Artemis Lunar Surface Autonomous Transportation System
S21-35
Capstone Design Program
Colorado School of Mines
1500 Illinois Street
Golden, CO 80401

May 6, 2021

Mines Aerospace Interest Group
1812 Illinois St.
Golden, CO 80401

Dear Mines Aerospace Interest Group,

We would like to thank you for your participation in our preliminary design review held on April 21st. We appreciated the thoughtful discussion we were able to have with you after the presentation, and we also appreciate the valuable feedback you left on our report. This letter is a follow-up to that meeting, and will include our design recommendation as well as plans for finishing this semester and moving into the next one.

Based on the feedback received following our preliminary design review we have implemented the following changes:

- Creation of Concept of Operations flow - This has been added to highlight how our design will be used in conjunction with other systems during pre operation and operation. This will be an important consideration to keep in mind throughout the design process.
- Function Tree - This diagram was included to better communicate a breakdown of the various functions required by the design. This will also serve as a good reference for the team in the future and will likely be added to as the design process progresses for each subsystem.
- Objectives Tree - Similar to the Function Tree, this is now included to help decompose top level objectives into a set of primary and secondary objectives. Moving forward this will serve as a good way to focus our development efforts on the priorities.
- Product Tree - The Product Tree illustrates the subsystems within the Artemis transport vehicle, and how all the subsystems integrate with one another to complete an entire system.
- Requirements/Constraints table - This serves to clarify the clear constraints of the project.
- Design Assumptions - This section has been including following feedback that the assumptions made surrounding the design needed to be clearer.
- Technical Risk Assessment - This has now been included following feedback. Considering risk throughout the design process will allow for attention to be focused more on high risk areas as well as aiding in the development of risk mitigation plans.

Attached to this document is our preliminary design report with incorporated feedback for review at your convenience.

The team's design recommendation moving forward includes the top choices from each subsystem along with some secondary ones. For the latching mechanism the twist locks will be implemented and scaled appropriately for the vehicle. The wire mesh wheels along with the wheg wheel design will be prototyped, tested, and evaluated. The passive suspension will be chosen going forward. For redundancy, to mitigate failure and immobilization, each wheel will have a dedicated motor. The vehicle will be utilizing a combination of nuclear power and battery with the assumed ability to charge at the Artemis lunar base. For ease of use and versatility ROS (Robot Operating System) will be the primary software being selected and implemented. A ¼ - scale for the prototype was chosen due to cost and practicality. Allowing for the ¼ - scale, additional testing can be implemented with multiple subsystems to provide proof of concept.

To facilitate scaled testing of the system, the team has developed the following preliminary budget. This budget is based on the ¼ - scale prototype and factors in potential unforeseen expenses. Critical components that cannot be made from scratch or locally will be prioritized when making purchases. The projected budget going forward is $2,190. For a full breakdown of the budget please reference the attached budget plan.

Total Estimated Cost - 1/4 scale		$2,190.00		
Subsystem	**Part/Material**	**Cost**	**Notes**	**Potential Vendor**
Wheels				
	Wire mesh	$200	Wheel Area: 0.12 sq m FOS = 2	48"x 5ft 0.016" Mesh
	Hub - With Water Jet cost	$300	area: .05 sq m FOS = 2	6061 0.25" Aluminum Plate
	Wheg - With Water Jet Cost	$300	FOS = 2	6061 0.25" Aluminum Plate
Suspension				
	Wire Mesh	$0	Wire mesh will act as the dampener	
	RC Shocks - Dampening for Whegs	$60	Dampening for wheg vibration FOS = 2	RC Shocks
Body				
	6063-152 Aluminum Rectancle Tubing	$20	FOS = 2	1" x 1.5" x 0.062" Rectangular Aluminum Tubing
Latching System				
	Twist Locks - 3D Printed	$0	PLA free on campus	
Cargo				
	3D Printed Crate	$0	PLA free on campus	
Power System				
	Motors	$600	FOS = 1.5	Brushless DC Stepper Motor 1.05 n-m 3000RPM
	Batteries	$300		E-Bike Battery with small form factor
	DC Brushless Motor Controller	$100	FOS = 2	36/48V 15A 250W/350W Brushless Controller
Computers/ electronics				
	Xbox Kinect	$0	Donated by Team member	
	Rasberry Pi	$0	Donated by Team member	
	GPS	$80	FOS = 2	adafruit GPS Module
	Lidar - Higher resolution thn Xbox Kinect	$230	Used if Kinect is undesirable FOS = 2	Garmin LIDAR - Lite
Budget:	$2,500.00		Percentage of Budget Left :	14.16%

In addition to attaching the improved preliminary design report, we have also attached our macro gantt chart which provides an overview of the schedule for next semester.

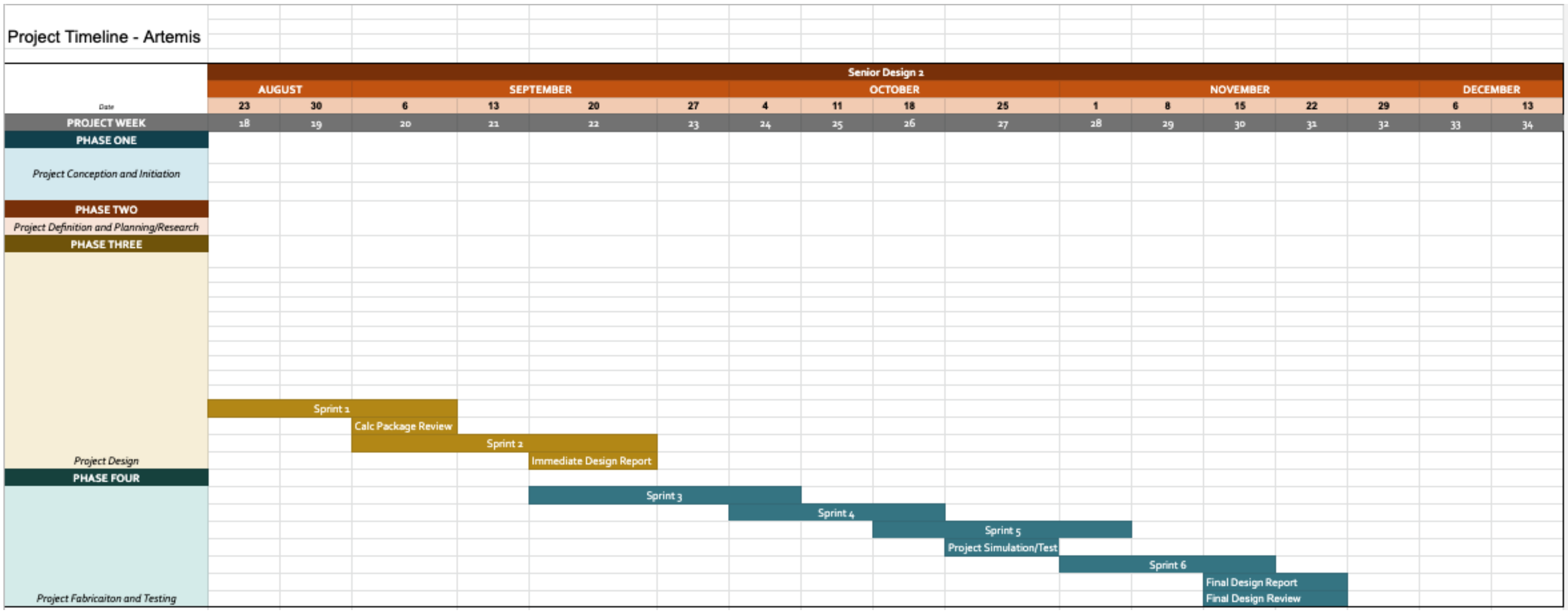
Moving forward we ask that you please review the accompanying budget and provide any final feedback you may have. We are grateful for the opportunity to be working on this project and look forward to resuming this project with you next semester.

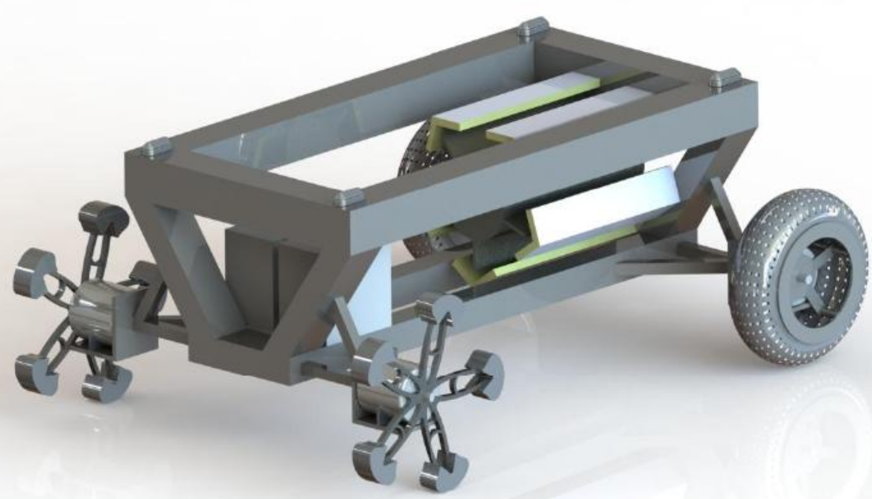
Sincerely,
Luis Cisneros, Tate Holmes, Ryan Hunter, Dillion Kolstad, Marcin Koral, Nathaniel White and Anand Zorig

Tate D Holmes   Dillon Kolstad

cc: Yosef Allam,

Second Semester Overview





B.L.A.S.T.E.R
Preliminary Design Report

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COLORADO SCHOOL OF
MINES

Colorado School of Mines
EDNS 491—Senior Design Team S21-35

April 2021

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Background, Boundaries and/or Characteristics

The world is entering a new era of space exploration. With it, countless challenges will be faced and technological innovation will be required to overcome these challenges. NASA's Artemis program seeks to put Americans back on the moon and explore more of its surface than ever before. The Artemis program will act as the stepping stone for the "next giant leap, the exploration of Mars" [1]. NASA is forming a coalition with industry and academia from around the world as well as working with other national space agencies to achieve the goals they have set. The Artemis plan is separated into two groups of missions: The Early Artemis Missions and The Sustainable Artemis Missions. The Early Artemis Missions aim to put American men and women on the moon by 2024 and establish early infrastructure. The Sustainable Artemis Missions aim to establish the Artemis Base Camp on the lunar South Pole which will allow for longer sustained expeditions on the lunar surface [1]. An important challenge to overcome for these longer sustained missions will be the transportation of equipment and resources over lunar terrain. To that end, this Senior Design project aims to develop an autonomous transportation vehicle that solves that very challenge.

