Final Report Presentation - ENAE788X

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Lunar Surface Transport and Exploration Rover (LSTER)
A LUNAR TERRAIN VEHICLE (LTV)

UNIVERSITY OF
MARYLAND

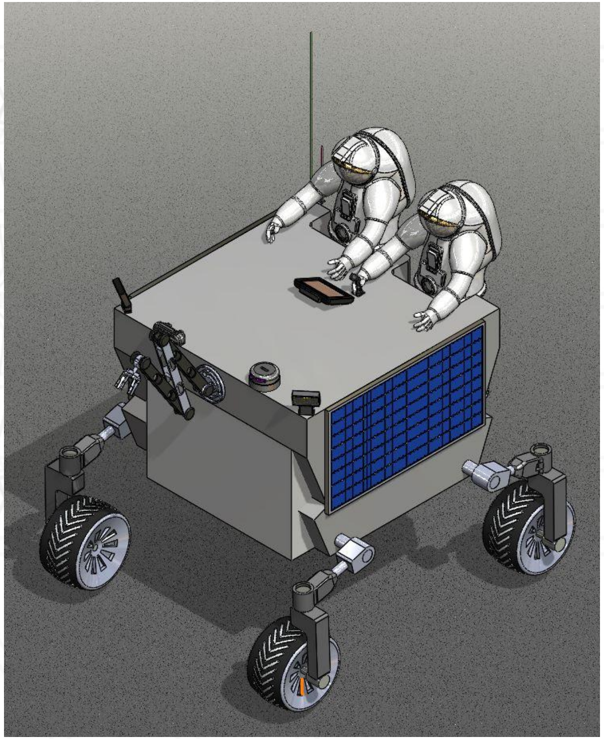
“3) Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.”

“4) Your best design efforts will inevitably wind up being useless in the final design”

-Akin’s Laws of Spacecraft Design

LSTER - Lunar Surface Transport and Exploration Rover

Lunar Surface Transport and Exploration Rover (LSTER) is a versatile logistics and exploration rover that performs a variety of tasks, including human operations, robotic science, exploration, logistics, construction, resource usage, and other tasks essential to sustaining human presence on the Moon, and other planets.



Reference to NASA LTV Key Attributes/Capabilities → L3

Project Requirements

- Design for LTV should include
  - Two suited crew plus 250 kg for Payload and crew support items
  - Max speed of 15 km/hr
  - Range of 20 km
  - Survive 100 hours of polar night time

Project Requirements

- Perform a detailed design of an LTV or LLT 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...)
- Design for Moon, then assess necessary modifications for Mars, and conversion to Earth analogue rover

Design Considerations

- Proposed LTV contains 4 wheel explicit steering and propulsion with independent active suspension.
- The LTV can be operated autonomously and manually by astronauts.
- Unlike the conventional LTV, this is designed for astronauts to stand on the vehicle while controlling it,to avoid bending the suit and for easier ingressing and egressing from the vehicle.
- The LTV's legs can be folded to make the transportation of the vehicle easier.
- Unique feature about this LTV is that, rover can carry cargo by attaching it to both the underside and top side of its chassis.

Specifications of the Proposed Rover

- Payload Mass: 500kg/1100 lbs
- Volume: 10.84 cubic meter
- Dimensions :
  - Length (fully extended) - 3 metres
  - Width - 2 metres
  - Height - 1.8 metres
  - Wheelbase - 2.5 metres
- Surface Velocity: 4.1m/s ~ 4 m/s
- Material Used : Aluminium Alloy 2219

Terramechanics - Soil properties

$$\text{Modulus of Cohesion of Soil Deformation} = k_c = 1400\frac{N}{m^2}$$

$$\text{Modulus of Fiction of Soil Deformation} = k_\phi = 820000\frac{N}{m^3}$$

$$\text{Soil heuristic parameter} = n = 1$$

$$\text{Angle of internal resistance of soil} = \phi = 0.6109$$

$$\text{Density of soil} = \gamma = 2472\frac{N}{m^3}$$

$$\text{Soil cohesion} = c = 170\frac{N}{m^2}$$

$$\text{Shear deformation modulus} = K_{shear} = 0.178m$$

Gravitation Resistance

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

Rolling Resistance

$$c_f(\text{coefficient of friction}) = 0.05$$

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

Terramechanics

Compression Resistance

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

$$z = \left(\frac{3}{3-n}\frac{W_w}{(k_c + bk_\phi)\sqrt{D}}\right)^{\frac{2}{2n+1}}$$

Tractive Force for Wheels with Grousers

$$N_g = \frac{\pi D}{N_{tot} l}$$

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

Bulldozing Resistance

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

$$\alpha = \text{angle of attack of wheel in soil} = \cos^{-1}\left(1-\frac{2z}{D}\right)$$

$$K_c = \text{Cohesive modulus of soil deformation} = (N_c - \tan\phi)\cos^2\phi$$

$$N_q = \frac{\exp\left[\left(\frac{3\pi}{2}-\phi\right)\tan\phi\right]}{2\cos^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)}$$

$$N_c = \frac{N_q - 1}{\tan\phi}$$

$$K_\gamma = \left[\frac{2N_\gamma}{\tan\phi}+1\right]\cos^2\phi$$

$$N_\gamma = \frac{2(N_q+1)\tan\phi}{1+0.4\sin(4\phi)}$$

$$l_o = z\tan^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right)$$

Terramechanics - Soil properties

$$\text{Modulus of Cohesion of Soil Deformation} = k_c = 1400\frac{N}{m^2}$$

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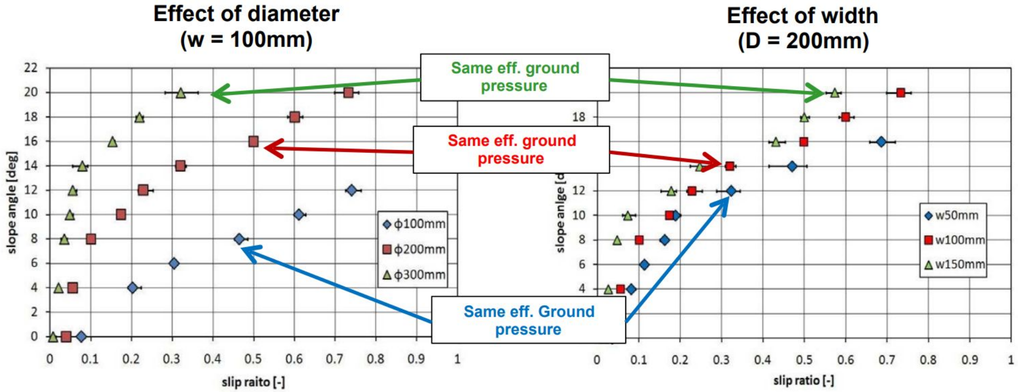
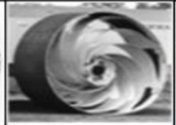
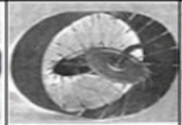
Terramechanics

- Higher diameter and width values have been considered for maximizing wheel-soil contact area using the data from the graph.



Plots courtesy of Sutoh et. al., “Traveling performance evaluation of planetary rovers on loose soil.” Journal of Field Robotics, Vol. 29, Issue 4, 2012

Terramechanics - Comparative study of Rover wheels

Wheel type:			Rigid rim	Pneumatic	Wire mesh	Spiral spring	Hoop spring	Elliptical	Cone	Hubless
Example reference:			Gromov 2003	Goodyear 1969	GM 1970a	Markow 1963	Bendix 1965	Markow 1963	Grumman 1970	Lockheed 1972
Criteria	Method	Weighting factor								
Mechanical reliability	J	0.15	**6.0**	4.5	5.0	4.7	4.7	1.7	4.0	1.9
Soft ground performance	C/E	0.14	3.8	7.3	7.3	**8.7**	**8.7**	8.2	8.3	**8.7**
Weight	C	0.14	6.6	3.3	**8.7**	2.5	4.5	1.0	5.8	0.5
Ride comfort	J	0.13	0.0	8.0	**9.0**	3.0	5.0	6.0	2.0	3.0
Obstacle performance	C	0.10	6.8	**7.4**	**7.4**	6.4	6.4	6.8	**7.4**	6.4
Stability	J	0.08	**8.0**	7.0	7.0	2.8	5.7	4.3	7.0	2.8
Wear resistance	J	0.08	3.0	1.5	5.3	**6.0**	**6.0**	**6.0**	5.3	**6.0**
Steerability	J/E	0.06	**7.3**	5.8	5.8	2.0	2.0	4.1	6.6	2.0
Environmental compatibility	J	0.06	**8.0**	0.0	6.0	7.0	7.0	6.0	6.0	3.0
Development risk and cost	J	0.06	**10**	1.3	8.0	8.0	8.0	4.0	5.3	2.7
Total		1.0	Eliminated	Eliminated	**7.1**	5.0	5.8	4.7	5.6	3.8

Key : C = Calculation, E = Experiment, J = Engineering judgment

Figure 8.—Wheel concept matrix.
[After Dr. M.G. Bekker (Bekker 1985). High scores are shown in red.]

Wheel Soil Interaction of Dragged Wheel

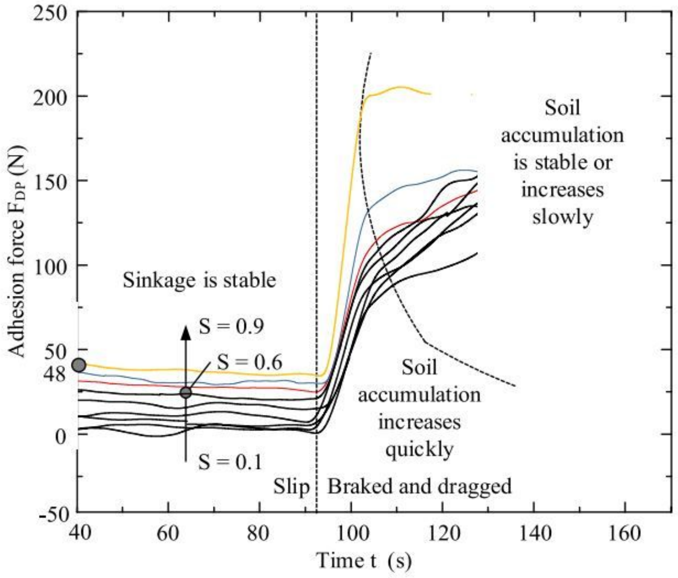


Fig. 6. Wheel–soil interaction test of dragged wheel.

Terrain Requirements

- Surface Characteristics:
    - Surface Area: 31.8 million sq. km
    - Surface gravity: 1.6ms^{-2}
    - Atmosphere: Little to none
    - Crust composition: Silicate rocks, highlands dominated by Feldspar rich rocks
    - Length of day: 23.93 hours
    - Surface temperature: -193°C to 111°C

Soil Characteristics - Trade Study

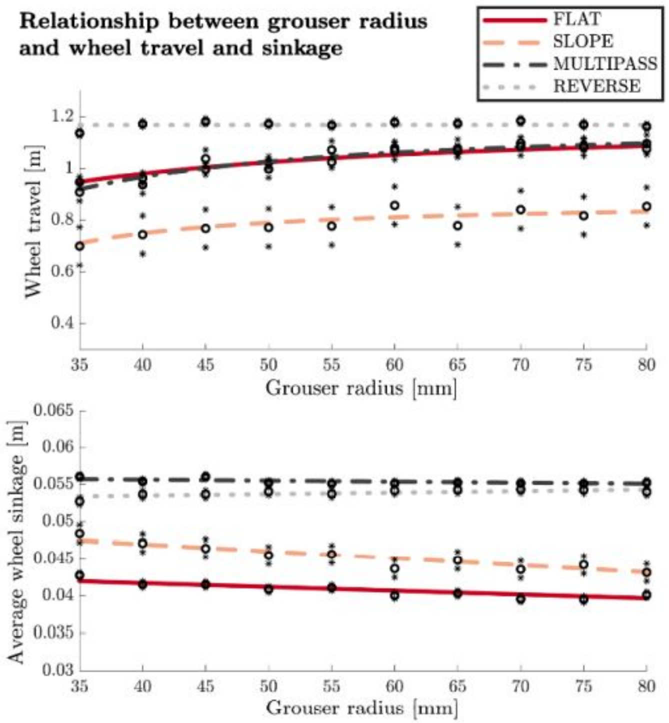
Soil	Specific gravity (ρg)	Soil Cohesion (Pa)	Friction angle (°)	K_c (N/m^{n+1}) *	K_ϕ (N/m^{n+2}) *	Consistency ($k=k_c+bk_\phi$)	Deformation coeff (n)**	Drawbar Pull (N)
DLR soil simulant A	4.24	188	24.8	2370	60300	8400	0.63	112.7
DLR soil simulant B	4.24	441	17.8	18773	763600	95133	1.1	155.0
VL1 drift	4.29	1600	18	1400	820000	83400	1.0	151.28
VL1 blocky	5.97	5500	30.8	1400	820000	83400	1.0	319.5
VL2 crusty-cloddy	5.22	1100	34.5	1400	820000	83400	1.0	378.8
PL drift	4.36	380	23.1	1400	820000	83400	1.0	215.2
PL cloddy	5.70	170	37	1400	820000	83400	1.0	421.45
Dry sand	5.67	1040	28	990	1528000	153790	1.1	293.2
Sandy loam	5.67	1720	29	5270	1515000	156770	0.7	298.8
Clayey soil	5.67	4140	13	13190	692200	82410	0.5	79.2
MER-B 'sandy loam'	4.24	4800	20.0	28000	7600000	788000	1.0	202.7
MER-B 'slope soil'	4.24	500	20.0	6800	210000	27800	0.8	137.2

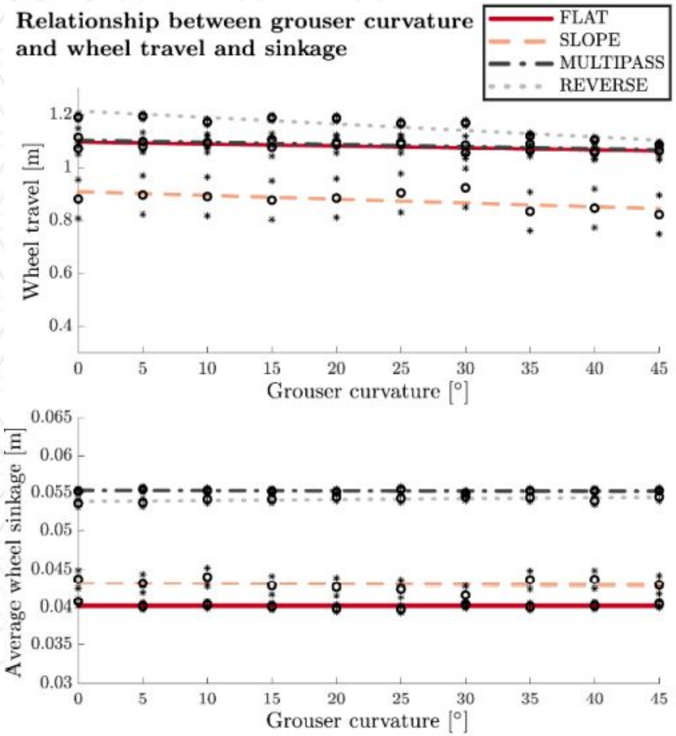
* as there is no experimental data from VL1, VL2 and PL, we have used lunar values for those soils

** as there is no experimental data from VL1, VL2 and PL, we have assumed n=1 for those soils

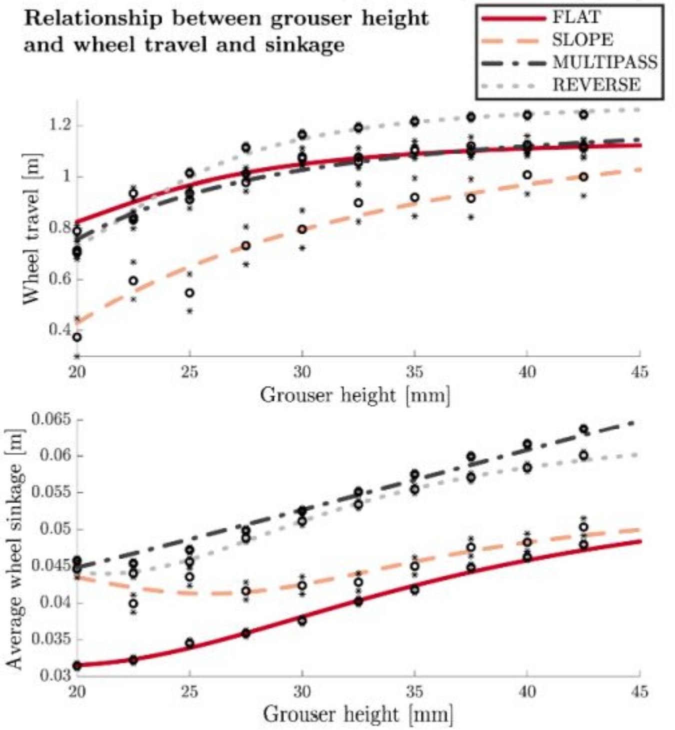
Table 1. Drawbar pull for the ExoMars rover configuration on different soils

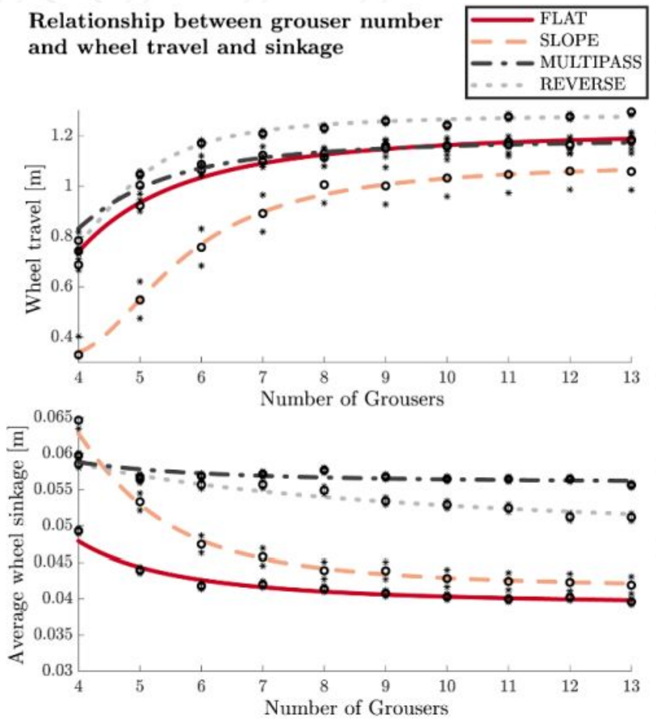
Grouser Trade Studies



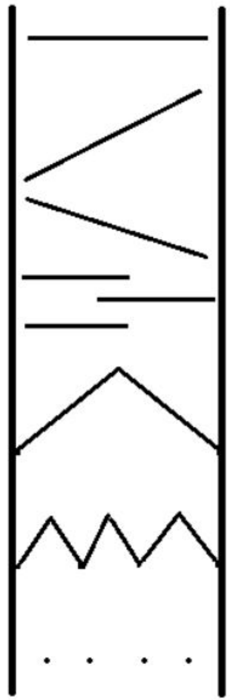


Grouser Trade Studies





Grouser Trade Studies



The straight line is probably the most common design. It is good for driving straight up hill and on flat surfaces. It is not good for side slopping on a hill or turning.

