ENAE788x COURAGE Rover

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Overview

- Project Requirements
- Final Design (intro)
- Terramechanics
- Stability
- Steering
- Suspension
- Power
- Mass
- Final Design (detailed)
- Earth & Mars efficacy
- Trafficability
- Design Evolution and Concepts

Project Requirements

Project Description:

- 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...)
- Design for Moon, then assess feasibility of systems for Mars, and conversion to Earth analogue rover

Requirements (Performance) :

1. Maximum operating speed of at least **4 m/sec** on level, flat terrain.
2. Accommodate a **0.3 meter** obstacle at minimal velocity.
3. Accommodate a **0.1 m** obstacle at a velocity of 2.5 m/sec.
4. Accommodate a **20° slope** in any direction at a speed of at least 1 m/sec and including the ability to start and stop.
5. A nominal sortie range of **54 km** at an average speed of **2.5 m/sec**.

Project Requirements

Requirements (Payload) :

1. Capable of carrying one 170 kg EVA crew and 80 kg of assorted payload
2. Payload may be modeled as a 0.25 m box
3. Capable of carrying a second 170 kg EVA crew in a contingency situation.
4. Incorporate roll-over protection for the crew and all required ingress/egress aids and crew restraints.

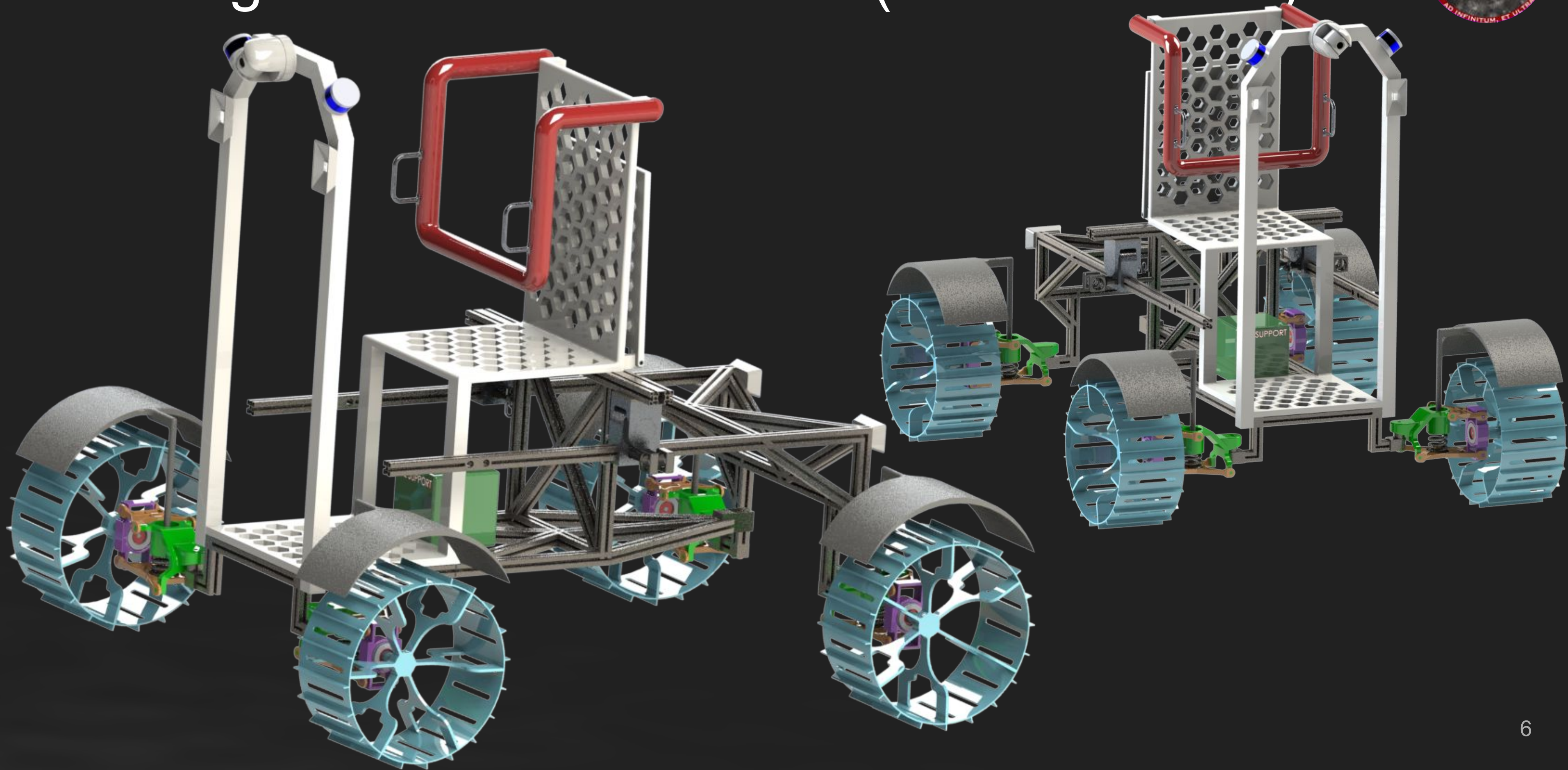
Requirements (Operations) :

1. A nominal sortie shall be at least eight hours long.
2. Two rovers must be launched on a single CLPS lander.
3. A single rover shall mass ≤250 kg.
4. Capable of operating indefinitely without crew present.

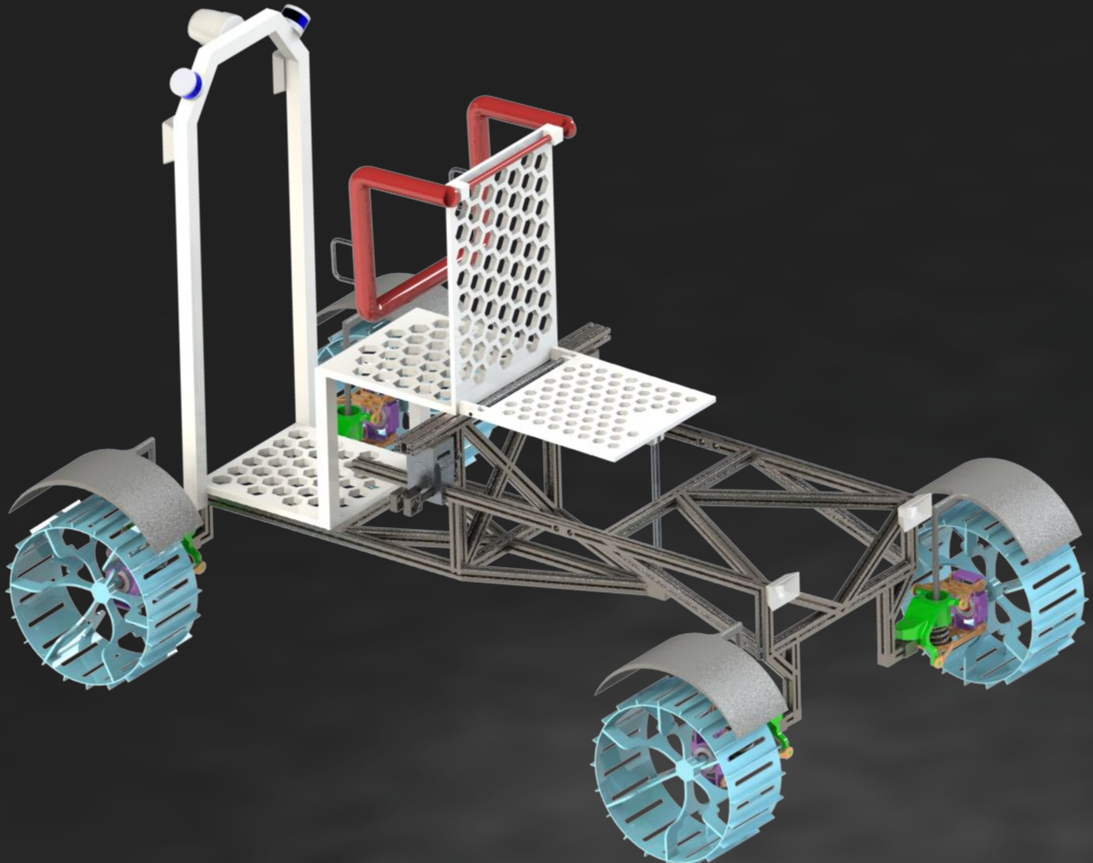
Requirements (GN&C) :

1. Capable of being controlled directly, remotely, or automated.
2. Capable of following an astronaut, astronaut's path, or autonomous path planning between waypoints.
3. Capable of operating during any portion of the lunar day/night cycle and at any latitude.

Courage Rover - Normal Use (Non Extended)

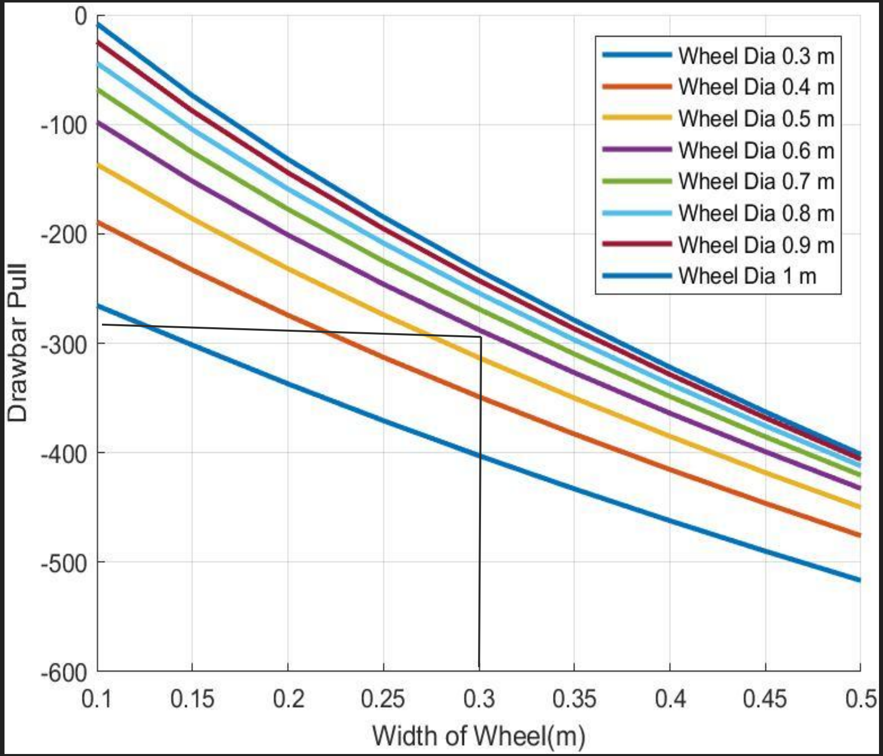


Courage Rover - Contingency Use (Extended)

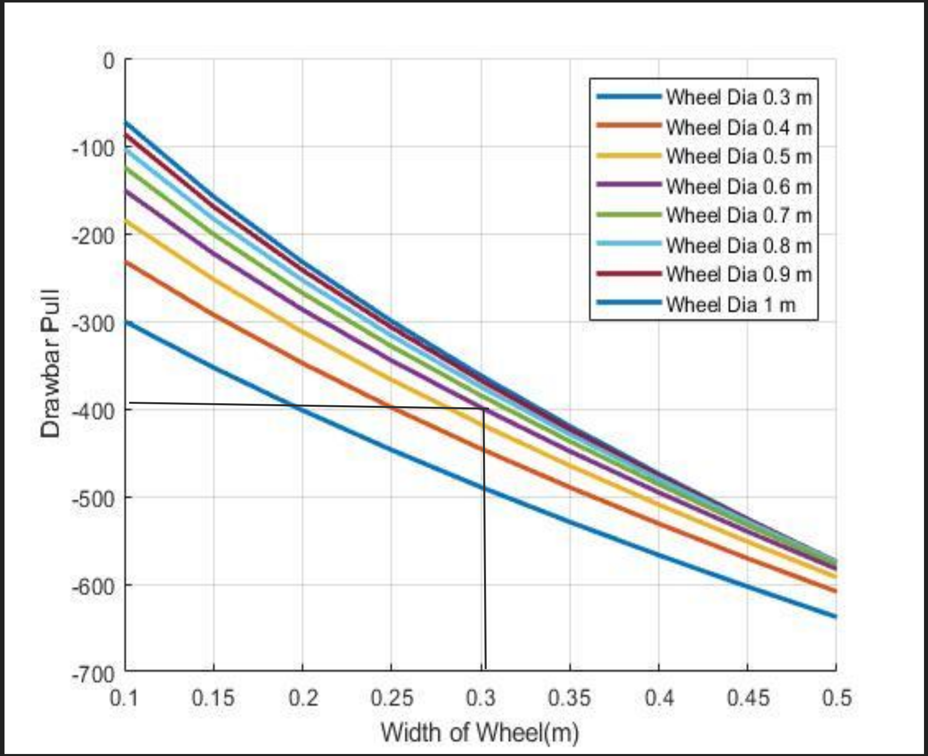


Terramechanics

Trade Study - Drawbar Pull - No Grousers - Flat Terrain

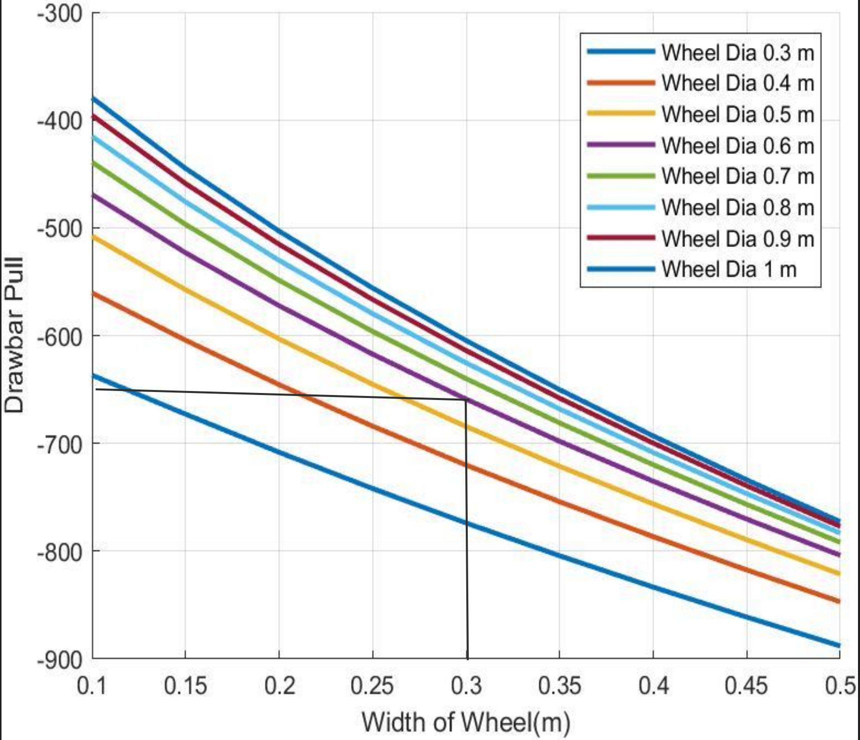


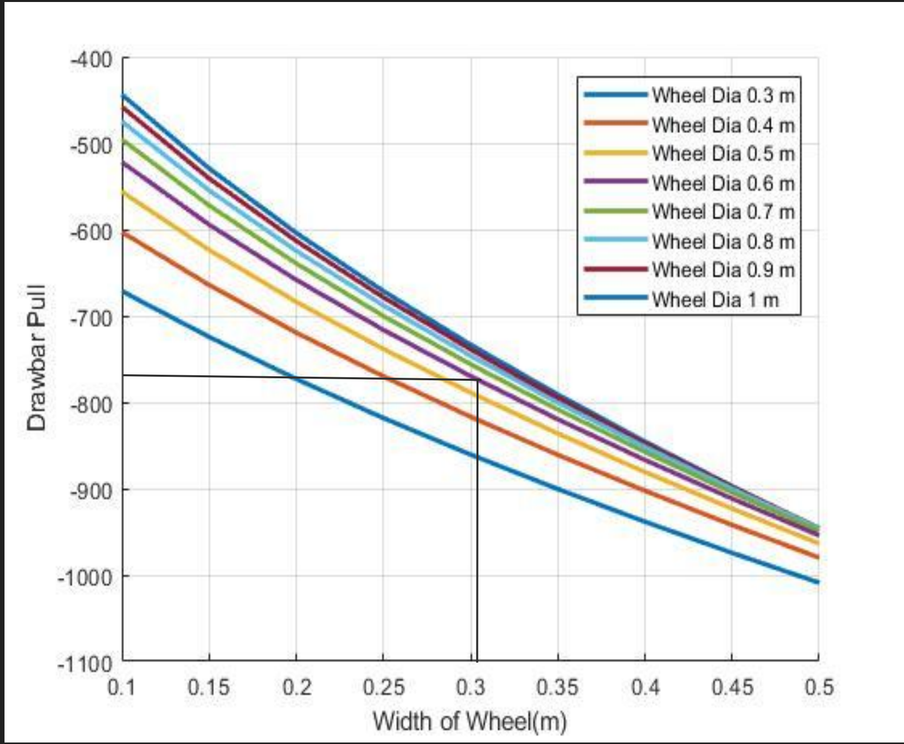
4 Wheels



6 Wheels

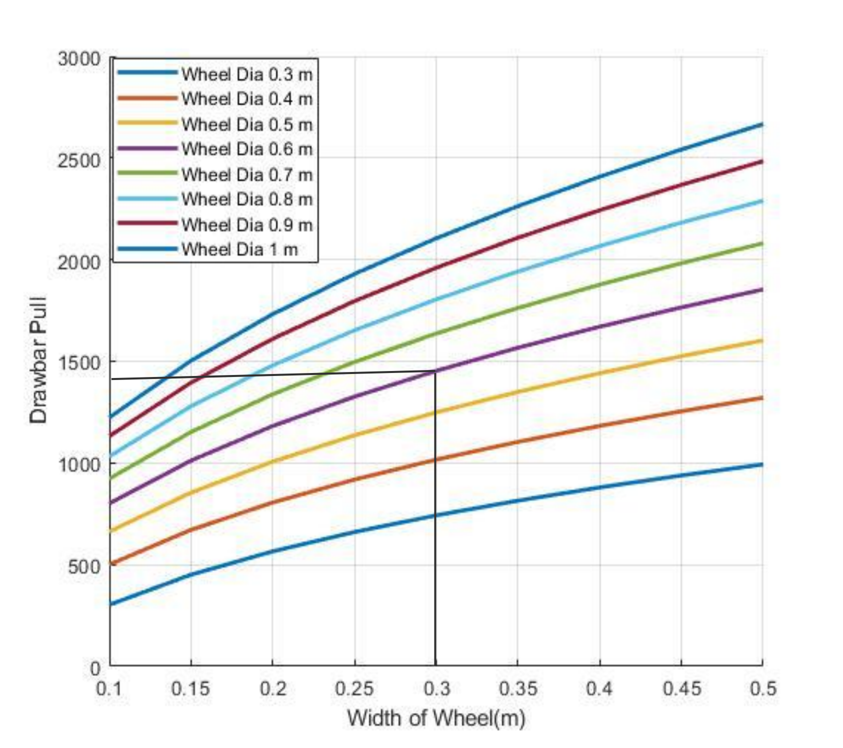
Trade Study - Drawbar Pull - No Grousers - 20 Slope



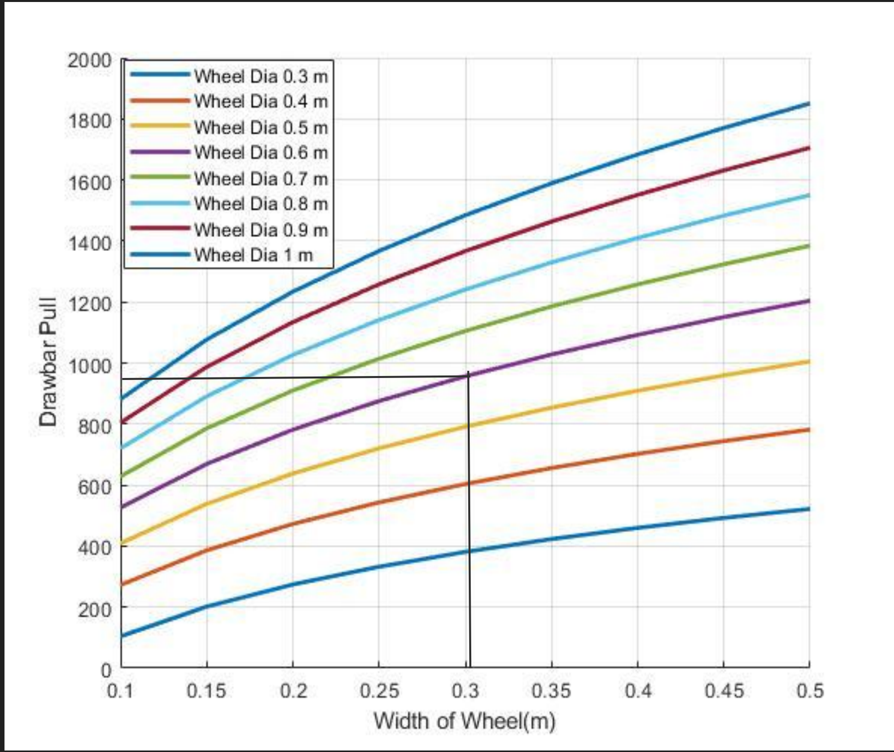


4 Wheels **6 Wheels**

Trade Study - Drawbar Pull - Grousers - Flat

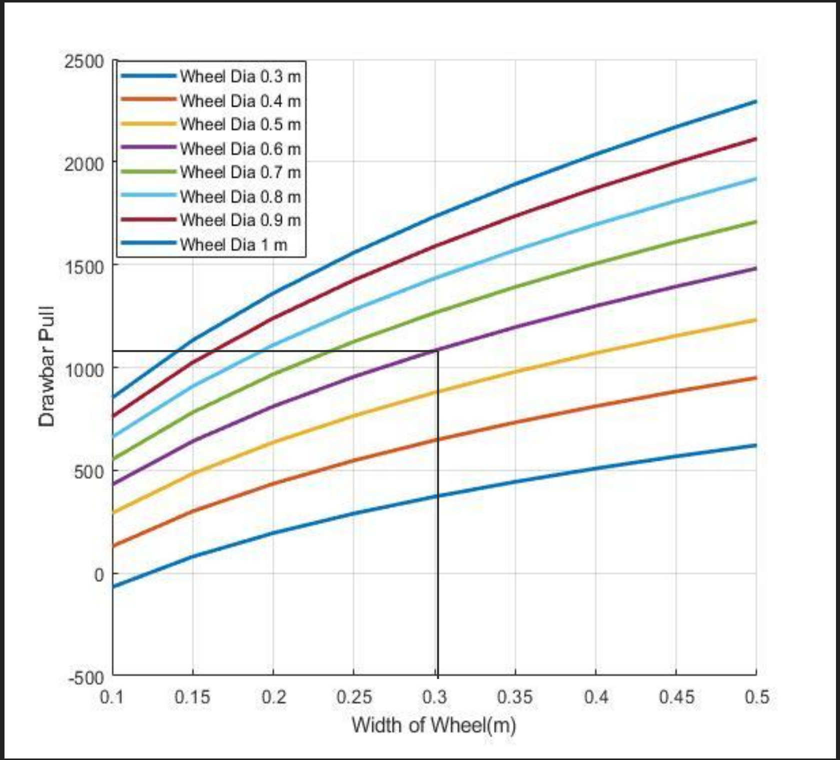


4 Wheels

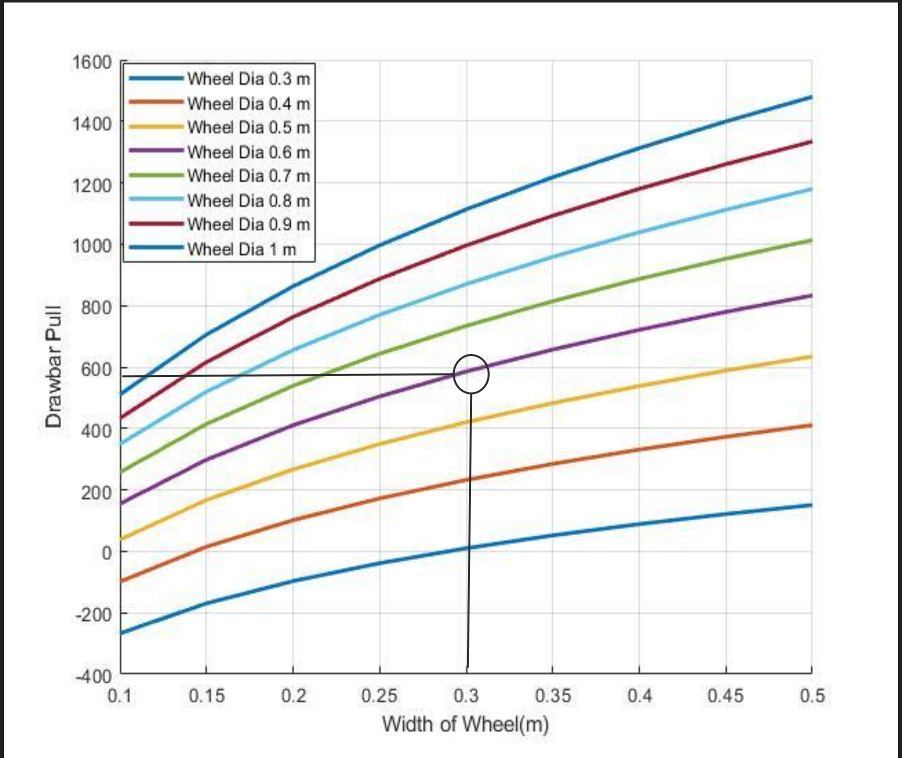


6 Wheels

Trade Study - Drawbar Pull - Grousers - 20 Slope

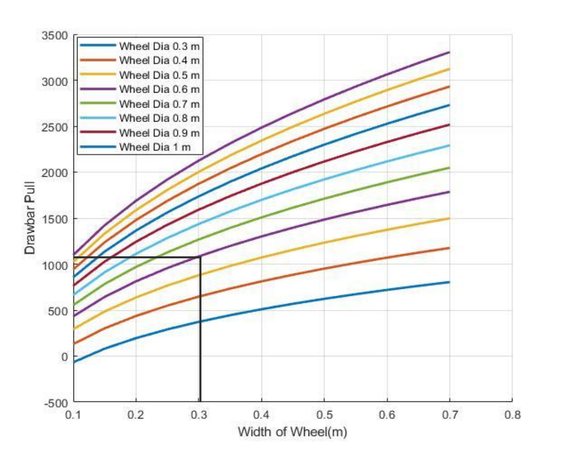


4 Wheels



6 Wheels

Drawbar Pull 4 Wheels - No. of Grousers



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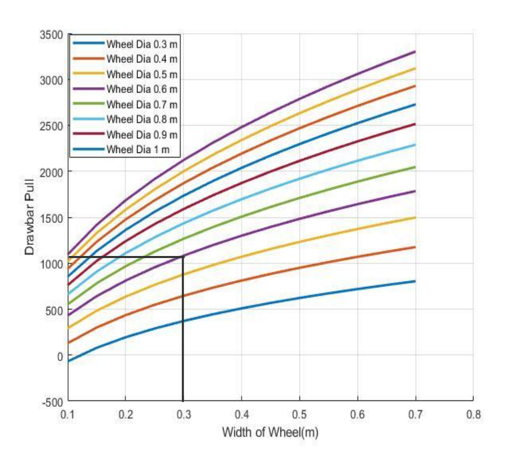

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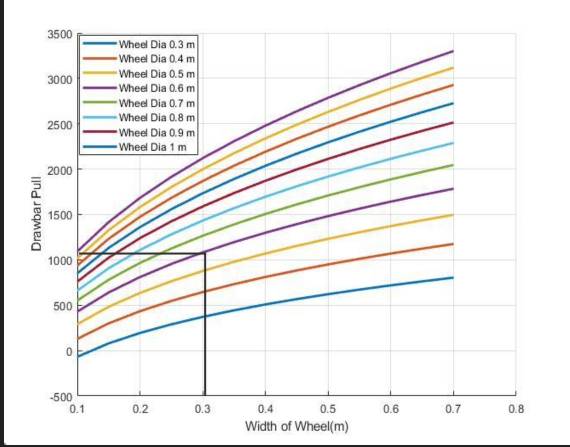

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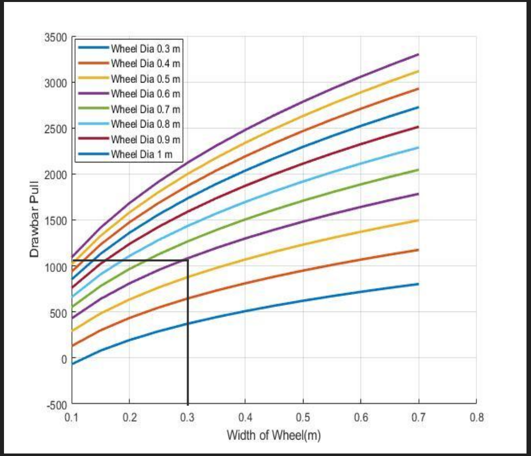

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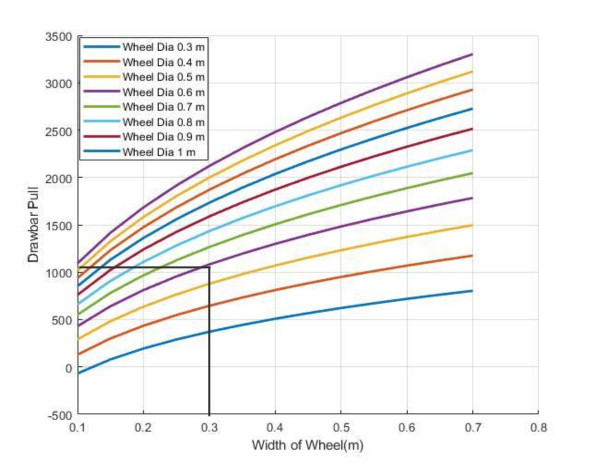
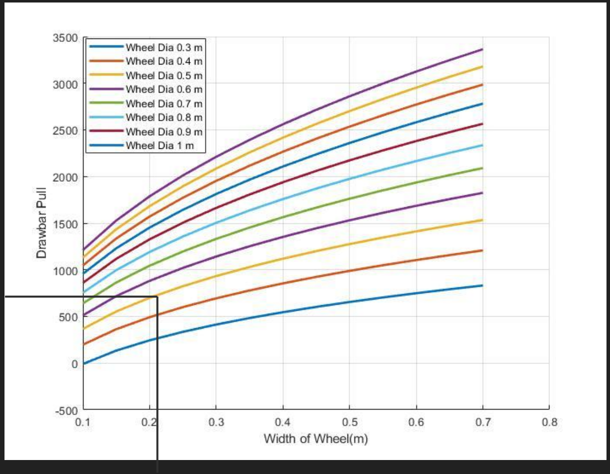
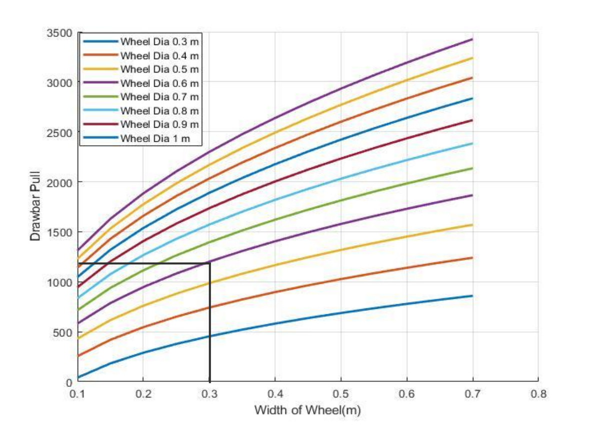
Drawbar Pull 4 Wheels - Height (cm)



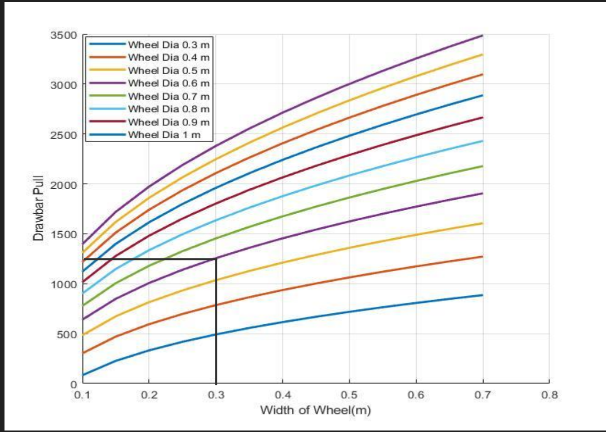
2 cm



3 cm

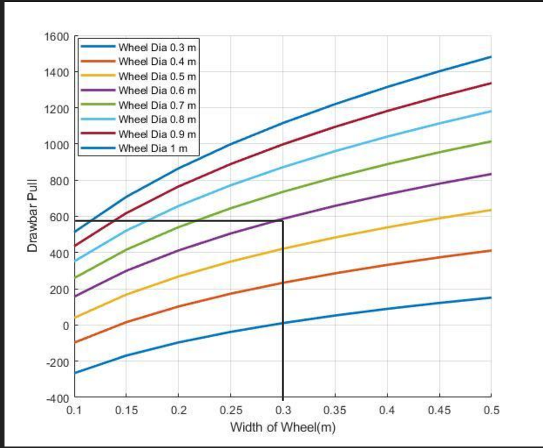


4 cm



5 cm

Drawbar Pull 6 Wheels - No. of Grousers



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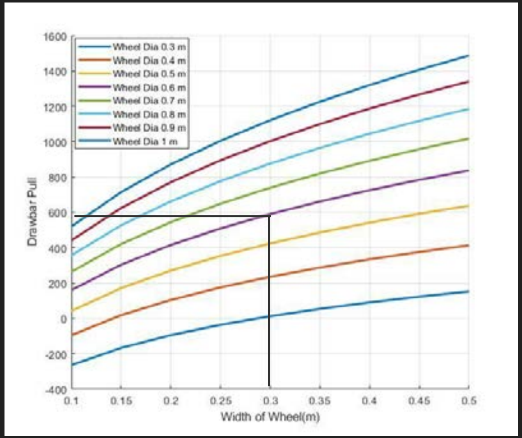

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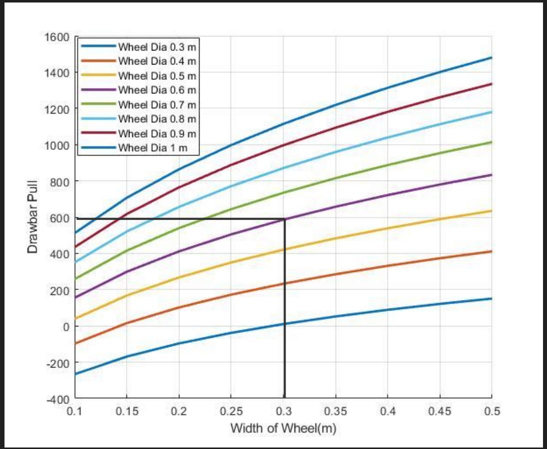

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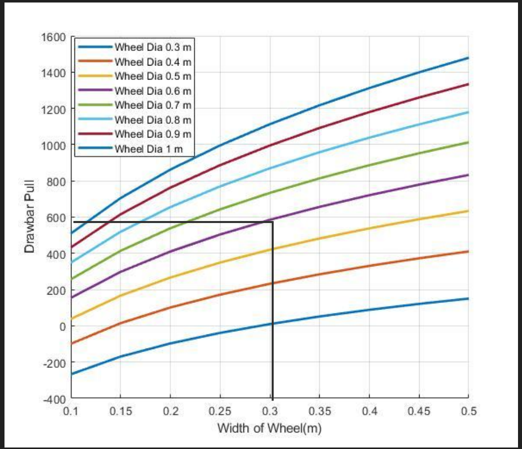

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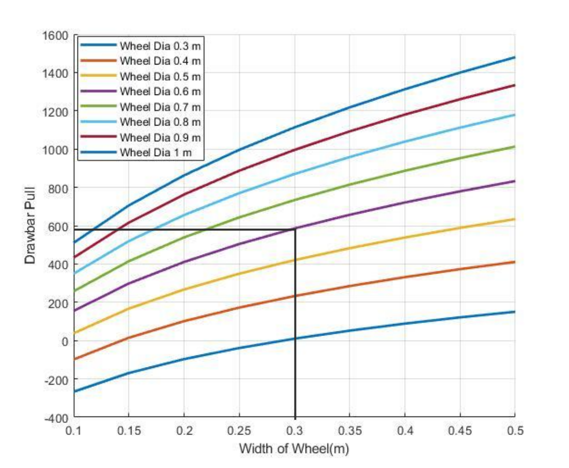
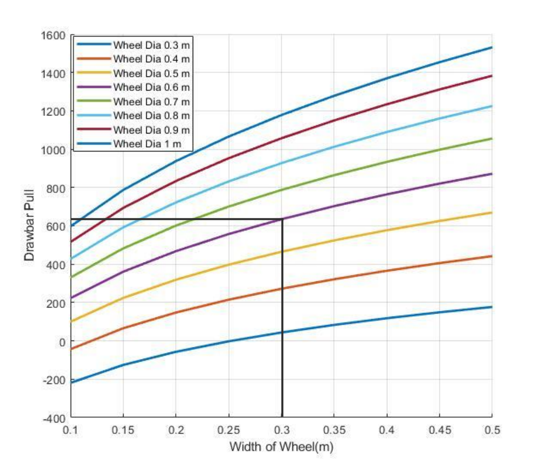
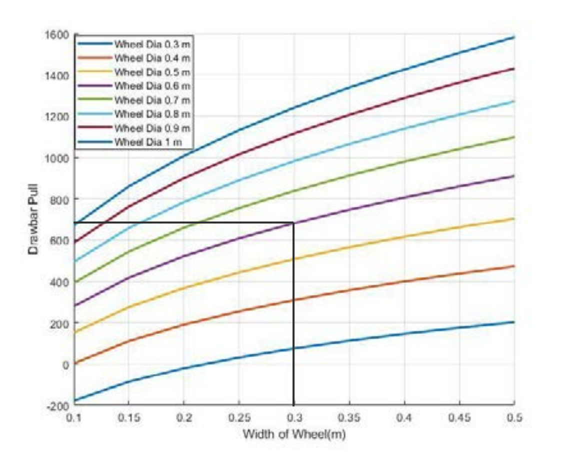
Drawbar Pull 6 Wheels - Height (cm)



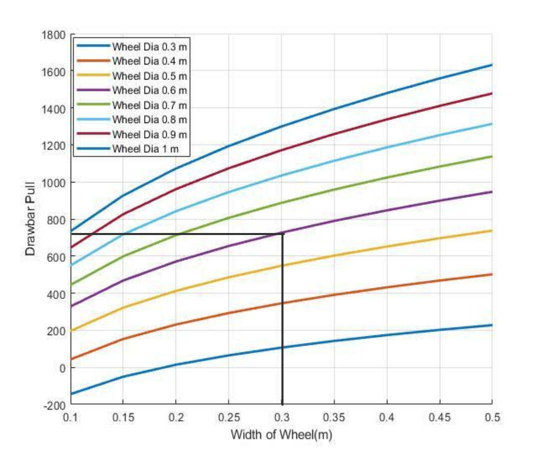
2 cm



3 cm



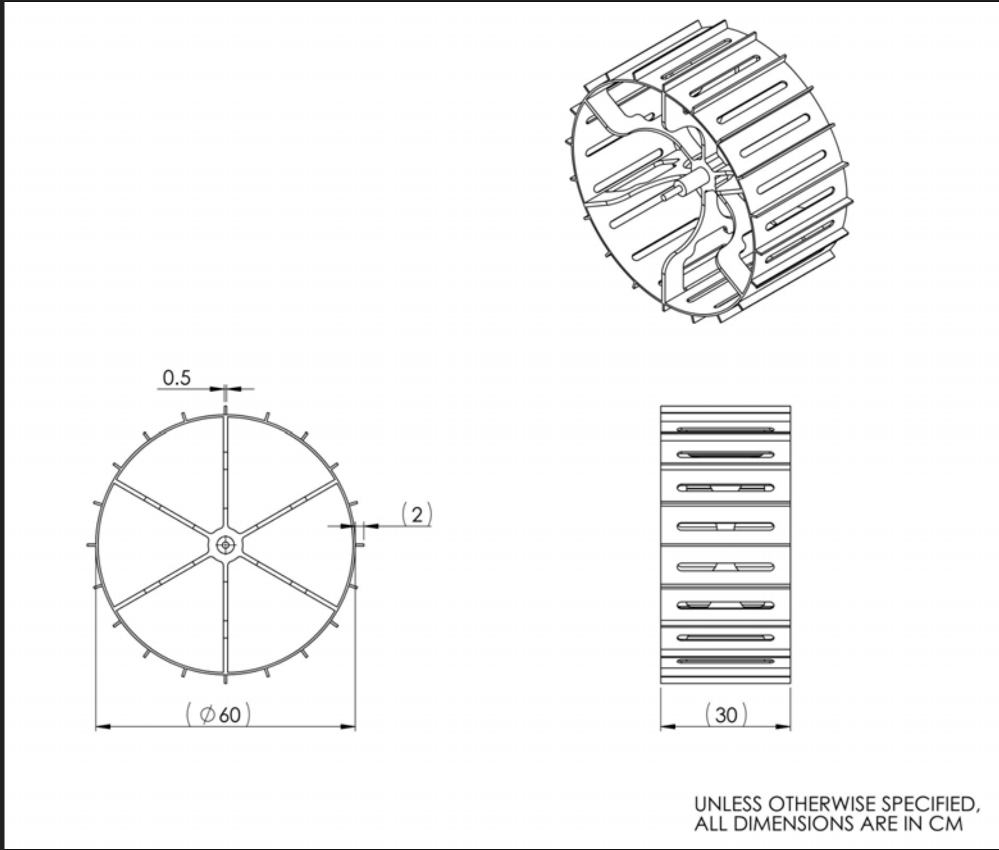
4 cm



5 cm

Wheel Drawing

Wheel Dimensions	
Diameter	60 cm
Width	30 cm
Grouser Height	2 cm
Number Spokes	6



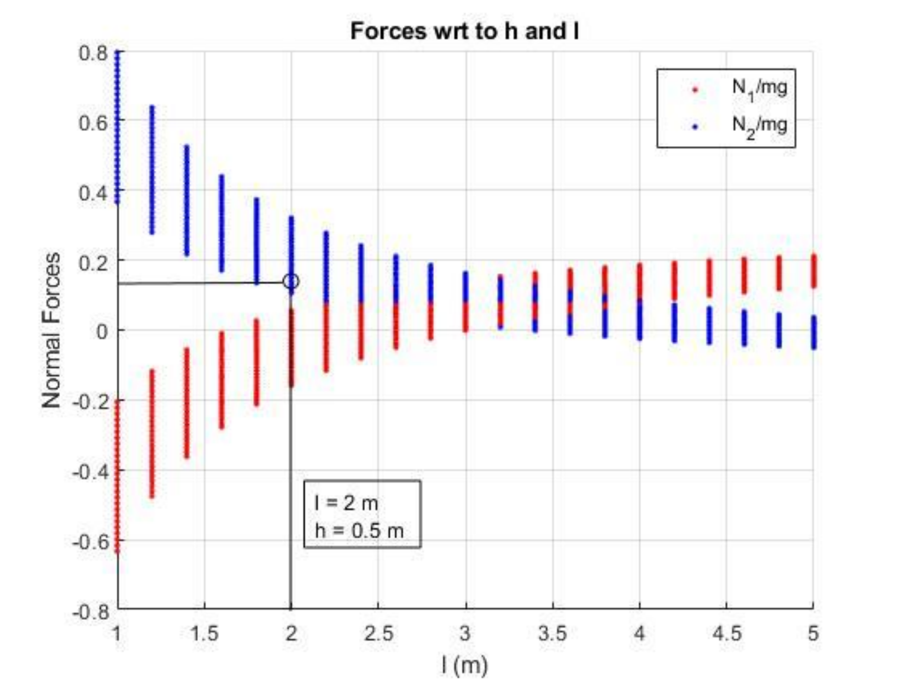
Terramechanics : Design Solution

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

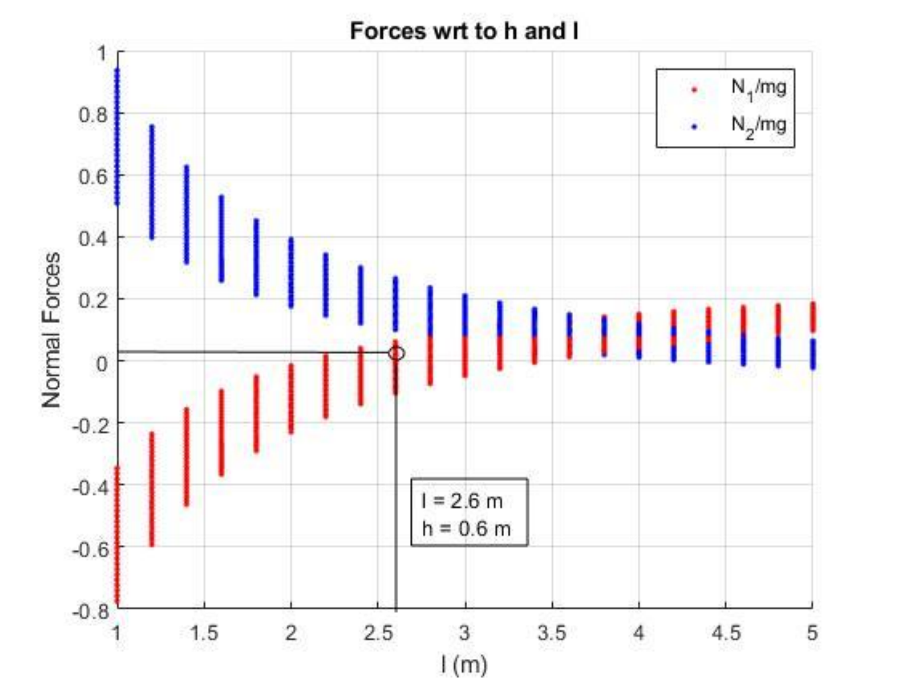
1. Diameter of wheel(d) - 0.6 m
2. Width of wheel (w) - 0.3 m
3. Number of grousers - 20
4. Height of grousers - 0.02 m = 2 cm

