Term Project Final Report

By

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Goal

The goal of the Term Design Project is to develop a preliminary design of the Artemis Lunar Terrain Vehicle [LTV] based on RFP specifications. The design must involve the selection of chassis system, support system, navigation and guidance systems for the rover.

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Lunar Terrain Vehicle Requirements

LTV is an unenclosed rover that astronauts can drive on the Moon while wearing their spacesuits. It should support at least 10 years of the Artemis Program.

Performance requirements can be found below:

- Two suited crew members plus 500 kg of cargo
- Max speed of 15 km/h
- Traverse 20 km on a single charge
- Survive 100 hours of polar nighttime
- Should be able to climb a 15 deg slope.
- Support 8 hours of EVA

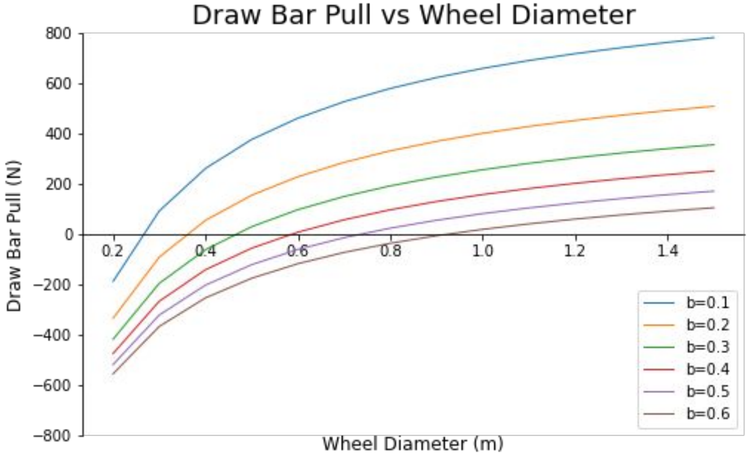
Terramechanics

Rover Mass Estimation

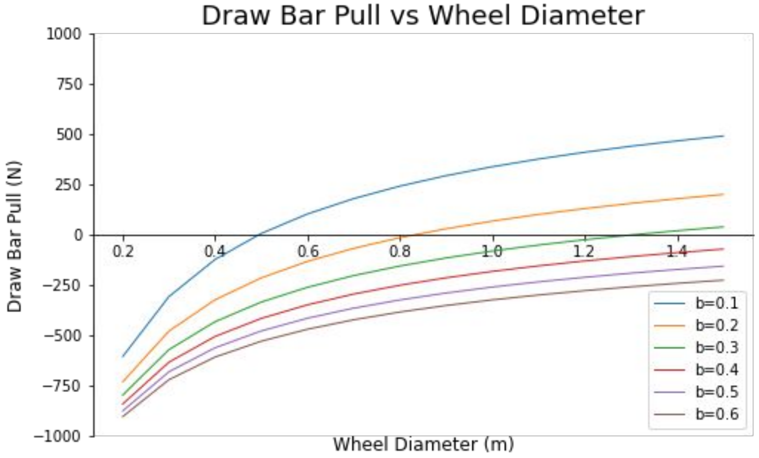
- Mass of EVA Spacesuit = 280 lbs = 127 kg
- Mass of Astronaut = 70 kg
- Mass of Cargo = 500 kg
- Mass of Rover = 300 kg [Curb Mass]
- Mass of Rover = 1194 kg [Gross Mass]
- Rover will be designed for a Gross mass of 1400 kg

Comparing Number of Grousers and Grouser Heights

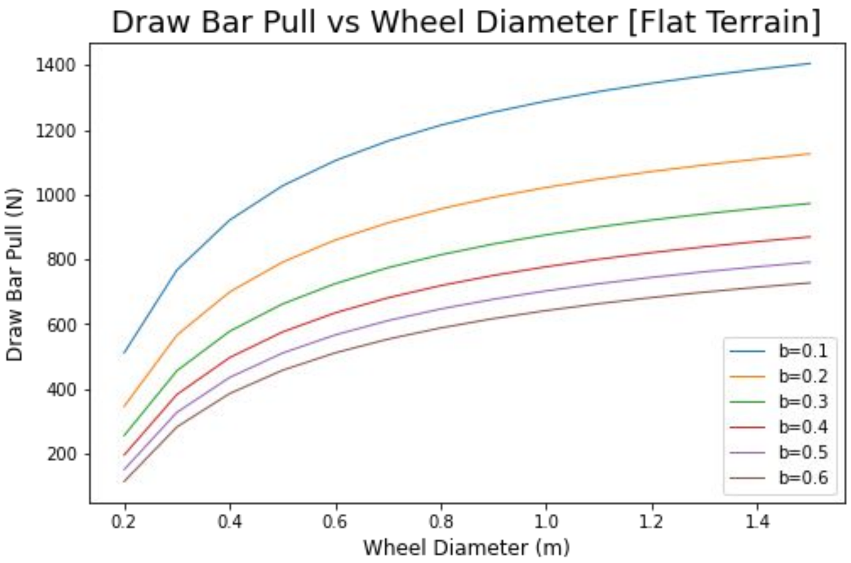
For a wheel with 16 x 6cm grousers, slip ratio is 0.6

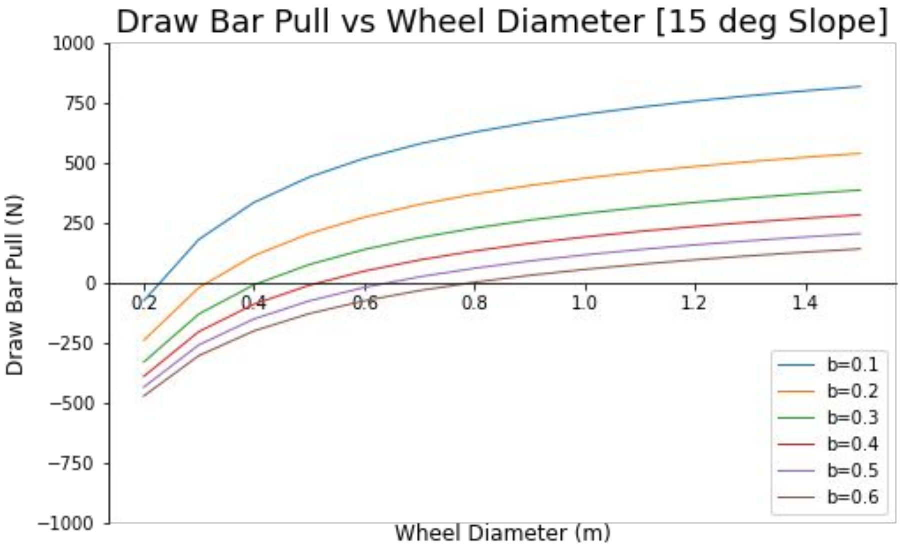


For a wheel with 16 x 6cm grousers, slip ratio is 0.3

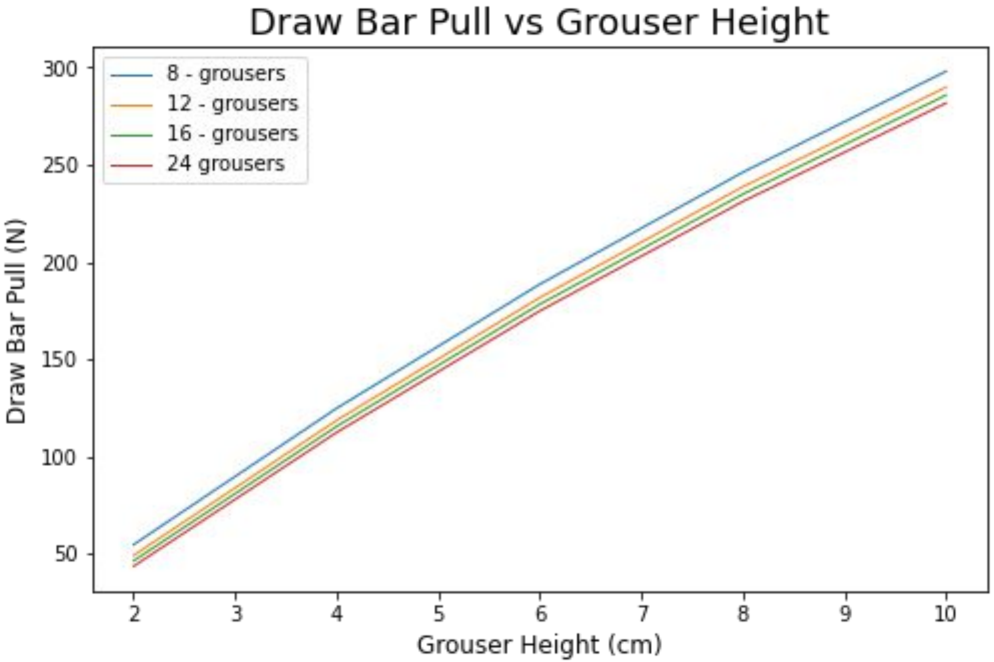


15 deg Slope vs Flat Terrain



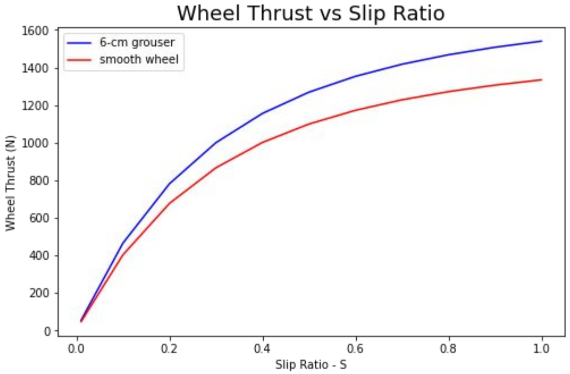


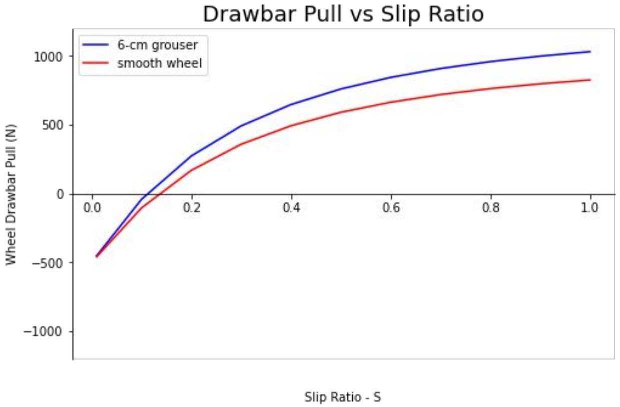
Comparing Number of Grousers and Grouser Heights



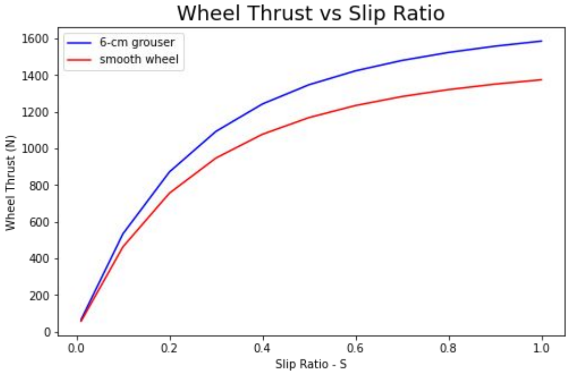
Wheel Thrust and Drawbar Pull for various Slip Ratios

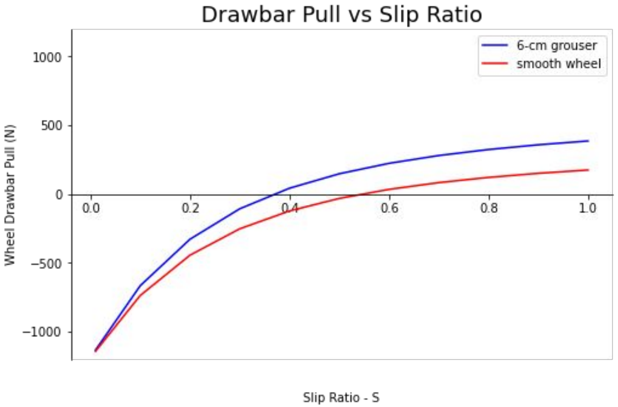
Study performed on 16x6-cm grousers of 1m diameter, 30cm width [Flat Terrain]





Study performed on 16x6-cm grousers of 1m diameter, 30cm width [15 deg Slope]





Final Wheel specifications

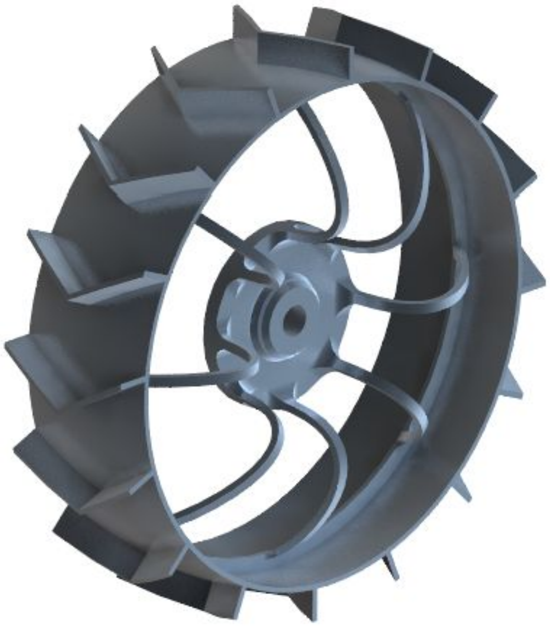
Conclusions:

- Grousers provide higher Tractive Force than Smooth Wheels.
- Compaction Resistance increases with Number of Wheels, but reduces as Wheel Diameter and Wheel Width increase. Therefore, Drawbar Pull is higher for larger wheels with shorter wheel widths.
- Increasing Grouser heights also increases Drawbar Pull.

