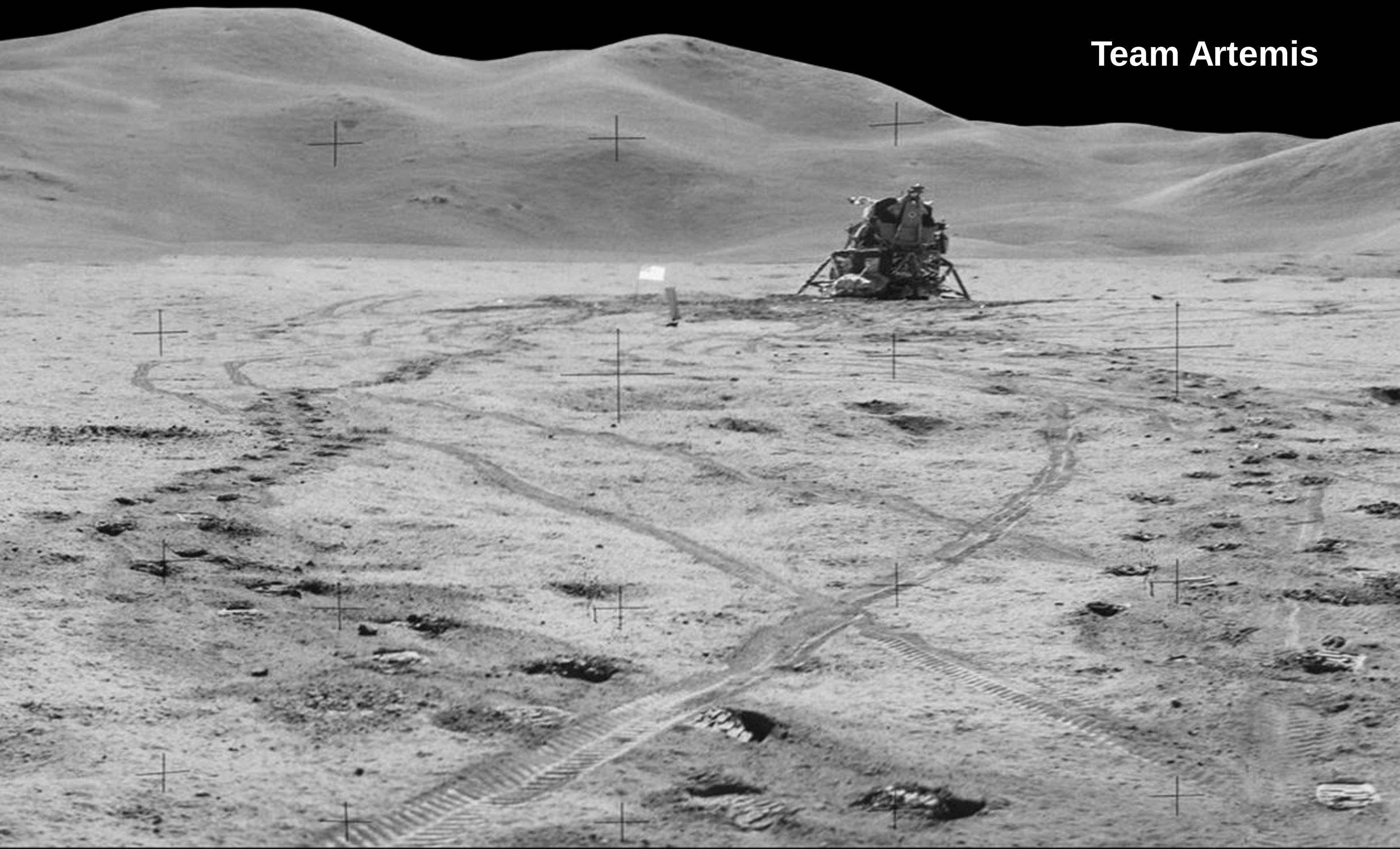
INDUSTRIALIZE THE MOON



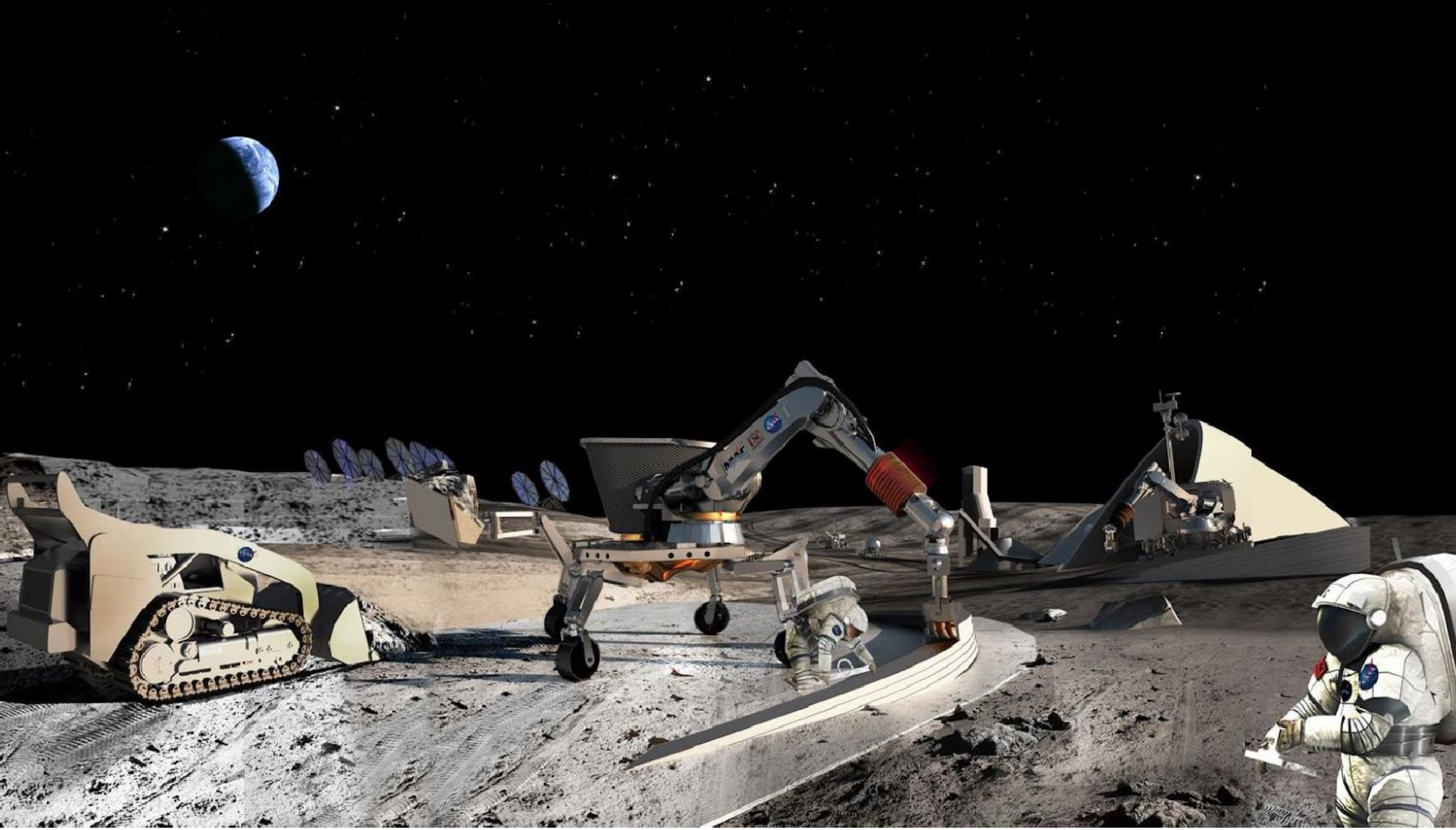
Team Artemis

Prologue

Space travel is hard, you either have high efficiency or high thrust and there was no easy way to get past the tyranny of the rocket equation. Yet hanging out at Earth-Moon L1 was humanity's first true spaceship, a kilometer long behemoth of aluminium and iron girders never meant to touch ground or kiss the atmosphere of a planet. On its bow stood 16 SpaceX Starships with enough room between them to fit several more. It's stern was dominated by cooling fins, gigawatt nuclear reactors, fuel tanks, and the massive argon fueled ion drive almost as wide as the ship itself. Such a ship would have been prohibitively expensive to have launched from Earth, instead the components for her construction were built in massive foundries on the Moon and assembled in lunar orbit.

Yet such a large construction did not happen overnight, it took decades until such a vessel could be built. A lunar colony had to be established, knowledge of how to process raw regolith into usable materials was required, the behaviour of molten materials in low gravity vacuum environments needed to be understood, and the vehicles to excavate the regolith had to be designed.

The mission proposal you are about to read is a first step to this grand vision of truly becoming a multiplanetary species. To test technologies that will lay the foundation of extraterrestrial human colonization, and industrialize the moon.



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Concept

The moon is exciting as Alaska was in the 1800s. It is a frontier where tremendous wealth will be created and resources will be extracted for humanity's expansion beyond the Earth.

— Peter Diamandis [1]

Future space colonization will present a need for not just in-situ resource utilization, but eventual industrialization, which we hope one day will be able to supply cislunar space and the greater solar system with material for buildings, vehicles, power plants, and even colossal spaceships.

Lunar regolith represents an ample supply of material that can serve both as an excellent thermal insulator to protect lunar bases from the extreme temperature environments of the lunar surface, as well as radiation protection, shielding astronauts from the solar wind and cosmic rays. Furthermore, the regolith can be used as a construction material in the structure of lunar bases — by sintering bricks, extruding basalt fibres, or the electrolytic refining of metal-rich ores to produce iron, titanium, aluminium, as well as oxygen.

In order to do the jobs of excavation, resource processing, and construction, our rover needed to be multifunctional and modular. To survive the harsh lunar nights our processes had to be creative. Above all it had to be able to perform all possible tasks fully autonomously, with no human intervention.

Here, we present a design for a lunar rover and mission profile intended to demonstrate the processing of lunar regolith into a construction material that provides both thermal protection and shielding against harmful radiations. Our mission exemplifies an asset for future lunar exploration and assisting in the construction of future installations on the lunar surface.

Objectives

The primary objective of this mission is to test an automated manufacturing system, one capable of doing excavation, processing, and base construction. If humans are ever going to colonize the solar system then the robotic excavation and processing of in-situ resources is a requirement.

The secondary objective of this mission is to test if it is possible to turn regolith into a useful material without the addition of any plasticizers for sustainable and cheap lunar base construction. Melting down regolith also allows characterization of a process that will be utilized in the future to extract metals and minerals, such as iron, titanium, aluminium, and thorium.

Obstacles

Constructing a lunar base comes with many obstacles, especially with a tight mass and volume budget. For example, the lunar night poses a significant challenge to any crafts on the lunar surface. Lasting over 14 Earth days, an enormous quantity of energy is required to keep electronics on the lunar surface warm when there is practically no sunlight to provide power or heat.

We tactfully circumvent the issue of the lunar night by deploying a “garage” buried under a thick layer of lunar regolith. Because regolith is such an effective thermal insulator, by covering a garage containing all sensitive electronic components of the design, we are able to effectively minimize radiative losses to space. In addition, even at only 50 centimetres below the lunar surface, the temperatures are stable at about 252 kelvin (minus 19 degrees Celsius), which is easily tolerated by our electronic systems.

Opportunities

We use a highly modular design, which makes expansion and scaling up of our miniature lunar base practically trivial. A need for more power can easily be resolved by adding more solar panels onto the payload manifest, while an increased brick production can be done by including more furnaces.

Furthermore, the rover element of our design can be easily customizable, and provides ample space for hosting customer payloads. Payloads can also be deployed, transported, and even relocated by the rover to sites across the lunar surface. In addition, the use of a thermally insulated garage to store electrical equipment means that customers no longer have to design their payloads to survive the lunar night or be constrained by a mission duration of 14 days before the electronics freeze and fail — we can simply store their equipment within a garage. As an example of our capabilities, a hypothetical lunar surface probe experiment could be installed and reinstalled at several locations near our base during the day, and stowed within the garage during the night. This is a demonstrable advantage over most previous lunar missions, which either only operated during the lunar day before leaving the Moon or succumbing to the frigid lunar night (e.g. Apollo, Chandrayaan-2) or heated their electronics with expensive and dangerous radioactive materials (e.g. Луноход[1], 玉兔[2]).

[1] *Lunokhod*
[2] *Yùtù*

Landing Site Evaluation

The selection of the landing site revolved around three criteria: iron concentration, terrain, and concentration of other metals. We used the software package JMARS to quantify these conditions. Beginning with iron, the highest concentrations seemed to be correlated with the lunar maria, likely due to their higher basalt concentration and geologic history.

