ENAE788X COURAGE Rover

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1 Project Description and Requirements

1.1 Project Description and Motivation

Perform a detailed design of a BioBot rover, emphasizing mobility systems, chassis systems (e.g., wheels, steering, suspension. . .), support systems (e.g., energy storage), navigation and guidance system (e.g., sensors, algorithms...). The system must be designed for the Moon, then evaluated for Mars and conversion to an Earth analogue rover.

1.2 Requirements: Performance

The rover must be capable of a maximum operating speed of at least 4 m/sec on level, flat terrain. It must be able to accommodate a 0.3 meter obstacle at minimal velocity, a 0.1 m obstacle at a velocity of 2.5 m/sec, and/or a 20° slope in any direction at a speed of at least 1 m/sec, including the ability to start and stop. A nominal sortie has a range of 54 km at an average speed of 2.5 m/sec.

1.3 Requirements: Payload

The rover must be capable of carrying one 170 kg EVA crew and 80 kg of assorted payload (modeled as a 0.25 m box). The rover must also be capable of carrying a second 170 kg EVA crew in a contingency situation. The design should incorporate roll-over protection for the crew and all required ingress/egress aids and crew restraints.

1.4 Requirements: Operations

A nominal sortie shall be at least eight hours long. Two rovers must be launched on a single CLPS lander; A single rover shall have a mass $\leq$250 kg. The rover(s) must be capable of operating indefinitely without crew present; it must be capable of being controlled directly, remotely, or operate autonomously. It must be capable of following an astronaut, astronaut's path, or autonomous path planning between waypoints, and capable of operating during any portion of the lunar day/night cycle and at any latitude.

2 Terramechanics

From the Terramechanics Lecutres [1] [2] [3] and the equations given below, we perform trade studies between rovers with 4 wheels and 6 wheels to analyze and deduce the width, diameter of our rover for a positive drawbar pull.

Compression Resistance

$$R_c = \left(\frac{k_c + bk_\phi}{n+1}\right) z^{n+1} \tag{2.1}$$

Bulldozing Resistance

$$R_b = \frac{b\sin(\alpha+\phi)}{2\sin\alpha\cos\phi}(2zcK_c + \gamma z^2 K_\gamma) + \frac{l_o^3\gamma}{3}\left(\frac{\pi}{2} - \phi\right) + cl_o^2\left[1 + \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right)\right] \tag{2.2}$$

Gravitation Resistance

$$R_g = W_v \sin\theta_{slope} \tag{2.3}$$

Rolling Resistance

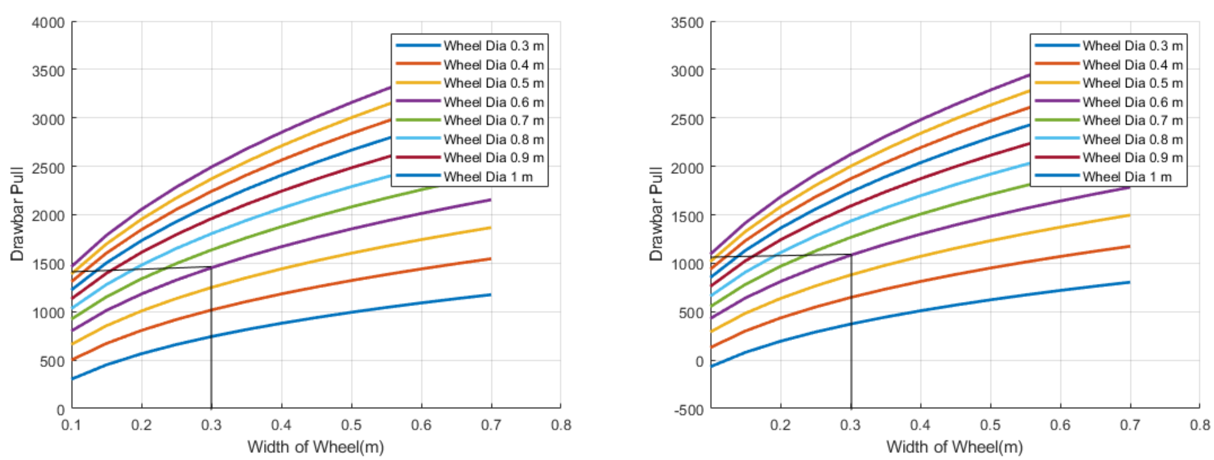
$$R_r = W_{tot}\, c_f \tag{2.4}$$

Tractive Force

$$H = \left[blc_0\left(1 + \frac{2h}{b}\right)N_g + W_w \tan\phi\left(1 + 0.64\frac{h}{b}\ \tan^{-1}\frac{b}{h}\right)\right]\left[1 - \frac{K_{shear}}{sl}\left(1 - e^{\frac{-sl}{K_{shear}}}\right)\right] \tag{2.5}$$

Drawbar pull:

$$DP = N_w H - (N_w R_c + N_w R_b + R_g + R_r) \tag{2.6}$$



(a) Flat

(b) 20° Slope

Figure 1: Drawbar pull with Grousers w.r.t. Width and Diameter of the Wheel - 4 Wheels

From the above trade studies performed between 4 wheels and 6 wheels (depicted in the presentation) for diameter, width of wheels against drawbar pull, number of grousers and height of grousers; we have have chosen the following values:

- Number of wheels (N) - 4
- Diameter of wheel (d) - 0.6 m
- Width of wheel (w) - 0.3 m
- Number of grousers - 20
- Height of grousers - 2 cm

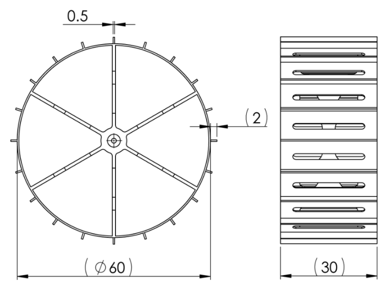


Figure 2: Wheel Drawing with dimensions

3 Stability

For our selected rover with 4 wheels we find its stability on both flat terrain and a slope of 20 ° in both the cases: Non-Extended and Extended.