The 2 slanted lines are not as common. It gives a balance when turning and when side slopping on a hill.

This overlapping pattern in the center allows for various grouser pitch's. For example the center can allow for smooth driving on hard terrain while the sides are good for softer terrain.

The chevron is a very common design that gives a mix of forward perfromace, slope climbing, and side slopes.

Similiar to the chevron above but gives more "pockets" to capture dirt for added traction (possibly).

Spikes are usefull for operating in ice conditions.

Terramechanics - Grouser Design

Number of Wheels = 4

Wheel Diameter = 609.5mm

Width = 350mm

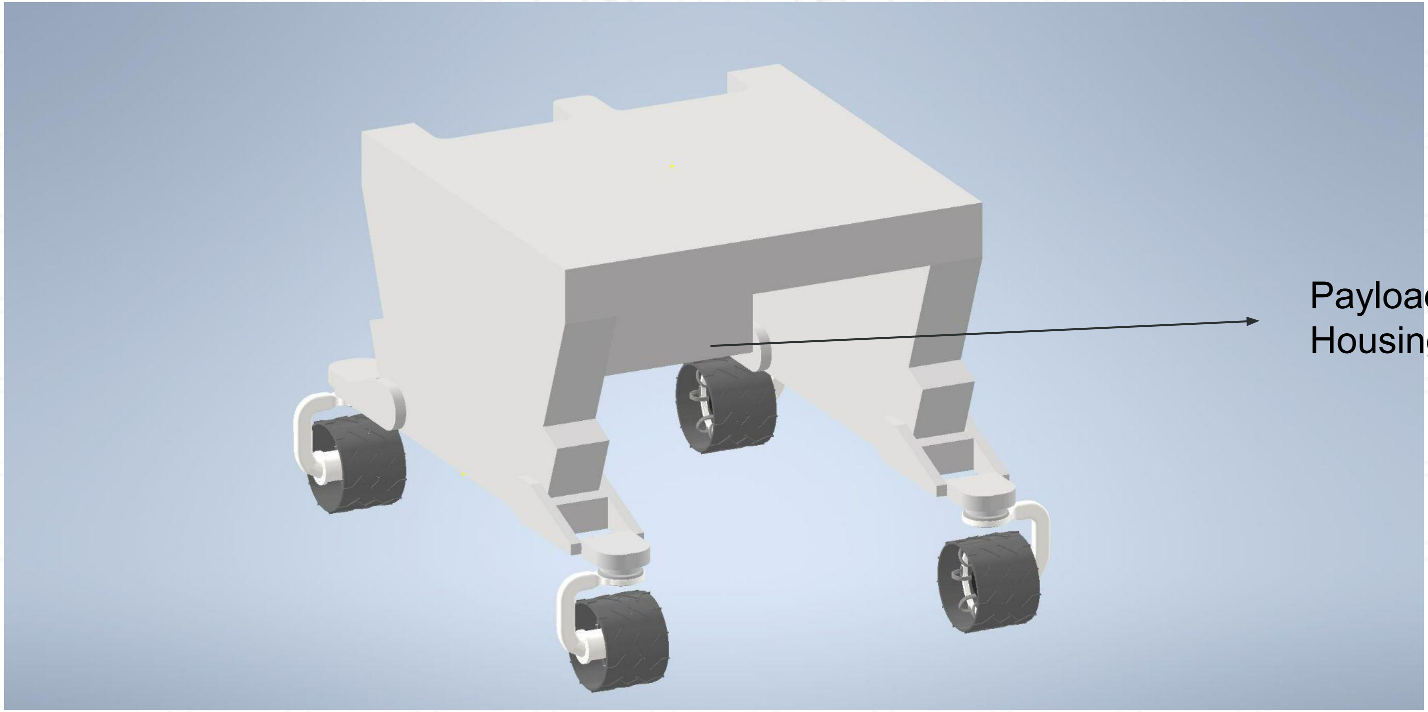
Number of grouser: 30

Grouser height: 10mm

Placement of Wheels = 4 corners of the chassis

PRELIMINARY DESIGN

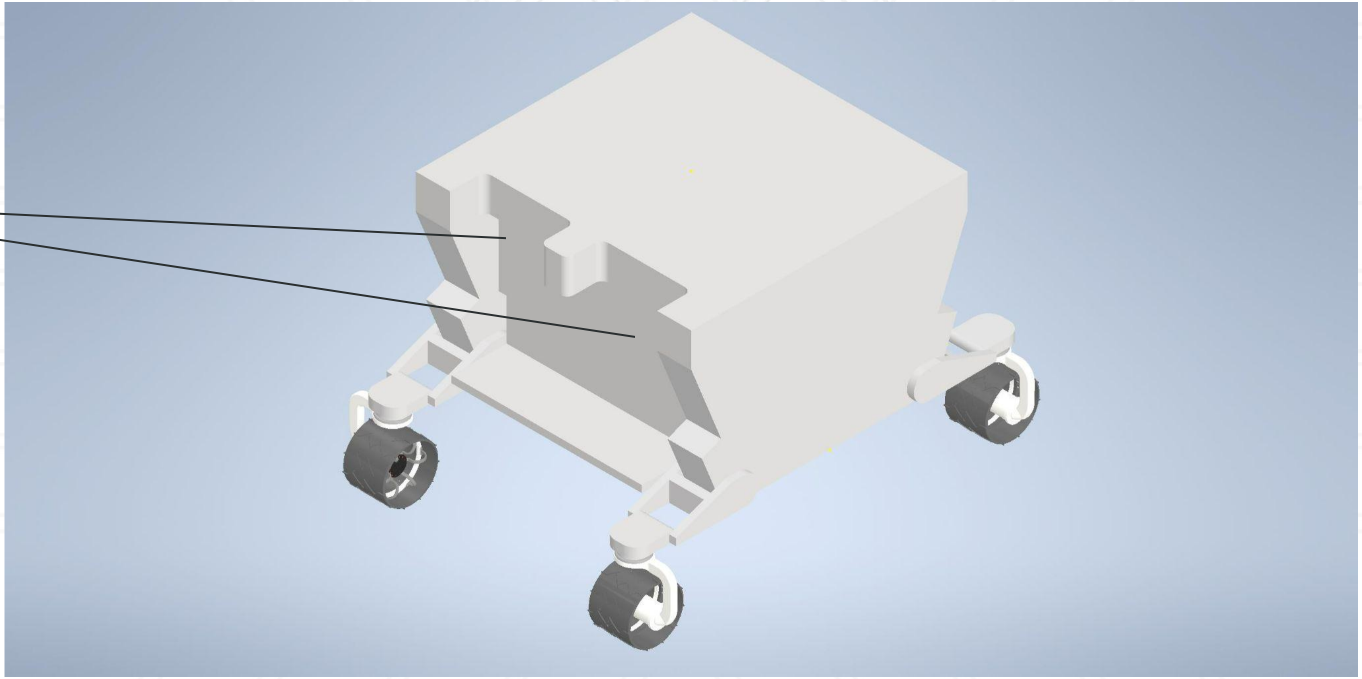
Preliminary CAD Model - Isometric Front View



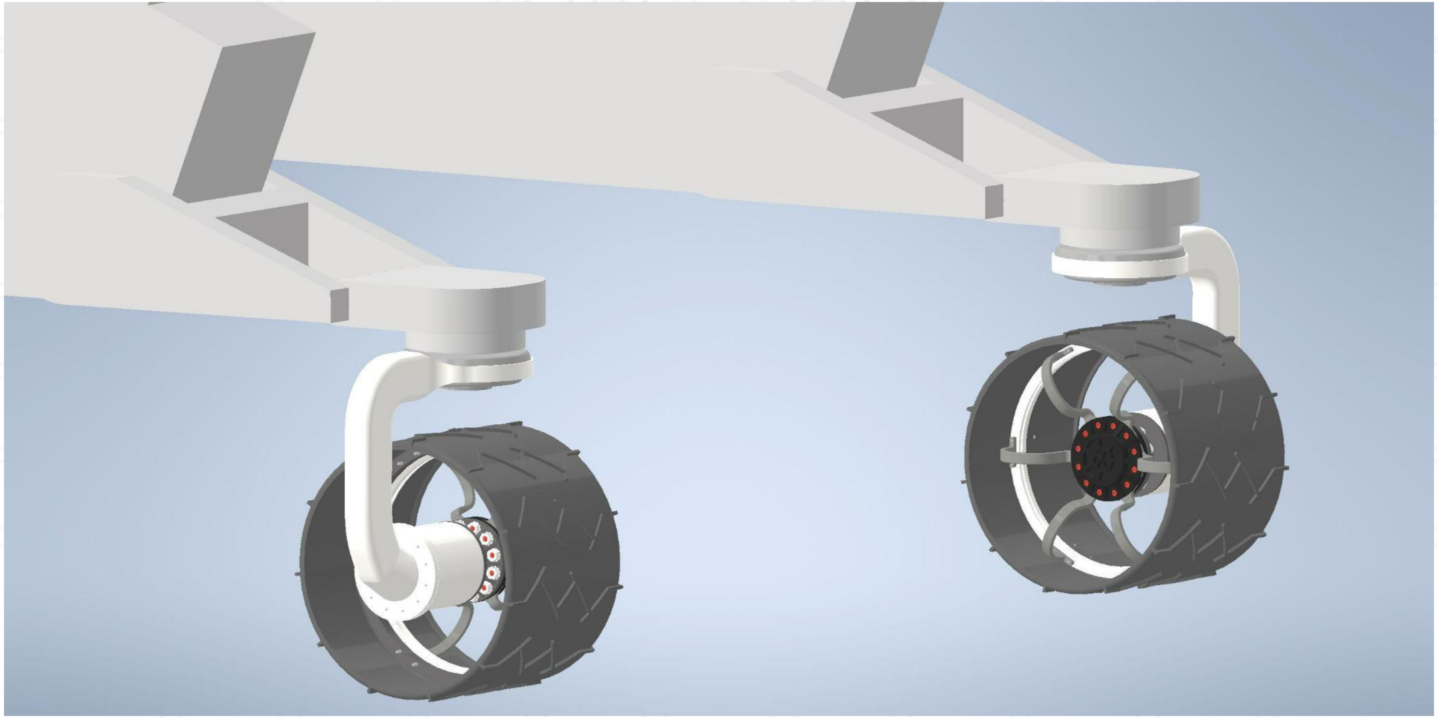
Payload/ Battery Housing Area

Preliminary CAD Model - Isometric Rear View

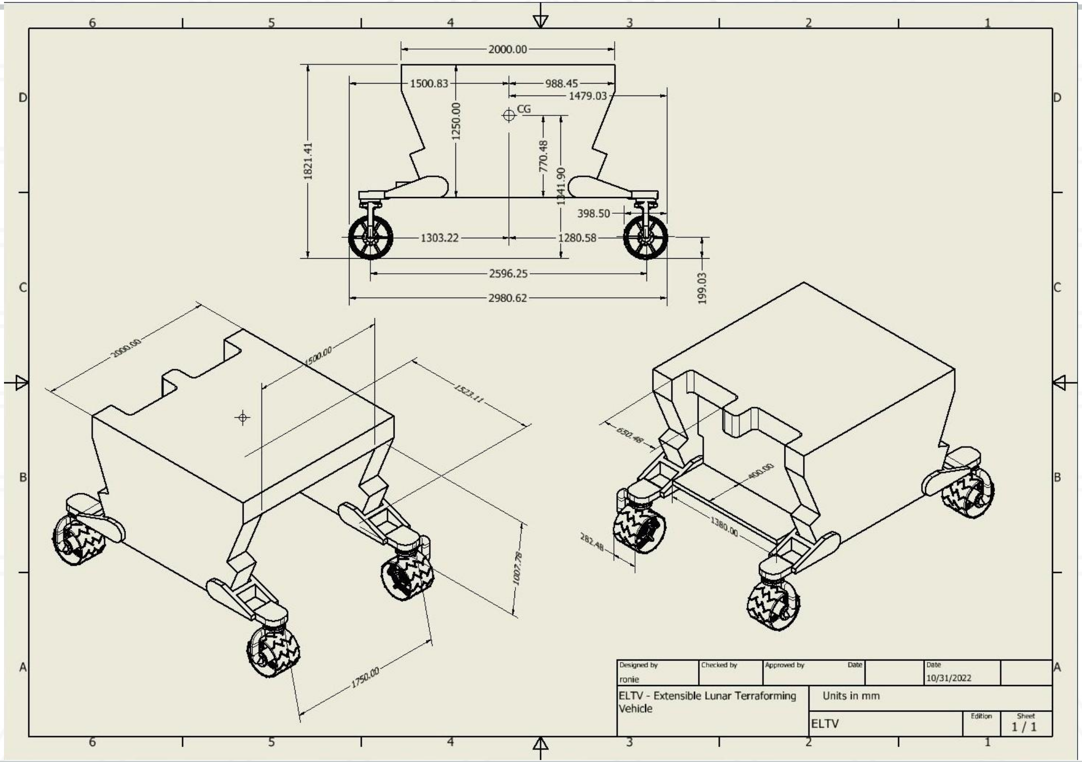
Standing Area for Astronauts



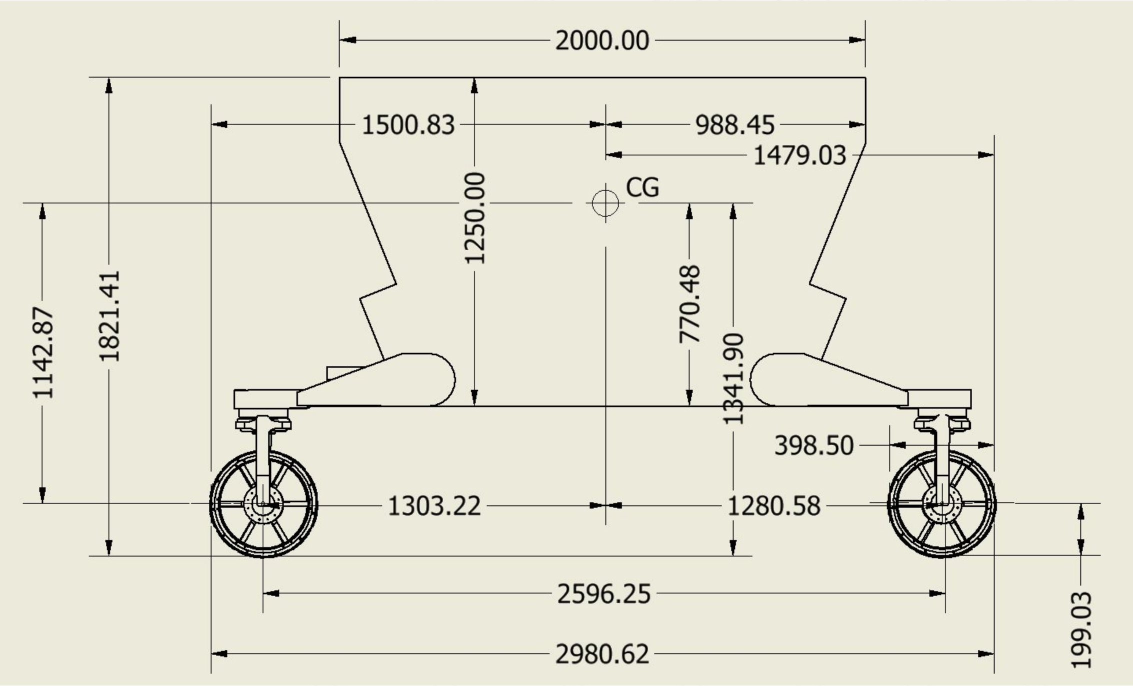
Preliminary Grousers on Wheels



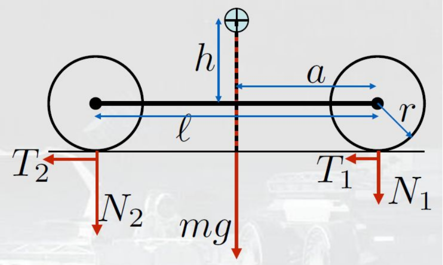
Preliminary CAD Model Dimensions



Preliminary Stability and Center of Gravity(CG)

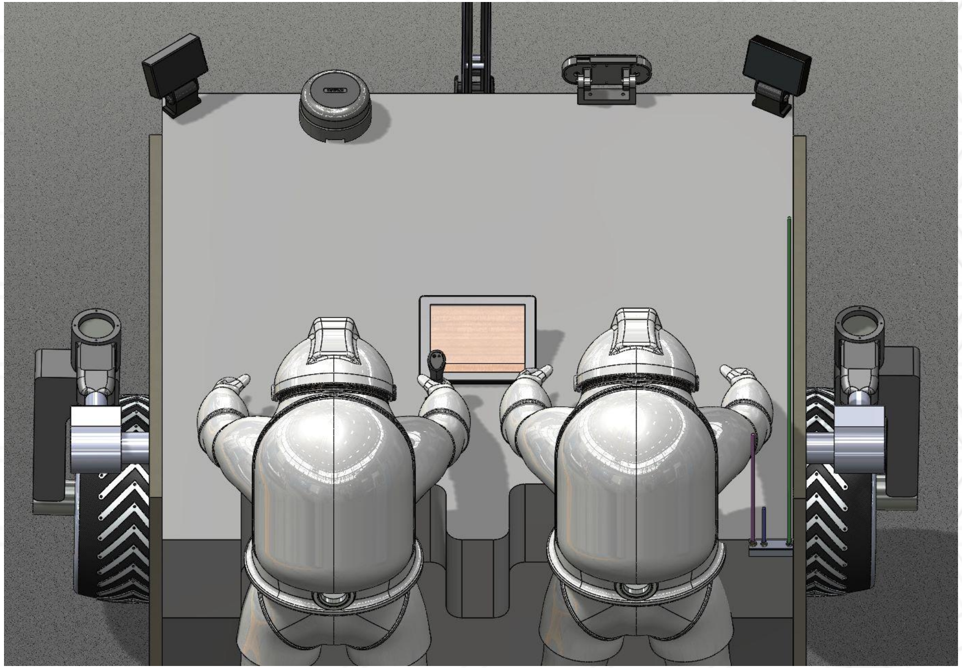


Wheelbase (l) = 2596.25 mm
Wheel track (c) = 1750 mm
Height of CG (ground) = 1341.9 mm
Mass (m) = 1000 kg
mg = 3240 N
Radius of wheel (r) = 199 mm
a = 1280.5 mm
h = 1142.8 mm
N1 and N2 = 810 N
b = 1303.2 mm