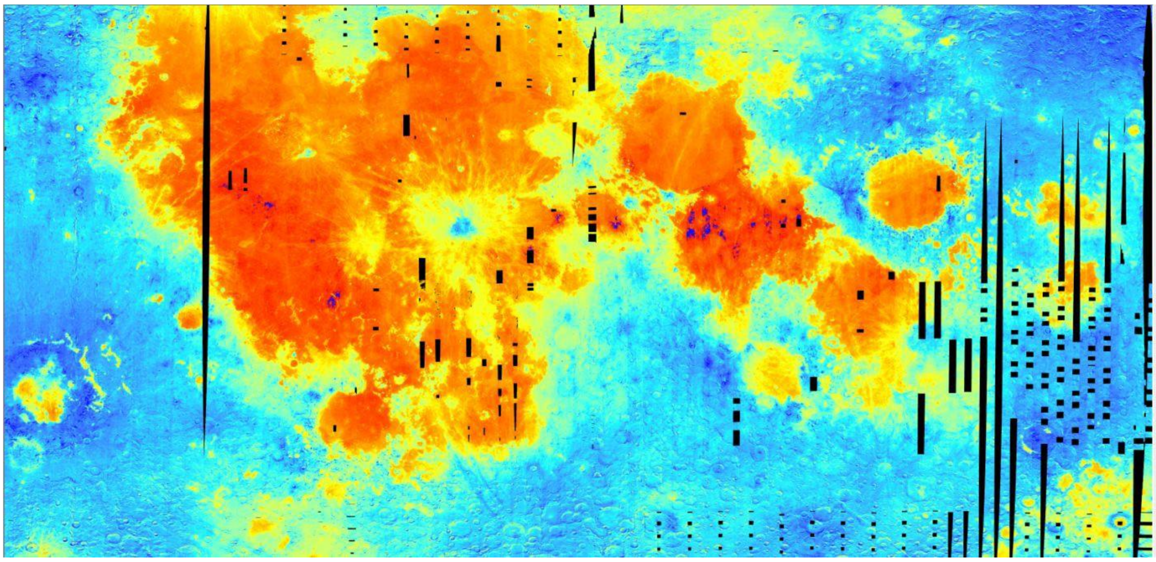


Figure 1: Lunar iron concentration, red is greater.

We then used a slope map, which allowed us to visualize which terrain was suitable for landing and which terrain would be too dangerous to traverse.

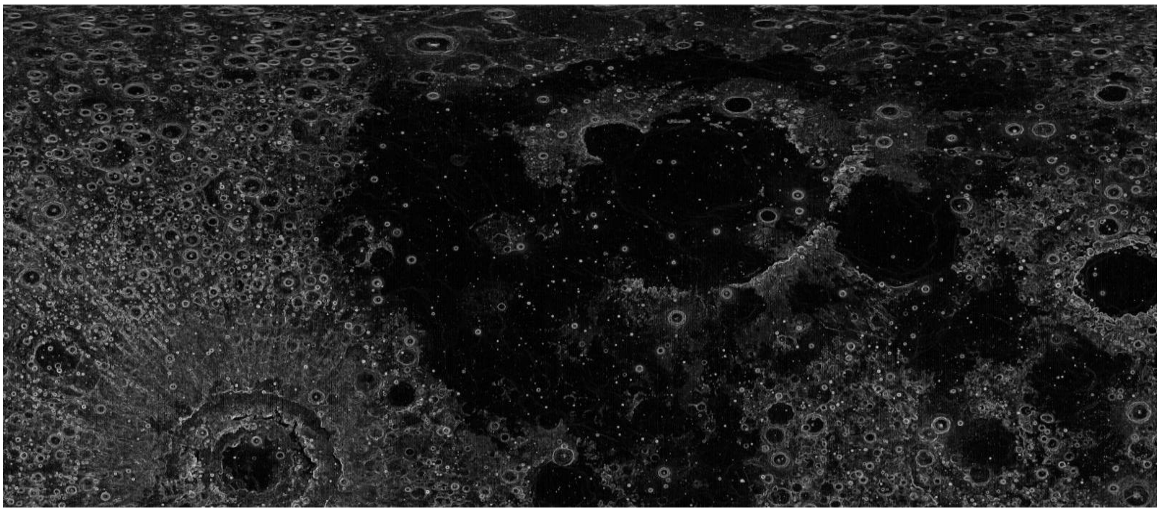
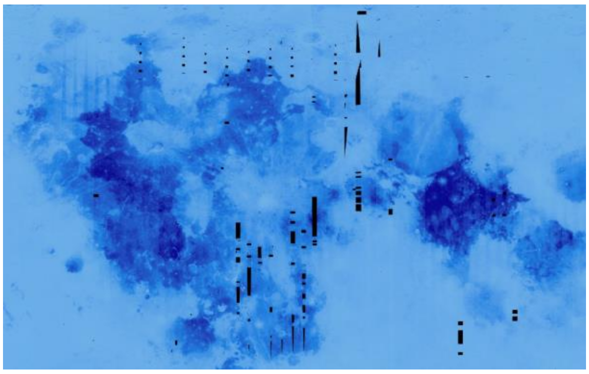


Figure 2: Lunar surface slope, darker is less sloped.

Interestingly, the flattest areas were also correlated with being in the lunar maria.

Finally, we observed concentrations of other metals, specifically for titanium and thorium — both of which are beneficial for future mining and industrialization.



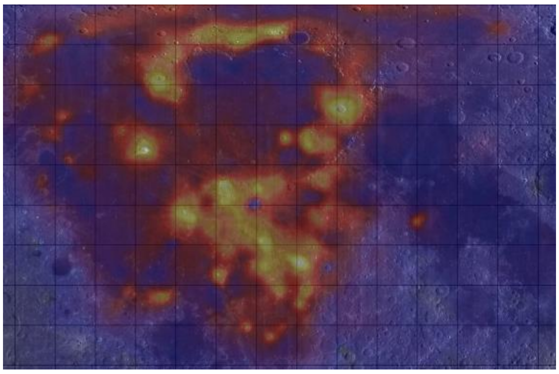


Figure 3: Titanium, darker is greater.

Figure 4: Thorium, brighter is greater.

Titanium concentration appears to correlate with iron concentration, while thorium appears to be less correlated to iron.

The Final landing site was chosen to be at 63.531W, 19.312N.

Figure 5: The selected landing site, southeast of Seleucus Crater, is not too far away from the landing site of the ancient Луна-13 lander.

The landing site is in an area of Oceanus Procellarum that has a high iron concentration and higher-than-average titanium and thorium concentrations. The large flat area allows for room for error with the landing and it happens to be, purely by coincidence, 25 miles away from the Луна-13[3] landing site. A potential mission extension would be to drive to and inspect the derelict Луна-13 probe.

Why not the Poles?

One of the greatest concerns that may be raised with our near-equatorial landing site is that it is not near the lunar poles, where water is found in significant quantities in the form of ice. Although water is a useful resource, used to produce hydrogen (for propulsion) and oxygen (for breathing), we realized that the extraction of water, in this mission profile constrained by mass, is simply not feasible.

Water Ice is not feasibly extractable within our mass budget.

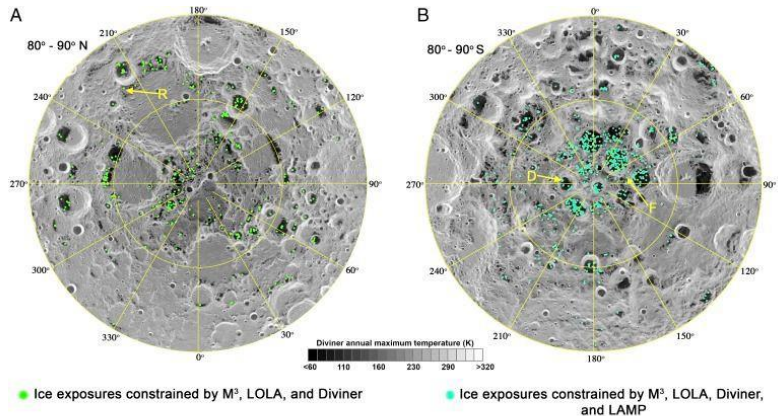


Figure 6: Map of significant water deposits, [2]

The most fruitful deposits of water on the Moon are located in permanently shadowed regions of polar craters. Any exploitative mission aimed at harvesting and processing lunar water in the bottoms of craters will have to deal with the issue of power. Permanently shadowed craters by definition absorb no sunlight at all, so generating power from solar panels is a non-option.

Although, one might raise the prospect that other methods of providing power at the bottom of craters exist. Namely, the most feasible solutions include power transmission and nuclear power. Power transmission is done by attaching a power cable to the rover that extends to a site upwards of the crater that receives sunlight. We investigated this solution, and found that although this method is feasible at delivering electrical power to the bottom of craters, it simply would not fit within the mass budget of this mission. Large, heavy power transmission cables would need to be deployed for lengths of kilometres or more between the rover and a site on the crater rim. Furthermore, the logistics of maintaining said cables from degradation from extreme temperatures and erosion from the lunar regolith, were deemed too risky.

Nuclear power, accomplished through bringing nuclear reactors or radioisotope thermoelectric generators, were another option considered for power generation. However, it was trivial to see why nuclear reactors or RTGs would be infeasible on our rover. For example, the Multi-Mission Radioisotope Thermoelectric Generator that powers the Mars

[3] *Luna-1* 3

rovers *Curiosity* and *Perseverance* masses around 40 kg and generates 110 W of electrical power — most RTGs have a very low power-to-mass ratio, at around 2 to 4 W/kg, in comparison, solar panels often have a specific power of 100 W/kg or more. In addition, the price of an MMRTG, around USD $93,995,000, is cost-prohibitive for our mission. [15] Furthermore, our attempts to contact suppliers for the procurement of the highly-radioactive plutonium-238 fuel used in RTGs have so far proven unsuccessful.

Nuclear reactors are, for similar reasons, precluded from our mission. The smallest nuclear reactor available, the KRUSTY reactor developed as part of NASA's Kilopower program, masses 134 kg — already exceeding the 60 kg mass cap. In addition, the reactor uses 28 kg of highly-enriched (weapons-grade) uranium, presenting further issues with acquisition and procurement. In fact, the United States had practically shut down the use of highly-enriched uranium in space [3]. We do not discourage the use of power transmission or nuclear reactors in future lunar exploration, (in fact, we are excited by the prospect) but the use of such sources in our rover was deemed infeasible due to mass and cost constraints.

Landing near the poles significantly complicates communications.

Due to the high latitudes of the poles, the Earth will be very low or even below the horizon for any rovers at the poles. This introduces complications with communication: if the rover were to venture behind a rock or into the depths of a crater, where the Earth is not visible, it would have to depend on communications with satellites in lunar orbit. Existing orbital satellites that regularly fly over the poles are not designed to be communications relays,[4] and the deployment of new satellites adds significant development and deployment costs to the mission.

Our landing site, on the lunar nearside, maintains a constant line-of-sight to the Earth and our ground stations on it, thus no additional orbital infrastructure is required for operation.

Polar craters constitute treacherous terrain.

We selected our landing site to be in the lunar maria, which have relatively flat terrain and significantly less hazards. The lunar poles and their cratered terrain poses navigation threats to any lander or rover that may be attempting to operate in the area. Steep gradients, crater rims, and mountain ranges are all dangerous to a rover if it were to suddenly find itself in shadow or out of sight from Earth.

Oxygen, one of the objectives of water mining, can be found elsewhere.

In experiments that our team has conducted and recorded, the heating of lunar regolith thermolyzes constituent minerals and releases oxygen gas. Future mining and processing installations will likely exploit the oxygen content of the lunar soil in order to extract oxygen for life support. However, we ultimately do not pursue the harvesting of oxygen from lunar regolith in this mission due to mass constraints and design complications.

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[4] the 鹊 桥 satellite, although purposefully built to be a communications relay, does not have line-of-sight to the lunar poles.

In-Situ Resource Utilization Experiments

Crucial to a successful execution of our mission and the construction of effective surface structures is to select the correct process in which to produce construction material from. Our team dedicated extensive research and physical testing to evaluating several methods of processing lunar regolith into a construction material including pure compression, solar melting, microwave sintering, and electric arc melting. The final method chosen, detailed below, was induction heating. It's minimal mass, ease of operation, and interesting properties making it an ideal candidate for our mission.

Regolith Compression

Initially the prospect of compressing the lunar regolith into solid bricks using mechanical force alone was investigated. Initially, this process was evaluated due to its reliance on mechanics alone, negating the need for electrical or thermal processes. However, numerous drawbacks were presented by compression, namely the requirement of heavy hydraulic and mechanical systems that require maintenance.

To test the force required to produce compressed regolith bricks, a setup was devised that used a hydraulic press to apply force to a pellet of basaltic lunar regolith simulant. Initially, we used a pellet with a diameter of 25 mm and a force of 50 kN, equal to a pressure of 2.5 GPa. Such a pressure failed to compress the regolith into a solid pellet. Continuing, the pellet size was reduced to 9.5 mm, and the force was changed to 40 kN, equivalent to a pressure of 5.3 GPa. The test resulted in damage to the walls of the steel container holding the pellet, and the resulting pellet was too friable to maintain any sort of structural integrity.

Thus it was that regolith compression was not a feasible method of producing bricks.

Figure 7: Left: Image of damaged steel container after 9.5 mm compression test.
Right: Pellet produced by such a test did not maintain rigidity.

Solar Heating

Using a large concentrating lens or mirror to melt lunar regolith into a construction material was a particularly interesting option. This method has the advantage of directly using sunlight to produce material, instead of converting sunlight into electricity to then perform work. We conducted some experiments with a Fresnel lens on a basalt sand material. The bar at the bottom right was the result of solar heating with an aperture of about 0.5 m^2, with a speed of about 0.1 mm s^{-1}.