Stability

Stability - Forces wrt h and l

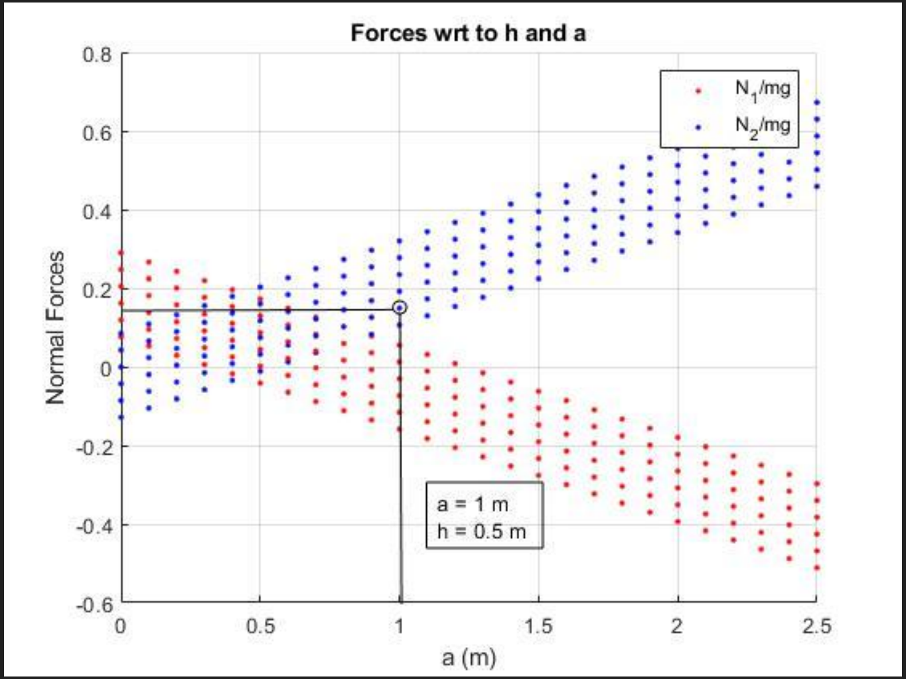


Non - Extended



Extended

Stability - Forces wrt h and a



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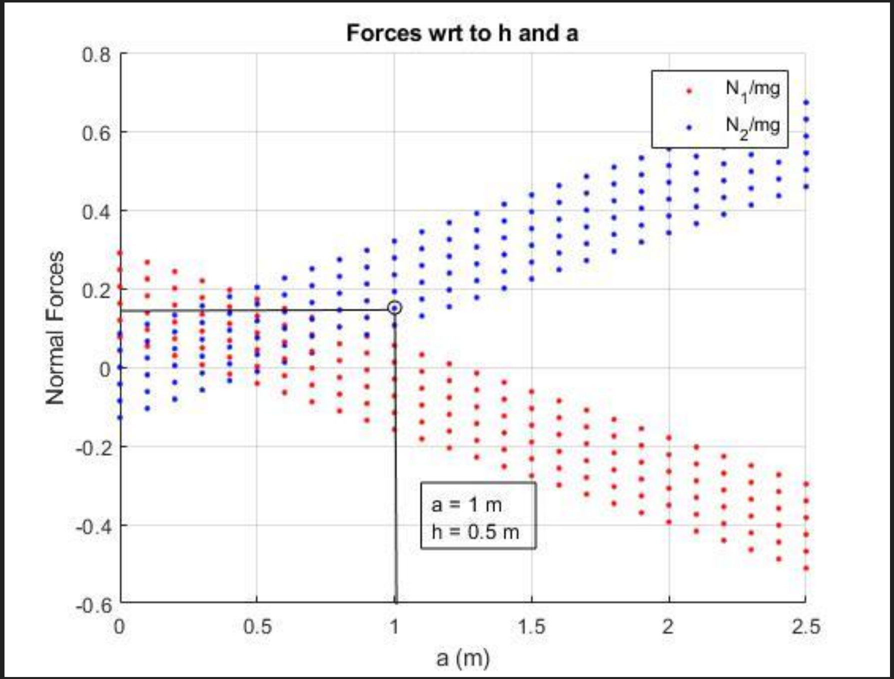
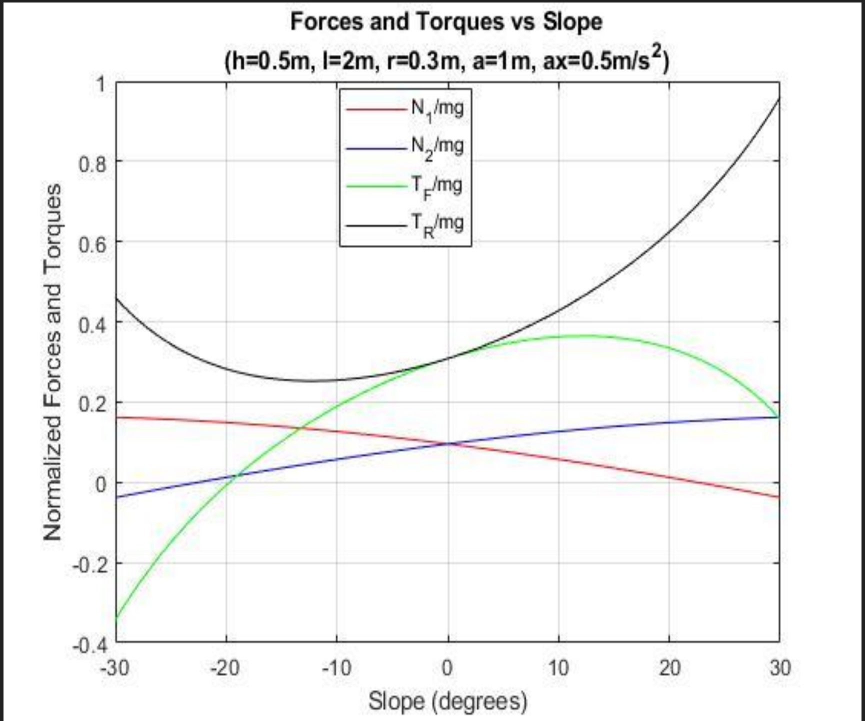
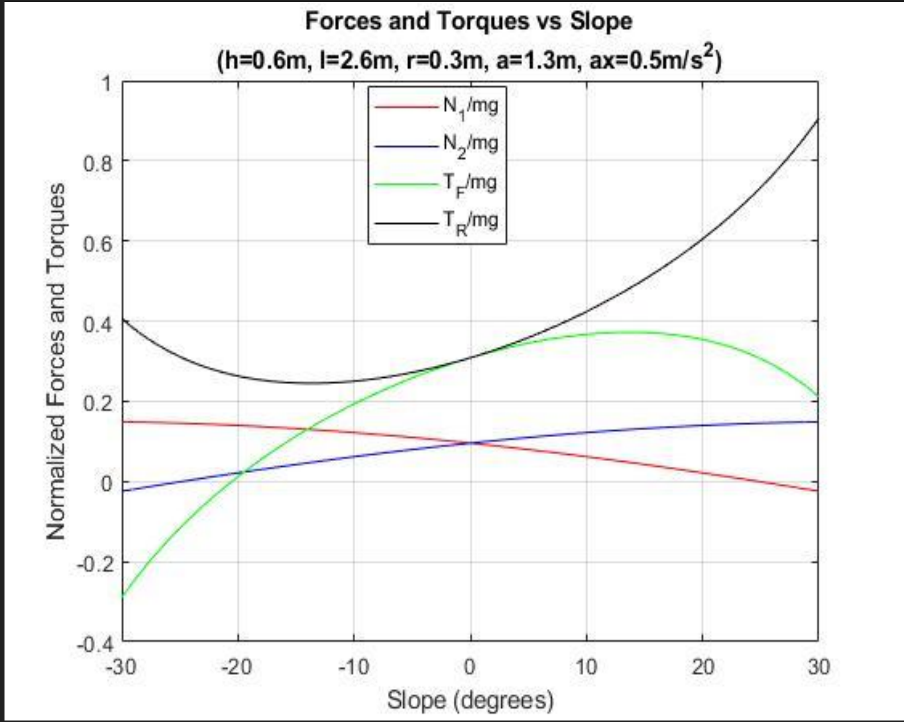


Extended

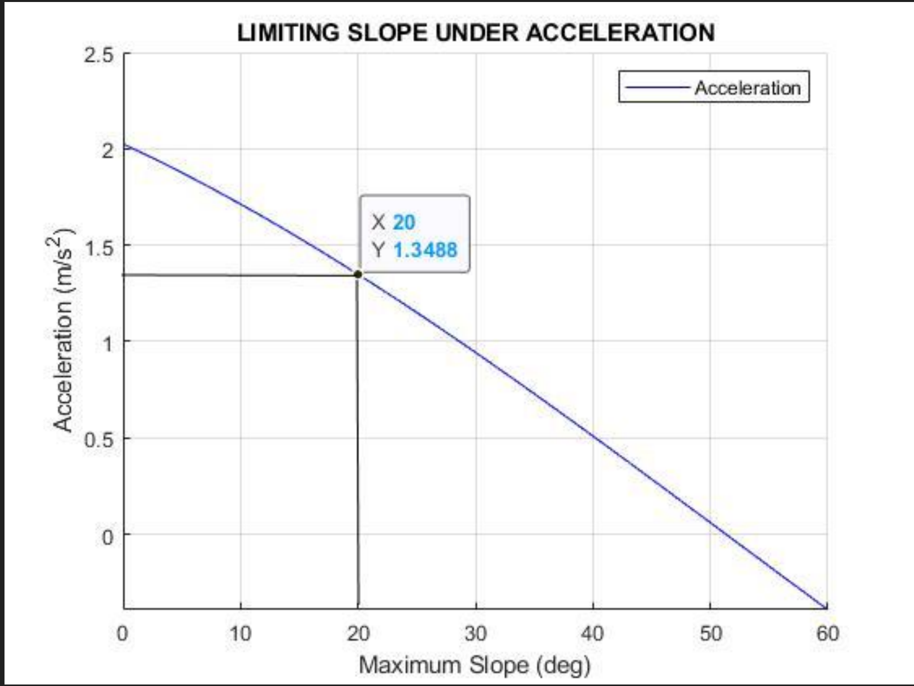
Slope Stability - Uphill / Downhill

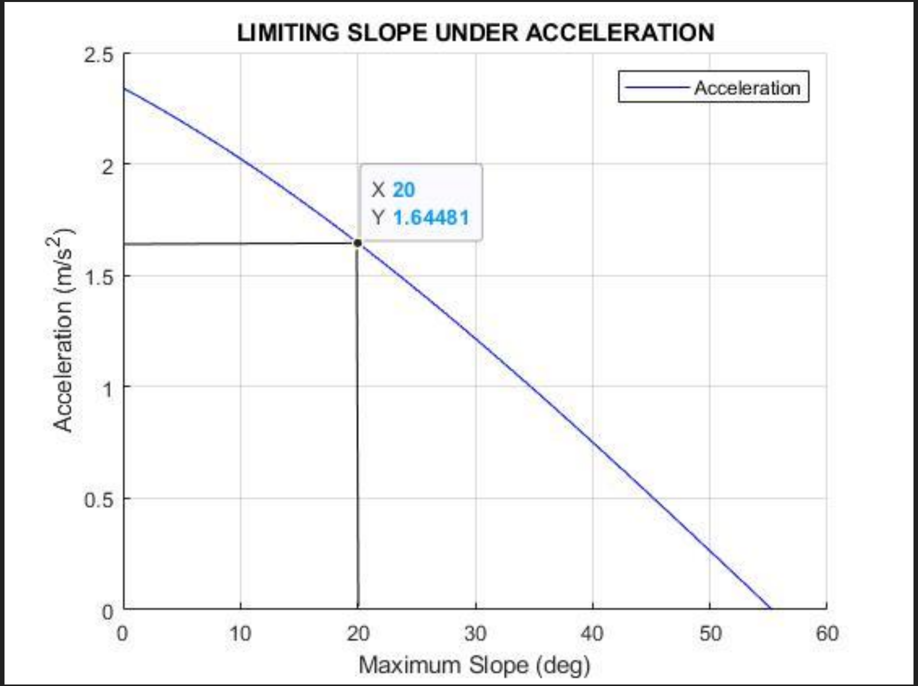




Non - Extended **Extended**

Acceleration Stability

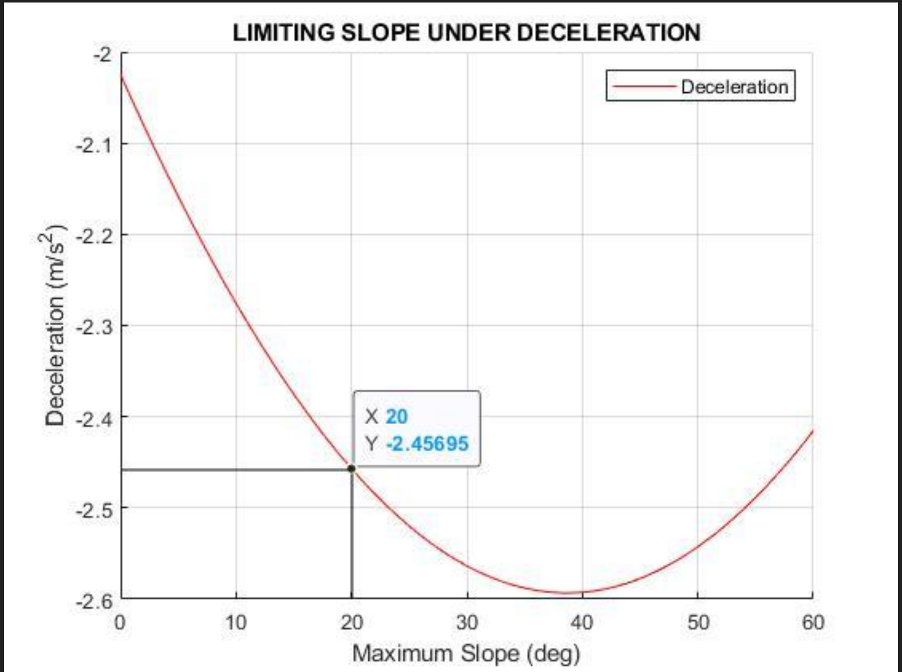




Non - Extended

Extended

Deceleration Stability



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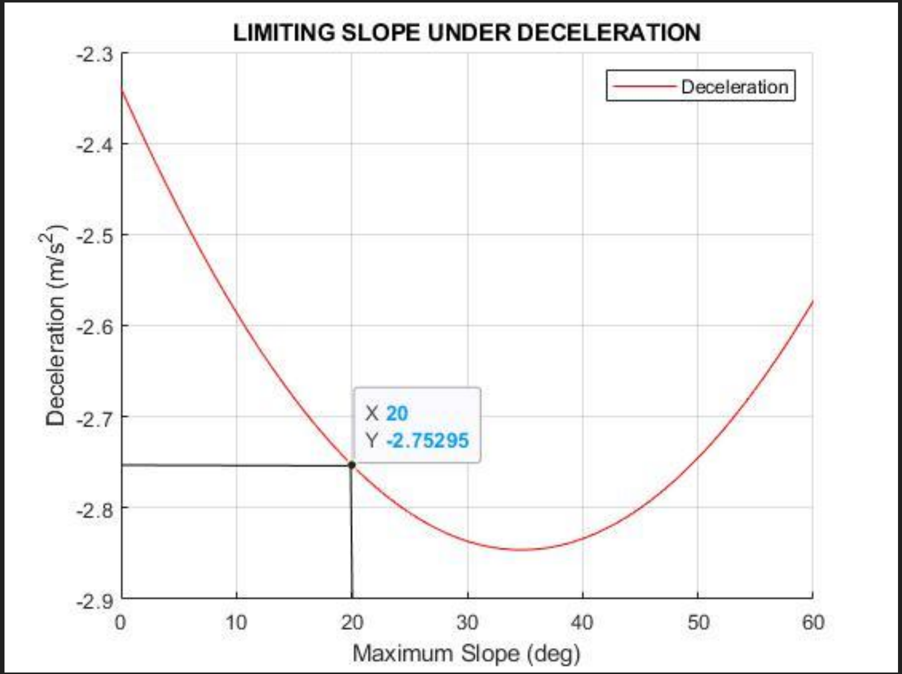


Extended

Stability - Design Solution

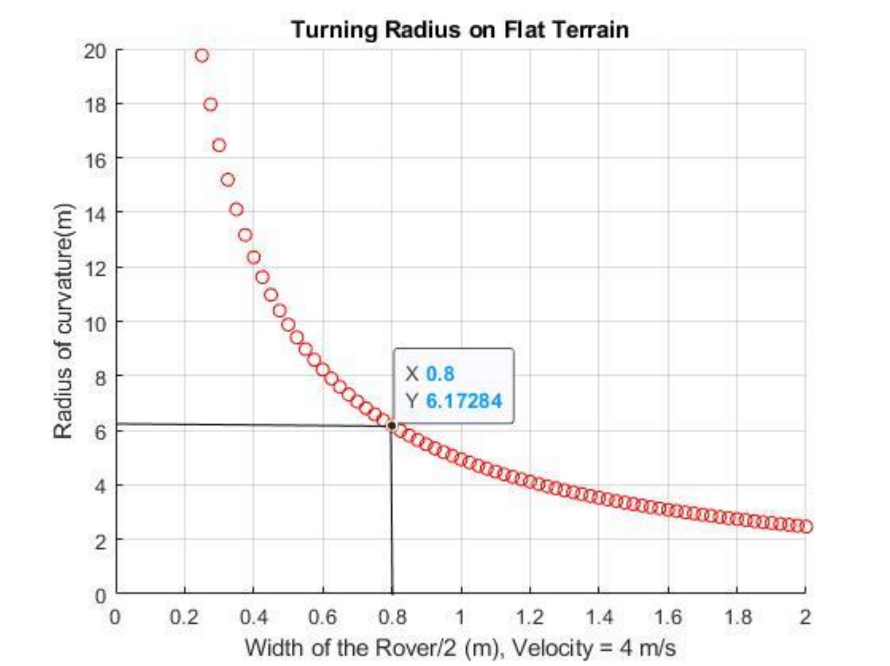
1. Non Extended - When the rover has only one EVA crew with an overall design mass of 500 kg.
    - Length of rover (l) - 2 m
    - Width of rover (c) - 1.6 m
    - Height of CoM (h) - 0.5 m
    - Length between front axle and CoM (a) - 1 m
    - Max Acceleration Rate (m/s^2)
        - Flat Terrain - 2.025
        - Slope - 1.3488
    - Max Deceleration Rate (m/s^2)
        - Flat Terrain - 2.025
        - Slope - 2.45695

Stability - Design Solution

2. Extended - When the rover has one EVA crew and one emergency EVA crew, for a total design mass of 670 kg.

- Length of rover (l) - 2.6 m
- Width of rover (c) - 1.6 m
- Height of CoM (h) - 0.6 m
- Length between front axle and CoM (a) - 1.3 m
- Max Acceleration Rate (m/s^2)
  - Flat Terrain - 2.34
  - Slope - 1.6481
- Max Deceleration Rate (m/s^2)
  - Flat Terrain - 2.34
  - Slope - 2.75295

Turning Stability - 4 Wheels - Flat Terrain



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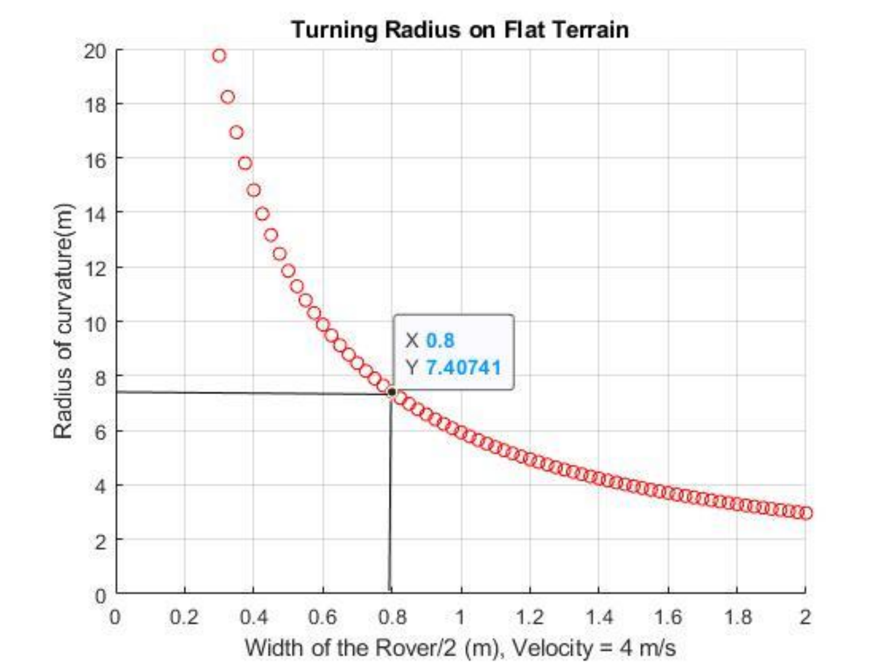
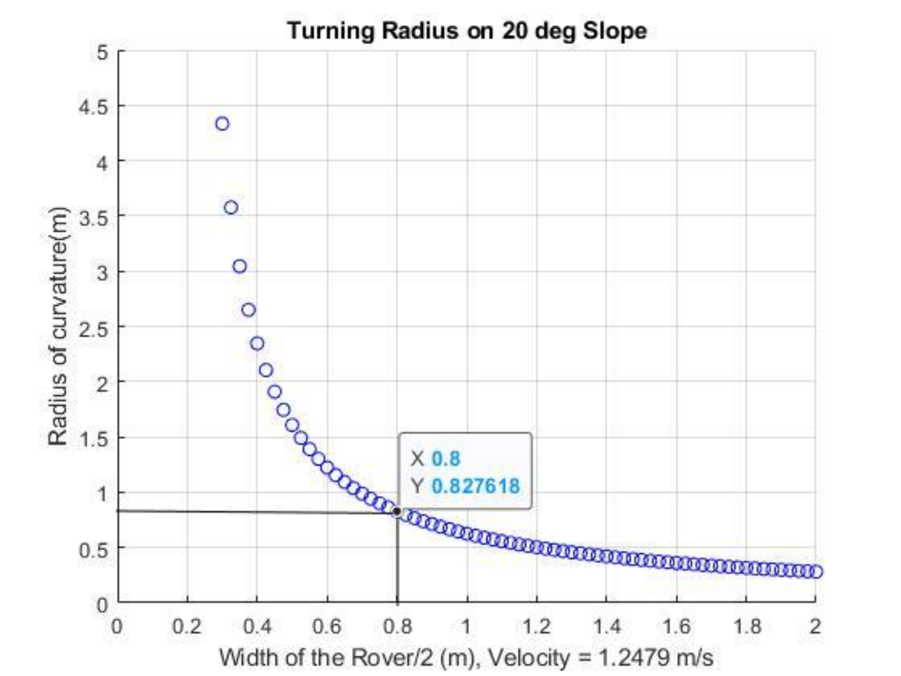


Extended

Turning Stability - 4 Wheels - Slope



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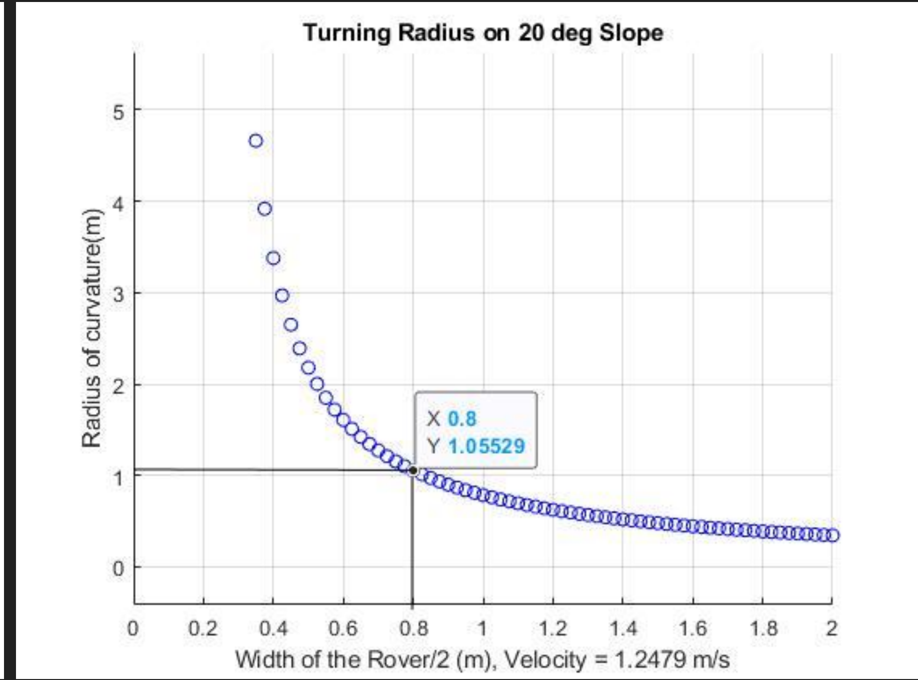


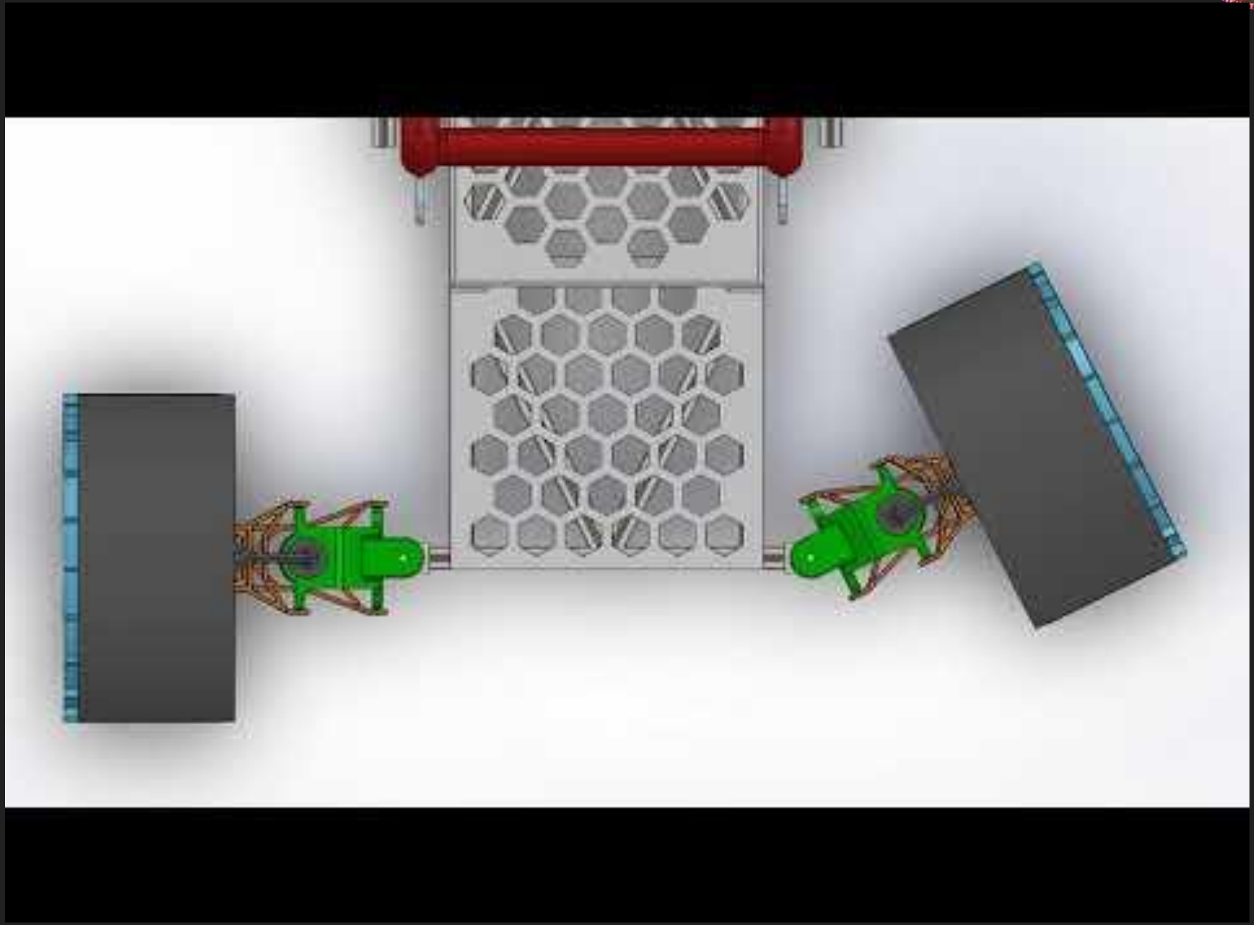
Extended

Steering

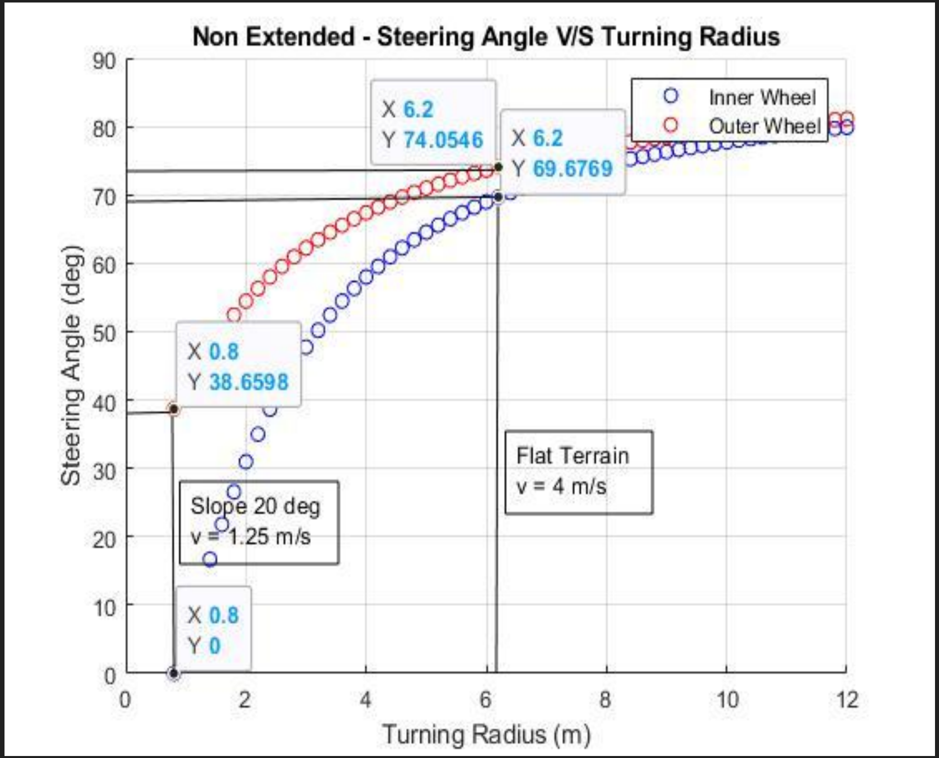
Steering Mechanism Design

Front two wheels are direct steered, each with a steering motor.

Rear wheels are fixed to the chassis



Steering Angle



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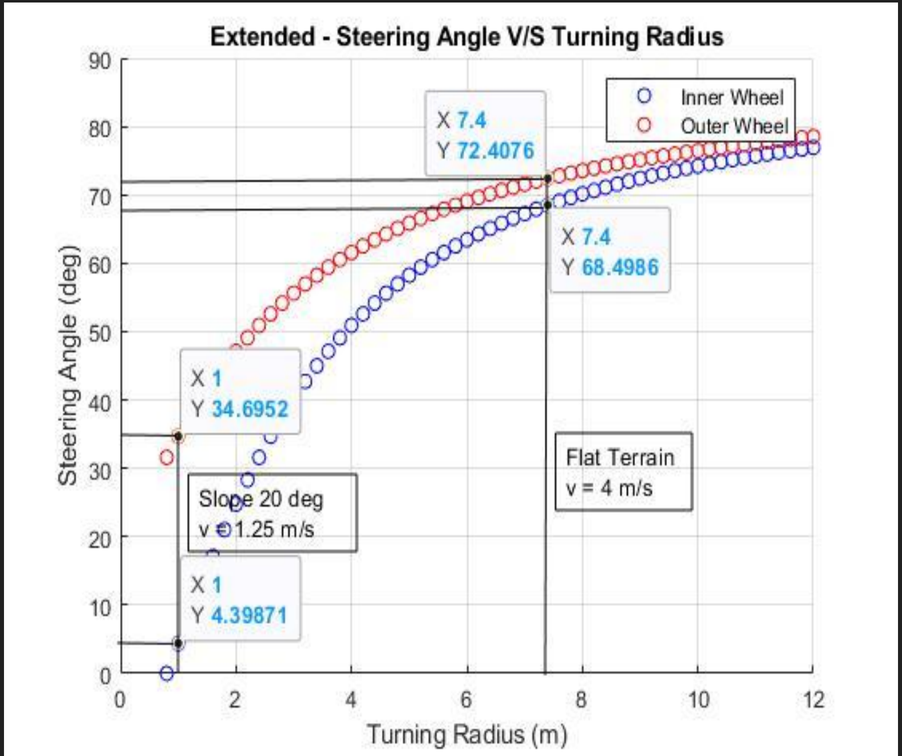
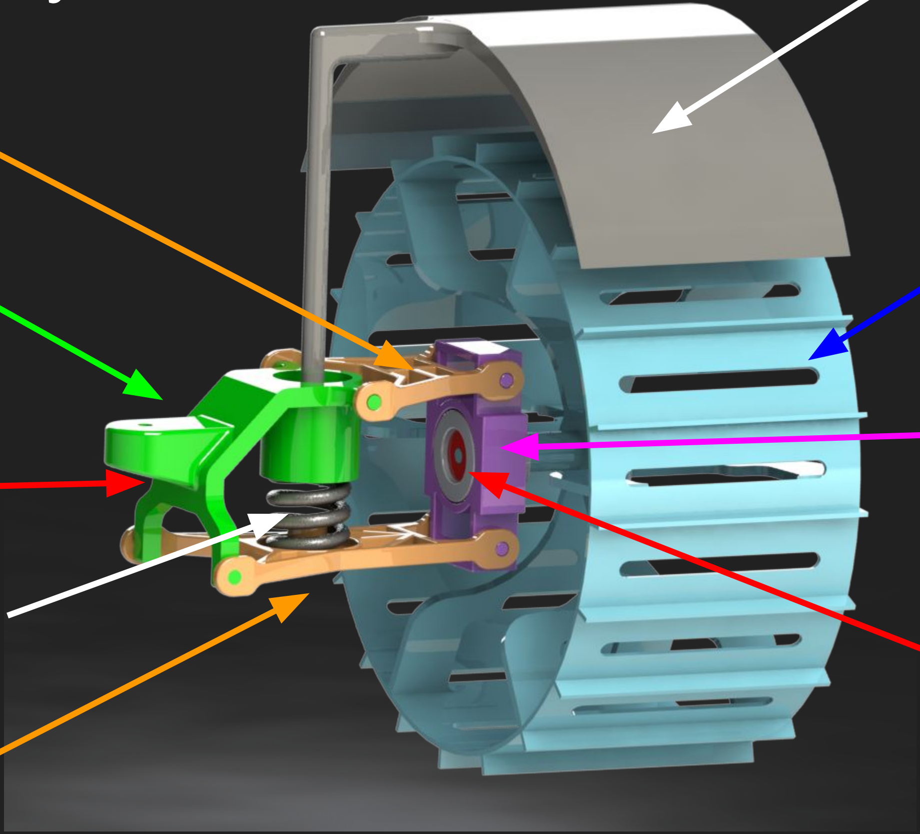


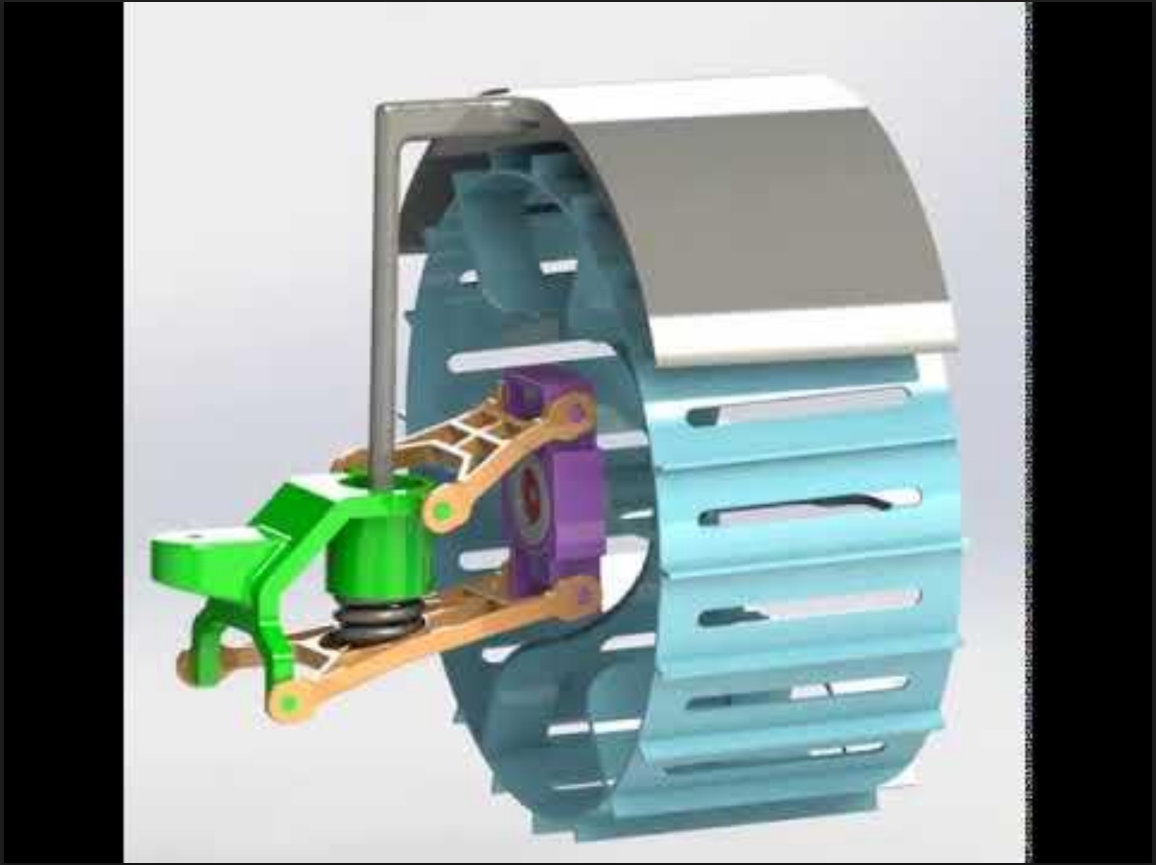
Extended

Suspension

Suspension System



Suspension

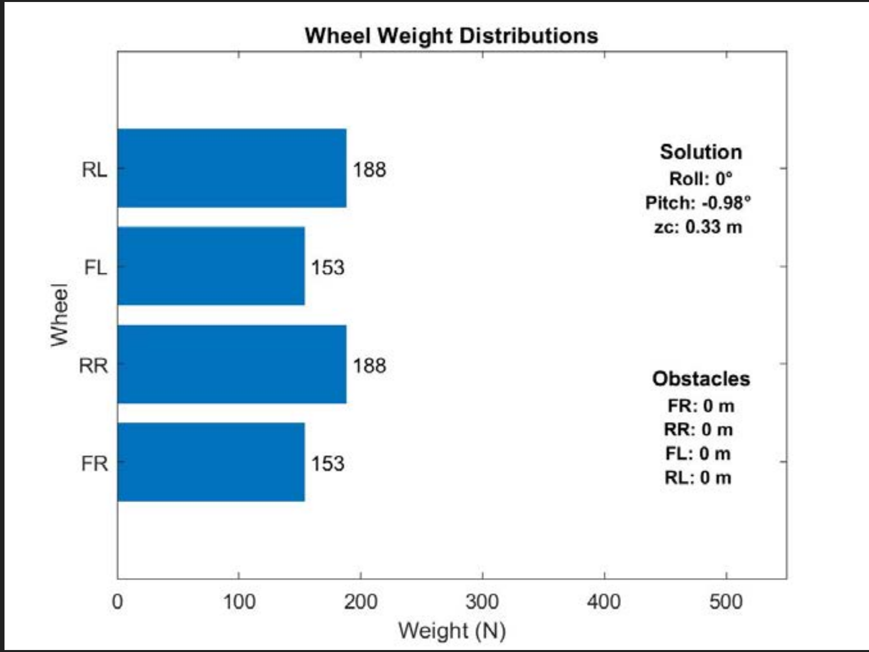


Suspension Statics

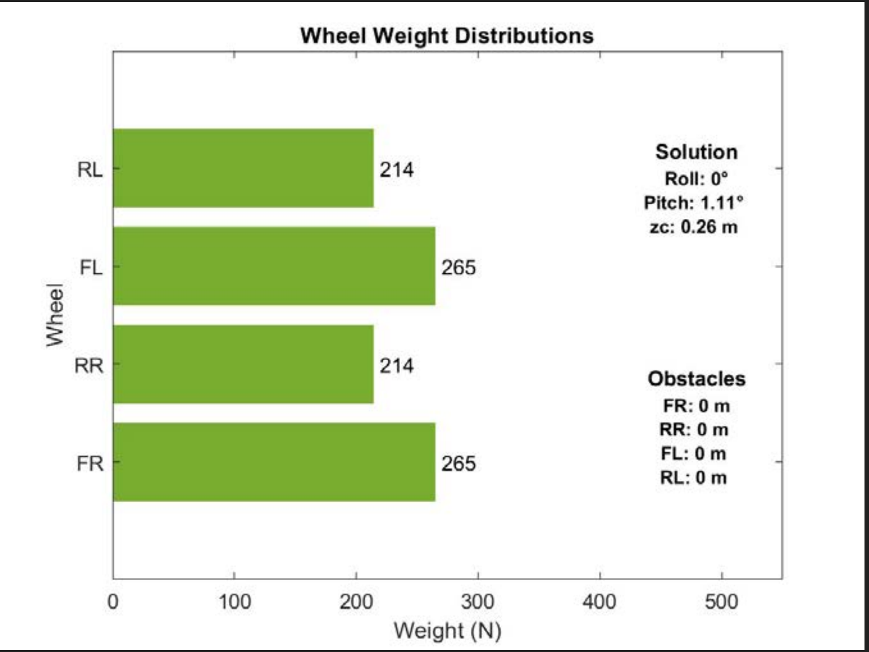
Using the method for N-wheeled independent suspension from class we can solve for weight distribution on each wheel including when wheels are on obstacles.

	Standard	Extended
COM Offset	$[X_{cg}]_v = \begin{bmatrix} 0.115 \\ 0 \\ 0.87 \\ 1 \end{bmatrix}$	$[X_{cg}]_v = \begin{bmatrix} -0.156 \\ 0 \\ 0.96 \\ 1 \end{bmatrix}$
Total Weight	682 N	957 N
Length	2 m	2.6 m
Width	1.6 m	1.6 m

Weight Distributions on Flat Terrain

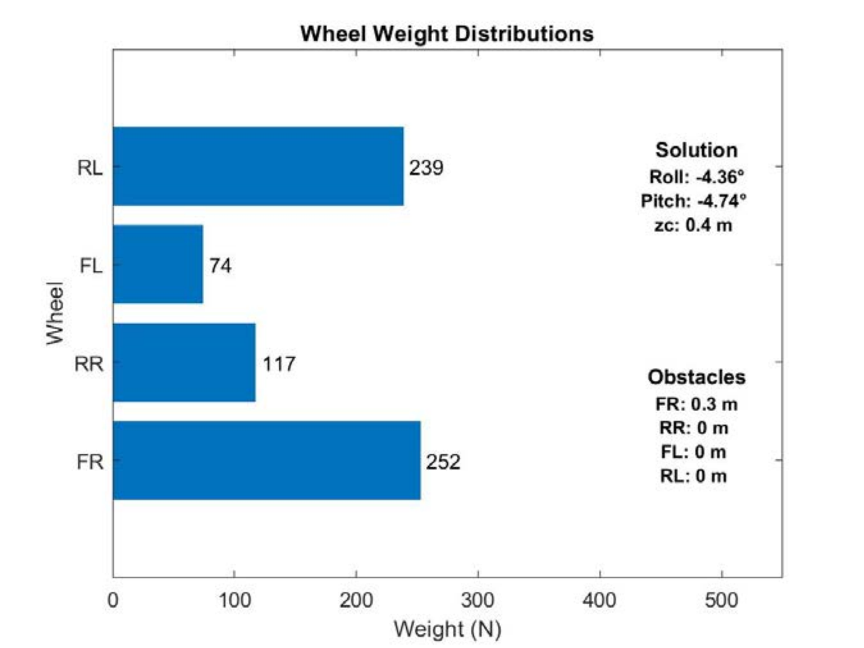


Standard Configuration

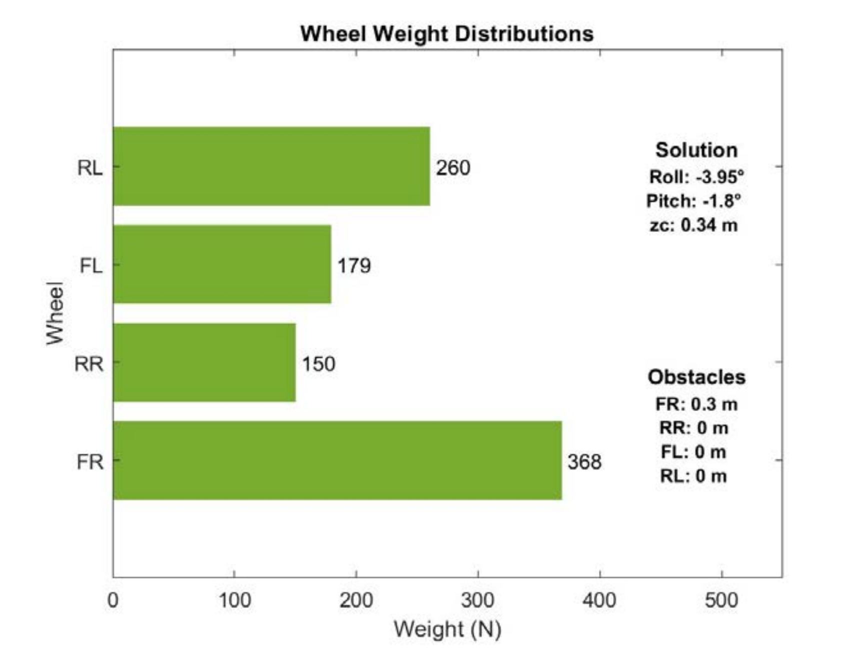


Extended Configuration

Weight Distributions (Front Right on Obstacle)

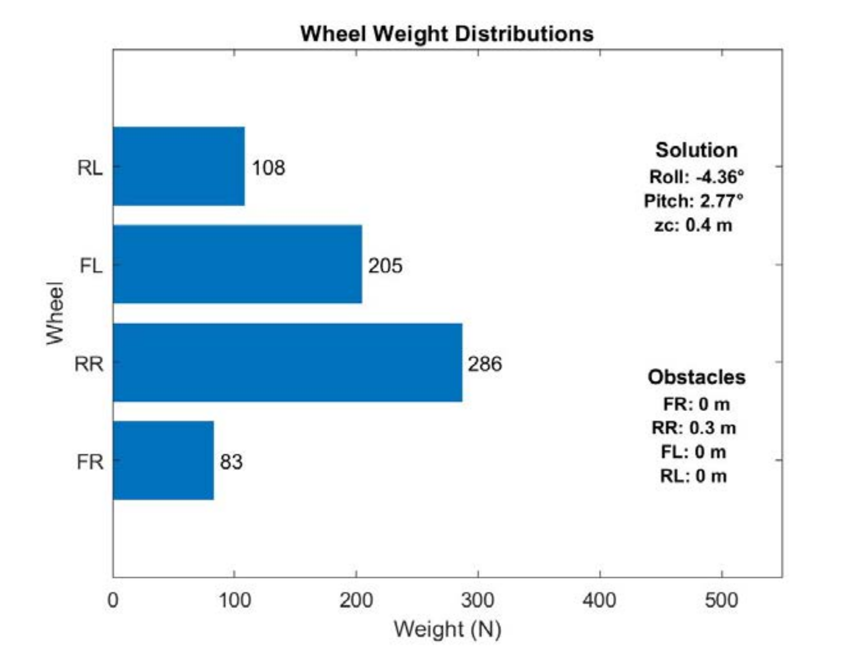


Standard Configuration

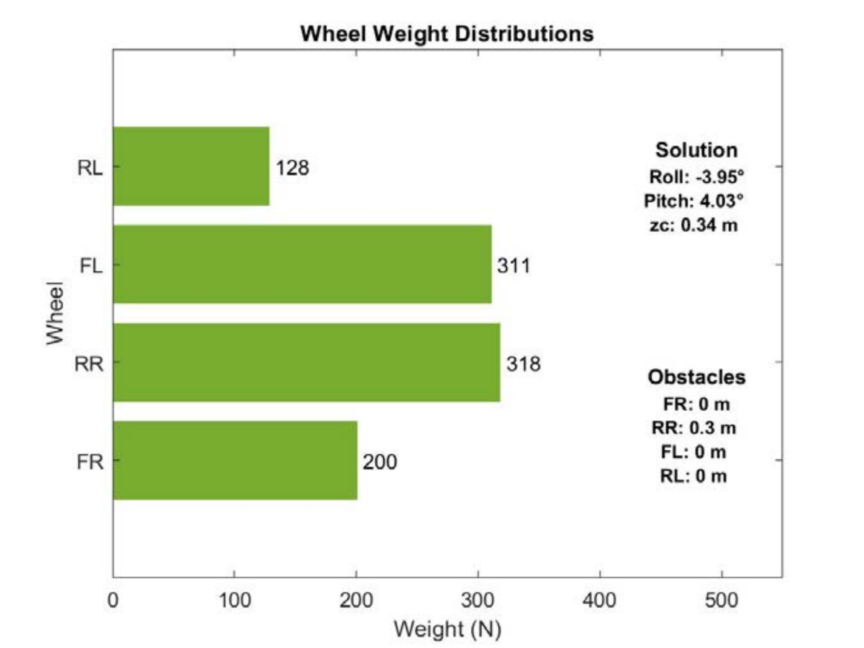


Extended Configuration

Weight Distributions (Rear Right on Obstacle)