Specifications:

- Wheel Diameter = 1 m
- Wheel Width = 30 cm
- Number of Grousers = 16
- Height of Grousers = 6 cm
- Slip Ratio = 0.6

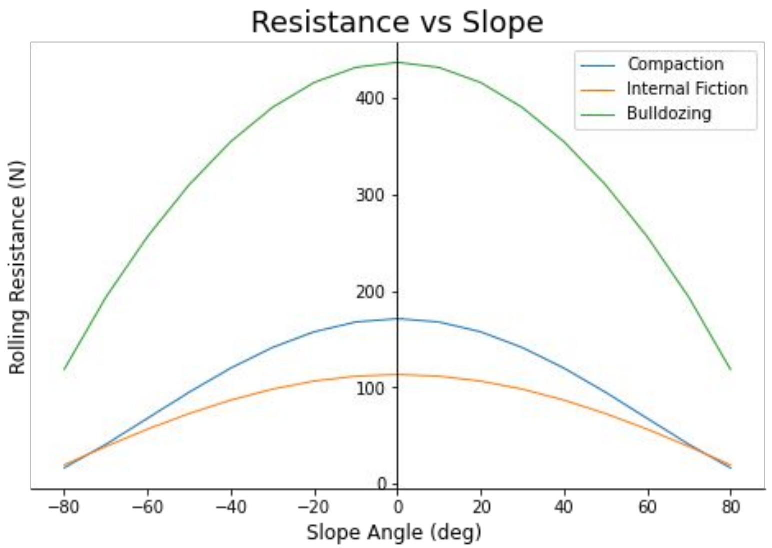
Wheel Design

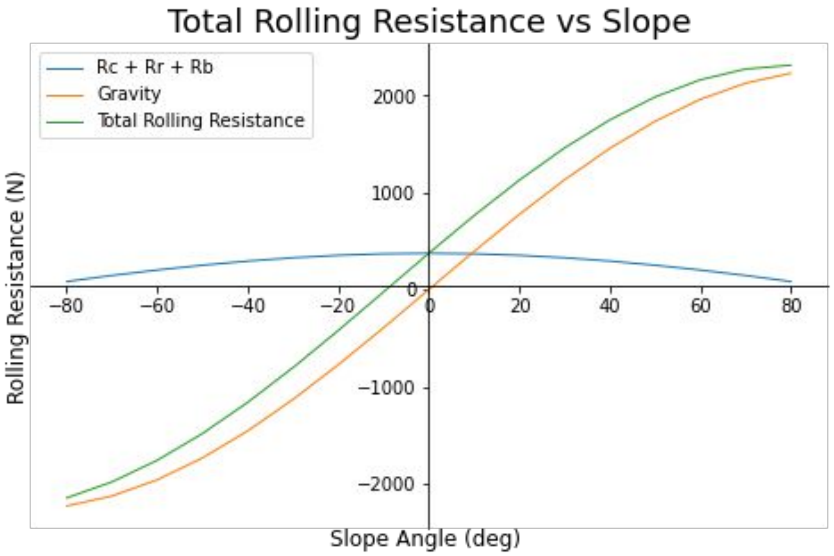


Specifications

- Wheel Diameter = 1 m
- Wheel Width = 30 cm
- Number of Grousers = 16
- Height of Grousers = 6 cm
- Material = Aluminium

Performance Graph for Selected Wheel Specifications





Suspension

Suspension System Comparison

Different types of suspension systems are compared based on criterias related to design requirements.

- Suspension Types
  - Rigid Suspension
  - Independent Suspension
  - Dependent Suspension
  - Rocker Bogie
  - Segmented Body
  - Active Suspension
- Criterias
  - Number of joints
  - Number of actuators
  - Mass
  - Wheel traction
  - Vehicle stability
  - Obstacle transversability
    Power consumption

Comparison Table for Suspension Systems

			Rigid		Independent		Dependent		Rocker-Bogie		Segmented Body		Active	
No.	Category	Weight	Rank	Weighted Score	Rank	Weighted Score	Rank	Weighted Score	Rank	Weighted Score	Rank	Weighted Score	Rank	Weighted Score
1	Number of Joints	1	6	6.00	3	3.00	4	4.00	1	1.00	5	5.00	2	2.00
2	Number of Actuators for Suspension	1	4	4.00	4	4.00	4	4.00	4	4.00	4	4.00	1	1.00
3	Total Mass	2	6	12.00	3	6.00	4	8.00	1	2.00	5	10.00	2	4.00
4	Wheel Traction	2	1	2.00	3	6.00	2	4.00	5	10.00	4	8.00	6	12.00
5	Vehicle Stability	2	1	2.00	4	8.00	3	6.00	5	10.00	2	4.00	6	12.00
6	Obstacle Traversability	2	1	2.00	3	6.00	2	4.00	5	10.00	4	8.00	6	12.00
7	Power Consumption	1	4	4.00	4	4.00	4	4.00	4	4.00	4	4.00	1	1.00
Totoal		**11**		**32.00**		**37.00**		**34.00**		**41.00**		**43.00**		**44.00**
Design Ranking			**6**		**4**		**5**		**3**		**2**		**1**	

Suspension System Design

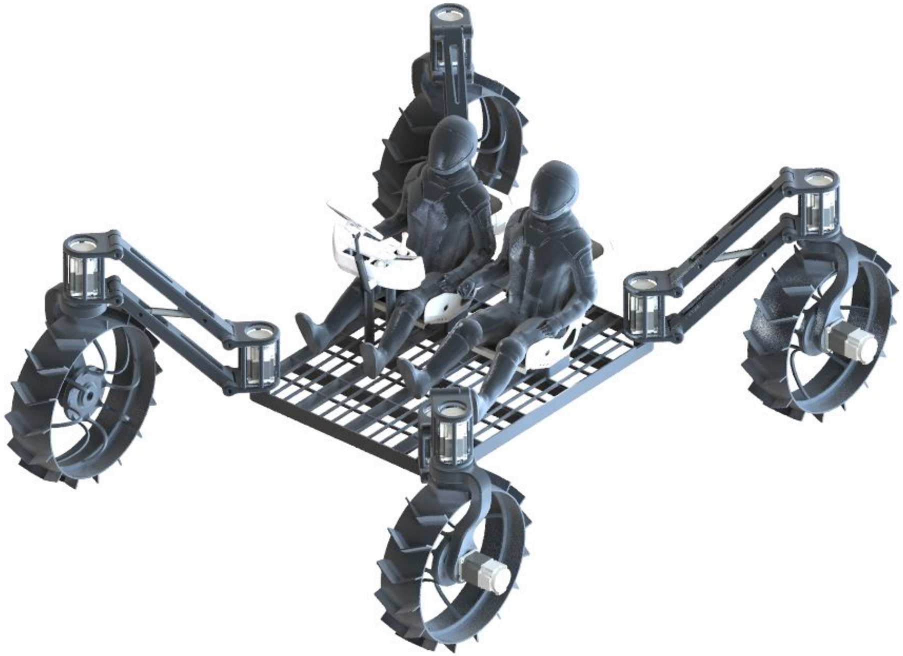
Specifications

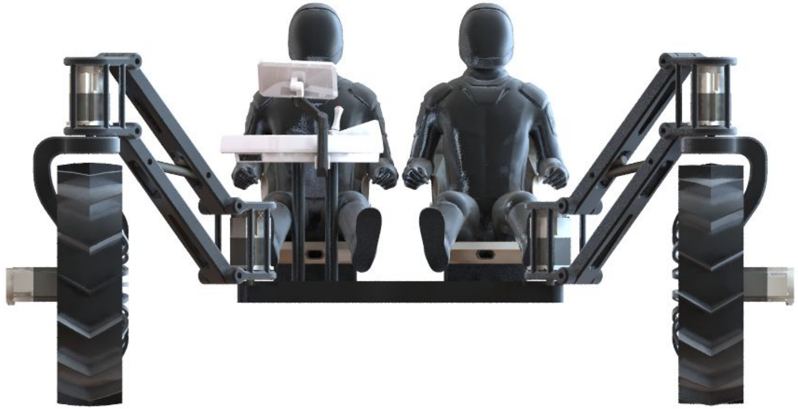
- Active Suspension
- Wheel height controlled by linear actuator
- Impedance control for suspension stiffness
- Legs are steerable to improve stability

LTV CAD Model

Normal Configuration

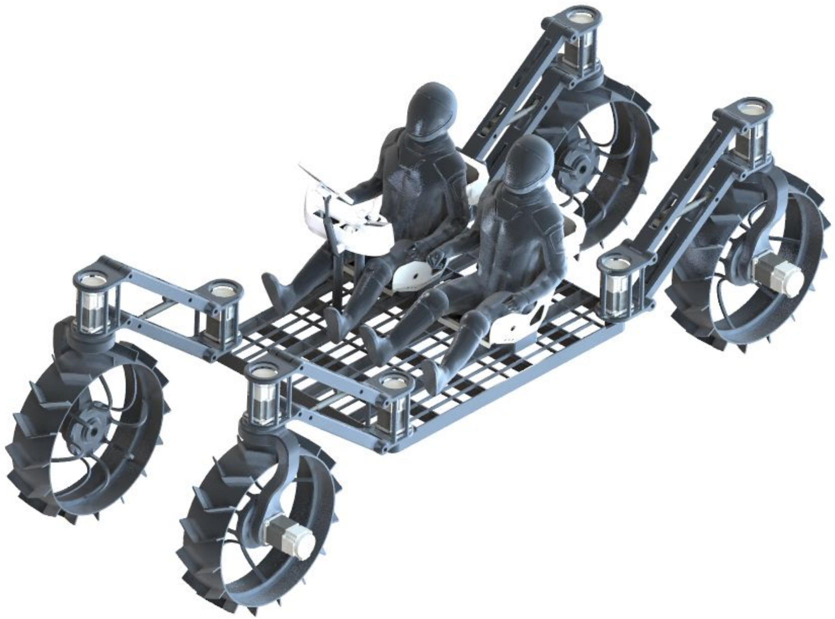
Balance between vehicle’s width and length.
Use for traversing flat terrains.