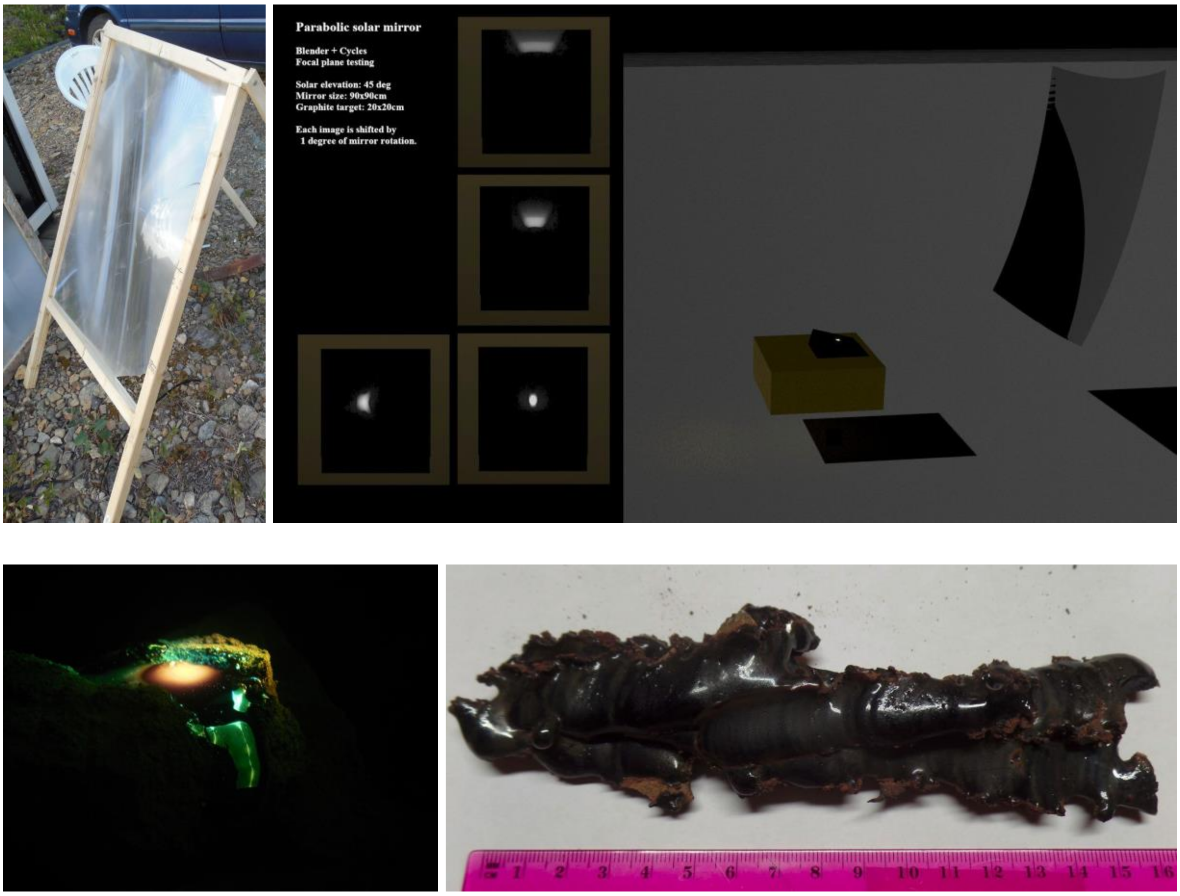


Figure 8: clockwise, from top-left: a Fresnel lens used for our solar melting experiment, an equivalent paraboloidal reflector, a molten and solidified bar of basalt, and the solar melting process while operating (through welding goggles).

Previous research has found that the solar sintering of lunar regolith into bricks produced a product whose compressive strength was far too low for practical use [4]. Furthermore, the precise control and manipulation of the Fresnel lens or a reflector for sintering regolith may be much more nontrivial than first impressions show.[5]

[5] Turns out concentrated sunbeams melt rovers as much as they melt regolith.

Electric Arc

Using electric arcs to melt and fuse regolith was investigated. Our experimental setup used an arc generated by a conventional arc welding machine with carbon electrodes and a metal plate. The basalt sample was placed on a graphite block and the electric arc turned on. With this method the regolith was successfully melted and formed into small beads of what appeared to be an obsidian glass material.

Figure 9: two still frames of the welding arc shot through #10 welding goggles. The left shows the arc lit; the right shows just after the arc went out. The tip of the graphite electrode must have been white hot in order to be this bright through welding goggles. This earlier shot shows the lighter deposit more clearly.

Unfortunately, some immediate issues arose with the setup. Unfortunately, the arc required over 200 amperes to start. Power consumption was also an issue as the arc welder consumed an estimated 6 kW of power, likely too intensive to be feasible for our mission.

Furthermore, the electric arc did not produce much of a cohesive product, instead splattering beads of glassy material. An issue similar to that experienced in solar sintering arose: precise control of the arc and what spot it acts on is a much more difficult problem than “just” 3D printing. Furthermore, electric arcs behave far differently in vacuum compared to air, and testing of such a vacuum arc welding setup would necessitate the construction and validation of a test rig within a vacuum chamber, significantly slowing down development progress.

Microwave

Next, we investigated the feasibility of using microwaves in order to melt lunar regolith.[5] The free iron content of the lunar regolith makes it susceptible to microwave heating.

The benefits of microwave heating is that it is a proven process, and microwave heating on the Moon will be much more efficient due to the absence of atmosphere to cause convection losses.

Figure 10: Iron-enriched basalt melts in a crucible within a household microwave oven.

However, microwaving lunar regolith presents several flaws, including the unsuitability of microwave-processed regolith for things other than roads. [5] We also identified the problem of outgassing causing structural issues, but this is likely not a concern in a vacuum where gas bubbles would be drawn out of the molten regolith.

Perhaps the most significant issue with microwave heating are that while the microwave magnetrons are rather light, the AC transformers are bulky, weighing several kilograms, and producing large amounts of waste heat.

Induction Heating

After learning that there is a sizable percentage of free iron in lunar regolith on the moon during a previous investigation into microwave sintering [6], we began evaluating the concept of using an induction furnace in order to liquefy and mould regolith into solid bricks. Iron oxide melts at roughly 1500 °C, graphite crucibles and ZVS circuit boards can achieve temperatures of 2000 °C. Induction also has similar benefits to microwave heating as there are no convective losses in vacuum. While this method has yet to be rigorously tested, high power induction furnaces are already known to be able to melt basalt and are used in the creation of artificial lava.

A small 1.5 kW induction furnace was used for this experiment. 200 grams of basalt dust[6] was loaded into the crucible, and the temperature was set to 1100 °C.

Basalt dust was observed explosively overflowing out of the crucible at 400 °C. In the region between 400 and 600 °C large volumes of outgassing were observed. Overflow happened again at 600 and 700 °C. Experimenter poked the sample with tongs to prevent another overflow at 800C, sample "deflated" back into the crucible.

[6] Unfortunately, UPS had mishandled the shipments of LMS-1 and LHS-1 lunar regolith originally intended for this experiment, so ordinary basalt dust was used.

Figure 11: induction furnace used for the experiment, after significant overflow of basalt materials was experienced.

At 895 °C basalt had become sticky and stuck to the stainless steel tongs, while the top layer had turned brown (perhaps due to the formation of iron oxides). No outgassing was reported at 900 °C. After reaching 1100 °C after about three hours and cooling down, a piece of solidified basalt was percussively extracted from the crucible.

Figure 12: Result of melting lunar regolith after about three hours.

The upper section of the extracted sample appeared to be sintered basalt and was very crumbly. The middle portion, with the bubbles, was remarkably sturdy. Even after repeated attempts to break it the sample did not break until it was hit with a metal hammer.

In order to dislodge the remainder of the sample, the experimenter reheated basalt and hit it with a wooden stick. This form of sintered basalt was highly resistant to further melting when it was hit. When hit, the wooden stick burst into flames, likely confirming that the outgassing substance was likely oxygen. Multiple repeated strikes were required before the sample fractured and was able to be extracted.

Figure 13: Ignition of wooden stick due to thermolysis in basalt, producing oxygen.

The basalt structure at the bottom of the crucible was similar to the bubbled structure at the top with large cavities in the interior, and smaller ones towards the surface.

Second test was to preheat the crucible and then pour in basalt. 40 g of basalt was used in this test due to the overflow issue described before. In this case, the basalt did outgas, however when poked with a wooden stick, the stick dramatically caught fire. It is suspected that the radiant heat from the graphite, combined with the outgassed oxygen caused the ignition. Once the sample was removed, poking the crucible with the stick did not result in as much fire, providing evidence that oxygen was coming from the basalt.

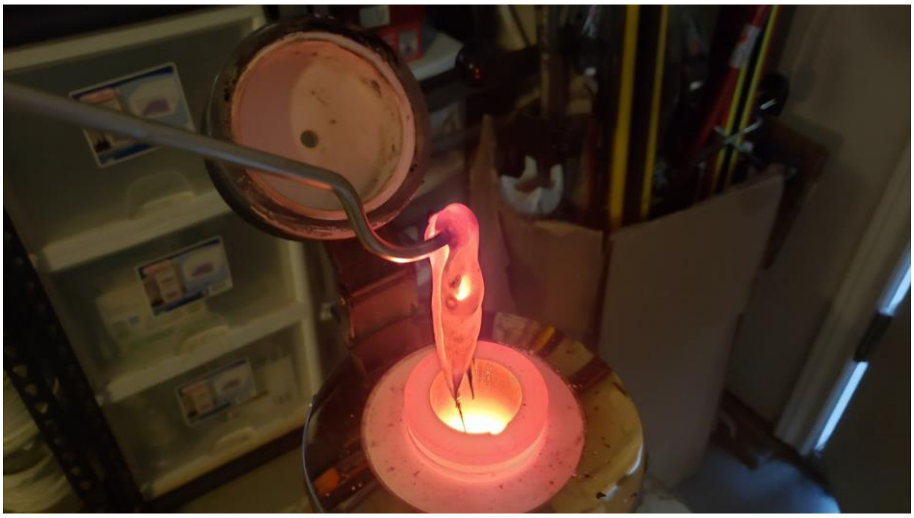


Figure 14: Molten Basalt drawn out of Induction furnace

The graphite was left for 4 hours to melt and outgas near completely. By the end of this 4 hour cycle, the basalt had transformed into an obsidian-like glass. The resulting shards showed signs of bubbles in their internal structures after cooling. These shards were much more brittle and very sharp.

Figure 15: Drawn shard of basalt, gas bubbles are clearly visible.

We believe that the oxygen gas emitted during the tests was a result of thermolysis occurring in the minerals that constituted our basalt sample. Although we are not attempting to capture and store this oxygen in our mission, future lunar bases will certainly harvest oxygen directly from the lunar regolith where and when another source, like water, is unavailable.

Should it prove to be successful, the induction method could allow us to produce structural materials, e.g. bricks, from lunar regolith without the addition of binding agents.

Mobile Worker Unit

- **Mass:** 25.7 kg (including bucket drum, not including any customer payloads)
- **Power:** 110 W generation, triple-junction solar cells, 165 W nominal consumption
- **Energy Storage:** 6x 350 W · h (1.26 MJ) lithium-ion battery packs, total 2.1 kW · h (7.56 MJ)
- **Objectives:**
    - Provide excavation and logistics services to surface installations
    - Construct and operate Power Units
    - Excavate lunar regolith using bucket drum
    - Supply ISRU unit with regolith feedstock
    - Move and transport ISRU unit, garage, and customer payloads

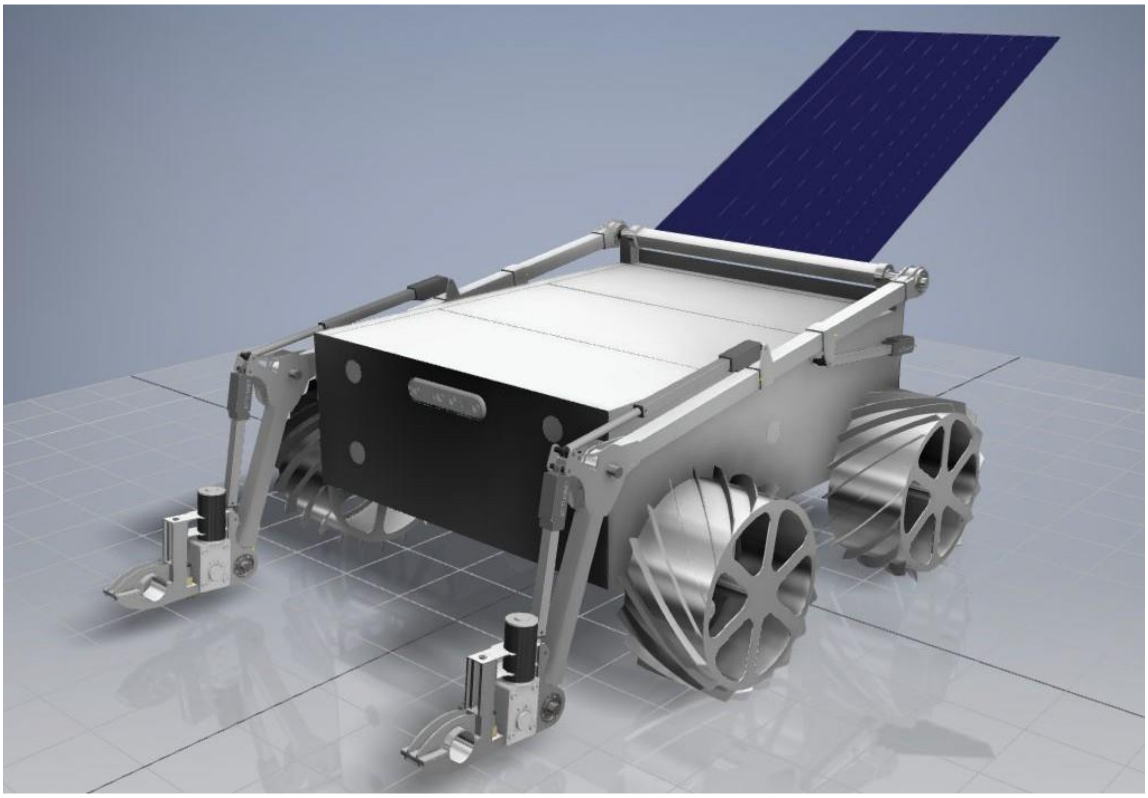


Figure 16: An illustration of the Mobile Worker Unit

The Mobile Worker Unit (MWU) provides the bulk of the motive force and logistics for our mission. The MWU is designed to be autonomous and versatile while extensively utilizing commercial off-the-shelf components to minimize manufacturing costs. It is capable of doing a wide range of tasks including exploration, excavation, assembly, construction, power transfer, deployment of assets and installations, and excavation of regolith using a bucket drum.