Standard Configuration



Extended Configuration

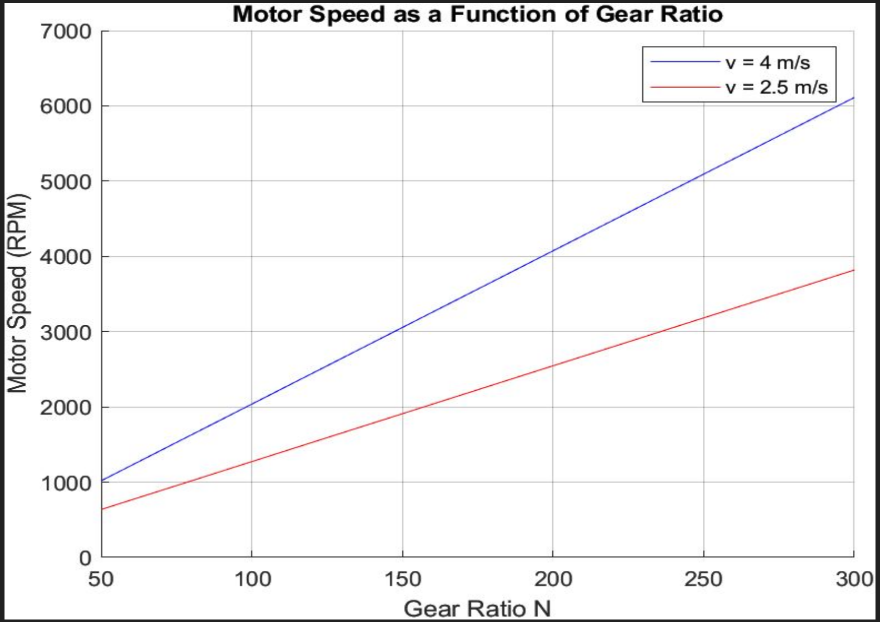
Motors

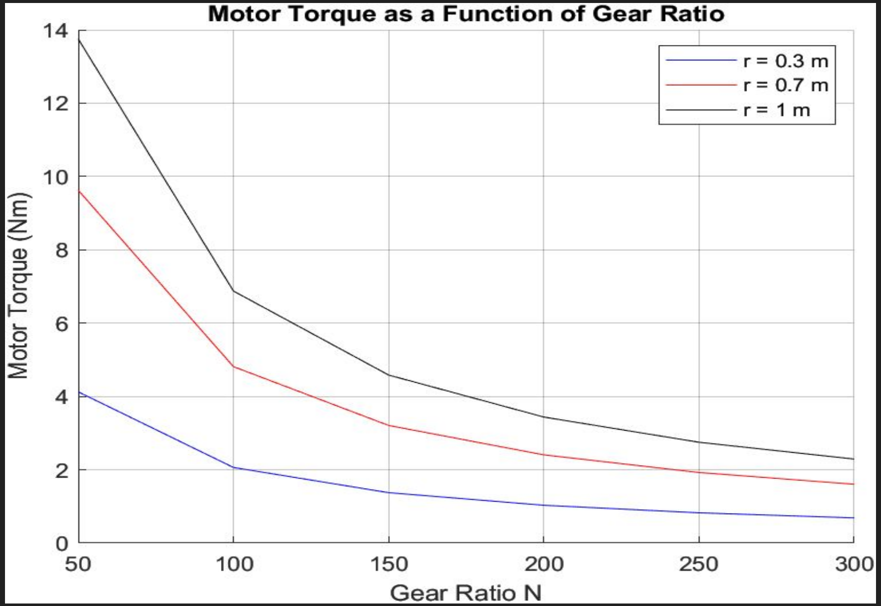
Motors Trade-Study

Type	Advantages	Disadvantages	Typical Applications	Typical Drive
Brushless DC Motor	➢ Long lifespan ➢ Low maintenance ➢ High efficiency	➢ High initial cost ➢ Requires a controller	➢ Hard drives ➢ CD/DVD players ➢ Electric vehicles	Multiphase DC
Brushed DC Motor	➢ Low initial cost ➢ Simple speed control (Dynamo)	➢ High maintenance (brushes) ➢ Low lifespan	➢ Treadmill ➢ Exercisers ➢ Automotive starters	Direct (PWM)
AC Induction (Shaded Pole)	➢ Least expensive ➢ Long life ➢ High Power	➢ Rotation slips from frequency ➢ Low starting torque	➢ Fans	Uni/Poly Phase AC
AC Induction (Split-Phase Capacitor)	➢ High power ➢ High starting torque	➢ Rotation slips from frequency	➢ Appliances	Uni/Poly Phase AC
AC Synchronous	➢ Rotation in-sync with frequency ➢ Long-life (alternator)	➢ More expensive	➢ Clocks ➢ Audio turntables ➢ Tape drives	Uni/Poly Phase AC
Stepper DC	➢ Precision positioning ➢ High holding torque	➢ Slow speed ➢ Requires a controller	➢ Positioning in printers and floppy drives	Multi-phase DC

Reference: Motor Comparison, Circuit Cellar Magazine, July 2008, Issue 216, Bachiochi, p.78

Drive Motor Requirements

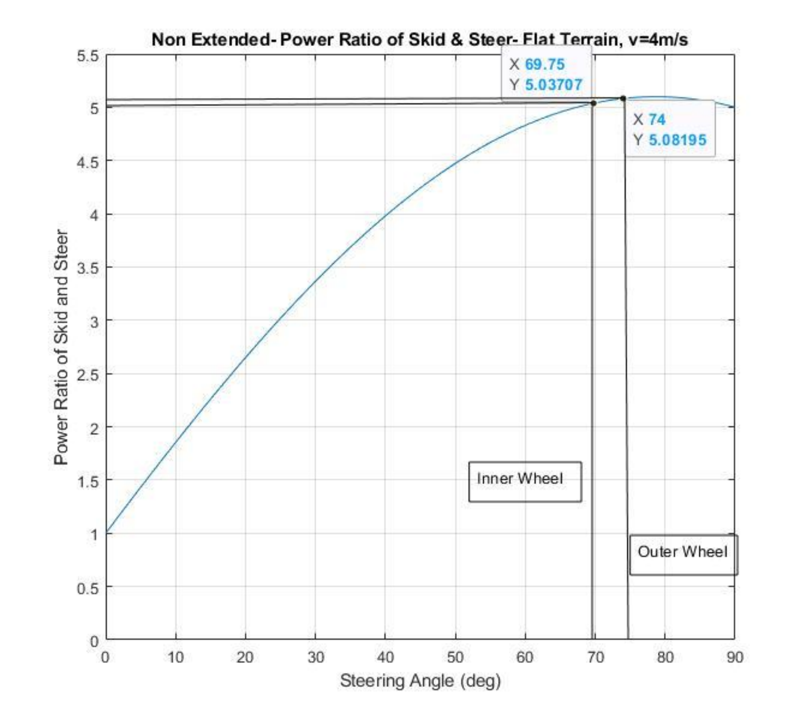


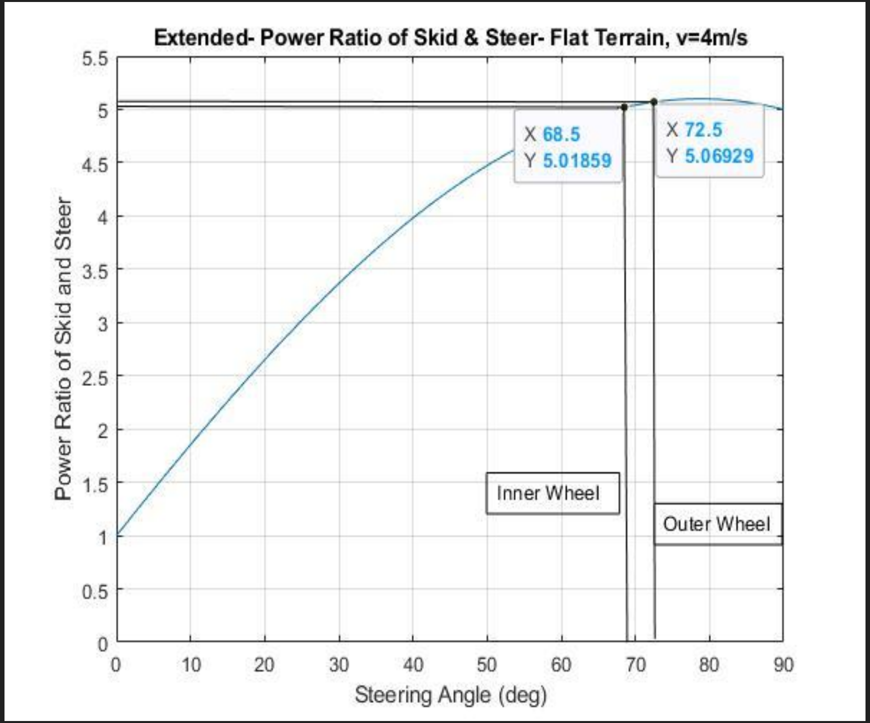


- As per velocity constraints, the rover requires a motor speed a little over 4000 rpm for a gear ratio of 200.

- Motor increases with increase in wheel radius
- For wheel radius = 0.3m, the motor torque required is around 1Nm when the gear ratio is 200.
- Assuming, gear efficiency is 80%, we require a motor with torque around 1.25 Nm.

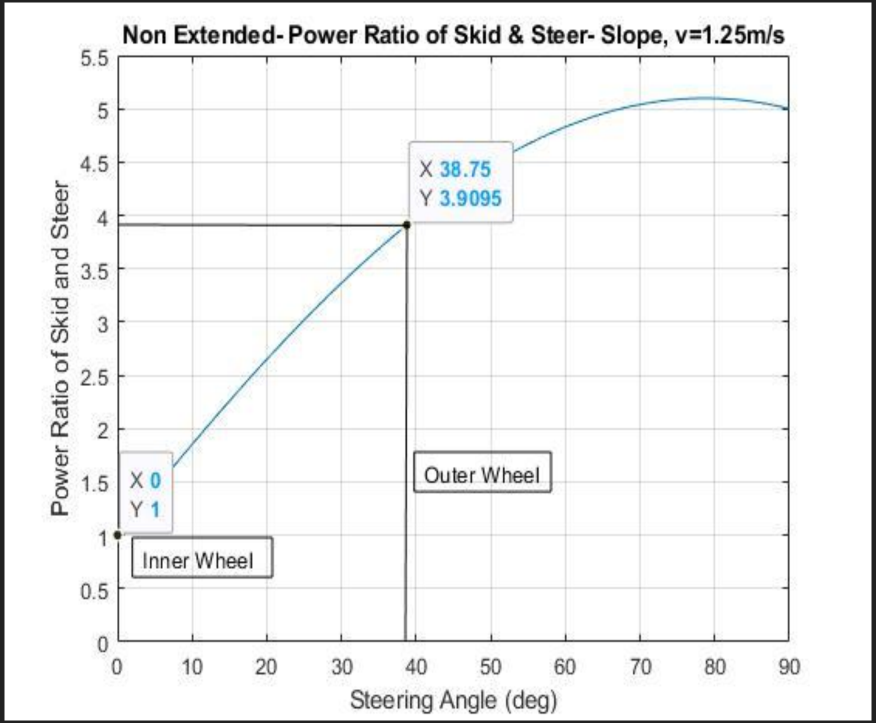
Power Ratio of Skid & Steer - Flat Terrain



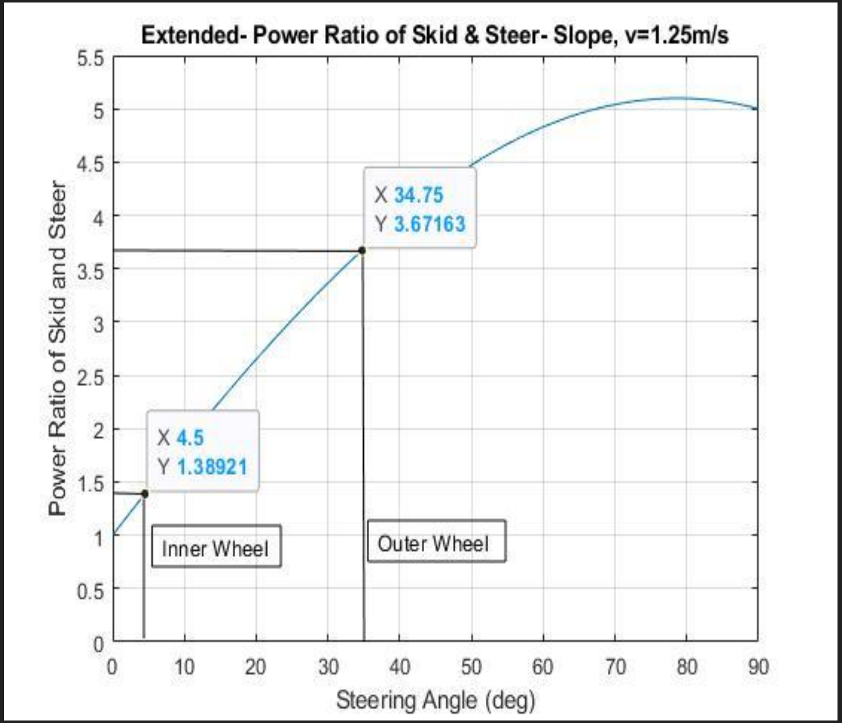


Non - Extended **Extended**

Power Ratio of Skid & Steer - Slope 20 deg

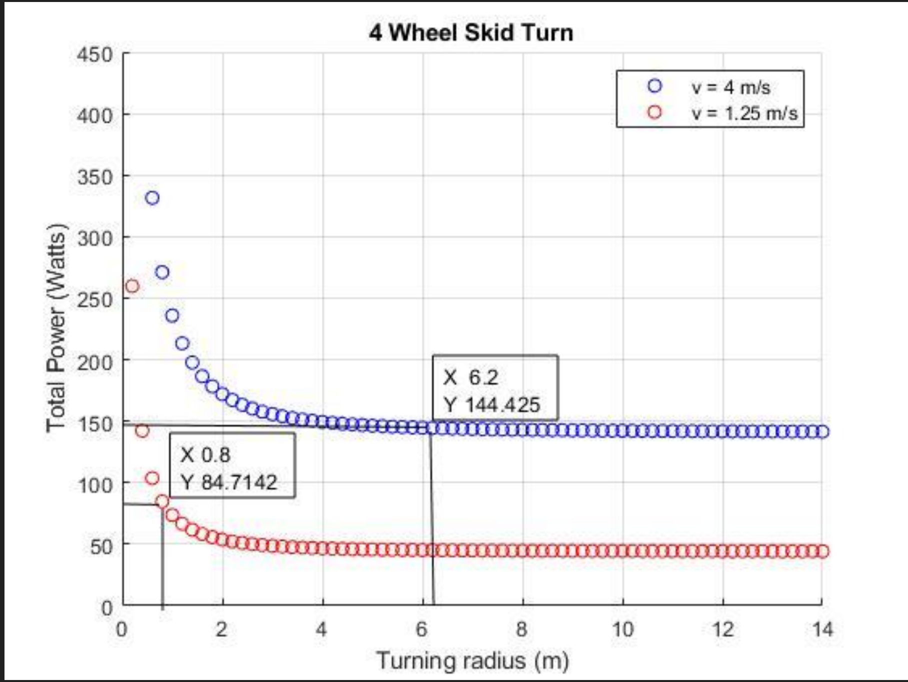


Non - Extended

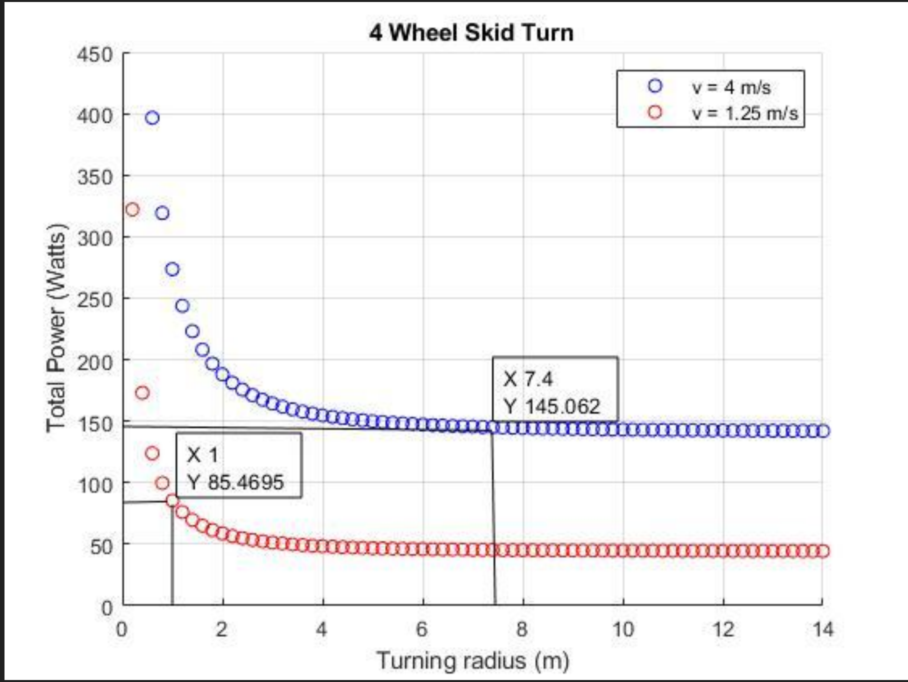


Extended

Power - 4 Wheel Skid Turn



Non - Extended



Extended

Motor Requirements

- Driving Motor
  - Brushless DC motors were chosen for wheel drive motors.
  - A motor from the RBE(H) 01212 series which complied with the torque and speed requirements was chosen.
- Steering Motor
  - For each wheel steering, a motor with output power ~160 watts is required.
  - A motor from the RBE(H) 01212 series which complied with the power requirements was chosen.

https://npm-ht.co.jp/_assets/wp-content/uploads/2019/12/RBE_Series_Motors_Brochure_01210.pdf

Sensors & Perception

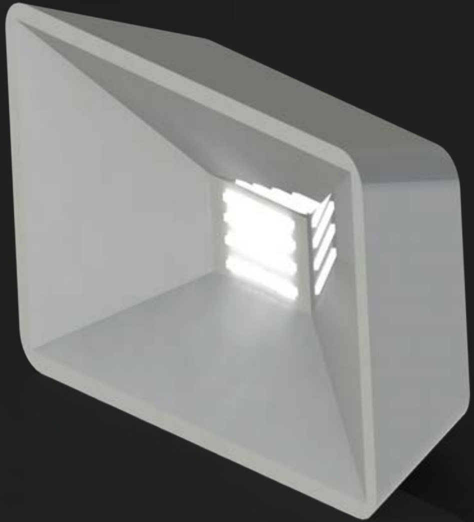
Lighting / LiDAR

4 LED Floodlights

- 35,000 lumens each
- 0.6kg each → 2.4kg total
- 30W each → 120W total

4 Velodyne Puck LITE

- 590g each → 2.4kg total
- 8W each → 32W total



https://velodynelidar.com/products/puck-lite

Cameras

2 Sony 4K PTZ cameras

- 1.8 kg each → 3.6 kg total
- 25W (max) each → 50W

4 stereo cameras

- 72g each → 288g
- 2W each → 8W

1 omni-directional camera (Go-Pro Max)

- 163g
- 8 W

https://pro.sony/en_EE/product-resources/diagrams/brc-x400-3d-cad

https://www.digitalcameraworld.com/buying-guides/best-360-cameras

https://store.intelrealsense.com/buy-intel-realsense-depth-camera-d455.html, https://www.intelrealsense.com/wp-content/uploads/2020/06/Intel-RealSense-D400-Series-Datasheet-June-2020.pdf

Computing

Autonomous path planning and full utilization of LiDAR + cameras requires non-trivial computing power.

Laptop style computer:

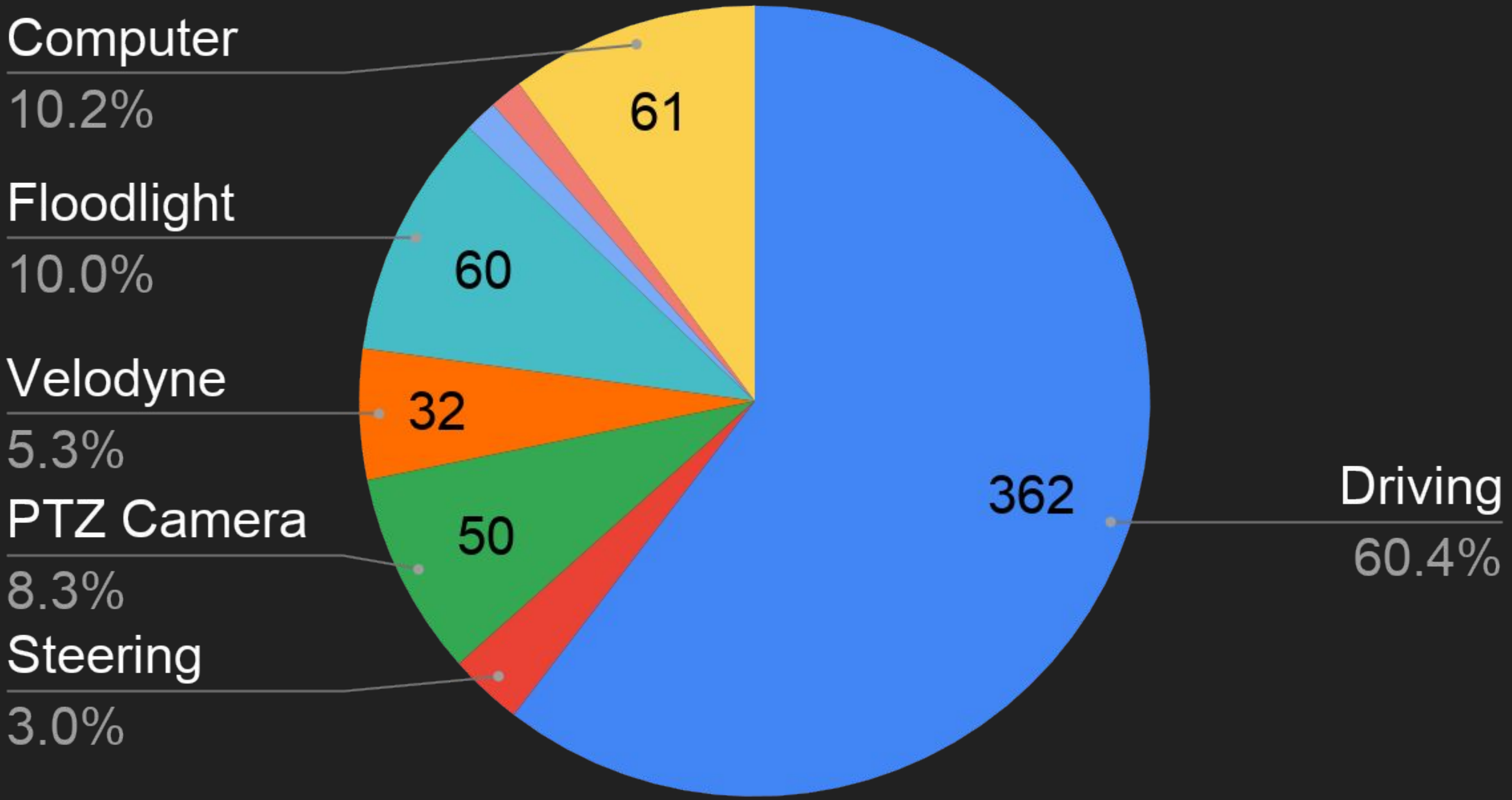
- 16GB RAM, 2.3GHz Quad Core CPU, 1.5GB Graphics
- 61W
- 1 kg

Desktop style computer:

- 64+GB RAM, 4.3GHz 8 core CPU, 8GB Graphics
- 650W
- ~6kg

Power

Total Power (W)



Power

Category	Part	Individual Power (W)	# Required	Duty Cycle (%)	Total Power (W)
Driving / Steering	Driving motors	181	4	50%	362
	Steering motor	181	2	5%	18.1
					0
Sensors / Lighting	PTZ Camera	25	2	100%	50
	Velodyne Puck LITE	8	4	100%	32
	Floodlight	30	2	100%	60
	Stereo Camera	2	4	100%	8
	Omnicamera	8	1	100%	8
	Computer (Laptop style)	61	1	100%	61

Total Power (W)	**599.1**
Total Energy - 8 Hour Sortie (Wh)	**4792.8**

	Total Battery Mass (kg)
@ 400Wh/kg	**11.982**
@ 260 Wh/kg	18.43

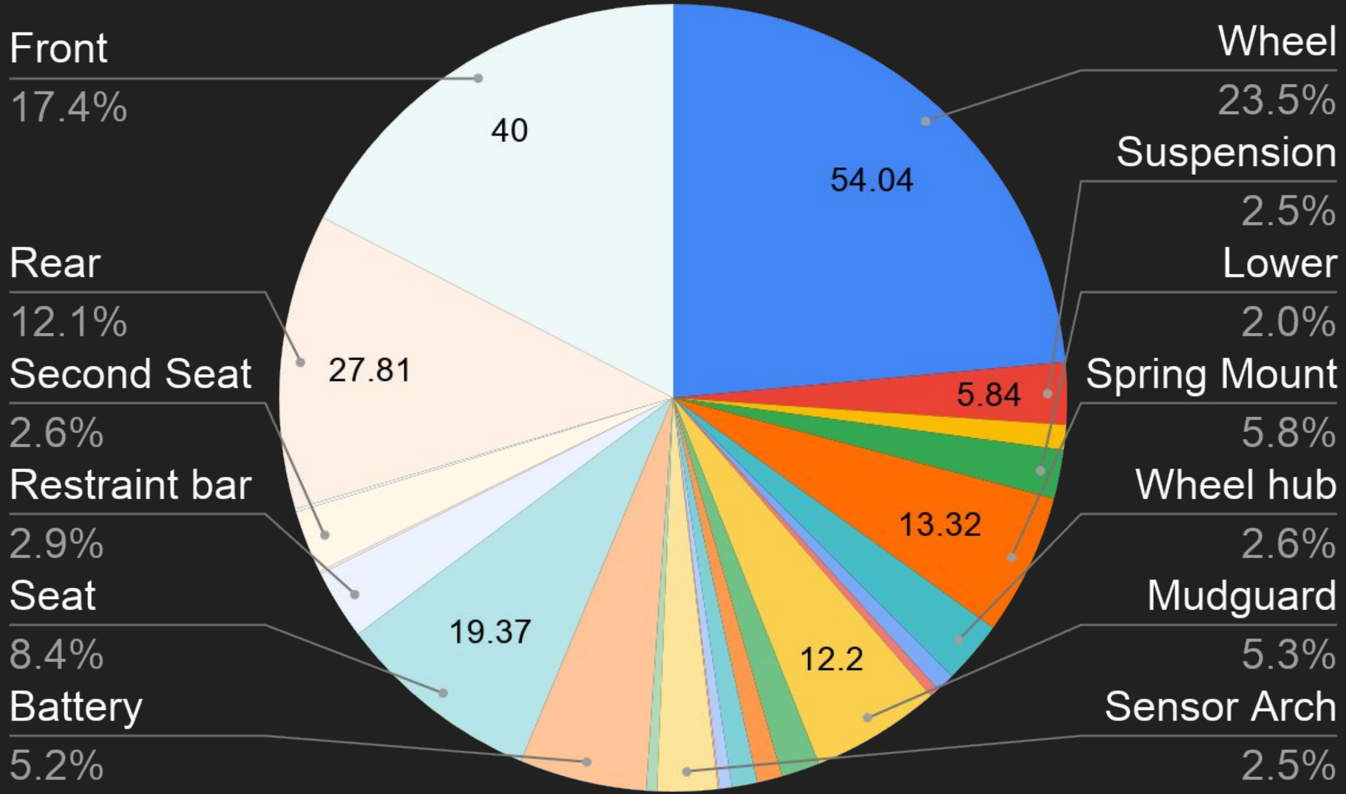
Battery

- 18.5 kg of Tesla's Model 3 Battery (260 Wh/kg)
- OR 12 kg of Tesla's planned battery (400 Wh/kg)

https://www.reuters.com/article/us-tesla-batteries/teslas-musk-hints-of-battery-capacity-jump-ahead-of-industry-event-idUSKBN25L0MC

Mass Summary

Mass Overview

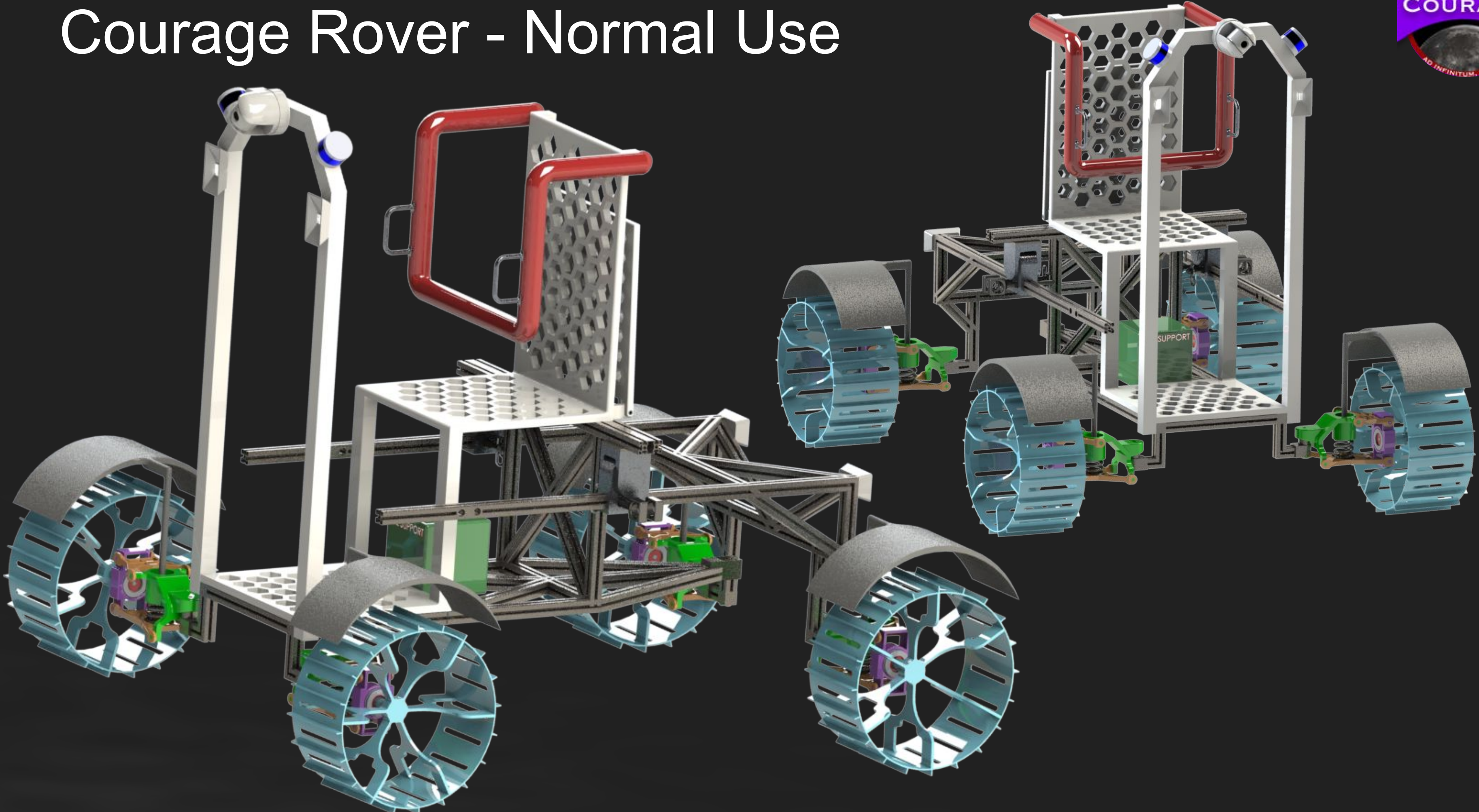


Mass Overview

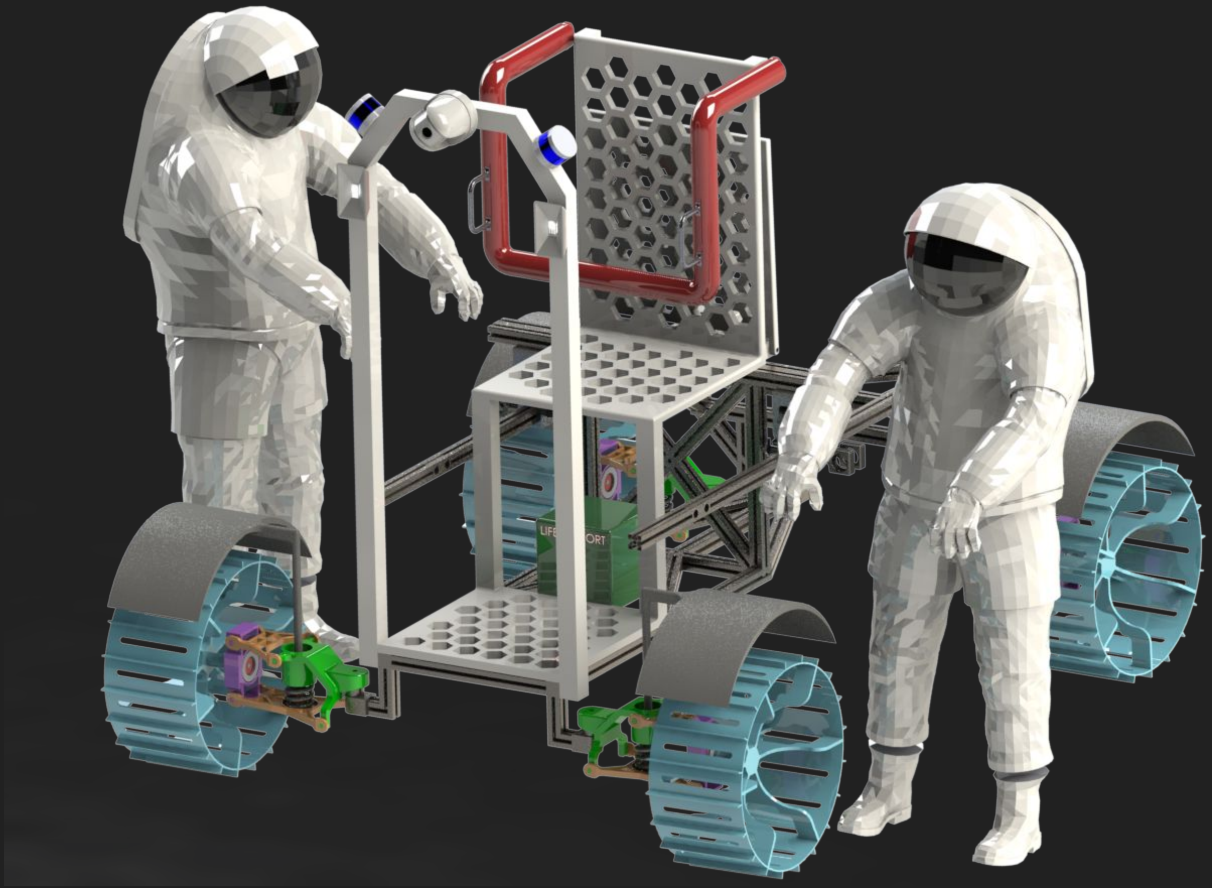
Category	Part	Material	Individual Mass (kg)	# Required	Total Mass
Suspension / Driving	Wheel	Aluminum 7075-O (SS)	13.51	4	54.04
	Suspension Spring	Stainless Steel	1.46	4	5.84
	Upper Wishbone	Aluminum 7075-O (SS)	0.59	4	2.34
	Lower wishbone	Aluminum 7075-O (SS)	1.15	4	4.6
	Spring Mount	Aluminum 7075-O (SS)	3.33	4	13.32
	Wheel hub mount	Aluminum 7075-O (SS)	1.47	4	5.88
	Driving motor	Various	0.447	4	1.788
	Steering motor	Various	0.447	2	0.894
	Mudguard	PE Low/Medium Density	3.05	4	12.2
Sensors / Lighting	PTZ Camera	Various	1.8	2	3.6
	Velodyne Puck LITE	Various	0.59	4	2.36
	Floodlight	Various	0.6	4	2.4
	Stereo Camera	Various	0.288	4	1.152
	Omnicamera	Various	0.163	1	0.163
	Sensor Arch	PVC	5.66	1	5.66
	Computer (Laptop style)	Various	1	1	1
Power	Battery (400Wh/kg)	Various	11.982	1	11.982
Seat	Seat	Very Low Density PE (SS)	19.37	1	19.37
	Restraint bar	Nylon 6/10	6.59	1	6.59
	Restraint bar handles	Aluminum 6061-T6 (SS)	0.12	2	0.24
	Second Seat	Very Low Density PE (SS)	5.94	1	5.94
	Second Seat Leg	Aluminum 6061-O (SS)	0.3	1	0.3
Chassis	Rear	Commercially Pure CP-Ti UNS R50400 (SS)	27.81	1	27.81
	Front	Commercially Pure CP-Ti UNS R50400 (SS)	40	1	40
	Hitch Pin	Chrome Stainless Steel	0.13	4	0.52
	Locking Pin	Plain Carbon Steel	1.56	4	6.24
	Pivot Mechanism	Aluminum 7075-O (SS)	7.36	2	14.72
				Total Mass (kg)	**250.95**