Lunar surface conditions are extremely harsh and worlds apart from conditions found on Earth. Gravitational acceleration of the moon is roughly 1/6th of Earths and the moon has little to no atmosphere or magnetic field [2][3]. As such the moon has very little protection and is shaped by meteor impacts, solar winds and cosmic rays. Solar and cosmic radiation provide a large threat to the designs electric systems in the cases of a single upset event or hard failure [3]. Moreover, radiation can also damage optical equipment that may result in compromised autonomous function [3].

The lunar surface or regolith has been defined by meteor impacts that have left many large-scale features such as large craters and boulders that pose a great challenge to any vehicle on the Lunar surface. One of the most desirable locations for the Lunar base would be Shackleton Crater, located on the south pole region [4]. The crater angle of repose is estimated to be between 35° - 45°. Currently, the locomotion limit for typical lunar rovers on friable slopes is between 30°-35° [3]. In addition, to large meteor impacts there are also frequent micrometeor impacts that have resulted in the lunar regolith consisting of a very fine, sharp, abrasive dust (<70 microns) [3]. Furthermore, the Lunar dust carries an electrostatic charge which allows it to cling to non-grounded surfaces, both conductive and non-conductive. This ultimately leads to Lunar dust coating equipment and eroding any mechanical parts and seals [3]. It is therefore an important consideration in the vehicle design. Additionally, there is the possibility of photoionization, caused by ultraviolet radiation, near the terminal border between lunar day and night which can result in the levitation of dust up to 10 m above the Lunar surface [3]. Given the mission's intended location near the Lunar south pole there is the possibility that the vehicle may pass through the terminal border.

As well as dust considerations, the thermal conditions on the Lunar surface also pose many challenges to the vehicle design. Lunar thermal conditions are a result of the latitude and the long 2-week lunar day/night cycles [3]. This will mean there are extended periods of intense heating followed by similar periods of intense cooling resulting in extreme temperature differences of 120 ℃ to -150 ℃ [3]. Extreme low temperatures of -260 ℃ can be found in the permanently shadowed region of the Lunar south pole where water ice is potentially located and where extended expeditions are likely to take place.

The following four figures layout the basic functions and objectives of the system. Their content is based on the previously discussed information about the moon's environment, as well as project requirements provided by the client. The first is the Concept Operations Flow Diagram which details the overall operation of the system from beginning to end, including a brief description of the operations it goes through prior to arriving at the moon. The second is the Function Tree. The function tree breaks down everything that the system does, starting at a high-level view, and then working its way down through the various parts of the system. The third diagram is the Objectives Tree, which lays out the overall objectives that must be accomplished by the system. Like the Function Tree, it also starts at a high level and then lists any pre-requisite objectives. The Product Tree illustrates the subsystems within the Artemis transport vehicle, and how all the subsystems integrate with one another to complete an entire system. Fourth and final is the Product Function Tree. This diagram simply shows the literal parts in the system, everything from the wheels to batteries and sensors.

Concept of Operations Flow Diagram

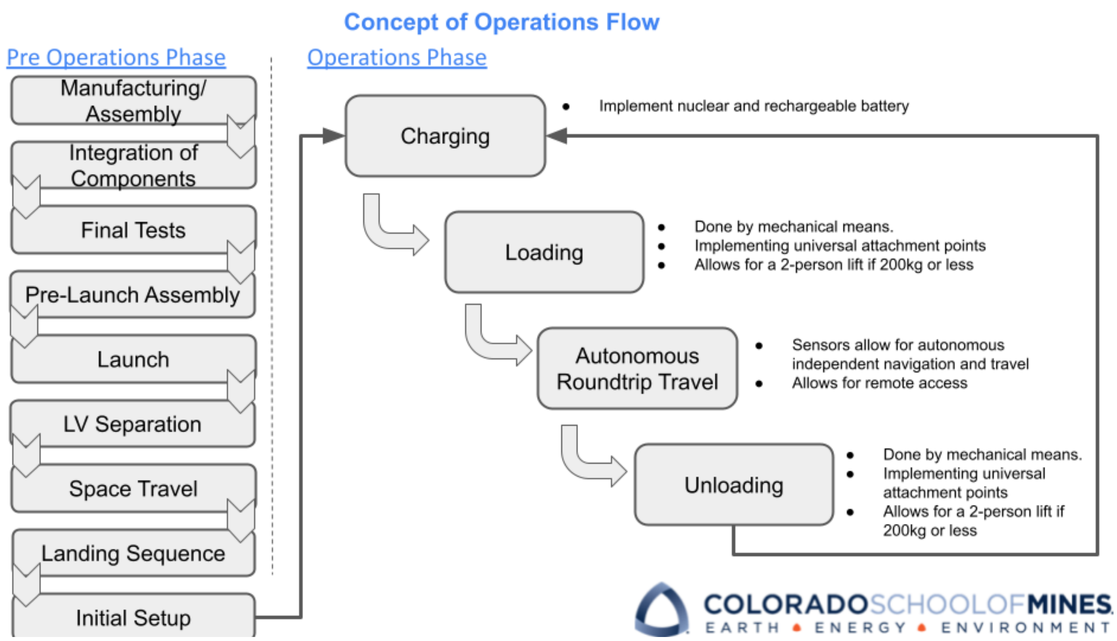


Fig. 1. Concept of Operations Flow Diagram

Function Tree

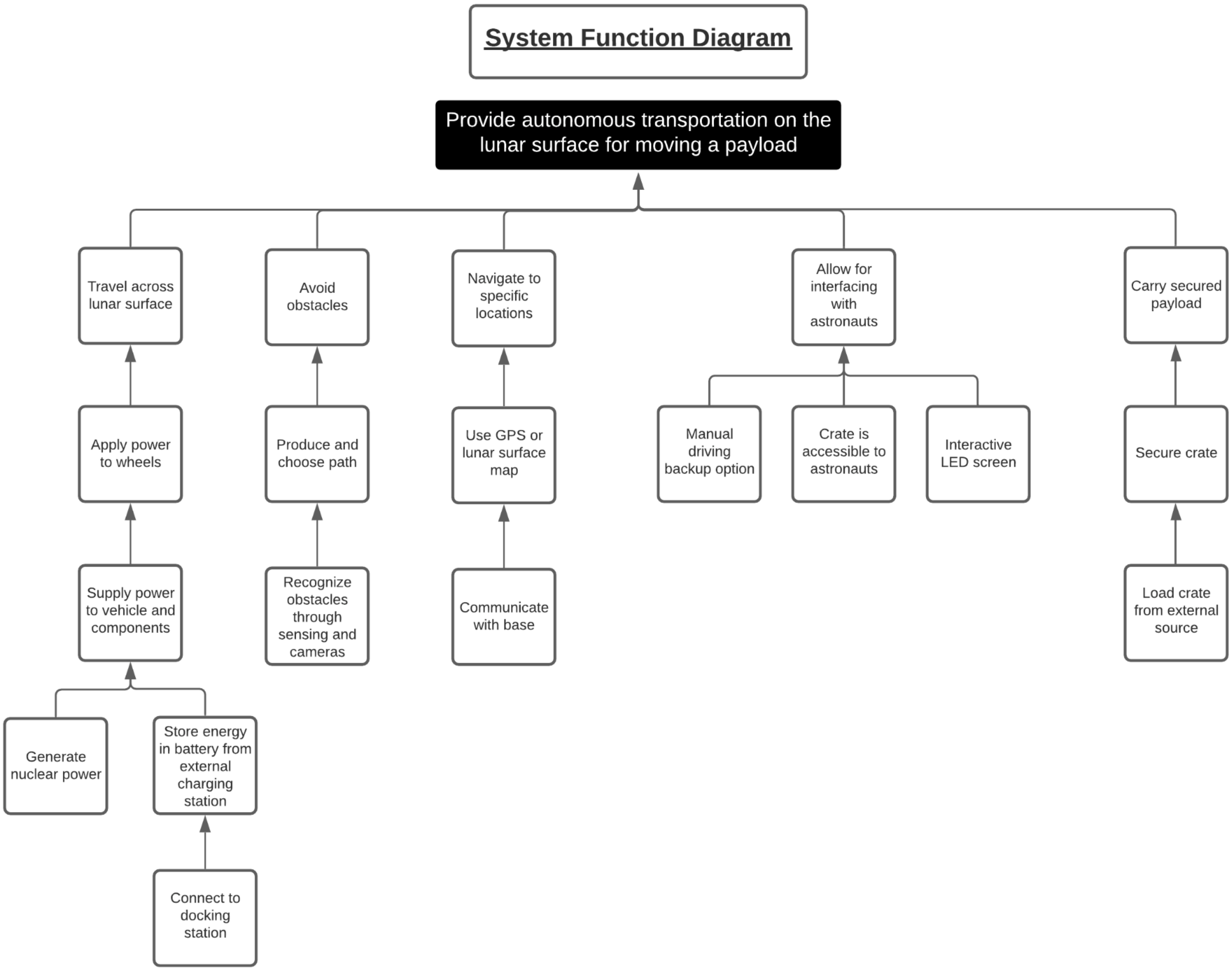


Fig. 2. Function Tree breaking down the various functions required by the design.