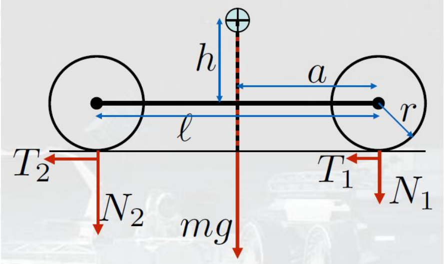


FINAL DESIGN

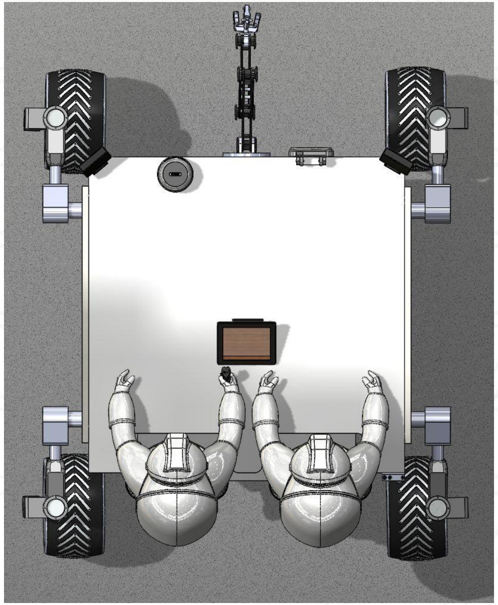
Final Design

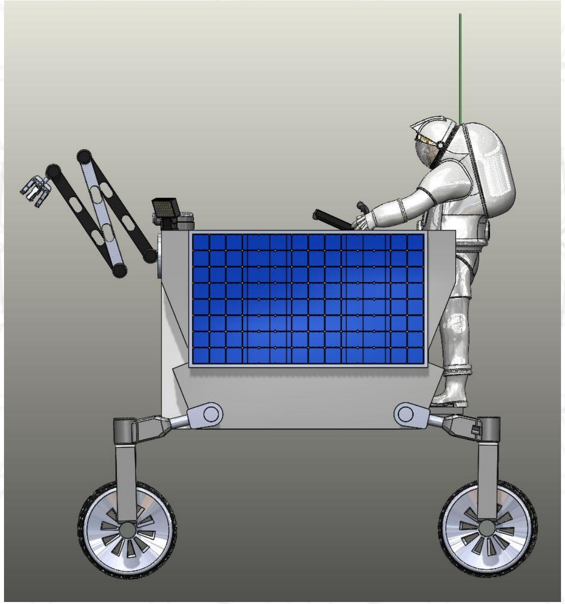


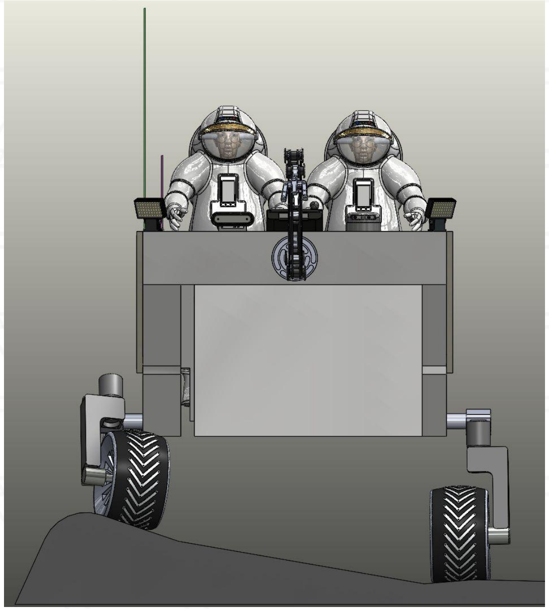
Wheelbase (l) = 2512.25 mm
Wheel track (c) = 2123.91 mm
Height of CG (ground) = 1460.94mm
Mass (m) = 2100kg (with payload)
mg = 3430 N
Radius of wheel (r) = 300mm
a = 1094.06 mm
h = 1160.94 mm
N1 and N2 = 857N
b = 1418.19 mm



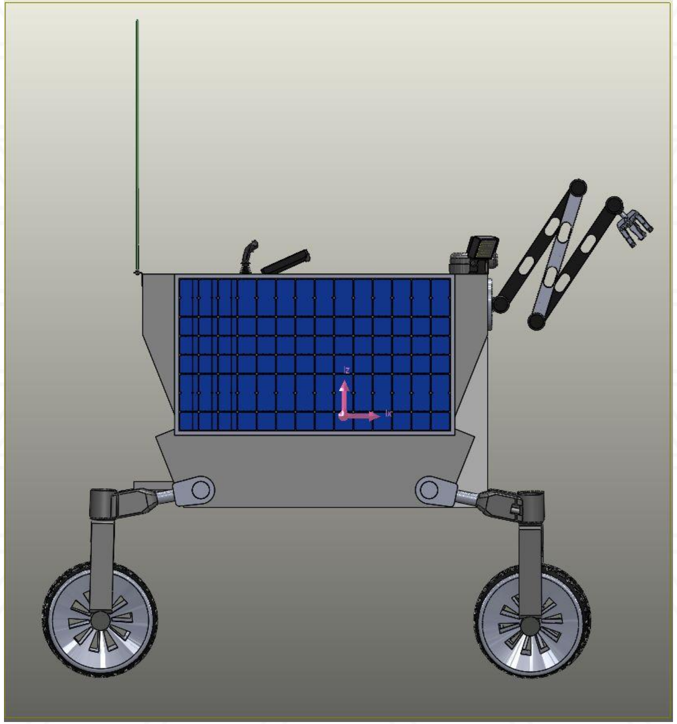
Final Design







Stability and Center of Gravity(CG)

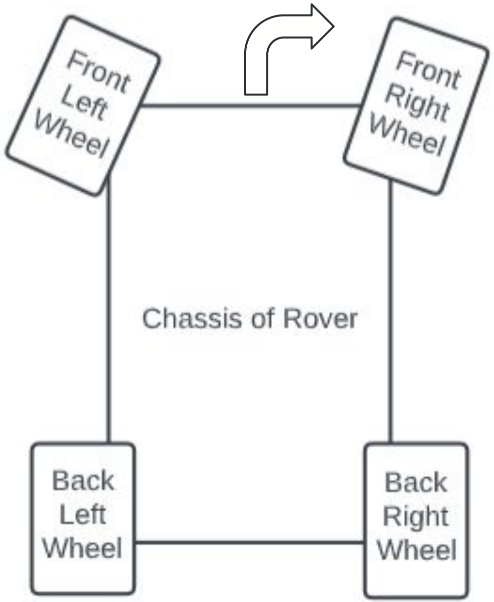


STEERING

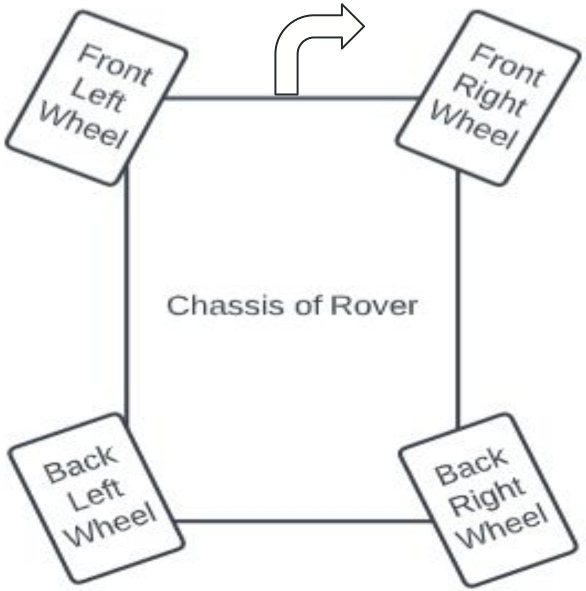
Steering - Assumptions

- We perform the trade study for the following types of steering:
  - Single Ackermann
  - Double Ackermann
  - Turn in Place (Steering)
- We make the following assumption to help with our calculations:
  - Normal force on each wheel is equal i.e, 1/4th the total mass of the rover (including astronaut mass)
  - Velocity is constant at 15km/hr
  - For off road conditions $\mu_s = 1$, $\mu_r = 0.2$
  - For some analyses, we have fixed the axle width at c=2m (for simpler calculations)

Steering Modes



Front Axis Ackermann



Dual Axis Ackermann

Steering - Single Ackermann

- In the first case we perform the analysis for the single ackermann steering of a rover with fixed track (c=2m). We vary the radius of turn for different wheelbase to figure out which wheelbase length is best for this type of steering.
- We see that the total power required is lesser for lower wheelbase lengths (best within 1-3 metres) to perform turns for lower radius

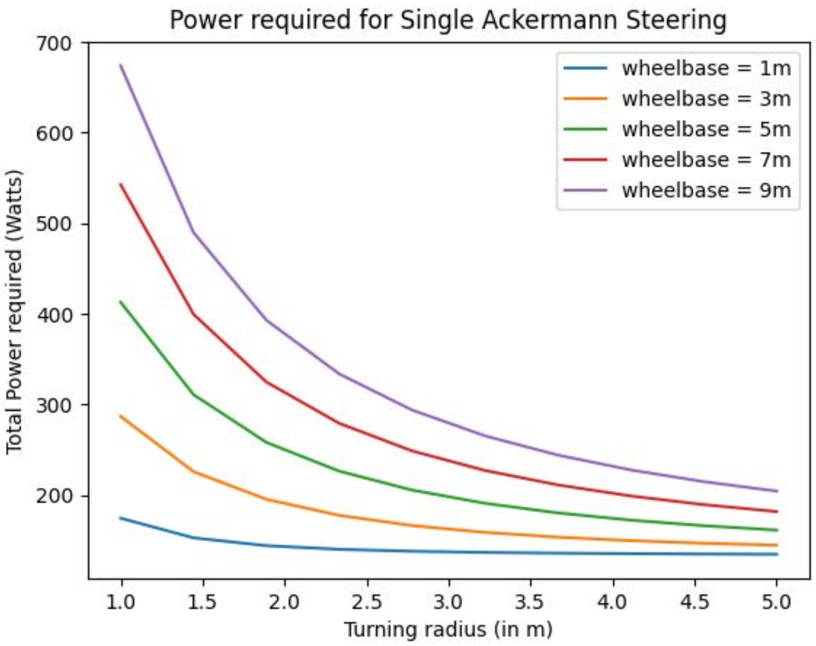
$$P_{r,of} = v_{r,of}\ \mu_r\ N_{of} = \omega\sqrt{\left(r+\frac{c}{2}\right)^2 + l^2}\ \mu_r\ N_{of} = V\sqrt{\left(1+\frac{c}{2r}\right)^2 + \left(\frac{l}{r}\right)^2}\ \mu_r\ N_{of}$$

$$P_{r,if} = = V\sqrt{\left(1-\frac{c}{2r}\right)^2 + \left(\frac{l}{r}\right)^2}\ \mu_r\ N_{if}$$

$$P_{w,or} = V\left(1+\frac{c}{2r}\right)\mu_r N_{or}$$

$$P_{w,ir} = V\left(1-\frac{c}{2r}\right)\mu_r N_{ir}$$

$$P_{total} = P_{w,of} + P_{w,if} + P_{w,or} + P_{w,ir}$$



Steering - Double Ackermann

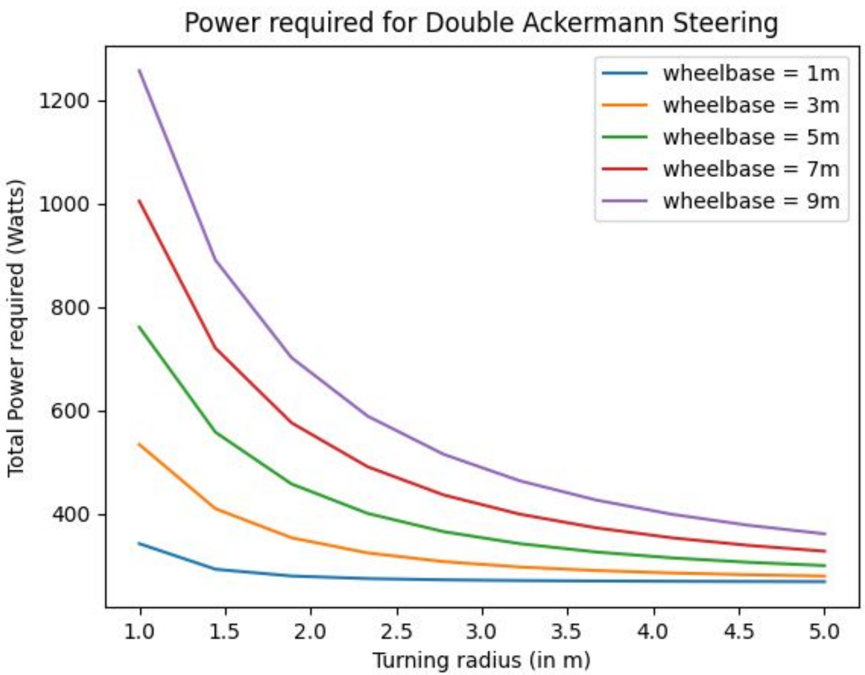
- Similar to single ackermann steering, we observe the total power required to turn different radii for increasing wheelbase lengths.
- We notice here that the behaviour is the same as single ackermann steering, but the total power is much higher.

$$P_{w,o} = \omega r_0 \mu_r N_o = \frac{V}{r}\sqrt{\left(r+\frac{c}{2}\right)^2+\left(\frac{l}{2}\right)^2}\,\mu_r N_o$$

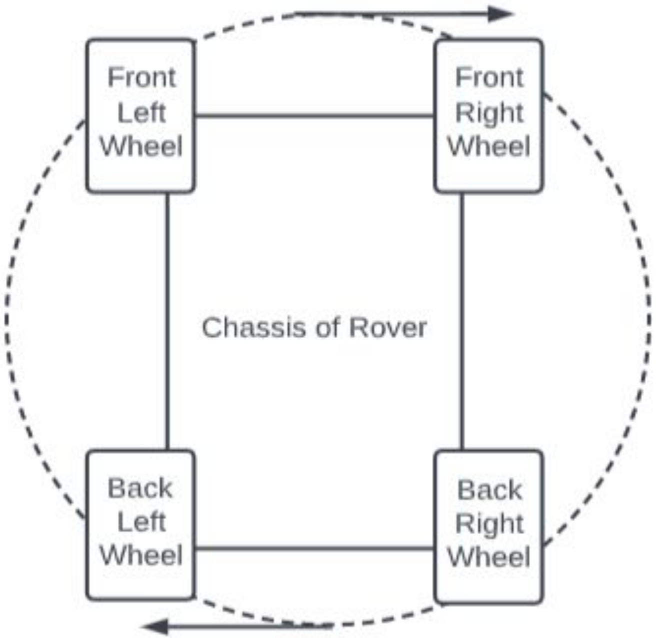
$$= V\sqrt{\left(1+\frac{c}{2r}\right)^2+\left(\frac{l}{2r}\right)^2}\,\mu_r N_o$$

$$P_{w,i} = V\sqrt{\left(1-\frac{c}{2r}\right)^2+\left(\frac{l}{2r}\right)^2}\,\mu_r N_i$$

$$P_{total} = 2\left(P_{w,o}+P_{w,i}\right)$$



Steering Modes - 4 Wheel Skid



Wheel Rotations

Front Left Wheels - Clockwise

Back Left Wheels- Clockwise

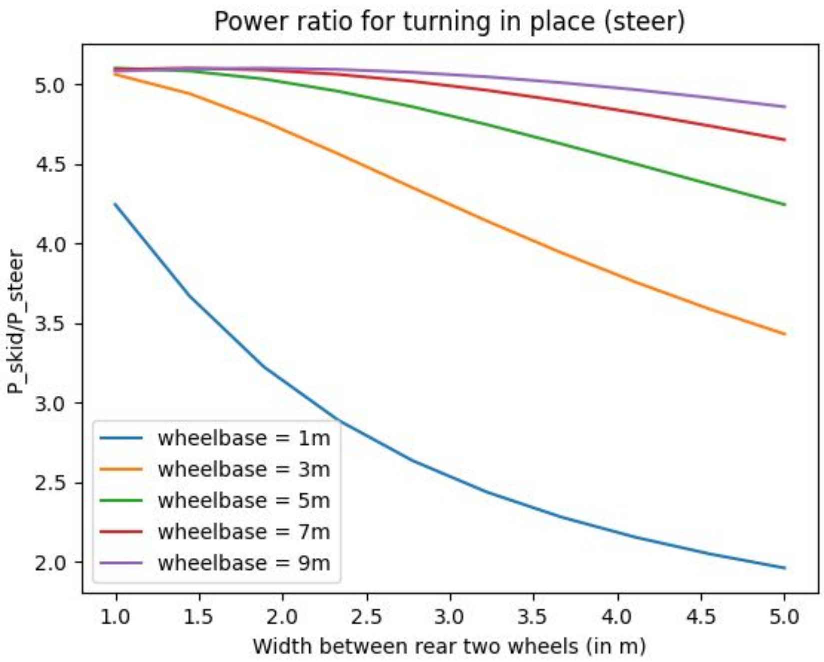
Front Right Wheels- Anti Clockwise

Back Right - Anti Clockwise

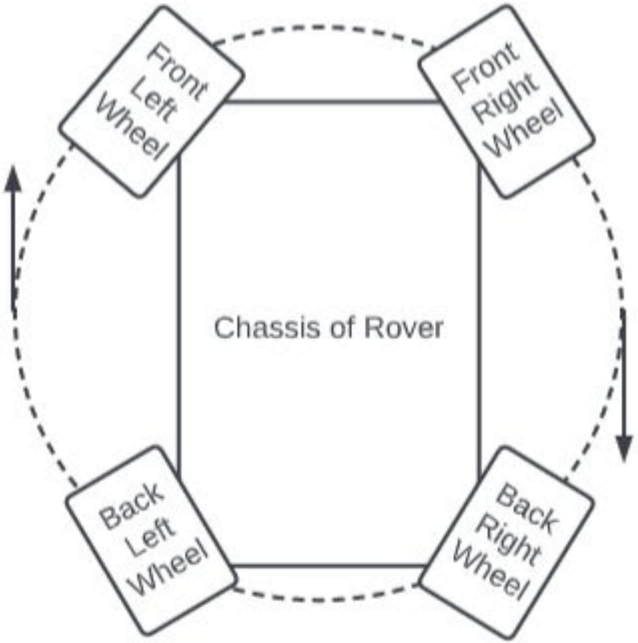
Steering - Turning in Place (Steering)

- In this case we perform a comparative analysis by varying both width between rear wheels and the wheelbase to find the ratio in power required in skidding to the power required to steer, so that a turn can be performed in place.
- Upon observation we see that the required power is lease for around a wheelbase of 1m and optimal for wheel width around 2-3m

$$\frac{P_{skid}}{P_{steer}} = \frac{c + \frac{\mu_s}{\mu_r} l}{\sqrt{c^2 + l^2}}$$



Steering Modes - 4 Wheel Steered



Wheel Rotations

Front Left Wheels - Clockwise

Back Left Wheels- Clockwise

Front Right Wheels- Anti Clockwise

Back Right - Anti Clockwise

Steering Power

Relative Power $\frac{\mu_s}{\mu_r}\sin\alpha = 1$

Pskid = Proll if $\frac{\mu_s}{\mu_r}$ = 5, r = turning radius

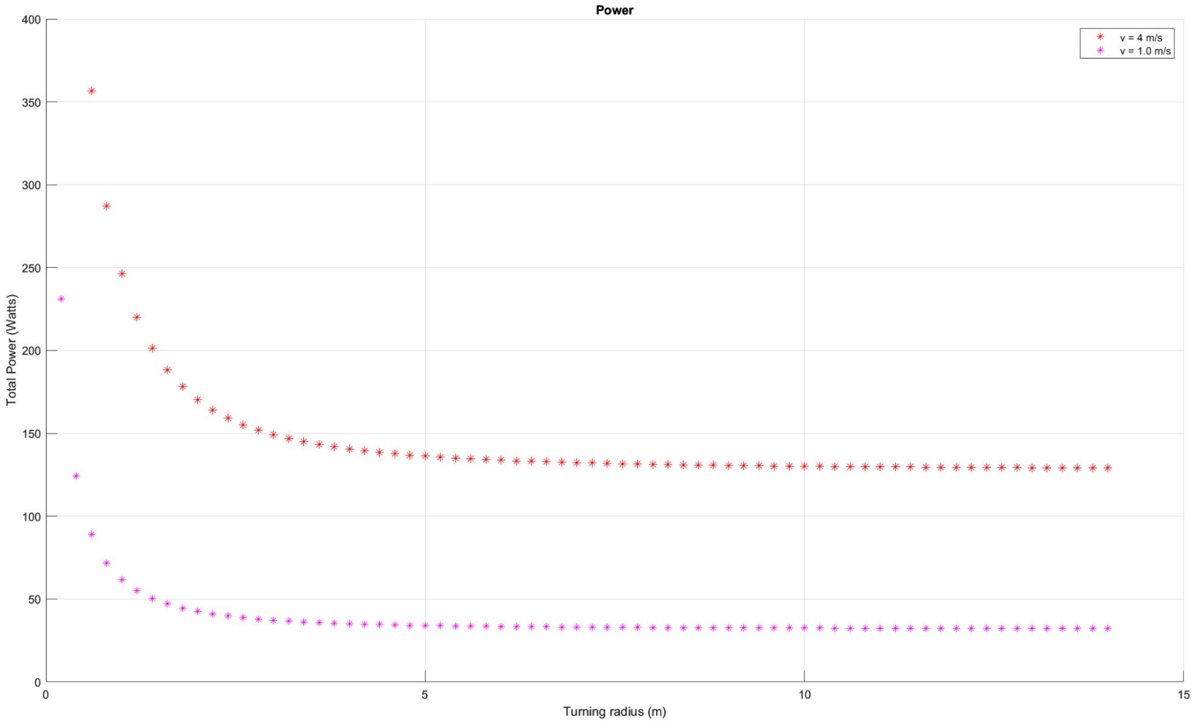
l = length (m) between the front and rear axles

v = velocity of the rover in m/s

N = Normal force into soil

$$P = \left(2r + \sqrt{\left(r - \frac{c}{2}\right)^2 + l^2} + \sqrt{\left(r + \frac{c}{2}\right)^2 + l^2}\right) * \frac{v}{r}\mu_r N$$

Steering Power



Steering

- From the trade analysis performed, we can see that, a wheelbase of about 2-3m and axle width of less than 2m is ideal to utilize the least power to turn the rover.
- Single ackermann uses less power but the surface soil characteristics make it difficult for steering
- Double ackermann steering requires more power hence it is eliminated.
- Turning in place requires the least power when the wheelbase and axle width are at the dimensions mentioned above.
- These trade studies have led us to decide on independent steering (turning in place) and to fix on a wheelbase of 2.5m with axle width of about 2m.

