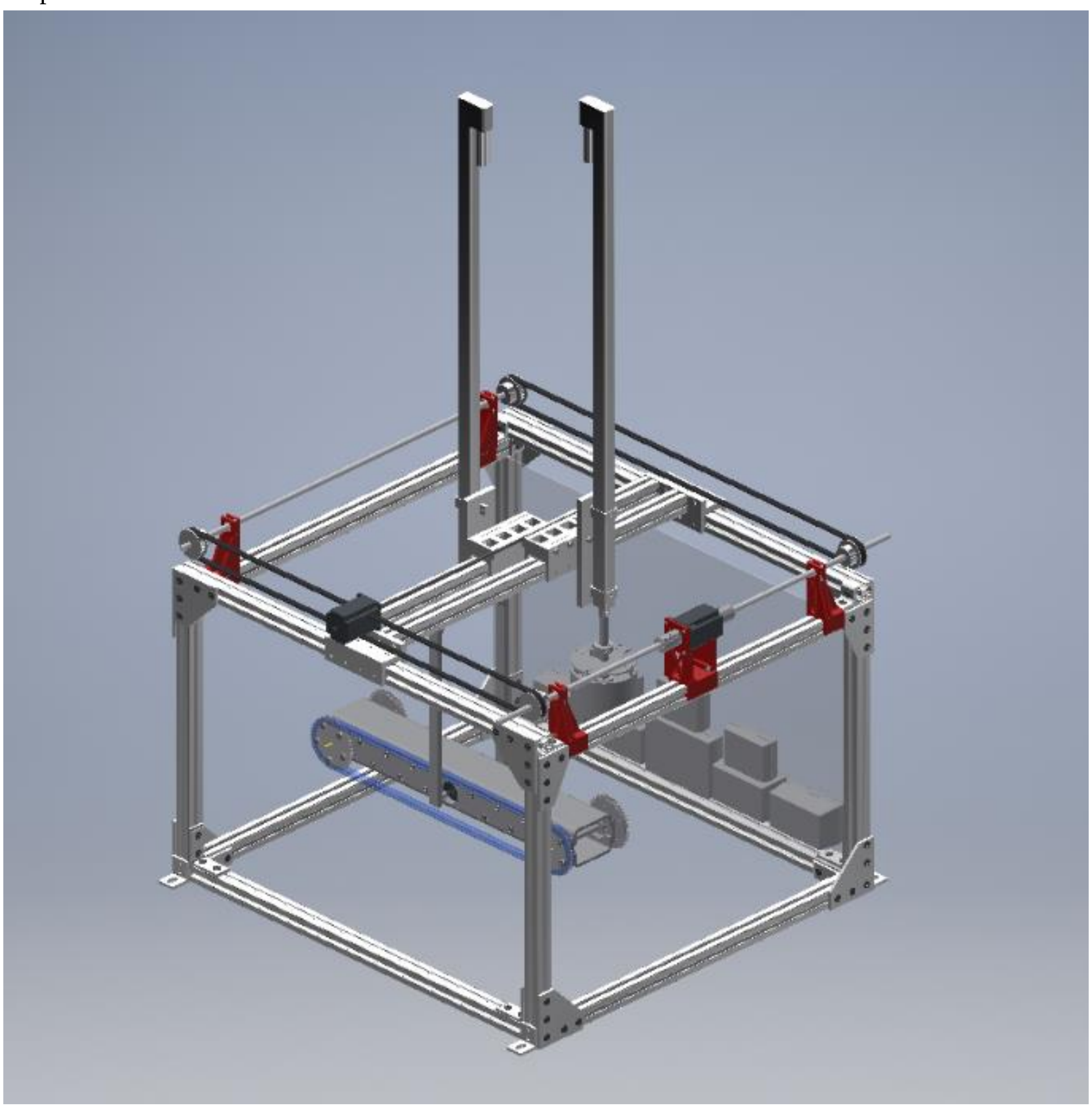

Figure 1: Model of 3-Axis Gantry System with Linear Actuators Attached

The first tool head acts as a trencher, moving overburden via scoop-shaped teeth carried on a sprocket-mounted chain as shown in **Figure 2**. Because the trencher sits above the overburden while operating, there is significantly less danger of it freezing into the deposit than a conventional drill or auger. An advantage of the trencher design is that, should it become jammed or stuck on a piece of overburden, it can be lifted and repositioned to try again without damaging the prototype.

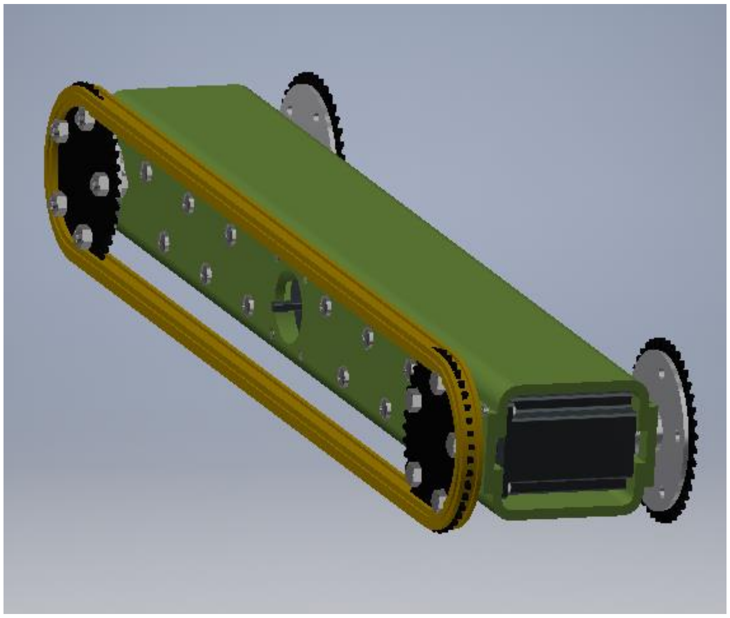

Figure 2: Trencher Unit with Teeth and Second Chain Removed

The second tool head is the water extraction unit, often referred to as the coffee can, the can, or the extraction can due to its geometry (**Figure 3)**. The extraction unit consists of a hollow aluminum cylinder with a resistive heating element affixed to the outside face in addition to a resistive heating element on the inside. The exterior heating element supplies heat to the entire can which maintains the water in its liquid phase as it travels through the hose, while also supplying heat to the can/ice interface. The interior heating element is affixed to a thin aluminum disk with insulation above it. Pin fins are affixed to the other side of the aluminum disk to increase heat transfer to the ice. The disk acts as the primary element for heating the core of the ice. A temperature probe is positioned just above the interior heating element and is used to ensure it is maintained at a temperature below 200 ^{o}C.