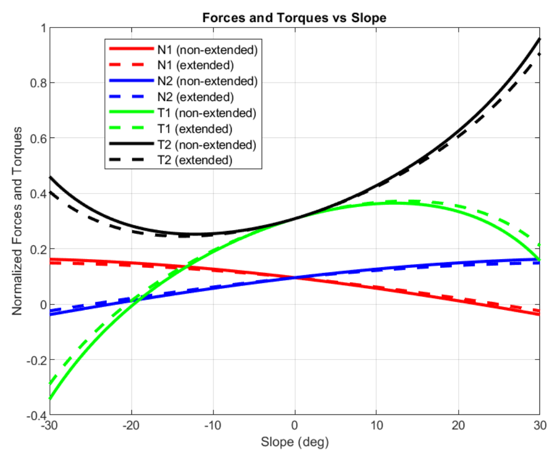
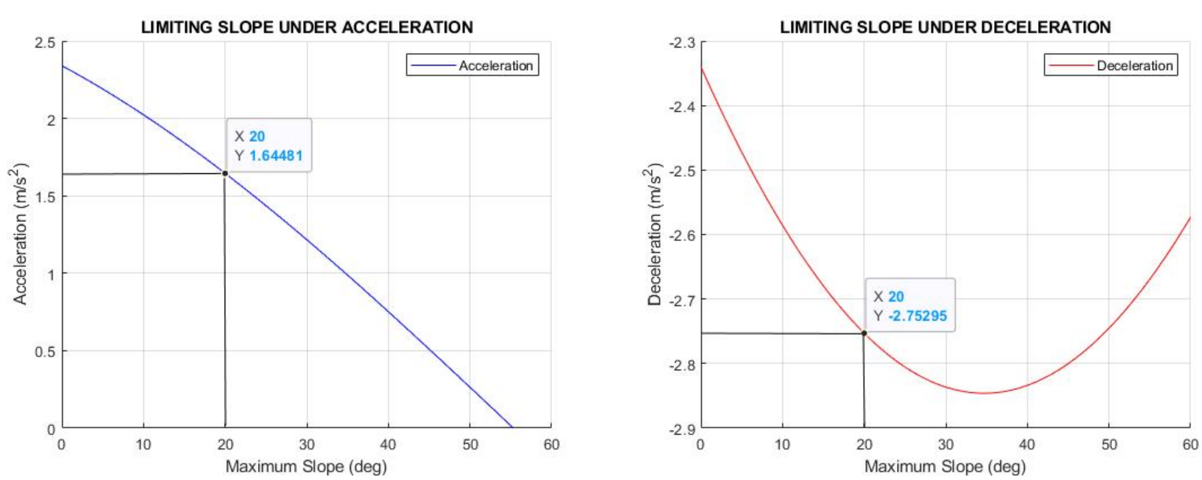


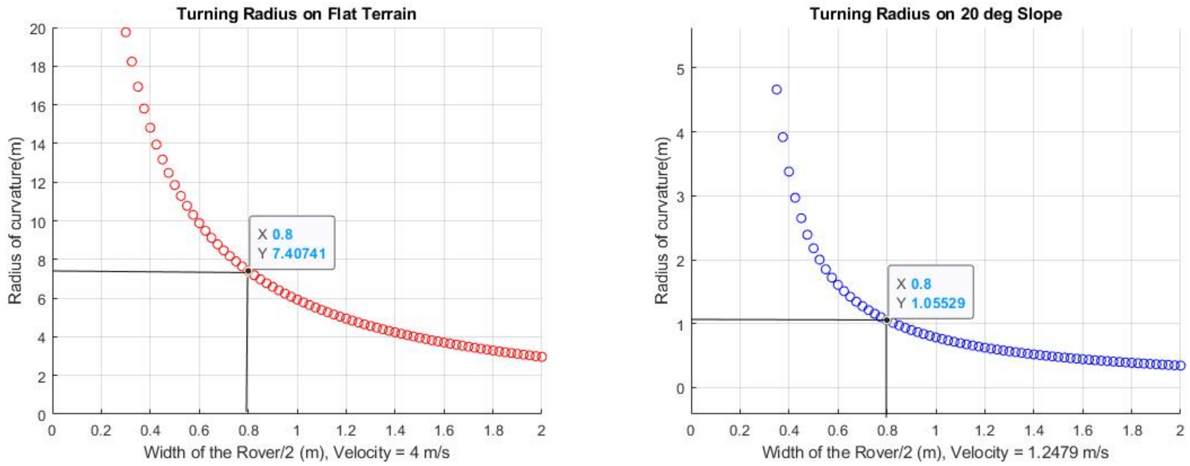
Figure 3: Normal forces and torque vs Slope



(a) Acceleration

(b) Deceleration

Figure 4: Limiting acceleration and deceleration on slope



(a) Flat Terrain (b) 20° Slope

Figure 5: Turning Stability

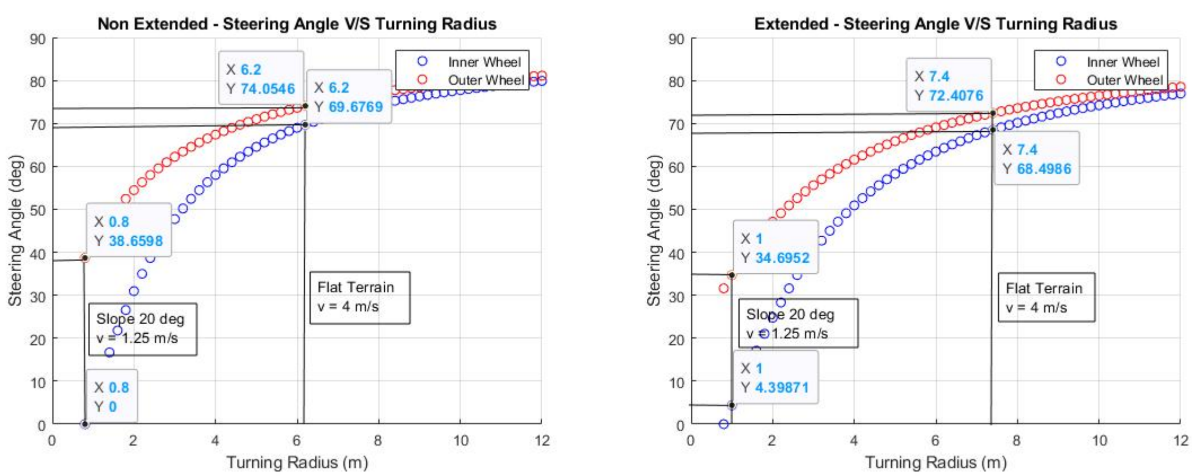
From the figures displayed above, we deduce the following results for both the states of our rover design: Non-Extended and Extended.