Objectives Tree

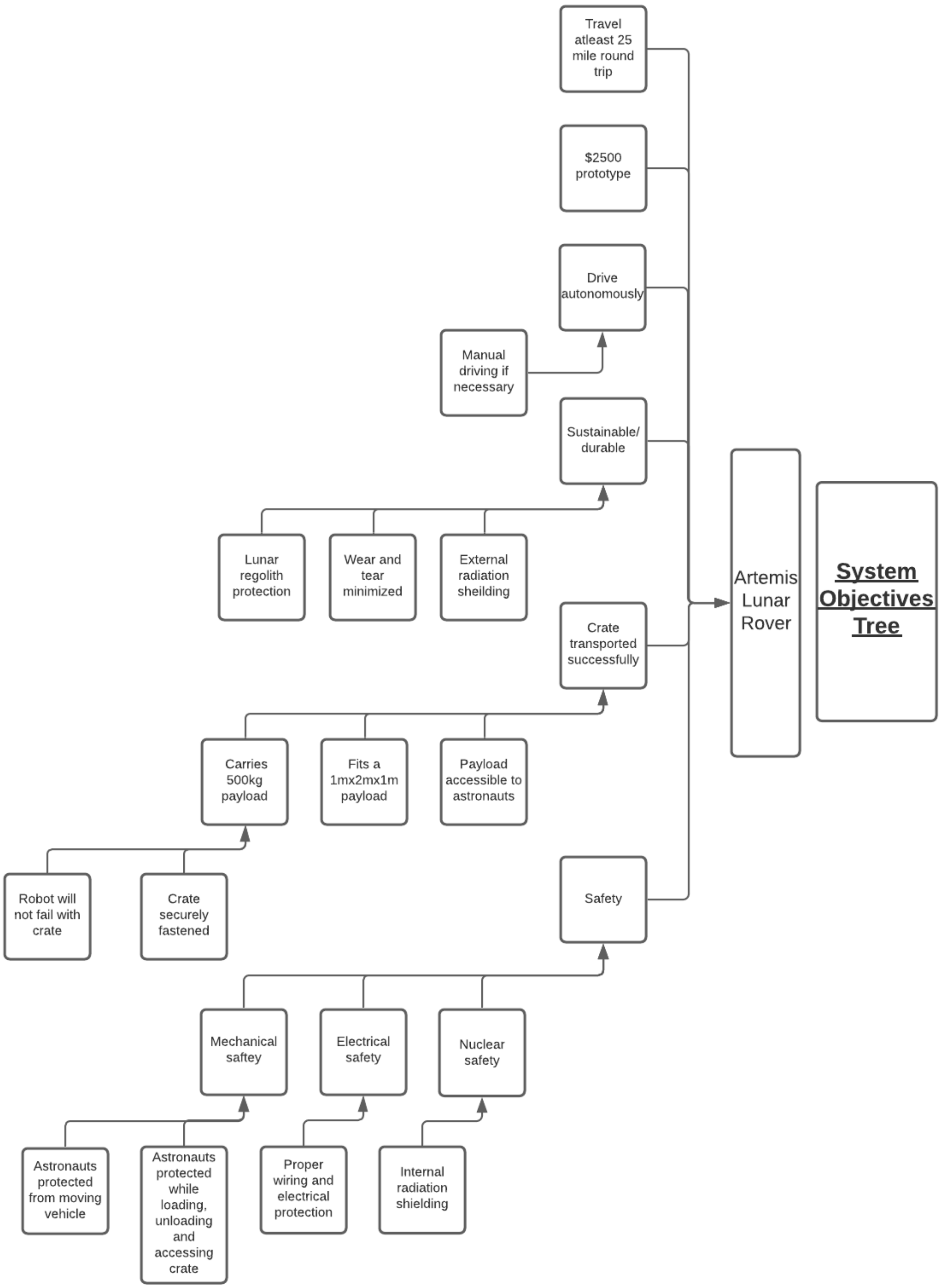


Fig. 3. Objectives Tree

Product Tree

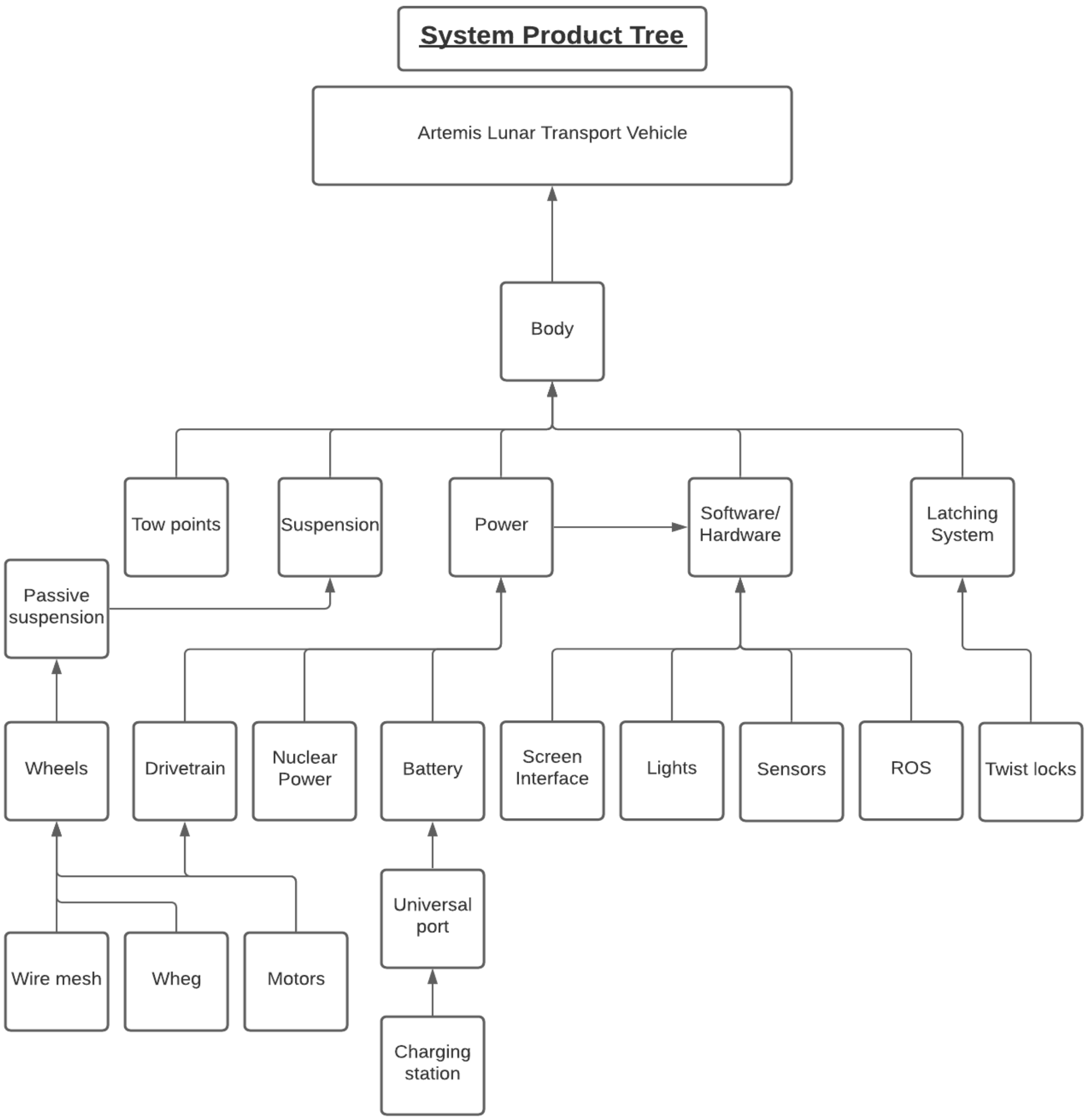


Fig. 4 . Product Tree For The Artemis Lunar Transport System

After this extensive background research and process development, the team brainstormed many vehicle concepts with the various environmental challenges in mind. To narrow down the concepts into one or two options, each subsystem was looked at more closely. The **Concept**

Exploration section of this report goes into further detail on the subsystem analysis and what options were considered for each one. An overall design was then selected based on the theoretical success of its subsystem concepts whilst also considering how these subsystem concepts worked together. The team hopes to provide sufficient proof of concept for our solution concept and take our solution into the testing phase.

Design Specifications (Constraints & Criteria)

The project spans two semesters, Senior Design I & II. The project involves designing a vehicle that is able to travel a minimum round trip of 25 miles (~40.2 km) autonomously. In addition to this, the vehicle is required to carry a payload that is 1 m x 2 m x 1 m and weighing up to 500 kg. The footprint of the vehicle is limited to 1.8 m x 2.8 m. A budget of $2,500 was provided to facilitate any physical testing and prototyping that may be needed to validate the design. The final design will be presented during the Senior Design showcase at the end of Senior Design II. A SolidWorks model of a crate, illustrated in Fig. 5, was supplied by the clients to use as a reference. The crate will be loaded and unloaded by mechanical means which is contained within the human landing system or within the Artemis base. Additionally, if the crate weighs 200 kg or less the vehicle must allow for a 2-person lift for astronauts to load and unload the crate. Other constraints and considerations, including the moon’s harsh environment and solar radiation, can be referenced in Table 1. In accordance with all that has been stated above, the vehicle shall operate according to the required constraints.

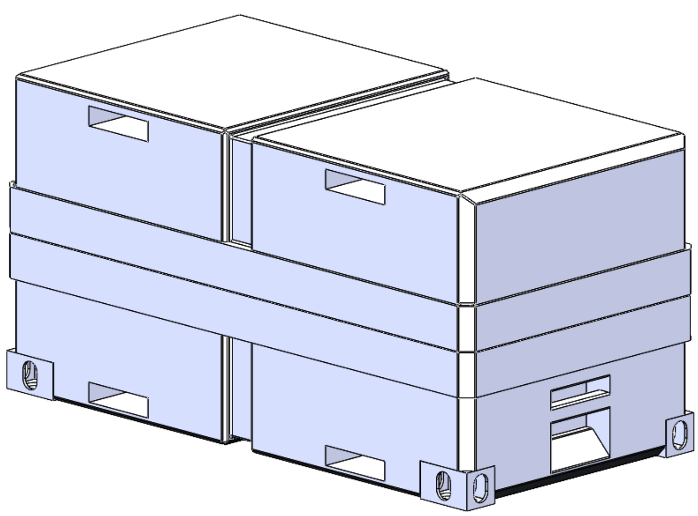


Fig. 5. Provided SolidWorks model of the storage crate that will be carried by the finalized lunar rover.