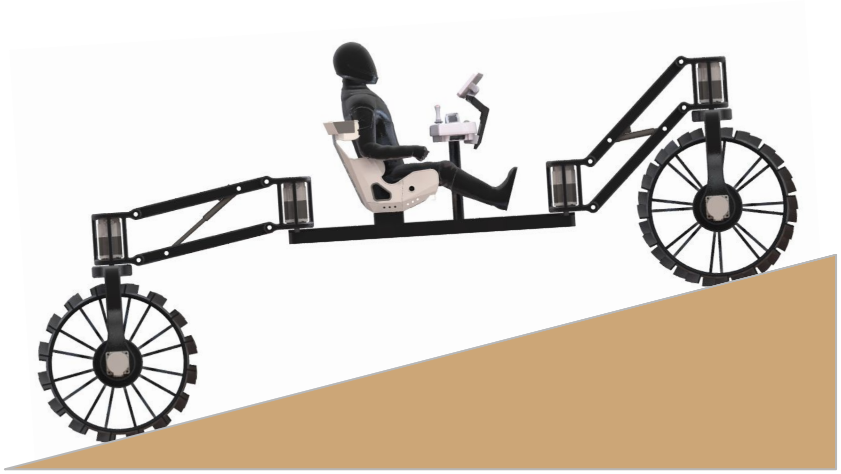




Uphill Configuration

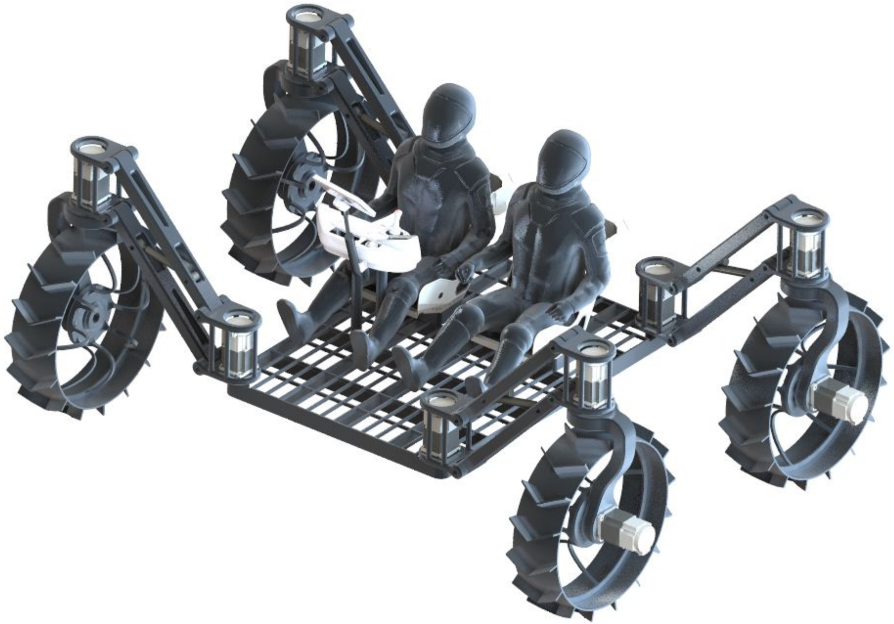
Increase vehicle length. Increase stability during acceleration, and helps climbing up slope

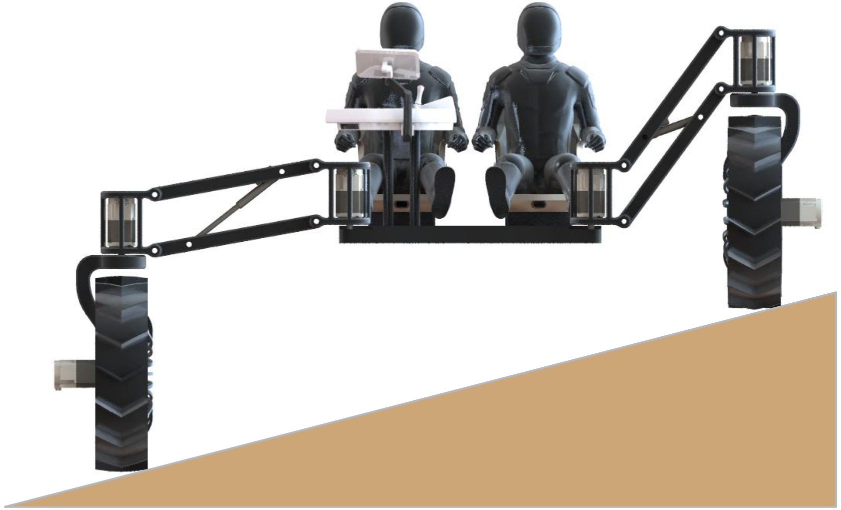




Sideway Configuration

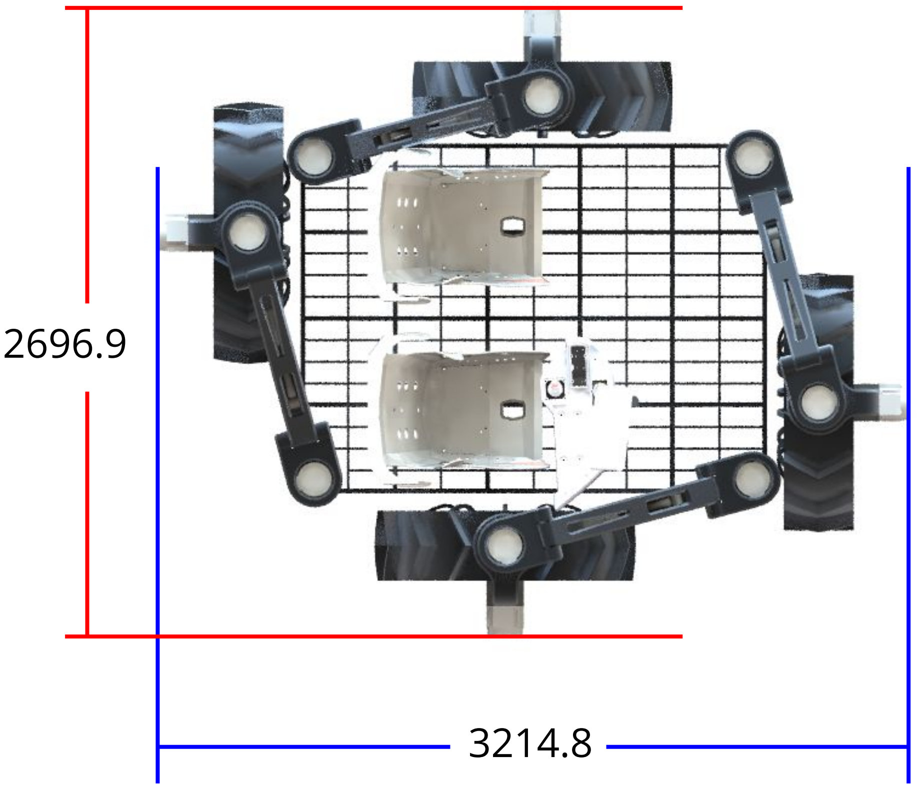
Increase vehicle width. Improve stability while turning, and helps traversing along the slope





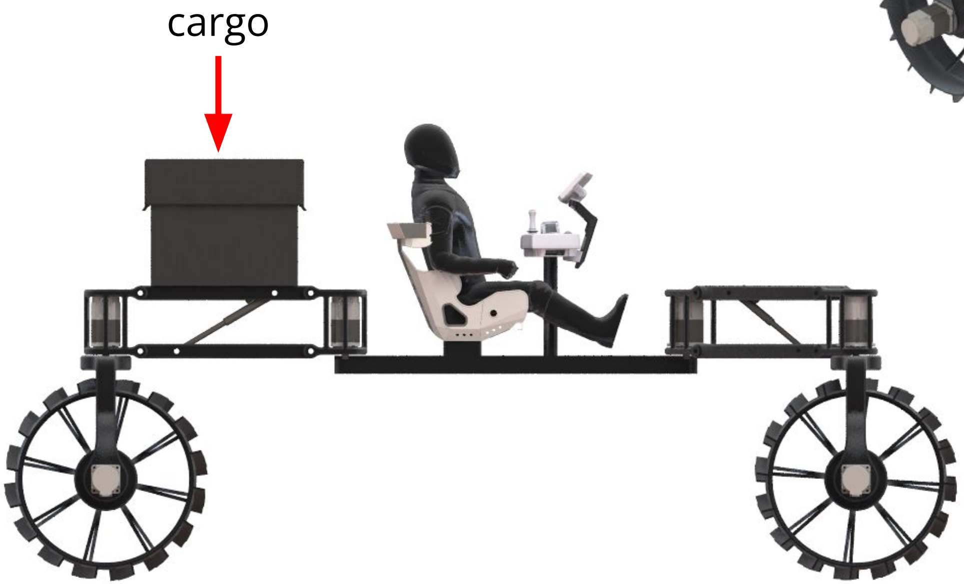
Deployment Configuration

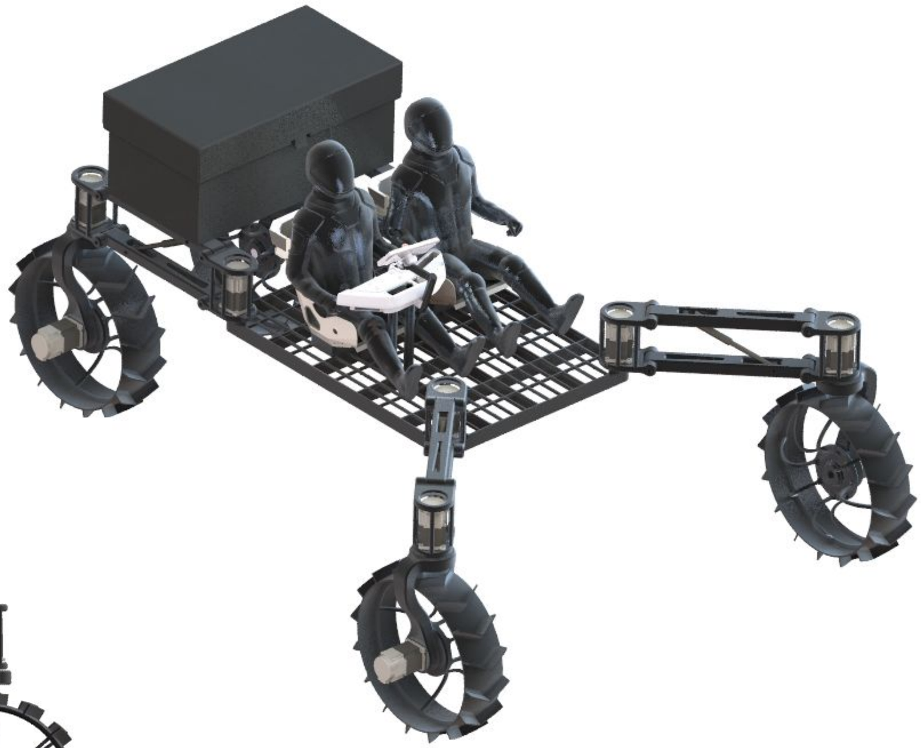
Minimize required space during deployment



Cargo Carrying Configuration

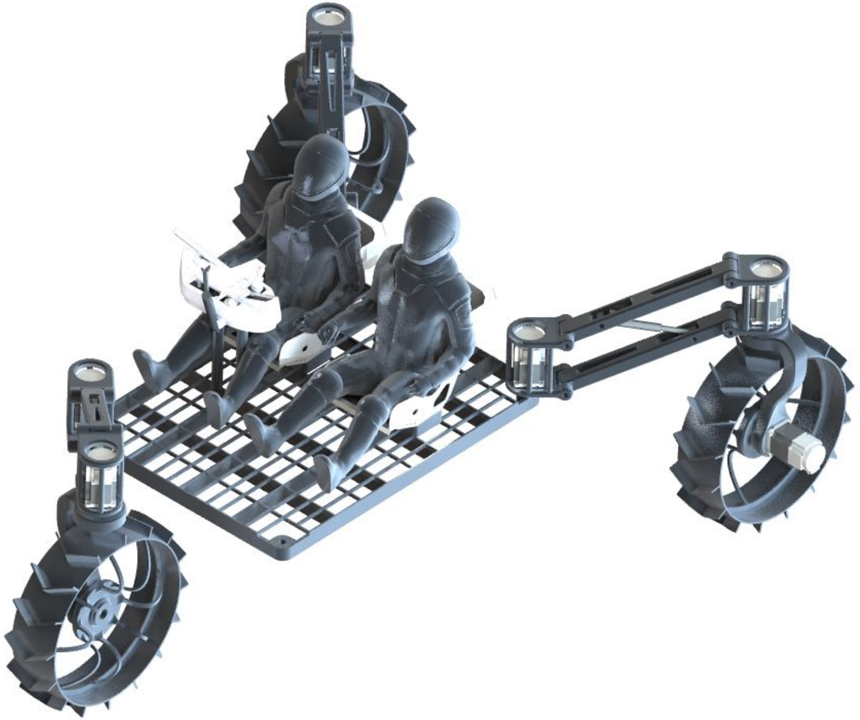
Lay rear legs flat to support cargo. The vehicle has to move at a lower acceleration due to higher center of mass.