Dimension	**Non-Extended** (500 kg)	**Extended** (670 kg)
Length of rover (l)	2 m	2.6 m
Width of rover (c)	1.6 m	1.6 m
Height of CoM (h)	0.5 m	0.6 m
Length between front axle and CoM (a)	1 m	1.3 m
Max Acceleration [Flat]	2.025 m/s^2	2.34 m/s^2
Max Acceleration [20° Slope]	1.3488 m/s^2	1.6481 m/s^2
Max Decceleration [Flat]	2.025 m/s^2	2.34 m/s^2
Max Decceleration [20° Slope]	2.45695 m/s^2	2.75295 m/s^2

Table 1: Table of key rover dimensions in both the non-extended and extended cases

4 Steering

The front two wheels are direct steered, each with steering motor. The rear two wheels are fixed to the chassis. You can view a video of the front wheels moving through their range of motion at `https://youtu.be/GnRjyFgl60c`. Please see Slide 153 for additional graphs related to steering. From the values obtained for the radius of curvature of the rover in Non-Extended and Extended states for the cases: Flat terrain and slope of 20°, we obtain the values for the steering angle required by each wheel (outer and inner) while undergoing a turn. This is depicted in the figures below:



(a) Non-Extended (b) Extended

Figure 6: Steering Angle v/s Turning Radius

5 Suspension

The suspension system we have chosen is known as a double wishbone suspension. This type of suspension is often used in commercial vehicles. The system has a main bracket that connects either to the steering motors in the case of the front wheels or directly to the chassis for the rear wheels. From this bracket there is a top wishbone and bottom wishbone each mounted on pivots. A spring lies between the wishbones that returns the system back to a neutral position. The other two ends of the wishbone connect to our drive motor bracket which it turn connects to the wheel. Figure 7 shows the major components. The main benefit of this type of suspension is that there is very little wheel camber relative to wheel motion. In other words the wheel should stay mostly perpendicular to the chassis throughout the range of motion. See a video of our suspension in action.

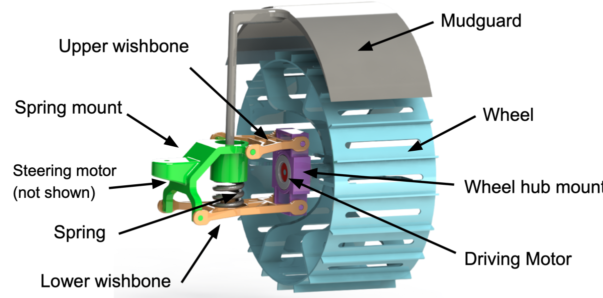


Figure 7: Diagram of suspension system

5.1 Independent Suspension Calculations

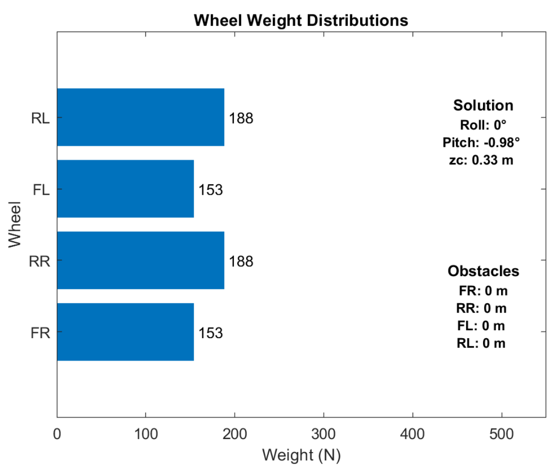
Following the steps for independent suspension calculations [4], we can determine the force on each of the wheels. The error for the three constrain equations below are minimized to find the roll, pitch, and z offset of the rover. These constraint equations ensure that the error for the sum of the forces and moments are close to zero. These values can be applied to our rover transforms to find the height of each wheel offset from the base frame of the rover. For our calculations we set the COM offsets for both the standard configuration and the extended configuration then use MATLAB's vpasolve to numerically solve the equations.

$$\sum_{1}^{\text{n wheels}} F_{spr(i)} = W_v \tag{5.1}$$

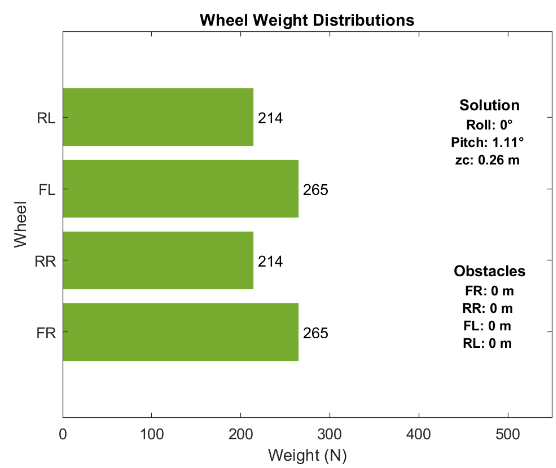
$$\sum_{1}^{\text{n wheels}} F_{spr(i)} x_{w(i)} + W_v x_{cg} = 0 \tag{5.2}$$

$$\sum_{1}^{\text{n wheels}} F_{spr(i)} y_{w(i)} + W_v y_{cg} = 0 \tag{5.3}$$

The results of the equations on flat ground in both the extended and standard case are shown in Figure 8. Other configurations with wheels on different obstacles can be seen in our slides.



(a) Standard Configuration



(b) Extended Configuration

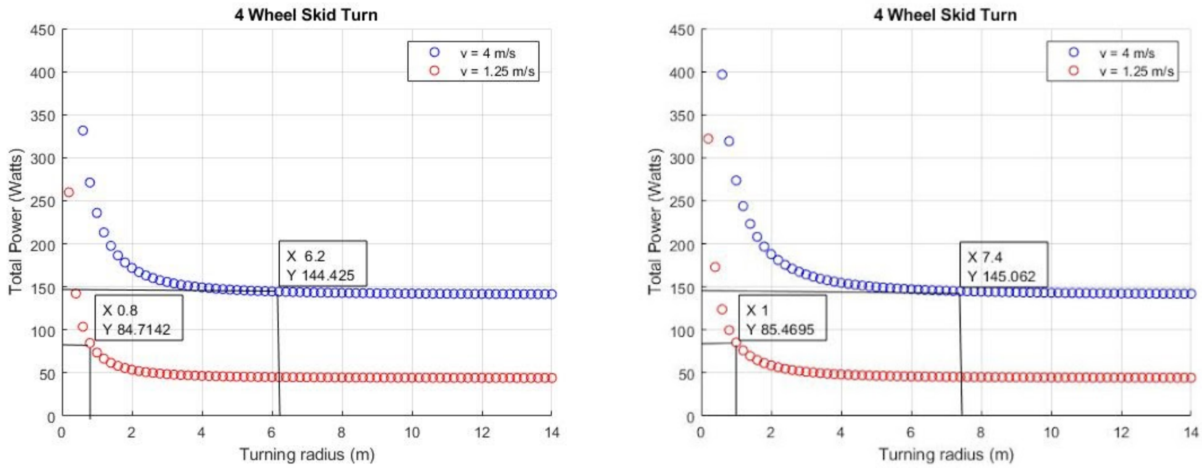
Figure 8: Independent Suspension Results