STABILITY ANALYSIS

Stability Analysis

Static equilibrium solutions

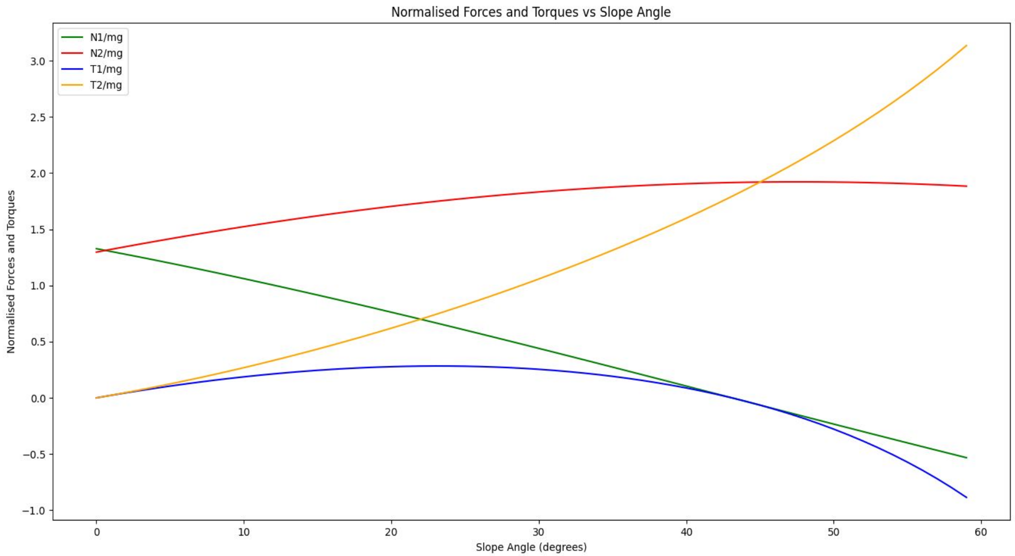
$$N_1 = mg\left[\left(1-\frac{a}{l}\right)\cos\theta - \left(\frac{h}{l}+\frac{r}{l}\right)\sin\theta\right]$$

$$N_2 = mg\left[\frac{a}{l}\cos\theta + \left(\frac{h}{l}+\frac{r}{l}\right)\sin\theta\right]$$

$$T_2 = \frac{N_2}{N_1 + N_2} mg\sin\theta$$

$$T_1 = \frac{N_1}{N_1 + N_2} mg\sin\theta$$

Stability Analysis

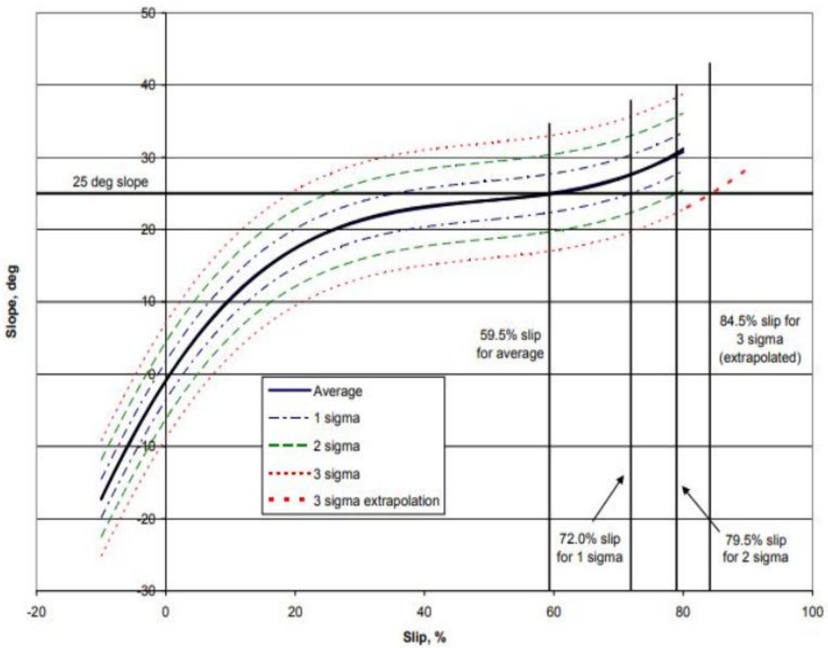


The graph describes how normal forces on wheels varies with slope of terrain.The system will remain on the ground for slope that results in a positive normal force on every wheel. The zero normal force condition is when the wheels lift off the ground.

Slip vs Slope

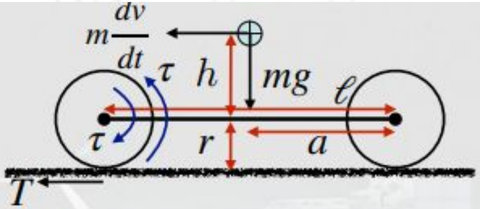
- Proposed Max Slope: 20°-25° which is confirmed by the analysis performed in the next few slides.

- Proposed Max Obstacles which can be crossed: 30 cm at lowest velocity



Acceleration Stability

- For our rover we have:
  - l = 2.51 m
  - r = 0.3 m
  - h = 1.16 m
  - a = 1.09 m
- Limiting acceleration = 1.58 ms^{-2}



$$\tau = Tr$$

$$T = m\frac{dv}{dt}$$

$$\tau = rm\frac{dv}{dt}$$

$\sum$ moments about rear axle at torque limit

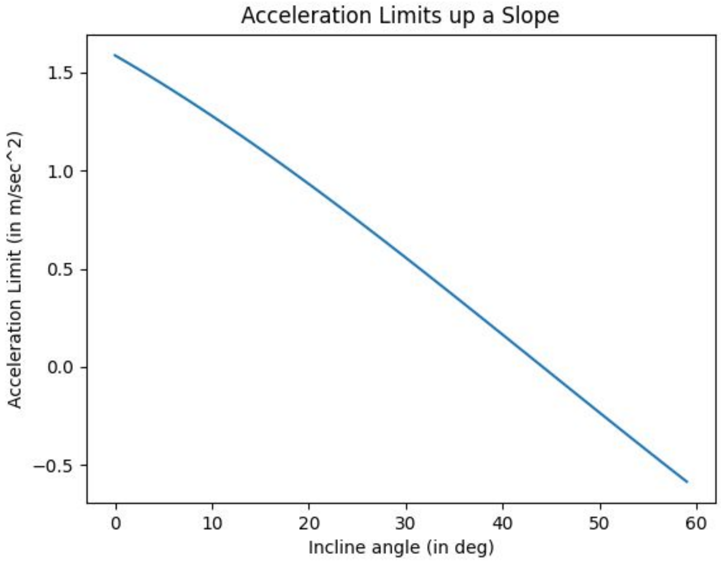
$$\tau + hm\frac{dv}{dt} = mg(\ell - a)$$

$$rm\frac{dv}{dt} + hm\frac{dv}{dt} = mg(\ell - a)$$

$$\left.\frac{dv}{dt}\right|_{\lim} = g\frac{\ell - a}{r + h}$$

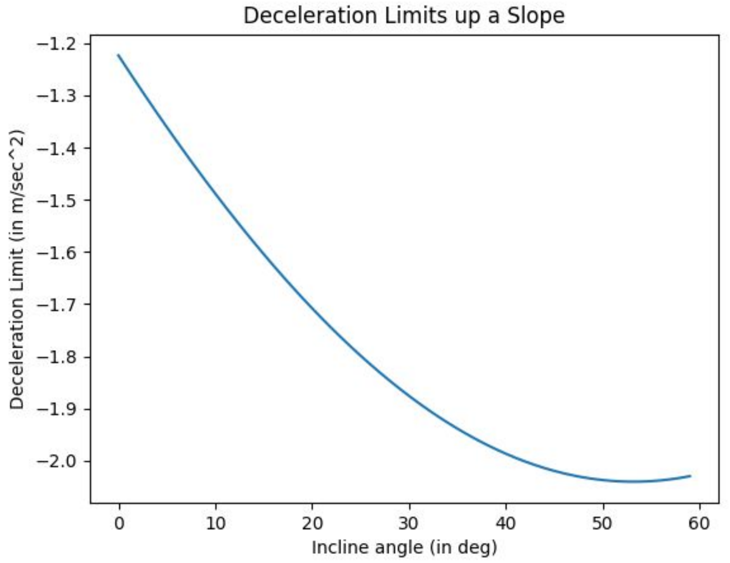
Acceleration Stability - Going up a Slope

- When accelerating up a slope, the acceleration limit decreases with increasing incline.
- For our specifications, we calculate the limiting acceleration for different inclines
- To maintain maximum acceleration and stability, it is ideal to avoid slopes of greater than 25°-30° .



Deceleration Stability - Going up a Slope

- We see the relation between the deceleration and the inclination angle of the slope in order to maintain stability of the vehicle.



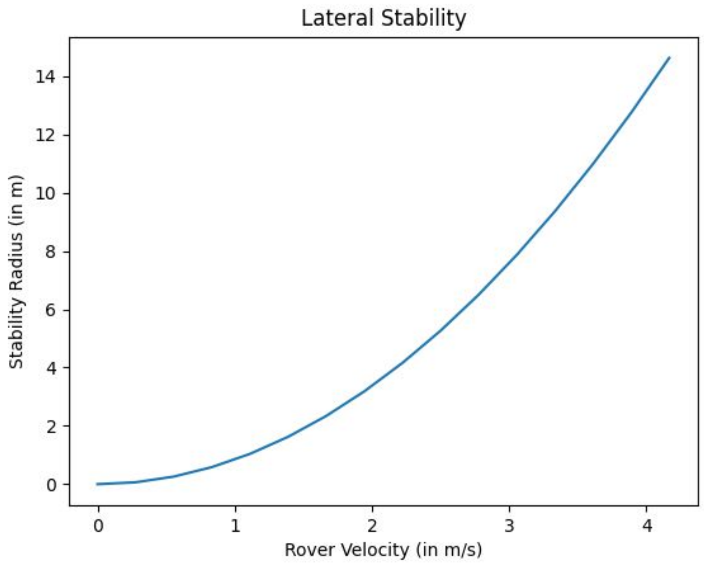
$$\left.\frac{dv}{dt}\right|_{\lim} = -g\left[\left(\frac{a}{h+r}\right)\cos\theta + \sin\theta\right]$$

Turning Radius Stability - Level Ground

- When turning on a flat surface, due to the reduced gravitational effect on the surface of the moon, the stability of the rover must be taken into account.

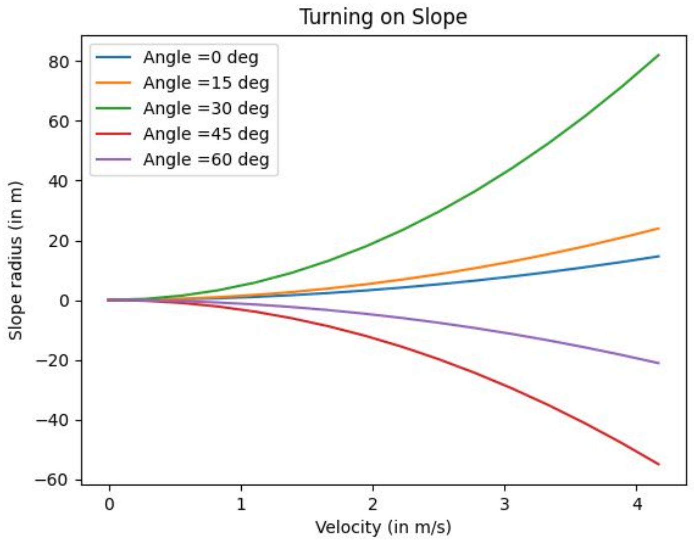
- Considering the centripetal acceleration while turning, the following graph determines the relationship between the rover velocity and the turning radius to maintain stability (without toppling)

- The analysis is done for velocities ranging from rest to 15 kmph (or 0-4ms^{-1})



Turning Radius Stability - On a slope

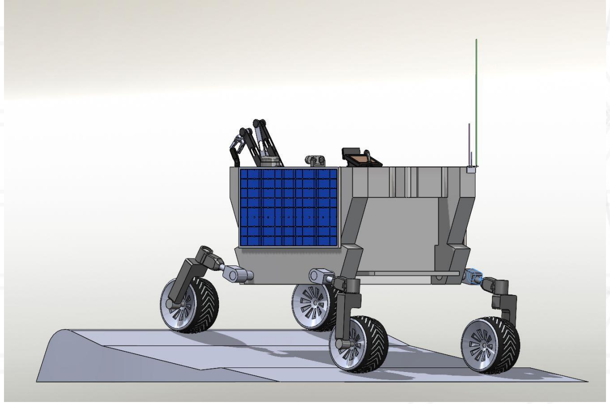
- When turning on a slope, the inclination angle must also be taken into consideration.
- Considering the centripetal acceleration while turning, the following graph determines the relationship between the rover velocity and the turning radius to maintain stability (without toppling)
- The analysis is done for velocities ranging from rest to 15 kmph (or 0-4ms^{-1}) for varying values of inclination.
- From this graph we can observe that the rover must be limited to traversing on inclinations less than 30°. The graph shows that anything above that the rover is highly unstable for the inclinations above 30°.

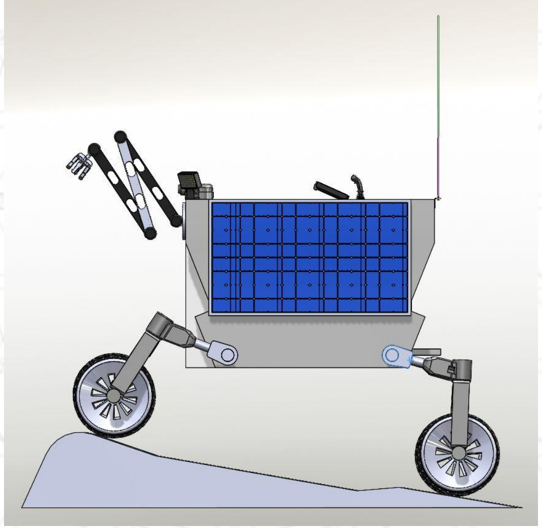


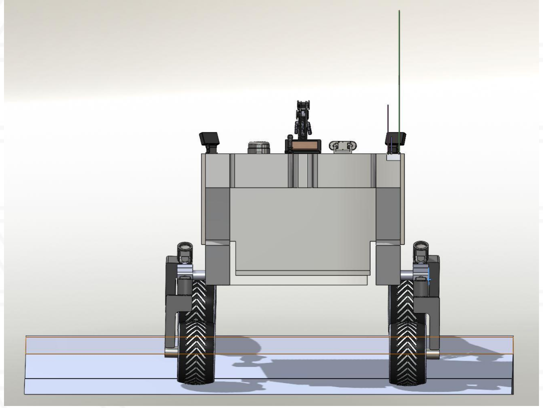
Suspension System Trade Studies

Suspension System	Advantages
Active Suspension (Independent Impendence Control)	1) Provides even wheel forces distribution to maximize traction 2) Allows climbing over rocks with more stable pose 3) Potential assist in relieving built-up drill forces.
Active Suspension (Kinematic Control)	1) Provides simple deploy capability. 2) Allows drill height and angle adjustment. 3) Allows greater ground clearance in rockier terrain. 4) Allows pitch and roll adjustments for improved CG on slopes and sun angle.