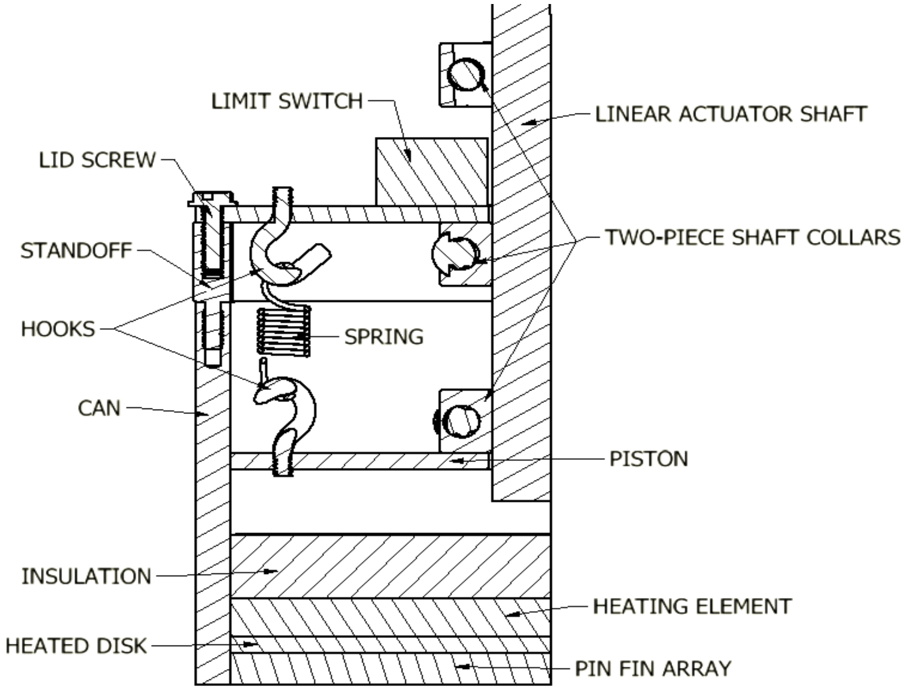

Figure 3: Cross-Section of Extraction Can

The can provides continuous pressure to the ice via spring force. When the can contacts the ice, the normal force will push the exterior of the can up and the springs will extend, creating downward force to keep the can on the ice. Based on the manufacturer-given spring constant of 2121N/m and four springs providing force, the maximum allowable deflection of the spring to maintain the force on bit under the prescribed 100 N maximum is 1.17 cm. The can is designed to operate well under that threshold as only a small force is required to maintain downward pressure. As an extra precaution, a limit switch has been placed on the top of the can and a small collar on the linear actuator; at the desired maximum deflection, the collar will depress the switch and restrict further movement of the can.

Table 1 outlines the technical specifications of the prototype. Because the system does not use a conventional drill or auger, some specifications which would apply to those devices are not listed. Weight-on-Bit was calculated for the trencher using the maximum achievable motor torque reported by the manufacturer and the length of a digging tooth. This represents the maximum downforce the trencher can exert during steady operation. The operating temperature is a reflection of the typical temperature of the unit during steady operation. The cutoff temperature refers to the temperature at which the heating element will be automatically disabled for safety. The maximum power draw was calculated by summing the draws of the individual components utilized while the machine is in melt mode, the most power-intensive of the operation modes discussed below.

Table 1: System Specifications

Overall	Overall Mass	49.5 kg
	Volume	.98x.98.1.625 m (LxWxH)
	Maximum Power Draw	1139 W
Excavation	Trenching Torque	2.2 N-m
	Tooth Length	5.1 cm
	Axial Downforce (Weight-on-Bit)	43.1 N
	Achievable Depth	1 m
Extraction	Heat Supplied	538 W
	Operating Temperature	~150 C
	Cutoff Temperature	200 C
	Axial Downforce (Weight-on-Bit)	75 N
	Max. Volumetric Extraction Rate	2.9 l/min
Electronics	Software	PyCharm
	Language	Python
	Controller	Raspberry Pi
	PSU	EVGA 500W PSU

The system is controlled through a Raspberry Pi, which runs a program written in Python. This program displays a Graphical User Interface (GUI) to the user’s computer through which the user can control the robot using an Xbox 360 controller and a control box. The program divides the control of other systems into distinct system modes as shown in **Figure 4**, allowing the operator to focus on the task at hand. This division of control modes also allows the operator to choose which system to route power to, preventing power management problems.