Operational Constraint	**Description**
Accessibility	Room for two people for manual loading and unloading
Vehicle Operation	Fully autonomous with manual override option
Travel Requirement	25 miles roundtrip
Vehicle Dimension	No larger than 1.8m x 2.8m
Payload Dimension	1m x 2m x 1m
Payload Mass	0kg - 500kg
Loading of Payload	Done by mechanical means
Environmental Constraint	**Description**
Ambient Pressure	Vacuum of space
Temperature	-260℃ to 120℃
Regolith Dust	</= 70 microns
Shielding	Against solar and cosmic radiation
Crater incline	</= 45 degrees
Design Team Constraint	**Description**
Time	Two Semesters
Design Personel	7 Team members
Design Budget	$2,500

Table 1. Table Summary of Constraints

Design Assumptions

There were a number of assumptions made when developing the design for this vehicle. The major assumption associated with this design is that this vehicle will be deployed during NASA's "Sustainable" Artemis missions. Many other assumptions were made based off of this. The "Sustainable" Artemis missions are intended to begin somewhere around 2028.
It can be assumed that:

- The Gateway is fully operational as well as other satellites in lunar orbit, such as access to LunaNet. This may aid in surface mapping, GPS for autonomous function and local communication systems leading to smaller signal delay.
- The autonomy of a final design is assumed to be scaled in conjunction with the resources of the Gateway and LunaNet
- Radiation and solar winds will be better understood as well as the ability to forecast environmental conditions on the surface.
- This design will be deployed in conjunction with a foundation surface habitat that will form the Artemis Lunar Base that is designed for one to two month expeditions.
- Artemis Lunar Base will have a significant base load power supply to survive long expeditions.
- Humans have returned to the moon and multiple manned missions have been conducted.
- Improvements to astronaut mobility and functionality on the lunar surface.
- Radiation protection and dust mitigation have been further studied and solutions have been developed that could be incorporated into our design.
- There will be serviceability on the lunar surface.
- This is a scaled prototype.
- Materials used in prototype design are not likely to be used in the final product.
- Final materials are possible given a larger NASA budget.

Concept Exploration - By Subsystem

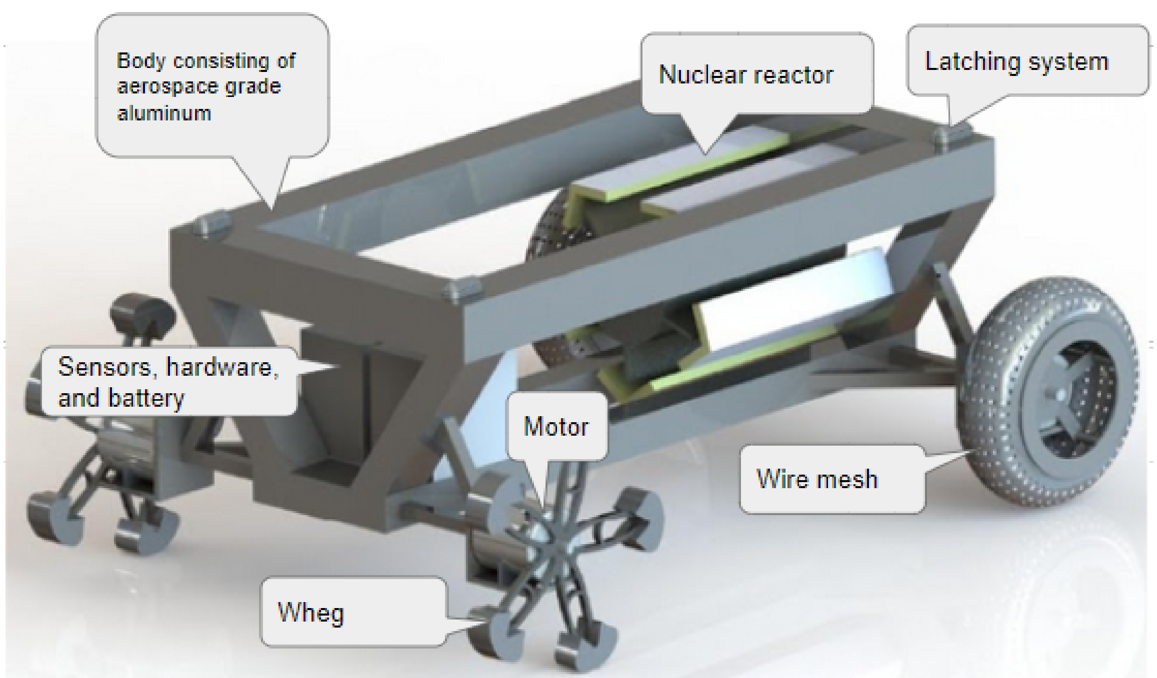


Fig. 6. Overall System View and Description

Latching System

Gate

A gate system is a door, or set of doors, that opens and closes to allow the loading and unloading of the cargo. The gate rotates on a set of hinges and locks into place when closed. When closed, the gate holds the cargo by not letting it back through once it has been loaded. In a decision matrix, the gate mechanism scored well in ease-of-use and strength, because it could be as simple as pulling a lever to unlock the doors, and the doors can be easily sized to be strong enough to hold the cargo back. The gate did not score so well in durability and interchangeability. Since the doors would most likely be held in place by a single lock at the bottom, there is a chance that they could come undone from the weight of the crate.

Button Release

The button release concept is similar to the seat belt locking mechanism in cars in which a part of the cargo interfaces with a fixed lock and is then released with the press of a button. This system is simple and would provide ample strength as current seat belt buckles are required to stop the force of a human moving at high speeds. Furthermore, astronauts interacting with the button release would be able to do so despite limitations of a spacesuit and requiring very little force to be applied. Despite the obvious advantages this design relies on a button mechanism which would encounter significant issues with lunar dust that could result in jamming and therefore an immovable payload.

Twist Locks

[25, 26, Fig. 7.] Designs of current dovetail and passive twist lock latching used in commercial shipping.

The twist lock is a common device used for attaching cargo containers together, as well as securing individual containers to flat-bed trucks and other such transports. A robust design allows the twist lock to withstand high loads, including a shear load of 420 kN and a tensile load of 500 kN. The design features a simple quarter-turn motion to lock and unlock, which is controlled by a single lever. The robust design means that the lock is also heavy, around 14 lbs, which might not be as desirable when being launched on a rocket or when power consumption is important. Overall, the twist lock allows for secure loading and is straightforward and simple to use.

Wheels

Hybrid Legged-Wheel Concept - “Wheg”or “Rimless Wheel”

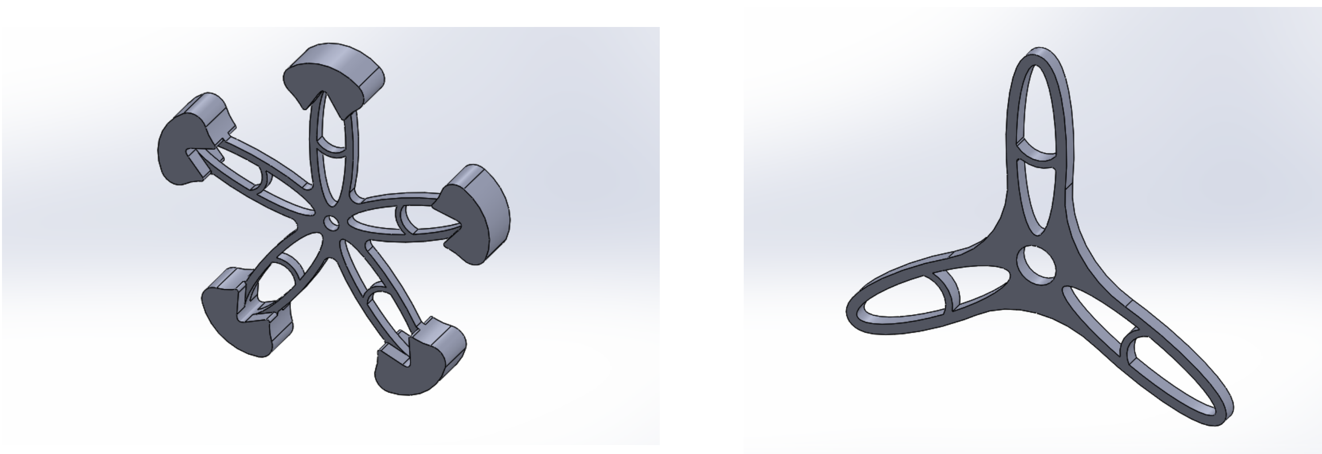
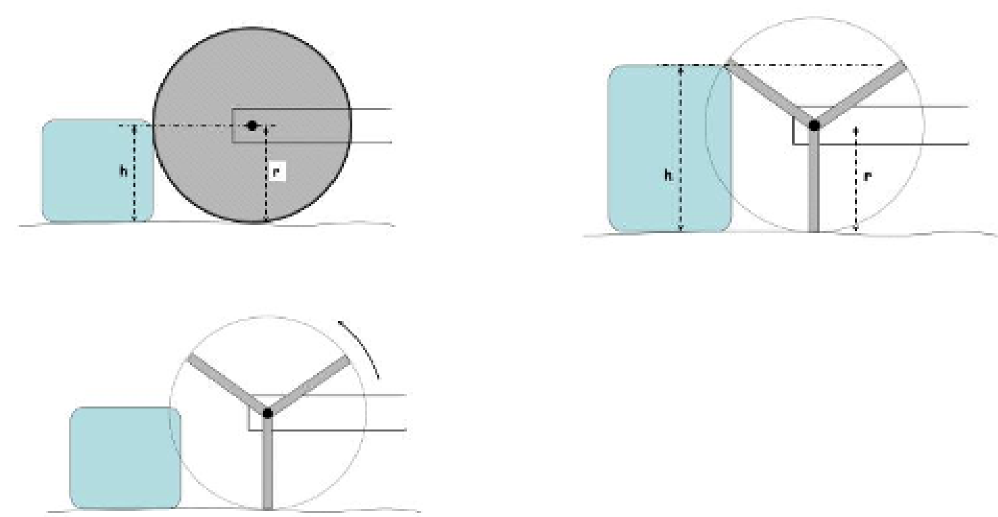


Fig. 8. SolidWorks renderings of potential wheg design with three and five legs respectively. The “penta-wheg” five-leg design includes tractive feet.