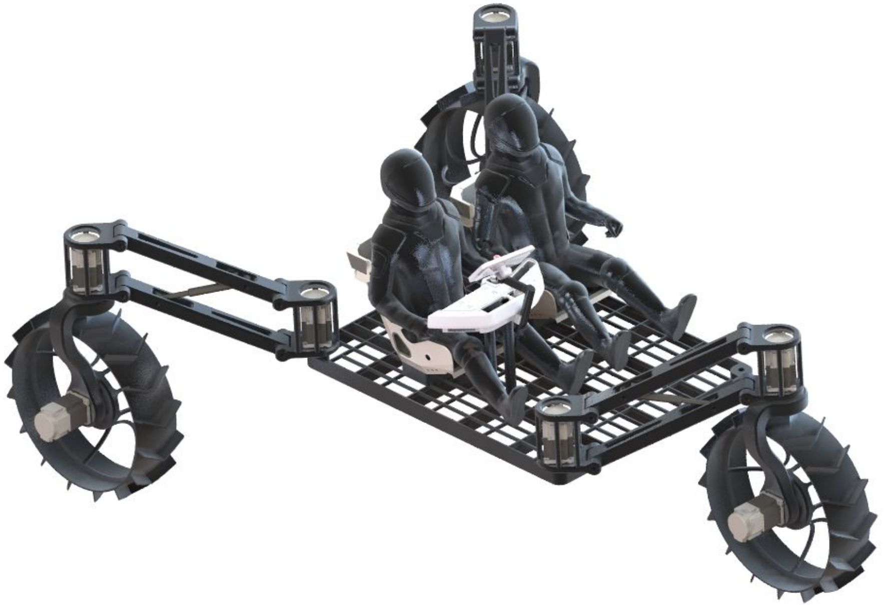




Emergency Configuration

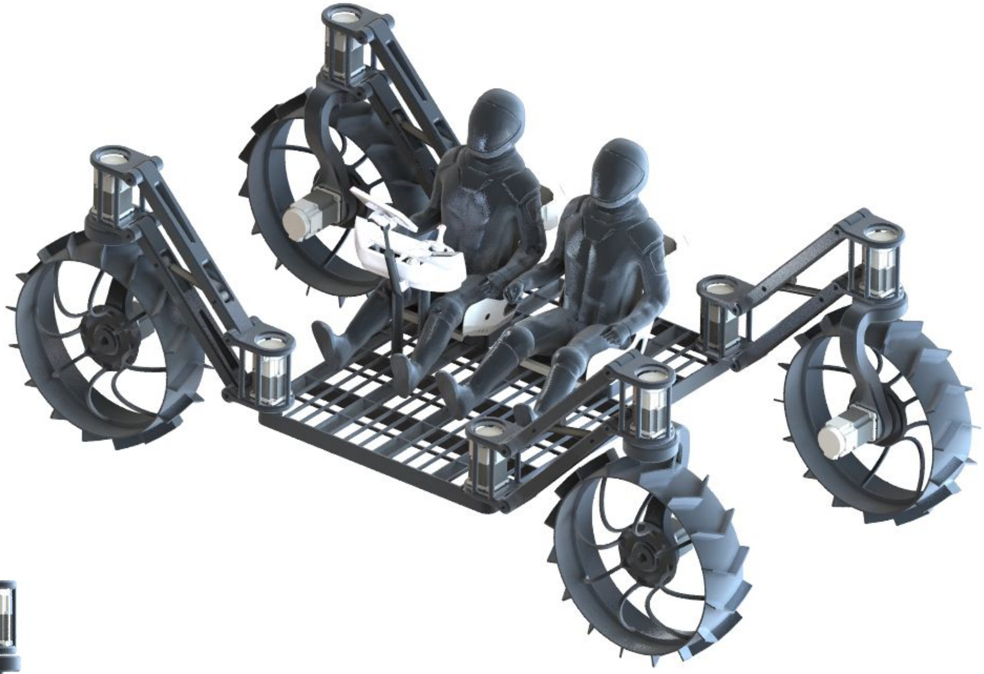
In case one of the legs are damaged, removes damaged leg and drive on 3 wheels





Holonomic Drive

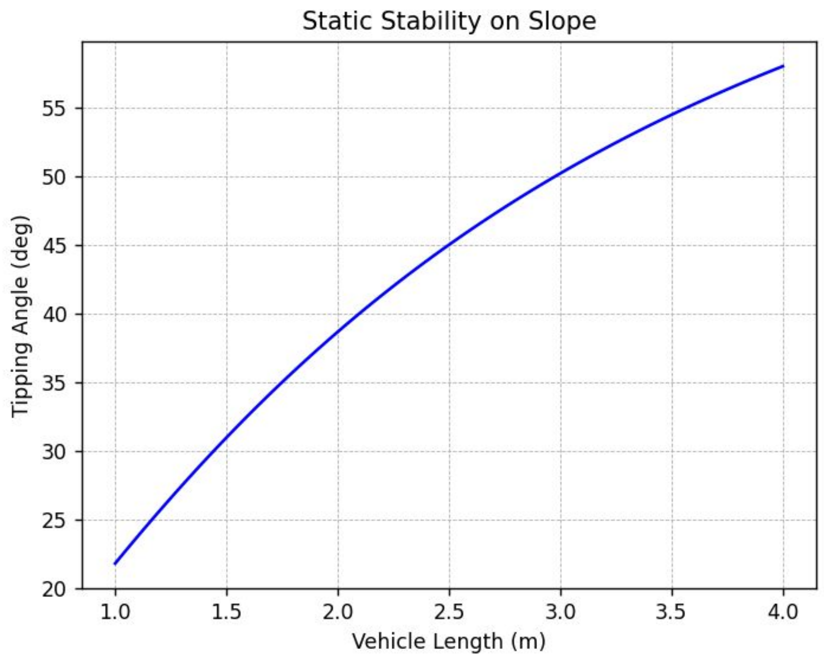
Vehicle is holonomic drive, and thus it has a higher chance of recovering when getting stuck.



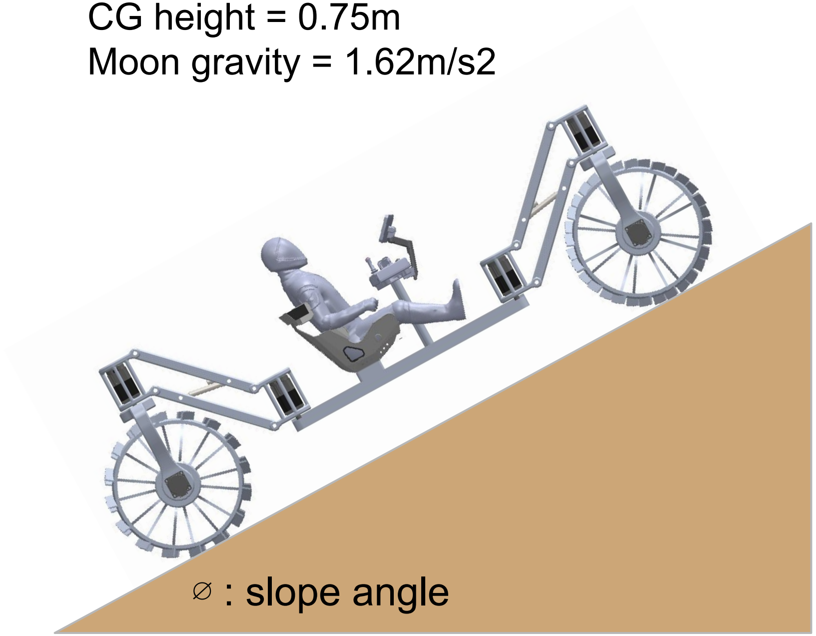
Stability

Static Stability on Slope

Relation between vehicle length and the angle that vehicle start to tip without acceleration.

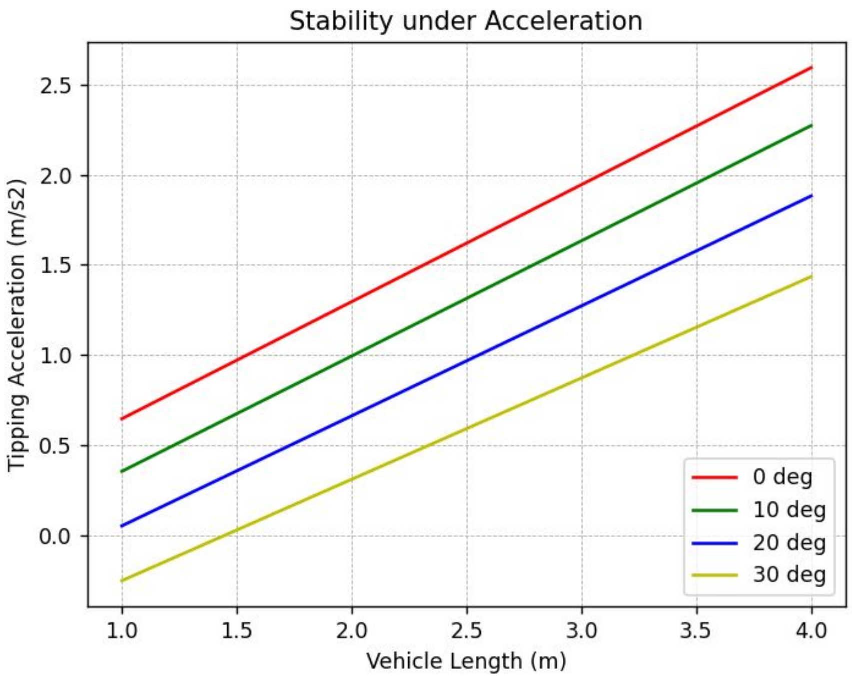


<u>Assumption:</u>
CG height = 0.75m
Moon gravity = 1.62m/s2



Stability Under Acceleration

Relation between vehicle length and acceleration(uphill) that vehicle start to tip on various slope.



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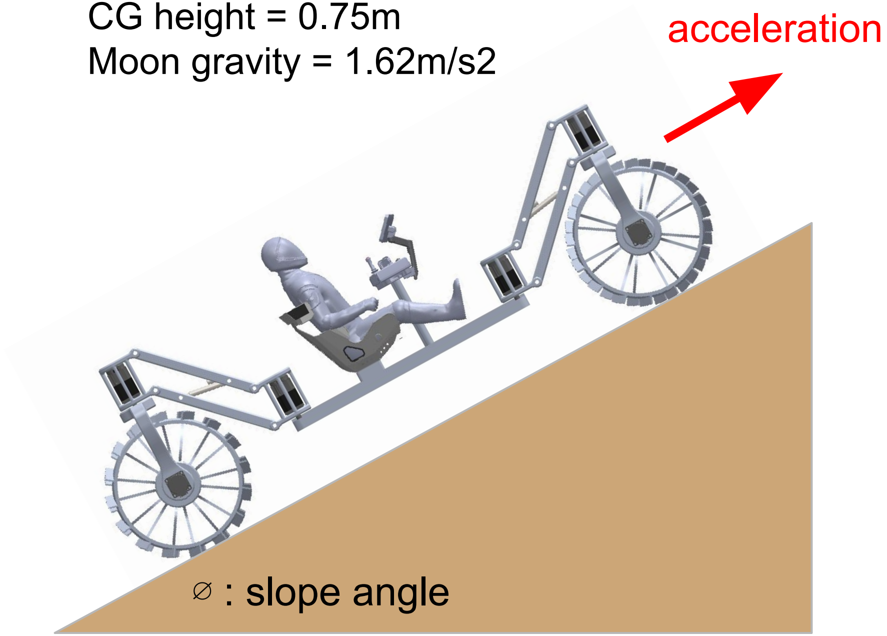
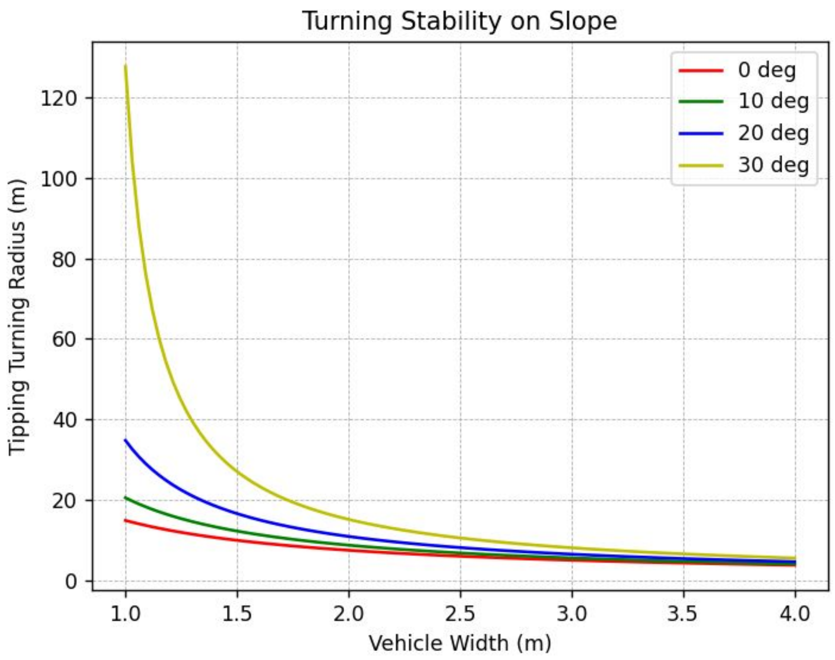


Stability when Turning on Slope

Relation between vehicle width turning radius that vehicle start to tip on various slope.