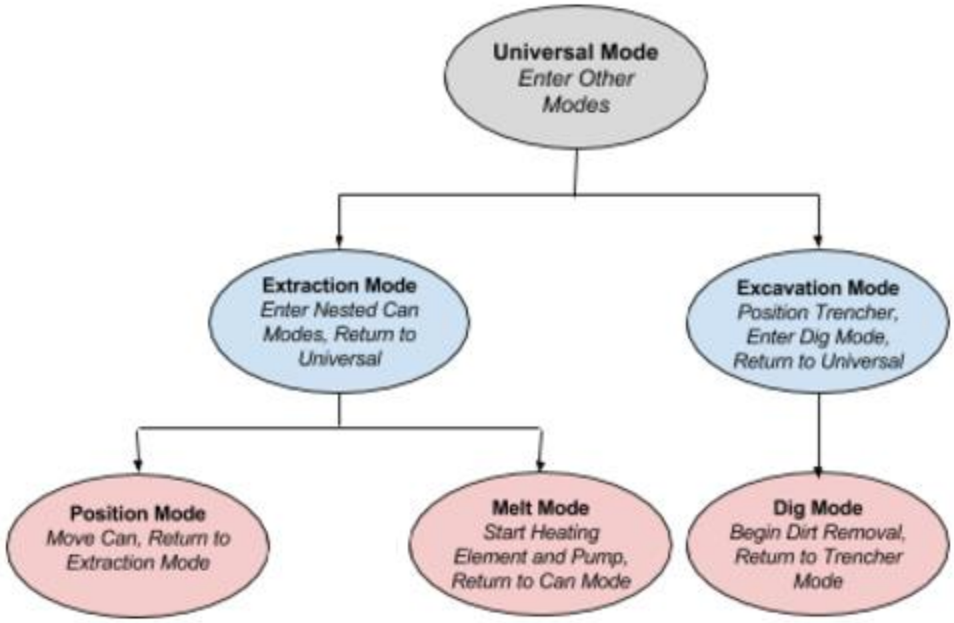

Figure 4: Nested Control Modes of Prototype

3. Design Changes and Improvements

Many design improvements have been made to increase the heat transfer rate from the coffee can to the ice. As will be discussed in later sections the extraction unit (coffee can) as outfitted for Martian operation does not need to supply a very large amount of heat to the ice to enable extraction. The power required for this will be better spent lowering the pressure inside the can to facilitate sublimation. The original design of the extraction can was drafted with this process in mind. However, this extraction methodology must be altered significantly for use on Earth, where pressure is high enough that water will not sublimate in useful quantities. Instead, the Earth-adapted extraction relies on heat flowing from the heating element to the ice, overcoming the heat of fusion, and melting the ice to an extractable liquid. This necessitated that the can be altered so heat would be transferred across the entire exposed ice surface rather than just the edges. To assist with this heat transfer further, pin fins were added to the interior heating element of the can such that they protrude from the ceiling of the coffee can and help heat penetrate deeper into the ice. The coffee can was also modified to be non-rigidly attached to the linear actuator so that a constant low pressure could be applied to help minimize thermal contact resistance with the ice while preventing weight-on-bit violations or damage to the system. The new attachment is regulated using limit switches which arrest the motion of the can as the force on bit reaches the maximum of 100 N. Additionally a new pump was acquired for the competition. This new pump has run-dry capabilities and also provides a significant weight reduction over the old pump. A passive filtration tract has been installed which consists of a strainer containing a size 40 mesh to remove coarse dirt and other larger contaminants before the water passes through the pump. After the pump, the water will flow into a small pail containing a carbon filter media supported by laboratory-grade filter paper. This three-stage filtration process will remove the smallest dirt particles from the water and also remove contaminants and impurities.

The excavation unit or “trencher” has also undergone numerous design improvements. The trencher is now made of lightweight structural fiberglass to decrease its weight while maintaining the rigidity required for its operation. The sprockets, axles, and teeth have all been replaced with more durable, lightweight parts which were precision machined, eliminating the misalignment problems which plagued earlier prototypes. Control of the trencher has also been fully integrated into the control program of the robot. The trencher has been reconstructed so as to be mounted to the chassis, and control of the trenching action and trencher pitch have been routed through the Raspberry Pi.

The chassis has been altered to implement weight-saving measures. The corner brackets have been replaced with lighter, smaller brackets still capable of sustaining design loads. Many low-load bearing members have been filed or had holes drilled in them to minimize weight as well. The ball-screw system which drove movement of the carriage in the Y direction has been replaced with a faster unit. The carriage has been re-assembled with more permanent attachments and with waste material removed. The new model is lighter, stronger, and more rigid than the old one. Axles have been replaced with carbon fiber reinforced polymer rods and bearings have been significantly downsized. Mounts for these components have been downsized as well. Overall, these substitutions have decreased chassis weight with neutral or positive impact on rigidity.

Numerous improvements have been made which give the operator real-time data on the state of the machine, and continuously log data for future review. A thermocouple has been added to the interior of the coffee can and is used to control heat input to prevent the heating elements from burning out or melting. A limit switch on the coffee can also ensure it does not violate the allowed weight-on-bit limit during operation. The trencher attachment is outfitted with flex sensors that report the force-on-bit for the excavation system. All of this data is stored for record and review.

A more accessible and more rigid electronics mounting platform was built. This new platform allowed the carriage working area to be expanded, and so some chassis elements were moved slightly to fill this space. The new platform shields the electronics from dirt and debris while continuing to provide easy access and airflow to the components. This new platform will hold easy-access compartments for the electronic components to ensure quick repairs in the event of an electronic failure.

4. Challenges

As anticipated, the greatest challenge facing the mechanical design team was the attachment of the trencher to the linear actuator. The trencher produces a significant moment about the actuator attachment point, which required strengthening at the cost of increasing the weight of the attachment point. This attachment has been strengthened with the addition of a flexible mounting element which uses linear springs and vibration absorbing film to mitigate the vibrational load on the actuator-carriage attachment point.

Another challenge was ensuring that the system remained under the 50 kg prescribed weight limit. As discussed in previous sections, many design elements were altered to reduce the system’s mass. Additionally, nonessential and oversized structural elements have undergone modification to reduce their mass. Specifically, a significant amount of weight has been removed from the lower horizontal structural elements of the chassis through drilling and filing methods.

Heating and extraction rates, which were lower than desired in earlier iterations of the prototype, have been increased with the design modifications discussed above, i.e. the addition of the pins to the extraction can.

Weight-on-bit considerations have posed issues in mechanical development, but not because of the force actually exerted by the machine. Most conventional methods for weight-on-bit measurement were developed for drills and augers, so adapting these methodologies to the less convention design employed here posed challenges in designing tool head attachment points. Neither tool head is anticipated to violate this requirement during demonstration, exerting a maximum force of 75 and 41 N for can and trencher respectively, but measuring these forces and mitigating damage from any non-axial loads were nonetheless challenges to be overcome.

5. Competition Strategy

Competition strategy for operation of the machine is straightforward. Early in the competition, the trencher unit will extract as much overburden as possible from the test bed to the near surroundings and extraction bed lid. As dirt is excavated, extracting the remaining dirt becomes more time consuming for the operator. The operator will then transition to moving overburden away from the center of the test bed. Trencher operation will be limited as much as possible to the first day of demonstration, allowing replacement of worn, damaged, or clogged trencher teeth if necessary. Once overburden has been extracted or moved away from the center of the test bed, the coffee can will be used on the center portion of the exposed ice. This water will be collected, concluding day one of operation. On day two, extraction will continue, moving radially out from the center of the test environment. Doing most of the excavation on day one and most of the extraction on day two will allow the operators more hands-on time with the trencher, which has more moving parts and is therefore more prone to damage, while taking advantage of the score multiplier for water extracted on the second day.