Given the designs' need for autonomous transport over challenging and unique lunar terrain a unique wheel is required. A hybrid wheel design allows for the combined advantages of a leg design and wheel design to be achieved. Pure leg locomotion allows for the advantage of extra agility over rough, uneven terrain as well as soft terrain when compared to wheeled locomotion due to contact occurring at discrete contact points. Wheel locomotion has the advantage of nearly 2 orders of magnitude increase in power consumption efficiency on hard, flat surfaces due to the requirement of less motors and its simplicity. In addition, despite legged locomotion tending being more efficient over uneven terrains it is inherently less stable than a wheel locomotion [5]. By combining the two into a hybrid wheel-leg (Wheg) design it broadens the range of practical applications for the vehicle's locomotion, something that would be extremely beneficial for the lunar vehicle [6]. Evidence for the success of a wheg design can be seen in the DARPA RHEX autonomous robot design [7] as well more recent success of the Coyote III, designed by the German Research Center for Artificial Intelligence [8].

Figures 8 and 9 show the obstacle clearing advantages of a “Wheg” in comparison to a wheel, highlighting the “Whegs” ability to clear obstacles greater than a wheel with the same radius. A key consideration for this design are the number of legs as this will affect the energy loss and stability/vibrations of the system, as well as the height obstacles that the “Wheg” can overcome. As the number of legs increases the “Wheg” begins to approximate the behaviour of a wheel and therefore vibrational stability is increased but obstacle clearing capability decreases. A further consideration is the width of the contact point of the leg as despite the advantages over uneven terrain, slender legs given an added payload could result in sinking in the lunar regolith. The inclusion of a wider contact point or “foot” as shown above would be able to mitigate this disadvantage whilst still maintaining the original concept advantages.



[27, Fig. 9.] Advantages of wheg locomotion over wheel locomotion when traversing large obstacles as visualized by the Arun Waves blog, 2010.

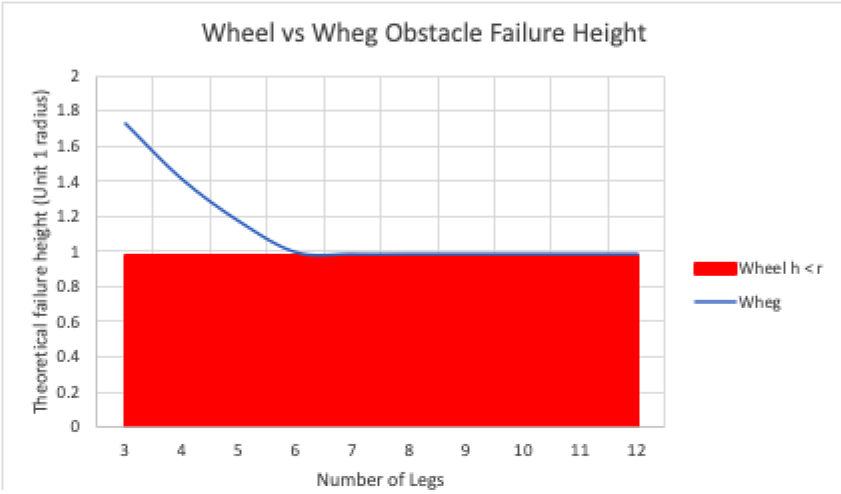


Fig. 10. Graphical representation of the height at which a wheel and the wheg design (with varying leg count) of identical diameter fails to climb an obstacle. With 6 legs or fewer, the wheg design offers an advantage, which increases as leg count decreases.

Standard Rover Wheel Concept

[9, Fig. 11.] Contrasted wheel design of the NASA Mars rovers Curiosity and Perseverance, emphasizing distinctions in tread shape in response to external factors.

The recent perseverance rover is using an updated standard version of the rover wheel with slight design changes. The wheels are typically machined out of a block of aerospace-grade aluminum with titanium spokes installed for dampening [9]. Things to note, Perseverance's wheels are slightly larger in diameter and narrower than Curiosity's, with the skins approximately a millimeter thicker. Curiosity included a 24 chevron-pattern thread design whereas Perseverance uses a 48 gentle curved thread design [9]. The design change was made and tested in the Mars Yard at NASA's Jet Propulsion Laboratory (JPL), and it was concluded that the new tread design works better to withstand pressures from rocks while improving grip on soft soils. The standard rover wheel design has been implemented on multiple rovers, the design has been improved over the years. Current vehicles being designed for lunar operations are implementing a rover-type wheel design. The rover-type wheel design, as used on the Perseverance, can withstand a tilt of 45 degrees in any direction, but is often restricted to 30 degrees for safety [9].

Mesh Wheel Concept

[28, Fig. 12.]. The wire-mesh wheel design used in the Boeing Lunar Roving Vehicle (LRV), in application on the moon. Photo published by Astronomy, 2019.

Several versions of the basic wire mesh wheel designs were tested for Boeing's Lunar Roving Vehicle (LRV), which were fabricated by General Motors Corporation for the Apollo missions

15, 16, and 17. During testing a Lunar Soil Simulant (LSS) was created based on soil samples from Apollo 11 and 12 flights. Varying wire mesh wheels were tested using the LSS to analyze the wheel's performance in a controlled environment. After testing it was concluded that the presence of a fender did not influence the wheel performance (paragraphs 38 and 47) [10]. The absolute power requirements increased linearly with the wheel load [10]. Generally, the sinkage increased with increasing loads. Moreover, the maximum slopes the vehicle could climb without using excessive power was around 20 degrees [10]. Performance parameters were independent of wheel speed (paragraphs 30, 40, and 49) and wheel acceleration (paragraph 32) [10]. The performance of the wheel was the same if it traveled forward or backward into undisturbed soil. Lastly, it was concluded that the wheels that were tested performed essentially the same on the given soil condition LSS4 (paragraph 41) with an average speed of 0.75 m/s (~2 mph) being used [10]. During lunar operations the vehicle traveled at speeds around 4 m/s (~9 mph).

Drive Train

Individual Motors

Installing individual motors on the vehicle allows greater control while maneuvering, by providing independent wheel control over each wheel, and navigating over the lunar terrain. Previous and current rover models, including rovers such as Curiosity and Perseverance, have implemented a design using individual motors for each wheel. Additionally, implementing individual motors provides redundancy to the system in the event of a motor failure. In the event of a motor failure, the remaining motors are able to keep the vehicle in operation to complete its mission. The addition of extra motors increases the cost of the vehicle. Moreover, additional motors may increase the overall weight and volume of the vehicle. Conversely, the power demand for each motor decreases with each additional motor dividing the power required among each motor. Lastly, it is important to note that the individual motors design won out of the three design choices in the decision matrix.

Single Motor System

A singular motor system, similar to what is used on a motor vehicle, has been in use for over 100 years. The singular motor drives the driveshaft transferring torque to the wheels. The implementation of a single motor reduces the overall cost and weight of the vehicle, versus implementing multiple or independent motors. By installing a singular motor there is no redundancy in the system, potentially causing a catastrophic failure causing the vehicle to be immobilized. The motor, being a critical component, needs redundancy considering the Artemis mission. A singular motor also reduces the number of potential design choices being considered for evaluation. Conversely, a singular motor design simplifies the overall build. The simplicity of the design awarded the single motor design second place in the decision matrix.

2-D Rotating Wheels

Wheels that allow 2-D rotation, in the xz-plane and the xy-plane, allow greater maneuverability and control while in operation. The intricate movement would allow the wheels to turn on a dime and also react to obstacles while maneuvering the lunar surface. Moreover, with all wheels implementing a 2-D rotation the vehicle's capabilities increase. Implementing 2-D rotational wheels requires additional motors and stress analysis on connection points. Additionally, connection points must be sealed to minimize dust contamination and inevitable wear and tear from the harsh lunar environment. Due to the additional required motors the overall weight of the system increases requiring additional power supplied. Due to the complexity and uniqueness of the design the 2-D rotating wheel design placed last overall in the decision matrix.

Power System

Hydrogen Fuel Cell

Hydrogen fuel is a rising technology that could be very promising for use in Lunar vehicles. The ability to harvest Lunar regolith containing solid water makes hydrogen appear to be the next chapter of fuels on the moon. However, the technology still has yet to bring this to fruition. Current models are massive, over priced, and underdeveloped and therefore should be left out of consideration for the time being.

Solar Powered

The use of solar panels has been a traditional method of power generation for previous Lunar rovers. However, ever since the solar powered Martian rover Opportunity was lost after a massive dust storm prevented its solar panels from seeing the sun, NASA has been looking into more resilient energy sources [11]. While solar panels are safer from dust on the moon, it would still be a concern if the vehicle was operating in areas of the moon that are perpetually shadowed [12]. Additionally, solar panels are still vulnerable to dust accumulation from static electricity and nearby takeoffs and landings stirring up the fine Lunar dust. With the development of nuclear fuels, it may be time to graduate to more reliable energy sources.