Structure

The Structure of the MWU is made from 20 millimetre 6061-T6 square tube stock along with sheets of aluminium metal. The structure is designed to be lightweight and easily manufacturable (therefore making the construction cheap and fast) while still providing the necessary functions of dust mitigation. thermal shielding, and structural integrity to the rover. The structure allows the fitting of various instruments, sensors, cameras, and other payloads.

To insulate the rover, we use 0.2 mm thick aluminium sheets, coated with a thin layer of silver. These panels have a very low emissivity and a very high reflectivity, allowing them to reflect almost all incident sunlight. The silver-coated panels also serve as an excellent form of insulation within the rover as the WEB and the exterior panels both serve as insulation. While not as effective as MLI, it is much lighter and more durable, resisting conditions that would otherwise potentially damage MLI.

Warm Electronics Box

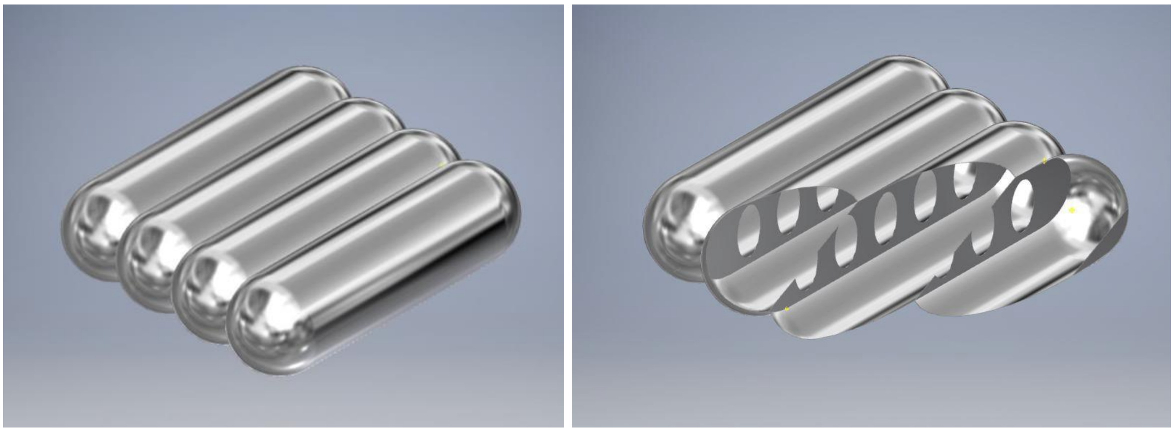


Figure 17: the Warm Electronics Box consists of several cylindrical sections and is designed like an air mattress.

The Warm electronics box (WEB) is a sealed and pressurized unit designed to keep COTS electronics at the correct operating temperature. It houses the computing equipment, batteries, control electronics, power regulators, and any potential co-hosted customer payloads. The WEB is hermetically sealed and minimally pressurized to a pressure of 30kPa Pressurizing the interior of the WEB leads to many simplifications in thermal design. The gas used to fill the WEB is sulfur hexafluoride, a known dielectric and an effective electrical insulator. A liquid coolant loop along with a gas heat exchanger allows for the heat to be transferred away to the radiator.

Due to it’s pressurized nature, the WEB is designed like an air mattress. To keep it lightweight, multiple cylindrical sections were used. Cables, pipes and hoses can be installed in airtight conduits entering and exiting the WEB as necessary.

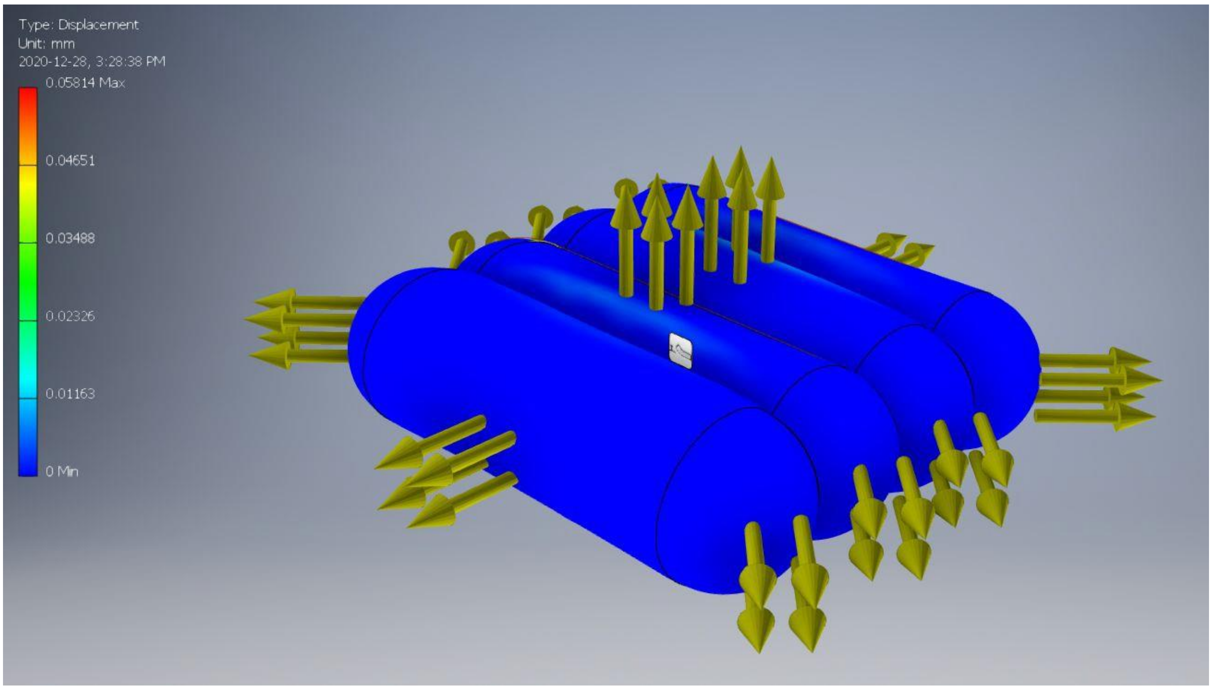


Figure 18: An FEA analysis of the 0.5mm thick aluminium structure of the WEB shows that even under 100 kPa, nearly 3 times the rated pressure, there is practically no deformation.

Equipment Deck

On top of the WEB is the equipment deck, a flatbed that can carry cubesat sized experiment payloads. These payloads can be deployed by the robotic arm onto the lunar surface, or integrated to the rover itself, depending on the customer's preference. In addition, large payloads may be stored on the equipment deck to be transported across long distances. Behind the equipment deck is a photovoltaic panel that folds out when in use, supplying about 110 W of power. This solar panel provides ready power to the rover's batteries and allows it to charge during the lunar day. The primary radiator is mounted on the rear of the solar panel allowing for direct heat dissipation.

Wheels and Powertrain

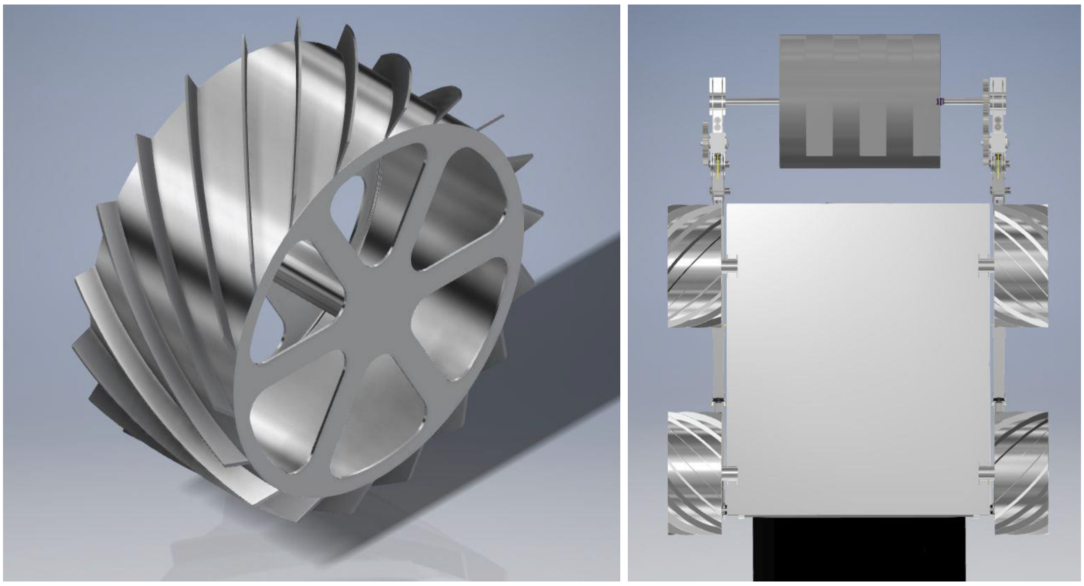


Figure 19: Left: an illustration of one wheel.
Right: the underside of the rover, showing the powertrain and the wheel configuration.

The wheels are constructed out of aluminium. Helical paddles are integrated into the design, which allows for a better grip on the soft lunar soil. The 45 degree angle on the paddles is deliberate and allows them to act in a similar manner to mecanum wheels allowing the rover to have lateral movement as the paddles grip the ground. The rims are supported by 1.5mm thick sheet metal spokes as they are easy to manufacture given the small size of the rover. The wheels are very wide preventing them from sinking into the lunar regolith. [6]

A skid steer mecanum drive allows us to simplify the powertrain. The power train consists of 4 independently controlled gearmotors located in the wheel hubs that allow the rover to move forwards, backwards, laterally, and turn.

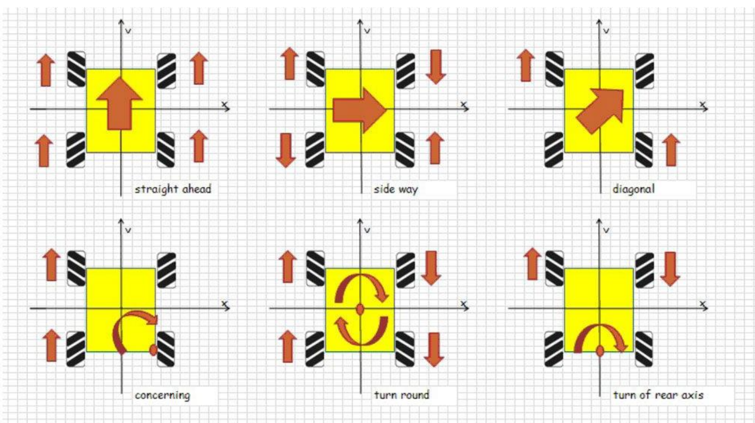


Figure 20: Mecanum Wheel Rotations, source: [7]

The power train has no suspension, which at first glance may appear unsuitable. It should be noted however that modern tractors, skid steers, excavators, and other industrial equipment either have very simple suspension systems or none at all as the primary objective of these systems is manipulating resources, not moving people. Additionally, suspensions are utilized in scenarios with rough or otherwise difficult terrain to minimize vibrations for delicat payloads. For our rover a suspension is rather unnecessary given the rover's small size, mediocre speed at 70 cm/s, the relatively tame terrain of our landing site, and the rover's ability to excavate and move obstructions.

Planetary geared motors were selected to drive the wheels due to their good torque and low power consumption. Although they may not They are not the fastest thing out there, however speed is not our priority on the moon, the ability to move components and excavate regolith is the top priority. However the MWU still needs to be faster than any previous unmanned rover by an order of magnitude otherwise we simply won't be able to get anything done.

Dexterity Enhancement Manipulator

A large portion of the design for this mission rests on the capabilities of our multipurpose manipulators. These are used to grab and transport components, bricks, and to carry mechanical and even electrical power. The manipulators consist of several parts:

Gripper (Autonomous Common Transfer Specification)

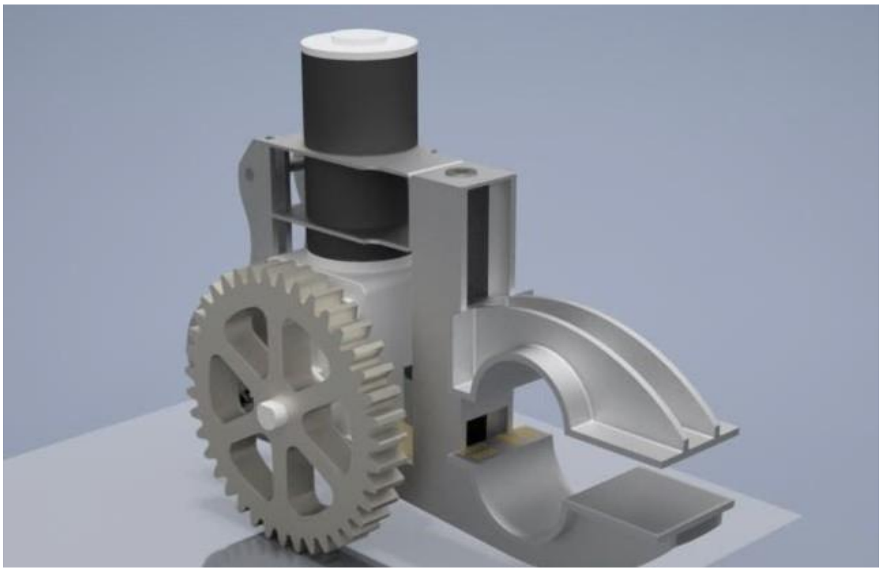


Figure 21: Isometric view of gripper

The gripper has three distinct areas, a large flat portion, a rounded portion, and a smaller flat portion. The large flat portion is used to grip objects in the same way as a traditional manipulator the gripping surface is patterned in order to allow for a better grip.

Behind the large flat portion is a rounded portion that is designed to grip onto a bearing on a shaft. The bearing allows this portion of the gripper to align the held shaft with the power assembly.