6. Summary of Integration and Test Plan

Because of the modular nature of the machine, integration and testing took place in distinct phases. The first phase was the individual testing of the three main mechanical systems, excavation, extraction, and chassis movement. This type of testing consisted of testing the trencher and extraction can in small test beds of overburden and ice respectively, to ensure they could perform their given function. The chassis was tested with tool heads attached but not powered to ensure it could move in all three dimensions. The extraction can test verified that the newly implemented sensors worked and reported valid data. The limit switch mechanism on the extraction can was tested, and found to not only prevent the extraction can from violating the weight-on-bit constraint, but prevent the extraction unit from being lifted too far and colliding with the chassis. The trencher tests focus on ensuring the trencher is securely attached to the chassis and that the buckets effectively remove overburden. Longer tests will be undertaken in the weeks before the demonstration to ensure the trencher teeth hold up to long-term tests. The second phase of testing was to ensure that the entire system could be controlled with the system control program and hardware. These tests are short and are intended to expose any bugs in the control system. The third phase of testing consists of longer tests intended to simulate demonstration conditions. This type of test is ongoing and will be until the time of the demonstration. Along with these types of testing, testing will be undertaken to ensure that the trencher's cutting teeth will be able to penetrate frozen overburden.

7. Contingencies and Redundancies

Due to the number of moving parts that make up the excavation unit and the precision required for continuously rotating machines to work properly, the design element of most potential concern regarding contingencies and redundancies is the trencher. The first safeguard against a potential hardware problem is the operation plan. Limiting trencher use as much as possible to the first "hands-on" day of testing allows small problems to be dealt with as they arise. The trencher itself is designed so that tooth, motor, and chain replacement are all easily manageable by the on-site team. Individual trencher teeth are not critical to operation, so if a small number are damaged during day two of the competition, operation can continue without a significant loss of efficiency.

In the event of a catastrophic failure of any design element, spares for most major parts, including motors, motor drivers, and an entire replacement extraction can have been fabricated or procured. In the event that the trencher be immobilized by ice or gravel, it will be reversed and lifted repeatedly. In the event that the extraction can be frozen in the ice deposit, it will be activated to re-melt the surrounding ice.

8. Safety Plan

Should the trencher be run too fast, the tool may eject broken teeth or loose debris. While in use, all limbs will be kept outside the frame to ensure safety. Robot operators are to avoid the sides of the test bed that are perpendicular to the long axis of the trencher in case of debris ejection. The heating tool can scald and burn, so handling should only be performed with thick gloves and be limited to when the coffee can has had time to cool down. No hazardous materials or chemicals are being used, however normal safety protocol should be followed including the use of personal protective equipment. This includes safety glasses and close-toed shoes when in close proximity to the system, and thick gloves when handling the extraction mechanism.

9. Project Timeline

Figure 5 displays the timeline for construction of the prototype, including time between report submission and demonstration.