6 Motors

There are two types of motors required for this rover design - steering motors and driving motors. Motors to be used were chosen depending upon the requirements of steering motor and driving motor.

6.1 Steering Motor Requirements

Using the turning radius value for non-extended and extended configuration,the power required to steer the rover was calculated. Fig 9 shows that the rover requires a steering motor with output power $\sim$ 160 Watts to steer the rover either in non-extended or extended configuration.

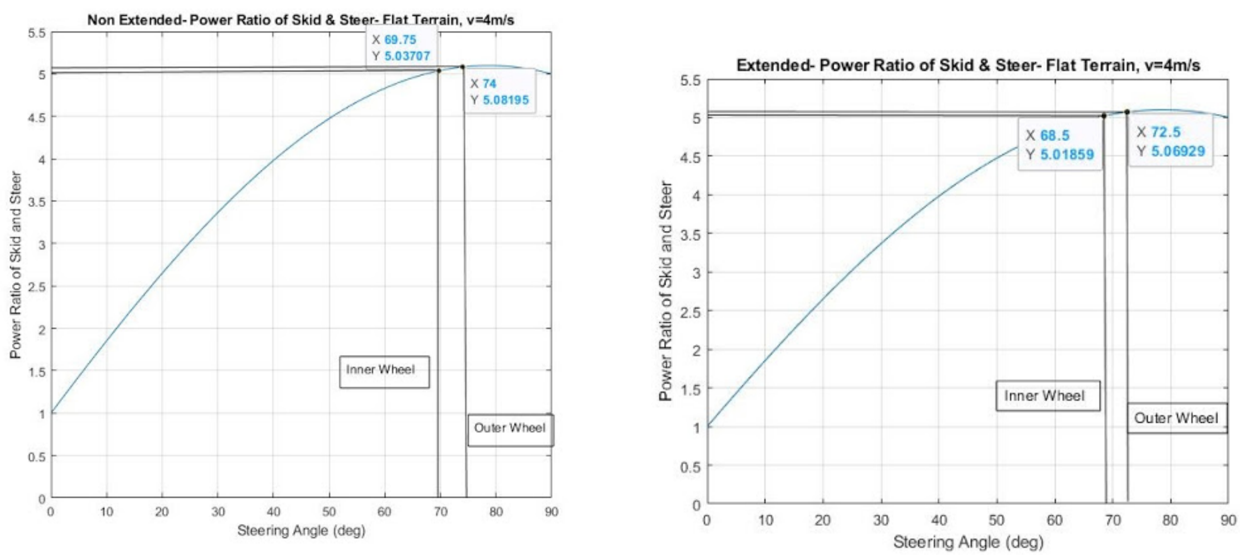


(a) Non-Extended

(b) Extended

Figure 9: Power requirements for steering

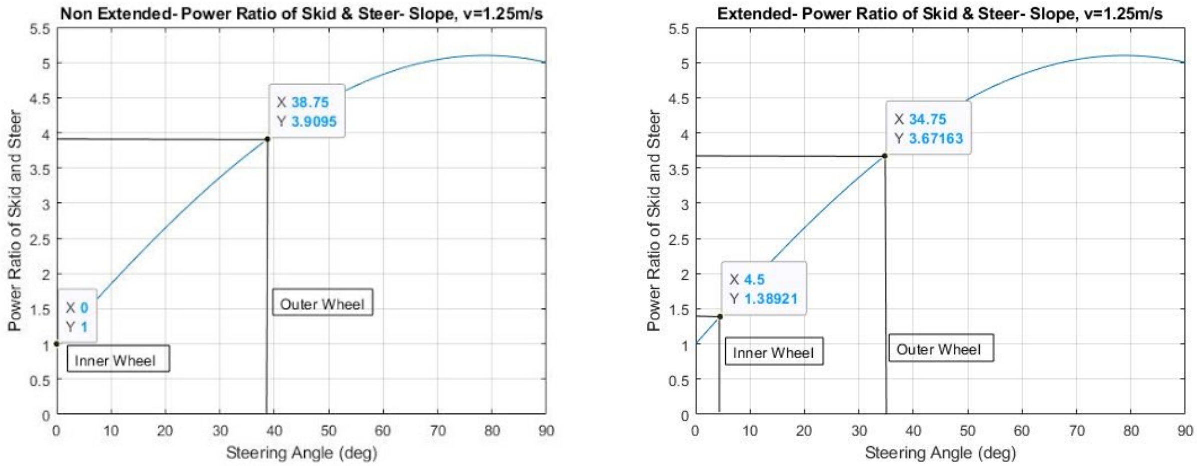
The power ratio for steering of the rover on both flat terrain and 20° slope was also calculated using the values from steering angle calculations.