Radioisotope Thermoelectric Generator

NASA's latest Martian rover, Perseverance, uses a multi-mission radioisotope thermoelectric generator to power the rover and charge its batteries [13]. It provides the benefit of sourcing the vehicle with power in addition to maintaining optimal temperatures in harsh conditions. Since Lunar temperatures can get as low as -232 Celsius, having some sort of heating element is essential in order for work to be conducted during these periods [14]. The drawback is that nuclear fuel is not the most cost effective per unit of energy. On Earth, nuclear power is estimated to cost $56 per MWh while solar, for comparison, costs $44 per MWh [15]. This may be a worthwhile investment given the added complexity and cost of relying on an external heating source to keep the vehicle's components warm.

Li-Ion Battery

The use of batteries to store power has been essential to the operation of unmanned rovers operating in environments where combustion engines fail. The batteries are responsible for holding the power used by the on board computer, sensors, cameras, and motors and are therefore critical to the overall success of the rover. Historically, two to four batteries with voltages ranging from 28 volts to 36 volts have been used for previous Lunar rovers [16][17][18]. Modern batteries sent out into space have used lithium-ion batteries to store the power generated from either solar or nuclear power generators [19]. Lithium-ion batteries are more considerably more expensive than other types of batteries, however they offer unparalleled advantages. Lithium-ion batteries excel when it comes to energy density, self-discharge rate, and maintenance needs. As long as lithium-ion batteries are connected properly and used in the proper temperature range, they will offer the best performance compared to alternative battery chemistries.

Estimated Power Requirement

The following calculations were performed in order to obtain an estimated minimum power supply necessary to aid in the evaluation of power system configurations.
Assuming the following values for the lunar gravitational acceleration and overall mass of the vehicle,

$$g_{moon} = 1.62\,\frac{m}{s^2}$$
$$M = 700\,kg$$

the force that some N number of motors must exert can be found using

$$F_{g,moon} = M \cdot g_{moon}$$
$$\tau_{motor} = \frac{1}{N} \cdot F_{g,moon} \cdot r_{wheel}$$

In order to obtain the power necessary for the motors, a desired velocity must be determined.

$$P = \tau_{motor} \cdot \omega$$
$$\nu = \omega \cdot r_{wheel}$$

Combining the above equations results in an expression for the power necessary in terms of the gravity, mass, velocity, and number of motors.

$$\begin{aligned} P &= \tau_{motor} \cdot \frac{\nu}{r_{wheel}} \\ &= \frac{1}{N} \cdot F_{g,moon} \cdot r_{wheel} \cdot \frac{\nu}{r_{wheel}} \\ &= \frac{1}{N} \cdot M \cdot g_{moon} \cdot r_{wheel} \cdot \frac{\nu}{r_{wheel}} \\ &= \frac{M \cdot g_{moon} \cdot \nu}{N} \\ &= 1418\, W \text{ (assuming a velocity of 5 m/s and 4 motors)} \end{aligned}$$

At these speeds, a 25 mile round trip could be completed in just over 2.5 hours of operation. This would mean that if the motors were operated at 36 volts, a 40 amp-hour battery would be required. These calculated values just so happen to be comparable to the power specifications reported on the 2021 Martian rover Perseverance [13].

The concept of using two batteries situated at the front of the vehicle has been a popular choice for previous Lunar vehicles [16]. By placing the batteries at the front, the heavy weight of the batteries provides a counter balance for the vehicle and improves stability. The batteries were made powerful enough such that in the event that one of the batteries had been compromised, the other battery could continue powering the system entirely on its own. This provided increased reliability and robustness, two factors that were critical for the original Lunar probes exploring unmanned terrain and any vehicle that would be operated on the moon today.

Modern rovers have utilized both nuclear power and battery power together in order to mask the weak points of each. For example, nuclear power is very reliable and is able to provide a consistent stream of power as well as much needed heat to the robot. However, nuclear power is not good at providing sudden bursts of power [13]. This could be necessary if the robot were to go up a sudden steep hill where extra torque would be placed on the motors. In this event, the batteries would be able to be switched to and then charged afterwards using the nuclear generator when the extra power was no longer necessary.

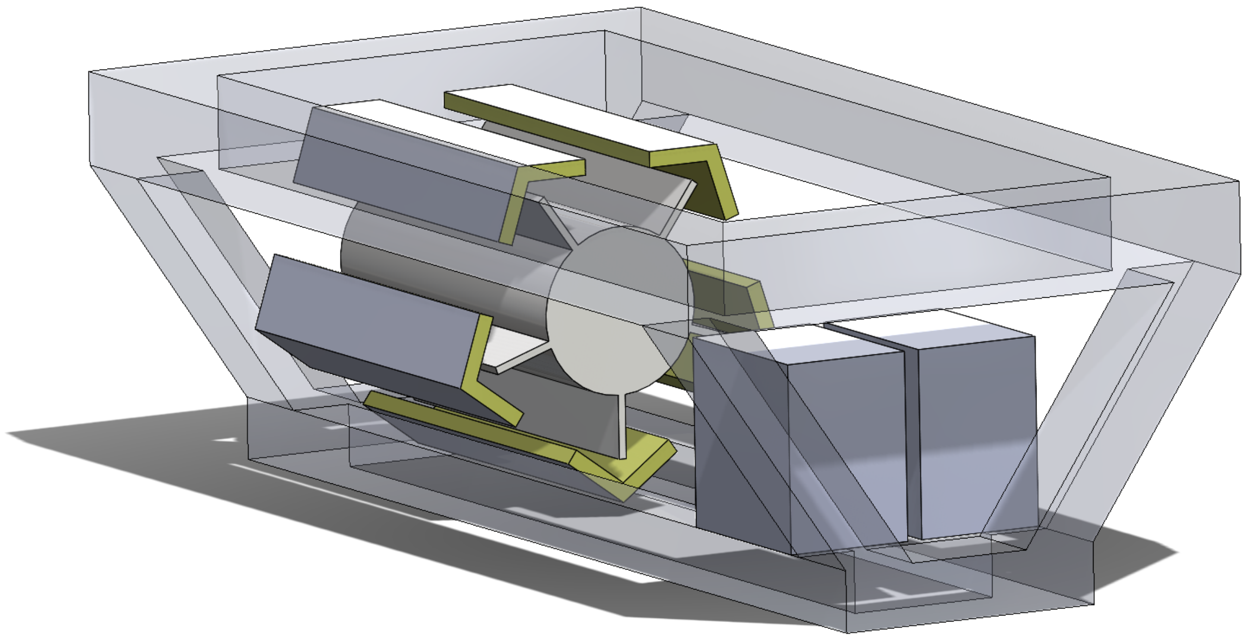


Fig. 13. Concept rendering of a nuclear reactor and pair of batteries situated in a generic chassis, with emphasis placed on the cooling fins situated around the reactor.

With this in mind, the best configuration that was determined through the use of decision matrices and research was a combination of a rechargeable fuel with nuclear energy. The configuration shown above depicts the relative location of the batteries and the nuclear generator in the frame of the rover. The front of the rover is where the 2 grey blocks are which represent the 2 batteries, while the back of the rover holds the radioisotope thermoelectric generator represented by the silver-gold pentagon figure. The pentagon shape was chosen for the nuclear generator as this shape allowed for a fit which minimized protrusion from the rover frame while maximizing the size of the generator. The core seen in the model has the same dimensions as the one used in the Perseverance Martian rover which was previously mentioned to be comparable to the B.L.A.S.T.E.R. rover in terms of power need. The corners surrounding the core of the generator is what captures the heat emitted from the heat fins attached to the core. Therefore it is advantageous to have more of that surface area surrounded while still allowing the core to cool down with the ambient Lunar temperature.

The batteries at the front of the rover would be directly below the computing circuity for the rover. This has an added advantage of using the batteries as a heatsink for the computer processing unit [16]. The front of the robot is also where the location of the charging and output power port will be situated. The charging port will be used when the rover is docked at a Lunar base which can charge the rover with power in order to extend the life of the on-board nuclear reactor. The output power port could be used to power equipment or supply an astronaut with backup power if necessary.

Suspension System

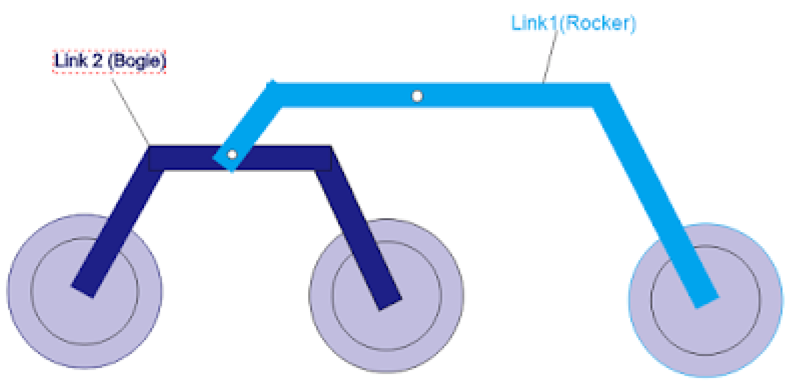
Fixed

[29, Fig. 14.] Solidworks model of a four-wheeled vehicle with fixed, zero-travel suspension.

A fixed suspension system consists of four or six wheels that has a direct drivetrain and no travel. This system is the simplest form of suspension and therefore has the advantage of being extremely robust with very few moving parts, allowing easier servicing whilst in operation. This is a critical advantage when considering the lunar environment, specifically dust challenges, and the limited resources available to astronauts during extended expeditions. This design also has the advantage of reduced weight, resulting in obvious cost savings for the design. A fixed suspension system would ideally use skid steering for simplicity sake. However, what this design gains in simplicity and robustness it loses in its ability to overcome challenging terrain. Due to the lack of travel, when this design encounters uneven terrain there are many use cases where one or more wheels lose contact with the surface, as shown in Figure 11 above. As a result maximum driving force is lost and obstacle clearing abilities are limited. The ride height of a vehicle with fixed suspension therefore becomes a limiting factor in obstacle clearing. However a ride height that is too high will raise the center of mass (COM) and could result in critical failure of the vehicle via tipping.