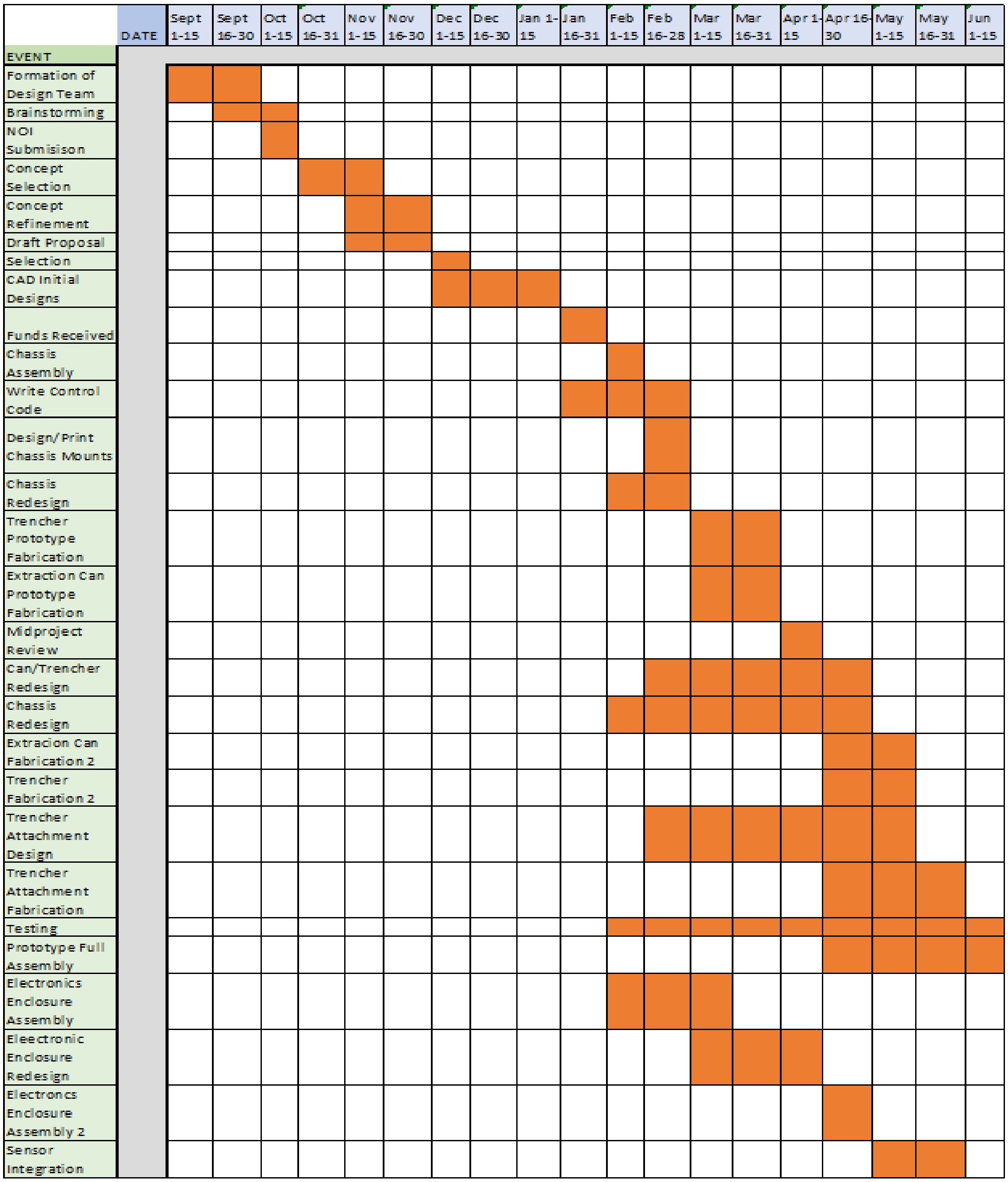

Figure 5: Project Timeline

10. Path-to-Flight

One of the largest path-to-flight considerations regarding the prototype is the re-adaptation of the design for use in the Martian atmosphere. The atmospheric conditions on Earth are such that water exists as a liquid above 0℃ and a solid below it. On Mars, atmospheric temperature and pressure are such that water is near its triple point, meaning that once ice deposits are exposed, it is possible that the ice could sublimate, melt, or remain ice, depending on the altitude of the excavation site, the time of day, and the weather at the time of extraction (2). The extraction mechanism was originally designed around the idea that small changes in temperature or pressure can be imposed on water at these conditions, forcing it to assume a state of matter which could expedite extraction. Specifically, the extraction can was designed to force water into the gaseous state in a controlled volume, which could then be easily collected.

Unfortunately, to replicate this process on Earth would require a testing chamber capable of matching these conditions. The University of Tennessee has no such testing location, and construction of one would be very expensive. Therefore, in order to approximate the expected sublimation rate of the device on Mars, mathematical analysis must be employed. The model presented serves as a justification of design choices and a tool for estimating the maximum achievable collection rate of the system. As mentioned later in this analysis, the model contains certain idealizations which are necessary for a complete analysis, but may overstate device capabilities. These assumptions can be eliminated by conducting small-scale experiments against which the model's results can be compared, allowing for refinements of the model to more closely reflect the real system.

The primary analysis tool for the system is the Hertz-Knudsen rate equation, Equation 1, which expresses the rate of evaporation or sublimation of a non-gaseous substance into its own vapor as a multiple of the difference between the current total pressure of the vapor and the equilibrium vapor pressure of the non-gaseous state (1, 9).

$$M_e = \int_0^t \int_0^A \alpha \left(\frac{m}{2\pi k_B T}\right)^{\frac{1}{2}} (P^* - P) \qquad (1)$$

This equation yields evaporation rates in $\frac{kg}{m^2 s}$, and must be integrated over time and area to provide the quantity of interest, kilograms of water collected. Restricting the analysis of the system to steady-state operation simplifies this to a multiplication by time and the internal cross-sectional area of the extraction can. This model estimates the equilibrium vapor pressure of ice using the Arden Buck equations, Equations 2 and 3 (6).

$$P^*(T) = 0.61121 \exp\left(\left(18.678 - \frac{T}{234.5}\right)\left(\frac{T}{257.14+T}\right)\right); \quad T > 0\ °C \qquad (2)$$

$$P^*(T) = 0.61115 \exp\left(\left(23.036 - \frac{T}{333.7}\right)\left(\frac{T}{279.82+T}\right)\right); \quad T < 0°\ C \qquad (3)$$

Figure 6 displays the total sublimation of a 10 cm diameter can over one hour for overpressures of 0 to 600 Pa and over a temperature range of -80 to 0 ℃. While this model can predict collection rates when given the internal conditions of the collection unit, it does not offer any insight into how those conditions may be brought about by an operator or control algorithm. To determine the internal conditions of the can, the ice inside the can was modeled as a disk sitting on a semi-infinite medium (8). This model considers the heat transfer to the ice deposit below the coffee can, but neglects potential heat transfer to the gas inside the can and any radiation that may be leaving the can. Assuming that the heating element in the adapted design converts all power supplied to it into heat, the power required to maintain a steady-state temperature that is equal to the heat transferred out of the system is expressed by Equation 4. The pressure in the extraction unit can be estimated by applying the equations governing the adiabatic compression of an ideal gas, then choosing a desired storage state, Equation 5. It should be noted that in the use of this equation, state one corresponds to conditions inside the coffee can and state two corresponds to conditions in the storage unit. For this analysis, the desired storage pressure was chosen to

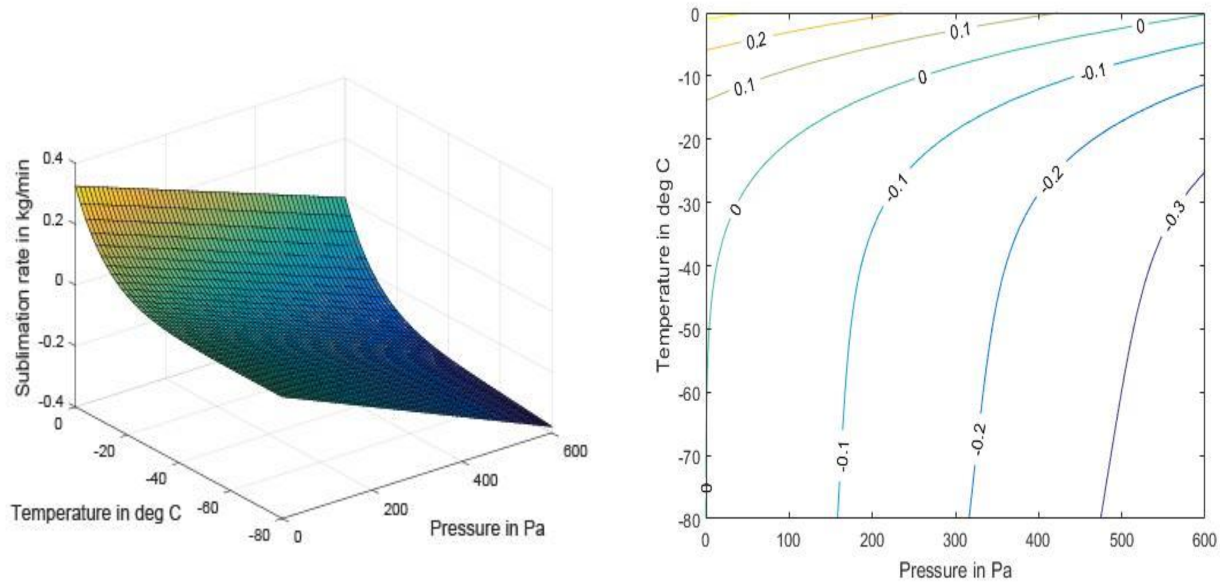

Figure 6: Sublimation Rate over a Range of Temperature and Pressure

be 1 kPa. This places the storage conditions comfortably within the range over which water exists as a liquid. While the ideal gas law no longer governs this region, it is important to note that the ideal gas law only stops applying once the water liquefies, at which point any additional pressurization is unnecessary. In real operation, this transition can be tracked with sensors to prevent overshoot.