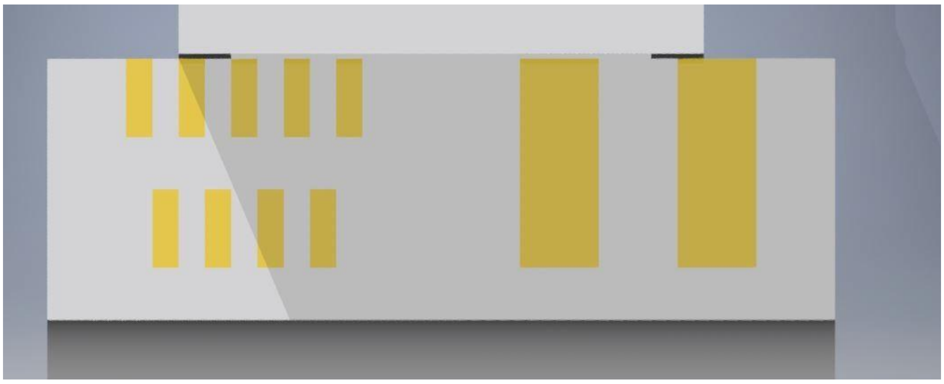


Figure 22: Contact Pinout of Gripper for Data and Power Transfer

The smaller flat portion is once again located behind the rounded portion. It has gold contacts allowing power and data to be sent over a connection utilizing a standard communication protocol such as USB 3.0 with the 9 pin standard on the left and dedicated contacts for power handling on the right.

The receiver need only be a similar flat section sticking out a sufficient amount from the package with a compatible pinout. However a self aligning receiver tab that can be supported on various implements termed the Autonomous Common Transfer Specification has also been designed. Under this specification the receiver tab may take on various forms but the common elements are a thin section for the pinout, a rounded section in order to use the rounded portion of the gripper as a self alignment tool, and a large flat section for mechanical stability. The ACT spec also supports shafts and flats.

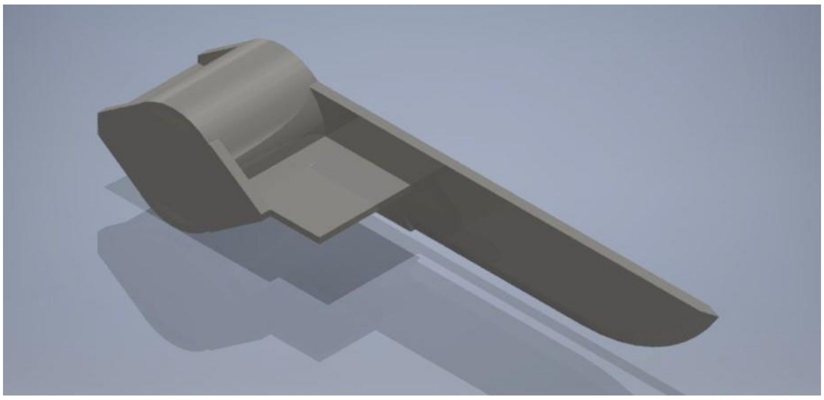


Figure 23: Render of a cutter tool using the ACT specification on it's handle. This knife is used to cut cables that secure objects within the garage during launch and landing.

The top jaw of the gripper is actuated by a linear slide actuator, a fabric sleeve protects the mechanical components from being damaged by lunar dust.

Power Transmission

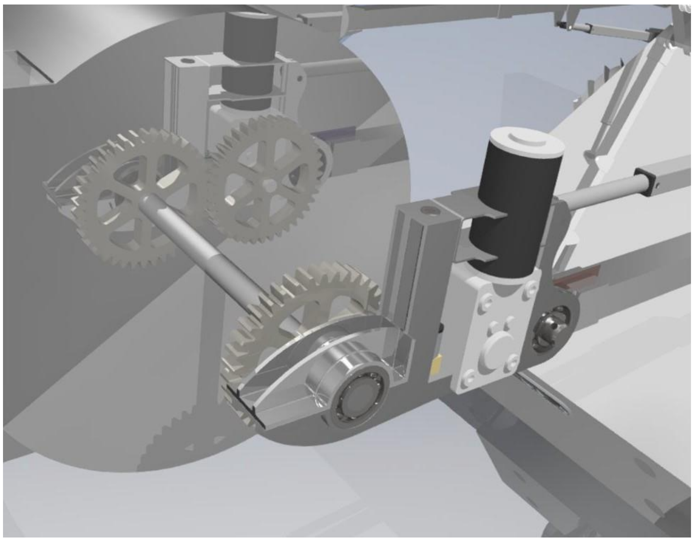


Figure 24: Gripper Meshing with Bucket Drum

The power assembly consists of a titanium power gear driven by a gearmotor. It allows the MWU to drive tools on the shaft by having the gear on the tool shaft mesh with the power gear on the rover. The power gear is located behind the gripper allowing us to transmit mechanical power directly to the shaft without the need for any electronics on the shaft itself. The reason for this design is so that we don't leave motors, encoders, or other delicate electronics outside in the lunar night. Instead, we can leave the "dumb" bucket drums and other such mechanically linked tools outside while the rover shelters sensitive electronics in the garage.

In order to maintain good alignment on the shaft we have elected to fix the lower jaw directly on the frame of the manipulator. The frame holds all necessary components in place and transfers structural loads to the rest of the arm. Most of the structure is made from aluminium, however in some high load power transfer parts, such as power screws and gears, titanium and steel are used for their better mechanical properties.

The Power Assembly is how we intend to spin the bucket drum on this mission. Other tools can be brought along if needed. These "manual" tools can be anything that is powered by up to 2 independent motors and may even include sampling drills and gantries.

Robot Arm

The arm is a fairly standard 2D arm layout reminiscent of a skid steer. This allows us to perform a wide variety of tasks and use a wide range of tools. It also helps for maintaining alignment between tools ensuring that a wayward motor or command does not completely disable the robot. The presence of an elbow joint in the arm means that it has a wider range of motion than a traditional skid steer, the arm itself is adjusted so that it is capable of reaching higher platforms allowing the regolith to be dumped more easily. The robot arms are covered in a mylar sleeve that prevents dust from getting into the joints, this sleeve is not visible in the renders.

Power

Item	Power required (W)	Nominal Voltage (V)	Operating current (A)	Quantity	Power Subtotal (W)
Raspi compute module	4	3.3	0.6	7	28
Arduino nano BLE Sense	1.5	3.3	0.5	3	4.5
EXA ICEPS Spacecraft Systems Core (12V)	3	12	3	1	3
Intel Realsense D455 (IR depth Camera)	5	3.3	1.5	4	20
Intel realsense D430 Depth Module	5	3.3	1.5		0
Robotic arm	20.6	6	3.5	2	41.2
Pump	30			1	30
SpectroLab XTE-LILT Panel	-110			1	-110
Gearmotor	9	12	0.62	4	36
DC-DC Converter	1	1.5	10	6	6
Close Range Radar sensor	0.0061	1.8	0.006	12	0.0732
			Gross Power Required (W)	Net Power Required (W)	Total Power consumption (W)
Nominal Operating Power under heavy workload			168.7732	58.7732	168.7732

Table 1: Power consumption of MWU electrical components and nominal operating power under heavy workload.

The MWU has a very small footprint yet a larger power consumption than the MSL rovers. Even with 110 watts of power from its solar panel, the rover is operating at an energy deficit. Therefore, the rover is equipped with six 350 W·h lithium ion batteries, discharged when the rover is performing particularly demanding tasks, and charged when the rover is not operating at peak power.

Thermal Management

“Energy cannot be created or destroyed. It can only be changed from one form to another."

— First Law of Thermodynamics

Radiator Design

The high power consumption of our rover will produce large amounts of waste heat that needs to be rejected from the rover body to prevent overheating.

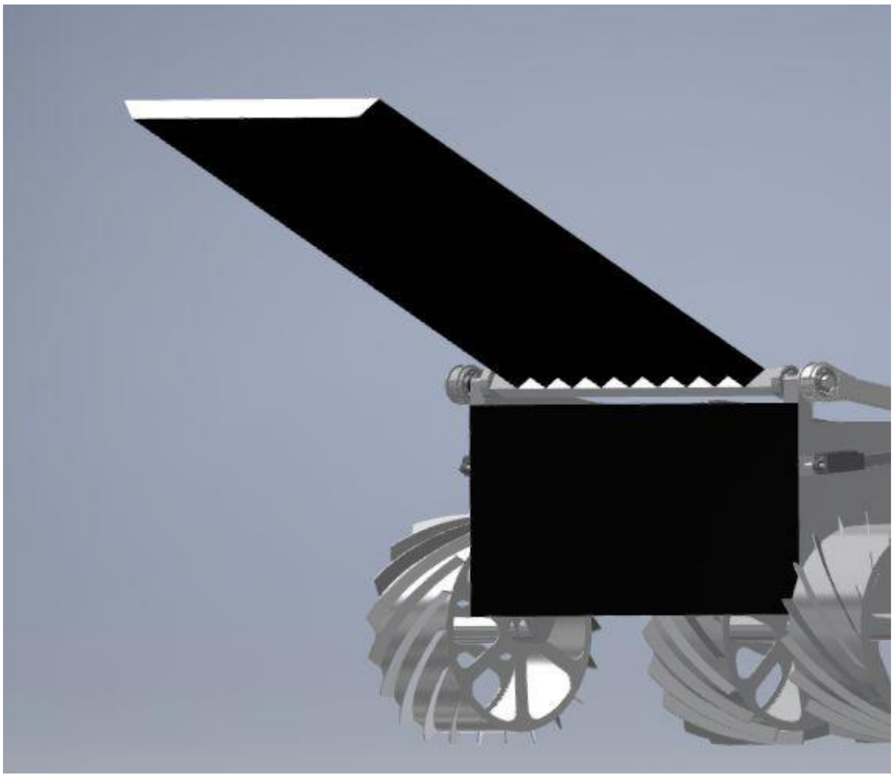


Figure 25: View of radiators on the MWU

The MWU has two radiators capable of dissipating a combined 340 W of heat. The primary radiator is located under the solar panel, while a smaller flat-panel radiator is installed on the rear face of the MWU’s main body. The large heat dissipation capacity is necessary due to the large amount of solar gain on the rover.

Thermal Control System

An estimated 330W of heat produced by the MWU during peak operation necessitates the use of an active cooling loop. The loop itself is formed from aluminium pipes connecting the WEB, other components, and the radiators.

For most of our electronics, sulfur hexafluoride gas immersion cooling will be used to control and regulate the temperature. The WEB is pressurized with sulfur hexafluoride gas, allowing electronics to be convectively cooled. Several temperature sensors placed around key locations in the WEB will allow precise control of the temperatures of the components.

Coolant Fluid

An active cooling loop needs a cooling fluid to function. A fluid was needed that would not freeze at -40 °C and would remain liquid up to 100 °C. The fluid must also have high specific heat capacity and be lightweight enough to carry on the mission. Finally the coolant must not react with aluminium. In order to determine the best coolant for our mission we conducted an assessment of multiple fluids

Water has a high heat capacity [8], allowing more heat to be moved for less coolant. However, water has one fatal flaw: it freezes at an intolerably high temperature (0 °C), and because water expands when it freezes, the consequences would be disastrous to our coolant manifolds during hibernation where the subsurface temperature drops below 0 °C.

Contrasting water is one of the most common spacecraft coolants, ammonia. It has an even higher specific heat capacity than water, which reduces the required mass. It is nonreactive with aluminium and has a long flight heritage. However for our purposes the boiling point of ammonia, -33 °C [9], was simply too low for it to be effectively used as a pumped coolant. Ammonia would require a refrigeration system that outweighs any mass savings gained from it’s high efficiency.

We also investigated mercury, gallium, and other liquid metals, which were initially attractive due their high thermal conductivity. Yet the high thermal conductivity of these liquid metals resulted in larger heat losses at night. Additionally the specific heat capacity of these liquid metals was far too low thus necessitating higher flow rates, specialized pumps, and more powerful pump motors.

Eventually a mixture of 60% propylene glycol and 40% water was selected. Propylene glycol possesses a melting point of -59 °C, well below the hibernation temperature of our robot, while it’s boiling point of 107 °C is well in excess of our operating margins. It’s specific heat capacity of 2.5 kJ $kg^{-1} K^{-1}$ [10], while not as high as water, is high enough to serve as a coolant for our radiators.

Electronics

The main computing power of the rover is supplied by three Raspberry Pi Compute Modules, selected because of their extensive documentation, their high computational power, low power consumption, and ease of use. Much like the SpaceX Dragon spacecraft, the rover utilizes multiple computers in order to provide redundancy in case one processor experiences a radiation fault or a transient failure. [17]

For communications, we utilize an X-band antenna in order to transmit data to and from ground stations on Earth. In addition, a 2.4 GHz transceiver operating on the 802.11 protocol[7] receives and transmits data to and from the ISRU unit, customer payloads, and other deployables.

Navigation

The rover uses a variety of sensors and instruments to assess its environment. Multiple 9 axis inertial measurement units (IMU), consisting of an accelerometer and a gyroscope, allows the rover to determine its location and orientation. The IMUs are complimented by an array of Intel Realsense tracking cameras, in pink below, and Acconeer XM112 radar sensors, in green below, and an Intel Realsense IR depth camera, in pink below, that allow the rover to sense and map its environment. Pulsed Coherent Radar (PCR) modules, shown in blue below, mounted around the circumference of the rover, allow sensing in “blind spots” of cameras. They would ensure that the rover does not approach too close to potential rocks, deployed surface assets, and other navigational hazards, as the IR Cameras cannot detect anything within 400 mm of the rover body. The radar sensors also assist in coupling with various tools and attachments.