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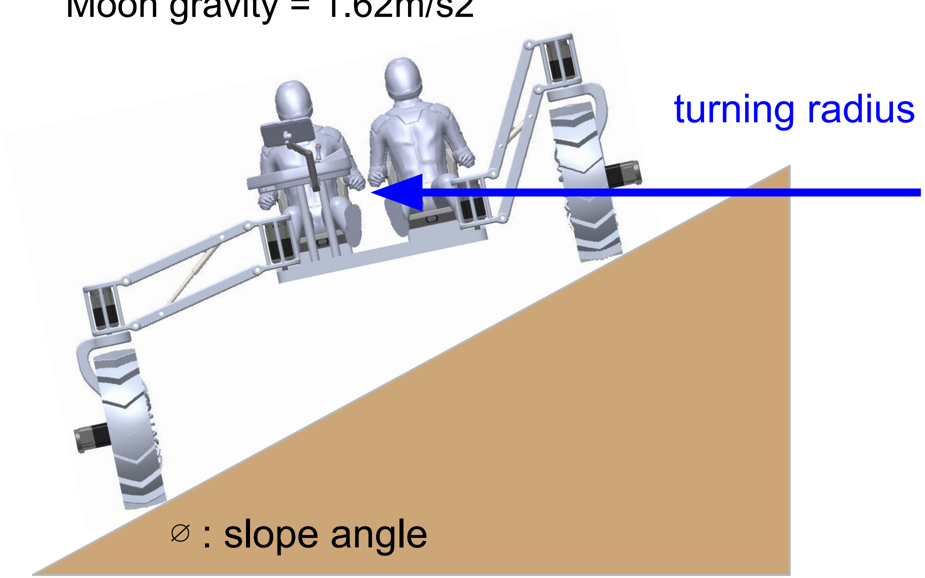
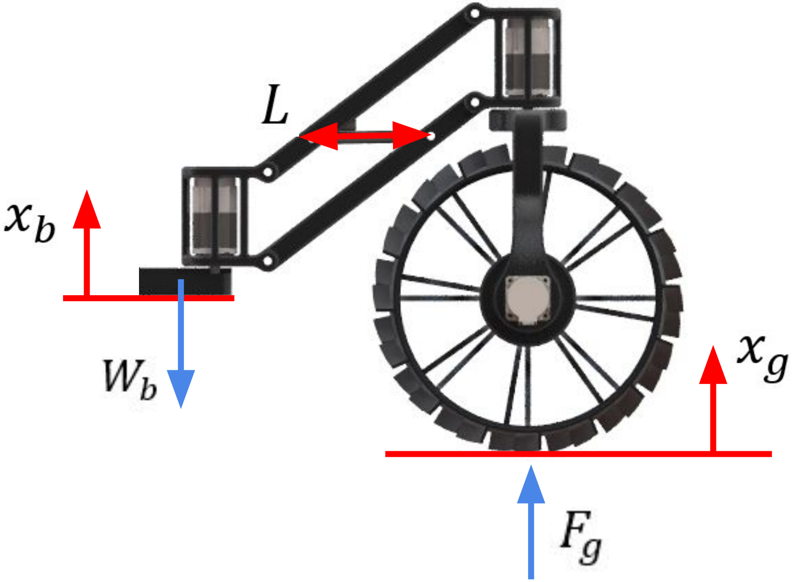


Advanced Analyses

Active Suspension

Control law for active suspension system



$$u = -(K_a \ddot{x}_b + K_v \dot{x}_b + K_L L)$$

Where

u = Actuator force input

L = Actuator displacement

x_b = Rover base displacement

x_g = Ground displacement

K_a = Rover acceleration gain

K_v = Rover velocity gain

K_L = Actuator proportional gain

F_g = Ground reaction force

W_b = Rover weight acting on suspension system

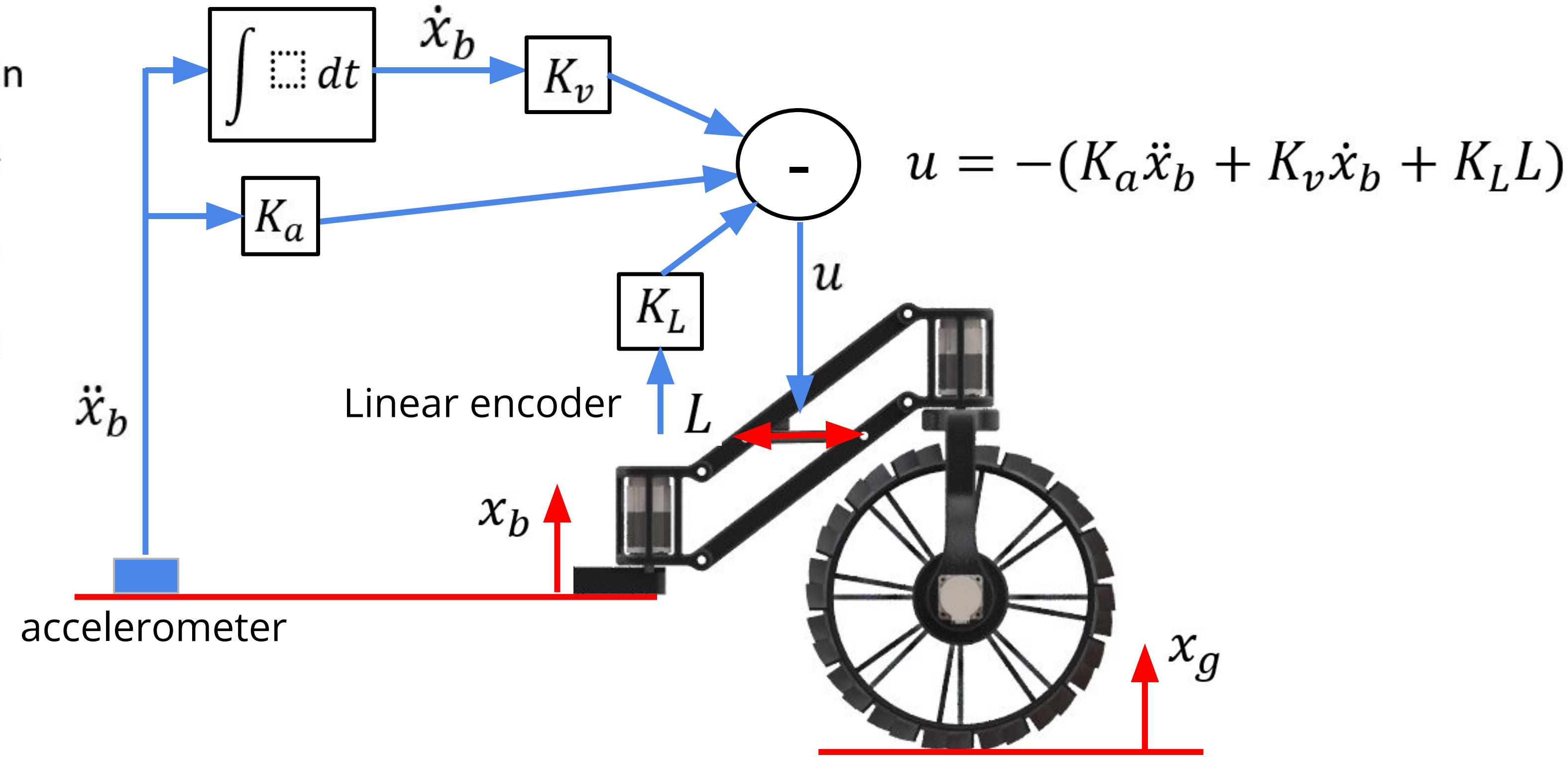
Active Suspension - Control DIagram

Controller Gain

$K_a = 2 \times 10^4$

$K_v = 5 \times 10^5$

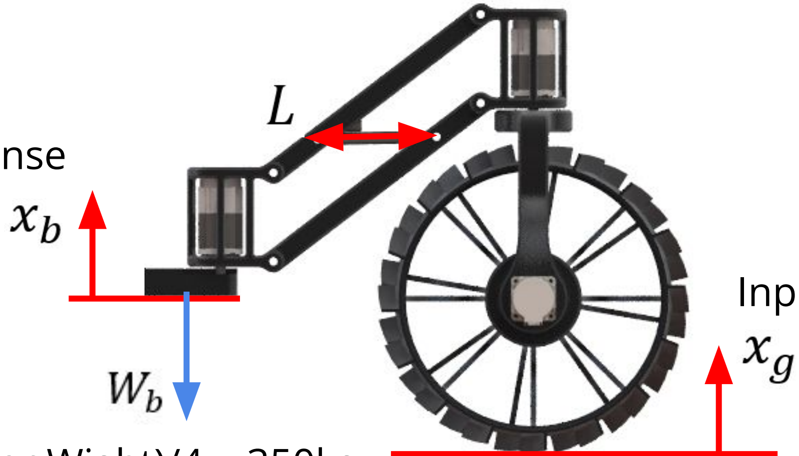
$K_L = 5 \times 10^5$



Active Suspension - Simulation

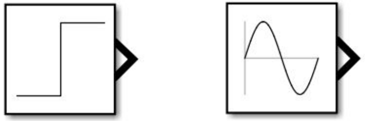
System modeling for simulation using Matlab Simmechanics