$$T_1 = \frac{q"A - 2DkT_2}{2Dk} \quad (4)$$

$$P_1 = \frac{1000}{\left[P\left(\frac{\gamma-1}{\gamma QRT}\right)+1\right]^{\frac{1}{1-\frac{1}{\gamma}}}} \quad (5)$$

This more complete analysis calculates the system conditions as a function power input, and then the expected rate of ice collection as a function of those conditions. The resulting design envelope is shown in **Figure 7**. This envelope considers the theoretical collection rate for a total power budget of 1150 W with

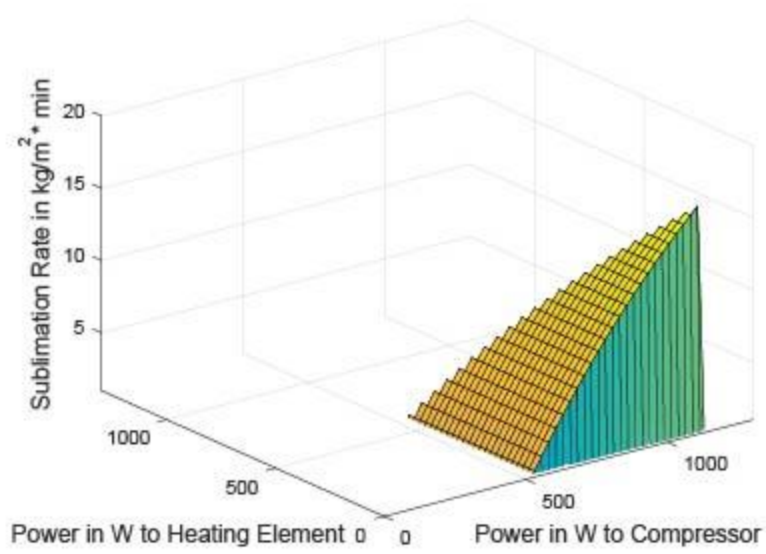

Figure 7: Functional Design Envelope

power distributed from 0 W to 1150 W to both systems (heating and pressurization) and all possible distributions of that total power between the two with a mesh size of 10 W, including cases where not all of the allotted power is used. It should be noted that Figure 7 excludes the region where power distribution does not induce sublimation, which will be discussed later. The unaltered plot, which includes values of zero at every point which violates the maximum power draw constraint is displayed in **Appendix A**. This analysis predicted a maximum sublimation rate of about 16 $\frac{kg}{m^2 minute}$

This envelope provides valuable insight into the behavior of the water collection system during steady state operation. Importantly, attempting to elevate the temperature of the system beyond 0 ºC results in a significant waste of energy. The system is not designed to collect liquid water, so while melting and subsequently heating water will increase its equilibrium vapor pressure, the power required to overcome water's heat of fusion does not contribute to raising the temperature of the system, and the opportunity cost of this melting in the form of system pressurization could potentially result in the pressure inside the coffee can rising above the equilibrium vapor pressure. This would force already vaporized water to be deposited back into the ice. With this in mind, it can be observed that very little heat transfer is required to keep the extraction surface at operating temperature. However, while choosing to operate the machine at the minimum required heat input allows for the maximum theoretical collection rate, it also makes the machine very sensitive to condition changes, as any increase in temperature would lower the equilibrium vapor pressure of the system to fall, making ice harvesting impossible.

As alluded to above, this model makes numerous assumptions which allow the analysis to be expressed in a workable, closed-form equation. The biggest assumption made by this model is the value of α, the sticking coefficient in the Hertz-Knudsen equation. This coefficient is a value between zero and unity which depends on the temperature and geometry of the surface in question and the kinetic energy of the vapor particles. Accurate calculation of this coefficient is often the sole subject of technical reviews (see ref (1)), and as such is outside the scope of this technical overview. It is recommended that an existing vacuum chamber is used to replicate Martian extraction conditions more closely, and a reasonable approximation of the sticking coefficient for this system could be experimentally determined. It was also assumed that the compression process was adiabatic. This can be approached through insulation, but some heat transfer is inevitable. To account for this, an appropriate value greater than γ must be determined and substituted into Equation 5. This model also neglects heat lost to the environment in the form of convection from the outside of the can, potential conduction to the ice outside of the coffee can, and net radiation from the extraction system to the environment. As discussed in other sections, the heat conduction to the ice surrounding the coffee can will necessarily be mitigated through insulation, lest that ice begin to melt or sublimate and break the seal the coffee can is forming. This model also assumes perfect transformation of power from the machine to usable energy (either in the form of heat or pressurization), which is not completely valid. Because most efficiency losses are due to heat, it is reasonable to assume that the heating element will be nearly 100% efficient. The pressurization unit on the other hand, will operate with some measurable losses. Additionally, the Arden Buck equation does not consider the potential effects that any dissolved salts or impurities in Martian ice deposits will have on water's vapor pressure. Finally, this model assumes average atmospheric conditions of Mars, and an ice deposit with initial conditions reflected in NASA's prescribed design requirements, -20 ℃. These initial conditions can be altered to determine the ceiling sublimation value in conditions of a landing site once it is chosen. In order to predict the extraction rate of a real system, these idealizations must be addressed individually, which would greatly increase the complexity of the analysis process.

Alternatively, an entire Mars-equipped extraction system could be built and tested, and the results compared to those given by this model. The model could then be modified by multiplying the result by something analogous to a discharge coefficient in fluid mechanics, accounting for all of the assumptions and inefficiencies by comparing experimental results to those predicted by the unaltered model.