To overcome the various disadvantages, this system would ideally be paired with a wheel concept that allows for some form of travel or has obstacle clearing advantages, as seen in the Mesh wheel or the Wheg designs. By combining a fixed suspension system with a wheel with more capabilities, simplicity and robustness would be maintained but with the added obstacle clearing advantages of the wheel concept.

Rocker-Bogie



[20, Fig. 15.]. Description of basic Rocker-Bogie passive suspension system, distinguishing each solid link from the other to indicate points of motion, 2019.

The Rocker-Bogie suspension system was designed and developed by NASA in 1988 and since then has been the de facto, proven design for off planet rover designs such as the Sojourner , Pathfinder and more recently Curiosity [20]. The Rocker-Bogie mechanism features two links and 3 wheels on both sides. The largest link (Figure 10 - Link 1(Rocker)) is the forward link whilst the smaller link (Figure 10 - Link 2 (Bogie)) featuring two driving wheels is the rear link [20]. The Rocker-Bogie mechanism, along with a differential connecting both sides, enables a six wheeled design to passively maintain wheel contact with all six wheels over severely uneven terrain. This allows even pressure distribution and therefore an important advantage over soft terrain such as the lunar regolith. Furthermore, whilst climbing uneven, challenging terrain, it allows all six wheels to remain in contact and therefore maintain maximum driving force thus allowing the Rocker-Bogie design to overcome obstacles twice the diameter of the wheel. [21]. The decision to stick with the Rocker-Bogie is largely due to its obstacle clearing abilities and relative stability provided to rover payloads on slopes up to 45° [21]. Despite such advantages, the Rocker-Bogie is designed with very slow speeds in mind, less than 0.1 m/s or 0.22 mi/hr, to reduce dynamic shocks through the suspension links and prevent flipping [21]. Given the scope and constraints of this project, it would be imperative that alterations be made to the design to allow for higher speed operation whilst still maintaining obstacle clearing abilities. One such alteration would be the use of two bogies featuring two driving wheels connected by an intermediary rocker between them. This eight wheeled design would allow the design to perform at higher speeds whilst reducing the risks of wheelies, dynamic shocks and risk of flipping [22].

Passive Suspension/Traditional Vehicle Suspension

A passive suspension design limits the motion of the wheel and chassis feature with the use of some sort of damping mechanism. Passive suspension is used in all sorts of modern day vehicles and is usually found consisting of springs or hydraulics. This design has also been implemented previously on the lunar rover and has been proven to work on the lunar surface. The passive suspension design is relatively simple to understand and model, and would not be outside the team's capabilities to assemble. For this particular vehicle, where the wheels are driven and steered independently, individual springs would connect the wheel and chassis. These dampeners would allow for the chassis to remain stable whilst the wheels travel with the contours of the surface. This design has the advantage of simplicity and lack of mechanical parts which is extremely important considering the abrasive nature of lunar dust. The value of this design stems from its feasible manufacturing and cost effectiveness, but is not as beneficial as other suspension options when it comes to navigating harsh terrain.

Active Suspension

[24, Fig. 16.] Demonstration of the Pratt and Miller Multi-mode Extreme Travel Suspension (METS) concept, which utilizes vehicle-height dampers for extreme mobility, including level operation on steep inclines.

An active suspension design is a concept that enables the system to adjust to its environment by changing the elevation of the chassis with respect to the wheel. The system is a dynamic design that changes ahead of time, and in the present, to efficiently overcome obstacles and limit shock to the cargo. According to the Canadian Space Agency in their study of the Artemis Sr. vehicle design, active suspension "makes it highly maneuverable, increases stability and allows the rover to spin around without moving" [23]. This differs from the passive suspension, which is unchanging and reactionary. In terms of this design, the vehicle will be able to control the extension of an individual wheel or any combination of wheels that may be advantageous in overcoming obstacles. Figure 11 depicts one side of the vehicle being lifted up to properly balance the body and decrease slippage. Another scenario may be the vehicle driving up an incline with the back raised, or one side of the vehicle climbing a rock and moving individual wheels over the obstruction. These scenarios are outlined and proven to be effective in the Pratt & Miller prototype of a combat vehicle [24].There are several advantages to this design that make it a viable option for our autonomous lunar vehicle. Most importantly, an active suspension allows the vehicle to traverse more complicated terrain such as climbing rocks and handling steep crater inclines. Active suspension can overcome difficult terrain by lifting wheels up over rocks and shifting the vehicle's weight less slipping. Additionally, this idea also acts as a dampener and decreases the shock the vehicle may experience when first coming into contact with an object and when it slips off. However, an active suspension design is more complicated than a fixed or passive suspension. It includes more motors and moving parts, which would lead to more wearing and need for service, not to mention the factor the lunar regolith plays. Since it requires more parts (motors) and protection (casings) from the environment, active suspension would ultimately be more costly than some other suspension types as well. An active suspension system could prove to be a good option as long as there are good solutions to its price and complexity.

Software

ROS

A key factor in the design of the rover is it being fully autonomous while having a backup remote control override. The best method of implementing this feature is by using a dedicated software that can simulate an environment and test the sensing capabilities of the robot. That is why the open source platform known as ROS (Robot Operating System) was chosen. It allows for versatility in coding by allowing multiple languages such as C++, Python, and MatLab to control the robot. Additionally, Within ROS a package called Gazebo lets the user create a virtual environment and import their robot's design into the simulation. This significantly eases the testing process of the sensors and cameras without having to construct the robot at all. Because object-oriented coding is versatile with ROS, advanced machine learning methods such as Deep

Reinforcement Learning can be utilized to train the robot to determine the optimal path of it's journey. ROS is currently only available on Ubuntu V18 which is a version of Linux and can run on laptops and microcontrollers such as a Raspberry Pi.

Any other possible choices

Other ways of coding the software for the robot consist of variations of making home-made ways to publish/subscribe data from the sensors to the motor. However, this would be highly inefficient and time consuming as ROS is a platform that already accomplishes these tasks. An arduino may also be a possible alternative, however the processing capabilities of it would be highly inefficient time and space wise.

Concept Selection

When choosing an overall design to tentatively move forward with, the design was broken up into subsystems, a concept from each subsystem was chosen and then the choices were combined together into one larger concept. This concept is illustrated in the Product Tree in Fig. 4. This method allowed for easier analysis of each aspect of the whole system since it is a slightly more complex system. Explored in earlier sections, the six main subsystems chosen to focus on were the latching mechanism, wheel, suspension, drivetrain, power and software. 3 - 5 ideas were brainstormed for each subsystem, and then with the guidance of research, calculations and design matrices, they were dwindled down to 1 - 3 ideas. The combination of all selected winning concepts should theoretically provide the best concept transportation system.

The following subsystem concepts were chosen for a preliminary design:
Latching Mechanism: Twist locks
Wheels: Wheg or Wire Mesh
Suspension: Passive Suspension
Drive Train: Individual Motor for each Wheel
Power: Charging Station + Nuclear Power Combination
Software: ROS (Robot Operating System)

The following concept art is presented to show how these subsystems will possibly look when put together. It must be noted that the final design will include only one wheel design for all the wheels, and that in the image, 1 pair of each type of wheel is shown for demonstration purposes.

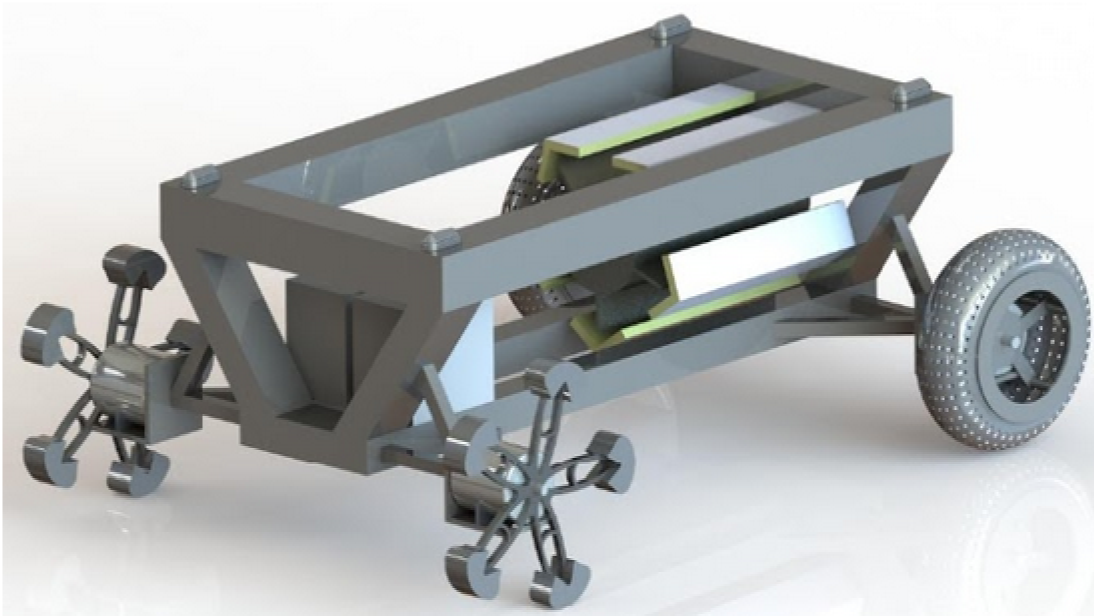


Fig. 17. Concept design rendering combining each of the selected subsystems.

Concept Critique

When determining an overall design for the project, a universal design scorecard was utilized in defining the usability of the product. This method consisted of seven design axioms which were used to calculate the total reliability of the product.

- Equitable Use: The rover is able to make provisions on privacy, security and safety equally amongst all intended users. However, the use of the product may not necessarily be the same for every user.
- Flexibility in Use: The rover will be ambidextrous as well as adaptive to the user's pace. Additionally, it allows for the user to utilize their own accuracy and precision. The downside is that the rover can only be used in a limited amount of ways due to the simple design.
- Simple and Intuitive Use: The rover will have straightforward indicators for users to gauge feedback on its current status and ideally communicate the necessary information to its users. However, there is a chance for the learning curve of the user interface (UI).
- Perceptible Information: The rover will have standard indicators for necessary components such as batteries, radioactive materials, storage as well as additional UI control schematics. This will be implemented in the most streamlined manner possible.