Output response



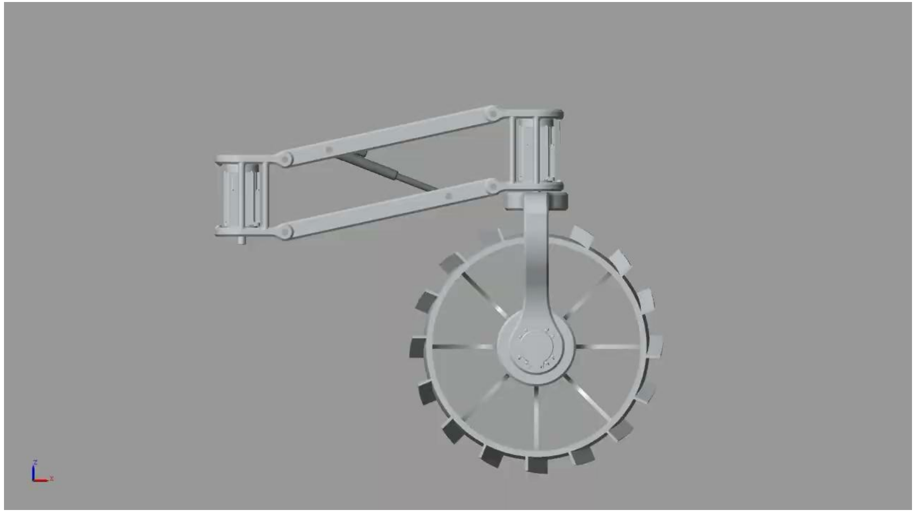
(Rover Wight)/4 = 350kg

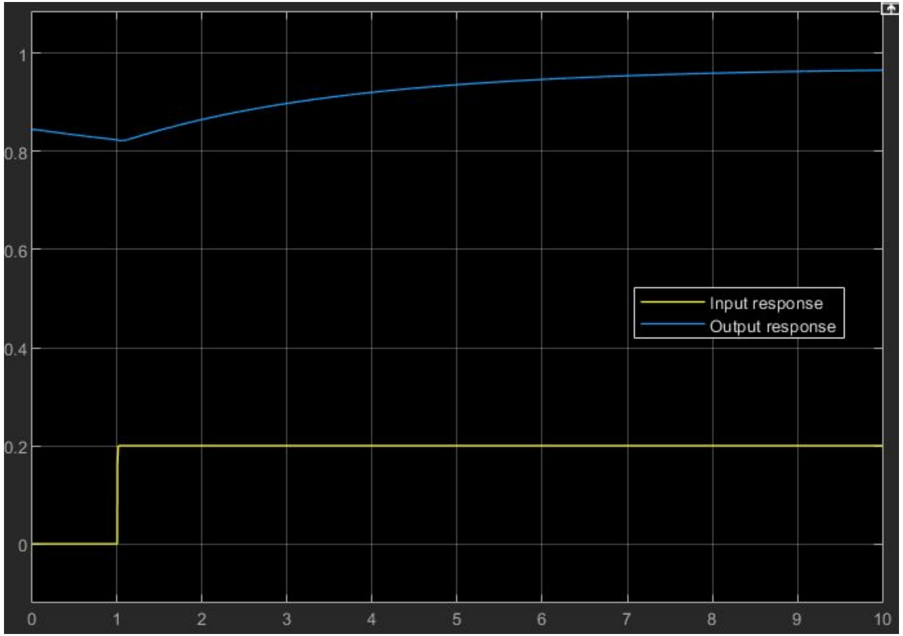
Input response: step, sine



Active Suspension - Step Response

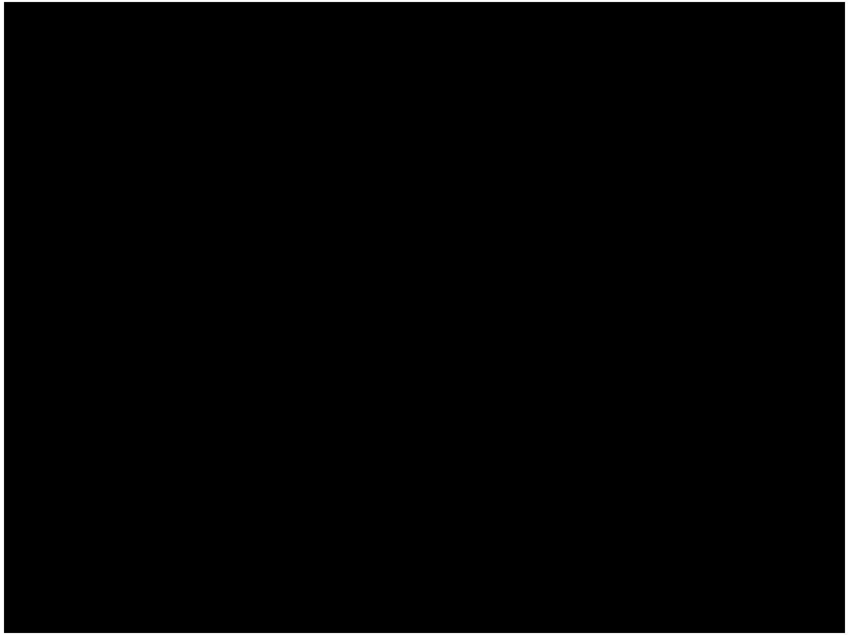
Input response: step function, step size 0.2m

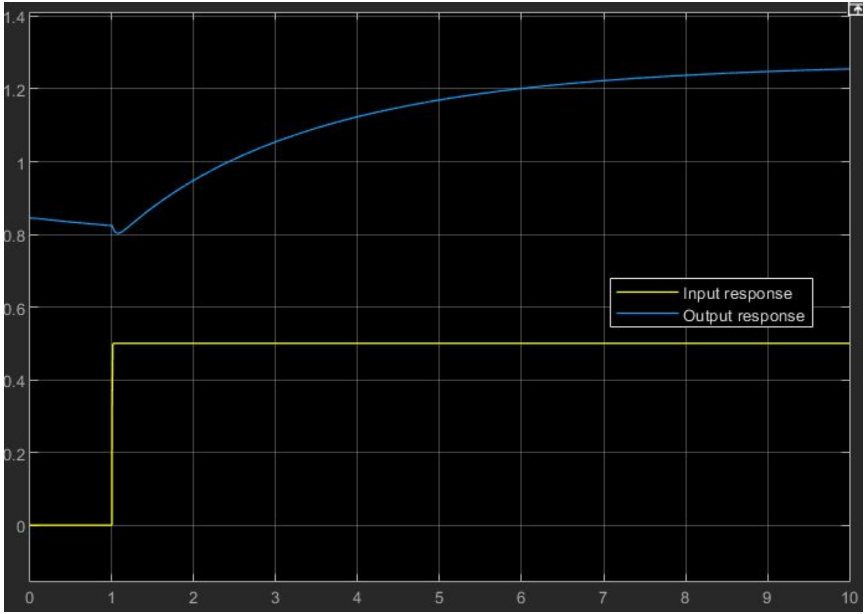




Active Suspension - Step Response

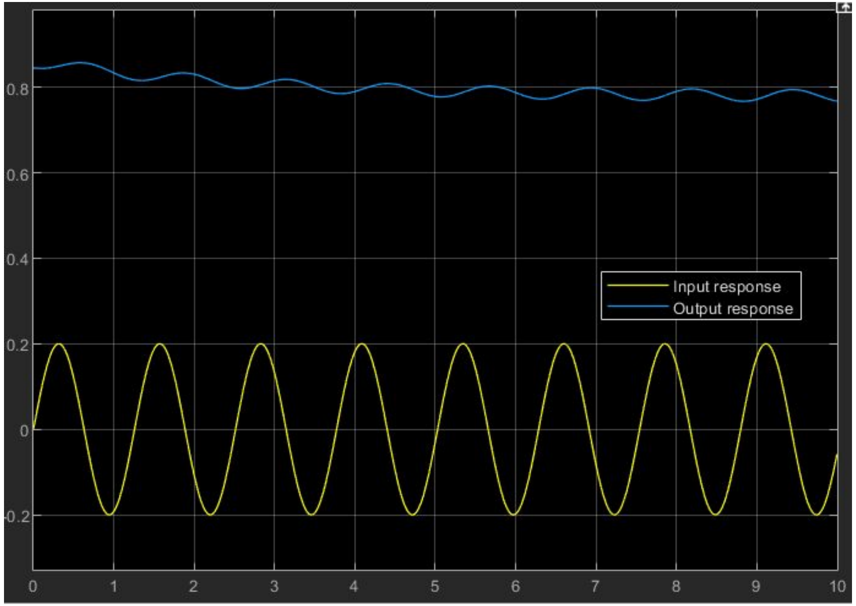
Input response: step function, step size 0.5m





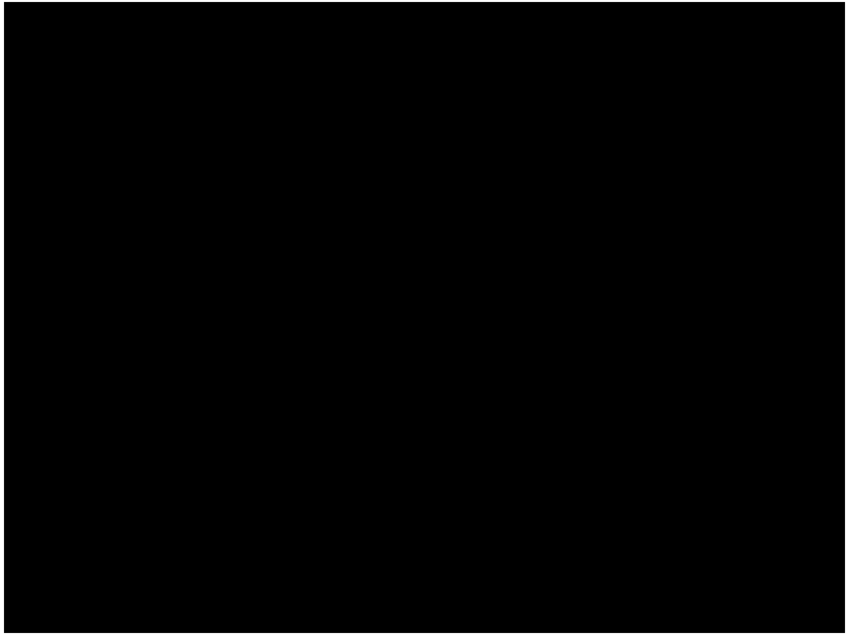
Active Suspension - Frequency Response

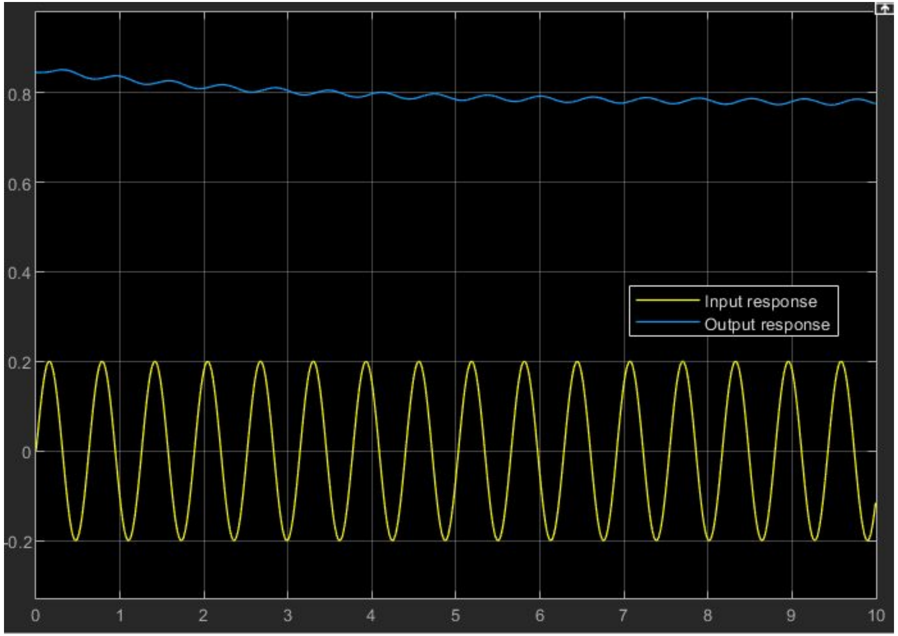
Input response: sine function, frequency 5Hz, amplitude 0.2m



Active Suspension - Frequency Response

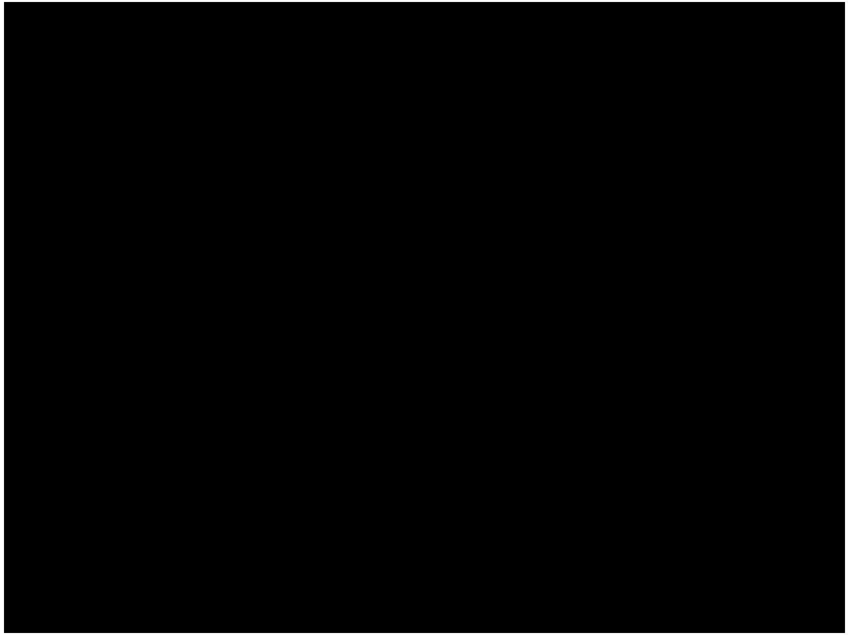
Input response: sine function, frequency 10Hz, amplitude 0.2m