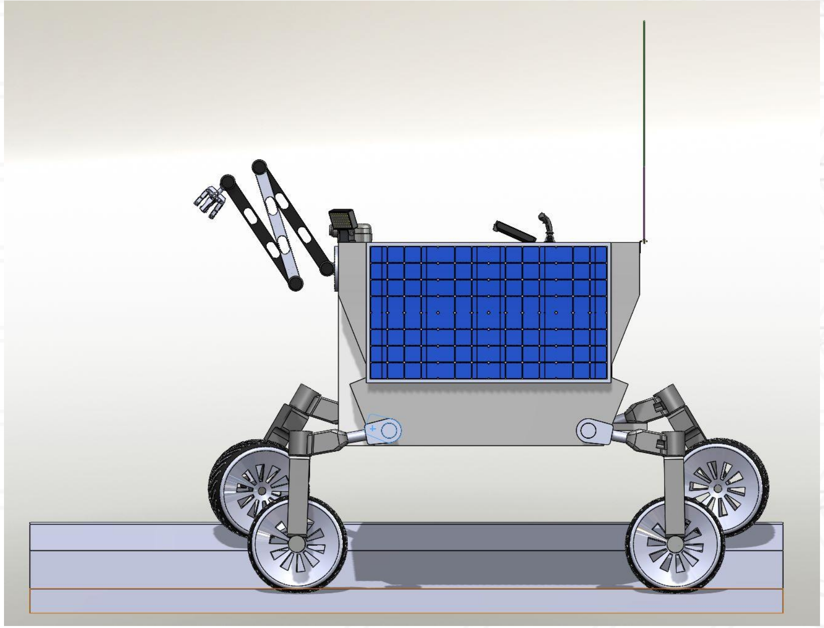
Suspension System - Active

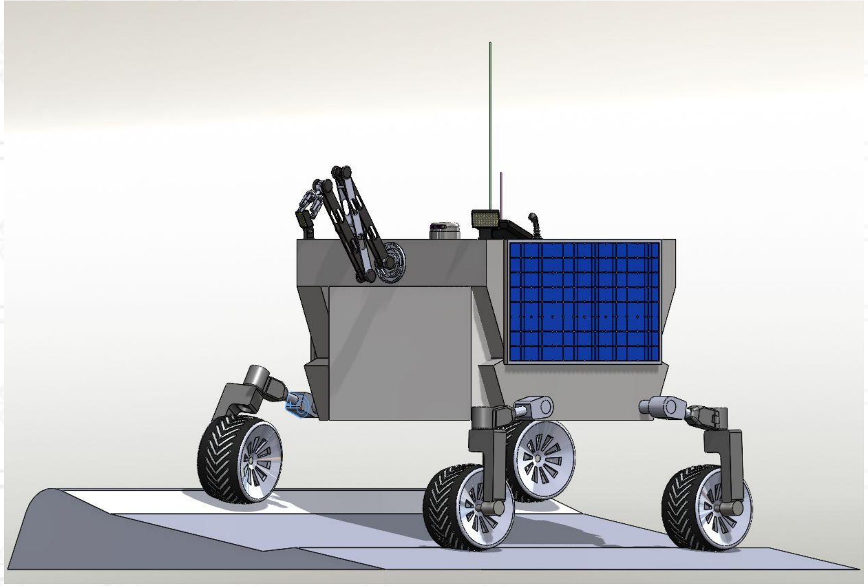




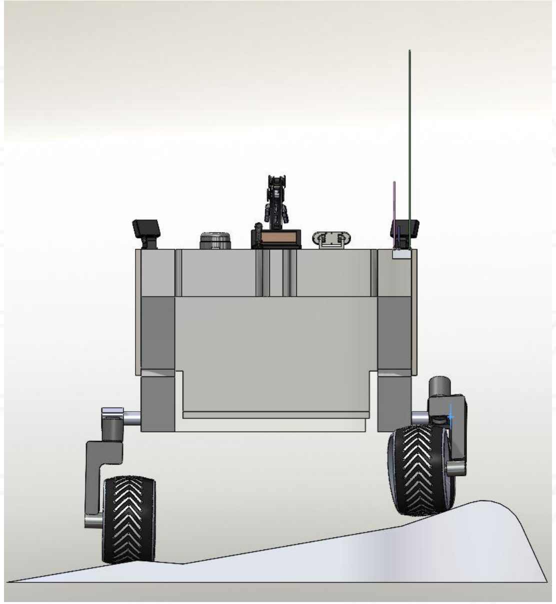


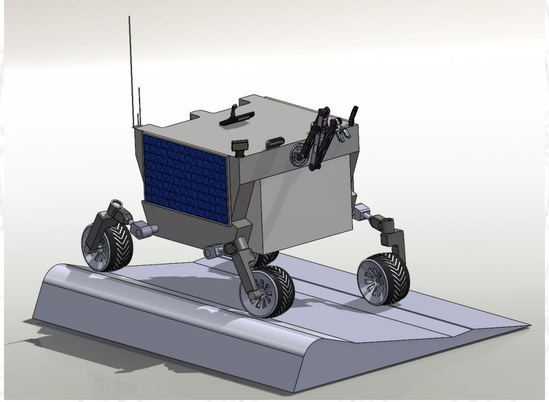
Suspension System - Active

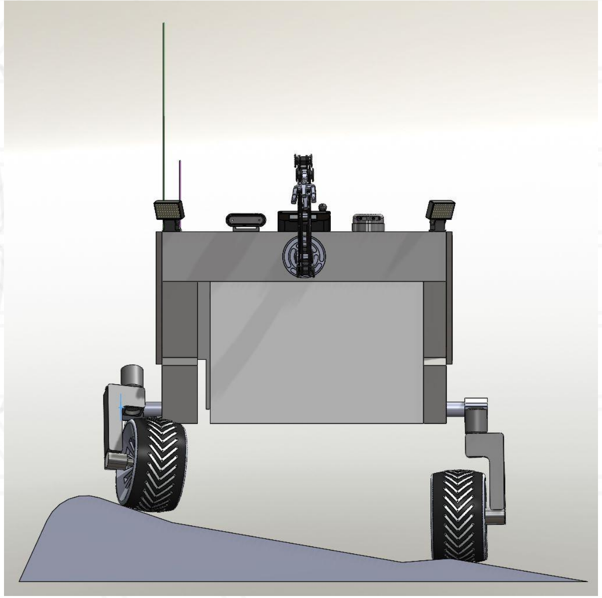




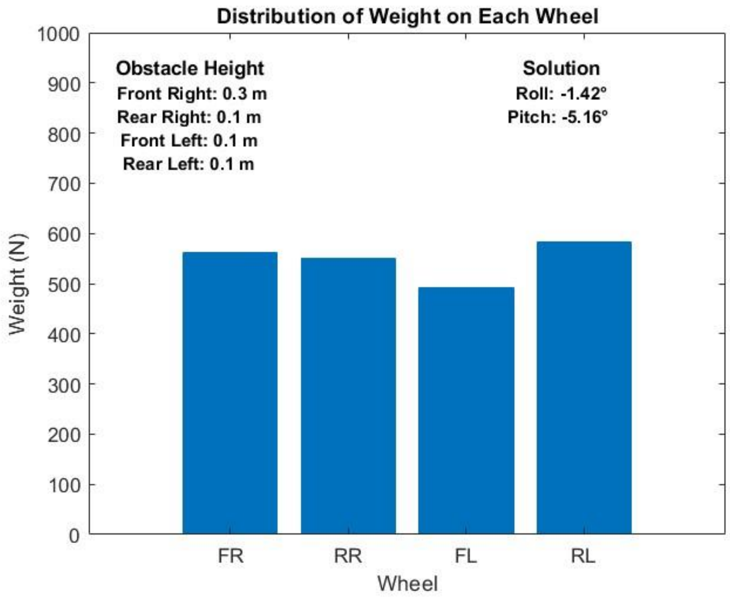
Suspension System - Active



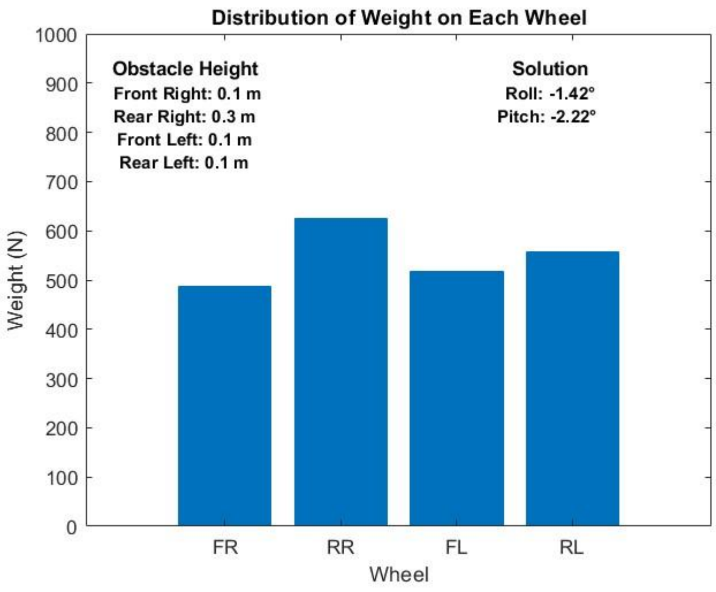




Suspension - Obstacle Clearance and Weight Distribution

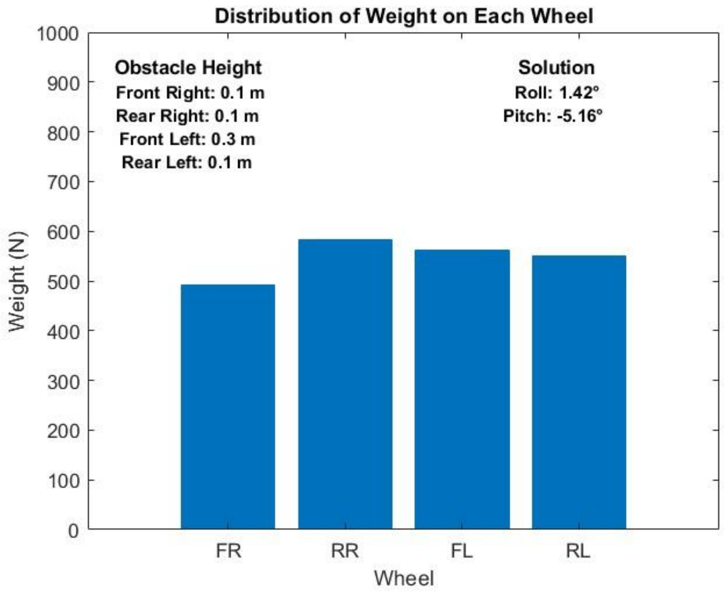


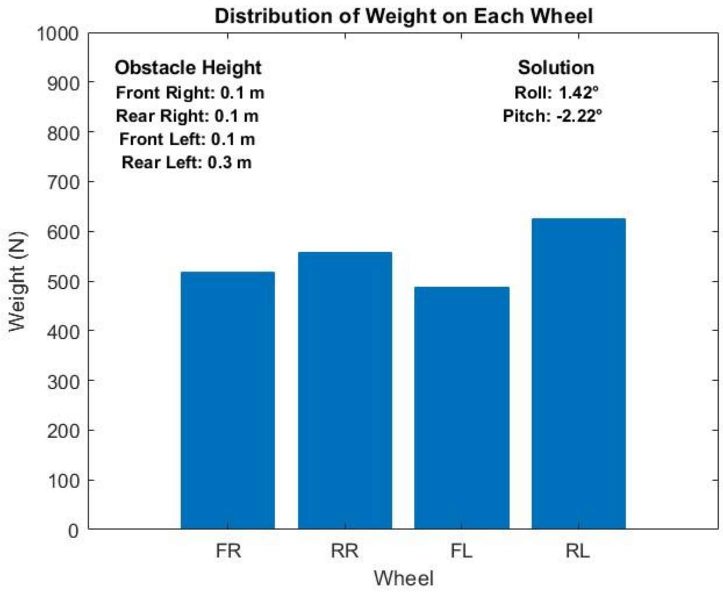
Front Right wheel goes over obstacle



Rear Right wheel goes over obstacle

Suspension - Obstacle Clearance and Weight Distribution

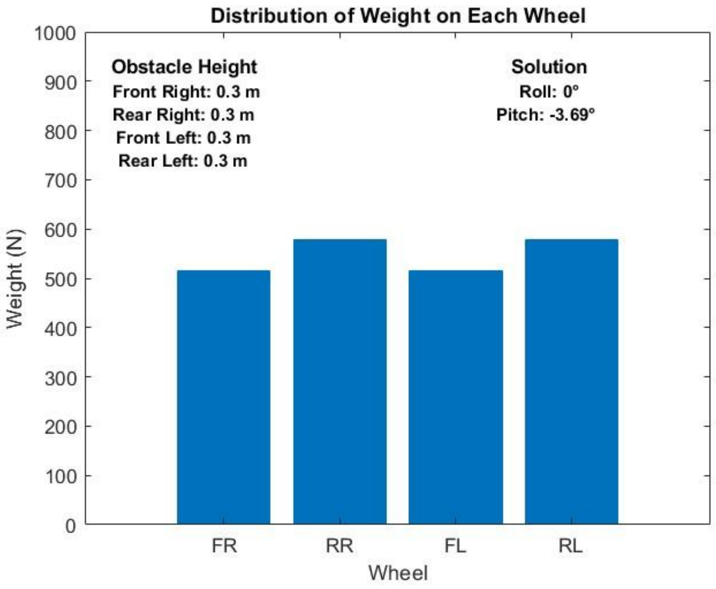




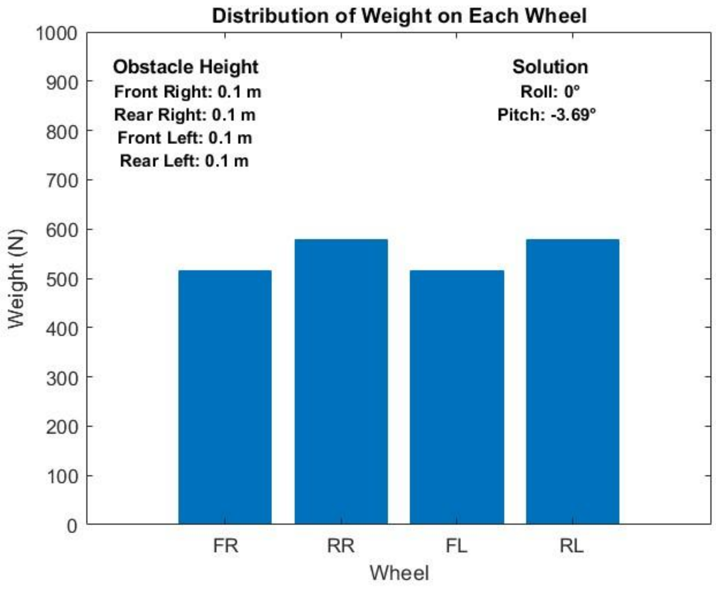
Front Left wheel goes over obstacle

Rear Left wheel goes over obstacle

Suspension - Obstacle Clearance and Weight Distribution

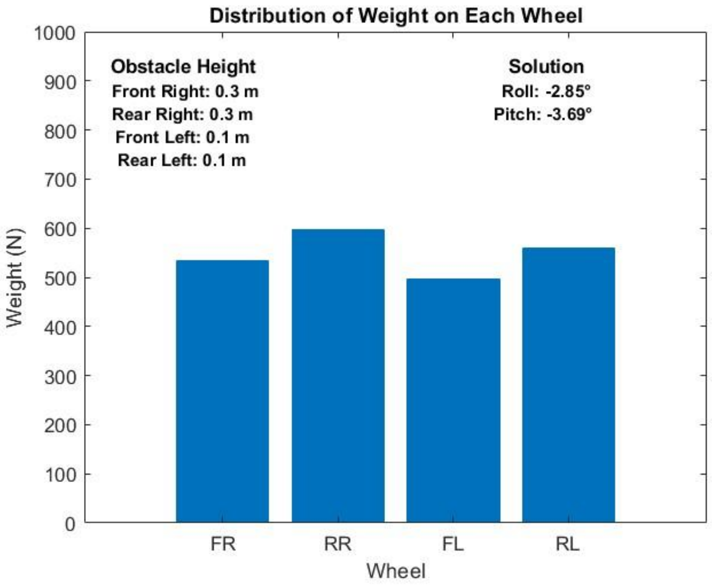


All wheels over the obstacle

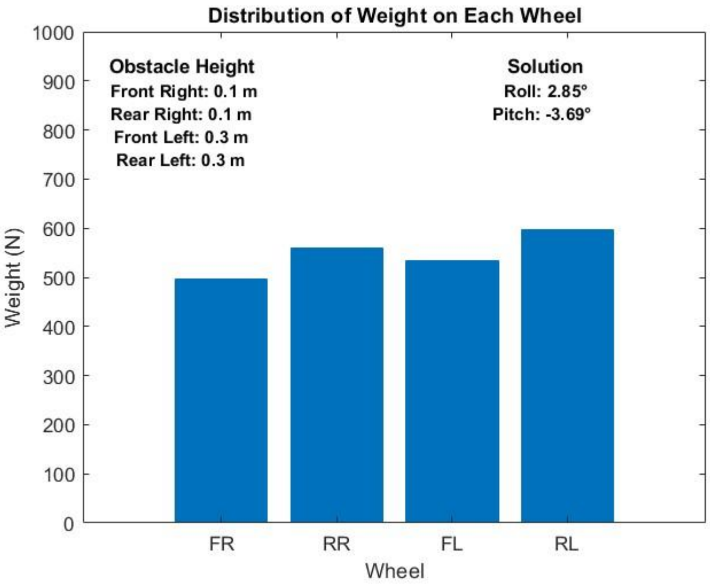


All wheels on level ground

Suspension - Obstacle Clearance and Weight Distribution



Right wheels going over the obstacle



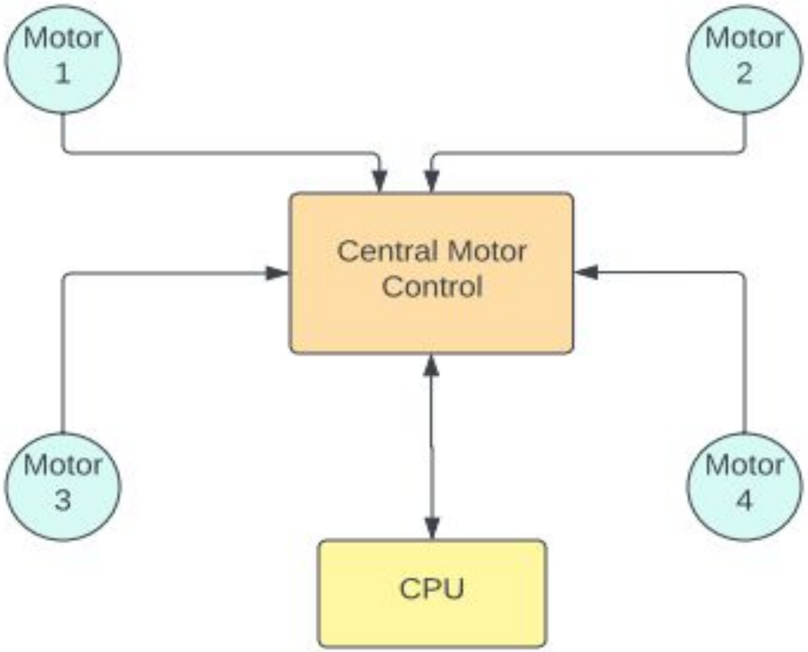
Left two wheels going over the obstacle

MOTOR

Motor Specifications

- Motors operate in temperatures up to -230 Degree Celsius.
- Dry Lubricant is used instead of wet lubricant on the bearings and gears to eliminate the wet lubricant freezeout.
- This helps in power efficiency and savings as heaters are eliminated.
- The system is highly reliable,modular and scalable.