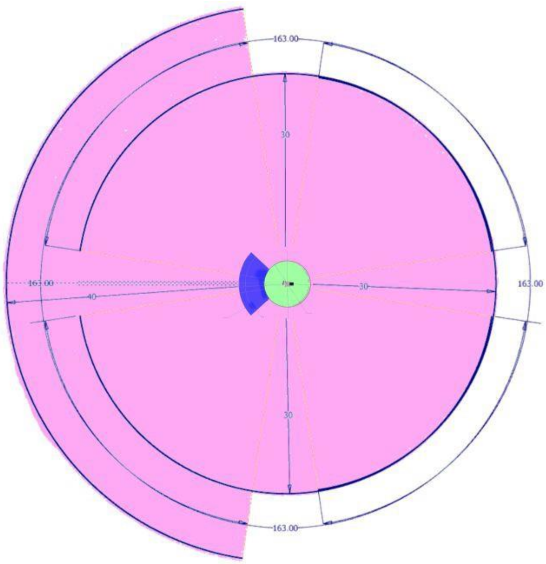


Figure 26: Rover Navigation Sensor Array, distance in meters

[7] Essentially Wi-Fi, but in SPACE.

The robot would use a Simultaneous Localization And Mapping (SLAM) Algorithm to compile the map from its sensors. The robot would then move the map to long term storage in SD cards and compile the map better during periods of low usage of the processor (e.g. during charging)

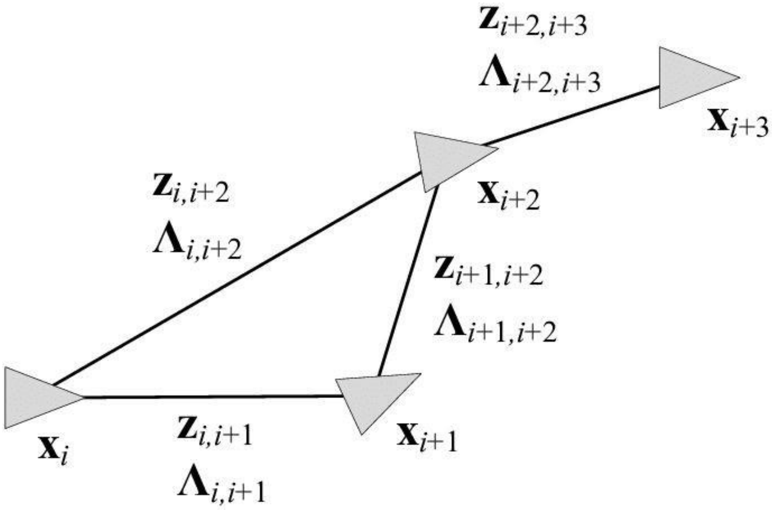


Figure 27: SLAM Algorithm

Due to the relatively unchanging nature of the Lunar Surface the map will most likely remain accurate in most instances, however, it would have to be recomputed in areas where the rover performs excavation or sets up installations. The rover would then use the Theta* algorithm to plot travel routes from one point to another. In a case where the robot would need to traverse a terrain which it has not mapped it would instead use the Field D* algorithm. This algorithm is better suited for traversing unknown and changing environments and is generally more efficient as it allows for any angle movement.

Mission Elements

Bucket Drum

- **Mass:** 3.757 kg
- **Power:** Supplied by power gear
- **Objectives:** Excavate lunar regolith for ISRU and construction

Our Team has designed a collapsible bucket drum to minimize space taken by the drum itself. During transit to the moon the drum will be in a compressed state while not deployed. A spring in the drum is for deployment and later structural stability when in operation. Most of the drum's outer sections are made of aramid cloth with the separation panels being made of aluminium.

Figure 28: The RASSOR mining rover, depicted above, uses two bucket drums to excavate regolith. Source: Adapted from [13]

There are many reasons why we chose bucket drums over other traditional methods. The main advantages of a bucket drum are that the excavation scoops are small and staggered — at any time, only one or two individual scoops are engaged on the regolith, keeping excavation forces low. [13]

The regolith excavated is contained within the interior of the drum. To empty the bucket drum, the rotation of the drum is simply reversed. This approach completely eliminates the need to have a separate regolith storage bin which is essential in a mass-constrained mission. [14]

We investigated the prospect of including two bucket drums on opposite sides of the rover, like the RASSOR robot in development at NASA. This provides the advantage that during operation, the excavation force from one drum would cancel the force from the other. However, we decided to just use one bucket drum, as one drum would already fulfill most of our objectives and attempting to mount two would result in further design complications.

The bucket drum has a capacity of about 9 litres. When operating, it excavates at a rate of about 3 litres per second, allowing us to dig a 1 metre wide trench in the ground for the garage in only a few hours.

ISRU Unit

- **Mass:** 7.95 kg
- **Power:** 1500 W, induction furnace
- **Objectives:** Validate the manufacturing of construction material, e.g. bricks, from lunar regolith for lunar construction applications.

The ISRU unit was designed in order to use induction heating to melt regolith, and pour the molten regolith into a brick-shaped mould. The crucible in which the regolith is heated is made out of graphite, encased in a refractory material made of silica-based HRSI.

The brick mould is also made out of graphite, and can rotate upside-down in order to release moulded bricks.

Thermal Management

For the electronics of the ISRU induction furnace, a dedicated heatsink is used as the heat output is far in excess of what can be done with immersion cooling. The active liquid loop is more efficient than immersion cooling as the antifreeze has a higher thermal capacity than the Sulphur Hexafluoride in the WEB. The ZVS board and power board circuitry are also much more compact than the WEB, minimizing the mass needed for liquid cooling systems. The radiator deployment mechanism is simple: nickel-titanium shape memory panels are attached between the radiator segments to both conduct heat, as well as unfold when exposed to heat. To retract, a set of pull-down cables pulls the radiator down to its folded position.

However, the majority of the heat will be emitted by the induction furnace at the front of the ISRU unit. Therefore, the front of the ISRU unit is coated with silver much like the paneling on the MWU, due to its absurdly high reflectance in infrared wavelengths ($R > 0.99$ for $\lambda > 0.7$ μm) [18], it reflects almost all of the blackbody radiation emitted from the induction furnace. At capacity, the ISRU unit is able to manufacture about one brick (measuring 160 mm by 80 mm by 30 mm) per hour.

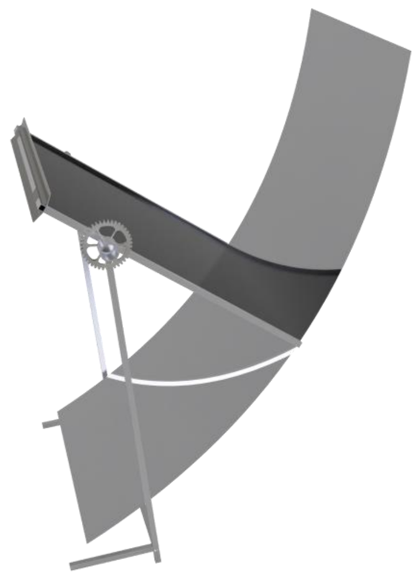
The ISRU unit's large power consumption is supplied by deploying several Power units per ISRU unit.

Power Unit

- **Mass:** 810 g (not including power cables)
- **Aperture:** 0.5 m^2
- **Power:** 280 W @ 150 V, concentrated solar power
- **Objectives:** Supply electrical power to power-intensive ISRU processes

The Power Unit is a concentrated solar power installation that is designed to be both light and easily assembled by the MWU rover.

Several power units may be deployed in parallel in order to produce more power. We utilize six power units, each generating 280 watts, to supply a total of 1680 watts of electricity to operate the power-intensive induction process. The Power unit consists of three individual components: the *stand* component holds the *concentrator* component, which in turn concentrates sunlight into a *photovoltaic* component. The components are designed for easy assembly by the MWU.



Radiator

Focusing a large area of sunlight onto a small area, as the solar concentrator does, generates immense amounts of heat. Each power unit, while generating 280 W of electrical power, in turn produces about 420 W of waste heat, which must be radiated away. Thus, we mount a single radiator panel on the Power unit measuring 0.5 m by 0.5 m, which is more than sufficient to cool the panel.

We investigated several materials with which to cool the photovoltaic cells. Initially, we used a 1 mm thick aluminium plate. Although it was effective at cooling the Power unit, it was quite massive, at about 675 grams per panel. Thus, we needed to find a radiator material that would be much lighter than aluminium plate.

Graphene has an exceptional thermal conductivity, at over six times that of aluminium — thus, if we made our radiator out of graphene, we could make it six times thinner, and over six times lighter[8]. However, sheets of pure graphene are exceptionally difficult to manufacture. Thus, instead of attempting to make a pure graphene sheet, we instead start with a sheet of aluminium foil and use vapor deposition in order to deposit about 250 μm of graphene onto the aluminium substrate. The resulting aluminium-graphene radiator, massing about 138 grams, is much lighter while providing better performance. However, it was much more expensive, as the vapor-deposited graphene layer must be created in a vacuum (and takes quite a long time to produce, owing to its thickness.) This expense is offset by the fact

[8] In addition to its higher thermal conductivity, graphene has a lower density than aluminium.

that launch costs for any sort of space hardware are exorbitantly high, and that cutting half a kilogram off the mass of the radiator results in thousands of dollars of mass savings.

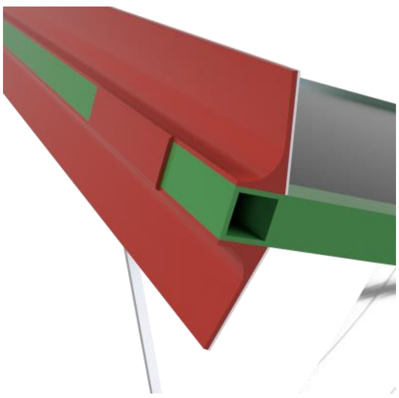
Assembly

The Power unit was designed in such a way that it folds flat to save space within the garage, and was easy to deploy by the MWU rover. The assembly process is simple:

1. The stand section of the Power unit is removed from the garage by the rover. The rover, carrying the stand with its grippers, drives to and places the stand at its intended operating location.
2. Next, the concentrator element is carried by the rover to the operating site, and is stacked on top.
3. The photovoltaic module is then stacked on top of the concentrator element, at the focal point of the reflector.

We employ several simple-but-profound design tricks in order to both minimize the mass and complexity of the Power unit. For example, the concentrator's reflector panels are made out of metallized BoPET (Mylar) film mechanically bonded to several nickel-titanium shape memory wires. When heated by sunlight, the shape-memory wires will assume a predetermined shape of the reflector, thus making our deployment simple and trivial.

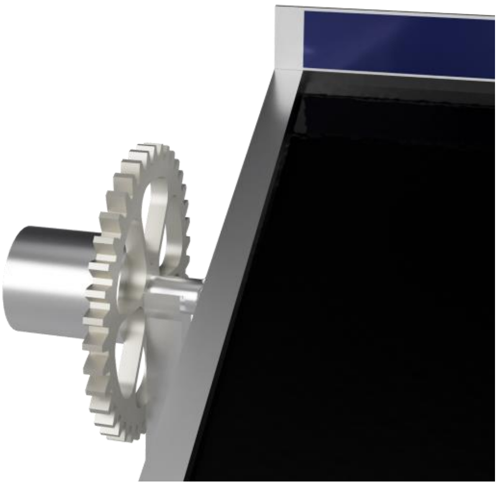
Furthermore, because the photovoltaic module is separable from the concentrator, we do not have to fold up the entire Power module for storage — during the lunar night, the MWU will simply remove the photovoltaic module from the Power unit and store it inside the garage, while the thermally insensitive components are able to tolerate the lunar night.



However, by making the photovoltaics detachable, we introduce a complication that we would need to have an attachment mechanism that would secure the photovoltaic module to the concentrator module during operation, as well as release it after sundown. Not wanting to waste exorbitant quantities of mass on a complex mechanical attachment system, we instead used a simple solution: the photovoltaic module, colored red on the left, is machined from *titanium*, while the concentrator frame segment that it attaches to is made out of *aluminium*. Aluminium has much greater thermal expansion than titanium. When the power unit is operating and subject to high temperatures, the aluminium expands and tightly fits against the titanium of the photovoltaic module. When the power unit is not being heated, the aluminium shrinks and the fit between the two components significantly loosens, facilitating attachment and removal.

Orientation

Concentrated solar power installations like our Power unit need to track the sun in order to generate power. Thus, the concentrator is mounted on the stand on a hinge, balanced on the concentrator's centre of mass. In order to track the Sun, we would need a way of rotating the concentrators to point directly at the Sun. Normally, this would be done by attaching a motor that would align the solar panels to the Sun. But using such a motor would introduce unnecessary complexity, and the motor would likely have to be dismounted during the lunar night and remounted during the day — a task that looks difficult in theory and even more so in practice.



Instead of using a dedicated tracking motor, however, we instead just utilize the grippers of the rover. Using the same mechanism that is used to drive the bucket drum, a rover gripper is able to reach out and couple to a gear on the axle of the concentrator. Because the photovoltaic module is connected to the ISRU unit, a sensor within the electronics package of the ISRU measures the power output of the solar panels, and the rover adjusts the panels accordingly until the power output is maximized.