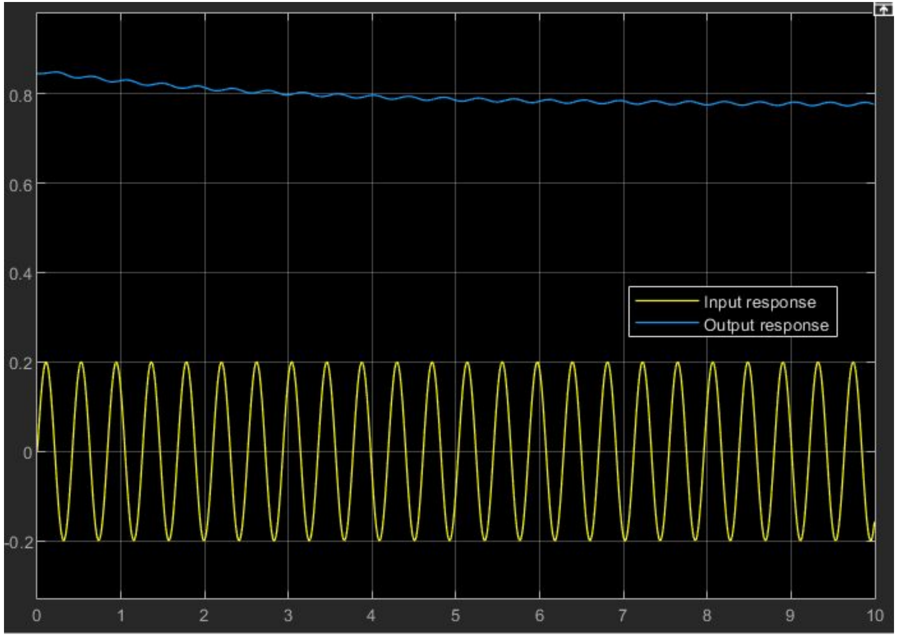




Active Suspension - Frequency Response

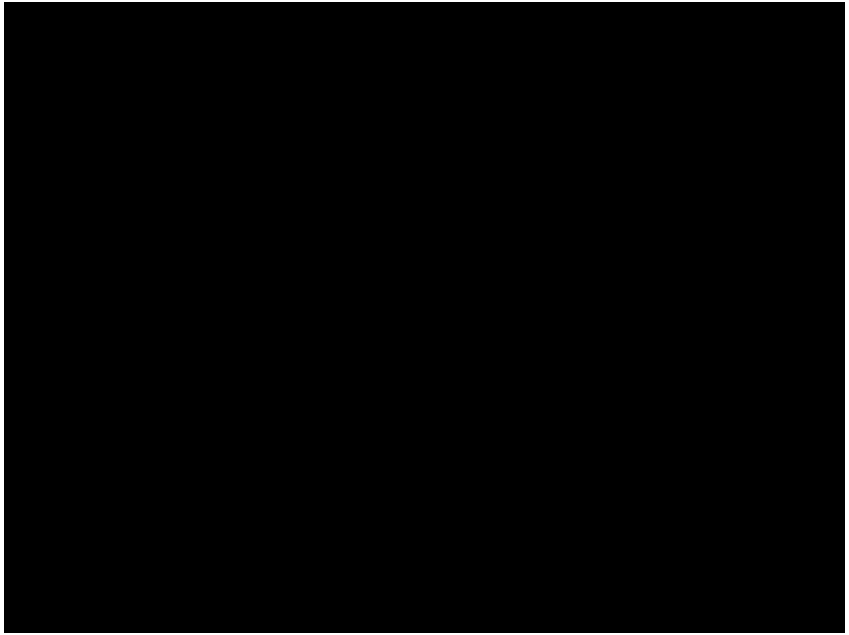
Input response: sine function, frequency 15Hz, amplitude 0.2m



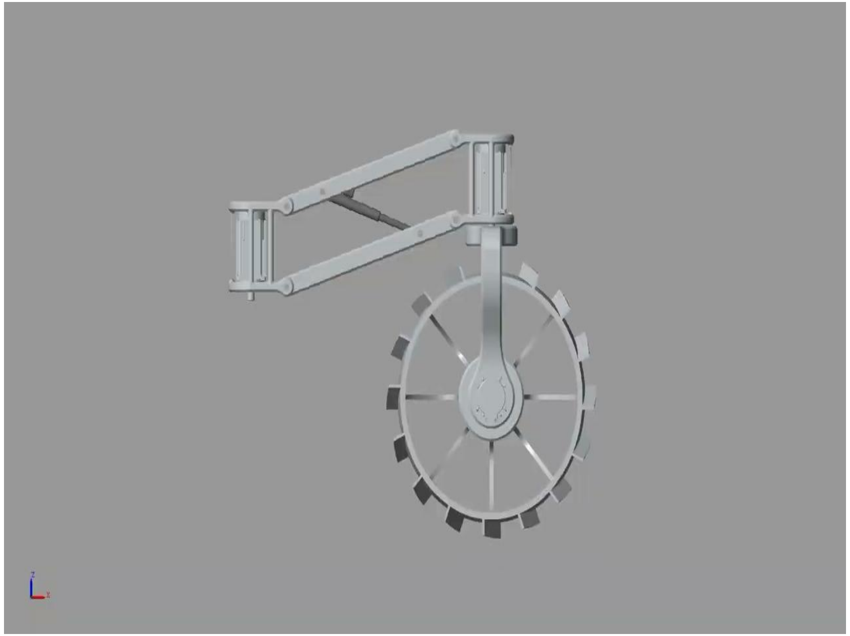


Active Suspension - Comparison with Passive

Comparison with passive suspension system with spring stiffness = 5x10^5, damping = 8x10^4



Active Suspension



Passive Suspension

Active Suspension - Weight Transfer

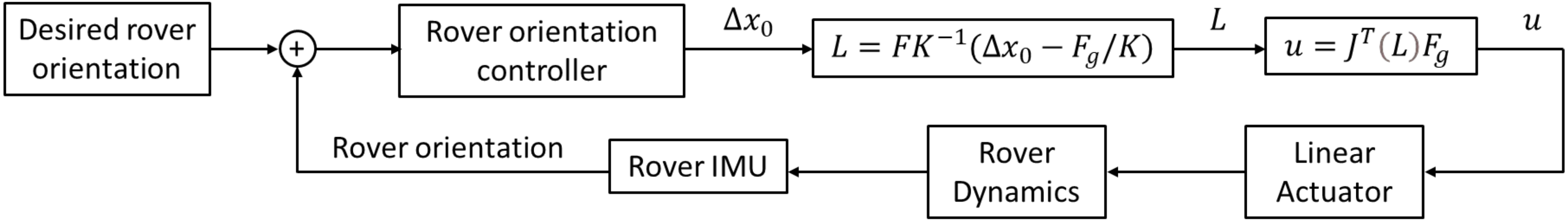
With active suspension, it is possible to distribute even load on all 4 wheels using impedance control. The formulation of impedance control is provided below. By constraining equal ground reaction forces (Fg) for all wheels and stable rover orientation, we would be able to find corresponding equilibrium point (dx0), actuator displacement (L), and actuator force input (u).

$x_g - x_b = \Delta x = FK(L)$	$FK = Forward\ kinematics$
$\Delta\dot{x} = J(L)\dot{L}$	$J = Jacobian\ Matrix$
$F_g = K(\Delta x_0 - \Delta x) + B(\Delta\dot{x}_0 - \Delta\dot{x})$	$Model\ system\ as\ spring\ damper\ system, \Delta x_0 = equilibium$
$F_g = K\left(\Delta x_0 - FK(L)\right) + B\left(\Delta\dot{x}_0 - J(L)\dot{L}\right)$	$Substitute\ FK\ and\ J$
$u = J^T(L)F_g$	$Principle\ of\ virtual\ work$
$u = J^T(L)\left[K\left(\Delta x_0 - FK(L)\right) + B\left(\Delta\dot{x}_0 - J(L)\dot{L}\right)\right]$	$u = Linear\ actuator\ control\ input$

Active Suspension - Weight Transfer

Control diagram for stable rover orientation and equally weight distribution on all wheels.

$$F_g = W/4$$



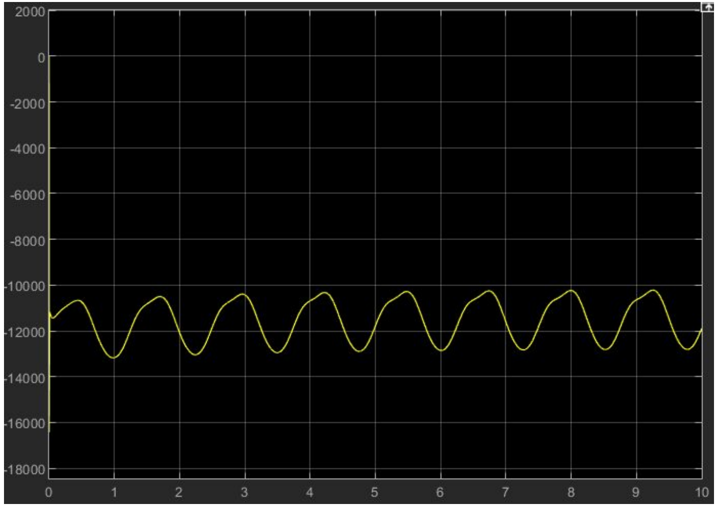
Mechanisms

Linear Actuator

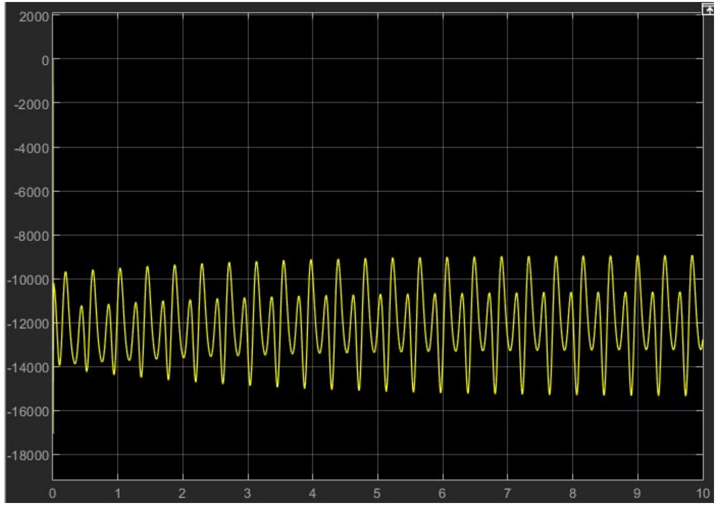
Plots below show required force for linear actuator under frequency response of 5hz and 15hz.

The maximum force is at 15.8kN at 15hz input response.

With a safety factor of 3, **we choose linear actuator with maximum force at 48kN**.



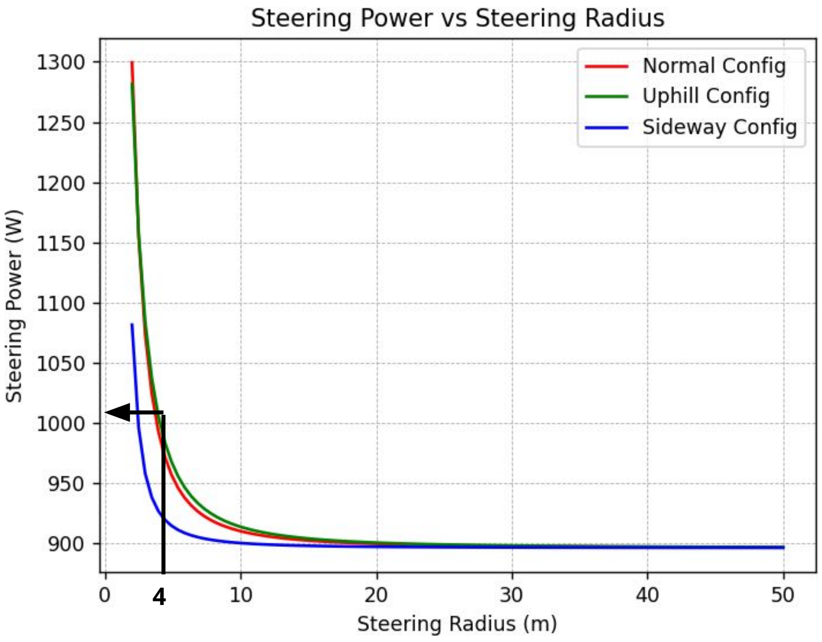
Sine wave input at 5hz



Sine wave input at 15hz

Wheel Motors

Wheel power with different rover configurations at different turning radius.