(a) Non-Extended

(b) Extended

Figure 10: Power ratio for steering on flat terrain

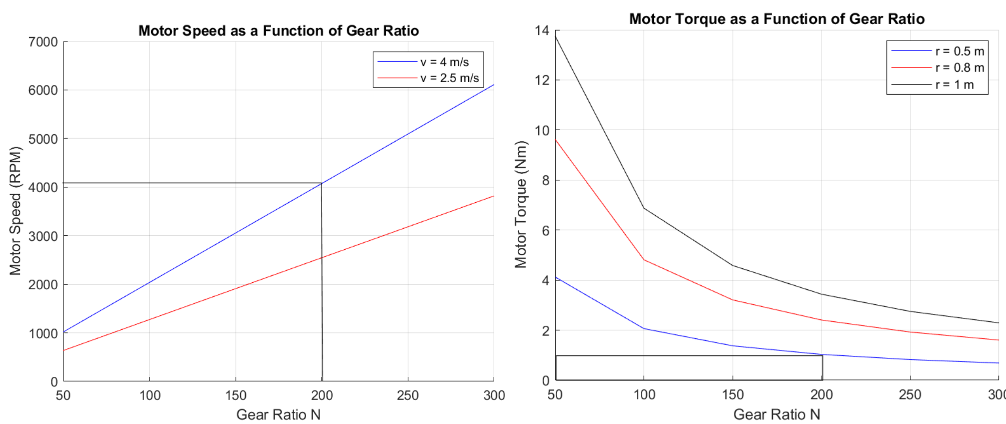


(a) Non-Extended (b) Extended

Figure 11: Power ratio for steering on 20° slope

6.2 Driving Motor Requirements

The driving motor needs to have sufficient torque as well as speed so as to turn the wheels. Fig 12 shows the speed and torque required for particular gear ratios. The gear ratio was taken to be 200 to get the driving motor requirements. The driving motor requires a speed $\sim$ 4000 rpm to satisfy both the speed conditions and a torque $\sim$ 1 N-m.



(a) Motor Speed vs Gear ratio (b) Motor Torque vs Gear ratio

Figure 12: Driving motor requirements

6.3 Motor Selection

Brushless DC motors were chosen as they require low maintenance and have long lifespan as well as high efficiency. A motor from RBE(H) 01212 series was chosen for both driving and steering motor as it satisfies all the power, torque and speed requirements.

7 Sensors, Perception, and Computing

The rover needs to be operable autonomously, so it needs sufficient proprioceptive and exteroceptive sensors and computational power to understand it's environment.

7.1 Lighting

Without an atmosphere to reflect ambient light, the lunar surface is dark and shadowy. Proper illumination will be important for the astronauts to work and for the rover's vision systems to function in a useful way. We've equipped the rover with four 35,000 lumen LED floodlights for illumination. LED floodlights have terrific energy efficiency (especially when compared to incandescent or halogen) and provide excellent brightness for very little weight. By far, most of the weight of the floodlight assembly is the plastic/glass/metal housing, and the LEDs themselves contribute negligibly.

7.2 LiDAR

The rover will be equipped with 4 Velodyne Puck LITEs for complete LiDAR coverage. The Puck LITE was chosen (instead of the Ultra Puck or Alpha Puck) for it's lower weight. The rover is one of just a few vehicles on the moon (as compared to hundreds of vehicles in the immediate vicinity of a car on an Earth highway) and therefore doesn't need the superior response time or resolution of these higher end pucks. The Puck LITE still provides an impressive 100m range, 30° vertical field of view, and 3cm accuracy [5].

7.3 Cameras

A comprehensive vision system will be valuable for autonomous rover operation, as well as more detailed science (especially science/operation conducted remotely from Earth). Camera quality has improved dramatically since the 1960s, and we can now supplement our rover with a number of very high quality cameras with little financial, power, or weight cost. We've selected 7 Earth-analog cameras which (when modified for a space environment) would be excellent for the rover system. We start with two Sony 4K BRC-x400 Pan Tilt Zoom (PTZ) cameras, each weighing 1.8kg and requiring 25W (max). The 3 degrees of freedom in these cameras make them very useful for exploring an environment.
Stereo cameras, in which two cameras side by side can provide binocular depth perception, are useful for both visual perception and depth. These supplement the Velodyne LiDAR pucks' ability to understand the geometry of the nearby environment, adding both additional information and failure-proofing redundancy into the system. Intel makes several stereo vision cameras, including the RealSense D455, which boasts a depth range from 0.4m to 20m.

The cameras listed above can only look in one direction at once. While there may be some overlap in their potential coverage, it will also be helpful to have a camera with an unobscured 360° view of the surroundings. The GoPro Max is incredibly compact, lightweight, and offers 6K video recording capabilities of the entire environment via two opposing wide angle cameras. The addition of this (or a comparable) camera ensures that the rover will have no blind spots and will be able to operate fully autonomously. This camera may also be useful for remote operation or remote troubleshooting.

To enable the rover to track the astronaut, each astronaut's EVA suit would be augmented with retro reflectors and fiducial markers (like April tags), which would be clearly visible to the cameras. Additional tracking features like ultra wide band triangulation or motion capture bulbs may also be implemented.

7.4 Motion Sensors

The rover will have encoders on each wheel as well as several multi-axis inertial measurement units (IMUs) on board to fully understand it's pose and how it has traveled. These will serve in feedback loops for the driving controllers to help ensure the rover drives to exactly where it intends to go. The exact details of these sensing systems depend tremendously on the detailed specifications of the entire rover as well as the control schema, the later of which is out of scope for this project.

7.5 Computing

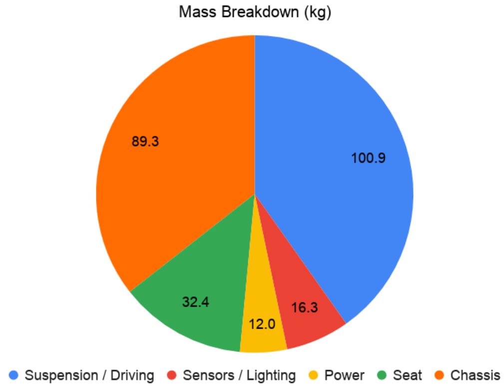
Autonomous path planning and full utilization of LiDAR + cameras requires non-trivial computing power, certainly more than we've sent to the Moon (or Mars) previously. Modern laptops are fairly capable, and it's possible that a very high end laptop would have sufficient computational power (and speed) to be useful in this scenario. In a slightly larger (and much more power hungry) form factor, a gaming desktop computer with a dedicated GPU, more RAM, and 8+ CPUs is certainly a capable solution to this task. The winning trade off between electrical power and computational capability would depend on the available power, weight, and needs of the system. We assumed that a high end laptop (minus the screen) would be viable for this project (1kg, 61W).