Final Design

Courage Rover - Normal Use



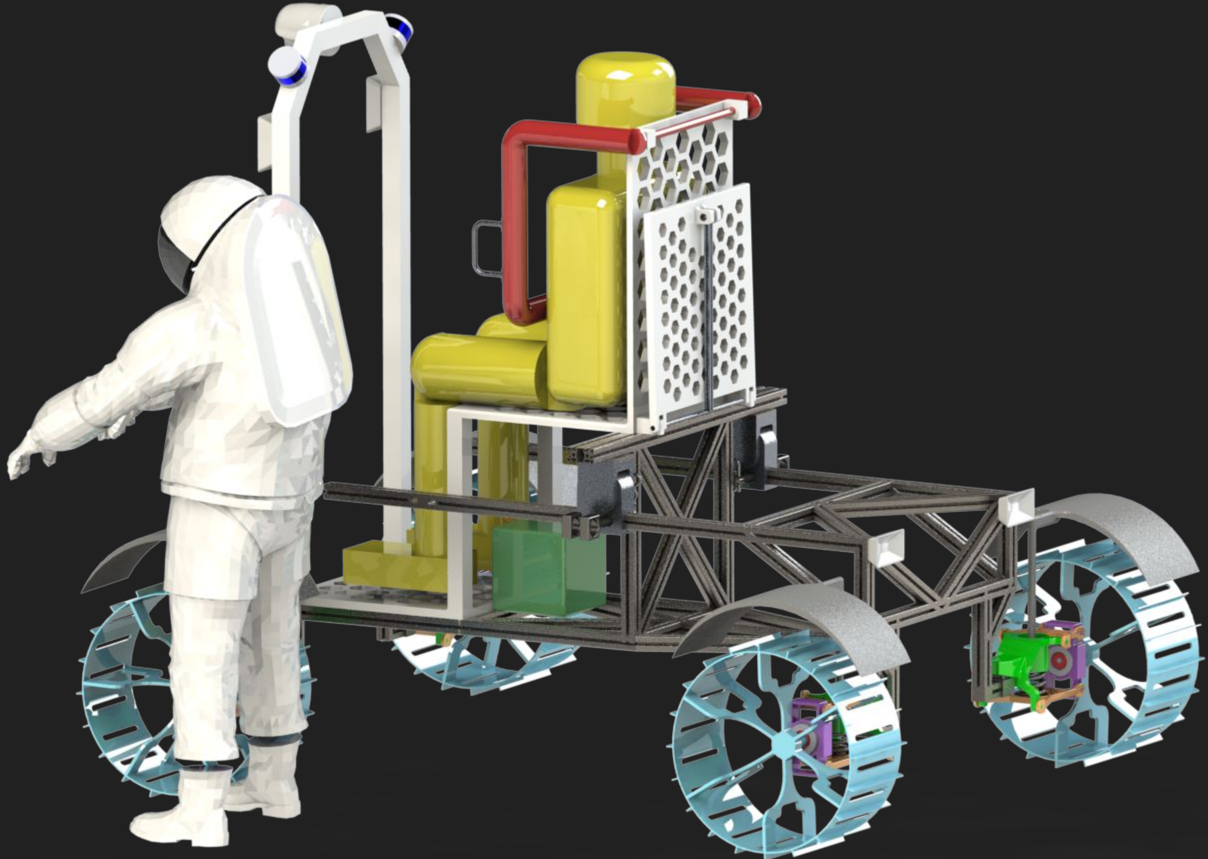
Courage Rover - Normal Use



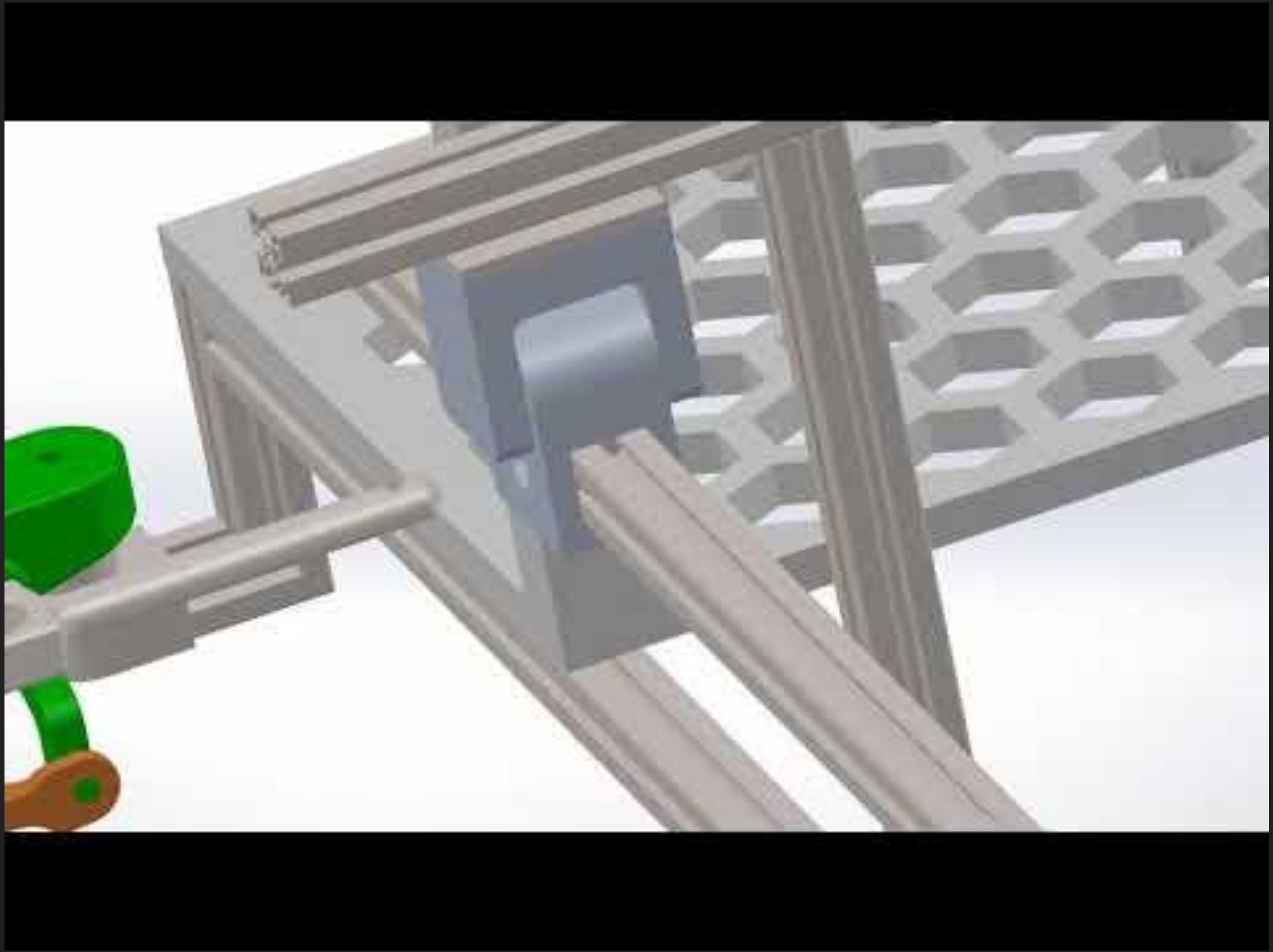
Courage Rover - Normal Use

- 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

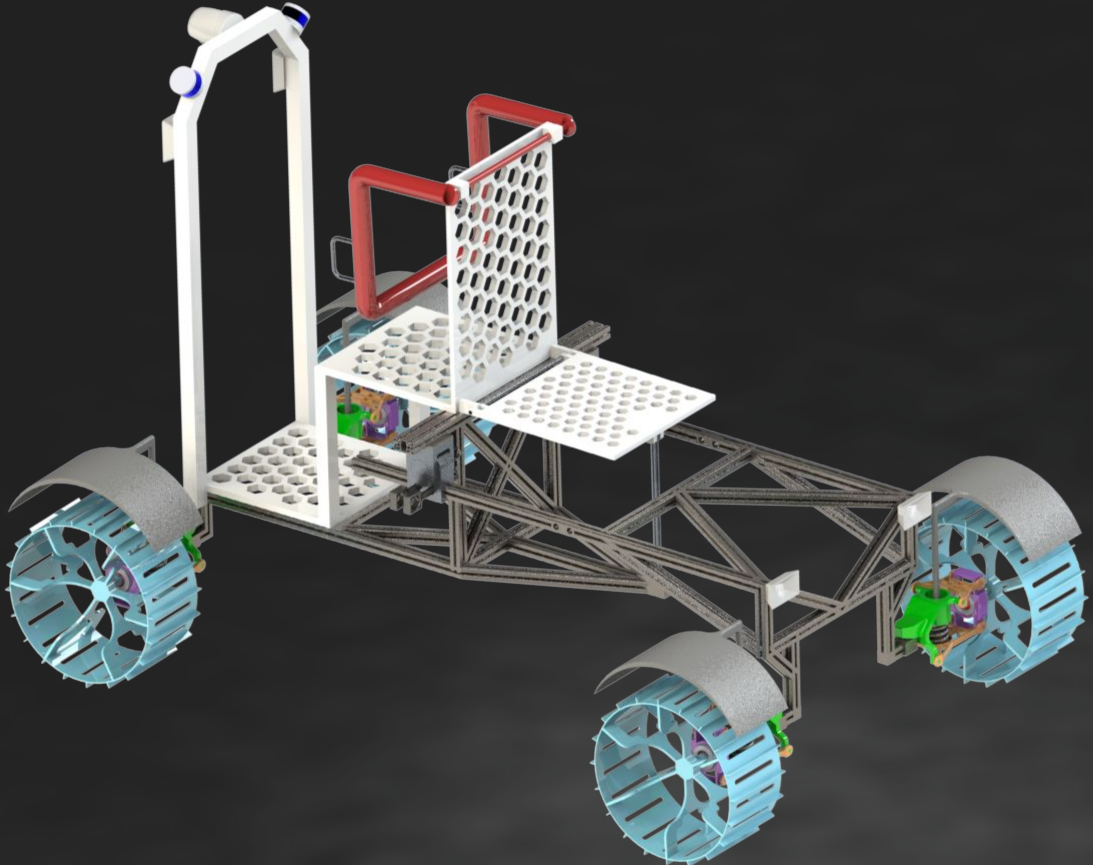
Courage Rover - Normal Use



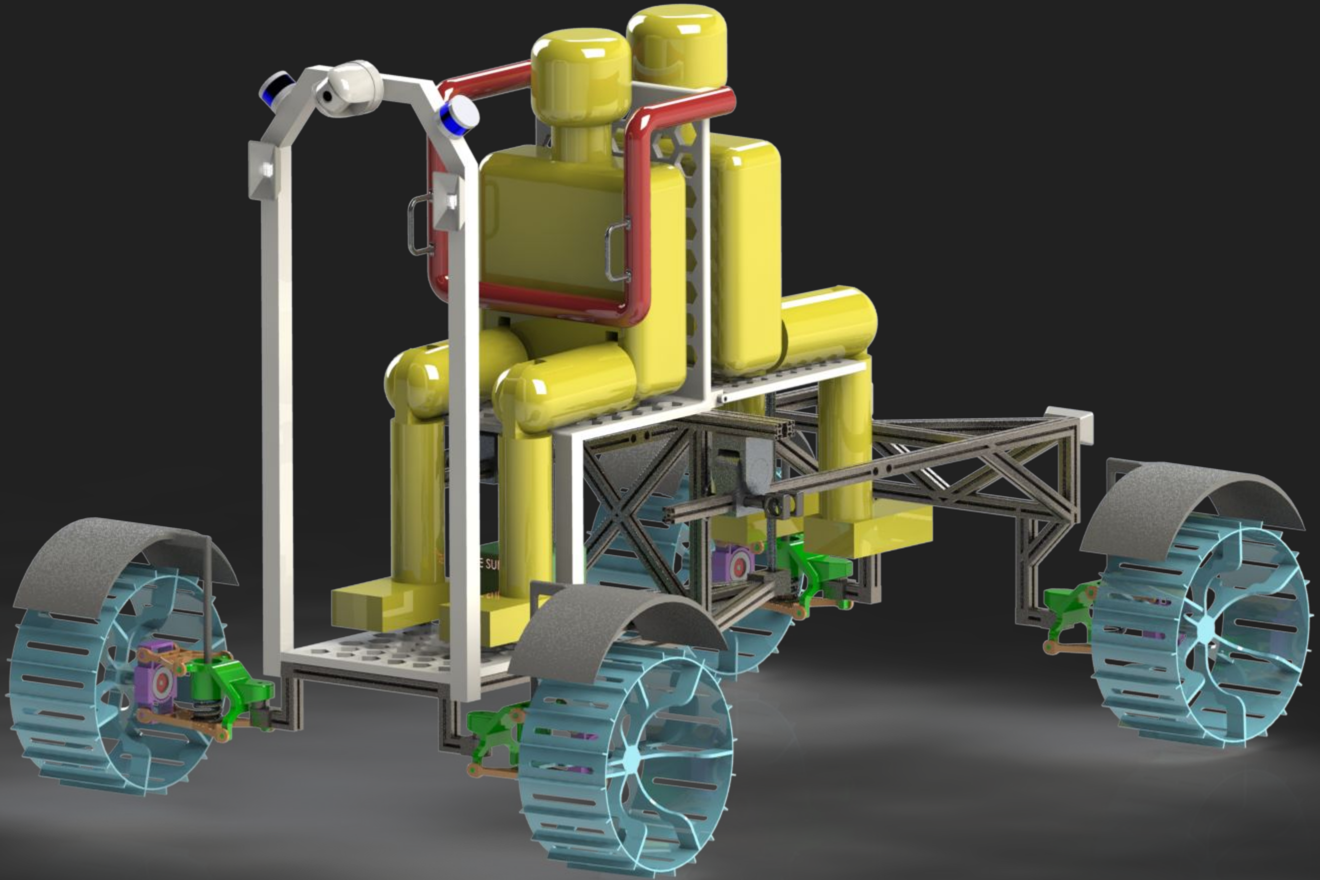
Courage Rover - Contingency Use



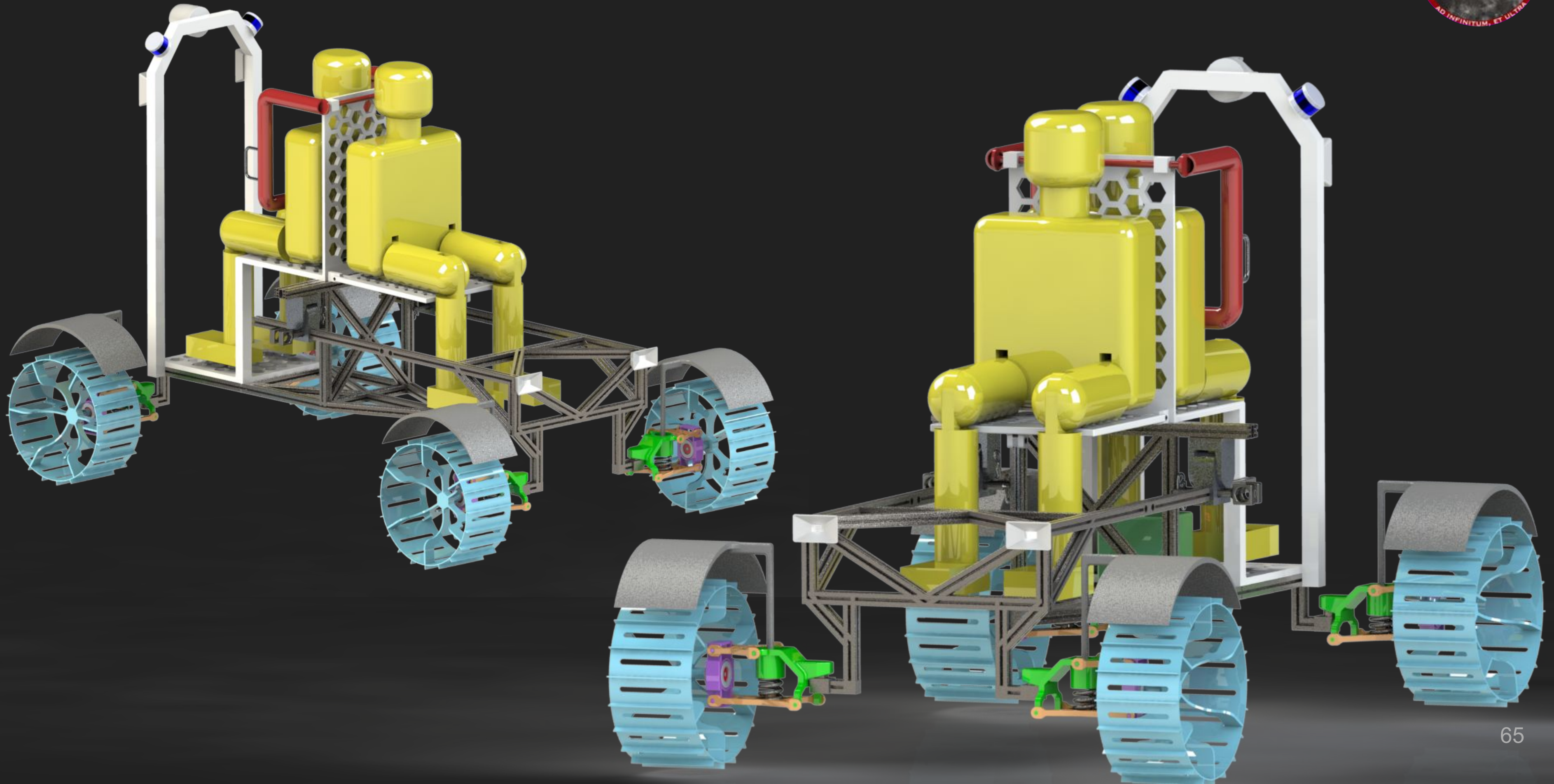
Courage Rover - Contingency Use



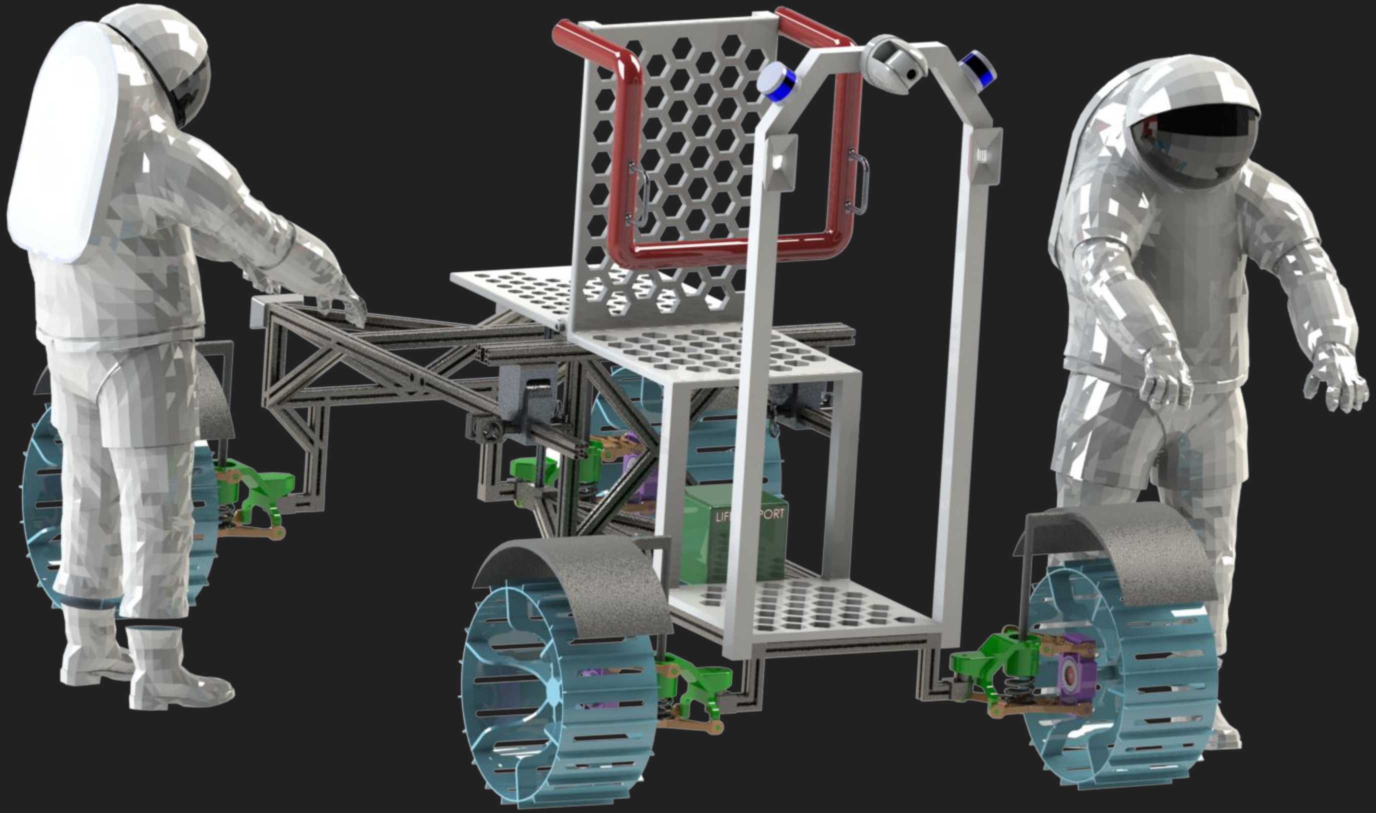
Courage Rover - Contingency Use



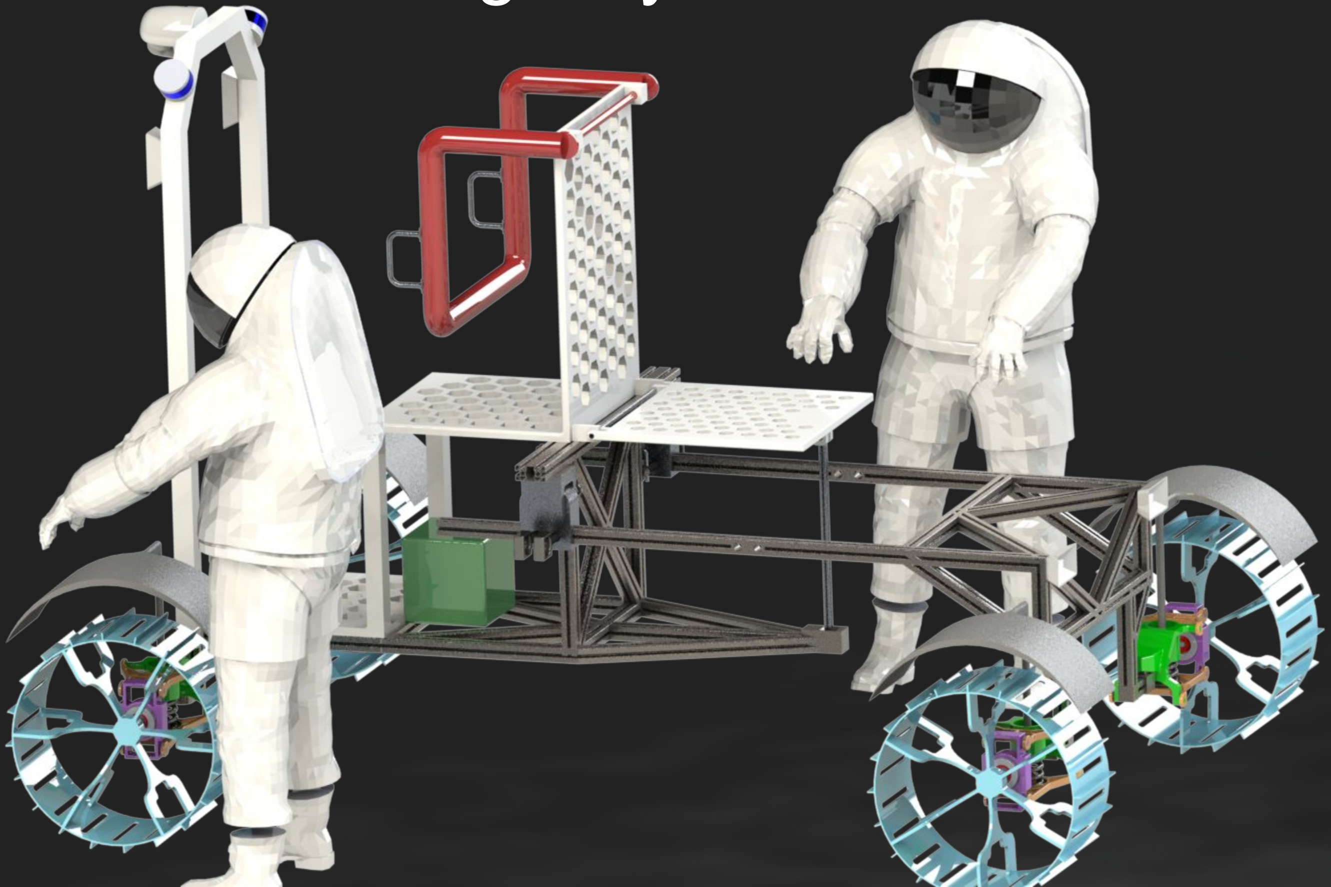
Courage Rover - Contingency Use (Rear)



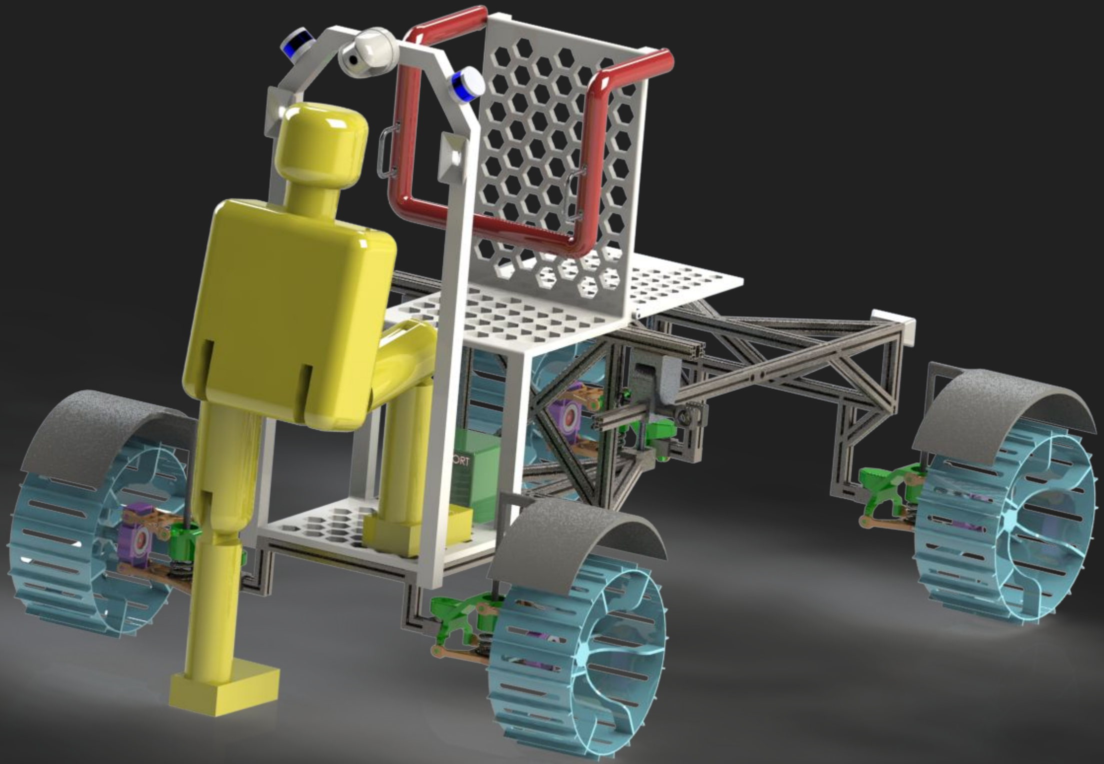
Courage Rover - Contingency Use



Courage Rover - Contingency Use



Ingress and Egress



Ingress and Egress

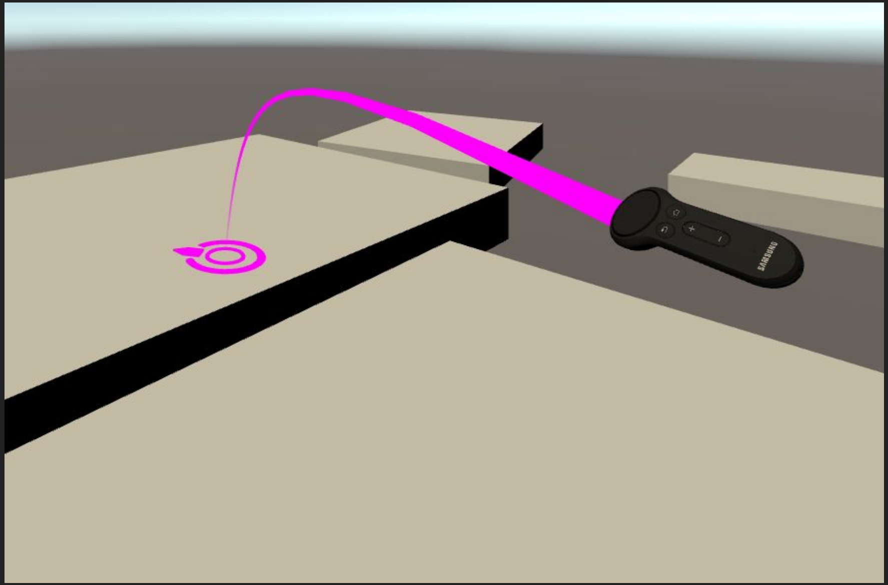
Driving

Manual [Driven by Astronaut]

Wireless steering wheel + control panel

Autonomous [Drive to Destination]

VR Remote + AR HUD in suit



https://developer.oculus.com/blog/teleport-curves-with-the-gear-vr-controller/?locale=en_US

https://www.logitechg.com/en-gb/products/driving/driving-force-racing-wheel.html

Adherence to Requirements

Category	Required	Actual	Satisfied
Mass	≤ 250 kg	251 kg	- / -
Max Speed	4 m/s	4 m/s	✓
Driving Speed/Range	Avg 2.5 m/s for 6 hours (54 km)	Avg 2 m/s for 8 hours (57.6km)	✓
Max Obstacle Size	0.3 m	0.3 m	✓
Max Slope	20 degrees	20 degrees	✓
Payload (Normal)	170 kg Astronaut + 80 kg payload	170 kg Astronaut + 80 kg payload	✓
Payload (Contingency)	Two 170 kg Astronauts + 80 kg payload	Two 170 kg Astronauts + 80 kg payload	✓
Driving Modes	Autonomous, Follow Astronaut	Autonomous, Follow Astronaut, Manual	✓

Earth & Mars Efficacy

Drawbar Pull Comparison

EARTH

$g = 9.8\ m/s^2$
$n = 0.5$
$k_c = 13190\ N/m^{1.5}$
$k_\phi = 692200\ N/m^{2.5}$
Assuming, $K_{shear} = 13190$ m
Soil type = Clay

Drawbar pull = 6154.99 N

MARS

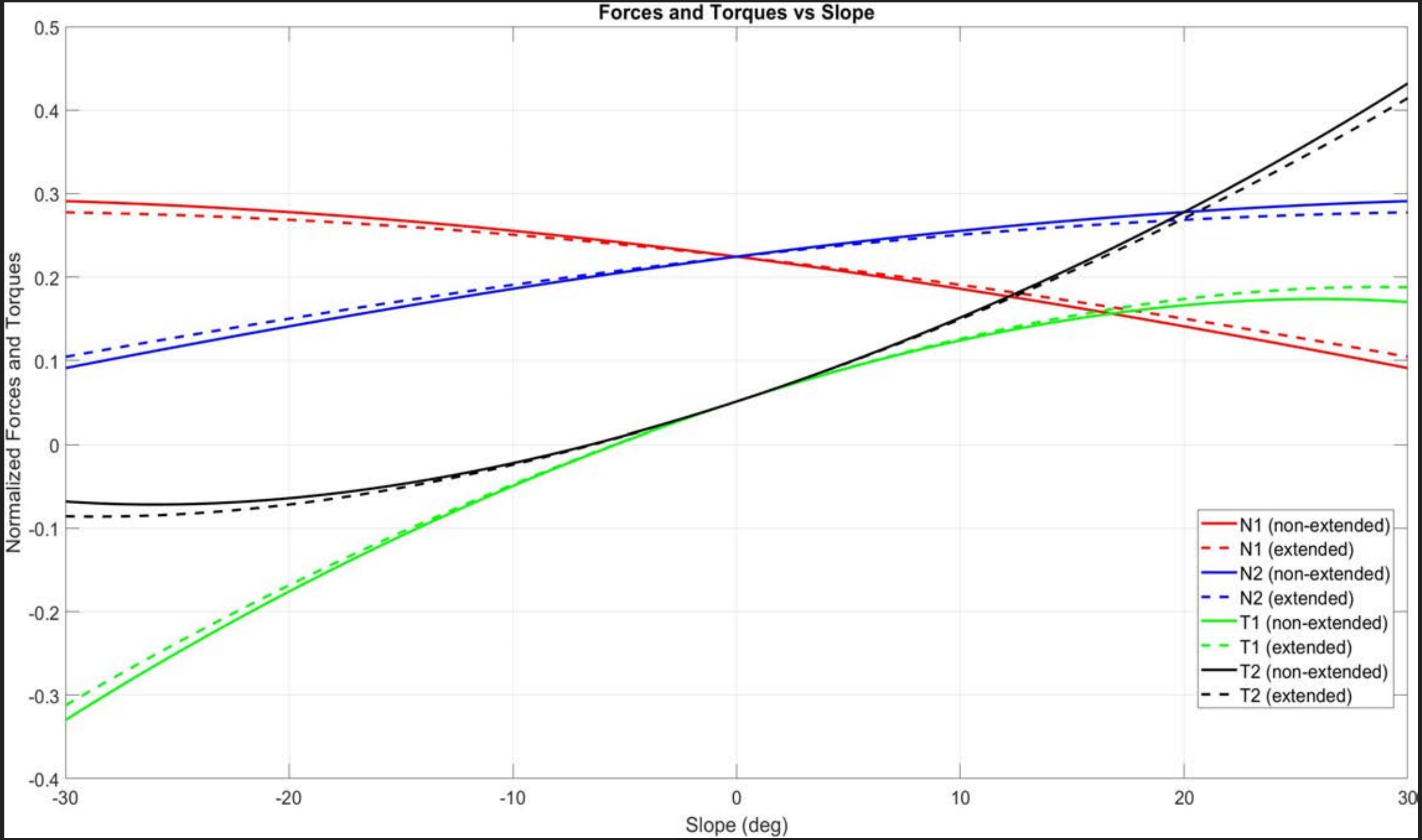
$g = 3.711\ m/s^2$
$n = 1$
$k_c = 28000\ N/m^2$
$k_\phi = 7600000\ N/m^3$
Assuming, $K_{shear} = 13190$ m
Soil type = Sandy Loam

Drawbar pull = 968.26 N

$g = 3.711\ m/s^2$
$n = 0.8$
$k_c = 6800\ N/m^2$
$k_\phi = 210000\ N/m^3$
Assuming, $K_{shear} = 13190$ m
Soil type = Slope soil

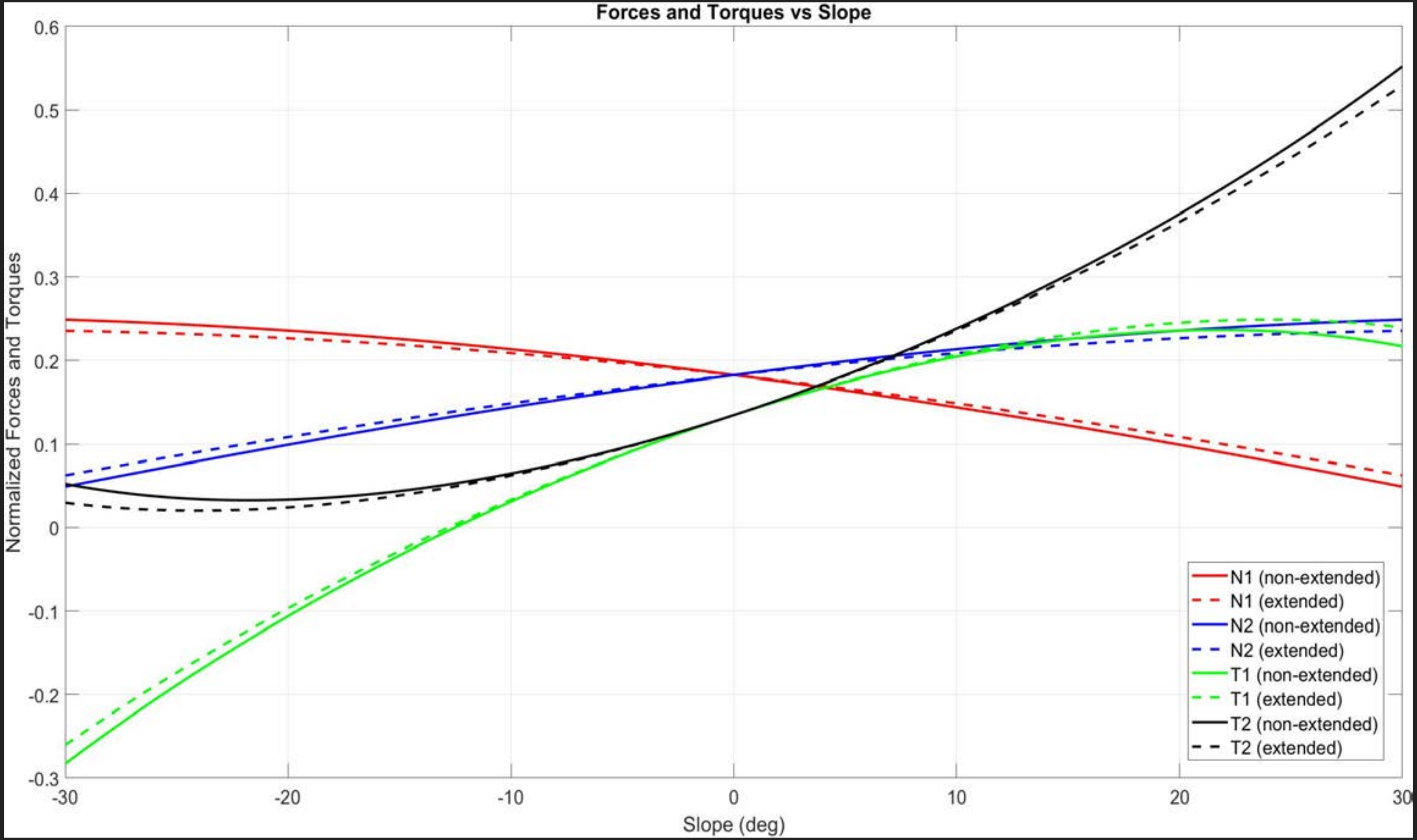
Drawbar pull = 7713.51 N

Stability check (Earth)



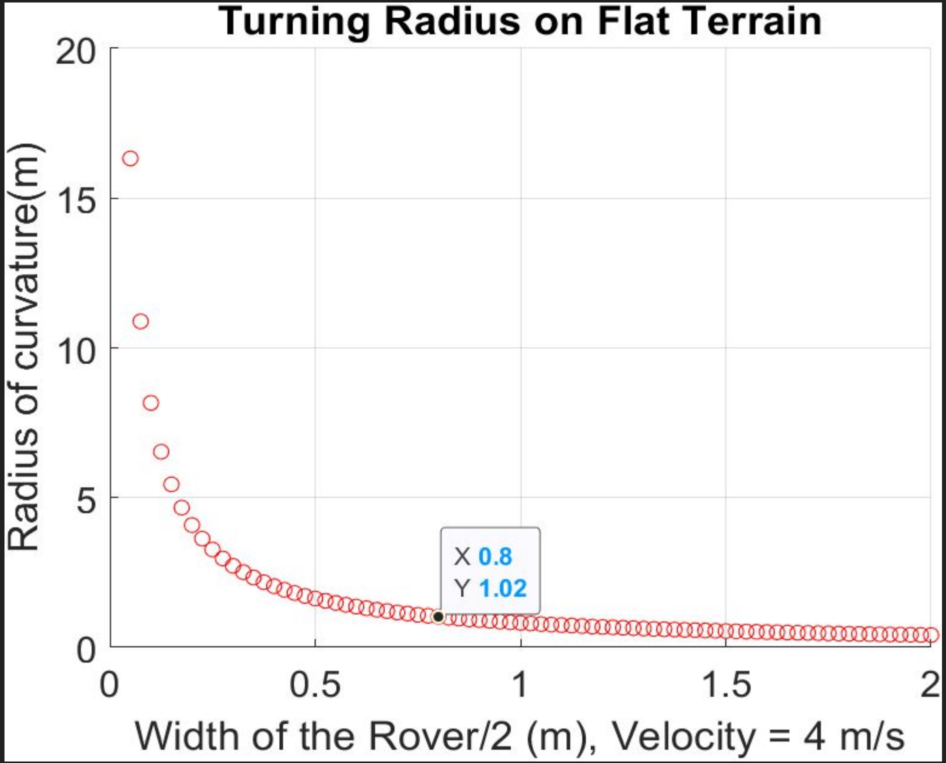
- Design is still valid for Earth environment.
- Uphill slope limit is more than 30 degrees.
- Downhill slope is less than 10 degrees.

Stability check (Mars)

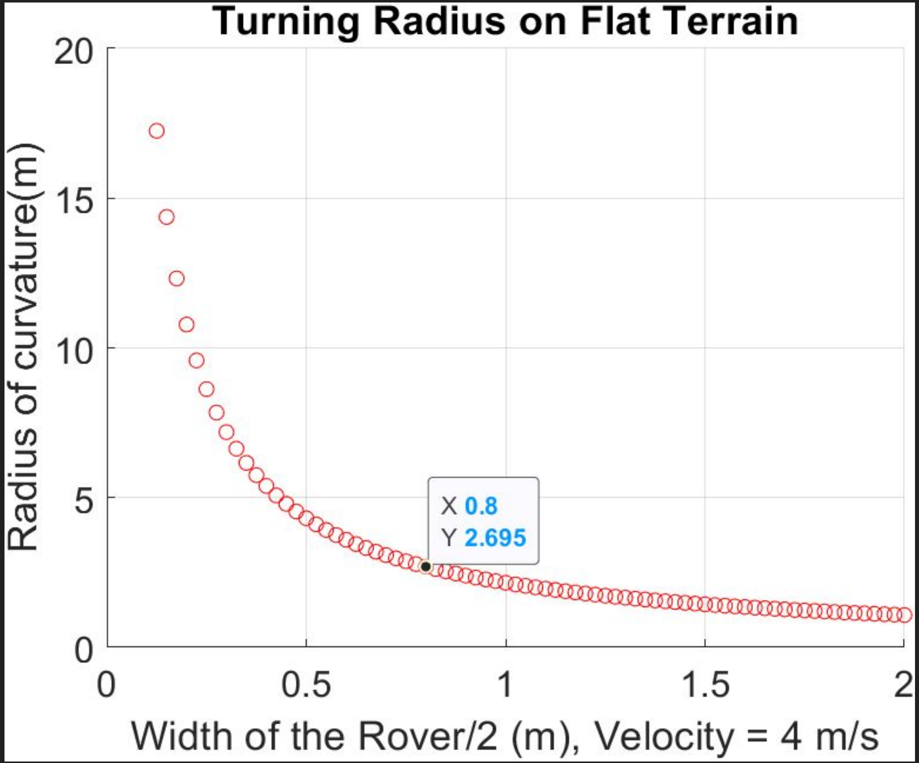


- Design is still valid for Mars environment.
- Uphill slope limit is more than 30 degrees.
- Downhill slope is more than 10 degrees.