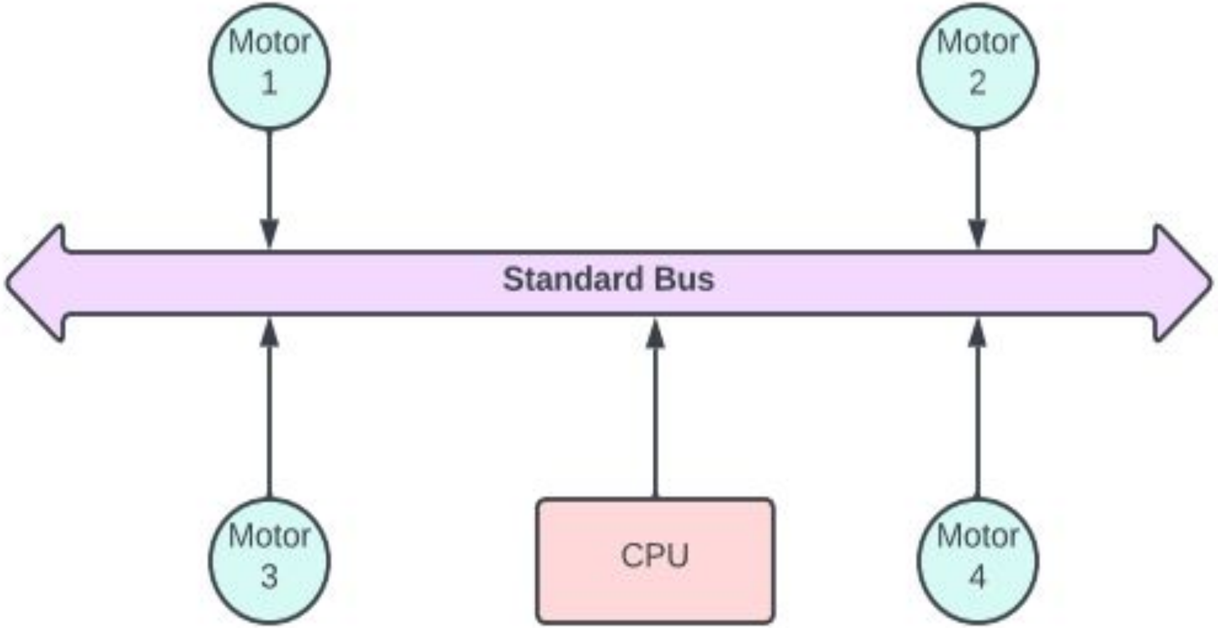
Traditional Centralized Motor Control



Traditional Motor Control

- Each motor has multiple wire connections
- 1000-2000 electrical wire harness around the system,which is extremely hard to manage and assemble.
- It is tedious to debug during experimentation as there are many wires to inspect.
- Insulating this system against heat, electromagnetic waves from other system would be expensive.
- This increases the weight and volume of the system.

Distributed Architecture for Motor Control



Distributed Architecture for Motor Control

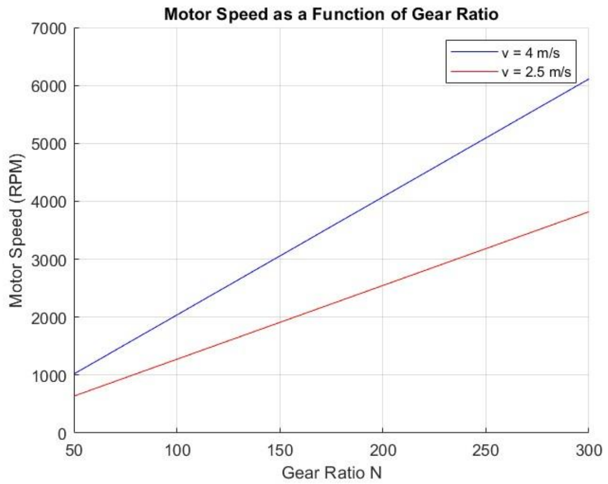
- This system consists of a standard bus for power and communication which is shared by all the the motors.
- Each motor and its corresponding sensors are attached to the standard bus.
- This eliminates the redundancies in electrical harnesses used for motors.
- This system helps in faster debugging and experimentation.
- Reduced noise and electrical power required

Electric Motor Trade Study

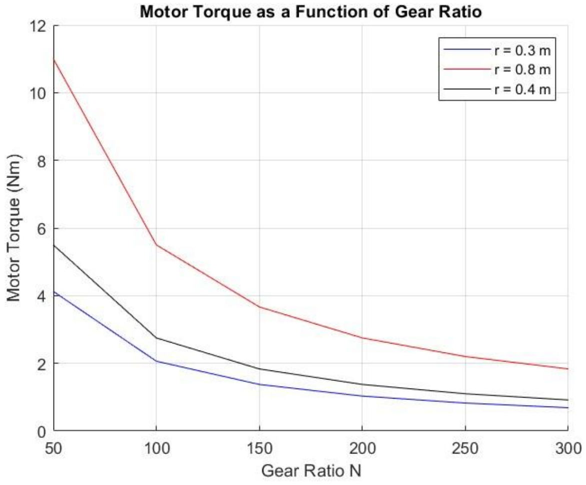
Motor Type	Applications	Drive	Advantages	Disadvantages
AC Induction	Domestic Appliances	Uni/Poly Phase AC	1)High Power 2) Least Expensive	1) Slip in Rotation
AC Synchronous	Electric Clocks	Uni/Poly Phase AC	1)Rotation is synchronous with frequency	1) Expensive
Stepper Motor	Positioning Systems	Multi-phase DC	1) Precision Positioning 2) High Holding torque	1) Lower Speed 2) Controller Required
Brushed DC Motor	Treadmill	PWM	1) Low cost 2) Simple control	1) Low Life Span
Brushless DC Motor	Electric Vehicles	Multiphase DC	1)Long Lifespan 2) Higher Efficiency	1) High Initial Cost 2) Requires a Controller

- Brushless DC Motor were chosen for wheel drive system of rover as they have higher efficiency and longer lifespan.

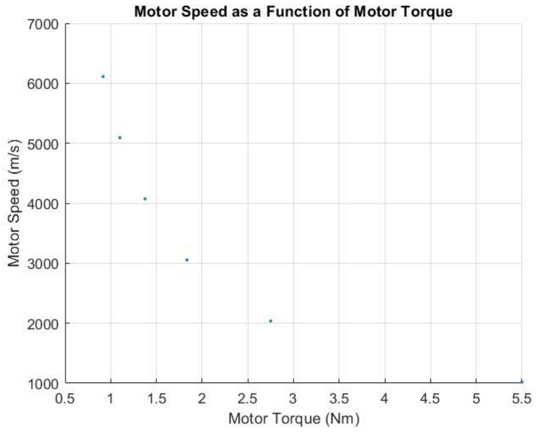
Electric Motor Analysis



Effect of gear ratio on motor speed



Effect of gear ratio on motor torque



Effect of motor torque on motor speed

Motor Trade Study

- Brushless DC motor selected for long lifespan and low maintenance
- Integrated motor-planetary gearbox motors were higher mass and volume than using harmonic drive
- Harmonic drive input rpm limits would not allow for wheel diameters smaller than 0.7m at rated torque for Earth-analogue
- Harmonic drive selected as motor gearbox for its lower mass and size, despite not being transferable to Earth-analogue

Motor Selection

- **Driving Motor**
  - Brushless DC motor selected for long lifespan and low maintenance
  - 4 high-RPM, low-torque motors.
  - 150W, 12V Motors, 0.48Nm Brushless, 3000 RPM, 3kg . https://www.ato.com/150w-bldc-motor
- **Steering and Suspension Motors**
  - Motors for steering and suspension require high torque, and do not necessarily require high RPM.
  - 4 motors for steering and 4 motors for suspension
  - 77 watt, 12V DC, 23 RPM, 30Nm, 4kg
  - https://www.grainger.com/product/DAYTON-DC-Gearmotor-12V-DC-1Z820

POWER - BUDGET, STORAGE AND SUPPLY

Power Budget

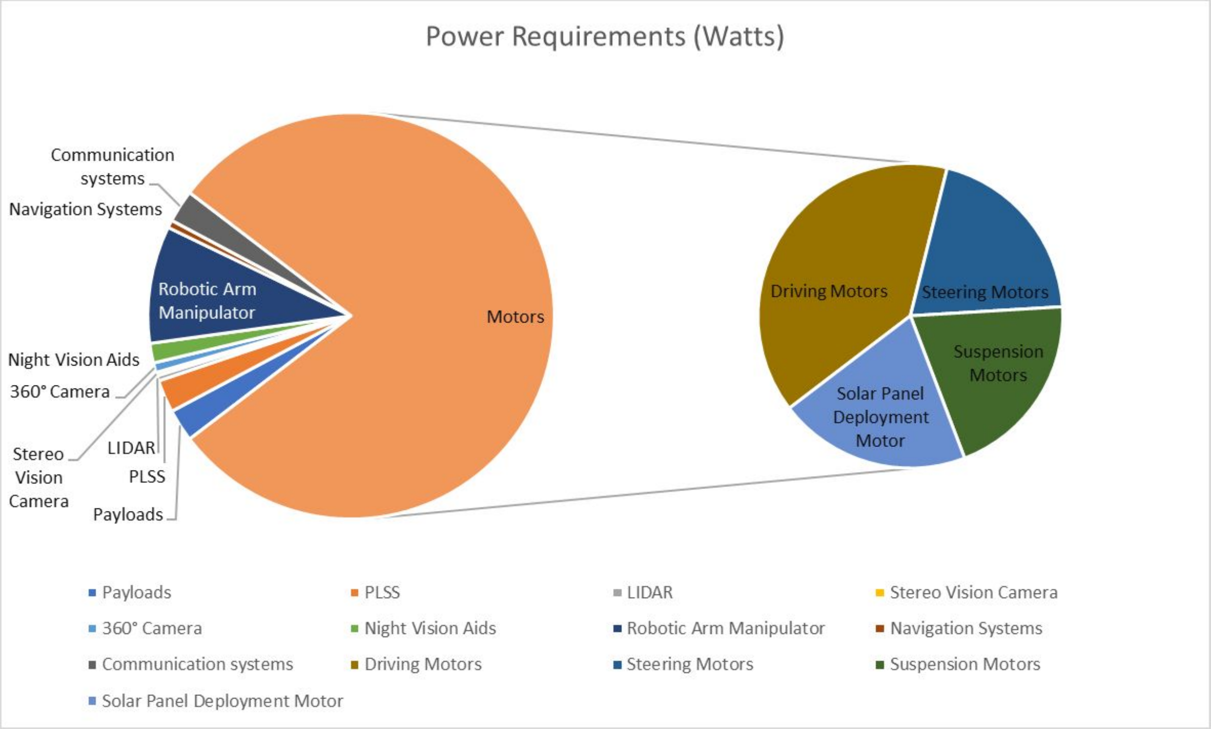
Component	Power Required (per component)	Quantity	Total power (Watts)
Payloads	50W	-	50W
Driving Motors	150W	4	600 W
Steering Motors	77W	4	308W
Suspension Motors	77W	4	308W
Solar Panel Deployment Motor	78W	4	312W
PLSS	50W	1	50W
LIDAR	8W	1	8W

Power Budget

Component	Power Required (per component)	Quantity	Total power (Watts)
Stereo Vision Camera	5.25W	1	5.25W
360° Camera	15W	1	15W
Night Vision Aids	15W	4	30W
Robotic Arm Manipulator	30W	6	180W
Navigation Systems	12W	1	12W
Communication systems	50W	1	50W

Power Budget

Total power required for max load ~ 2kW



Battery

- As calculated from the power budget, we may require a maximum of 2kW for full load conditions.
- Considering that the LTV will be traversing permanently shadowed region (PSR) for at least 2 hours and 2 hours outside PSR within a single charge.
- For our LTV, we will be using Li-ion batteries with 10.5kWh/kg with 6 kg of batteries, taking into account the redundancies and the mission life time of 10 years.
- Batteries are enough to traverse at least 30 km without recharge

Battery

- Battery capacity is sufficient for the LTV to last 150 hours continuous shadow (with power down at hibernation points)
- One battery will be connected specifically to the Payloads as a redundancy to keep it powered with 50W minimum even during shadow.
- Battery will be house within the frame of the chassis to maintain Center of gravity and to keep the rover compact.

Battery

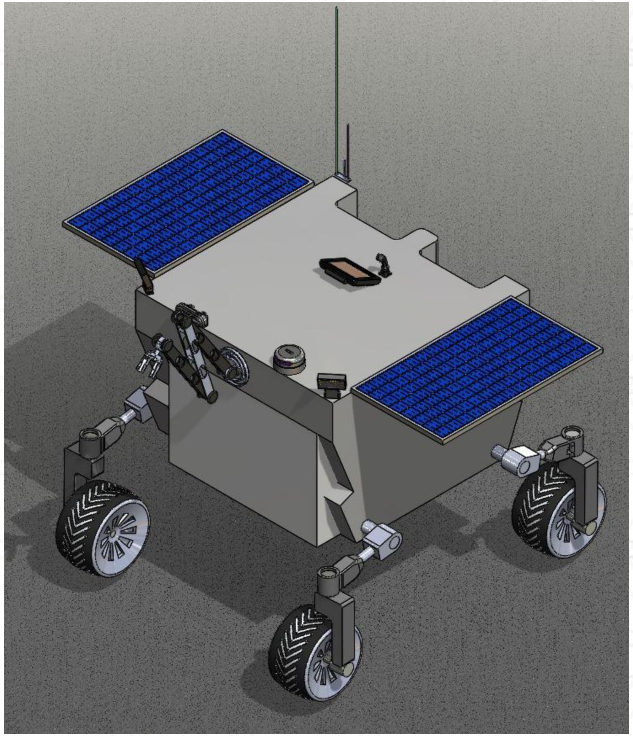
Hibernation is a state of reduced activity that allows a lunar vehicle to conserve energy and resources while on the moon. When selecting a location for hibernation, it is important to consider factors such as the availability of solar power, the level of radiation exposure, and the potential for dust contamination. Here are five potential locations for hibernation of a lunar vehicle:

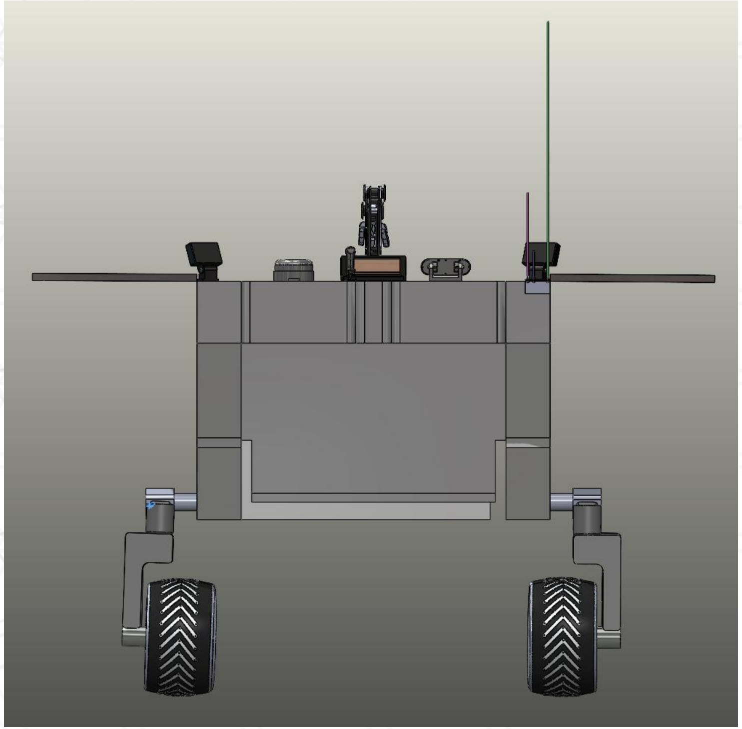
- Lunar poles: The lunar poles are areas on the moon where sunlight is available almost constantly, making them good locations for solar-powered vehicles to hibernate.
- Craters: Craters on the moon can provide shelter from the sun and cosmic radiation, making them good locations for hibernation.
- Lunar mountains: The sides of lunar mountains may offer partial protection from solar radiation, making them good locations for hibernation.
- Lunar caves: Lunar caves, also known as lava tubes, are underground tunnels that may provide protection from the harsh lunar surface environment. Caves where LTV can be stored should be analysed for safety and retrieval.

Solar Power

- From power budget earlier we see that maximum requirement at a given time would be approximately 2kW.
- At the same time we have 10.5 kW/kg required to recharge the battery.
- In addition to this, we need to consider the space constraints of the on the LTV.
- Hence we use deployable solar panels on the side of the LTV that can be folded by almost 90 degree using stepper motors with high torque. Each panel is approximately $3m^2$.
- High end solar panels are capable of delivering 110 W/m^2 for direct sunlight with an efficiency of 10%. Hence our solar panels are capable of delivering maximum of 6kW/h under ideal conditions.

Solar Power





Mass Budget

Mass Estimate (Kgs)	
Subsystem	Mass
Chassis and wheels	800kg
Motors (Steering,Driving, Suspension, Solar Cell Deployment)	4*4kg +4*3kg+ 4*4kg + 4*8kg = 76kg
Batteries	6*100kg = 600

Mass Estimate (Kgs)	
Subsystem	Mass
Solar Panels	2*25kg
Sensors and Electronics	10-15kg
Communications	5kg
Life Support System	5kg
Manipulator	50kg

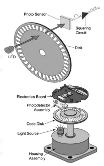
Operational Modes of Rover

- Odometry based motion model is used in this rover.
- The following modes will be implemented on the rover according to the assigned task and weather conditions :
  - Autonomous Mode
  - Tele-Operated Mode
  - Manual Mode
  - Safe Mode

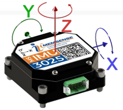
Sensors Onboard

- **Autonomous Navigation :**
    - Lidar & Cameras :
        - The combines Lidar and cameras provides vision to the rover for autonomous mode.
        - It is capable of building terrain models with 2cm accuracy,hence creates an accurate geometric information in 3D.

    - Wheel Encoders :
        - Measures the distance travelled by the rover by detecting the rotation of rover wheels.
        - It is capable of accurately measure the distance as the accuracy is about 0.20 degrees.



    - Inertial Measurement Sensor (IMU):
        - Provides 3-Axis information about rovers position and orientation,enabling accurate roll,pitch,yaw movements in autonomous mode.
        - Helps in estimating the degree of slope the rover is experiencing for further analysis.