7.6 Communication

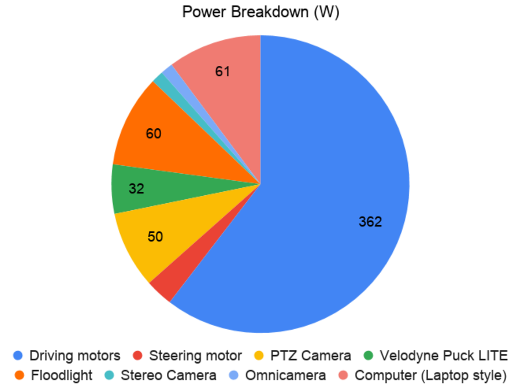
The idea of a several 8 hour sorties implies that there will be an established habitat ("Hab") on the moon prior to the arrival of the rover or astronauts. We assume the Hab is well equipped with sufficient radio equipment to communicate with Earth at an excellent speed duplex. The rover only needs to be capable of communicating with the Hab, which would then relay any Earth bound communications in that direction. The rover has a specified driving range of 54km. Assuming the astronauts have to be in the Hab at the end of the sortie, the furthest they can drive is 27km (half of 54km out, and the other half back). Modern smart phones communicate wirelessly over a range of cellular data protocols, most of which are fairly long range and high bandwidth. The smart phone requires very little mass or power to engage in these communications. It's not hard to imagine that a Hab equipped with comparable cell tower technology could communicate with the rover in a similar way, and that the requisite communication apparatus in the rover would be negligibly small in mass and power. We'll roll these communication mechanisms into the on-board computer.

8 Mass and Power

The Hab must be equipped with it's own power supply (nuclear or solar, likely). The rover only needs to carry enough power for an 8 hour day of use, and can be recharged overnight by the Hab.



(a) Mass Breakdown



(b) Power Breakdown

Figure 13: Mass and Power Charts

9 Final Design

9.1 Overview

The chassis is comprised of a series of titanium beams in 8020's 45-4545 Lite beam profile for an excellent strength to weight ratio. For a detailed breakdown of the rover's subassemblies, please see our slides.

9.2 Non-extended Configuration

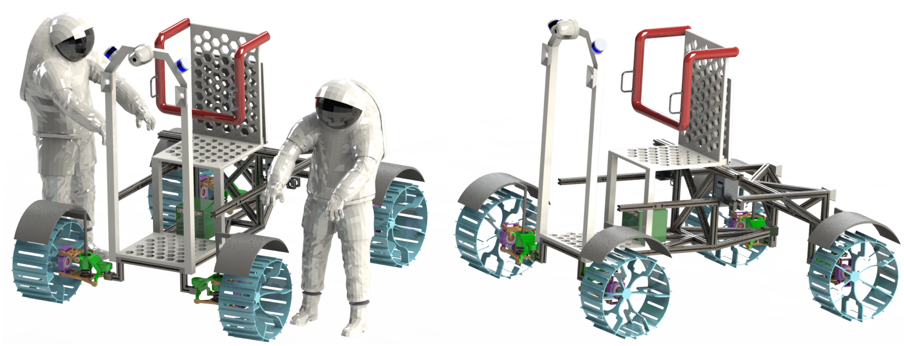


Figure 14: Two views of the final rover in its normal use (unextended) configuration

9.3 Extended Configuration

In the contingency case, the rover chassis can extend to permit more room for the 2nd astronaut. This extension helps maintain a center of mass that is centered on the vehicle (front/back) with the addition of the 2nd passenger. You can view an animation of the extension mechanism at `https://youtu.be/2NqaSqYTE7E`. The extension mechanism is mounted on a pivot, which allows for the rear wheels to not be coplanar with the rest of the rover (ex: when exiting a hill). Two locking and hitchpins on each side of the rover secure the rear chassis to this mechanism.

The 2nd seat has a traditional 3 point fabric seat restraint to secure the 2nd astronaut. This was done to reduce weight and eliminate the complexity of two roller coaster style restraint bars.

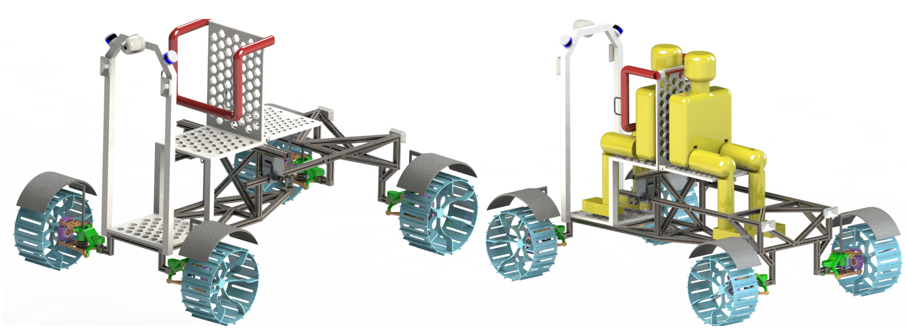


Figure 15: Two views of the final rover in its contingency use (extended) configuration

9.4 Specifications

Mass: 250.96kg
Power: 599 W
Driving Time: 8 hours assuming a 50% duty cycle for the drive motors.
Payload: one 80kg life support package, two 170kg astronauts
Max Speed: 4 m/s
Max Obstacle Size: 0.3m
Max Slope: 20 deg
Driving Modes: Autonomous [Drive to Destination], Autonomous [Follow Astronaut], Manual

9.5 Ingress and Egress

To enter the rover, the astronaut simply stands on the seat foot rest and easily climbs into the vehicle. Once seated, the seat restraint can be lowered and locked in place to secure the astronaut.

9.6 Trafficability

Our trafficability analysis shows very little change in the position of the center of mass regardless of the configuration, orientation, or position of the rover on an obstacle(s). For detailed renders of the rover in different obstacle configurations, please see our slides.

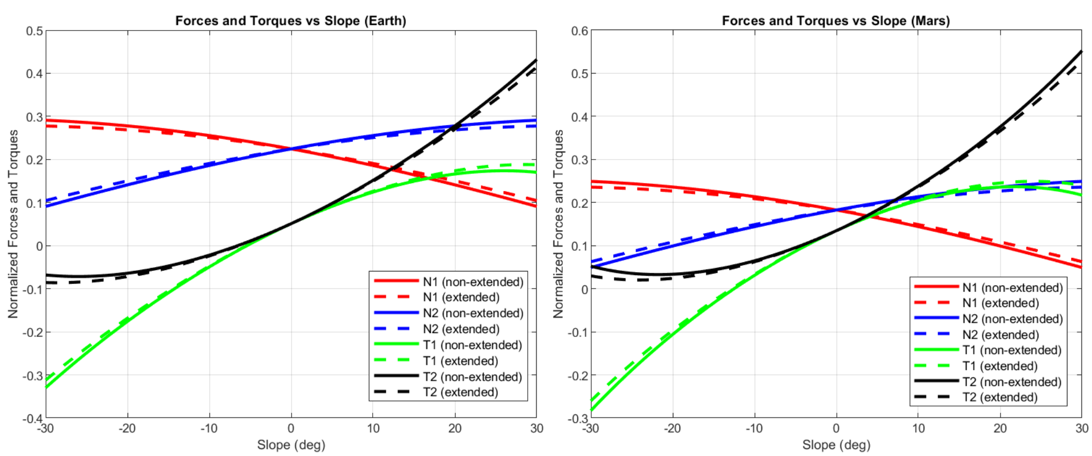
9.7 Earth and Mars Efficacy

The validity of rover design was also checked for Earth and Mars environment. The rover design can be said valid for any environment if the rover satisfies the following conditions.