Turning Radius on Flat Terrain: Earth & Mars

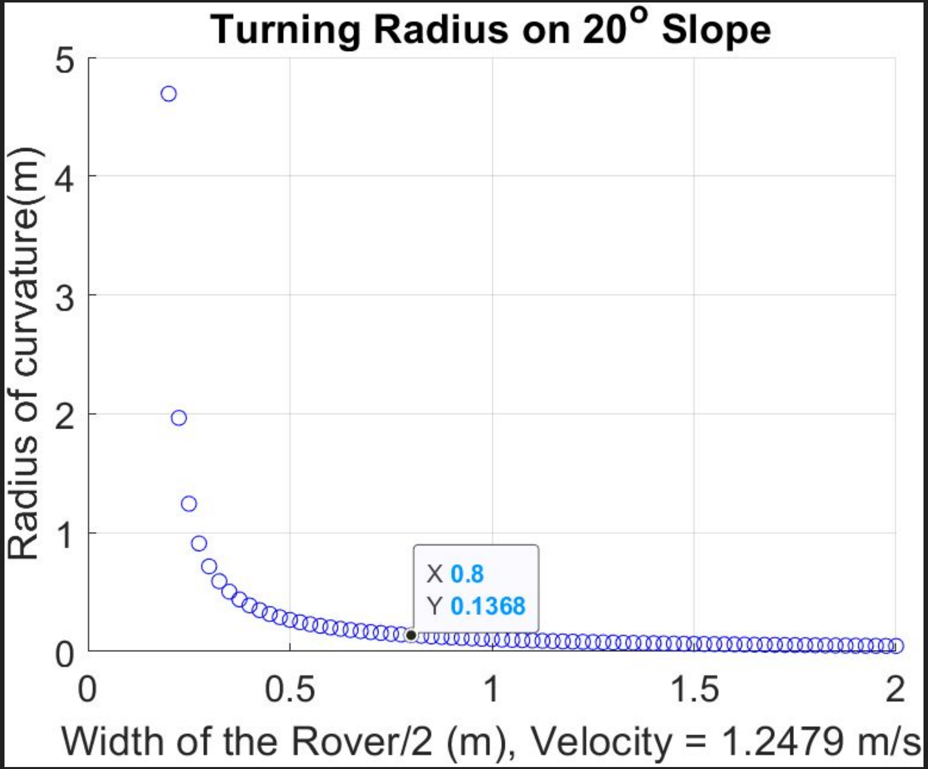


EARTH

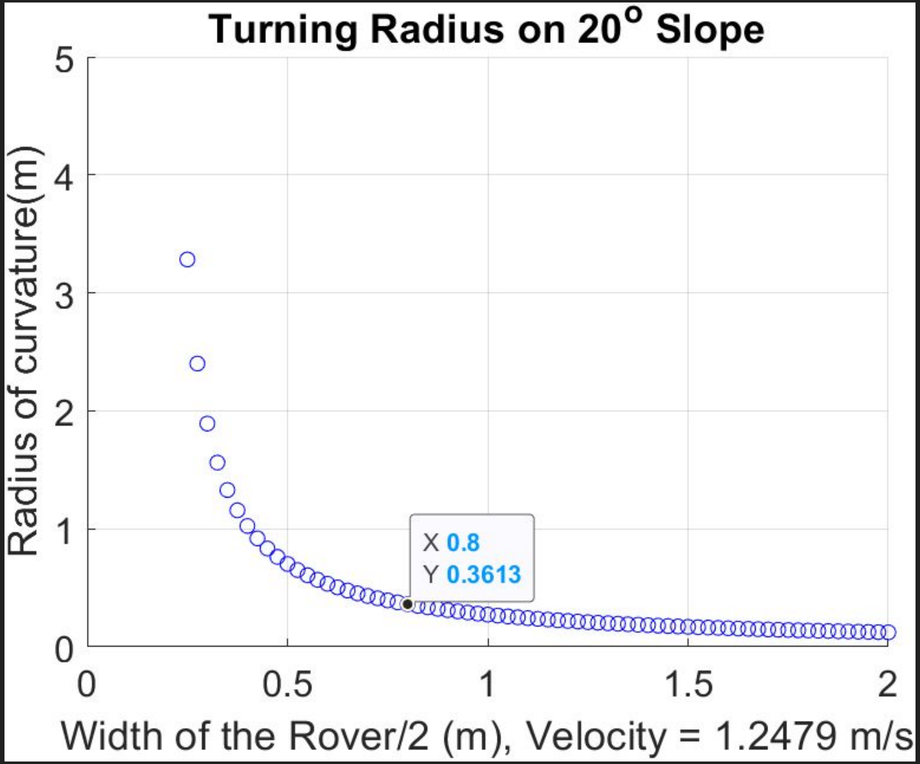


MARS

Turning Radius on 20º Slope: Earth & Mars



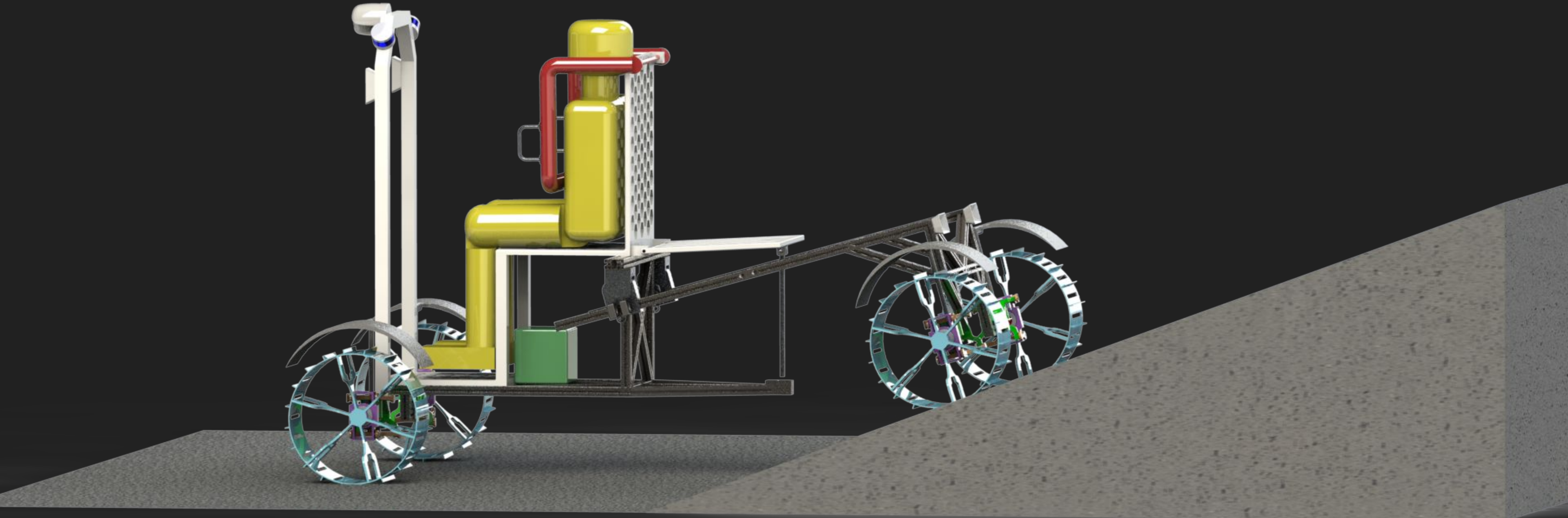
EARTH



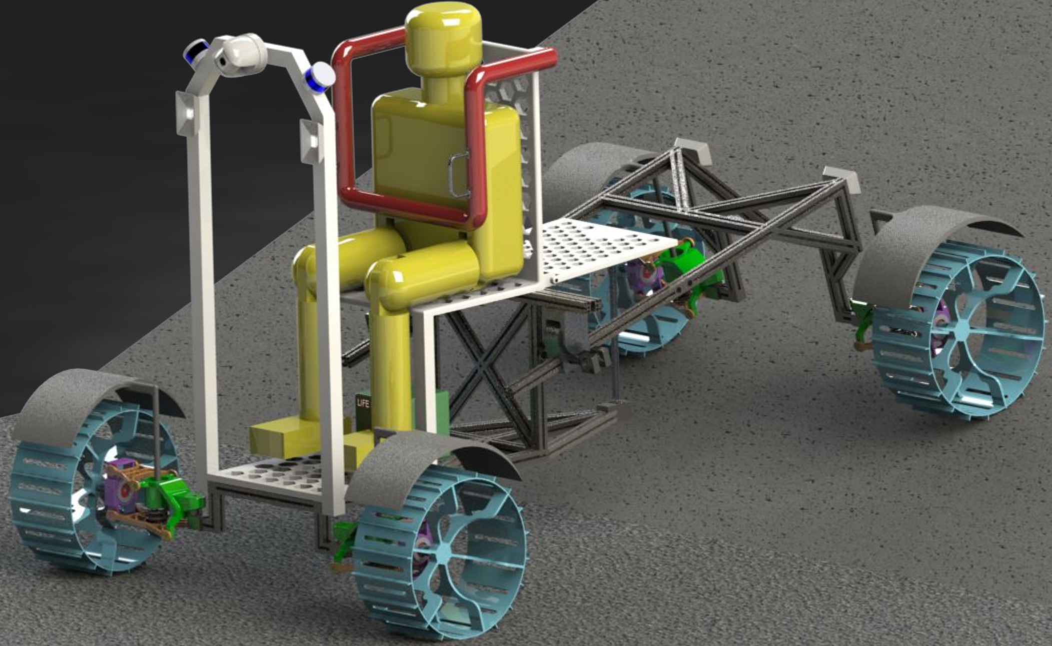
MARS

Trafficability

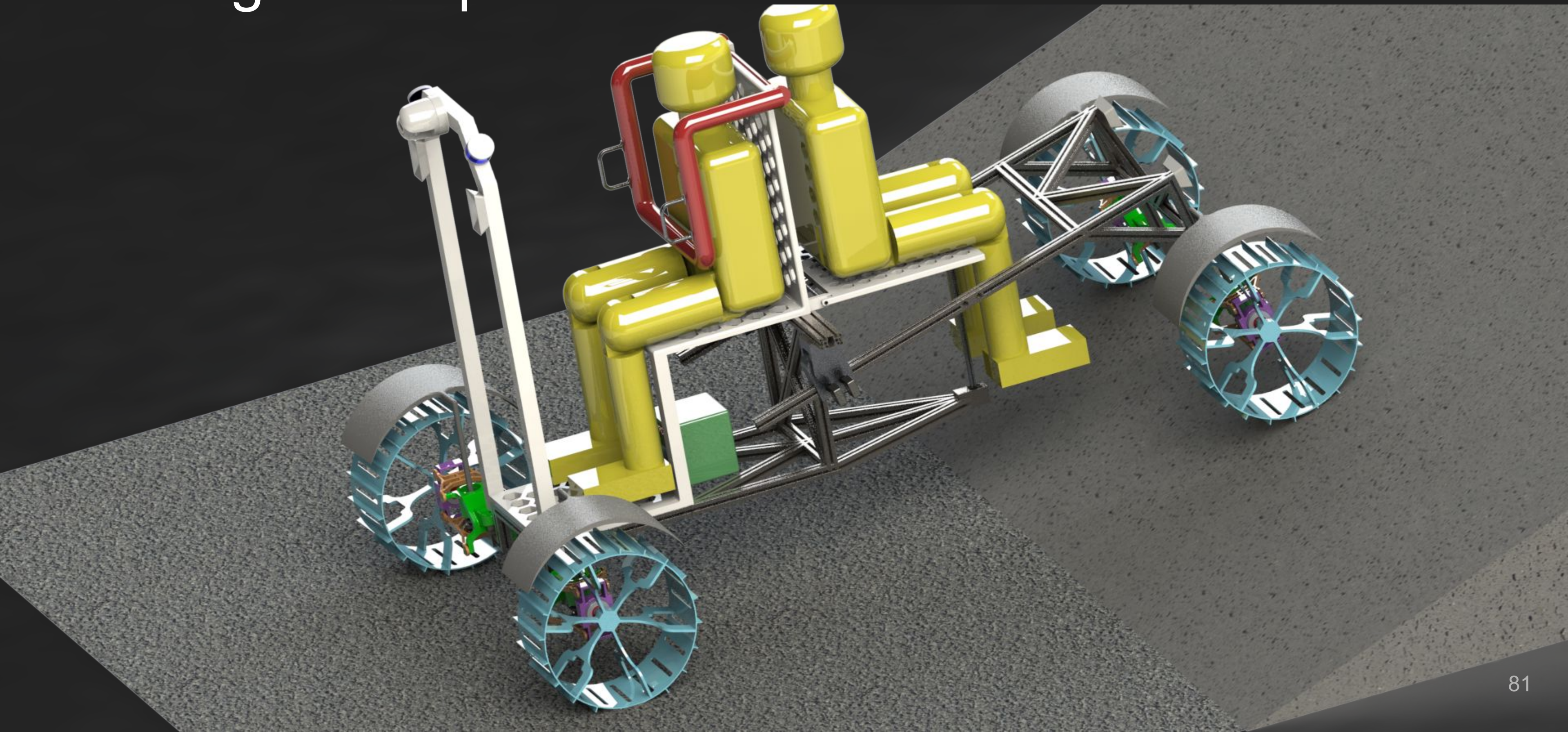
20 Degree Slope - Downhill



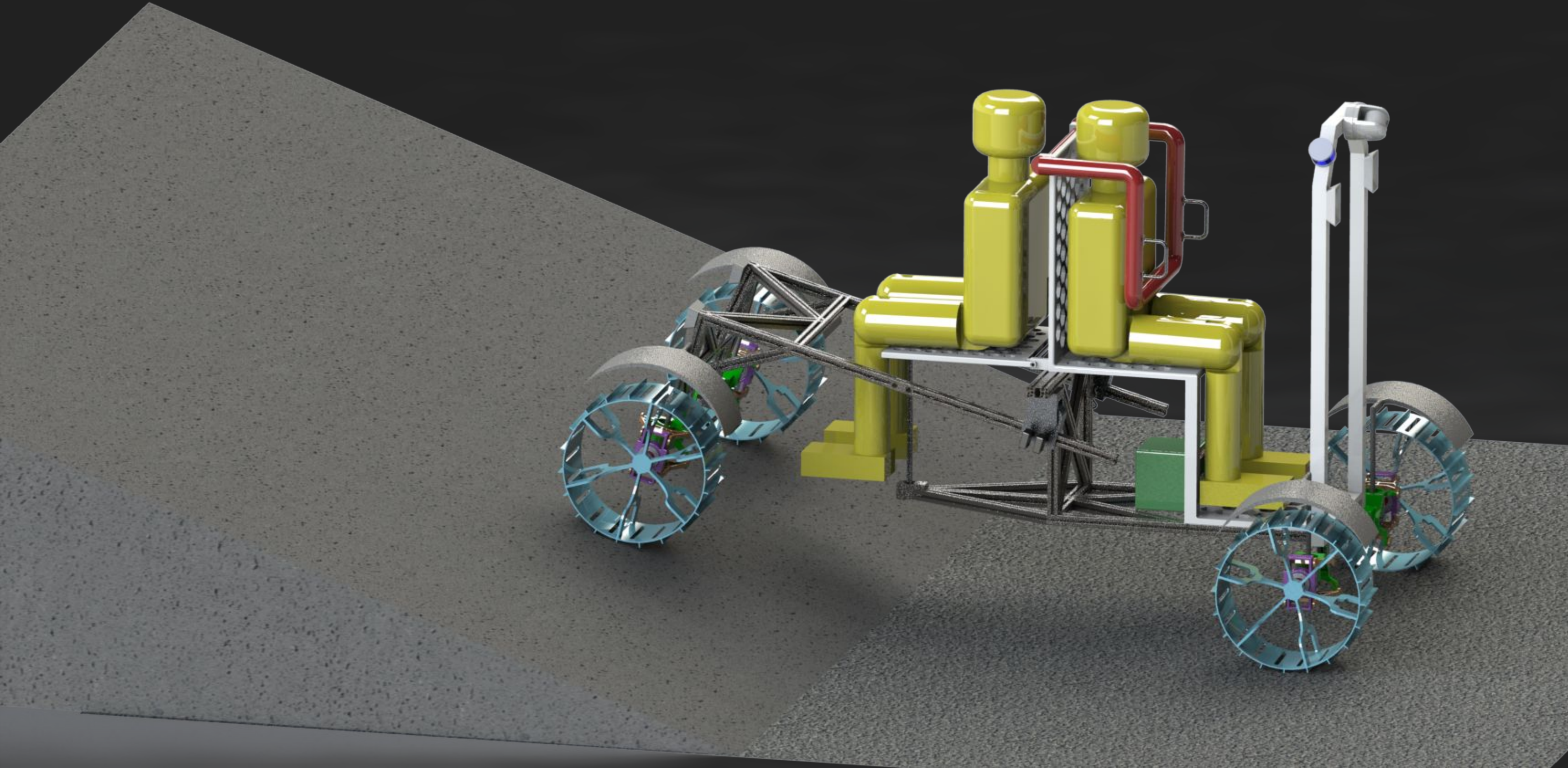
20 Degree Slope - Downhill



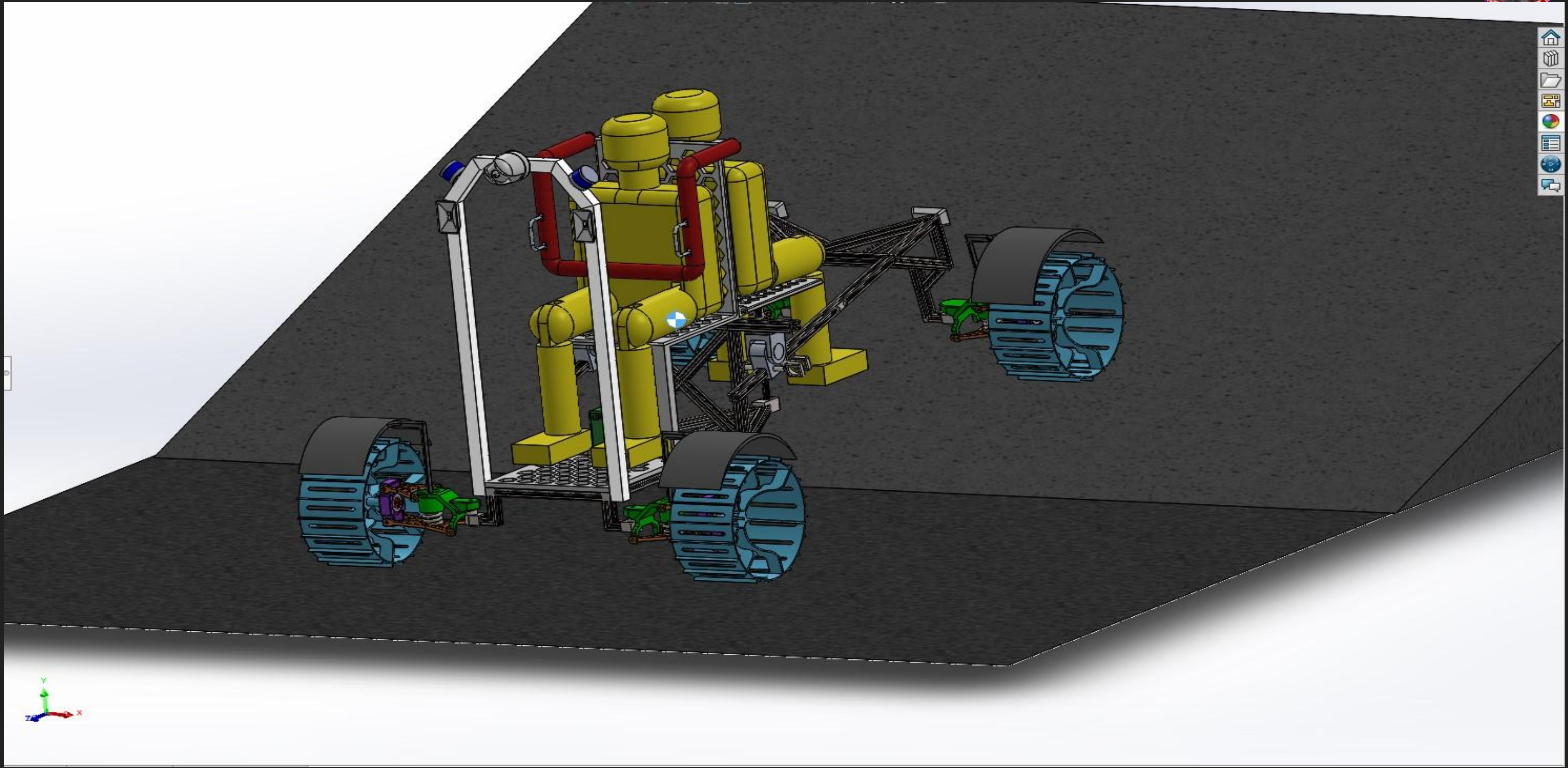
20 Degree Slope - Downhill



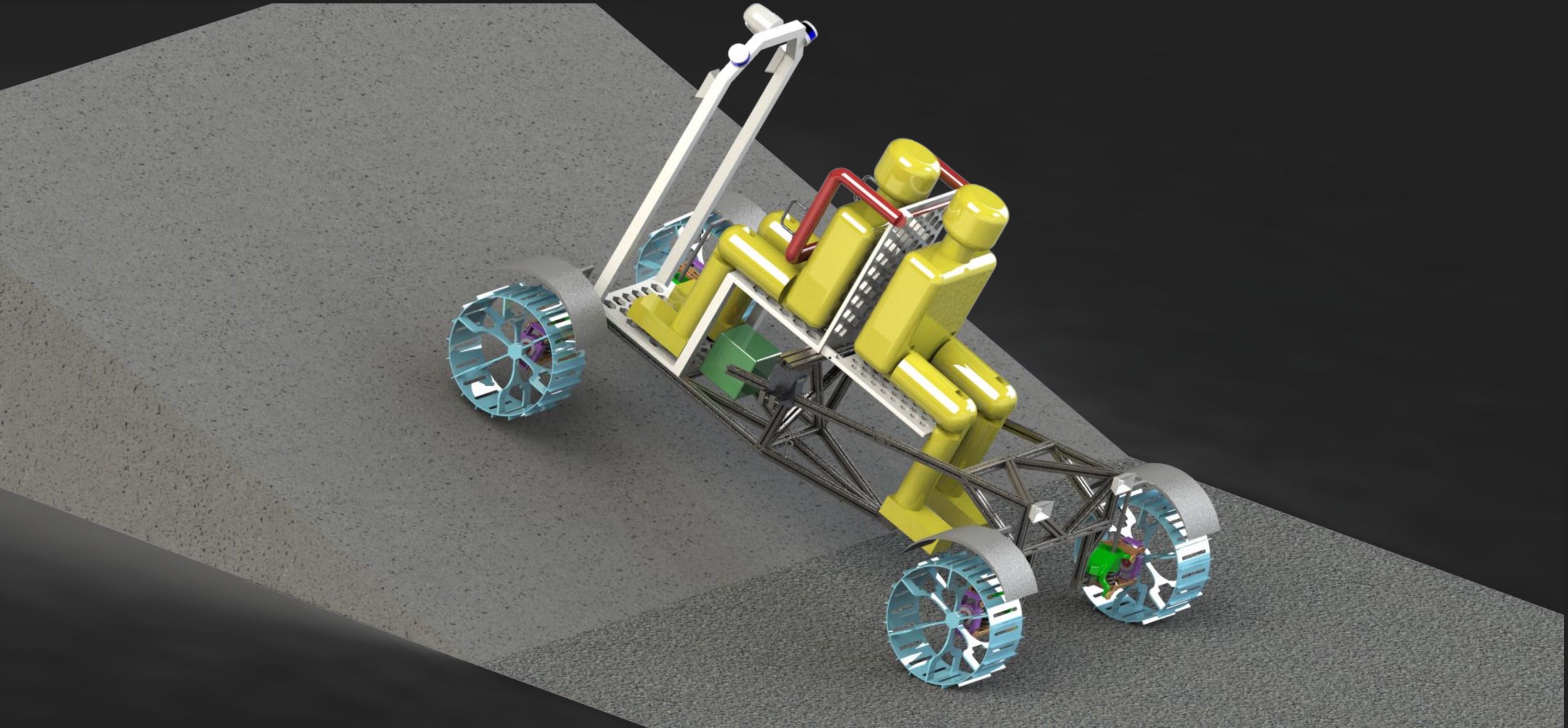
20 Degree Slope - Downhill



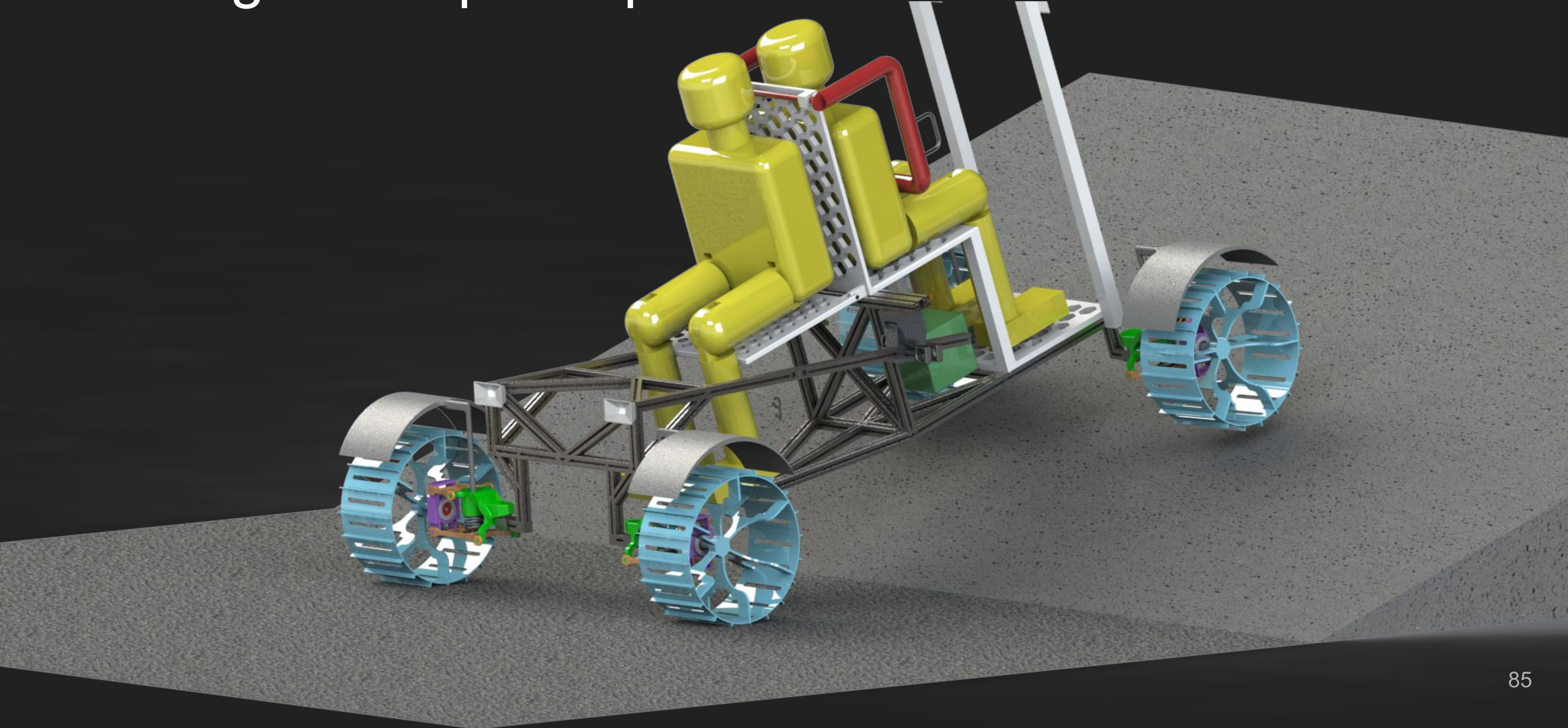
20 Degree Slope - CoM



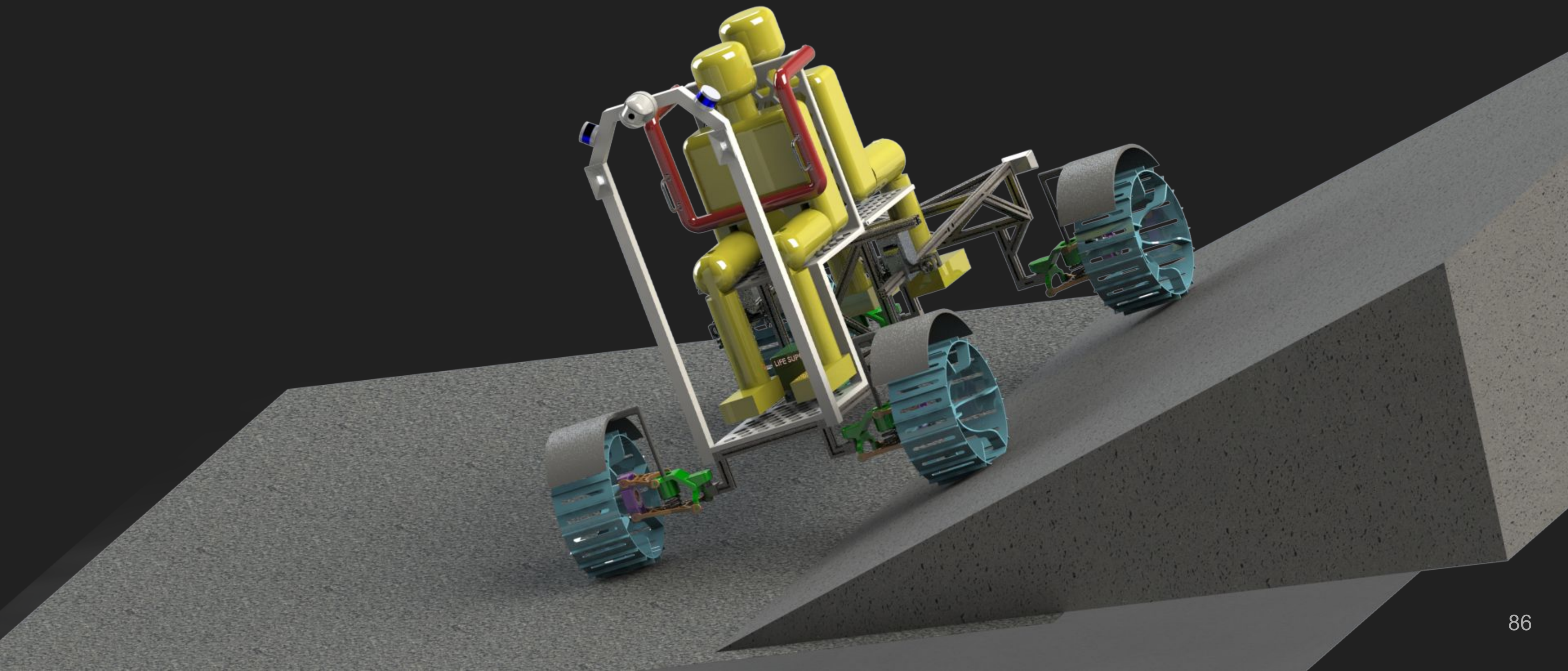
20 Degree Slope - Uphill



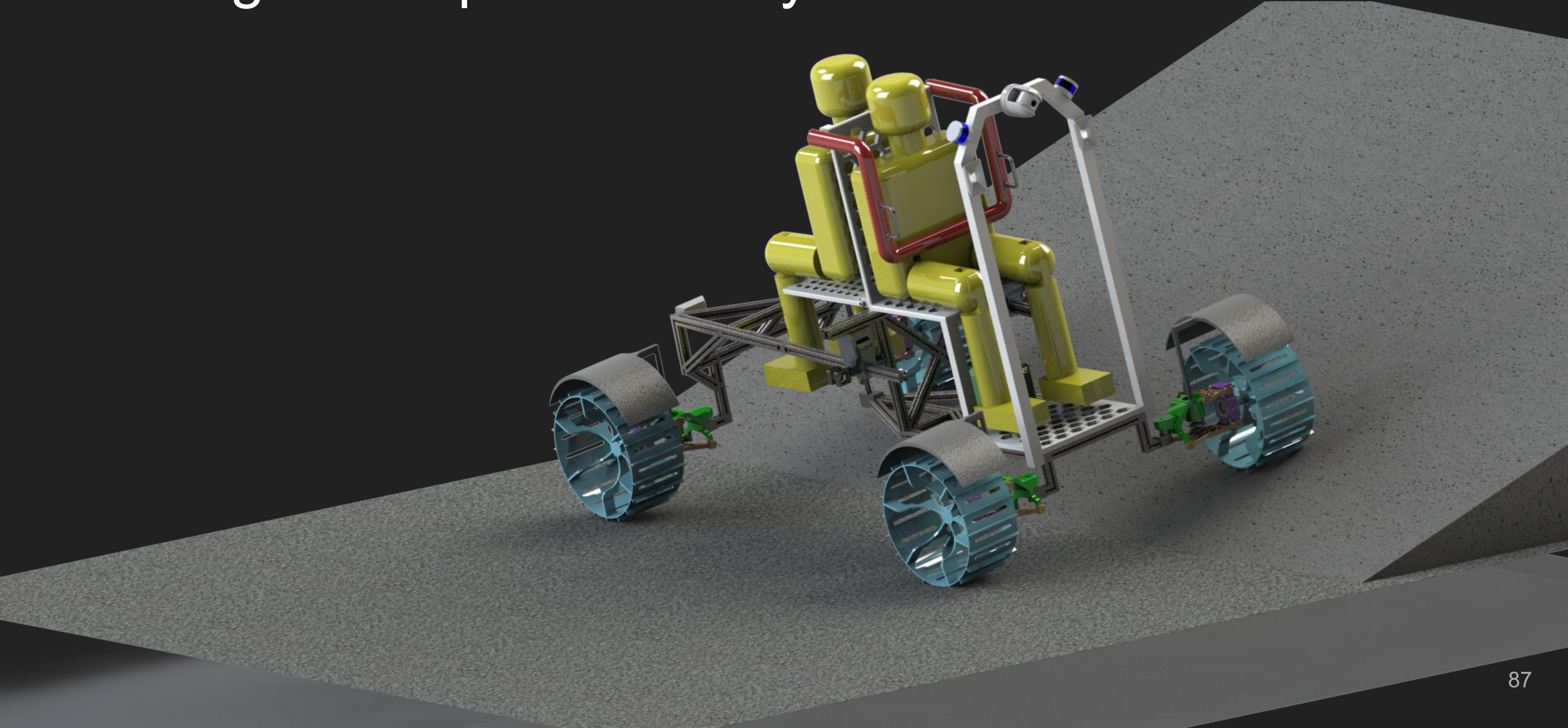
20 Degree Slope - Uphill



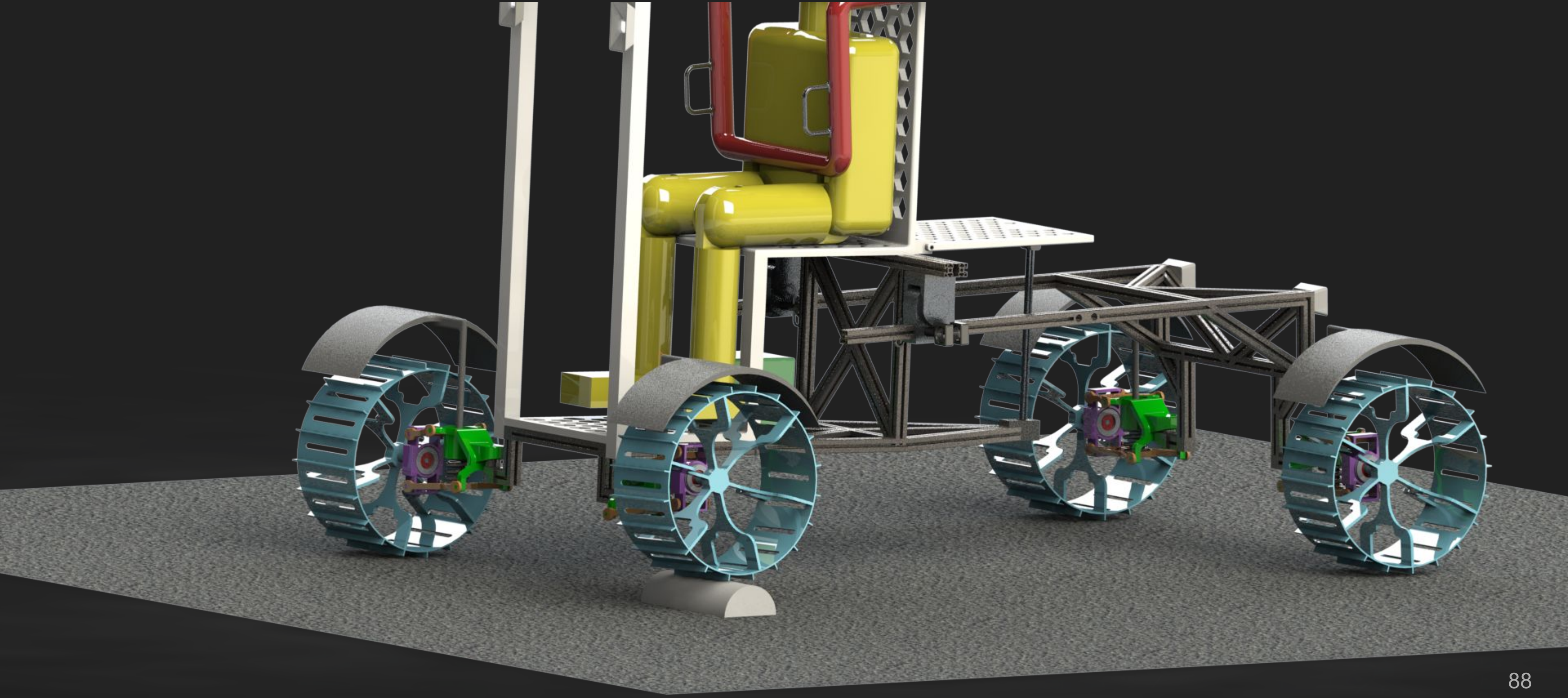
20 Degree Slope - Sideways



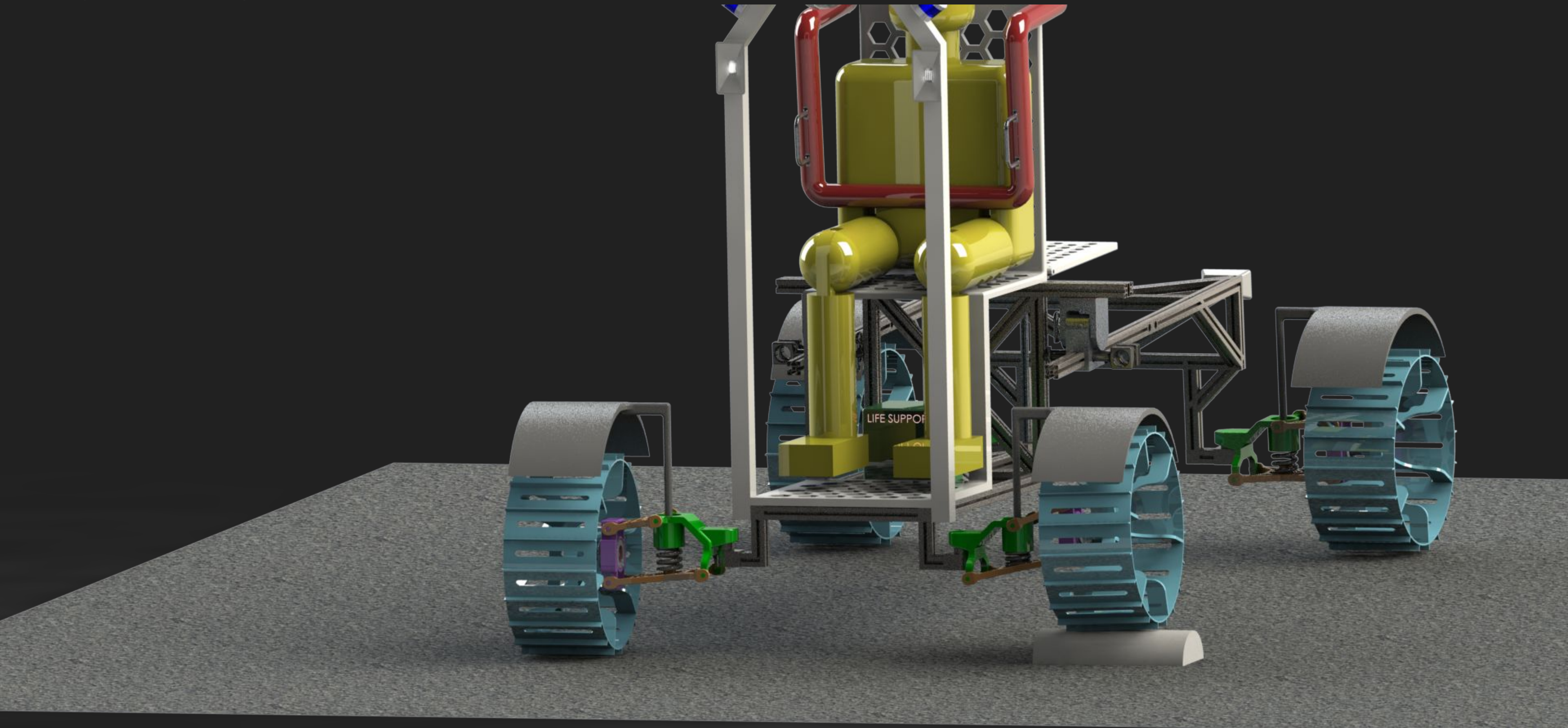
20 Degree Slope - Sideways



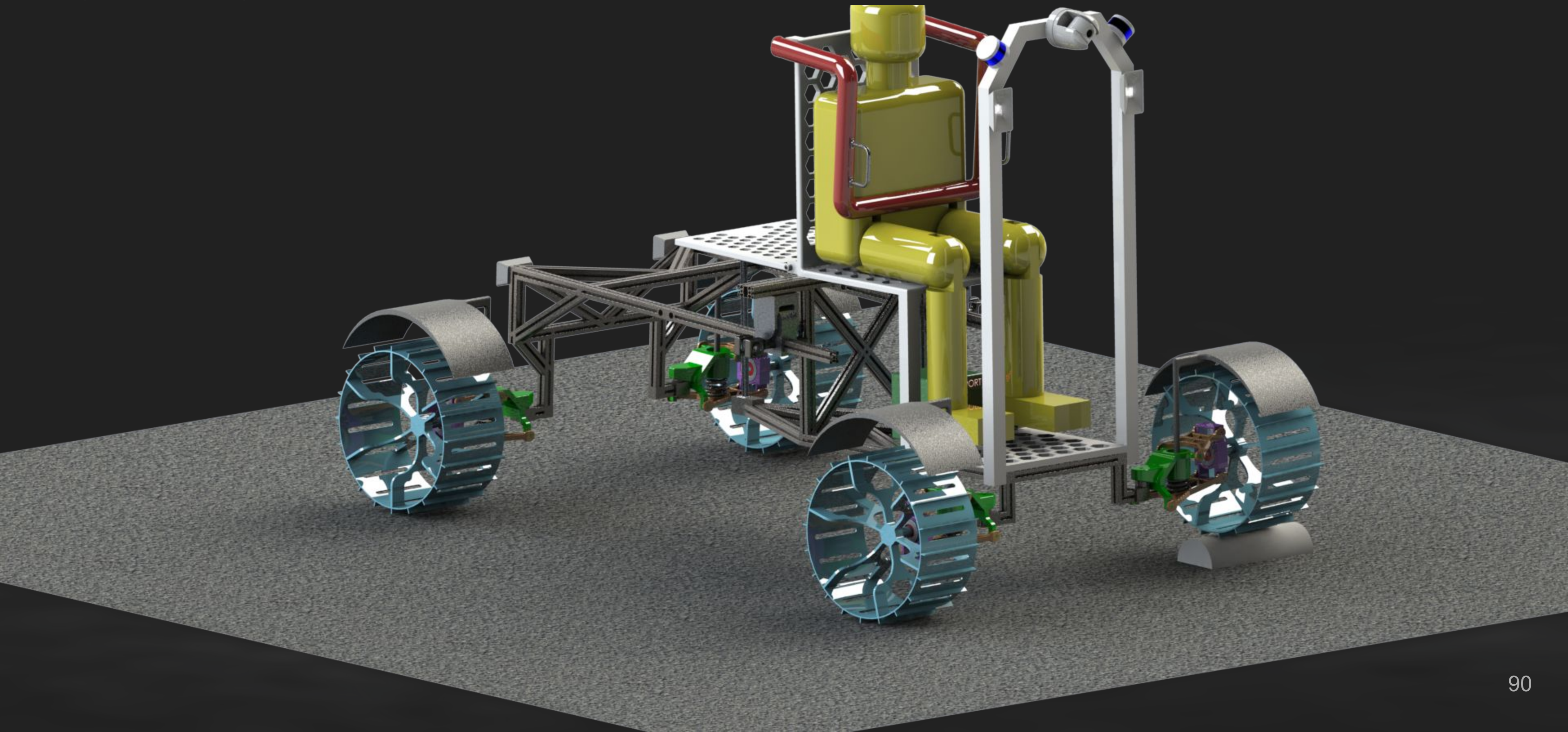
0.1m Obstacle



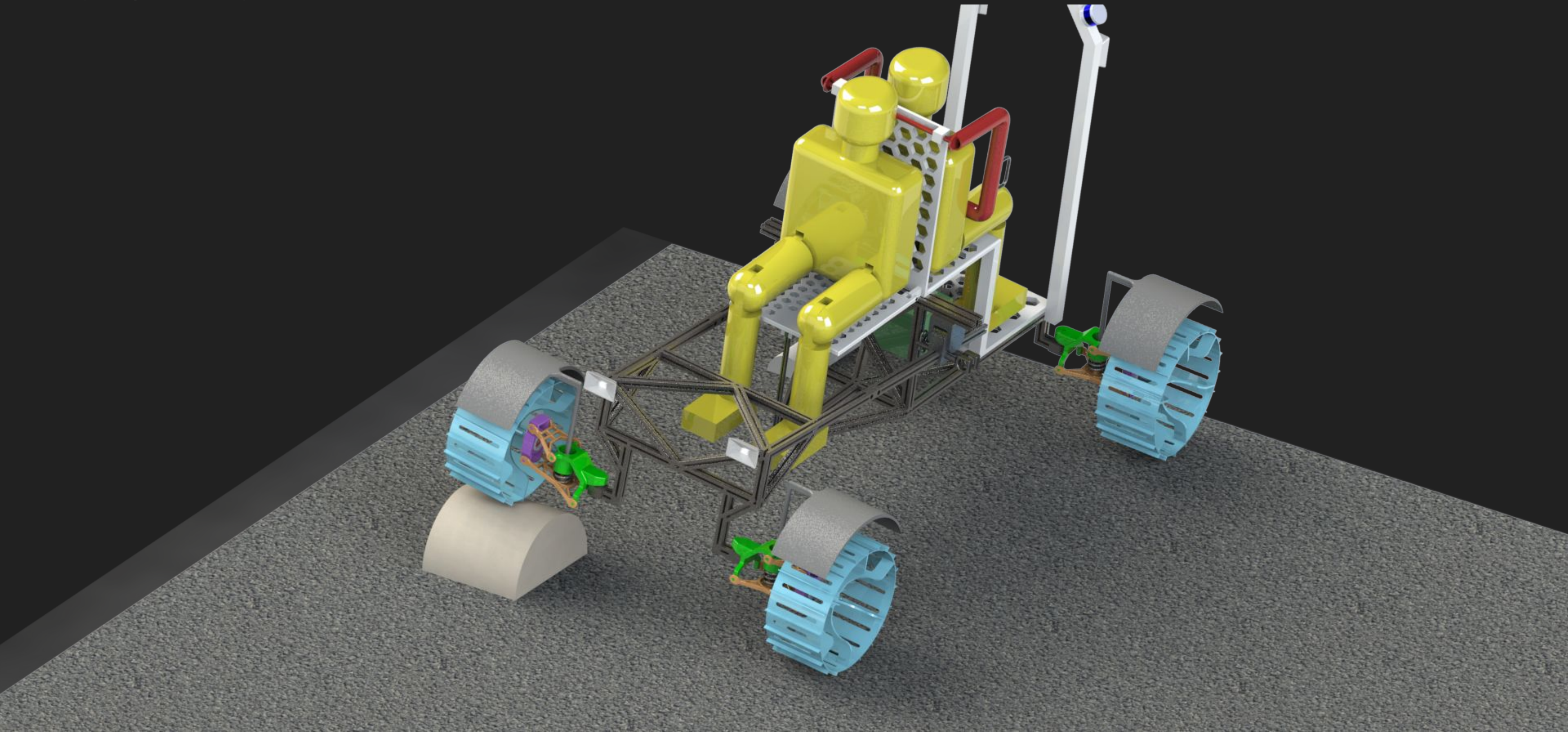
0.1m Obstacle



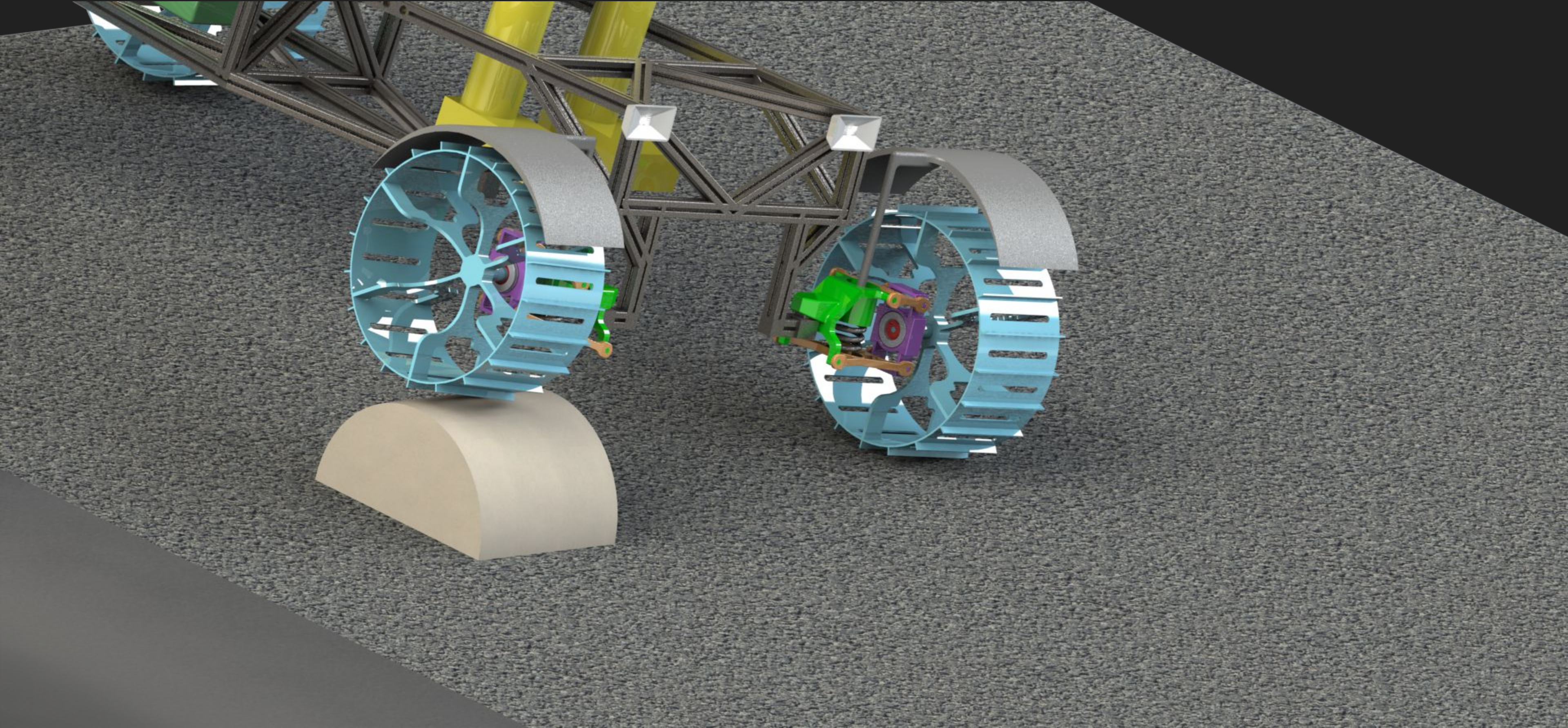
0.1m Obstacle



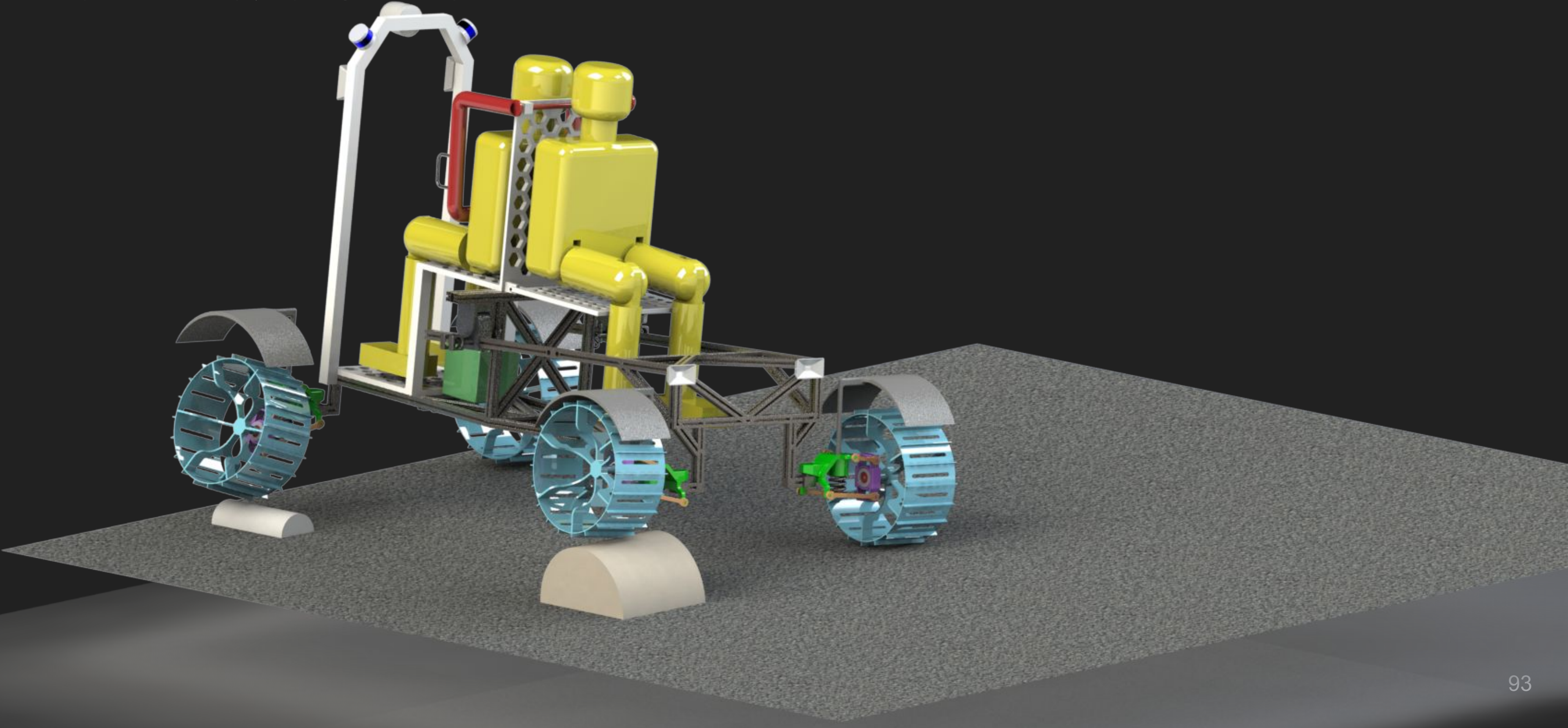
0.3m Obstacle



0.3m Obstacle



0.1m & 0.3m Obstacle



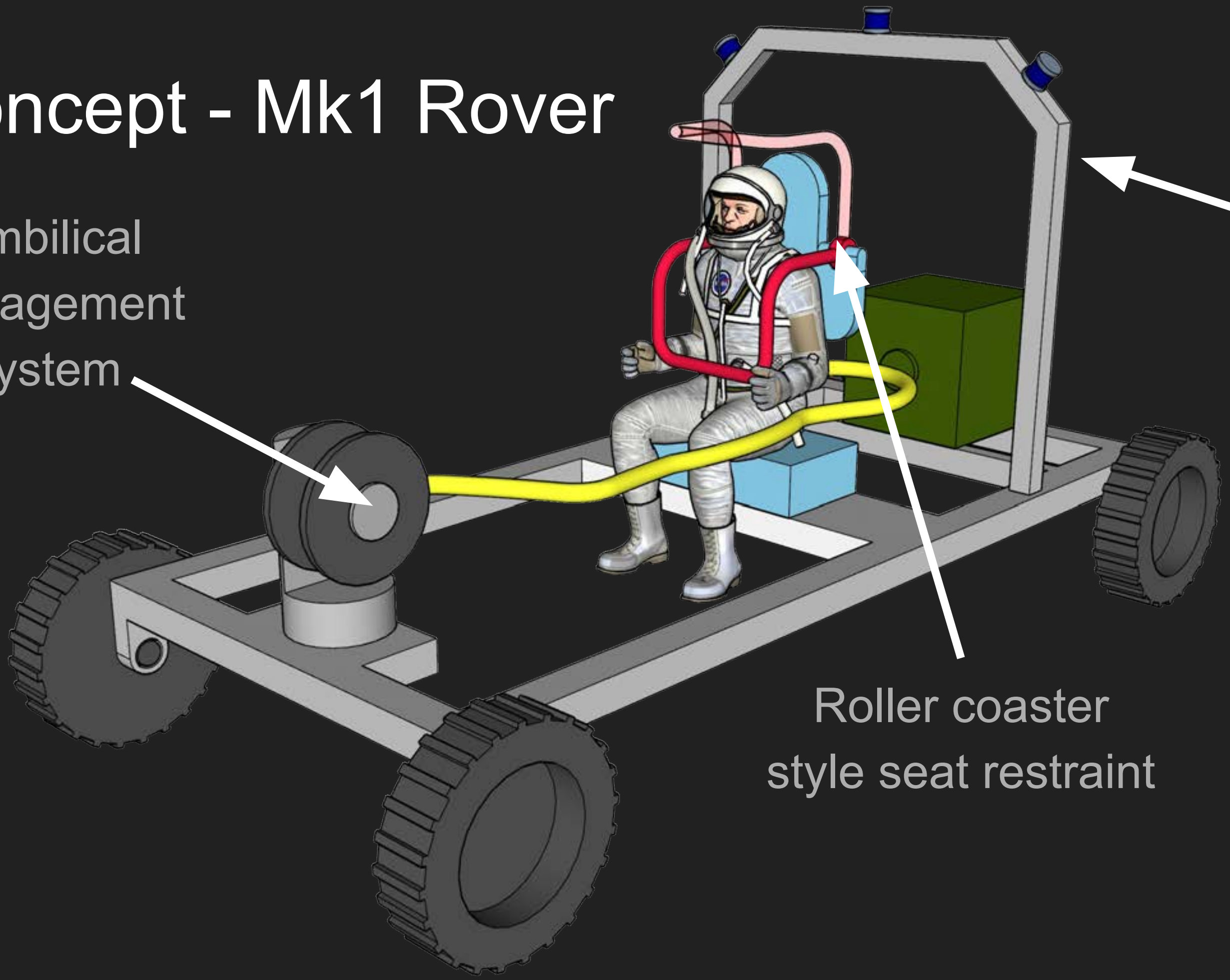
Design Evolution

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

Concept - Mk1 Rover



Umbilical management system

Roller coaster style seat restraint

Sensor arch with Velodyne LiDAR pucks, flood lights, and several PTZ cameras (not shown).