<u>Normal Configuration:</u>
Vehicle length = 3.50m
Vehicle width = 3.21m

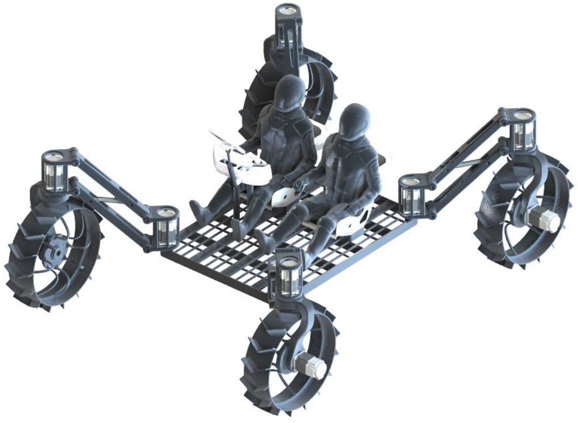
<u>Uphill Configuration:</u>
Vehicle length = 3.97m
Vehicle width = 1.38m

<u>Sideway Configuration:</u>
Vehicle length = 1.88m
Vehicle width = 3.47m

Rolling friction coefficient = 0.2
Skid friction coefficient = 1
Vehicle speed = 4m/s (≈15km/hr)

At turning radius 4m, max total wheel power is 1020W.
Power per wheel = 255W
With SF = 3, choose motor with power 760W.

Power Requirements for Driving Motors



Driving Motors					
Motor Type	Quantity	Per Motor Peak Power (W)	Peak Power Estimate (W)	Safety Factor	Total Required Power (W)
Steering DC Motors	8	75	600	3	1800 W
Wheel DC Motors	4	255	1020	3	3060 W

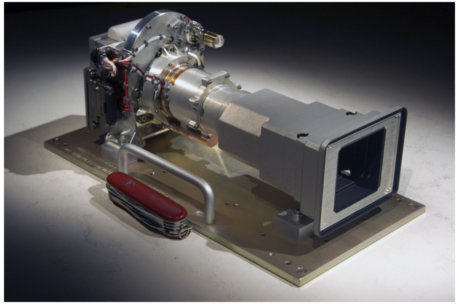
Sensors

Exteroceptive

- 3D - Lidar
- Cameras
  - Hazcams [Front and Rear]
  - Navcams
  - MastCams
- Range Finders
- Temperature Sensors
- Radiation Detectors [RAD]
- and Dust Sensors
- Inclinometers
- Thermal Infrared Sensors
- Antenna
  - Ultra-High Frequency Antenna
  - The X-Band High-Gain Antenna
  - The X-Band Low-Gain Antenna
- Microphones

Proprioceptive

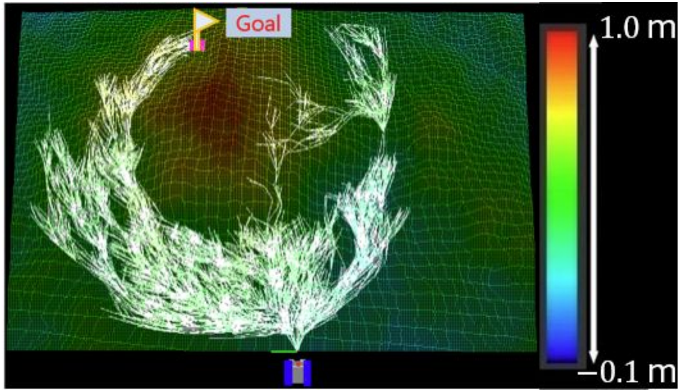
- Magnetic Encoders
- Gyroscope
- IMU
- Force sensors
- Internal Temperature Sensors



Path Planning Strategies

2 Levels of Autonomy:

1. **Completely Autonomous:**
    - Lidar Based RRT* path planning.
    - Sampling based methods are computationally more efficient in high dimensional environments.
    - 3D - Lidar can scan terrain features during lunar days and lunar nights.
    - Will leverage the information from directional Gyro and odometry.
    - Optimal paths are generated based on a cost function composed of terrain information.



2. **Crew Controlled:**
    - Lidar Based RRT* algorithms will be used to recommend paths.
    - The crew member driving the Lunar Rover will have the ultimate control over the rover's path.

Power Requirement

Power Input and Output

Charging Docks

Sensors Suite

Brains/Processors

Driving [DC Motors]

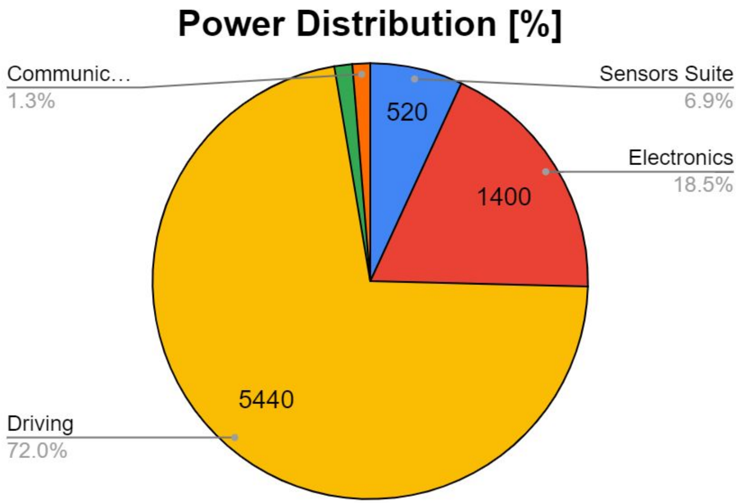
Suspension System

Communication Systems

Requirement: Needs to support 8 hrs of EVA and it should yield a 20 km range per charge.

Charging Capacity: 30 [kW]

Battery System: lithium-ion rechargeable batteries

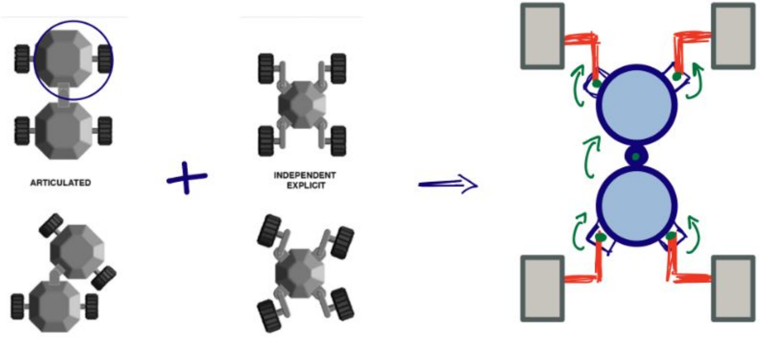


Sensors Suite	
Part	Peak Power Estimate (W)
3D Lidar Ouster OS1	80
Navcams [Mastcams]	40
Others	400
Total	520 W
Electronics Suite	
HeadLights	80
On Board Brain	600
Batteries	0
Control and Display	200
Others	500
Total	1400 W
Driving Motors	
Steering DC Motors	1800
Driving DC Motors	3600
Total	5400 W

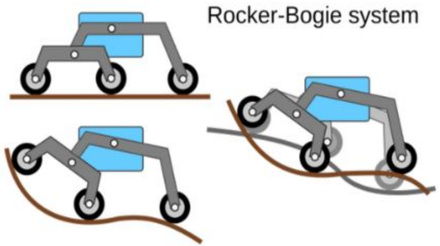
Alternate Concepts

Design Brainstorming

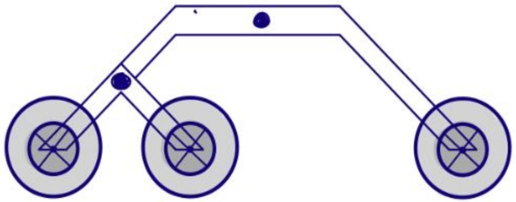
IDEA 2 : Innovative Steering



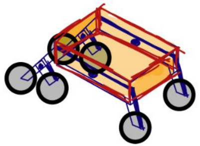
IDEA 1 : Rocker Bogie



★ Side View



★

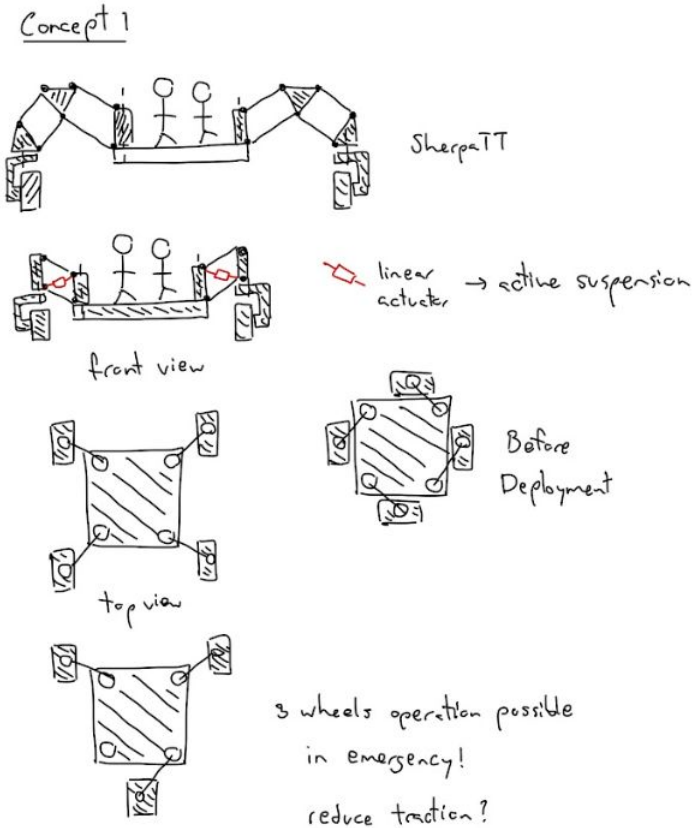


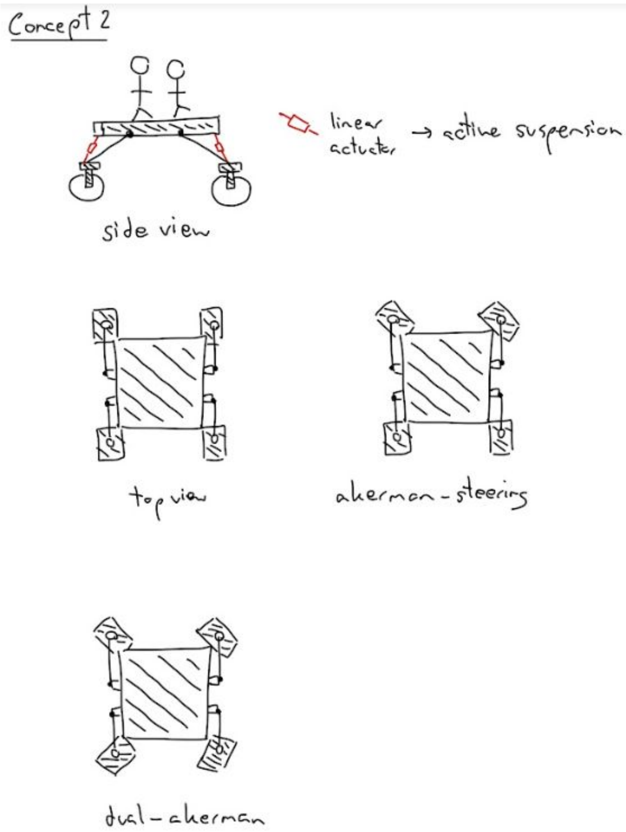
→ left & right side work independently

→ 6 x Wheel Drive

→ Differential Steering

Design Brainstorming





Alternative Concepts Comparison

			Current Design		Track		Legged	
No.	Category	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
1	Obstacle Traversability	2	2	4.00	1	2.00	3	6.00
2	Number of Joints	1	3	3.00	1	1.00	2	2.00
3	Number of Actuators	2	2	4.00	3	6.00	1	2.00
4	Mass	2	2.5	5.00	2.5	5.00	1	2.00
5	Power Efficiency	1	2	2.00	3	3.00	1	1.00
6	Travel Speed	1	2	2.00	3	3.00	1	1.00
7	Stuck Recovery	1	2.0	2.00	1	1.00	3.0	3.00
8	Terrain Adaptation	1	2	2.00	1	1.00	3	3.00
Totoal		**11**		**24.00**		**22.00**		**20.00**
Design Ranking			**1**		**2**		**3**	

<u>Comparison with alternative designs : legged & tracks</u>

From comparison, we decide to stick with our current design. While track concept offers great efficiency, it suffers from high maintenance and traversability in extreme terrains. Legged concept thrives when adapting to unseen terrain, but suffers from poor efficiency.

References

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