Another important consideration for Martian deployment of the device is the selection of the deployment site. While site selection involves many variables which are either beyond the scope of this report or are dependent on mission architecture and goals, preliminary insight can be gained by studying the model presented above. The device works well in conditions with a high equilibrium partial pressure and low atmospheric pressure. Because for a given material, in this case ice or water, equilibrium partial pressure is only a function of temperature, the device will work best in areas with high temperature, so elevated areas near the equator will be better choices than low-lying areas near the poles.

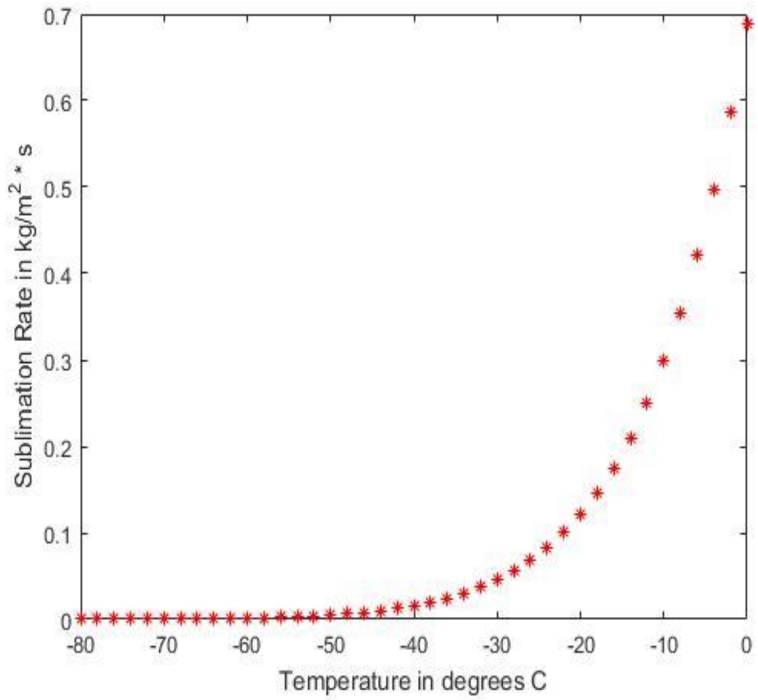

Figure 8: Sublimation Rate as a Function of Temperature for a 10 cm Diameter Unit in a Vacuum

Even if it is not feasible to design a mission around optimal ice-extraction conditions, daily atmospheric fluctuations should be considered when selecting system settings and planning expected daily ice totals. In order to make such predictions, it is enlightening to examine sublimation as a function of temperature and pressure independently. **Figure 8** displays sublimation into a vacuum for an ice deposit as a function of temperature only, while **Figure 9** displays sublimation of an ice block at 0 ℃ as a function of pressure.

As shown by these figures, sublimation rate is much more sensitive to temperature changes than to pressure changes, especially at temperatures near 0 ℃, which was already established as the optimum sublimation temperature. Because of this, priority should always be placed on maintaining the internal temperature of the system, regardless of the ambient pressure. In light of this, it makes sense that the device will be much more efficient during the middle of the day, when the ambient conditions make achieving the ideal sublimation temperature easier. It should also be noted that sunlight will also help to melt any ice mixed with overburden on top of ice deposits, which will soften soil and make excavation easier as well. Sublimation of ice crystals mixed with

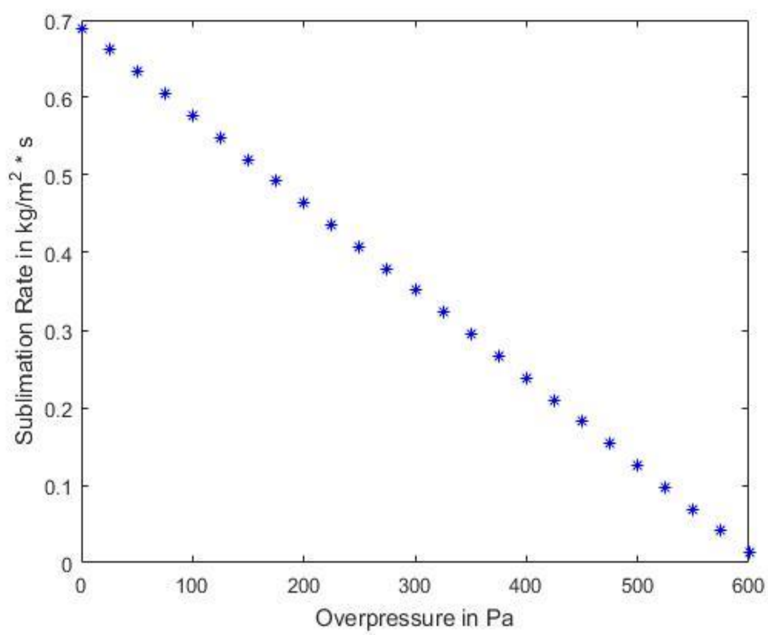

Figure 9: Sublimation Rate as a Function of Pressure for a 10 cm Diameter Unit

large quantities of Martian overburden occurs much more slowly than the predicted rate, meaning this type of extraction approach is not well suited for extraction moisture from overburden even if it is present (5).

The machine would also need other small modifications to make it usable in the Martian environment. The current prototype was built to function as just that, a prototype. The machine was designed to be easily disassembled, modified, repaired, and transported, so the chassis is constructed primarily of modular materials like 80-20 aluminum extruded beams. These components usually require mechanical fastening and are available in a few sizes or configurations, none of which will be perfect for any one application. This means that most electronic components, such as the relays and controllers, are arranged to increase accessibility, which would make them vulnerable in the Martian environment. The atmosphere of Mars is cold, dusty, and usually at a pressure much lower than that of Earth. Therefore, the electronics would need to be insulated and protected from the semi-magnetic dust that makes up the Martian surface which would increase the cost and potentially the weight of the machine. The current machine chassis is also significantly oversized in order to fit the test bed dimensions in the competition. The ability to use custom-built parts which can be permanently joined without worrying about frequent disassembly and reassembly of the machine will significantly reduce the weight of a deployment-ready robot.

The trencher would also need to undergo modifications to increase its robustness in preparation for excavating through Martian regolith. The prescribed conditions simulate a deposit buried beneath overburden, the loose, clay-like material which sits on the top layer of the Martian surface. Regolith beneath the surface can be much more compacted and pose substantial challenges to excavation efforts (4). The trencher should be adapted to a tooth geometry more closely resembling those used in large-scale mining operations on Earth.