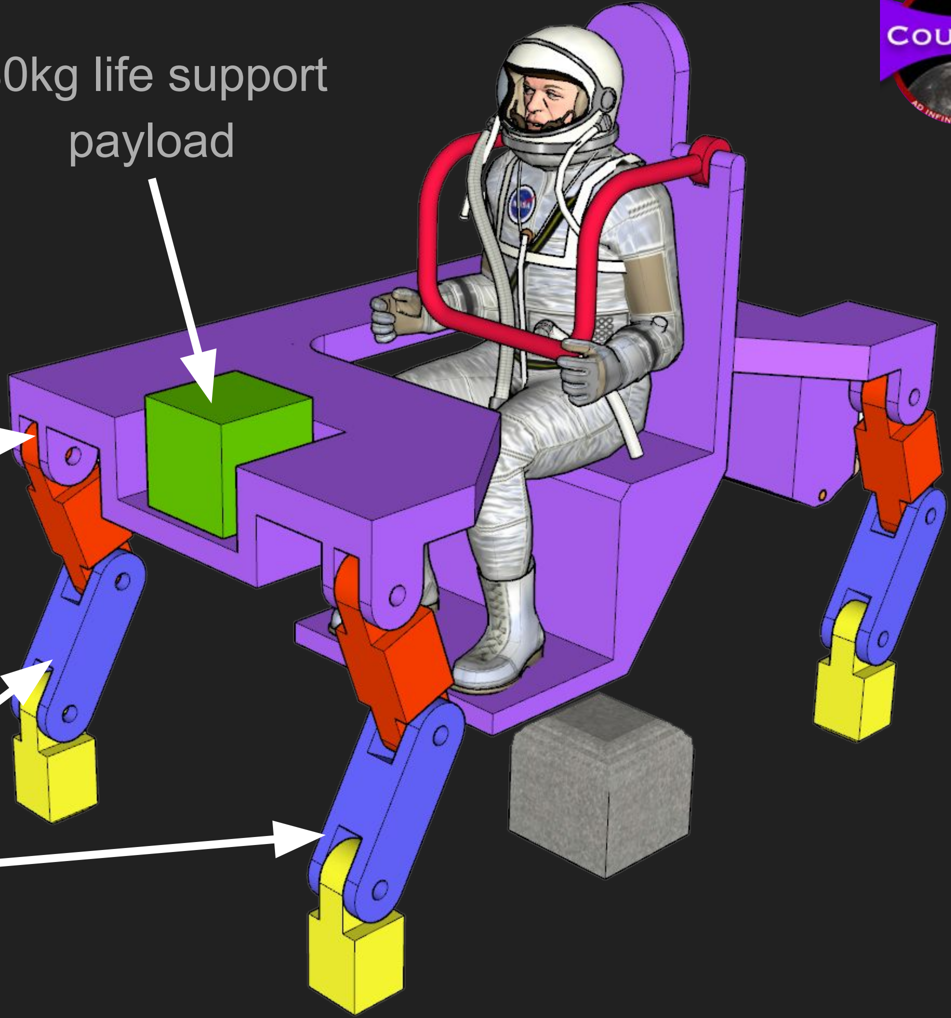
Configurations with 2 or 3 sensor arches are also possible with this design

Concept - Horsebot

- Bio-inspired legged locomotion

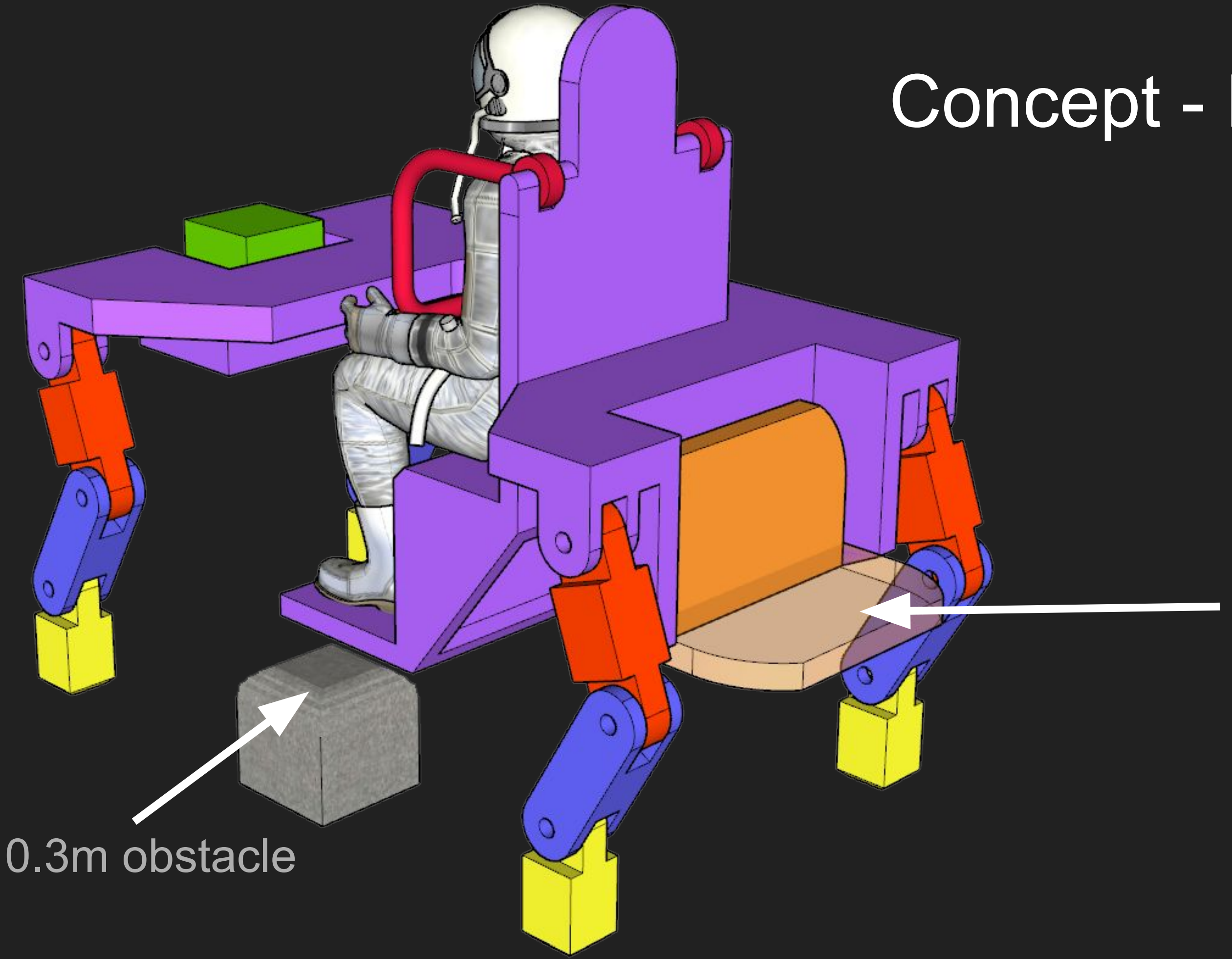
80kg life support payload

Hip rotation joint (not shown)



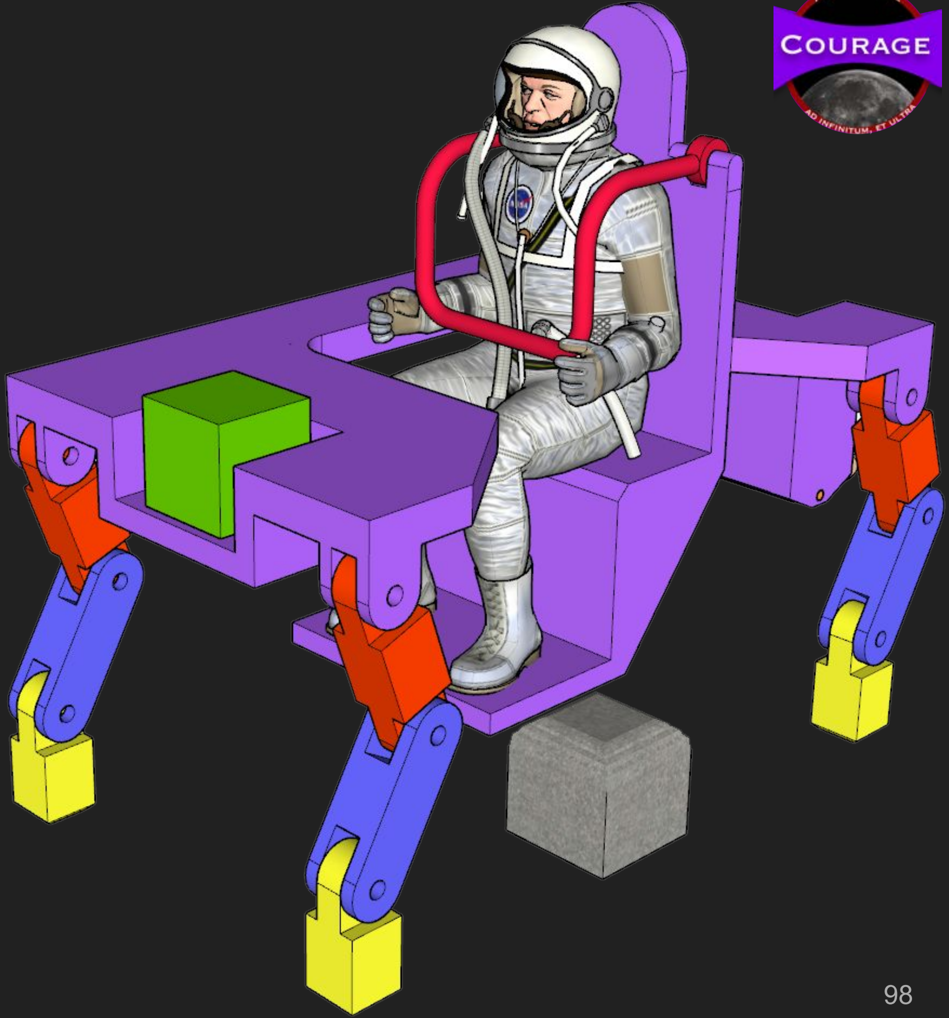
Four 4 DoF legs

Concept - Horsebot



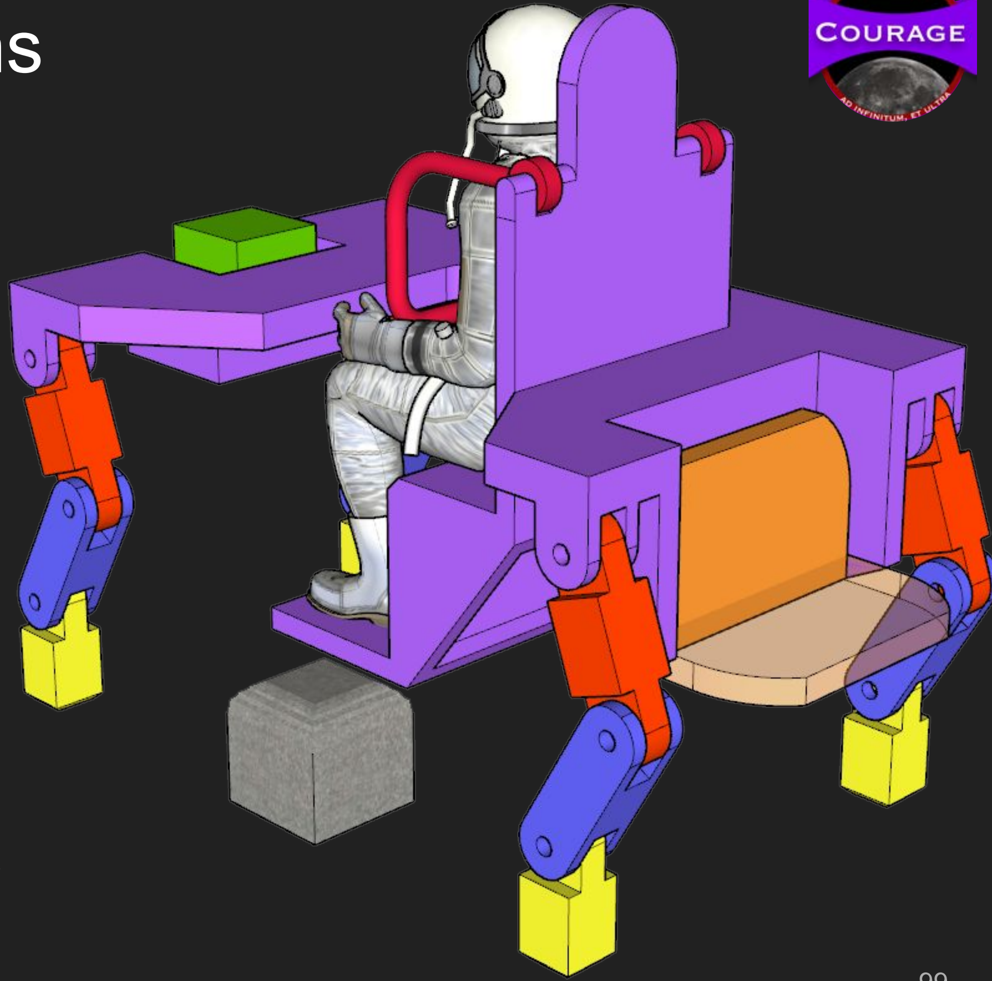
Concept - Horsebot - Pros

- Legged locomotion easily clears any obstacle
- Works well on rugged/uneven terrain
- 360° rotation hip joint allows Horsebot to walk sideways (or at arbitrary angle) with its standard gait
- Easy to incorporate second rider
- Seat position keeps center of mass relatively low
- Novel and interesting



Concept - Horsebot - Cons

- Legs are more complex than wheels (more ways to fail)
- Legs require more actuators (more weight)
- 4 m/s would require a medium trot/slow gallop gait, which are only dynamically stable
- Trot/Gallop gait requires much faster and higher torque motors (more weight, more power)
- Additional DoFs (ex: hip abduction, ankle pronation) might be needed for walking on slopes



Concept - Wheeled Horsebot

Similar to the Horsebot shown in previous slides, this concept 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.

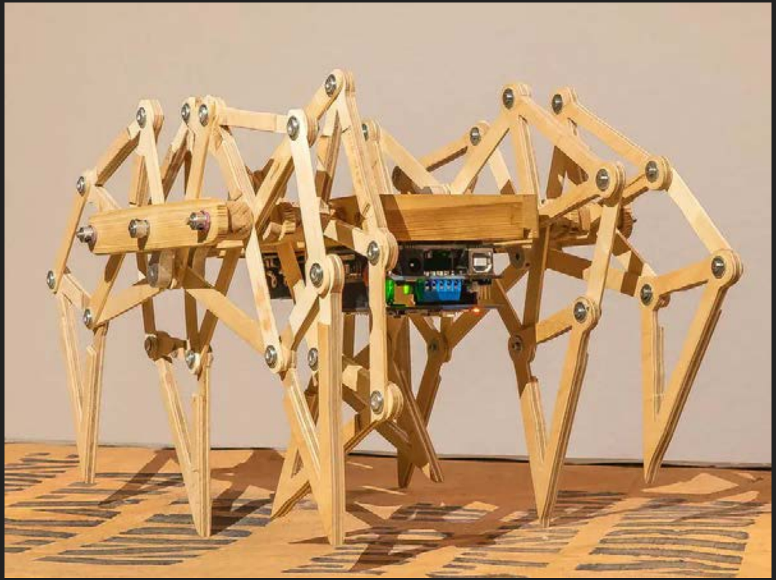
The increased weight from the extra motors makes this concept impractical for this mission

Concept - Strandbeest Locomotion

Locomotion inspired by Theo Jansen's Strandbeests and other similar designs

https://www.newmobility.com/2018/09/spider-chair/

https://www.newmobility.com/2013/07/walking-wheelchair-with-12-legs/



https://www.hackster.io/fx4u/strandbeest-a-robotic-project-7e1e23

Concept - Strandbeest Locomotion - Pros

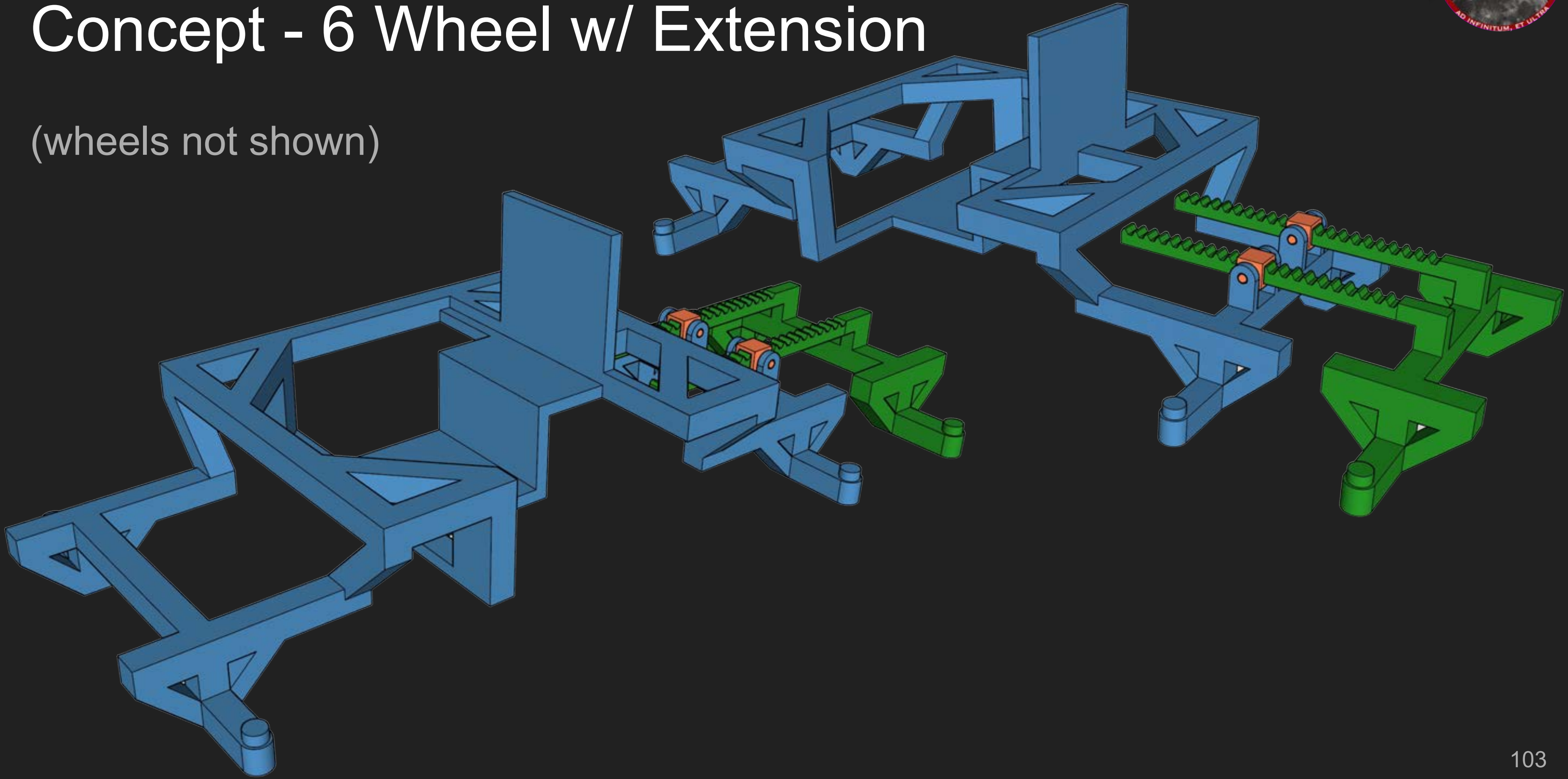
- Legs can be actuated with very few motors
- Chair centric design is compact and relatively lightweight (center photo on previous slide is 96 kg)
- Novel and interesting design

Concept - Strandbeest Locomotion - Cons

- Very high mechanical complexity (*many* ways to fail)
- Well tested on sand, but not well tested on rugged/uneven terrain
- Largely incompatible with stair climbing (due to leg lengths)

Concept - 6 Wheel w/ Extension

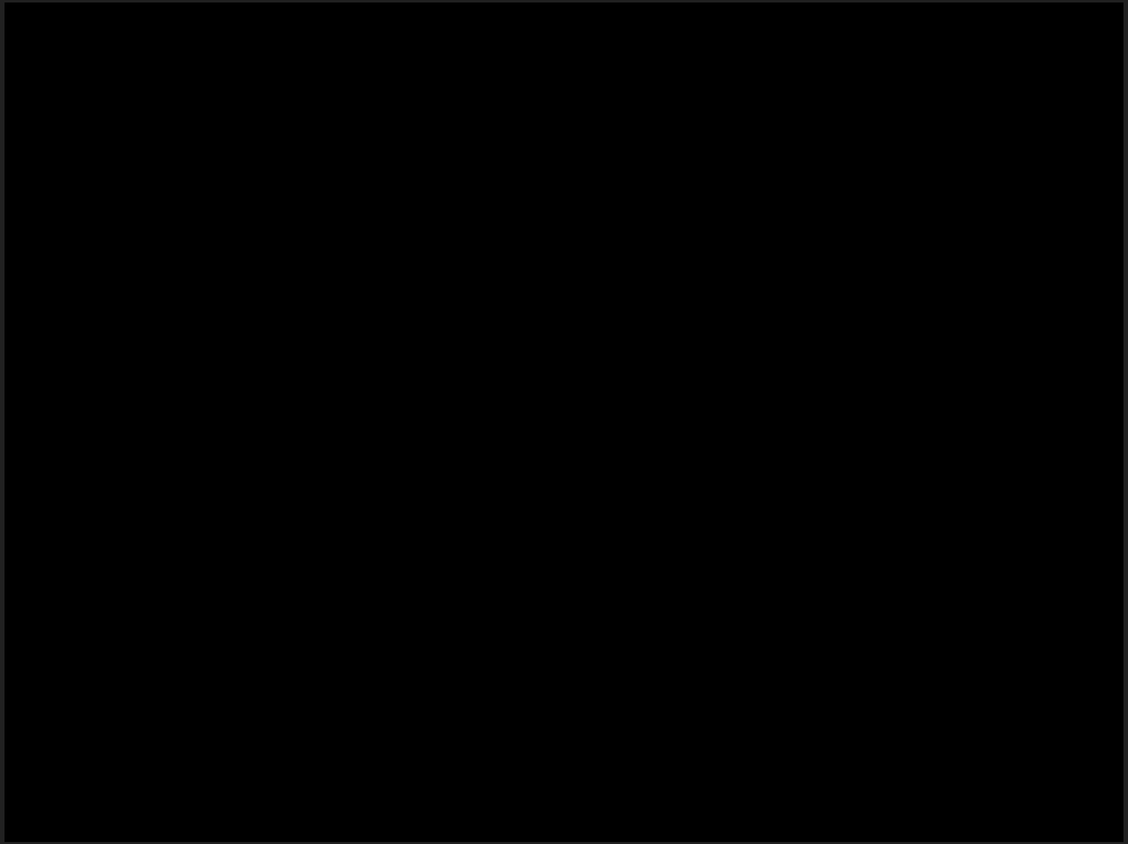
(wheels not shown)



Concept - 6 Wheels w/ Extension

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 wider 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 on the previous slide) for improved stability, as well as an additional pivot (orange, on the previous slide), allowing for the rear wheels to not be coplanar with the rest of the rover (ex: exiting a hill)

Crank Actuated Extension



Structure

Strength Analysis - Rear Arch Cross Beam

$F = 670kg * 1.62m/s^2 * 0.5$

$$\delta_{max} = \frac{Fa}{24EI}(3L^2 - 4a^2)$$

L=1.5m
a=0.25m

https://mechanicalc.com/reference/beam-analysis

45-9090 Type Aluminum Extrusion

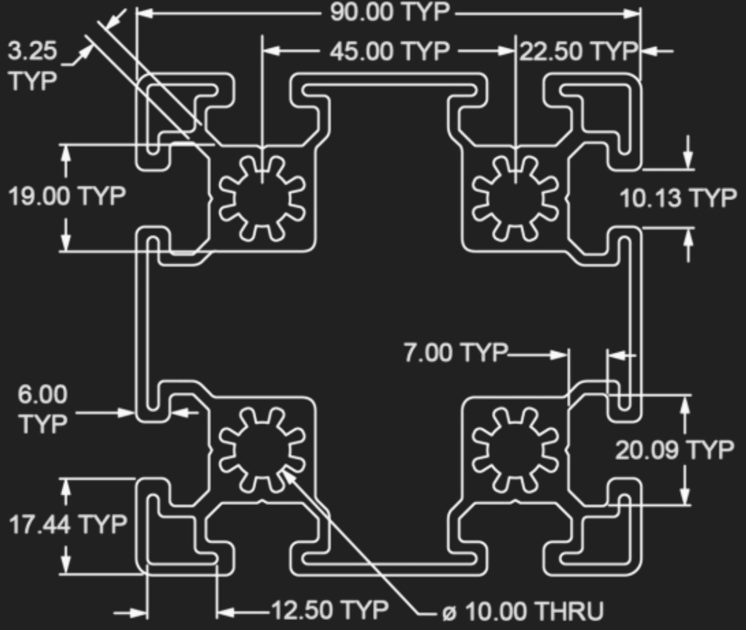
Young's Modulus=$70*10^9$ Pa

I = 179.4968 cm^4

A = 20.014 cm^2

Total Mass: **8.104 kg**

Max Deflection (@x=L/2): **0.29 mm**



https://8020.net/45-9090.html#

45-4545 Lite *Titanium* Extrusion

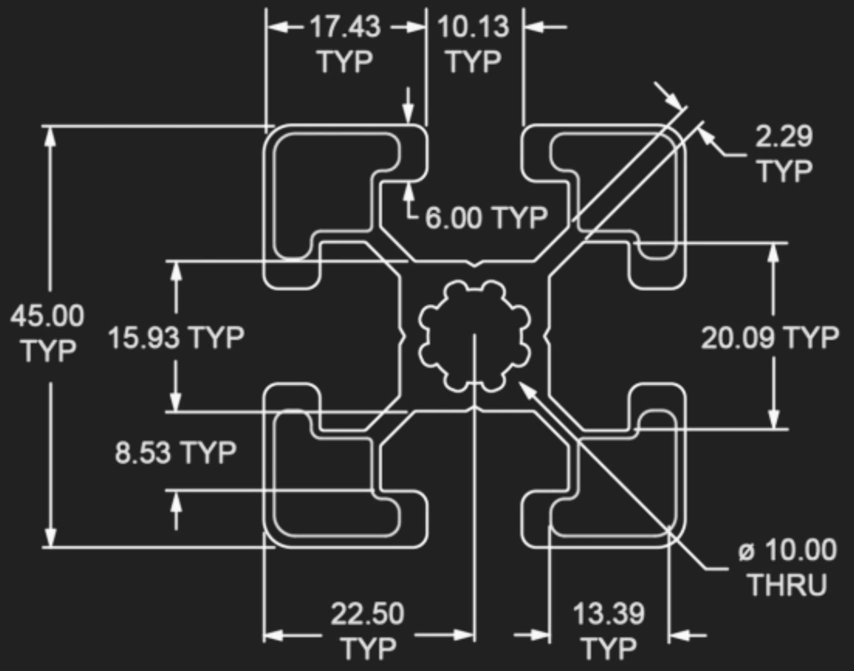
Young's Modulus=$170*10^9$ Pa

I = 9.2029 cm^4

A = 5.167 cm^2

Total Mass: **3.49 kg**

Max Deflection (@x=L/2): **3.3mm**

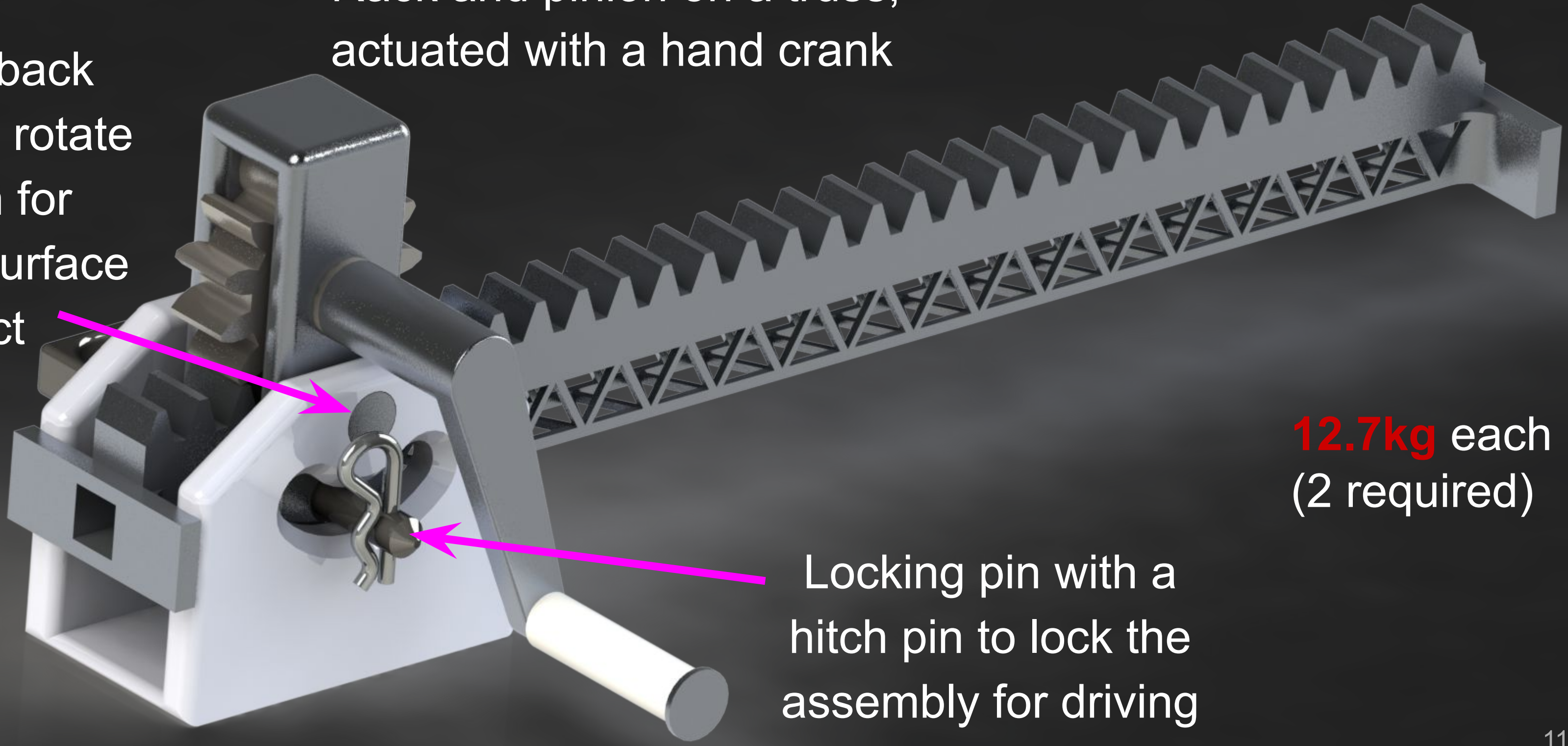


https://8020.net/45-4545-lite.html

Extension Mechanism - Original

Rack and pinion on a truss, actuated with a hand crank

Hinged - back wheels can rotate up/down for improved surface contact



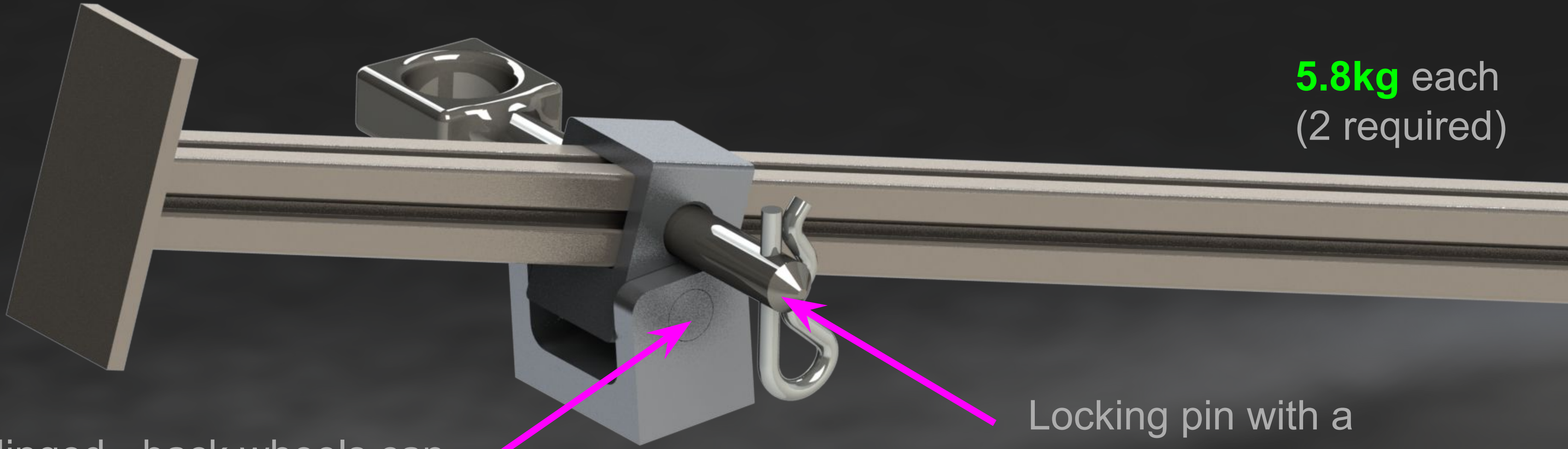
Locking pin with a hitch pin to lock the assembly for driving

12.7kg each (2 required)

Extension Mechanism - Simplified for Weight

Sliding 45-4545-Lite Titanium beam on rollers, actuated by reversing rear wheels

5.8kg each
(2 required)



Hinged - back wheels can rotate up/down for improved surface contact

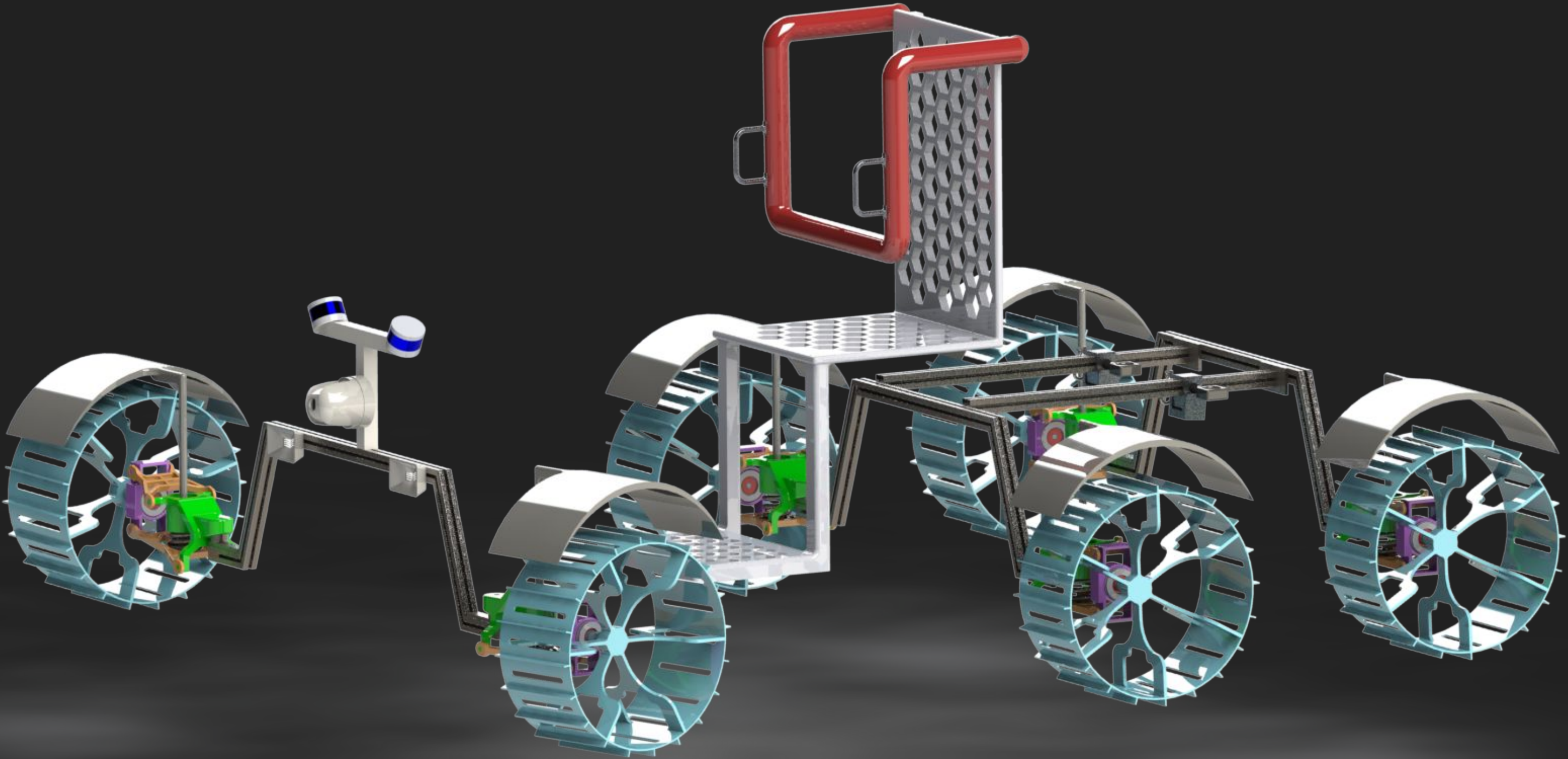
Locking pin with a hitch pin to lock the assembly for driving

Extension Mechanism

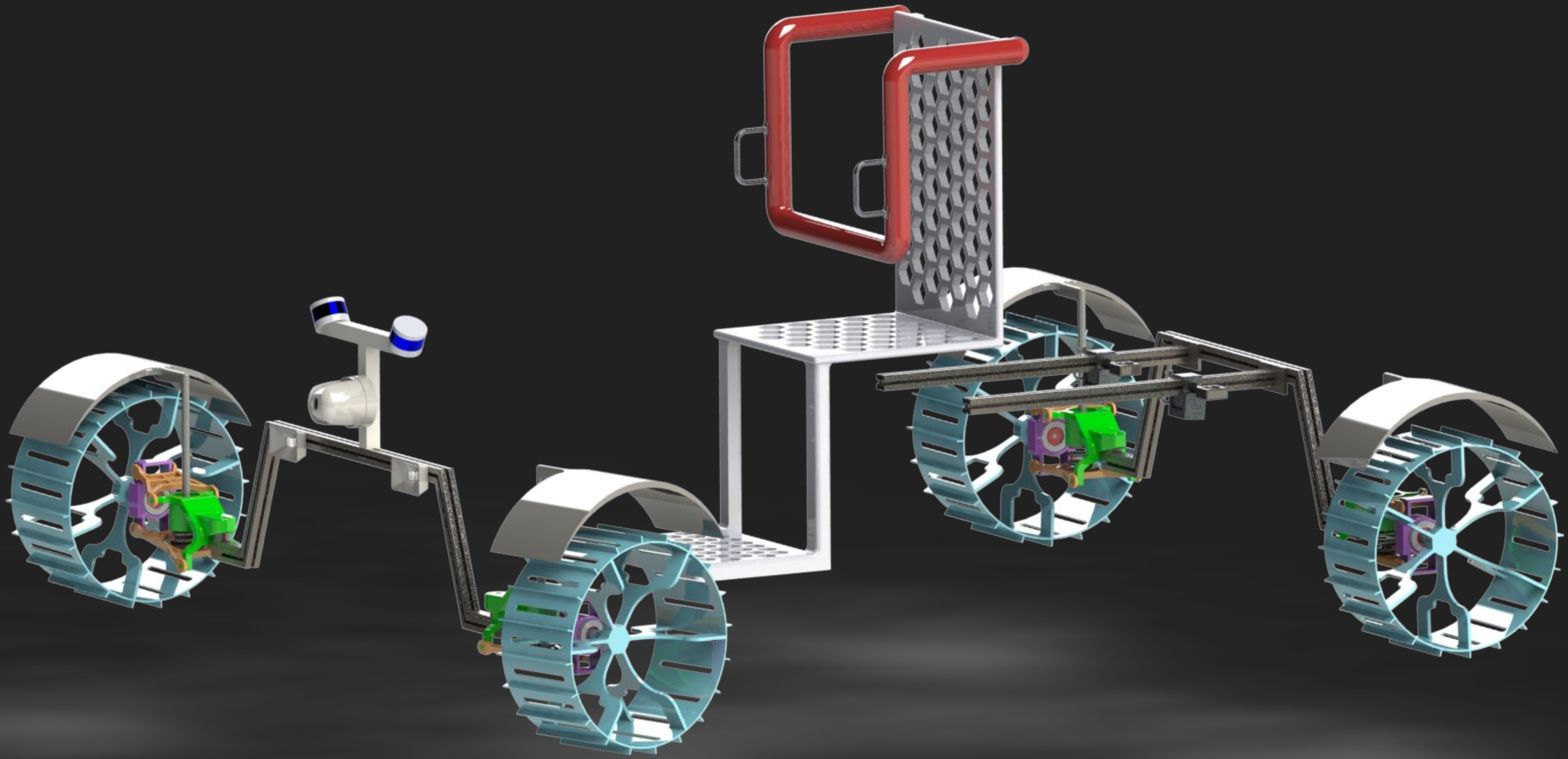
This extension mechanism revision was done when the rover still had arched chasses. The benefit of the weight savings in switching profiles and materials far exceeded the small decrease in structural strength. The sliding mechanism is now actuated by driving the rear wheels in reverse (and/or also driving the front wheels forward) to separate the two chassis halves.

Later revisions on this concept continue to use the titanium sliding beam, but offer additional reinforcement elsewhere in the structure (various braces and cross beams) and a much stronger pivot mechanism. The sliding box includes small rollers on the inside (like a skate wheel conveyor) to minimize friction.

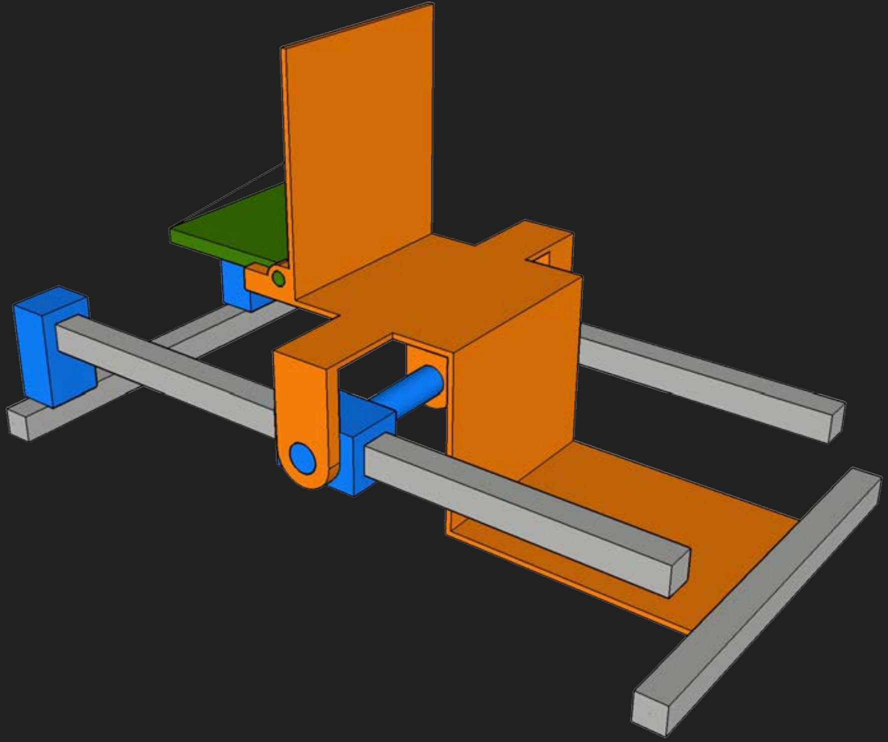
6 Wheel Rover, Chassis Arches

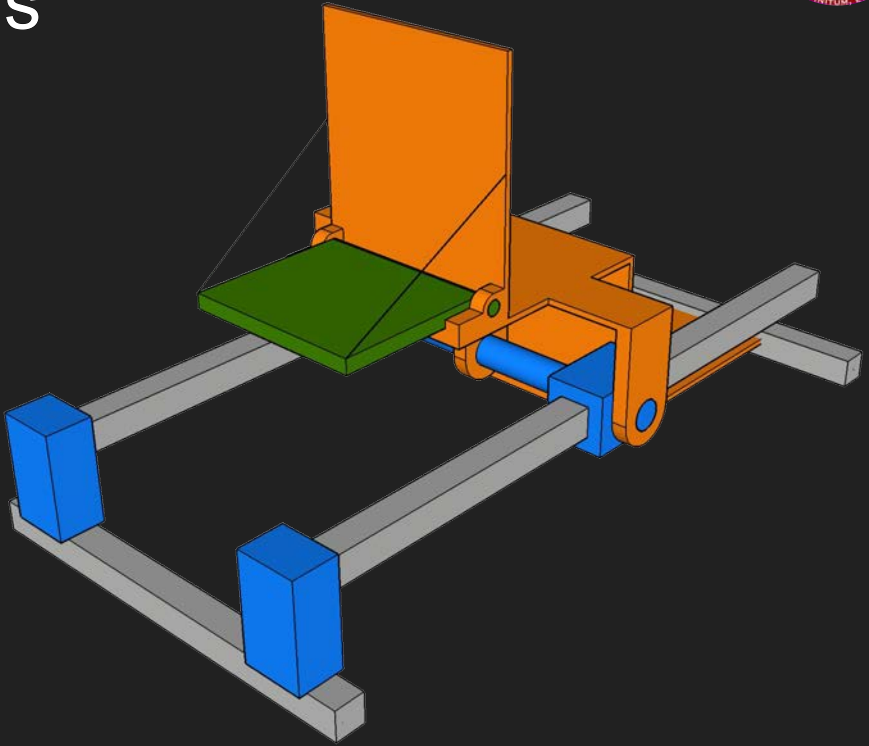


4 Wheel Rover, Chassis Arches

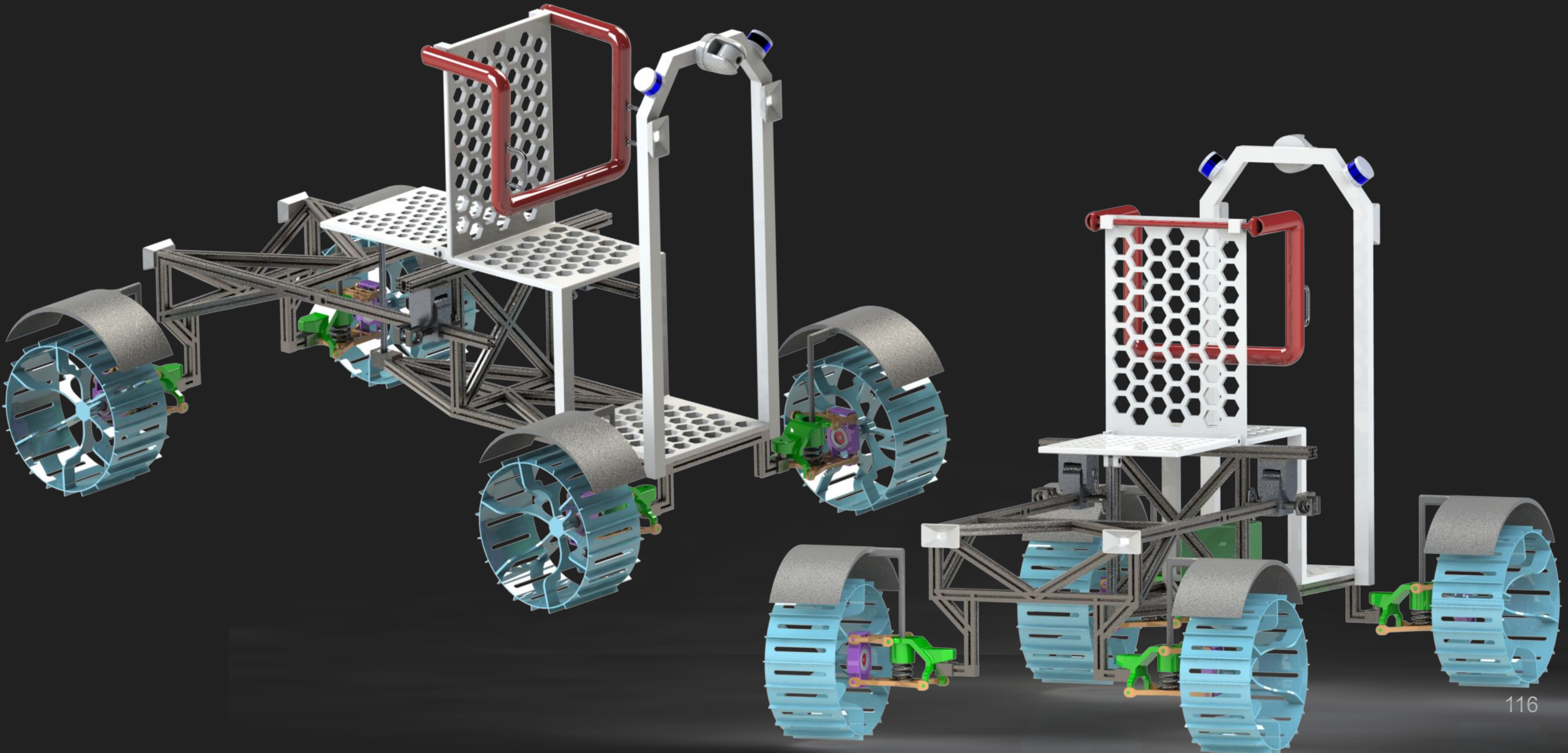


4 Wheel Rover, Flat Chassis





4 Wheel Rover, Flat Chassis (Final)



Thank You!

TOTAL SLIDE DECK

ENAE788x COURAGE Rover

Justin Albrecht
Brian Bock
Prateek Bhargava
Sayani Roy

Project Requirements

Project Description:

- 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...)
- Design for Moon, then assess feasibility of systems for Mars, and conversion to Earth analogue rover

Requirements (Performance) :

1. Maximum operating speed of at least **4 m/sec** on level, flat terrain.
2. Accommodate a **0.3 meter** obstacle at minimal velocity.
3. Accommodate a **0.1 m** obstacle at a velocity of 2.5 m/sec.
4. Accommodate a **20° slope** in any direction at a speed of at least 1 m/sec and including the ability to start and stop.
5. A nominal sortie range of **54 km** at an average speed of **2.5 m/sec**.

Project Requirements

Requirements (Payload) :

1. Capable of carrying one 170 kg EVA crew and 80 kg of assorted payload
2. Payload may be modeled as a 0.25 m box
3. Capable of carrying a second 170 kg EVA crew in a contingency situation.
4. Incorporate roll-over protection for the crew and all required ingress/egress aids and crew restraints.

Requirements (Operations) :

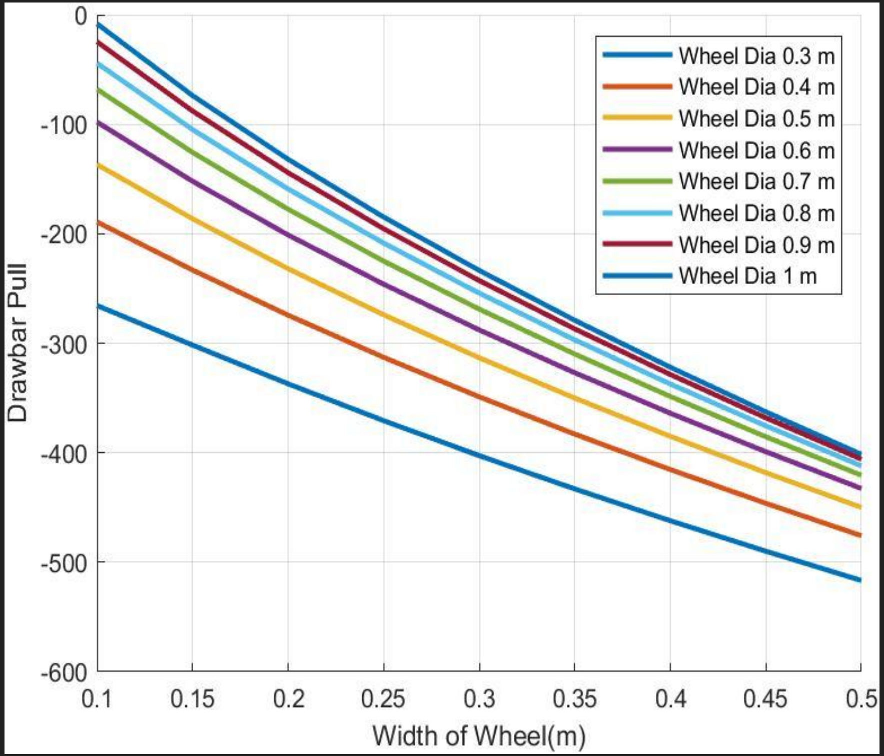
1. A nominal sortie shall be at least eight hours long.
2. Two rovers must be launched on a single CLPS lander.
3. A single rover shall mass ≤250 kg.
4. Capable of operating indefinitely without crew present.