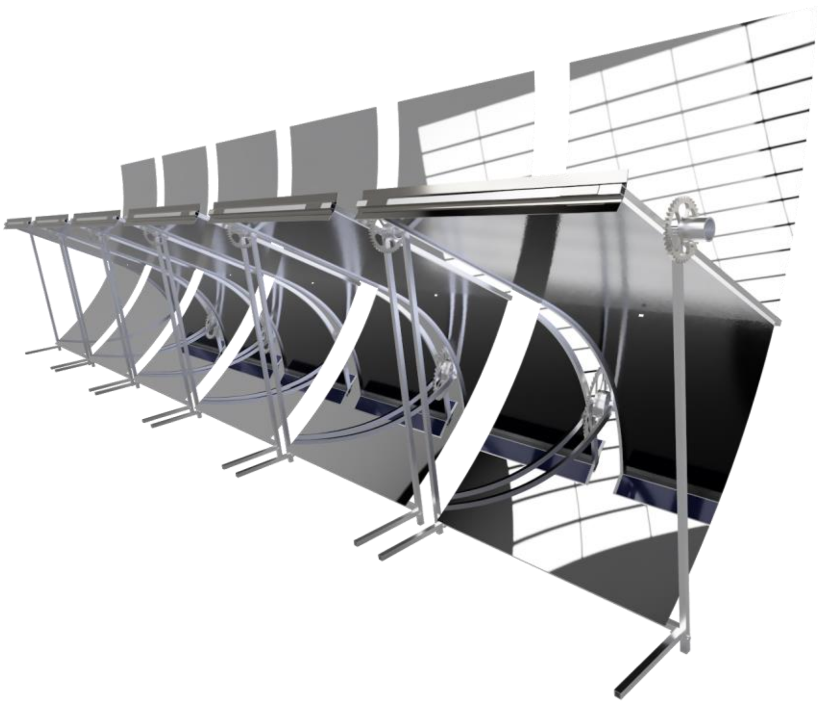


Figure 34: Several Power units are deployed in parallel, as depicted in this illustration.

Garage

- **Mass:** 10.72 kg
- **Size:** 1 m × 1 m × 1 m, precisely within the volume limits.
- **Objectives:** Contain all components during launch and landing, and serve as a thermally insulated shelter during the lunar night.

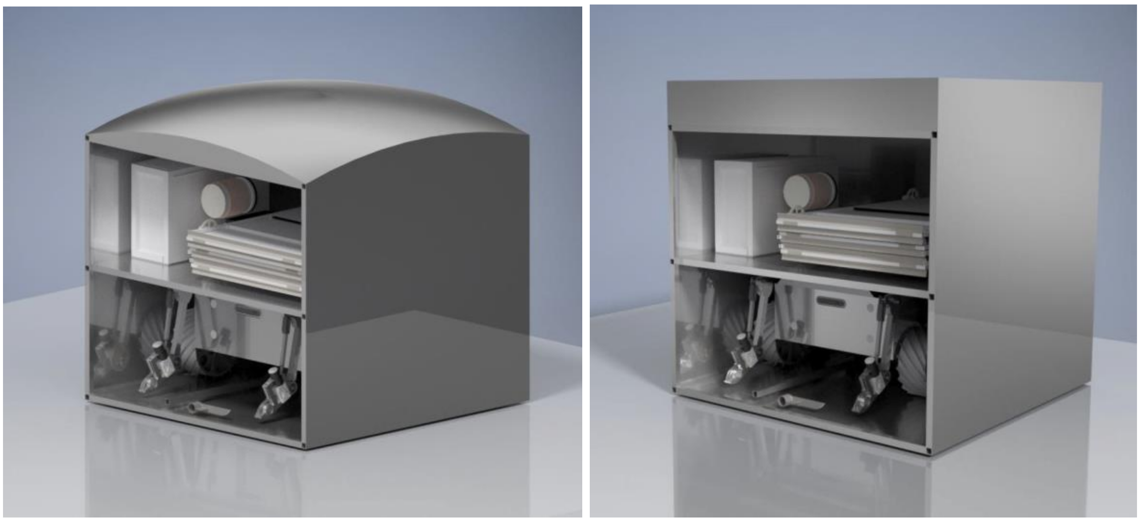


Figure 35: The Garage is simply metal box with two compartments and a domed top.

One of the greatest issues we experienced with a lunar rover design at first was the immense heat loss experienced throughout the night. Even if we were to cover the entire rover with MLI several centimetres thick, we would still require 12 watts of heating for half of a month, adding mass for both the MLI and the batteries. In fact, we would require over 20 kilograms of batteries for the rover alone — not even counting the additional insulation for the rover, as well as batteries *and* insulation required to keep the electronics of the Power and ISRU units at a stable temperature throughout the night.

Therefore, in order to save on battery and insulation mass, we have elected to contain our rover within a garage structure, which is in turn placed in a dugout trench with nearly half a metre of lunar regolith piled over it. Because lunar regolith is an exceptional insulator, this decreases our energy requirements for heating during the lunar night drastically. Furthermore, by storing all the components in the same container, we are able to keep all electronics heated by using only a single heater on the rover, eliminating the need for individual heating elements and batteries on the ISRU and Power modules.

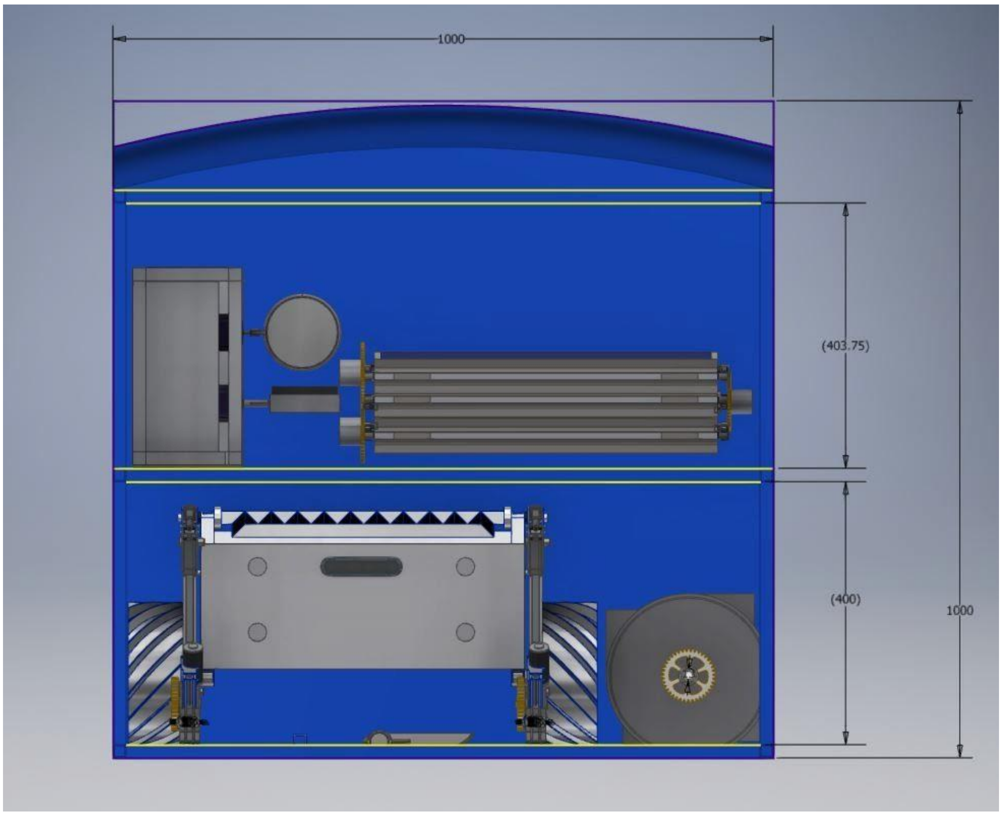


Figure 36: Depicted is a possible storage solution for the garage. On the top rack, the ISRU and Power modules, on the bottom, the MWU and bucket drum. Large volumes are left open for storing additional hardware, such as more power modules or customer payloads if included.

The roof of the garage must be designed to support the loads experienced by being buried under several centimetres of regolith. Therefore, the top of the garage is manufactured in the shape of a dome in order to distribute forces to the walls of the structure. An orthogrid structure made out of sheet aluminium is constructed and welded to the underside of the roof to provide exceptional support.

With an exceptionally low thermal conductivity and emissivity, the lunar regolith provides better insulation than most commercially available insulation on Earth. Lunar subsurface temperatures vary considerably less than the surface temperature. This shorter variability combined with the insulating effect of the regolith will allow us to maintain the correct hibernation temperature for our mission units without expending as much power as a more traditional approach. In some cases it is possible that less than a watt of additional power may be needed as subsurface temperatures 1m below the surface, at 252K, with a variation of +/- 3 K exceed designed minimum hibernation temperature of the rover at 234K. [12].

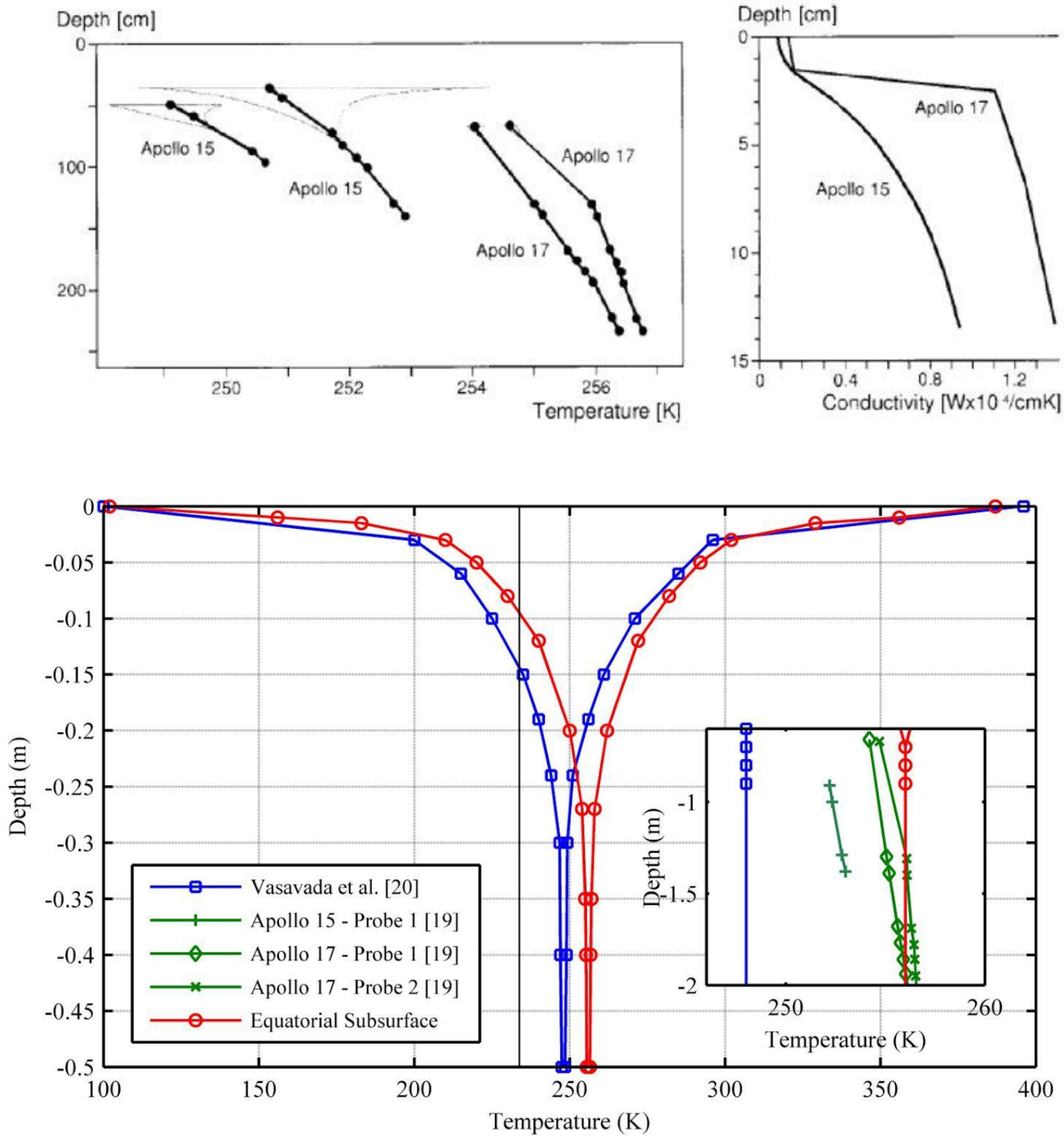


Figure 37: Temperature of lunar regolith at certain depths, as measured by instruments deployed during Apollo 15 and 17. Observe that even at 50 cm underground, the temperature is remarkably stable, and averages tolerable temperatures of around 252 K. Sources: [16, 19]

The garage is sturdy enough to withstand a rocket launch even when all components are stowed in the . During the launch, all components are secured to the walls and paneling of the garage with thin cables. After landing on the Moon, the door to the garage opens, the rover extricates itself, and uses a cutter tool in order to sever the tie-down cables and extract the other components.

Mission Profile

Launch, Transfer, Landing

The rover, ISRU, power, and all other equipment is secured on the interior of the garage before launch, and the garage is secured to a lunar lander with the necessary propulsion and control systems. The launch vehicle will likely be a Falcon 9 rocket, and our payload will likely rideshare on a GTO or TLI rideshare mission.

After separation from the Falcon 9 second stage in GTO, the lander with integrated rover then performs a burn at perigee to transfer to a trans-lunar injection.[9] Subsequently, the lander enters orbit around and lands on the Moon in the appropriate landing site.

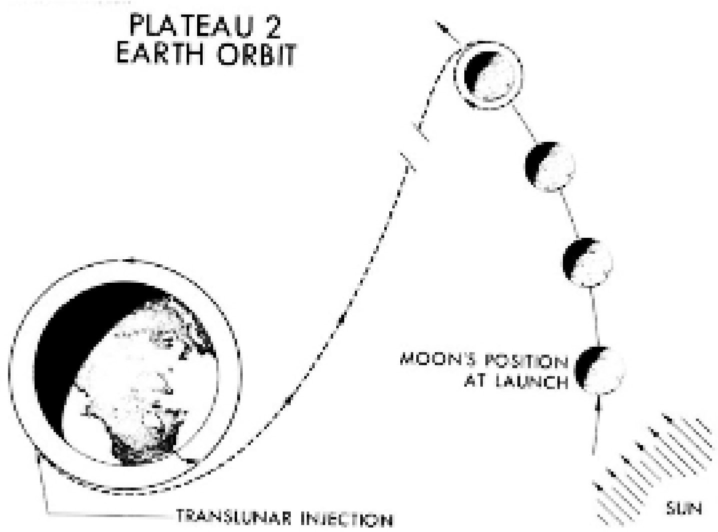


Figure 38: Translunar Injection
Source: Adapted from [21]

Another viable option is to use landers developed through the Commercial Lunar Payload Services program, and outsource the payload delivery to private companies. However, this is not cheap, with prices of above 1 million USD per kilogram to the lunar surface.