Modifications to the whole system would also need to be made to adapt the robot to work in conditions different from those in the regulated test environment. It may be desirable to extend the actuator on the coffee can to allow the machine to collect ice from deposits which extend more than one meter below the surface. The chassis as a whole should be redesigned to suit the method of deployment chosen by mission architecture designers. It is recommended that the robot be mounted to a rover, allowing collection of ice deposits much larger than the 1x0.5 meter working area in simulated test conditions. The design of such a rover is beyond the scope of this report, but such a setup would eliminate the need for most of the chassis frame, significantly reducing nonproductive weight of the system.

The deployment of this or any similar device to Mars leads naturally to questions about the requirements of a human exploration of the planet. Such an undertaking would require transportation of supplies, collection of water, and gathering of scientific data on the planet. In order to limit the variety of supplies such a mission would have to bring to the planet's surface, it is logical that as much of the equipment should be made of similar parts. In order to help facilitate this, a single "stock" rover could be designed with an open utility bay, which could then be outfitted with apparatuses like the water extraction unit presented here. The design of such a rover would be a significant undertaking in and of itself, but would make many aspects of mission planning and on-mission maintenance more straightforward. Another benefit of this mission approach would be having standard power, weight, and size restrictions which could be given to third-parties who design and build some or all of the utility units.

Additionally, the current prototype is designed to maximize ice extraction in the prescribed working area. In real operation, the desired working area is another variable which can be tailored to the Mars-adapted design. If the system were mounted on a rover, which would be able to drive forward and backward, the need for any type of longitudinal movement of the tool heads would be eliminated. This would greatly decrease the size, and weight of the extraction mechanism, as well as reduce its complexity.

11. Budget

The budget given at the mid-project includes remaining funding from the first phase, and with the addition of the second phase of funding, $3300 was allocated towards improvements of the robot. This budget sets aside ample funding for travel costs, emergencies and replacement parts. Over the course of the second phase, however, the expected costs were much higher than reality. Each system has used less than half their allotted budget, a result of conservative spending and requiring less parts to purchase to improve the robot. The cost to recreate the competition-ready robot is estimated to be $3,450. A breakdown of the cost towards each system can be seen in **Table 2**.

The University of Tennessee's Mechanical, Aerospace, and Biomedical Engineering Department covered the cost of acquiring the tools necessary to proceed with production. The sum value of the tools equates to $715 in donation and the team would like to thank the department for their support throughout the project.

Table 2: Prototype Budget

Fabrication Cost	
System	Cost
Aluminum Chassis	$800
Chassis Drive	$300
Carriage	$550
Carriage Drive	$100
Coffee Can	$600
Electronics	$700
Trencher	$400

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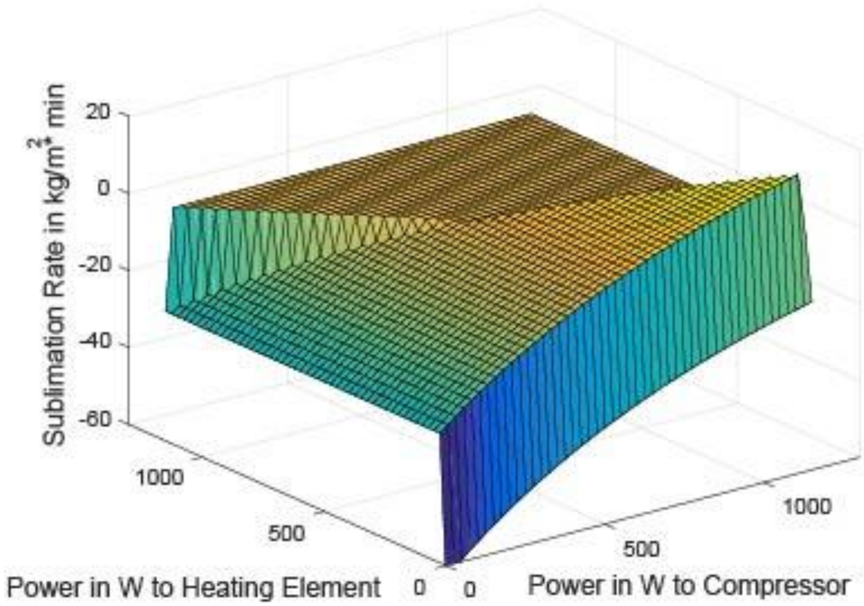
Appendix A: Theoretical Sublimation on Mars

This sublimation is calculated in $\frac{kg}{m^2 minute}$ as a function of power distribution to heating and depressurization.



Appendix B: Budget Allocation

Of the $11,200 NASA allocated to the University of Tennessee as funding for the project, $8,050 was spent. This includes money spent on initial prototypes, materials to recreate the competition test bed, replacements and improvements and back-up materials as well. Also included in the total spent was travel and registration costs. Along with the funding from NASA, the University of Tennessee Mechanical, Aerospace, and Biomedical Engineering Department donated $715 worth of tools for the team. The team would like to thank the department for their continuous support and providing lab space for the past year as we prepared for the competition.

Total Funds Used	
System	Cost
Can	$700
Mechanical	$2,600
Electrical	$900
Trencher	$750
Travel	$2,000
Registration	$1,100
Total	$8,050

Appendix C: Analysis Details

The following function was written in MATLAB R2016A and used to calculate sublimation rates for a given temperature, pressure, and working radius. It was used along with other scripts to produce all sublimation plots in the Path to Flight section of this report.

```
function EVAP = evapfinder(T,P,L)

% you used the Arden Buck Equation
rm = L;
N = length(T);


% establish constants
Na = 6.022 * (10^23);
kb = 1.380648 * (10^-23);
%

%properties of water and book keeping

mass = 0;
m = (18.153/1000)/Na;
alpha = 1;

    if T >= 0
        pst = (.61121* (exp((18.678-(T/234.5))*(T/(257.14+T)))))*1000;

    else
        pst = (.61115 * (exp((23.036-(T/333.7))*(T/
(279.82+T)))))*1000;

    end



    delP = (pst - P);
    area = L^2*pi();
    const = (alpha)*sqrt((m)/(2*3.1416*kb*(T+273)));
    dm = const*area*delP;


    mass = mass + dm;


EVAP = mass;

end
```