Requirements (GN&C) :

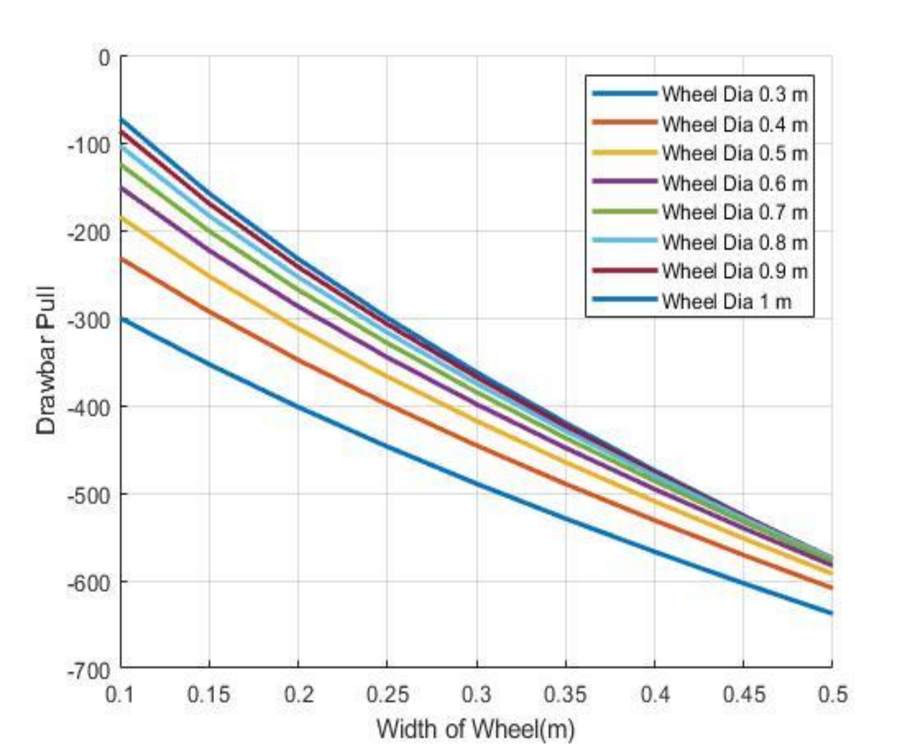
1. Capable of being controlled directly, remotely, or automated.
2. Capable of following an astronaut, astronaut's path, or autonomous path planning between waypoints.
3. Capable of operating during any portion of the lunar day/night cycle and at any latitude.

Terramechanics

Trade Study - Drawbar Pull - No Grousers - Flat Terrain

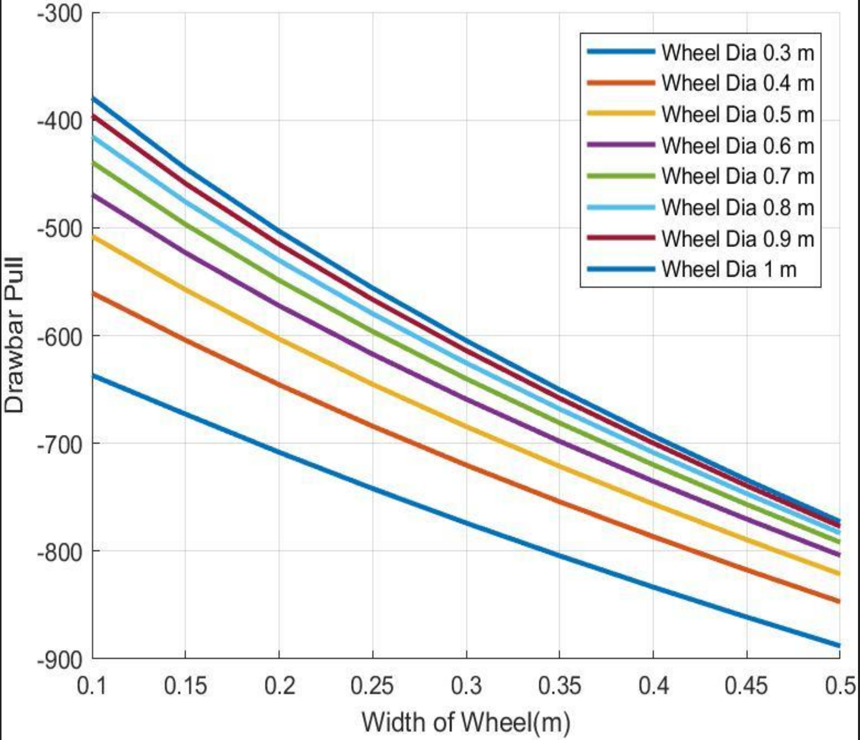


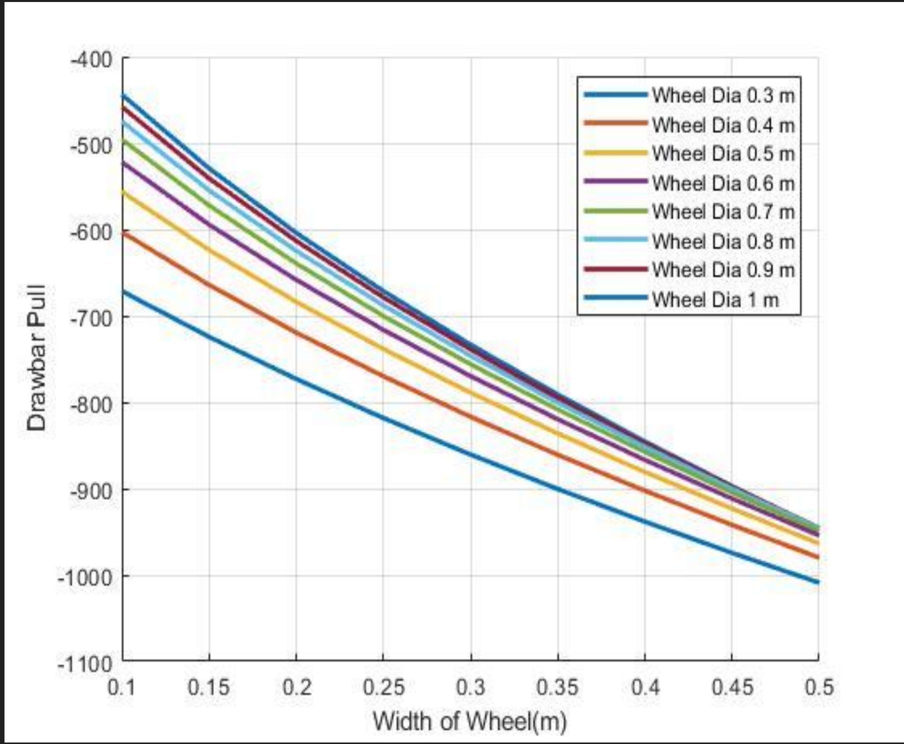
4 Wheels



6 Wheels

Trade Study - Drawbar Pull - No Grousers - 20 Slope

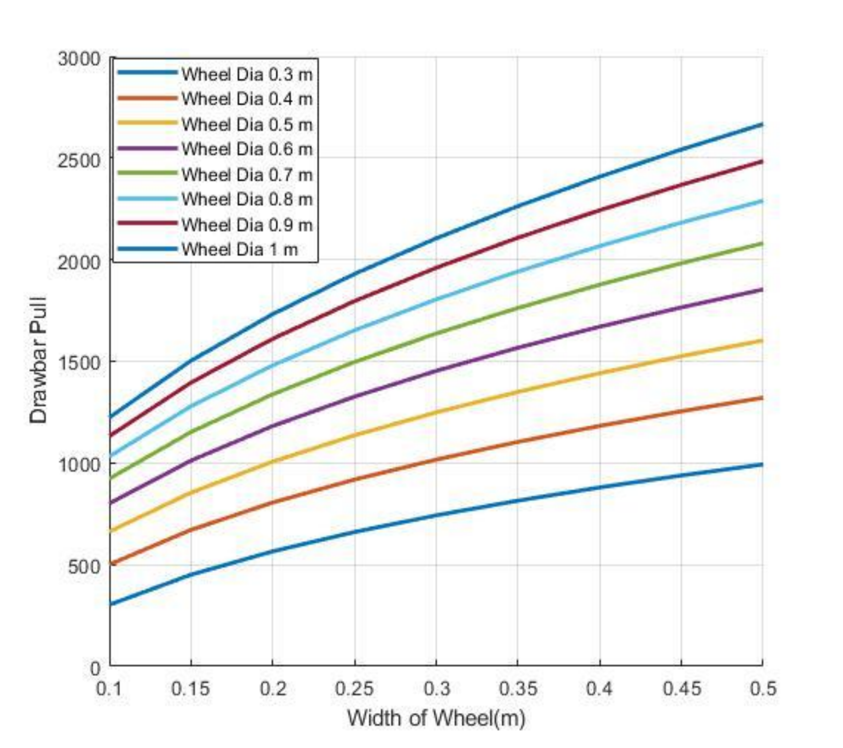




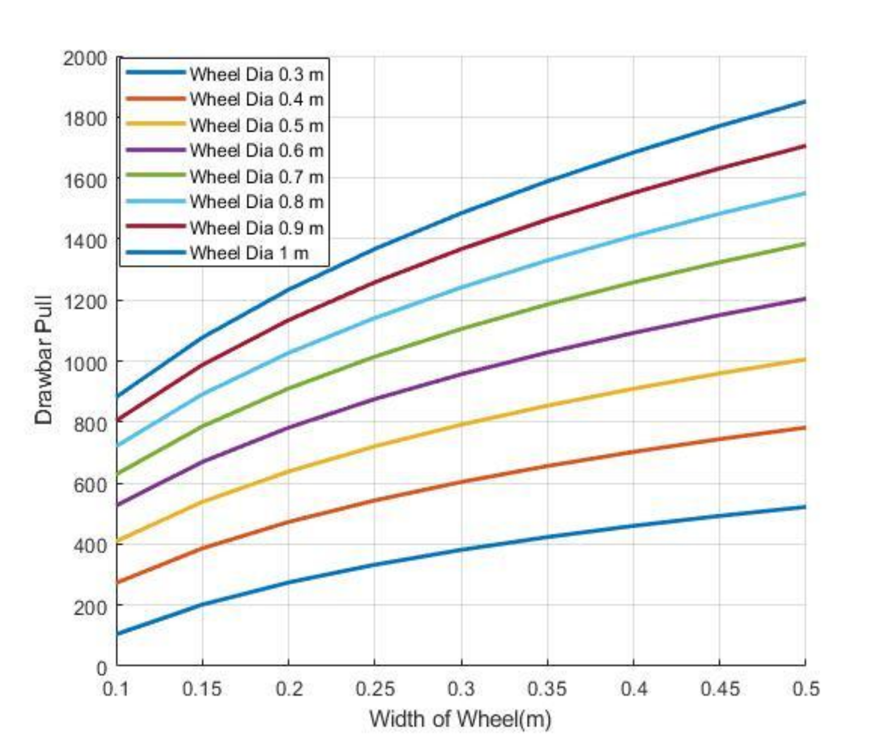
4 Wheels

6 Wheels

Trade Study - Drawbar Pull - Grousers - Flat

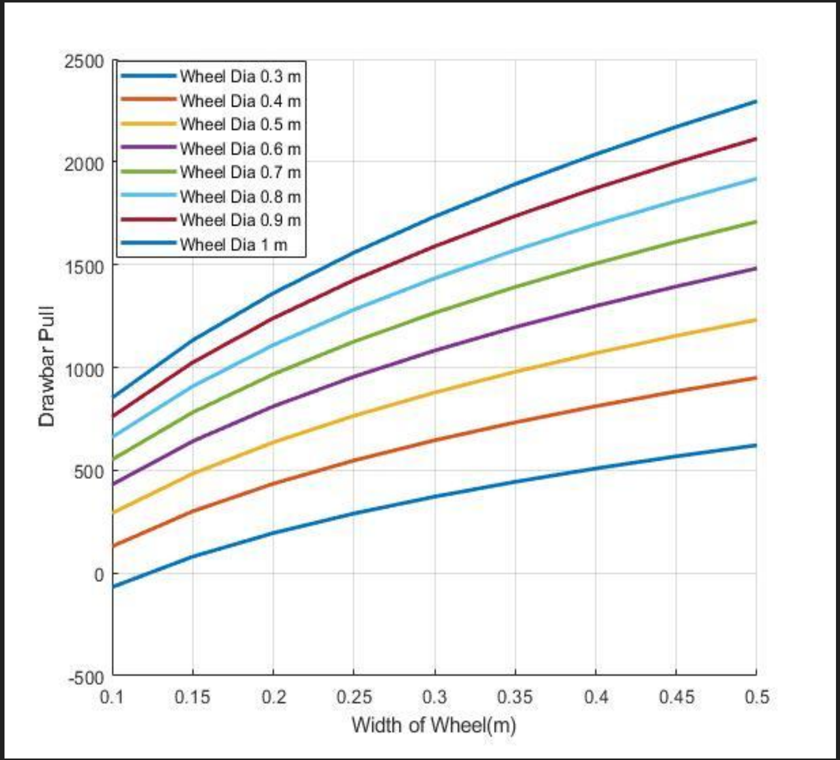


4 Wheels

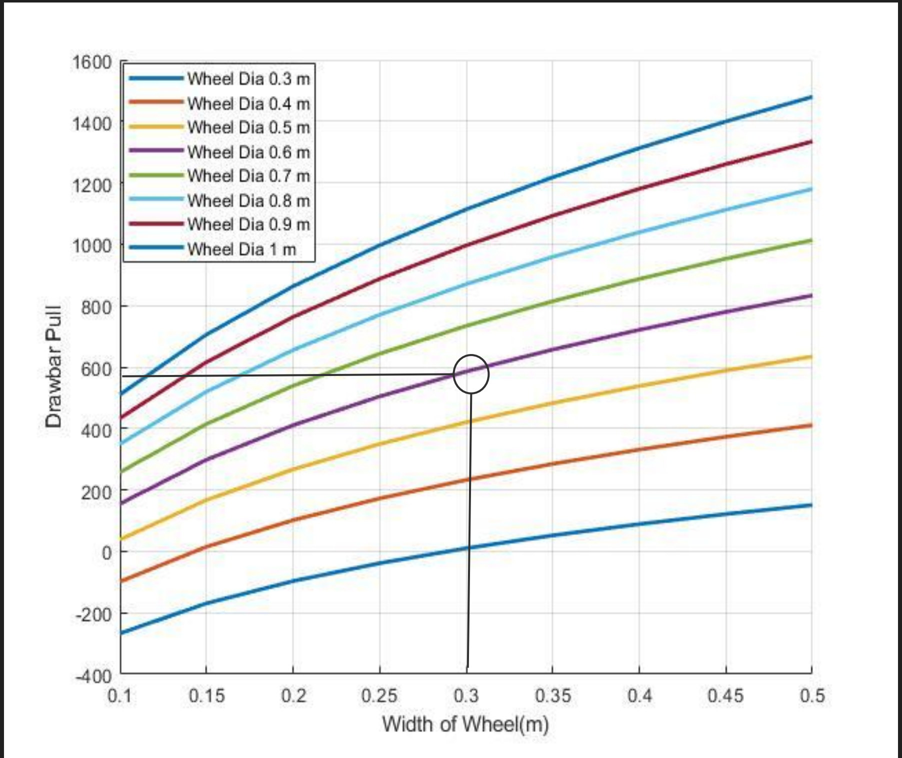


6 Wheels

Trade Study - Drawbar Pull - Grousers - 20 Slope

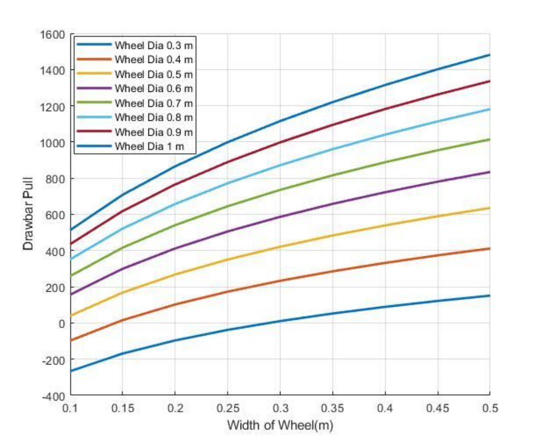


4 Wheels



6 Wheels

Drawbar Pull 6 Wheels - No. of Grousers



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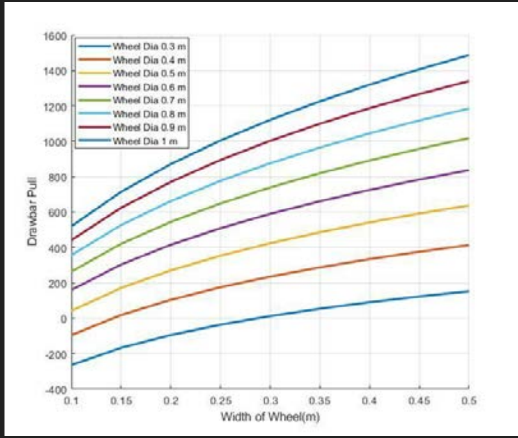

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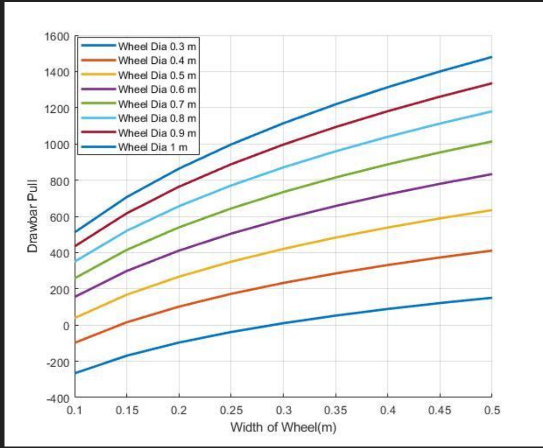

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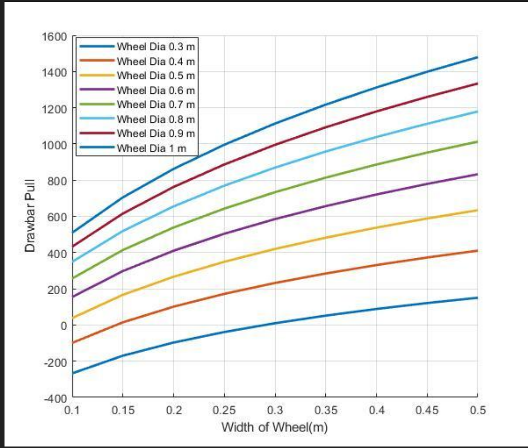
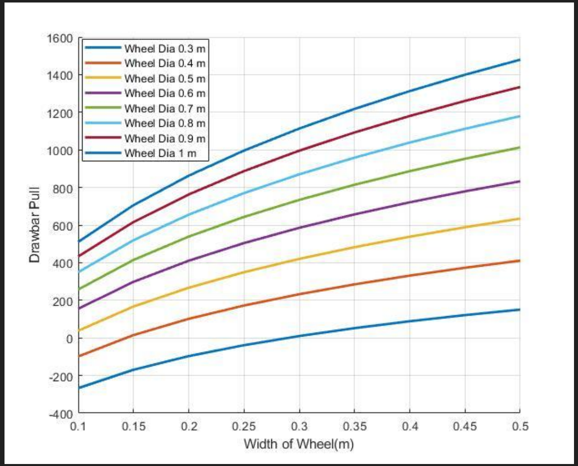
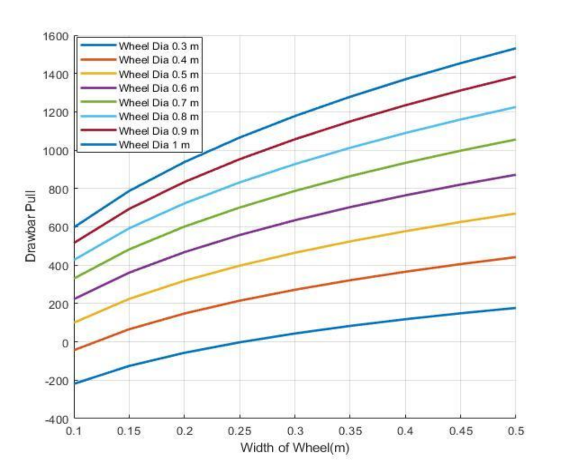


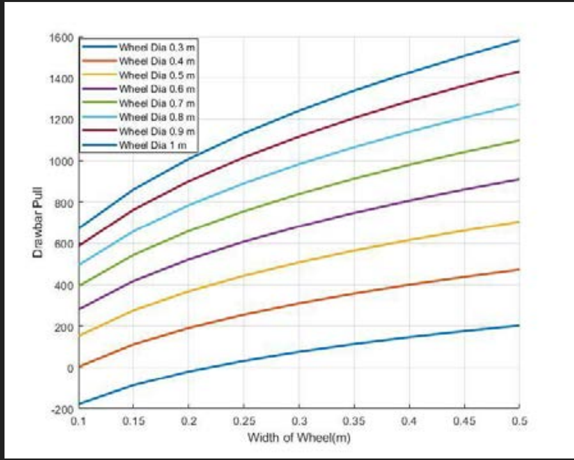
Drawbar Pull 6 Wheels - Height (cm) : 2 vs. 3 vs. 4 vs. 5



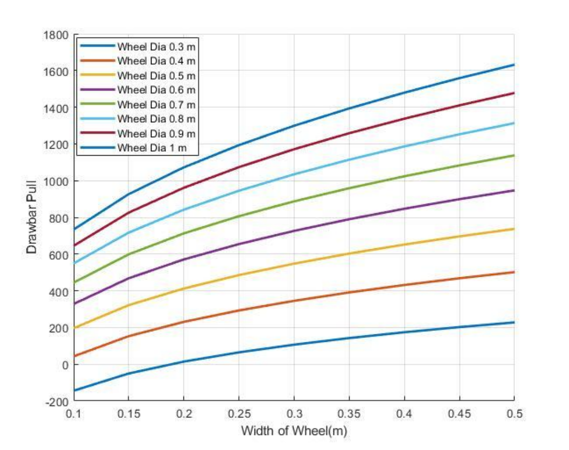
2 cm



3 cm



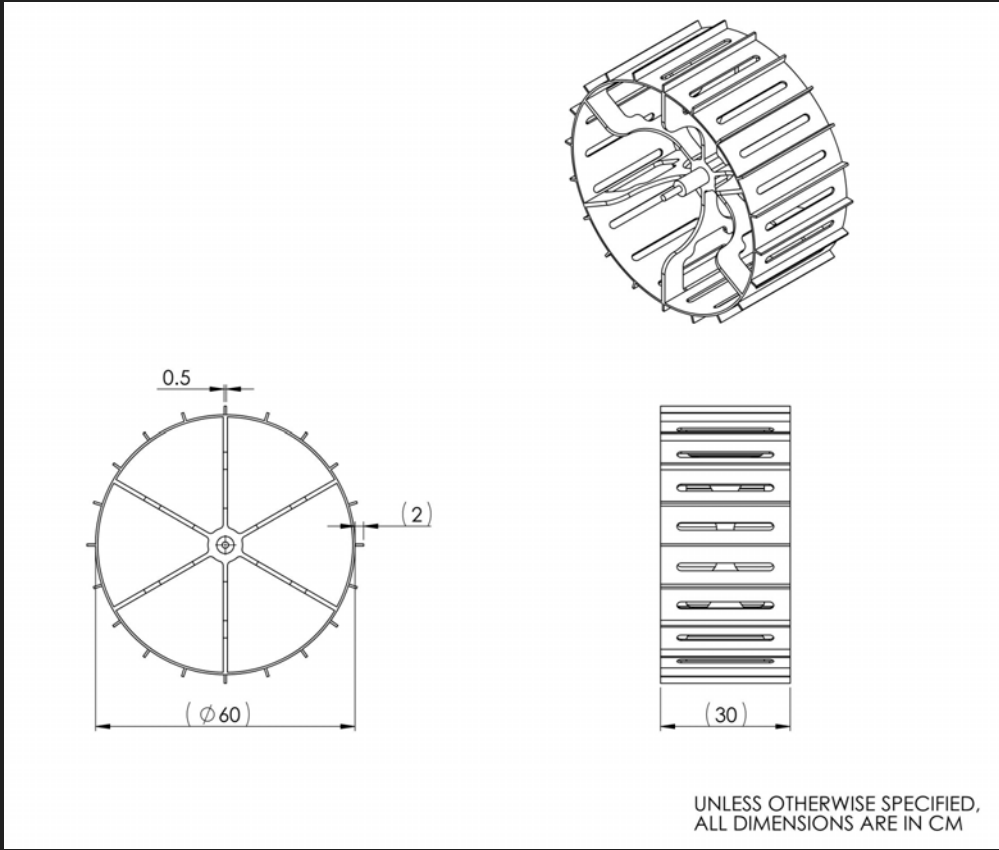
4 cm



5 cm

Wheel Drawing

Wheel Dimensions	
Diameter	60 cm
Width	30 cm
Grouser Height	2 cm
Number Spokes	6



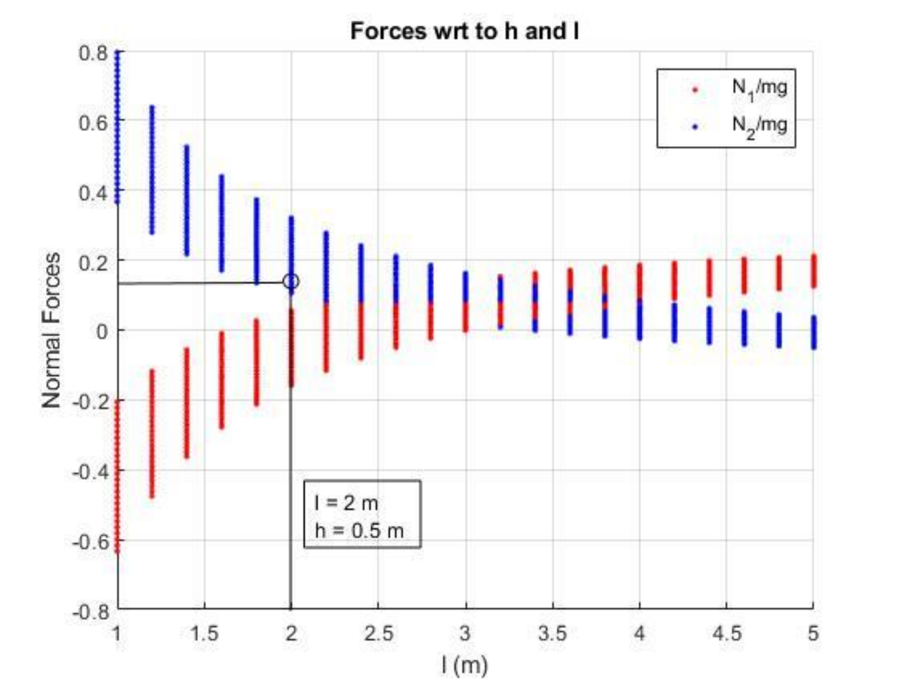
Terramechanics : Design Solution

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

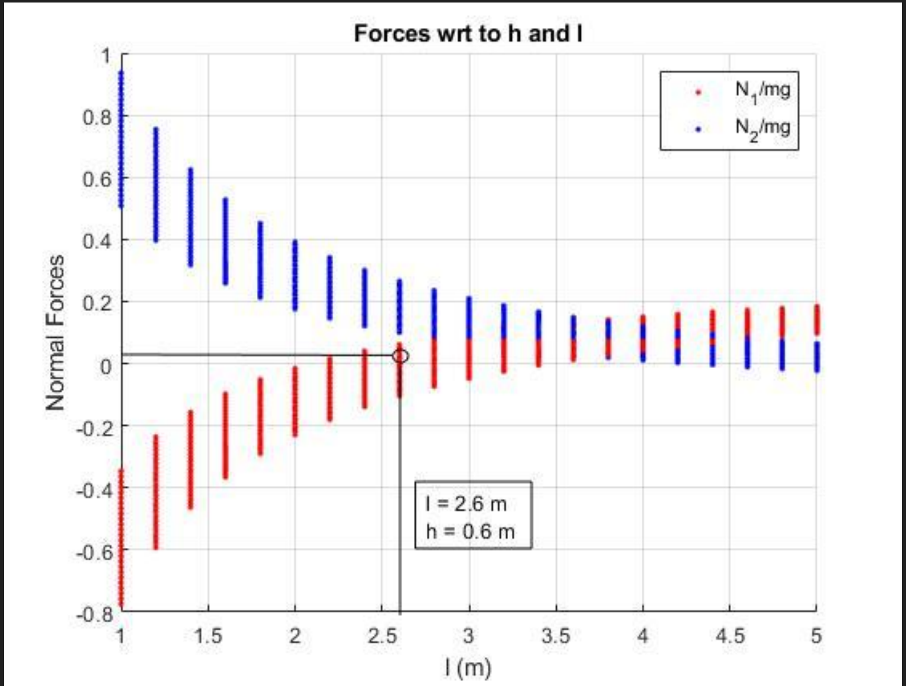
1. Diameter of wheel(d) - 0.6 m
2. Width of wheel (w) - 0.3 m
3. Number of grousers - 20
4. Height of grousers - 0.02 m = 2 cm

Stability

Stability - Forces wrt h and l

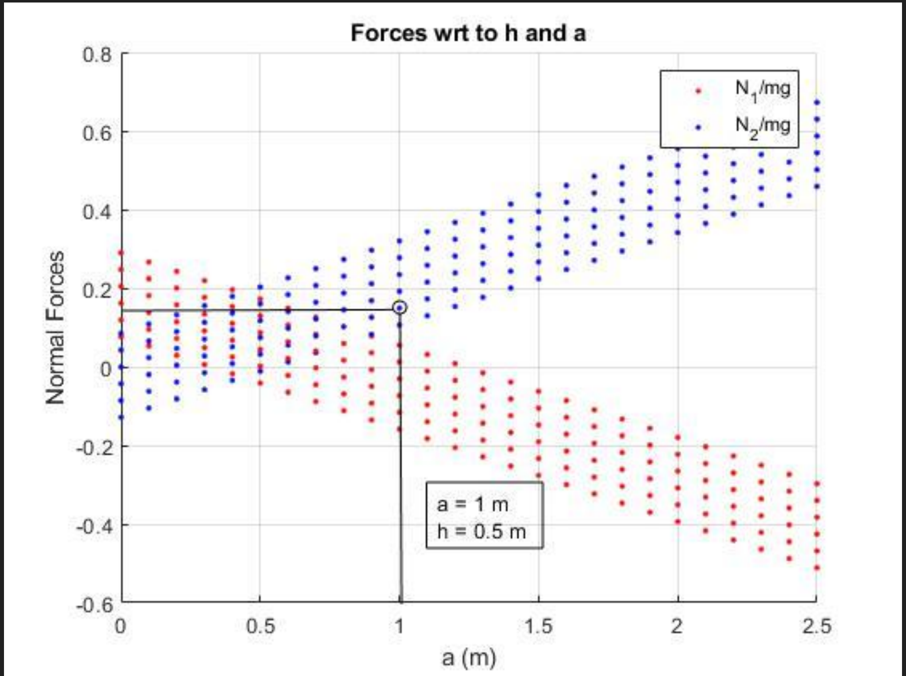


Non - Extended

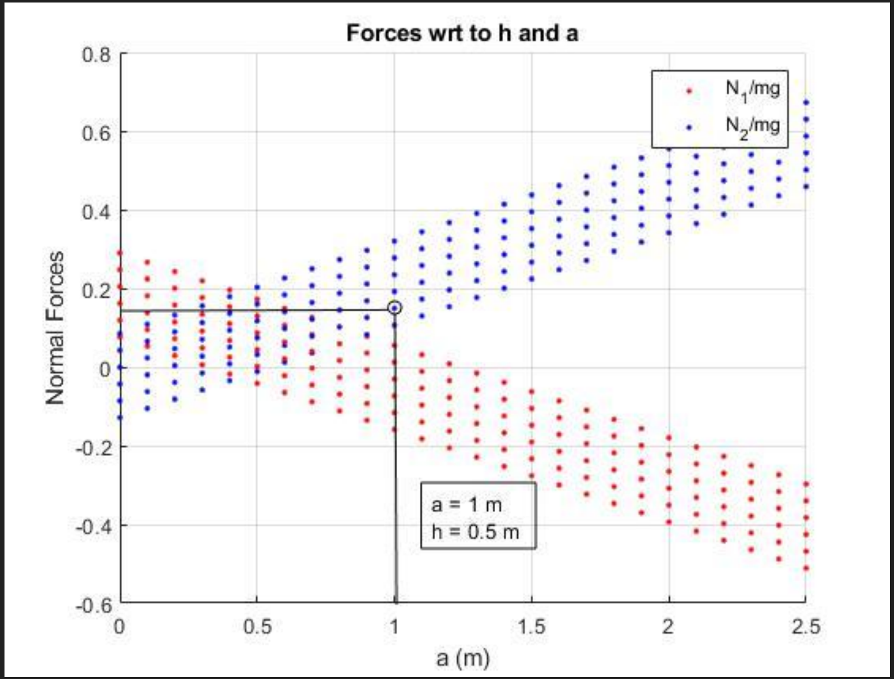


Extended

Stability - Forces wrt h and a

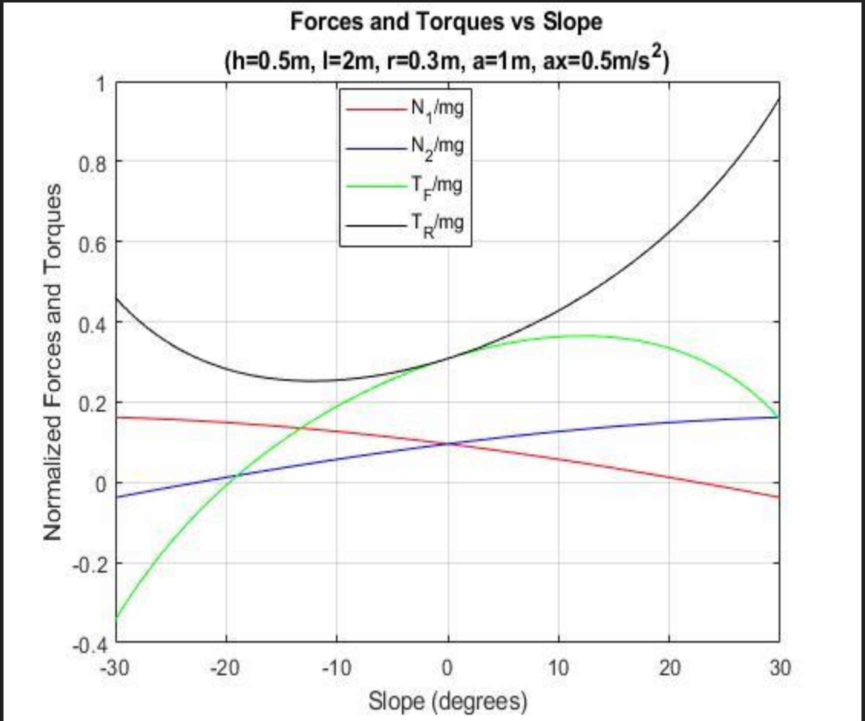


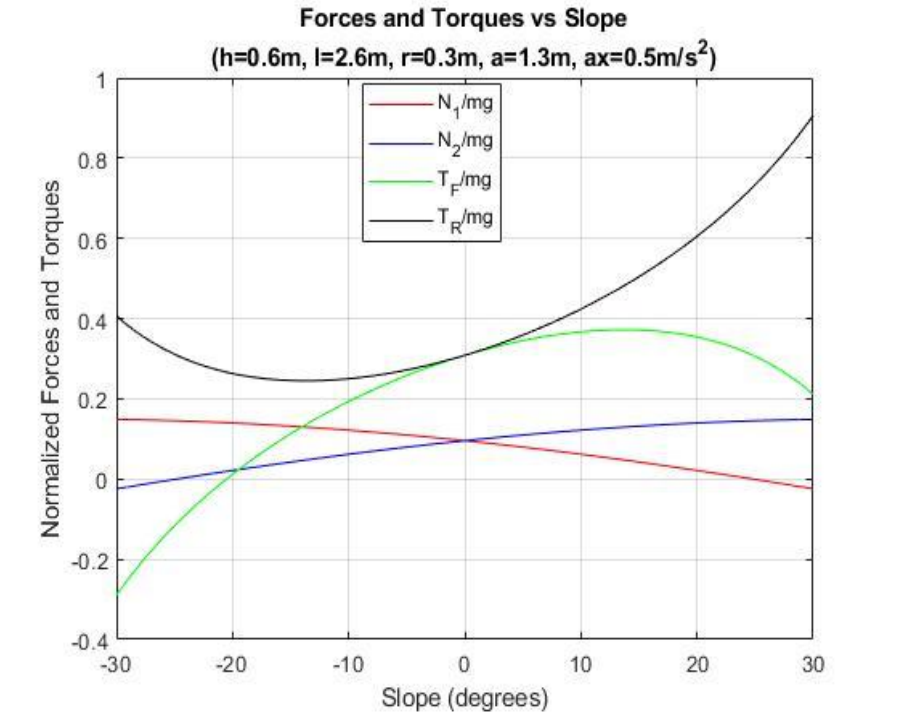
Non - Extended



Extended

Slope Stability - Uphill / Downhill

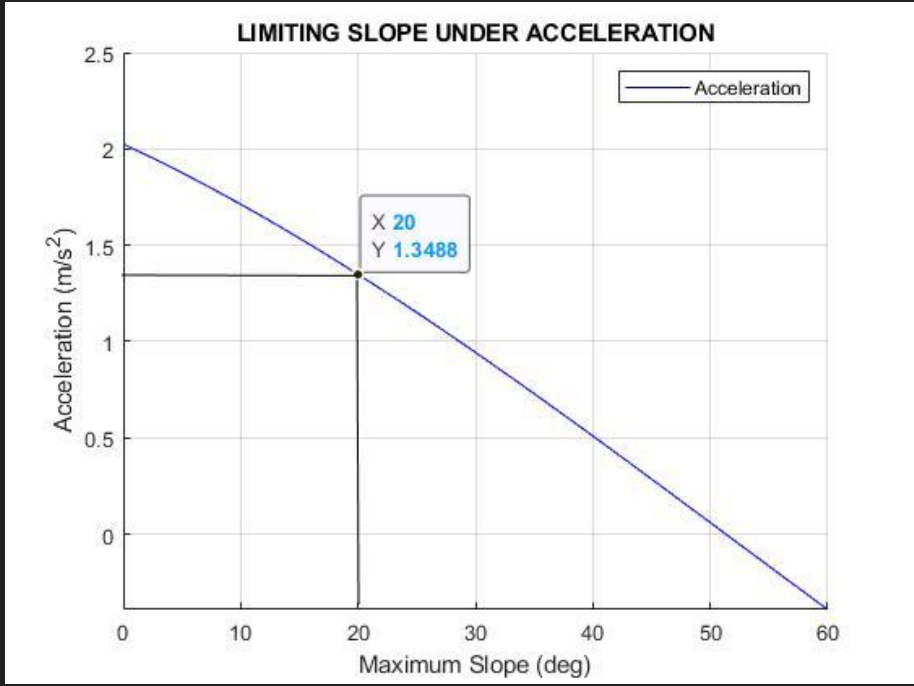




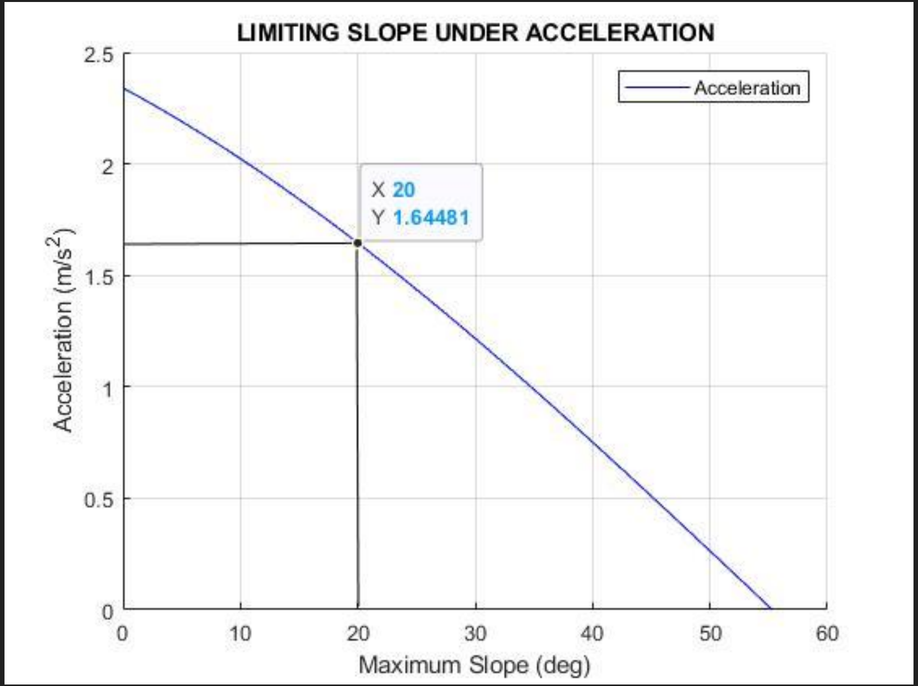
Non - Extended

Extended

Acceleration Stability

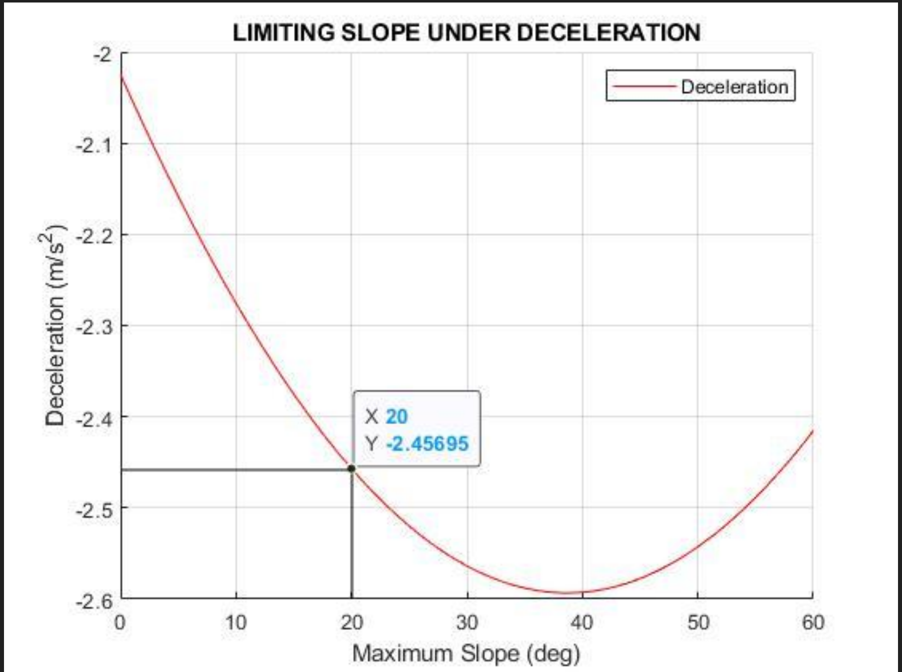


Non - Extended

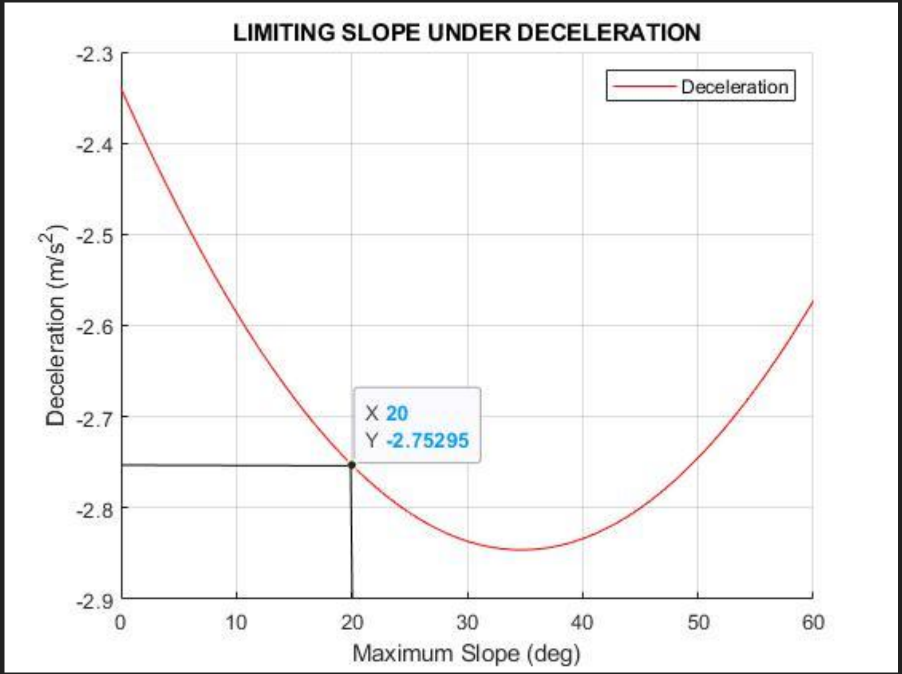


Extended

Deceleration Stability



Non - Extended



Extended

Stability - Design Solution

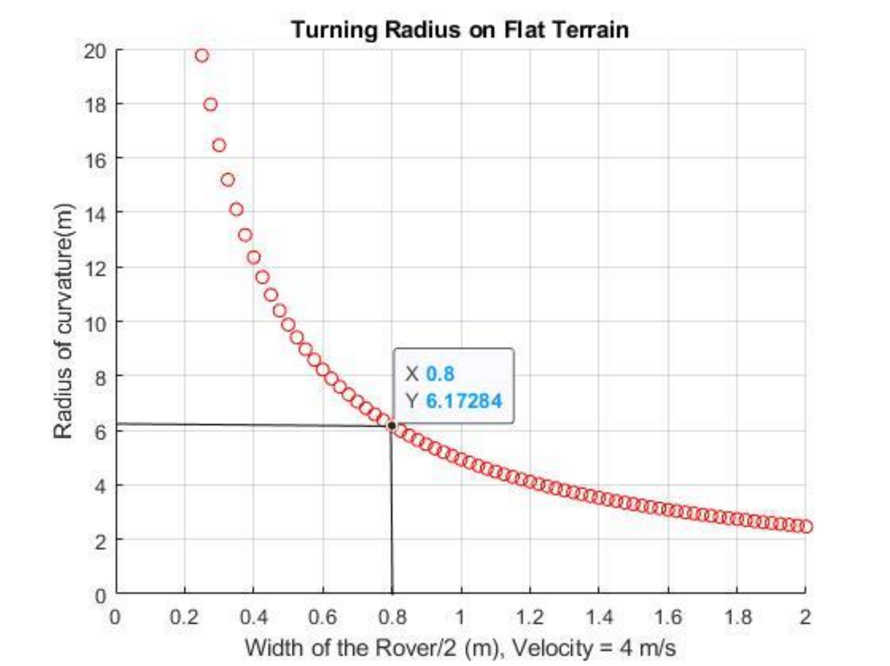
1. Non Extended - When the rover has only one EVA crew with an overall design mass of 500 kg.
    - Length of rover (l) - 2 m
    - Width of rover (c) - 1.6 m
    - Height of CoM (h) - 0.5 m
    - Length between front axle and CoM (a) - 1 m
    - Max Acceleration Rate (m/s^2)
        - Flat Terrain - 2.025
        - Slope - 1.3488
    - Max Deceleration Rate (m/s^2)
        - Flat Terrain - 2.025
        - Slope - 2.45695

Stability - Design Solution

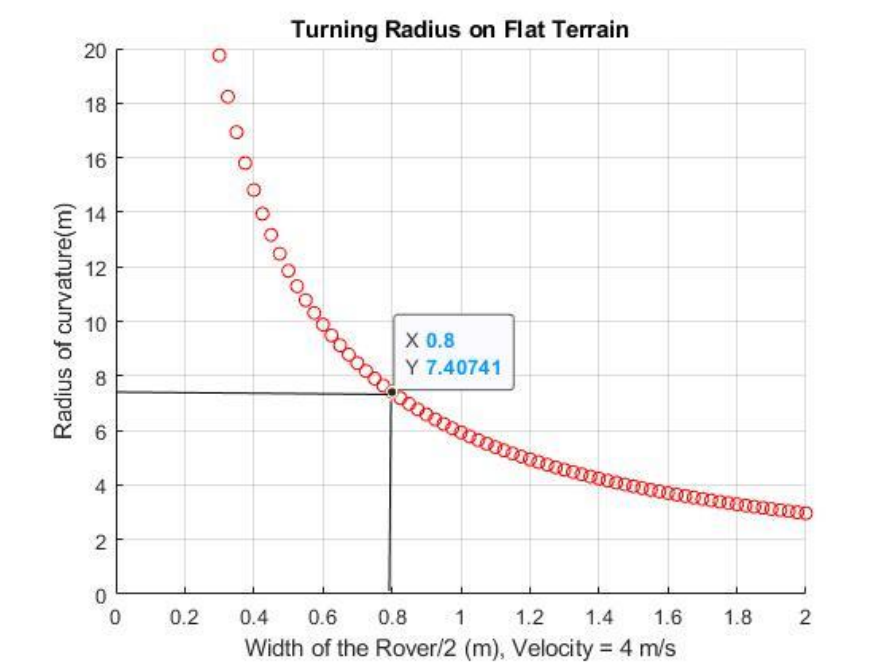
2. Extended - When the rover has one EVA crew and one emergency EVA crew, for a total design mass of 670 kg.