[9] Obviously, if we elect to launch on a TLI rideshare mission instead, we are already on a TLI trajectory.

Surface Operations

Setup

After landing on the Moon, the door to the garage is opened, and the MWU exits the garage, driving off a ramp to the lunar surface. Initially, it spends a couple of hours driving around and assessing the area immediately outside the landing site, identifying regions of interest, and charging its batteries from the solar panels.

After identifying a particularly flat region of ground near the lander, the MWU attaches the bucket drum, and begins excavating and processing a strip four metres long and about half a metre wide until it is perfectly level. This is where the Power Units will be installed. Next, the rover extracts the Power Unit stands, unfolds them, and transports them to the flat strip. The Power Unit concentrators are then transported to and mounted on the stands. Finally, the photovoltaic cell assemblies are attached to the concentrators, and the cables are connected. This completes the setup of the Power Units.

The Power Units are placed such that they are parallel to each other, and the line that they lie on is aligned to the north-south axis. This makes sun tracking easier and more effective. Because the Sun moves across the sky, the MWU must periodically (about once every hour) adjust the rotation of the concentrator units on the stands using its arms such that they are pointed directly towards the Sun.

After deploying the Power Units, the rover then transports the ISRU unit to its final location a few metres north of the Power Units, and connects the ISRU unit to the power cables. After being set up, the ISRU unit will be able to produce bricks at a rate of approximately one per hour.

Next, the MWU begins excavating the trench (about 1 metre wide by several metres long) in which the garage will be installed. If the rover were to dig constantly, it would be able to complete the excavation in mere minutes. However, it would need to empty the regolith drum every few seconds, and dump the regolith elsewhere. Therefore, a more realistic estimate for the trench excavation time will be on the order of hours.

Once the trench is excavated, the rover transports the garage[10] and places it at one end of the trench. The rover then starts pouring large quantities of regolith on the garage until it is covered under nearly half a metre.

Lunar Day

During the remainder of the lunar day, a variety of tasks are carried out, pausing whenever the rover adjusts the solar panels and refills the ISRU induction furnace periodically. The rover will perform science experiments with onboard customer payloads[11] (as per customer directions). Using the bricks generated by the ISRU unit, it might begin construction on a large (9 m diameter) landing pad to facilitate future landers. Such a landing pad will take about 12 months to construct. Alternatively, the rover might construct a domed structure in

[10] Lunar gravity is a very unintuitive concept, as items that would normally be too heavy are lifted with ease.

[11] These payloads are not accounted for in the mass and cost budget of this mission proposal

which future habitation modules will be placed, shielding them from radiation. Customer science payloads may be operated according to customer instructions, allowing for the operation of science experiments as well as the primary mission objectives.

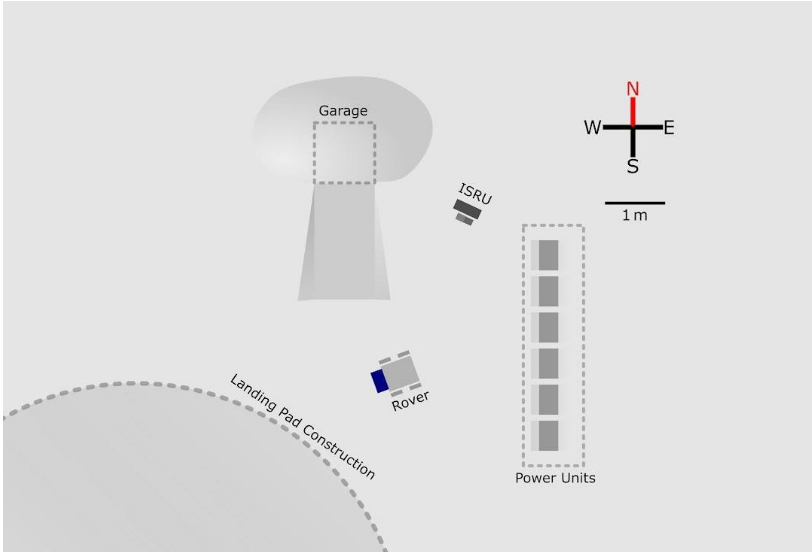


Figure 39: Hypothetical landing site layout. Once the landing pad is completed, the garage and other assets may be removed from their current position and moved elsewhere.

Lunar Night

To survive the lunar night, all electronic equipment must be stored within the temperature-controlled garage such that they are not damaged by the cold temperatures if left outside. Shortly after sunset, the rover moves the ISRU unit into the garage. Next, it detaches the photovoltaic cell assemblies from the Power units, and stows them in the garage. Finally, the rover itself drives into the garage, and shuts the door. Components that do not contain temperature-sensitive electronics, such as the Power units' stand and concentrator parts as well as the bucket drums, are left outside.

During the lunar night, around 6 watts of heat will flow out of the door despite 2 centimetres of multi-layer insulation. This is mostly counteracted by the heat flow from the regolith into the garage, in addition to the rover running heaters[12] off its large battery banks.

[12] We do not actually need to pack dedicated heating elements on the rover. In fact, we could just make do with performing computational processes with the computers for the sole purpose of generating waste heat. This then led to the inside joke of mining cryptocurrencies on the Moon.

Cost Estimation

We conducted a preliminary investigation of the costs of various components. This is by no means a final cost estimate. For example, many components such as the solar panels are custom-made and do not have fixed prices, making estimates of their price exceptionally difficult. In addition, the cost of a spacecraft is mostly determined by assembly, integration, and validation — except perhaps in the instance of mass-produced, well-characterized cubesat design and manufacturing [26], these costs are notoriously difficult to estimate without extensive, deep insider knowledge of the aerospace industries. In addition, many components planned to be manufactured in-house, such as the MWU wheels and the Power unit graphene radiator sheets, are difficult to assess for the same reasons.

Item	Cost (USD)	Quantity	Cost subtotal	Source
Mobile Worker Unit				
Electrical				
Raspi compute module	25	6	150	raspberrypi.org
EXA ICEPS Spacecraft Systems Core	64872.64	2	129745.28	Cubesat Shop
Arduino nano BLE Sense	32	3	96	Arduino USA
Spectrolab Solar Panels		0.24	0	Spectrolab
EXA TITAN 1 Battery (275 Wh/kg)	48960.48	6	293762.88	Cubesat shop
Intel Realsense D455 (Active IR depth Camera)	239	4	956	Intel Store
Water Pump	30	1	30	Amazon
Linear actuator (Actuonix L16-R)	70	6	420	Actuonix
Gripper actuator (Pololu Gearmotor)	21	2	42	Robot Shop
Power transmission motor	25	2	50	Amazon
Acconeer XM112 Radar sensor	84	8	672	Robot Shop
ISIS UHF Antenna	10404.1	1	10404.1	Cubesat Shop
Intel Realsense T265 (Ambient SLAM Camera)	199	4		Intel Store
Structural				
Aluminium 6063-T52 square tube stock (1m)	22	8.388	184.536	Metals Depot
Aluminium sheet 0.5mm	50	1.32	66	aluminummetals.com
Aluminium sheet 0.2mm	50	2.98	149	
Aluminium sheet 1.5mm	50	11.60	580	
Aluminium sheet 2.0mm	50	1.00	50	
Bearings	15	20	300	Bearings Canada
Titanium gear	2000	4	8000	Custom Part
Lead screw	10	1	10	Amazon

Thermal				
Propylene Glycol (/kg)	12	1	12	Sigma Aldrich
90mm PC Heat exchanger	27	3	81	Newegg
Flexible hose	15	0.25	3.75	Global Industrial
Labour				
CNC machine (per hour estimate)	120	400	48000	Manufacturing.net
Aluminium Welding	100	700	70000	
Other specialist services	1000	50	50000	
ISRU unit				
Induction Furnace ZVS	200	1	200	Amazon
Aluminium 6063-T52 square tube stock (1m)	18	5	90	Metals Depot
Aluminium sheet 0.5mm	50	2.00	100	aluminummetals.com
Silver (grams)	0.86	100	86	apmex
UHMWPE skid surface	70	1	70	McMaster
Nitinol Joints	50	30	1500	eBay
Power Unit			0	
Nitinol Wire (1m)	8	4	32	
Aluminium-Graphene Radiator (0.5*0.5 m)	25000	1	25000	
Titanium Bracket	6	42	252	MetalsDepot
Concentrator Photovoltaics (1 cm*1cm)	100	1200	120000	
Launch Costs			0	
Commercial Lunar Payload Services (/kg)	1000000	60	60000000	
Total Cost			60761094.55	

Table 2: Estimated costs of mission elements

Nonetheless, the launch costs are so exceptionally high that the costs of developing and producing the hardware are, for all practical purposes, negligible.

Further Investigation

Further pursuit of this mission concept will need to address issues that we have not investigated within the scope of this report.

The rover and other components are designed to provide resistance against damage from the highly abrasive lunar regolith. However, occasional, thin “clouds” of electrostatically charged lunar regolith can form on the Moon. The dust impingement from these “clouds” of dust should be evaluated and taken into account.

Degradation of electronics and other power systems due to radiation and other environmental factors has not been assessed, however, the electronics of the rover and other installations have been designed with several redundancies for each component.

Conclusion

We have presented a design architecture consisting of a lunar rover, concentrated solar power units, and induction furnaces with a launch mass of about 56 kg. The design fulfills the mass and volume constraints of 60 kg and 1 cubic metre, respectively, set by the competition. Our design is highly customizable, easily expandable and very flexible: more power and ISRU units may be easily included in our design for an increased launch mass, and customer payloads may be hosted on board the rover or deployed elsewhere on the lunar surface.

Our design will provide experience with many different procedures, including robotic assembly of surface installations, large scale excavation and regolith transportation, production of bricks in-situ from available resources, construction of large structures on the Moon, and methods for protecting electronics against the lunar night by using regolith as a thermal insulator. The execution of these procedures will provide valuable insight into technologies and procedures to enable future lunar industry and enable the colonization of the solar system.

Appendix A — Power Generation Investigations

Nuclear Power

Radioisotope thermoelectric generators were not considered for the power source of the rover due to issues with procuring substantial quantities of radioactive substances. Further analysis showed that RTGs would be too heavy to fit within the mission profile. A kilowatt range nuclear reactor (KRUSTY) was explored but was far too heavy, bulky, and impractical to transport for our mission. In addition, procurement of radioactive materials is near-impossible especially for a mission of our calibre, and even if we were able to obtain RTGs or nuclear reactors, they would be prohibitively expensive (hundreds of millions of dollars each) [15].

Photovoltaic Cells

Early designs of the ISRU power source operated with the premise of using several square metres of standard multi-junction solar panels. This approach was the simplest and most conventional approach to power generation. However, several issues were identified, most significantly the high mass of the panels would mean that large installations would be incredibly heavy. Small installations, however, are practical, and a small photovoltaic panel is used on the MWU.

Solar Thermal (Turbines)

The prospect of using concentrated sunlight to drive a turbine was was briefly considered but ruled impractical, as while the technology shows promise, the added mass of the working fluid, as well as the complexity of the turbines and equipment mean that using solar thermal power would impose more constraints than benefits.

Concentrator Photovoltaics

Finally, we investigated and eventually selected concentrator photovoltaics as our power generation method of choice. Concentrator photovoltaics offer numerous advantages as compared to other power generation systems, such as normal, unconcentrated photovoltaic panels. Using solar concentrators means that the heavy photovoltaic elements themselves can be minimized in size and therefore mass, while the actual concentrator surfaces themselves can be constructed of ultra-light materials such as metallized BoPET film suspended by wires.

There are numerous drawbacks to concentrator photovoltaics, such as the necessity of cooling and sun-tracking, but these issues were easily resolvable, and concentrator photovoltaics still comes out as an improvement in mass over conventional solar panels.

Appendix B: Mass Estimation

Item	Mass (kg)	Quantity	Mass Subtotal	Link
Electrical				
Raspi compute module	0.025	6	0.15	raspberrypi.org
EXA ICEPS Spacecraft Systems Core	0.1	2	0.2	Cubesat Shop
Arduino nano BLE Sense	0.015	3	0.045	Arduino USA
Spectrolab Solar Panels	2	0.24	0.48	Spectrolab
Coolant Pump	0.3	1	0.3	Amazon
S band antenna	0.075	1	0.075	Cubesat Shop
Intel Realsense T265 (Ambient tracking Camera)	0.055	4	0.22	Intel Store
Thermal				
Propylene Glycol (/kg)	1	1	1	Sigma Aldrich
90mm PC Heat exchanger	0.3	3	0.9	Newegg
Flexible hose	1	1	1	Global Industrial
Structure				
Rover (bucket drum included) (6 batteries)	25.7	1	25.7	
Garage	11	1	11	
MLI door	1.2	1	1.2	
ISRU	8	1	8	
Power unit	0.8	6	4.8	
PTFE-insulated Copper Cable (16 AWG, 1m)	0.014	20	0.28	Bulkwire
Nitinol Wire	0.046	1	0.046	Nexmetal
Metallized BoPET film	0.06	5	0.3	Amazon
Margin	1	3	3	
Total Mass			55.696	

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