- The rover wheels have sufficient traction power to get the rover moving. This can be easily determined from the drawbar pull force using the soil characteristic properties.

- The configurations of rover is stable in that particular environment. The stability calculations can determine the validity of static and dynamic stability of the rover.

Using soil characteristics for Earth and Mars [1] and assuming shear deformation modulus to be same as Moon, the drawbar pull of the wheels on both Earth and Mars was calculated. The drawbar pull of the rover on Earth was 6154.99 N and on Mars was 968.26 N for sandy loam soil and 7713.51 N for slope soil.
In Figure 16a, the stability calculations of the rover in non-extended and extended configuration on Earth shows that the rover is static stable as well as can travel uphill at an angle over 30° and downhill at an angle less than 10°.



(a) Stability on Earth

(b) Stability on Mars

Figure 16: Stability on Earth and Mars

In Figure 16b, the stability calculations of the rover in non-extended and extended configuration on Mars shows that the rover is static stable as well as can travel uphill at an angle over 30° and downhill at an angle more than 10°.

The values from the drawbar pull calculation and the stability calculations lead to the conclusion that both non-extended and extended configuration of the rover design is valid for Earth and Mars environment.

10 Concepts Explored and Design Evolution

3. "Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.
4. Your best design efforts will inevitably wind up being useless in the final design."
-Akin's Laws of Spacecraft Design

10.1 Inspirational Designs

We explored a number of inspirational concepts early in the design phase. Briefly, these included vehicles with very large wheels (a Lunar "Monster Truck"), high speed vehicles with treads big wheels, systems with high DoF suspension/leg articulation, and vehicles with treads assemblies instead of wheels. While our final design borrows little from these concepts, we still believe many of them still have merit and are worth further investigation.

10.2 Mk1 Rover

The Mk1 rover was a preliminary layout prototype. It draws heavily from the Apollo LRV, and features 4 wheels with individual suspension. This design incorporates a sensor arch, on which LiDAR, lights, and cameras are mounted, as well as our roller coaster style seat restraint, both of which were incorporated in our final design. This system also demonstrates an umbilical management system (at the front of the vehicle) which is mounted on a rotating platform to always face the astronaut. There are many similarities between this design and our final design in terms of general structure and layout. However, this design was poorly sized (both too long and too wide) and doesn't easily accommodate a second astronaut. In this configuration, one option for a second astronaut was to have the seat (on both rovers) be mounted on a track. In the contingency case, the seat on the first rover would slide sideways, and the seat from the second rover could be detached and added to the first. However, in an emergency situation, this amount of rover reconfiguration is highly impractical, especially if the seats are heavy.

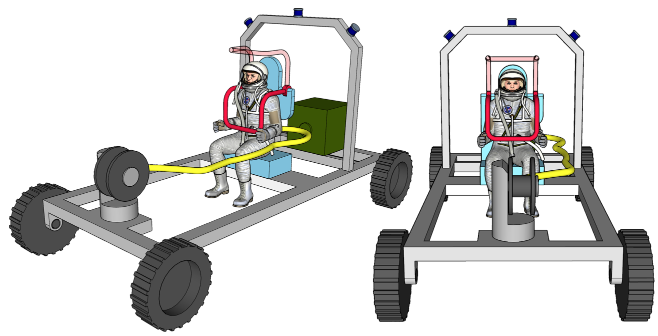


Figure 17: Concept sketch of the Mk1 Rover Design

10.3 Horsebot

After the midterm presentation, we pivoted away from a traditional car inspired rover and began looking at more novel, bio-inspired concepts. The Horsebot was our next major design concept. It's (as the name implies) a horse inspired design with four 4 DoF legs (there is an additional hip rotation joint that is not shown in Figure 18). The green box is our 80kg life support payload (0.25m on a side). There is a fold down seat in the rear of the vehicle to acomodate the second astronaut in the contingency situation.

10.3.1 Pros

There were a number of benefits to this idea that made it appealing. The tall legged locomotion easily clears any obstacle, and works well on rugged/uneven terrain. The hip joint has an additional 360° hip rotation joint (not shown) which allows Horsebot to walk sideways (or at any arbitrary angle) with its standard ("forward") gait. The incorporation of a second, fold down seat makes it easy to incorporate a second astronaut (this fold down seat is one element of this design that was kept for the final design). The integrated primary seat is strategically positioned to maintain a relatively low center of mass, which is great for stability. (A more directly horse inspired design would have the rider atop the vehicle; much higher up). Ingress and egress in this design are very easy. The right side of the vehicle is open to allow the astronaut to enter with ease, and the entire system can "kneel" (lower itself closer to the ground) to allow the astronaut to simply step onto the foot rest (level with or close to the ground)

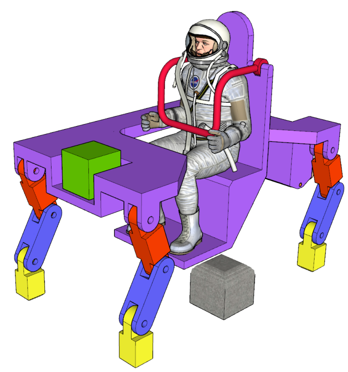


Figure 18: Concept sketch of the Horsebot Design

10.3.2 Cons

While there are several legged locomotion robots (ex: Cheetah, Spot, ANYmal) in various stages of development, we do not yet have a robotic horse analog on Earth. Robotic legged locomotion with a human passenger is not a well tested concept, and should be proven feasible on Earth first before it is attempted on the Moon.
By their nature, legs are more complex than wheels (ignoring suspension) and therefore offer more avenues for failure. Unlike a wheeled vehicle, which requires 2 motors per wheel (driving and steering), this Horsebot design requires 4+ actuators per leg (for 16+ actuators), which significantly increases the total weight of the system and it's required power. Additional Degrees of Freedom, such as one for hip abduction and another for ankle pronation, might be required for walking on slopes.
The project details require that the rover be capable of a max speed of 4m/s. This speed would require a medium trot or a slow gallop gait, which are only dynamically stable. Trot/Gallop gaits require much faster and higher torque motors, which then drive up the weight and power. An Earth gallop gait is likely not directly reproducible in the 1/6th gravity of the moon.