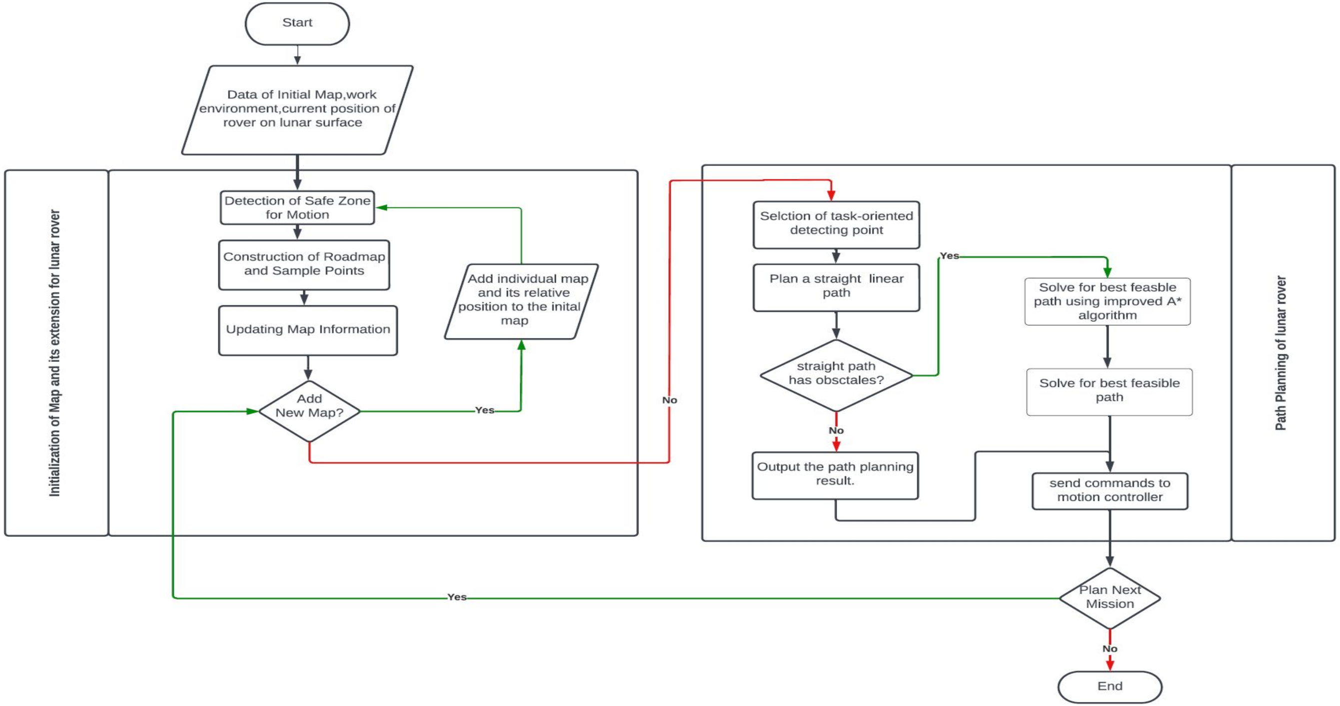
Sensors Onboard

- **Safety Sensors :**
  - Obstacle Detection Sensors :
    - Helps detects any obstacle around the rover to help maneuver carefully.
  - Electrical Thermal Sensor
    - Monitors the temperature of the onboard electronics and electrical systems,to optimize the battery charging cycle and extend the battery life
  - Voltage and Current Sensors:
    - Monitors for spikes in voltage and current across the components for fault detection and correction.

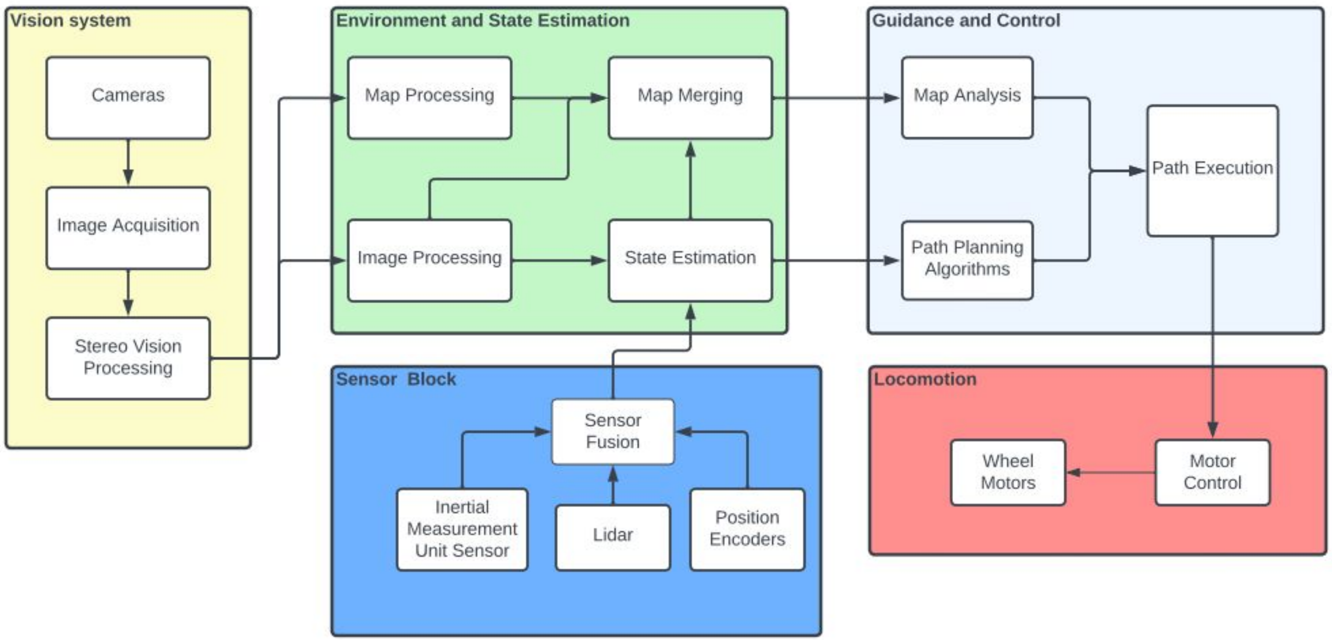
Sensors Onboard

- **Environment Sensors** :
    - Temperature Sensor
    - Pressure Sensor
    - Radiation Sensor
    - Relative Humidity Sensor
    - Wind Speed and Direction Sensor

Path Planning Flowchart



Navigation and Guidance Block Diagram



Autonomous Safety Systems

- Rollover Predictions Feature:
  - Generates an alternative path to the destination by predicting if the rover can traverse the slope of the terrain using its lidar and camera sensors.
  - In manual driving mode, it warns the astronauts about the steep terrain in their pathway so that they can maneuver the rover carefully.
- Return to home Feature:
  - If the rover detects any faults in mechanical or electrical system, it can autonomously return back to the base for further analysis and repair as it keep tracks of the waypoint while travelling without a planned destination.
- Self Diagnostic Feature:
  - The rover would run self diagnostics to check faults,cracks using its multiple sensors. It will signal a problem for repair when it tries to compare the optimum working conditions data and the present working condition data.

Communications

Communications are an extremely import part of space exploration.Communication can be accomplished using antennas which are powerful enough to either directly transmit data to the earth or to the nearest orbiters or station set up in the moon’s surface.

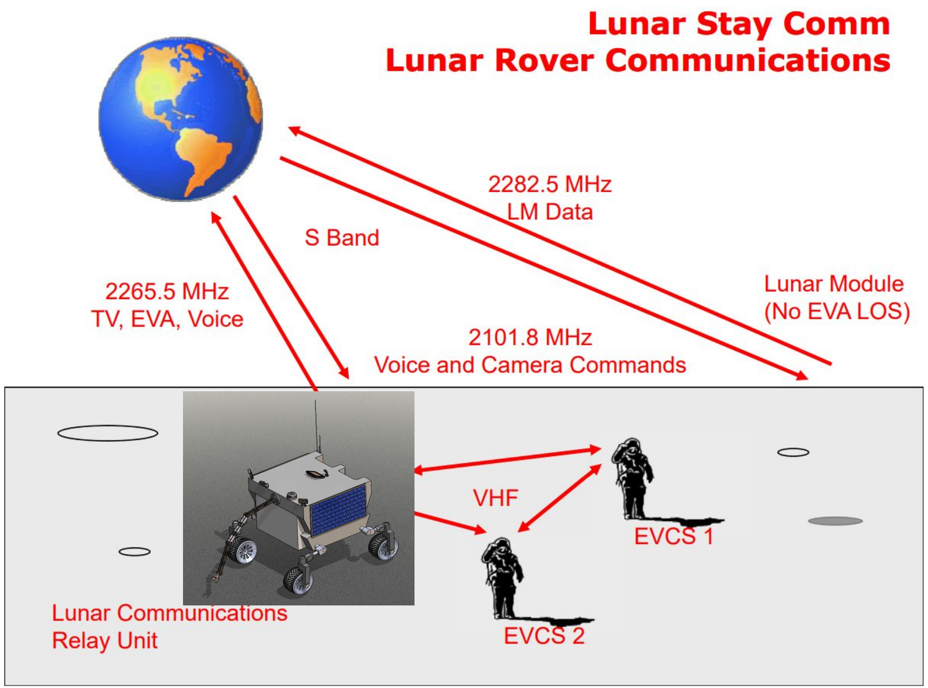
To communicate with the nearest orbiter or station,which can further relay the information to earth:

- Ultra High Frequency Antenna is used, as it operates at about 400 megahertz band. It transmits data at the speeds of 2 megabits per second.

Communications

- High gain antennas and low gain antennas are used to communicate with earth directly:
  - The X band high gain antennas operate at 8 gigahertz.It transmits data at the speed varying from 150-3000 bits per second. The advantage of this antenna is that it is steerable so that it can be pointed at the optimum position to focus its beam and transmit data faster
  - The X band low gain antennas also operate at 8 gigahertz. It is fundamentally used for receiving signals. It is omnidirectional,hence it can send and receive information efficiently.
- The communication system can receive commands remotely from the NASA Lunar surface by the NASA crew.

Communications



Video and Imagery

- Cameras are selected based on specific needs and requirements of the mission.
- Apart from cameras dedicated to autonomous operation of LTV, cameras are required to obtain video and still imagery of LTV operations and the lunar surface.
- The factors selecting a camera for use in a lunar vehicle include it’s weight/size, durability, image quality and power consumption.
- Camera should be able capture high resolution images of lunar surface/scientific targets of interest, given the harsh conditions of space(temperature, radiation, vacuum) and limited power supply.

Video and Imagery

Following are earth based cameras when modified for space conditions serve the required goals.

- Sony BRC-X400 4K with 8.5MP, operates on 12V 25.5 W Max power consumption. It weighs around 3 lbs(1.8kg) and supports wide range of interfaces. It's a PTZ (Pan-Tilt-Zoom) camera also supports image stabilization. This allows us to survey environment with 2 DoF and zoom in on object of interest.

Video and Imagery

- Luxonis OAK-D Pro W with 12MP, operates on 5.25V 7.5 W Max power consumption. It weighs around 91 grams and supports wide field of view(120°/150°). It supports active stereo depth, night-vision, edge detection, feature tracking, object detection, semantic segmentation, motion zooming and estimation.
- When attached to 2 or 3 DoF mast, it can track astronauts in 360°, with 15-35 depth perception range can feed information to AI based system for further analysis.

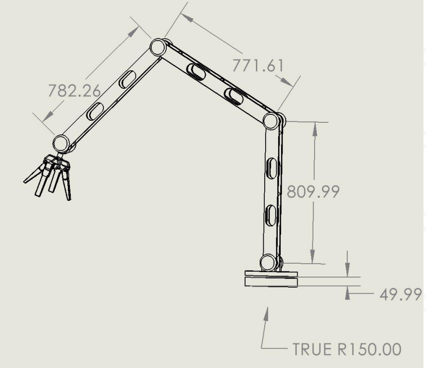
Video and Imagery

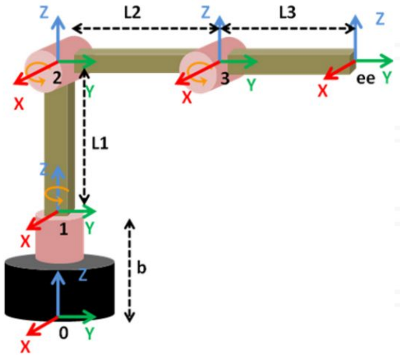
- THETA Z1 with 23MP 7K, operates on 5V 15 W Max power consumption. It weighs around 182 grams and supports 360° vision. It supports spherical 360° video or images capture, noise reduction at low light conditions, and ability to create immersive VR experiences of lunar surface.
- To cover entire space around LTV and capture all events in single frame this 360° camera comes handy. It can also work as remote troubleshooting camera.

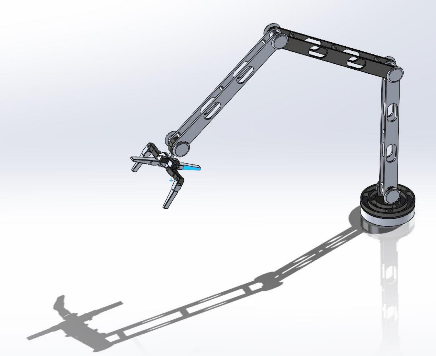
Robotic Manipulator

A lunar vehicle robotic manipulator, also known as a robotic arm, is a mechanical device that is used to perform tasks on the surface of the moon. These tasks may include tasks such as:

- Collecting samples: A robotic manipulator can be used to collect samples of soil, rock, or other materials from the lunar surface.
- Deploying instruments: A robotic manipulator can be used to deploy scientific instruments or other equipment on the lunar surface.
- Performing maintenance: A robotic manipulator can be used to perform tasks such as cleaning or lubricating components of a lunar vehicle.
- Manipulating objects: A robotic manipulator can be used to move, lift, or position objects on the lunar surface.





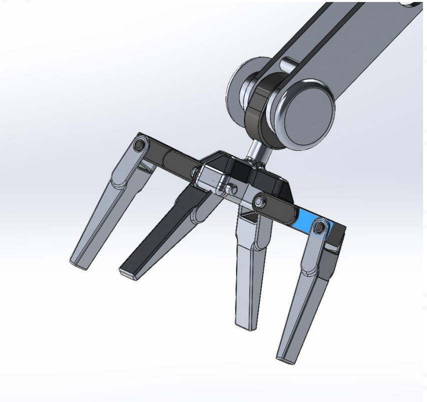


Robotic Manipulator

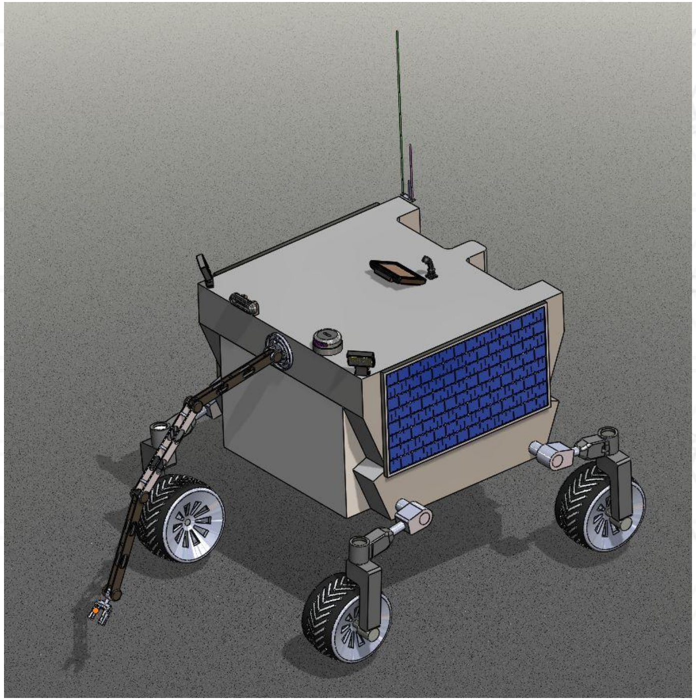
An end effector is a tool or device that is attached to the end of a robotic arm and is used to perform a specific task. Some examples of end effectors that might be used on a lunar robotic arm include:

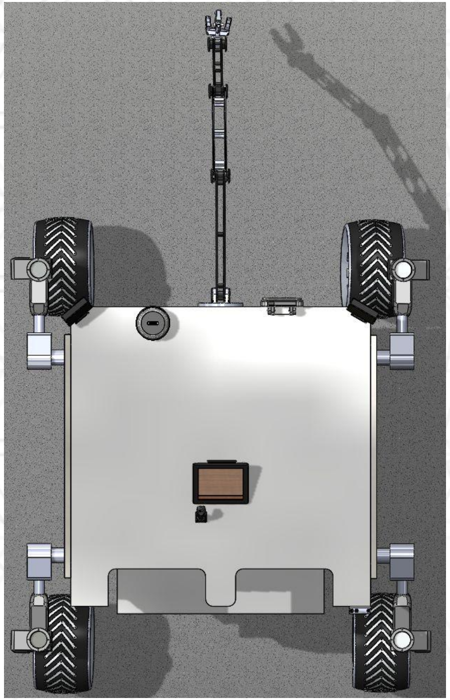
- Grippers: Grippers are used to grasp and manipulate objects. They may be designed to grip a wide range of objects, from small rocks to large structures.
- Drills: Drills can be used to bore holes into the lunar surface or to collect samples of soil or rock.
- Cameras: Cameras can be used to take images or video of the lunar surface or objects on it.
- Sensors: Sensors can be used to gather data about the lunar environment, such as temperature, humidity, or radiation levels.
- Sampling tools: Sampling tools can be used to collect samples of soil, rock, or other materials from the lunar surface.

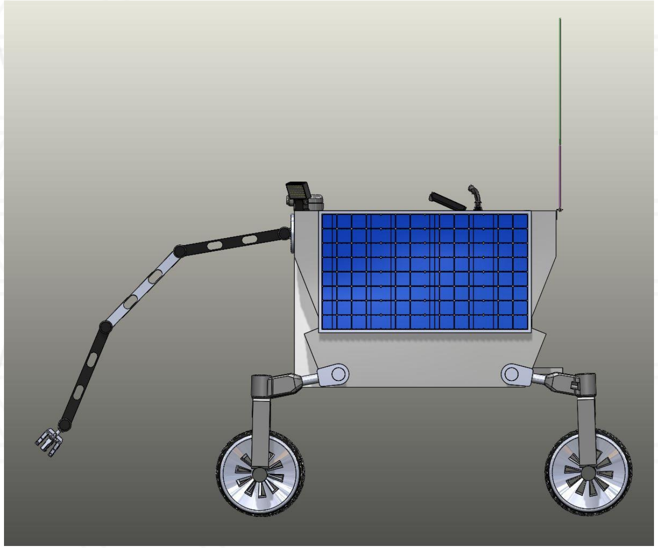
Thus new and different end effector can added as per requirement of the operation and according to the design the robotic arm can easily be removed and stored when not in use. Tools are provided for astronauts for easier addition and removal of new end effector.



LSTER With Robotic Manipulator

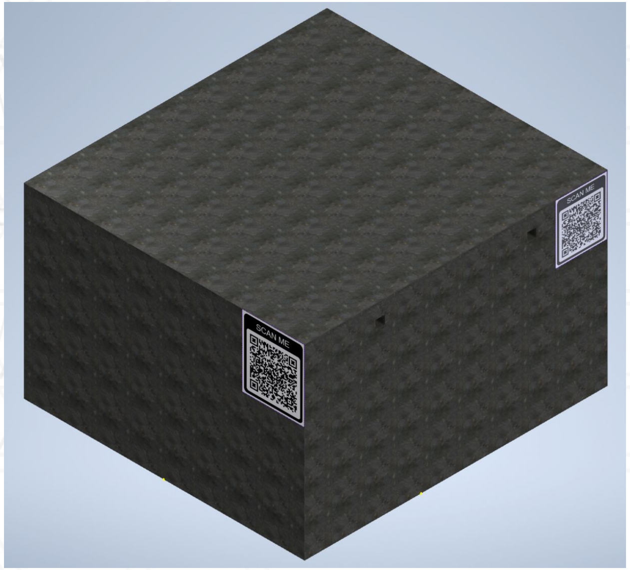






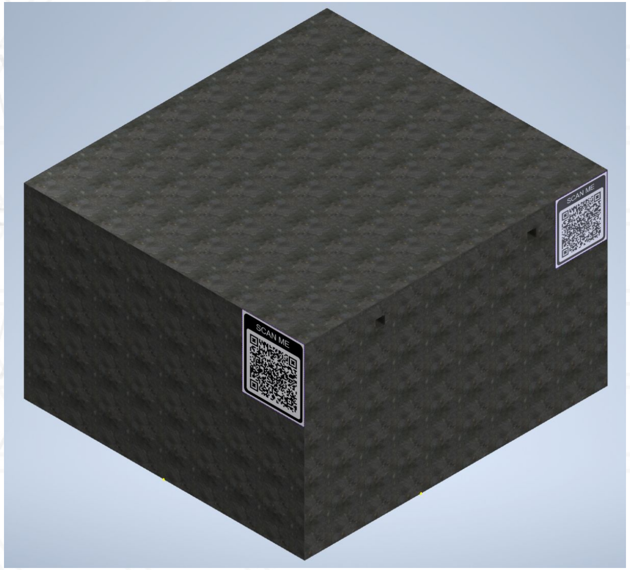
Payloads/Cargo

- Payload/Cargo is generally a cuboid box which can sealed/opened by astronauts.
- Payload/Cargo can have max volume of 2.43 m^3. Is designed to protect equipments from harsh conditions of lunar surface.
- Payload/Cargo can be picked up or jettisoned on control of EVA crew or remote operation.