- Tolerance of Error: Failsafe features for the rover include the ability for a user to manually remote control it at any time. Additionally, appropriate warning labels and fixtures will be placed.
- Low Physical Effort: The rover is intended to be used to carry equipment on the moon's surface. Therefore the placement of the storage compartments are to be placed at the most efficient locations. In addition, the rover is autonomous as such, controlling the rover should not be a priority unless the remote control feature is used.
- Size and Space for Approach and Use: The design of the rover allows for most hand-types to easily utilize the product. As the main intent is to transport equipment, spacing is not a concern and clear line of sight for all users to all important elements are accounted for.

With these design constraints in mind, the autonomous rover maintains a satisfactory design that allows all intended users to accomplish their tasks with limited hindrance.

Technical Risk Assessment

The following figure is a table listing many of the potential problems that could occur during normal operation of the vehicle. The primary focus of this analysis is on the system failures and does not include consequences affecting time or cost. This is primarily due to how far into the future this system will actually be implemented, and how a larger organization like NASA operates.

	Risk	Probability	Consequence	Risk Score
Technical				
Risk 1	Battery Failure	1	5	5
Risk 2	Structural Damage	2	4	8
Risk 3	Dust Abrasion	5	3	15
Risk 4	Sensor Malfunction - Dust	4	3	12
Risk 5	Material Fatigue	1	5	5
Risk 6	Thermal Damage - Temperature Extremes	4	4	16
Risk 7	Stuck	2	2	4
Risk 8	Tipping	1	4	4
Risk 9	Software Bug	1	3	3
Risk 10	Signal Loss	1	4	4
Risk 11	Nuclear Failure	1	2	2

Risk Probability					
Almost Certain 5			Risk 3		
Likely 4			Risk 4	Risk 6	
Possible 3					
Unlikely 2		Risk 7		Risk 2	
Almost Never 1		Risk 11	Risk 9	Risk 8 Risk 10	Risk 5 Risk 1
	Negligible	Low	Moderate	High	Extreme
	1	2	3	4	5
				Risk Consequence	

Fig. 18. Technical Risk Assessment based on most common technical challenges.

Project Progress / Alpha Prototype

Moving forward, the winning ideas that were established in the decision matrix will move to the next phase. An initial Bill of Material (BOM) will be created to determine feasibility of producing a prototype. The initial BOM stage will include determining what sensor, motors, and components will be used. Materials and components will be ordered as needed. The winning designs will be further improved based on the iterative design process, and models using SolidWorks will be created. Once models of the designs are created using SolidWorks, analysis will be conducted on the models to determine stresses. Finite element analysis (FEA) will be the primary simulation method of the physical model being used. Using the FEA method will aid in verification and validation of the chosen design. Following stress analysis, drawing packets for each subsystem will be created along with the complete assembly of the chosen design. During the second semester, Senior Design II, the team will be working on a scaled physical prototype of the chosen design. The alpha prototype will implement the ROS software with Q-learning algorithm to develop an autonomous system. The current software being used, ROS, will be further developed and tested implementing an Xbox control and place holder model vehicle. The physical prototype and software will be integrated to produce a scaled version of the chosen design. During testing and implementation of the physical vehicle, the prototype will learn actively as it maneuvers through varying terrain.

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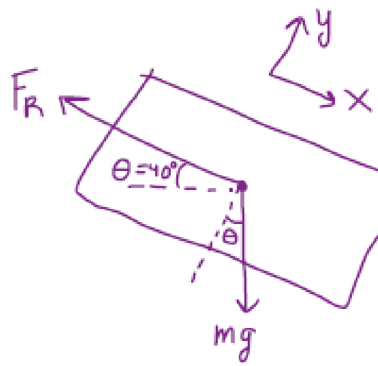
Appendix

1. Subsystem Quick Calculations

Twist-Lock Size Requirement



$g = 1.62\ m/s^2$

$m = 500\,kg$

Ti-6Al-4V (Grade 5) annealed

$\tau_{max} = 550\ MPa$

$\Sigma F_x = 0$

$mg\sin\theta - F_R = 0$

$F_R = mg\sin\theta$

$= 500(1.62)\sin(40)$

$F_R = 520.66\,N$

Total weight the locks must support

Distribute weight between 4 locks

$n = \#$ of locks

$F_L = \frac{F_R}{n} = \frac{520.66\,N}{4}$

$F_L = 130\,N$

force on one individual lock

$\tau_L = \frac{F_L}{A_L} = \frac{F_L}{\frac{\pi}{4}D^2}$

$D = \left(\frac{F_L}{\frac{\pi}{4}\tau_L}\right)^{1/2}$

$= \left[\frac{130\,N}{\frac{\pi}{4}(550\,MPa)}\right]^{1/2}$

$\boxed{D = 5.49 \times 10^{-4}\,m}$

min Ø required for each twist lock

Fig. 13. Twist Lock Required-Diameter Calculations

2. Subsystem Design Matrices

Suspension Decision Matrix								
Design Alternatives	Scale 0 = worst 5 = Best							Overall Score
	Design Objectives (criteria)							
	Minimum Requirements				Bonuses			
	Max Angle of Inclination	Feasibility	Cost Effective (Estimated)	Lifetime	Modularity	Ability to Carry Cargo Smoothly	Terrain Mobility	
Importance	3	3	2	5	2	4	5	
Rocker-bogie	4	4	3	5	5	5	4	105
Fixed	3	5	5	3	5	2	2	77
Active Suspension	4	3	3	4	4	5	4	95
Passive Suspension	3	4	4	4	5	4	3	90
Criteria Definition:								
Max Angle of Inclination	*Can ascend steep slopes of incline*							
Feasibility	*The design is simple enough where it can be reasonably accomplished*							
Cost Effective (Estimated)	*Cost effectiveness correlates to cheaper manufacturability and maintenance*							
Lifetime	*What is the expected time that the suspension will be able to operate without maintenance*							
Modularity	*How easy is the design to implement across a variety of different body types*							
Ability to Carry Cargo Smoothly	*Ability to carry delicate equipment safely through uneven terrain*							
Terrain Mobility	*Ability to maneuver across a variety of obstacles without getting stuck or having to avoid it*							

Fig. 14. Suspension Decision Matrix

Wheels Decision Matrix						
Design Alternatives	Scale 0 = worst 5 = Best					Overall Score
	Design Objectives (criteria)					
	Max Angle of Inclination	Lifetime/durability	Modularity	Soft Terrain Performance	Obstacle Clearance	
Importance	4	5	2	3	2	
Hybrid-legged (wheg)	5	4	4	4	5	70
Rover style	4	4	5	4	3	64
Wire mesh	4	5	4	5	4	72
Criteria Definition:						
Max Angle of Inclination	*Can ascend steep slopes of incline*					
Lifetime/durability	*Ability for long term, stable use*					
Modularity	*Ease of application on already developed manufacturing techniques*					
Terrain Mobility	*Ability to traverse more intense lunar surfaces such as rocks and loose soil*					
Obstacle Clearance	*Ability to clear a variety of obstacles*					

Fig. 15. Wheels Decision Matrix

Drivetrain Decision Matrix							
Design Alternatives	Scale 0 = worst 5 = Best						Overall Score
	Design Objectives (criteria)						
	Turning Ability	Ease of Construction	Cost Effective (Estimated)	Lifespan/ Durability	Simplicity	Power Efficiency	
Importance	2	3	3	4	2	5	
Individual Motors for each wheel	4	4	3	4	4	3	68
Singular Motor System	3	2	3	1	2	4	49
2-D rotating wheels	5	2	1	3	2	2	45
Criteria Definition:							
Turning Ability	*Ability for long term financial feasibility*						
Ease of Construction	*Ability to produce repeatedly*						
Cost Effective (Estimated)	*Want by consumers and the general public*						
Lifespan/ Durability	*Ability for long term, stable use*						
Simplicity	*Ease of application on already developed manufacturing techniques*						
Power Efficiency	*How conservative is the design with regards to power consumption*						

Fig. 16. Drivetrain Decision Matrix

Latching System Decision Matrix						
Design Alternatives	Scale 0 = worst 5 = Best					Overall Score
	Design Objectives (criteria)					
	Strength	Lifetime/durability	Ease of use	Interchangeability	Safety	
Importance	3	5	5	3	5	
Gate Mechanism	4	3	4	3	3	71
Turn locks	5	4	4	4	4	87
Button release	4	3	3	4	4	74
Criteria Definition:						
Strength	*Can it support the required load?*					
Lifetime/durability	*Can it handle loading and off-loading a crate many times over its lifecycle?*					
Ease of use	*Can an astronaut use this with little to no trouble?*					
Interchangeability	*Does it fit on multiple body types?*					
Safety	*What might its estimated margin of safety be?*					

Fig. 17. Latching System Decision Matrix

Power Decision Matrix						
Design Alternatives	Scale 0 = worst 5 = Best					Overall Score
	Design Objectives (criteria)					
	Light Weight	Reliability/ Robustness	Long Lifetime	Cost Effective (Estimated)	High Safety	
Importance	3	5	3	4	5	
(Hydrogen) Charging station battery	2	5	2	4	5	78
Solar power with battery power	2	3	3	4	5	71
Nuclear	4	4	4	1	3	63
H Fuel based	3	5	3	2	4	71
Nuclear with Batteries	2	5	5	3	4	78
Criteria Definition:						
Light Weight	*Ability for long term financial feasibility*					
Reliability/ Robustness	*Ability to produce repeatedly*					
Long Lifetime	*Want by consumers and the general public*					
Cost Effective (Estimated)	*Cost effectiveness correlates to cheaper manufacturability and maintenance*					
High Safety	*Ease of application on already developed manufacturing techniques*					

Fig. 18. Power Decision Matrix