10.4 Wheeled Horse

The wheeled horse concept is similar to the Horsebot shown in Section 10.3, but includes wheels (mounted on either the ankles or knees) for a reconfigurable driving configuration. Obstacle avoidance would be done at slow speeds with a walking gait, while normal (higher speed) travel on smooth ground would be done with the wheels. This reduces the need for high speed/torque motors for a gallop/trot gait, but requires an additional motor for each wheel. The leg motors act as electromechanical suspension in driving mode. The added complexity and weight of the wheels and their driving motors makes this idea less practical than either a traditional wheeled rover or the original Horsebot.

10.5 Strandbeest

While exploring options for legged locomotion, we briefly evaluated a series of designs inspired by Theo Jansen's Strandbeests and other similar designs. These designs allow for complex leg articulation with very few motors, and can be made to be fairly lightweight. However, the legs have very high mechanical complexity, which offers many different failure modes. Many of these designs are well tested on sand, but few (if any) are well tested on rugged/uneven terrain, and they are largely incompatible with stair climbing due to their leg lengths.

10.6 6 Wheels with Extendable Chassis

This concept involves a 6 wheel rover with two possible configurations. In the normal driving mode, the rear 4 wheels are close together and act as tandem wheels. In the contingency configuration, the chassis extends to provide a longer base so the shifted center of mass (due to the second astronaut) is still centered (front/back) on the rover. In its original implementation, this extension would be actuated via a hand crank which turned a pinion to move the rack (the extender). Subsequent iterations on this design used two extending beams (as shown in Figure 19) for improved stability, as well as an additional pivot (orange, in Figure 19), allowing for the rear wheels to not be coplanar with the rest of the rover (ex: exiting a hill). A later design iteration abandons the crank and rack/pinion and uses the wheels driving in opposite directions to separate the two chassis halves.

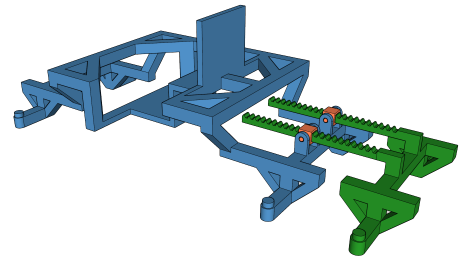


Figure 19: Concept sketch showing the 6 wheeled rover (wheels not shown) with a pivot (orange) rack and pinion (green) extender mechanism

10.7 6 Wheels, Chassis Arch

This was one of more recent design iterations, and the among the first to be realized in SolidWorks. Much of this assembly (nearly everything except the chassis) was reused in all subsequent designs. This was the first design to incorporate an 8020 extrusion profile for the chassis structure. Originally modeled with an aluminum 45-9090 beam, the chassis was later switched to a titanium 45-4545 Lite beam profile for greatly improved weight reduction at the cost of a small bit of structural rigidity. See this design in the slides.

10.8 4 Wheels, Chassis Arch

The middle two wheels in the 6 wheel design were excluded from our stability calculations (as well as other evaluations) and we realized that these two wheels contributed little except additional driving power and structural stability. Evaluating a 4 wheel rover proved much simpler than trying to evaluate a 6 wheel rover, and the middle two wheels (and entire middle chassis assembly) were discarded. See this design in the slides.

10.9 4 Wheels, Flat Chassis - Final

The chassis arches were designed to get the rover body higher off the ground so that it wouldn't catch on obstacles. However, our wheel design places the wheel hub 0.3m above the ground, so any chassis flush with or slightly above the wheel axles would satisfy this obstacle avoidance requirement. This next iteration of the design focuses on a much flatter chassis for simplicity and strength. This would become our final design, with additional braces and structural reinforcement for improved rigidity and strength. See a preliminary sketch model of this design in our slides.

Appendices

A Future Work

With additional time and resources, there are a number of additional design improvements that we'd like to explore.

Suspension: While we believe our suspension system (as designed) satisfies the project requirements, having a larger, more robust suspension would empower the rover to handle larger obstacles and more uneven terrain.
Extender Beam Safety: The pivot aspect of the rear chassis extender mechanism poses a nontrivial safety risk. The potentially rapidly moving rear extender beams could pinch/crush or otherwise injure an astronaut's fingers/toes or other extremities. To mitigate this issue, we propose a safety covering or sheath around the extender beams. This covering would extend from the floor to the maximum height of the beam, and could be made of plastic or metal, and be either solid or cage-like.
Ingress: While it is easy to step into the front (primary) seat, the higher geometry of the rear chassis makes entering the 2nd seat much more difficult, especially in a stiff legged EVA suit. The easiest way to enter that seat would be via a fold out set of stairs on the rover side (either left or right) that would give the 2nd astronaut smaller steps to climb up.
Structure: We expect that a more rigorous structural analysis of the chassis design would result in improved strength and decreased weight of the structure. It's likely that an exploration of advanced manufacturing techniques (ex: Direct Metal Laser Sintering) combined with computational design methods (FEA, Topology Optimization) could produce chassis geometries with an even greater strength to weight ratio.
Storage: A future version of this chassis design should incorporate cargo/stowage space for samples and tools.

B CAD and MATLAB

The entire works related to this project are accessible via our Github page: https://github.com/BrianBock/ENAE788x_Project. You can view our final presentation and many more associated videos/animations/renders at https://drive.google.com/drive/folders/113_eTfvzxWGKhZmb-tjgHEhFOzATDLpB?usp=sharing. The slides include many additional views of many components of the finalized rover as well as each of the concept designs.

C Image and Model Credits

Moon image used in logo from https://en.wikipedia.org/wiki/Moon
Z2 Astronaut from https://nasa3d.arc.nasa.gov/detail/nmss-z2
8020 Beam Profiles from 8020.net and https://www.3dcontentcentral.com
Velodyne Puck LITE from https://velodynelidar.com/products/puck-lite/

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