Payloads/Cargo - Electronics

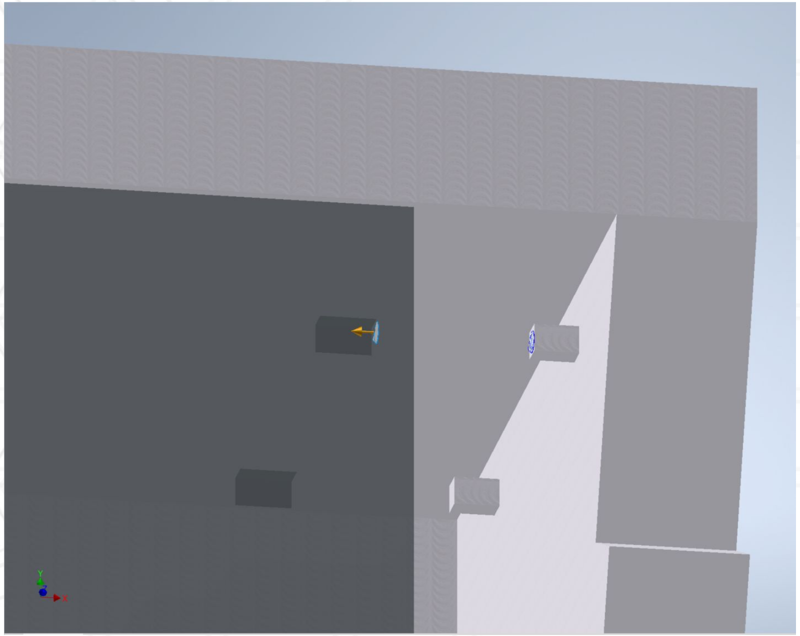
- Payload/Cargo has QR code labeled which can be recognised by on-board cameras.
- Payload/Cargo takes DC input 12V 50W from chassis.
- Payload/Cargo has NFC ISO 15693 standard, through which LTV can read from distance of 3 feet.
- Payload/Cargo communicates with LTV and lunar base station using VHF 296.8 MHz.



Payloads/Cargo - Handling

- The LTV is designed kneel down so as to load or unload the payload/cargo.

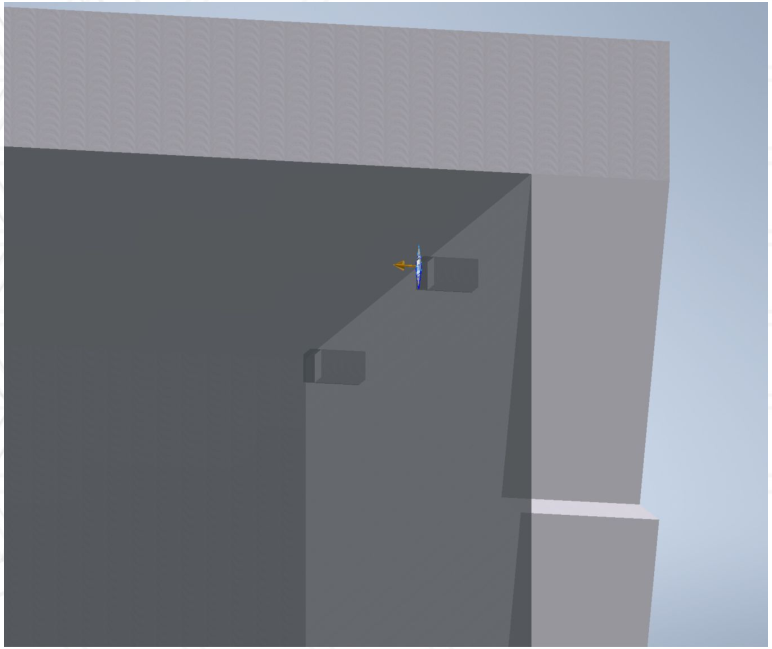
- As shown in figure, there is an interlocking feature between LTV and the payload.



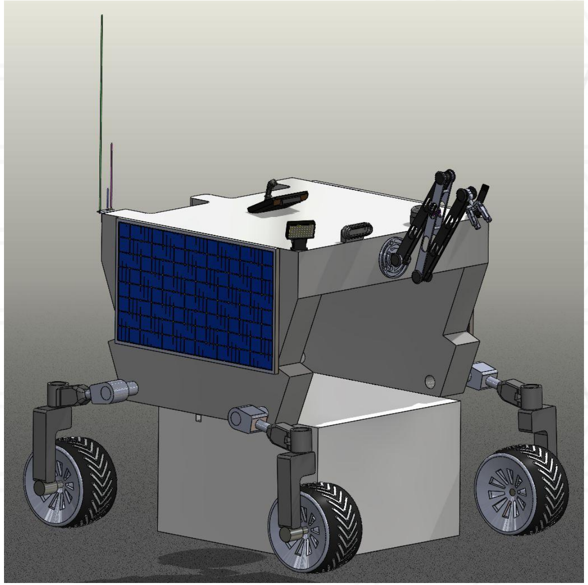
Payloads/Cargo - Handling

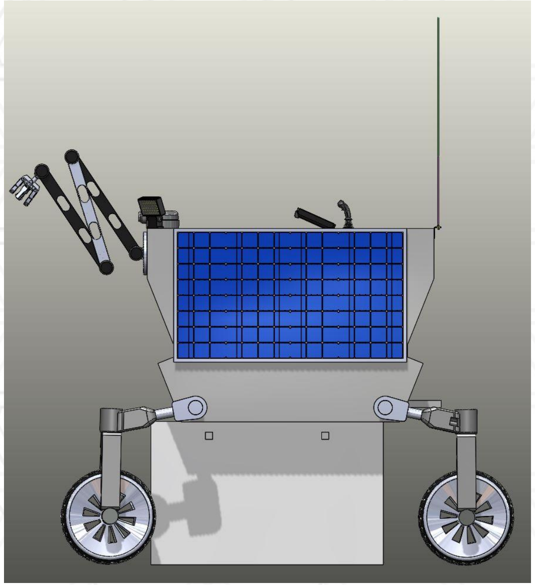
- Once the payload/cargo is aligned, the interlocking parts move into payload so as hold it in place as shown in figure.

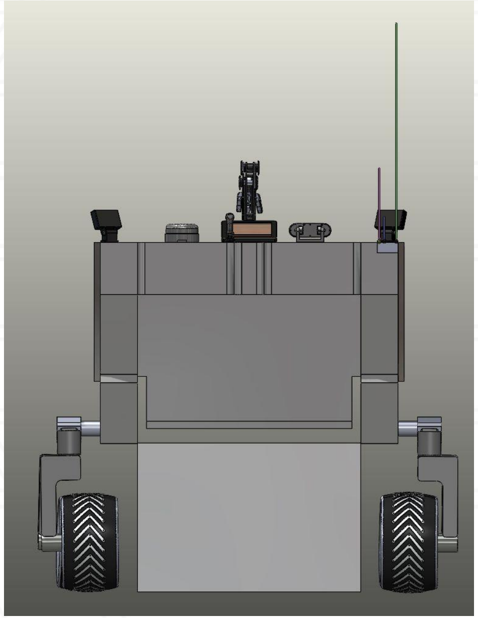
- These interlocking interface also double as electrical power input, connected electronics bus to the LTV.



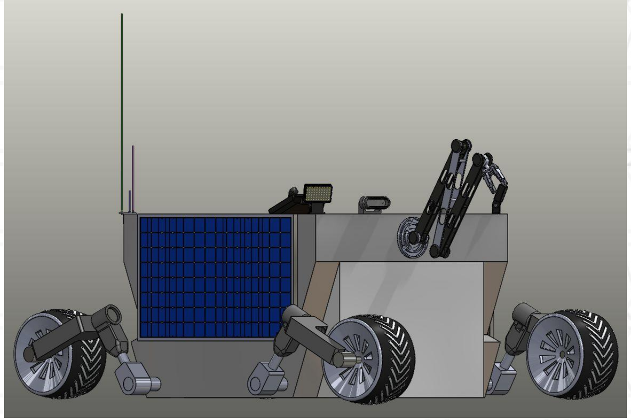
Payloads/Cargo - Loading alignment

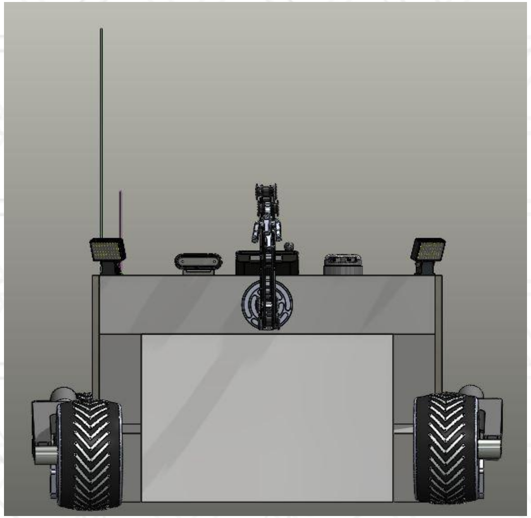


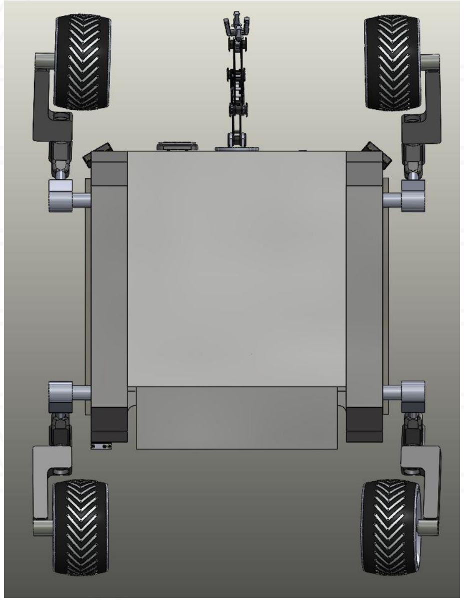




Payloads/Cargo - Locking & secure



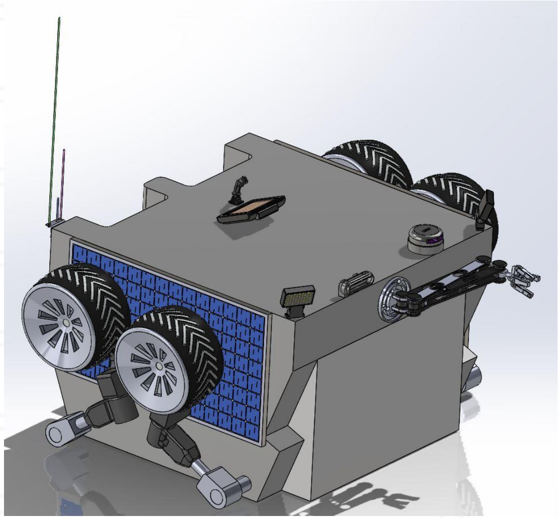




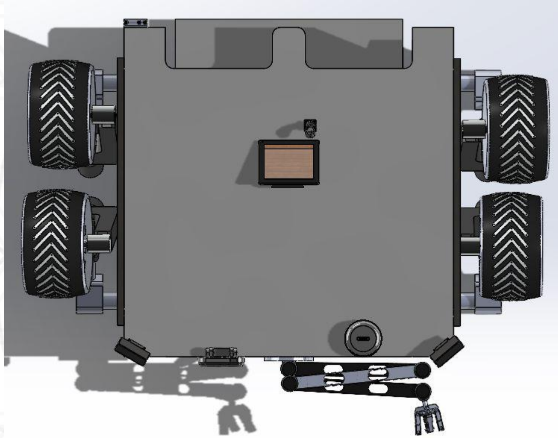
Delivery System

- The LTV will be delivered to the lunar surface by the lunar module. The lunar module consisted of two parts: the descent stage, which was used to land on the Moon, and the ascent stage, which was used to return to orbit and rendezvous with the command module.
- The LTV will be stored in the descent stage of the lunar module and will be deployed after the lunar module has landed on the Moon. To deploy the LTV, the astronauts first have to open the lunar module hatch and lowered a folding ramp to the lunar surface. Then drive the LTV out of the lunar module and onto the surface of the Moon.
- Once on the lunar surface, the astronauts were able to use the LTV to explore the surrounding area and conduct scientific experiments.

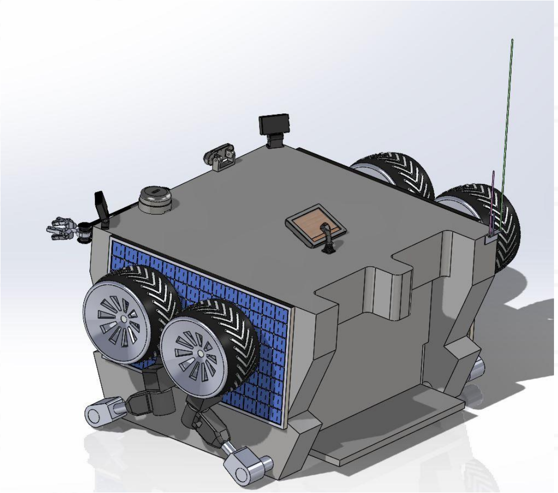
Delivery Package



LSTER in storage mode with payload (Front -Right Side View)



Packed LSTER (Top View)



LSTER in storage mode with payload (Rear-Left View)

Service life

Additional spare parts for LTV or payload can be sent in initial or subsequent flight missions to increase the service life of the LTV missions.

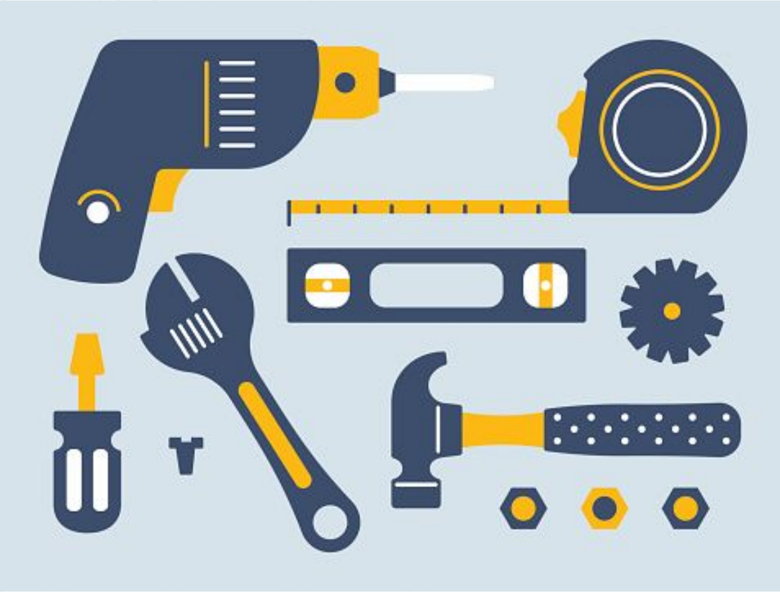
Ways to increase service life of lunar vehicle:

- Use durable materials: Materials that are resistant to extreme temperatures and rugged terrain can help extend the service life of a lunar vehicle.
- Utilize robust communication systems: Reliable communication systems that can transmit data over long distances and through challenging terrain can help ensure that the vehicle can be effectively monitored and controlled, which can help extend its service life.
- Implement effective power management: Properly managing the vehicle's power consumption can help extend the life of its batteries and other power sources, which can help extend the overall service life of the vehicle.
- Implement effective maintenance procedures: Regular maintenance and upkeep can help prevent wear and tear on the vehicle and extend its service life.
- Use efficient design: An efficient design that minimizes the number of moving parts and reduces the overall weight of the vehicle can help reduce wear and tear and extend its service life.

LTV Lunar Surface Maintenance

- Astronauts will be equipped with all the necessary tools with LTV during the initial flight to lunar surface.

- Subsequent flight missions to moon can bring much more sophisticated tools and spare units to make maintenance an easier task. Tools can evolve over time, thus giving astronauts state of the art tools.



LTV Lunar Surface Maintenance

Lunar surface vehicles require regular maintenance to ensure that they continue to function properly and to extend their service life. Some specific tasks that may be included in the maintenance of a lunar surface vehicle include:

- Inspecting and replacing worn or damaged parts: This can include things like tires, wheels, and other components that may be subject to wear and tear.
- Cleaning and lubricating moving parts: Lubricating moving parts can help reduce friction and wear, while cleaning can help prevent dust and debris from causing damage.
- Checking and maintaining power systems: This can include tasks such as inspecting and replacing batteries, checking solar panels for damage, and ensuring that the vehicle's power management systems are functioning properly.
- Testing and calibrating sensors and instruments: Ensuring that the vehicle's sensors and instruments are functioning properly is critical for its performance and safety.
- Conducting system checks: Periodically checking the overall functioning of the vehicle's systems can help identify any potential issues and ensure that it is operating at its best.

Crew System - Ingress & Egress

- The rover can accommodate two astronauts.
- The astronauts stand while operating the rover manually to avoid bending the suits.
- The astronauts are strapped on to the rover using a 5 point harness.
- The rover has a fault protection algorithm which would prevent the rover from crossing the stability limits of the rover.
- Ingress and egress refer to the process of entering and exiting a vehicle or other enclosed space. In the context of a lunar rover, ingress would refer to the process of an astronaut entering the rover, while egress would refer to the process of the astronaut exiting the rover.
- It is important to carefully plan and execute ingress and egress procedures, as they can be risky in the harsh environment of the Moon. For example, an astronaut may need to be tethered to the rover or to a safety line to prevent them from floating away in the low lunar gravity.

Mars Testing Considerations

- Torque and speed for driving and steering motors will need to be recalculated to account for the Martian terrain environment.
  - With increase in weight due to Mars' gravity:
    - Drive motors will require increased torques
    - Speed may remain the same for safety purposes
    - Gearing ratios will need to be reaccounted for as the motor mass increases
    - Steering motors will require more torque due to increased gravity
- Slight adjustments in wheelbase, axle length will be required due to gravity.

Future Works

- Perform Thermal Analysis on the rover.
- Make the rover compatible for martian atmosphere.
- Research command and data handling components to size
- Research on higher efficiency power generators like Radioisotope Thermoelectric Generator.
- Develop modular wheel concepts
- Multi LTV swarm deployment.

Conclusion

The current design of this project, adheres to the design mobility requirements.

- The proposed design would accommodate 2 astronauts and the required payload.
- The wheel design and motors selected would provide ample amount of torque and speed and can handle all types of lunar terrain.
- The power system can handle and provide energy for required range and duration
- The rover is has adequate stability to keep the astronauts and payload safe.

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