- Length of rover (l) - 2.6 m
- Width of rover (c) - 1.6 m
- Height of CoM (h) - 0.6 m
- Length between front axle and CoM (a) - 1.3 m
- Max Acceleration Rate (m/s^2)
  - Flat Terrain - 2.34
  - Slope - 1.6481
- Max Deceleration Rate (m/s^2)
  - Flat Terrain - 2.34
  - Slope - 2.75295

Turning Stability - 4 Wheels - Flat Terrain

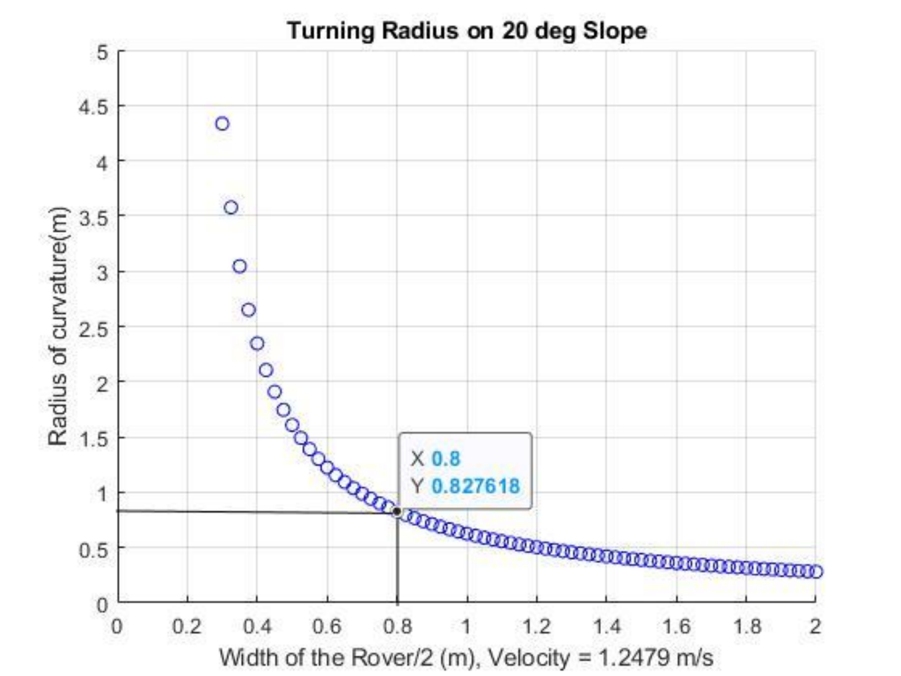


Non - Extended

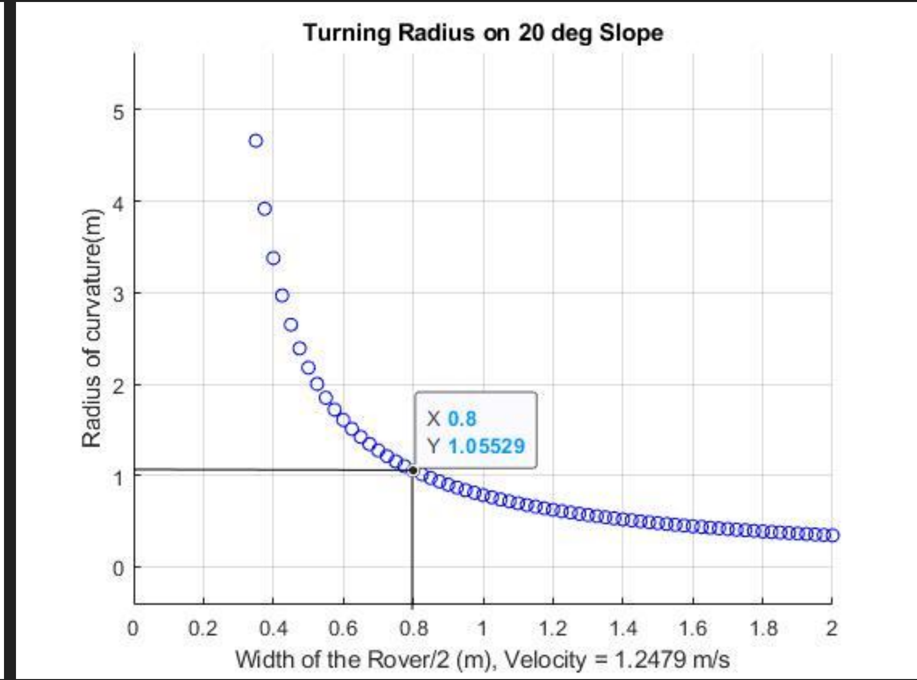


Extended

Turning Stability - 4 Wheels - Slope



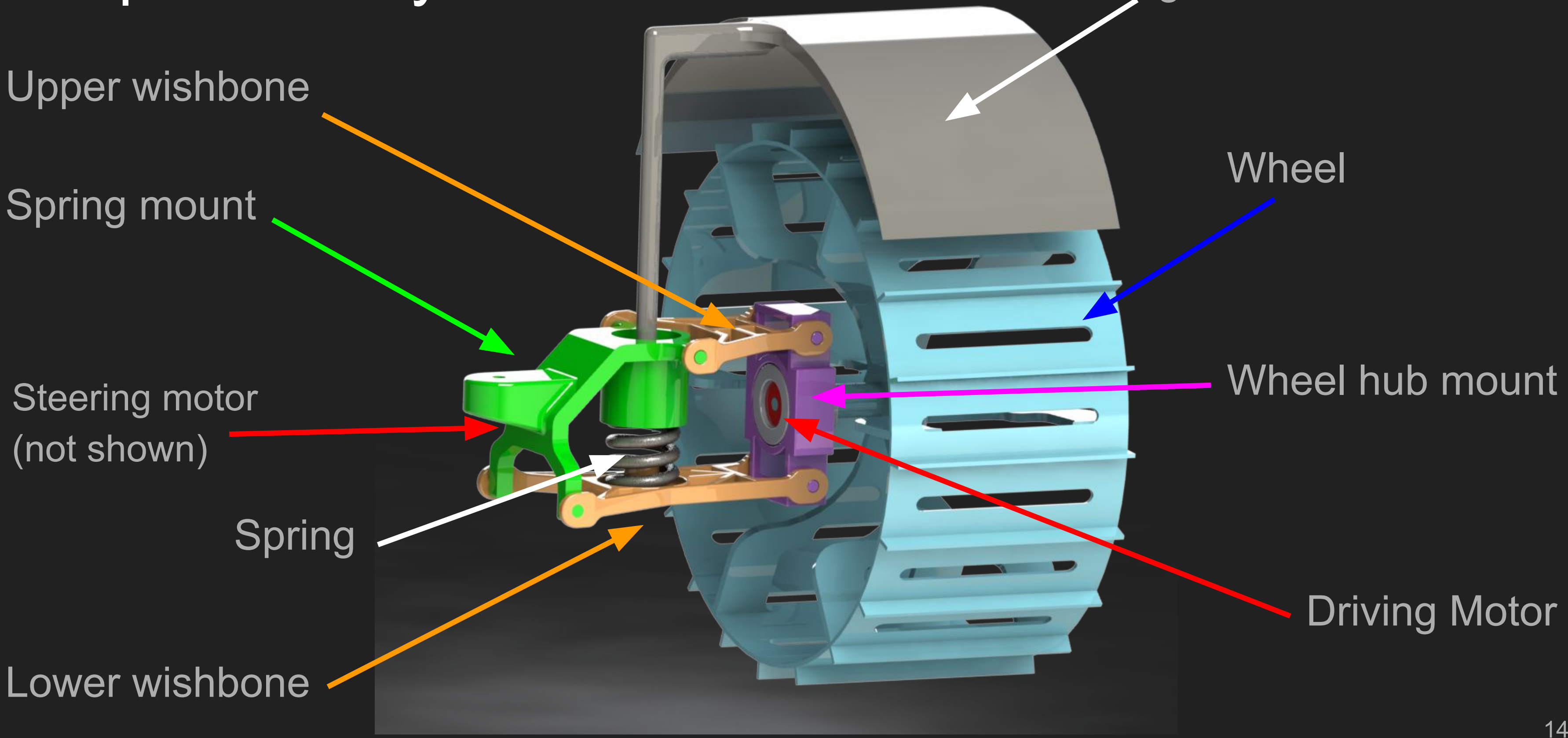
Non - Extended



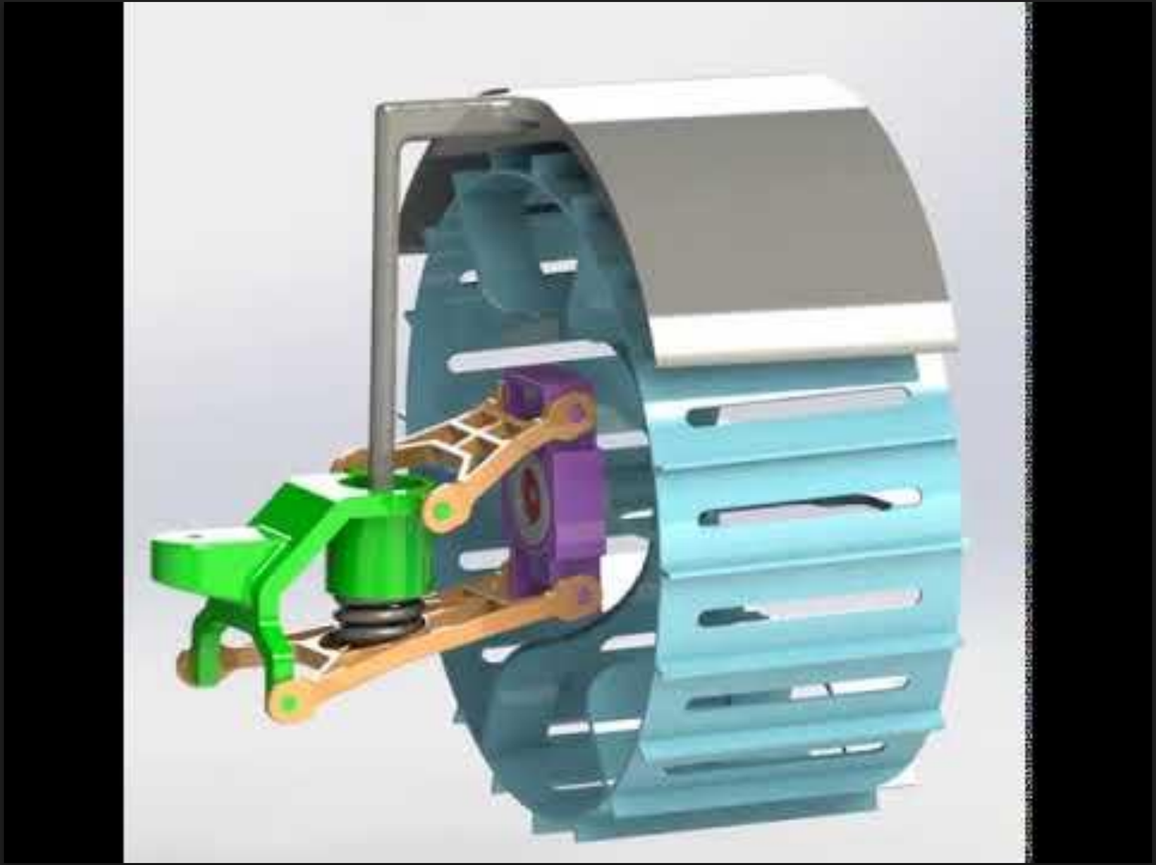
Extended

Suspension

Suspension System



Suspension

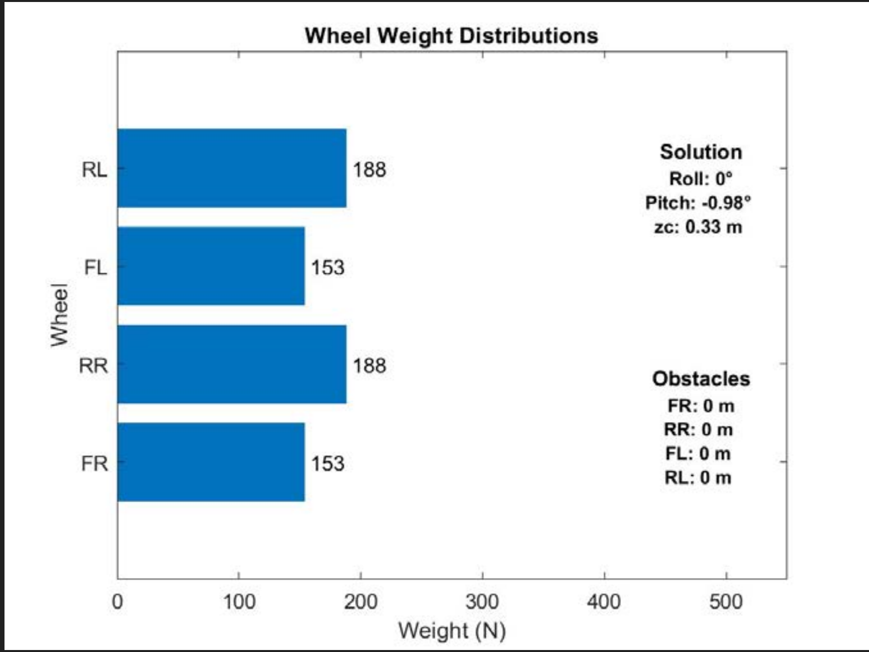


Suspension Statics

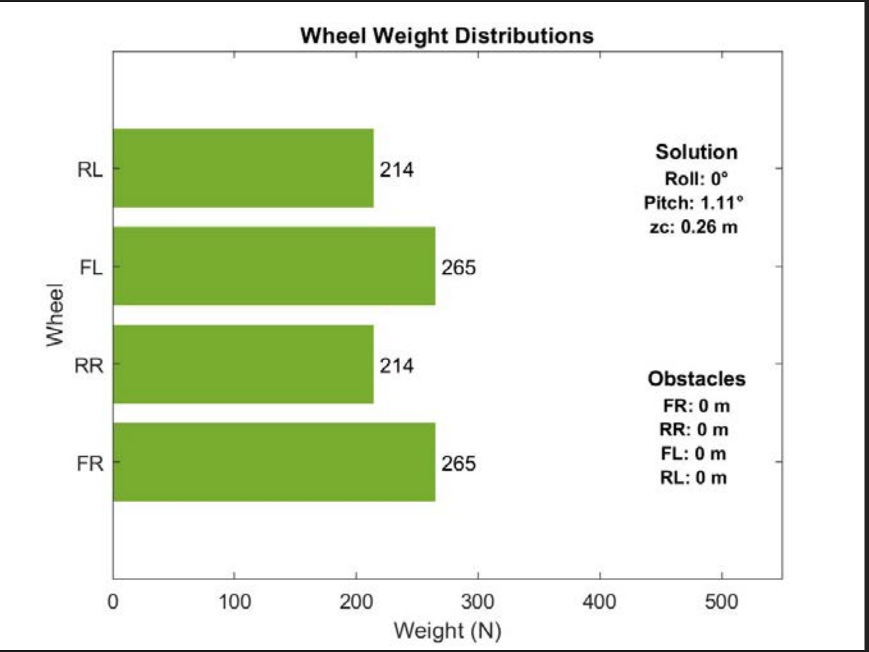
Using the method for N-wheeled independent suspension from class we can solve for weight distribution on each wheel including when wheels are on obstacles.

	Standard	Extended
COM Offset	$[X_{cg}]_v = \begin{bmatrix} 0.115 \\ 0 \\ 0.87 \\ 1 \end{bmatrix}$	$[X_{cg}]_v = \begin{bmatrix} -0.156 \\ 0 \\ 0.96 \\ 1 \end{bmatrix}$
Total Weight	682 N	957 N
Length	2 m	2.6 m
Width	1.6 m	1.6 m

Weight Distributions on Flat Terrain

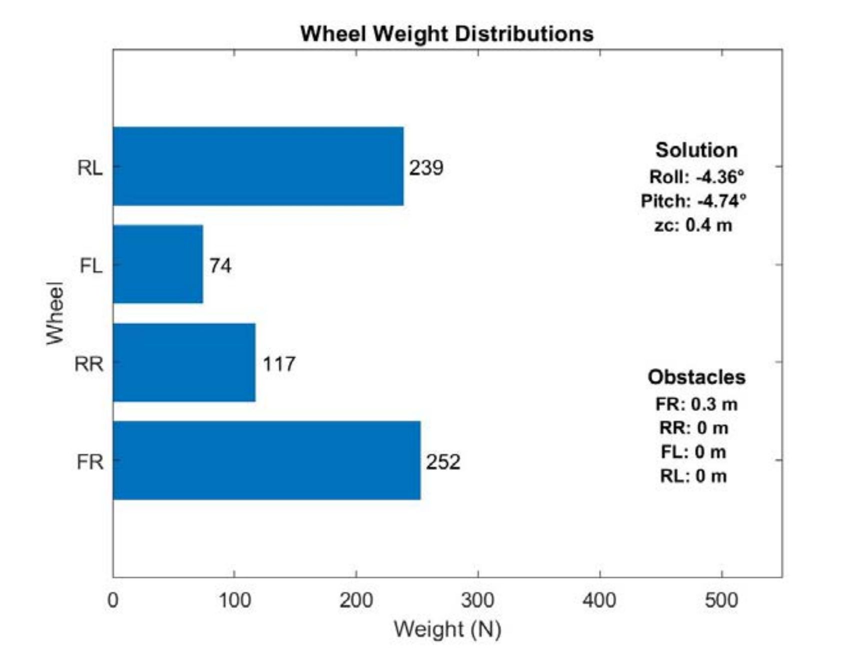


Standard Configuration

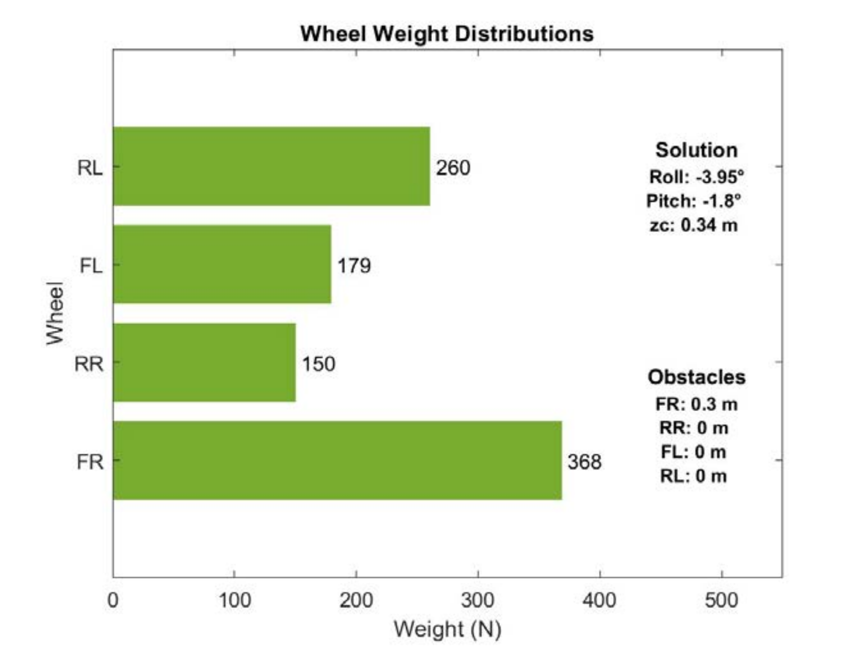


Extended Configuration

Weight Distributions (Front Right on Obstacle)



Standard Configuration



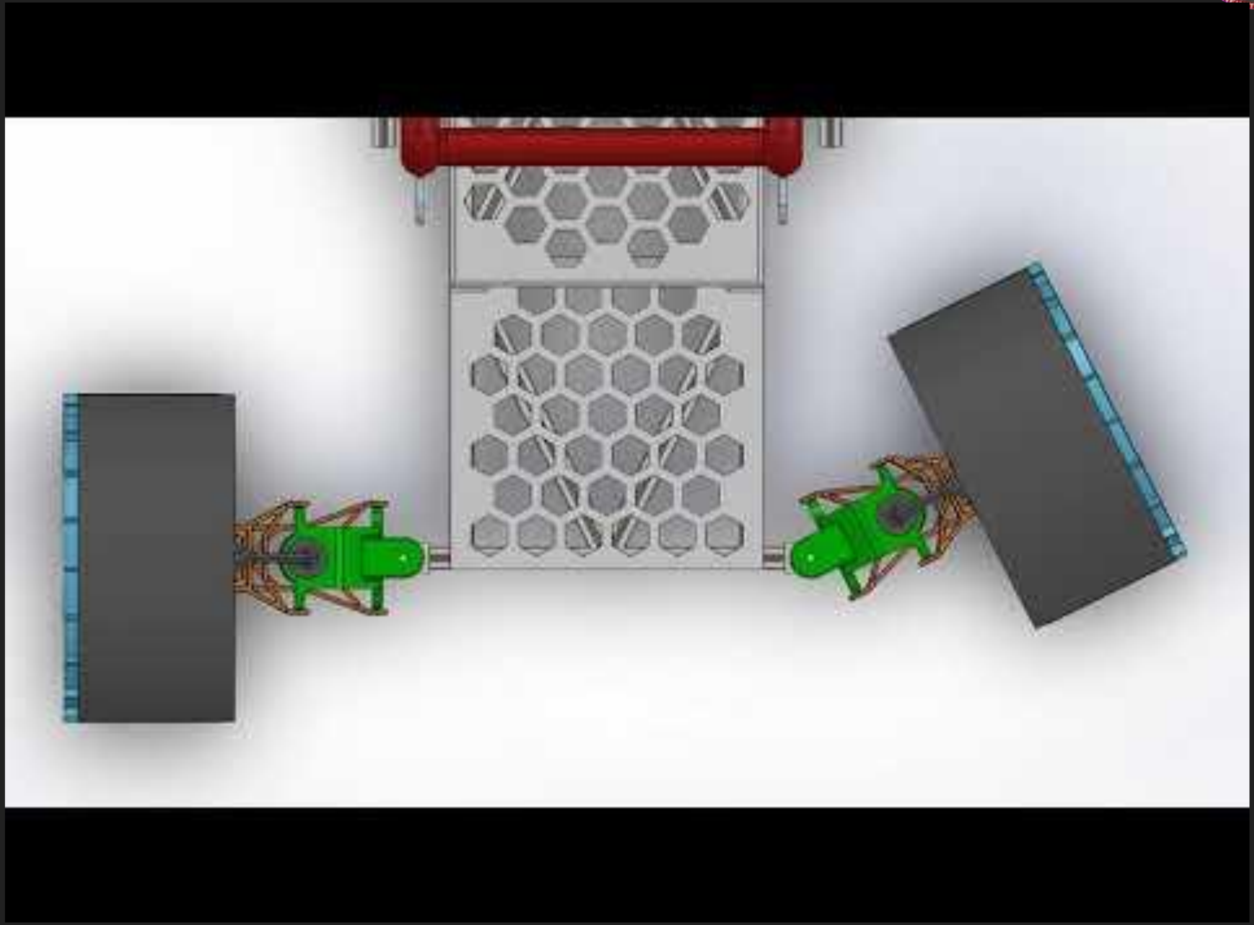
Extended Configuration

Steering

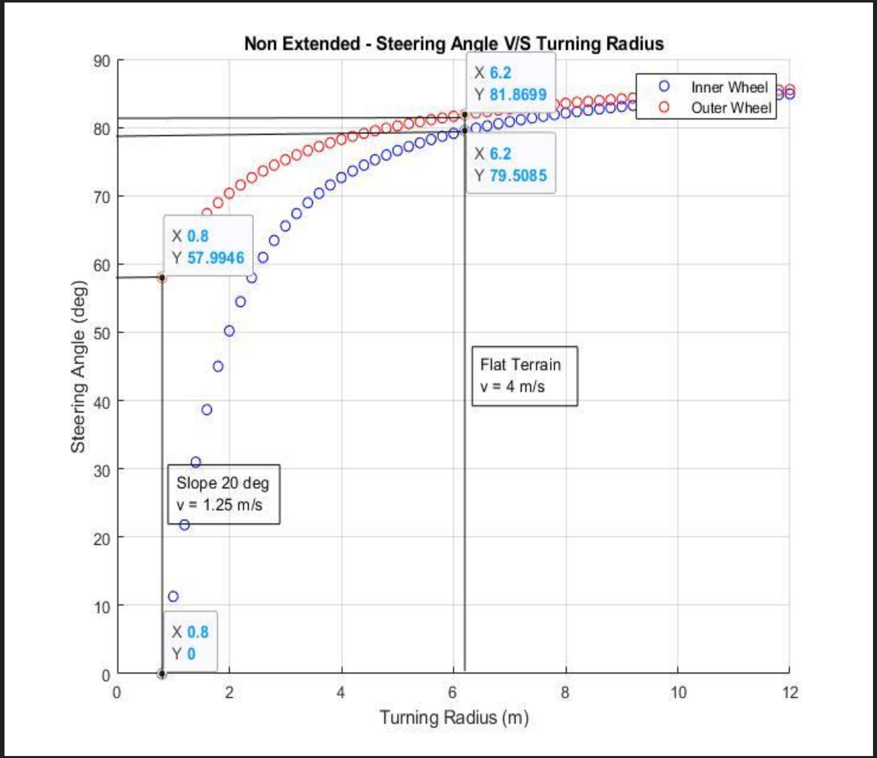
Steering Mechanism Design

Front two wheels are direct steered, each with a steering motor.

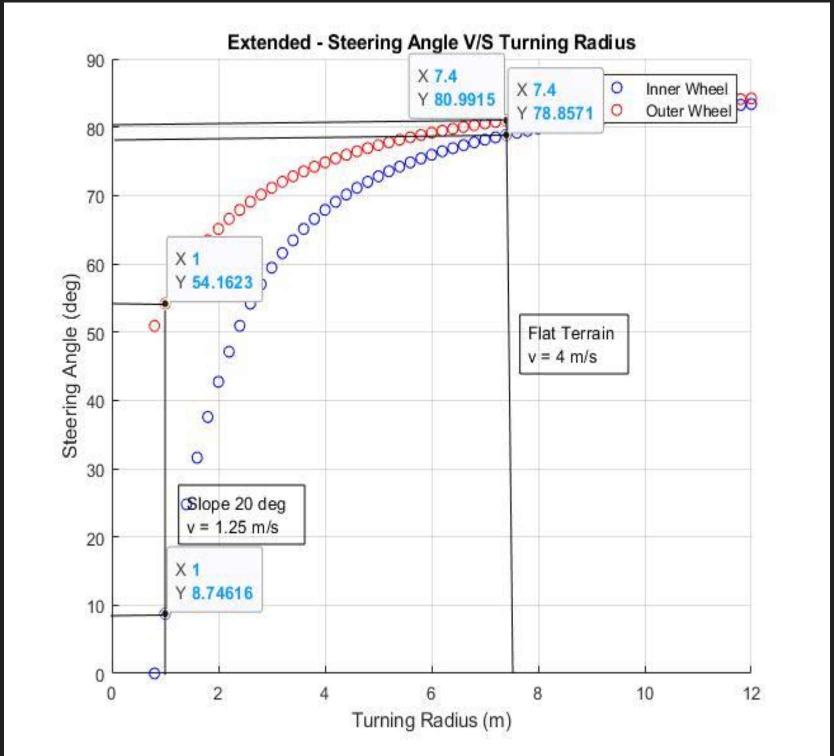
Rear wheels are fixed to the chassis



Steering Angle



Non - Extended



Extended

Steering Motor Requirements

- For each wheel steering, a motor with output power around 160 watts is required.
- A motor from the RBE(H) 01212 series which complied with the power requirements was chosen.

https://npm-ht.co.jp/_assets/wp-content/uploads/2019/12/RBE_Series_Motors_Brochure_01210.pdf

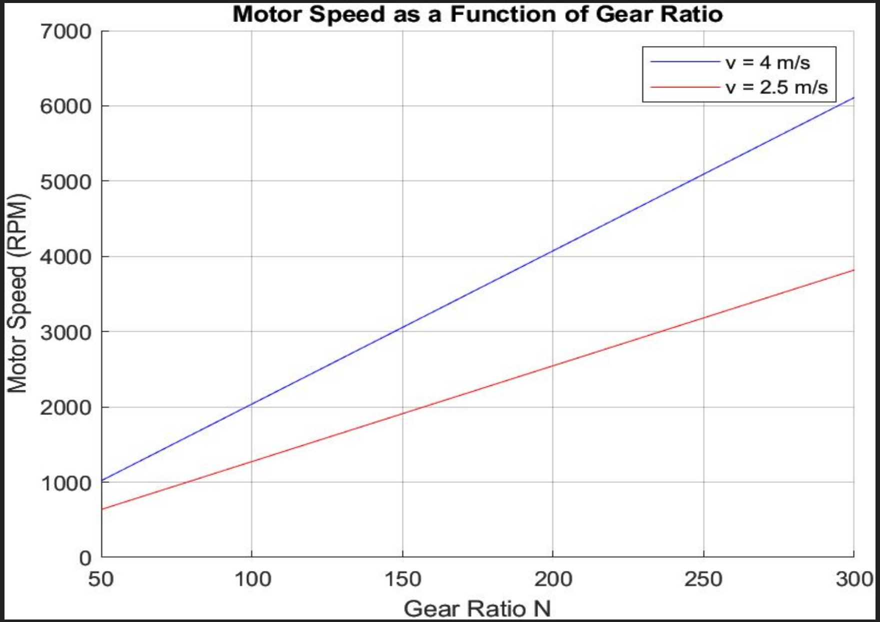
Driving Motors

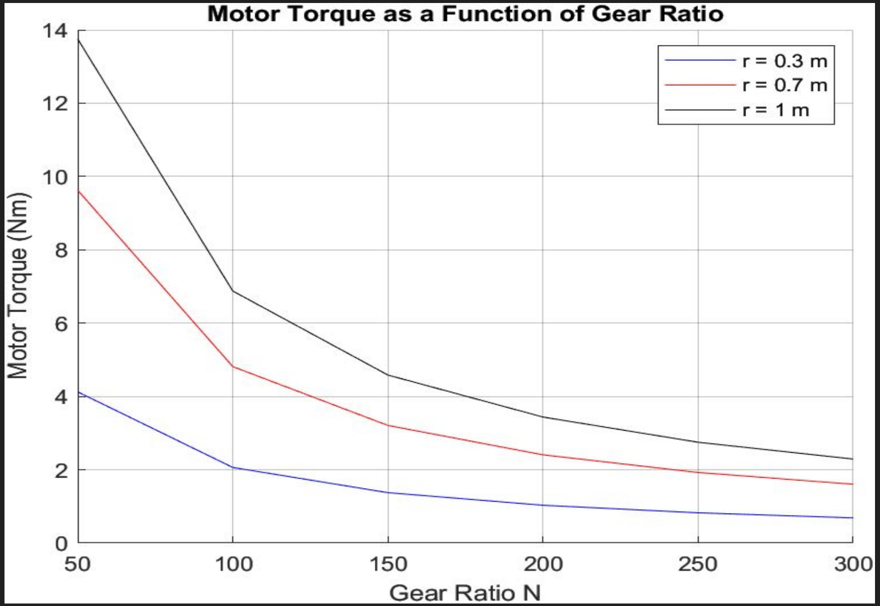
Motors Trade-Study

Type	Advantages	Disadvantages	Typical Applications	Typical Drive
Brushless DC Motor	➢ Long lifespan ➢ Low maintenance ➢ High efficiency	➢ High initial cost ➢ Requires a controller	➢ Hard drives ➢ CD/DVD players ➢ Electric vehicles	Multiphase DC
Brushed DC Motor	➢ Low initial cost ➢ Simple speed control (Dynamo)	➢ High maintenance (brushes) ➢ Low lifespan	➢ Treadmill ➢ Exercisers ➢ Automotive starters	Direct (PWM)
AC Induction (Shaded Pole)	➢ Least expensive ➢ Long life ➢ High Power	➢ Rotation slips from frequency ➢ Low starting torque	➢ Fans	Uni/Poly Phase AC
AC Induction (Split-Phase Capacitor)	➢ High power ➢ High starting torque	➢ Rotation slips from frequency	➢ Appliances	Uni/Poly Phase AC
AC Synchronous	➢ Rotation in-sync with frequency ➢ Long-life (alternator)	➢ More expensive	➢ Clocks ➢ Audio turntables ➢ Tape drives	Uni/Poly Phase AC
Stepper DC	➢ Precision positioning ➢ High holding torque	➢ Slow speed ➢ Requires a controller	➢ Positioning in printers and floppy drives	Multi-phase DC

Reference: Motor Comparison, Circuit Cellar Magazine, July 2008, Issue 216, Bachiochi, p.78

Drive Actuator Requirements

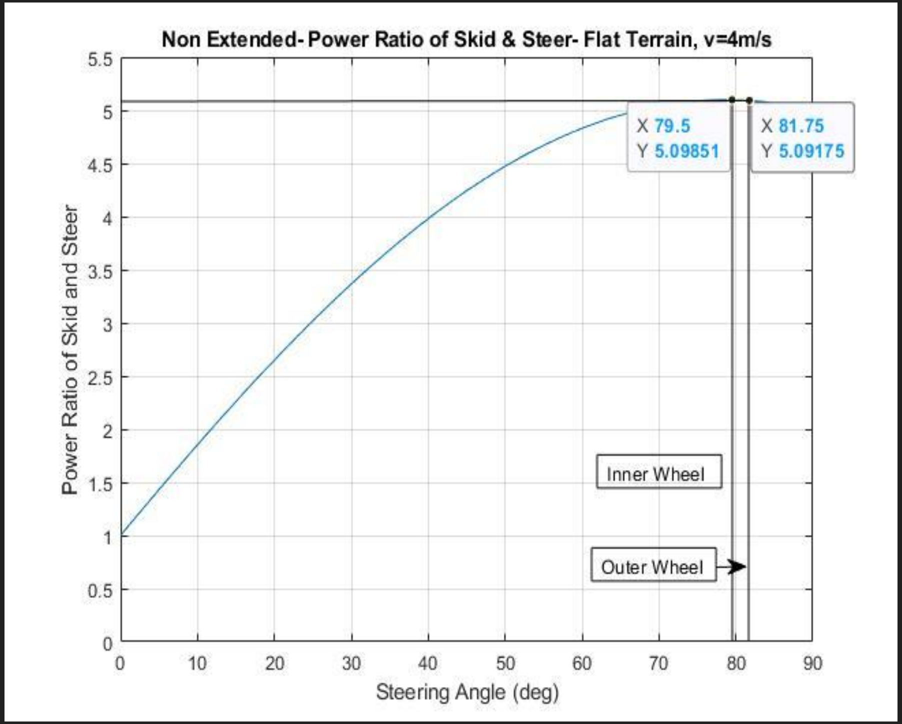




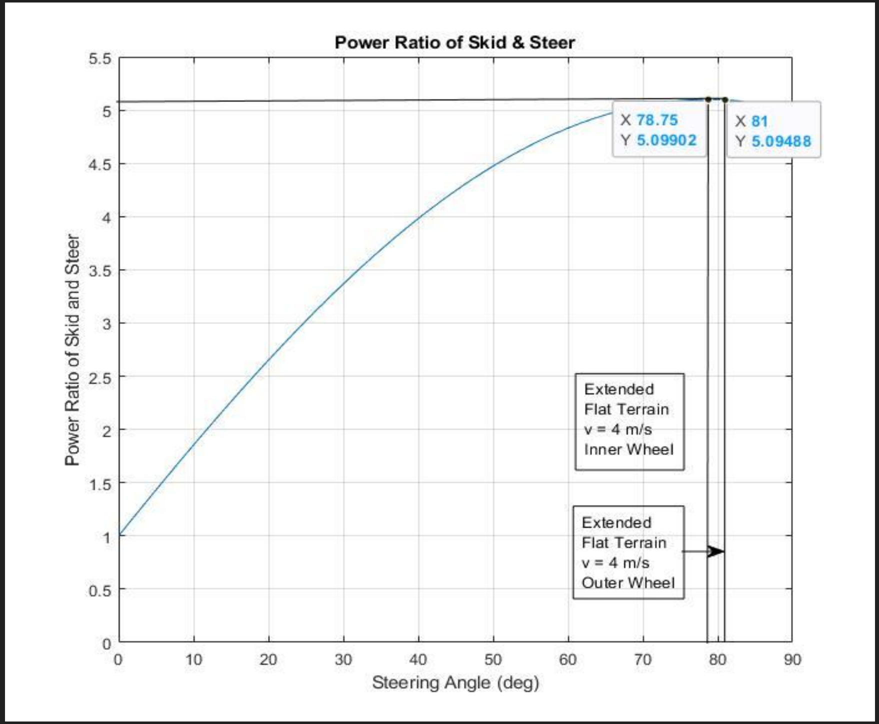
- As per velocity constraints, the rover requires a motor speed a little over 4000 rpm for a gear ratio of 200.

- Motor increases with increase in wheel radius
- For wheel radius = 0.3m, the motor torque required is around 1Nm when the gear ratio is 200.
- Assuming, gear efficiency is 80%, we require a motor with torque around 1.25Nm.

Power Ratio of Skid & Steer - Flat Terrain

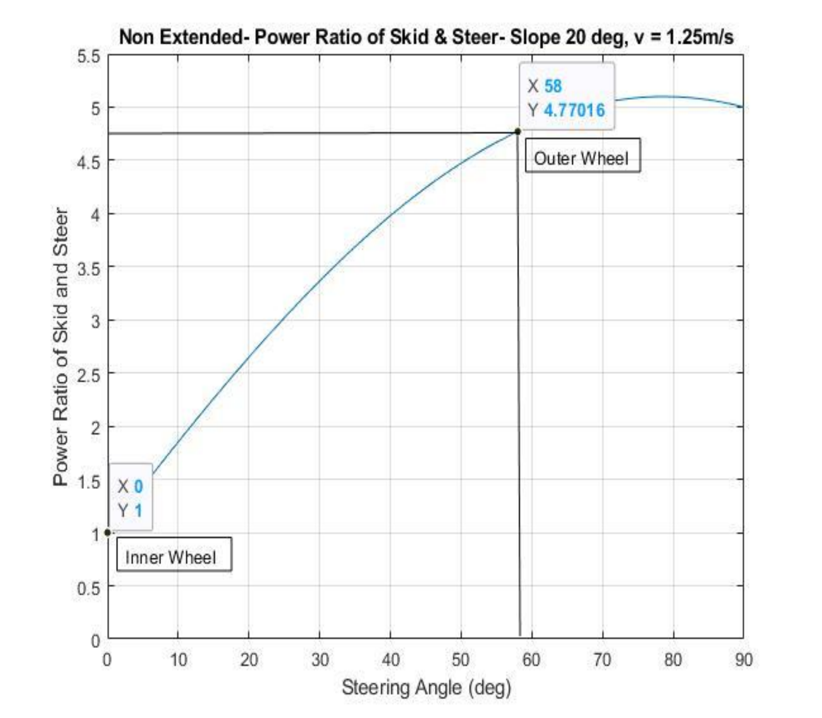


Non - Extended

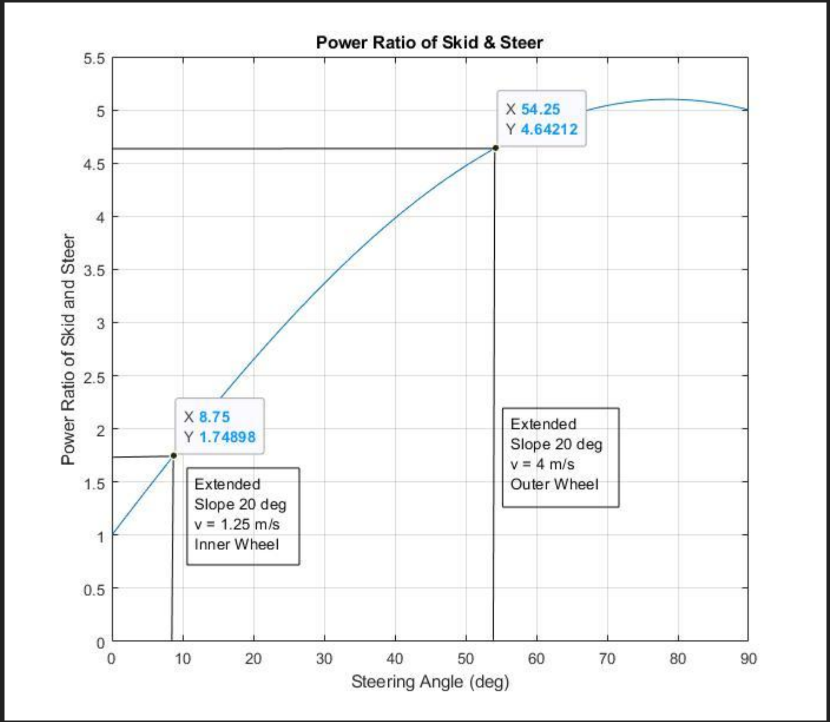


Extended

Power Ratio of Skid & Steer - Slope 20 deg

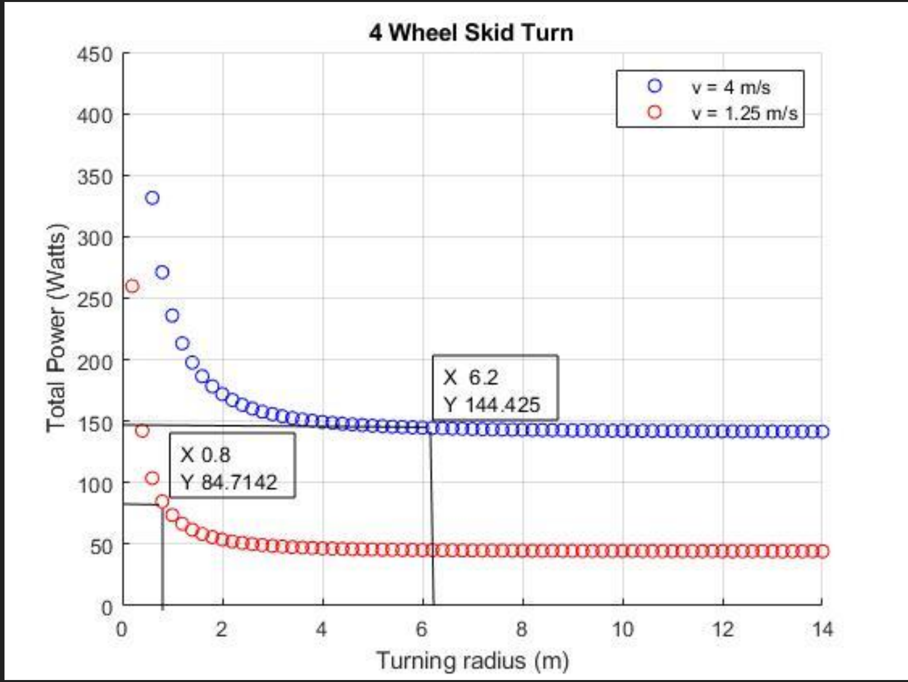


Non - Extended

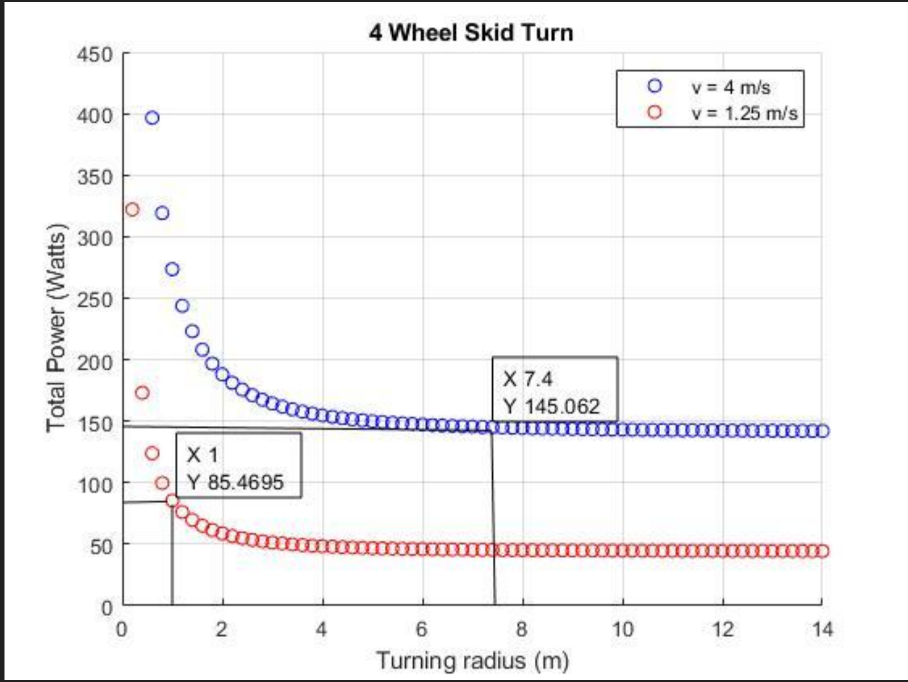


Extended

Power - 4 Wheel Skid Turn



Non - Extended



Extended

Motor Selection

- Brushless DC motors were chosen for wheel drive motors.
- A motor from the RBE(H) 01212 series which complied with the torque and speed requirements was chosen.

https://npm-ht.co.jp/_assets/wp-content/uploads/2019/12/RBE_Series_Motors_Brochure_01210.pdf

Sensors & Perception

LiDAR

4 Velodyne Puck LITE

- 590g each → 2.4kg total
- 8W each → 32W total

https://velodynelidar.com/products/puck-lite

Lighting

4 LED Floodlights

- 35,000 lumens each
- 0.6kg each → 2.4kg total
- 30W each → 120W total

Cameras

2 Sony 4K PTZ cameras

- 1.8 kg each → 3.6 kg total
- 25W (max) each → 50W

4 stereo cameras

- 72g each → 288g
- 2W each → 8W

1 omni-directional camera (Go-Pro Max)

- 163g
- 8 W

https://www.digitalcameraworld.com/buying-guides/best-360-cameras

https://pro.sony/en_EE/product-resources/diagrams/brc-x400-3d-cad

https://store.intelrealsense.com/buy-intel-realsense-depth-camera-d455.html, https://www.intelrealsense.com/wp-content/uploads/2020/06/Intel-RealSense-D400-Series-Datasheet-June-2020.pdf

Computing

Autonomous path planning and full utilization of LiDAR + cameras requires non-trivial computing power.

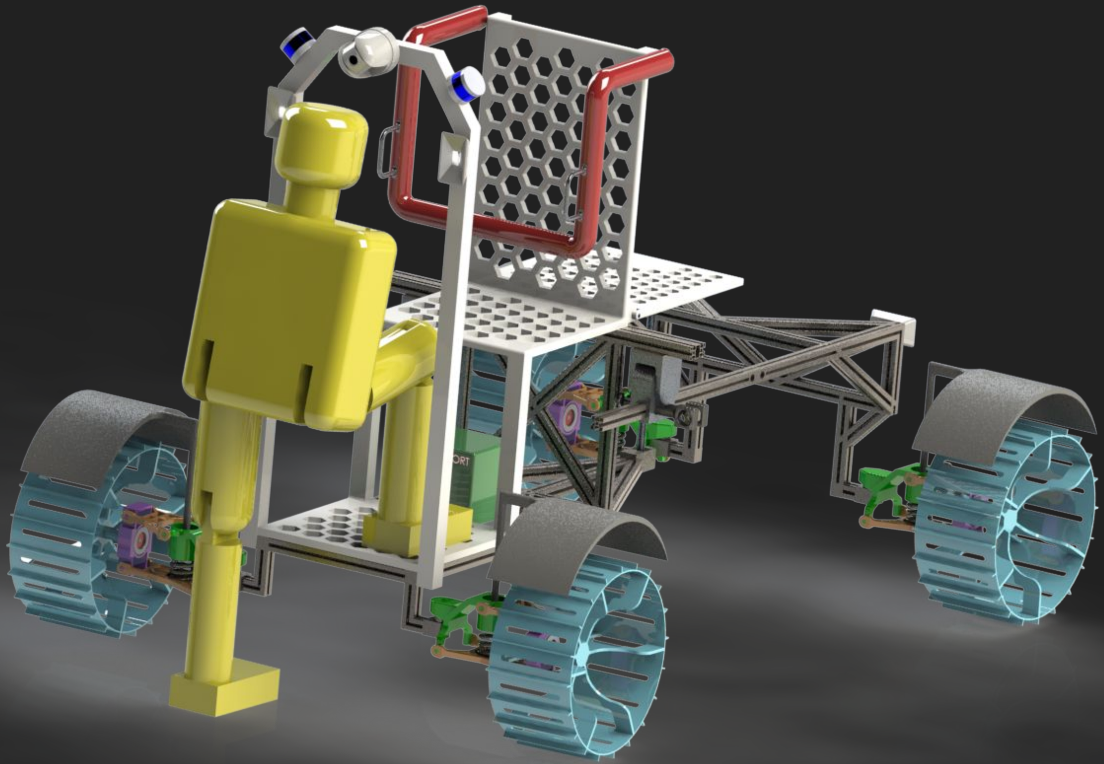
Laptop style computer:

- 16GB RAM, 2.3GHz Quad Core CPU, 1.5GB Graphics
- 61W
- 1 kg

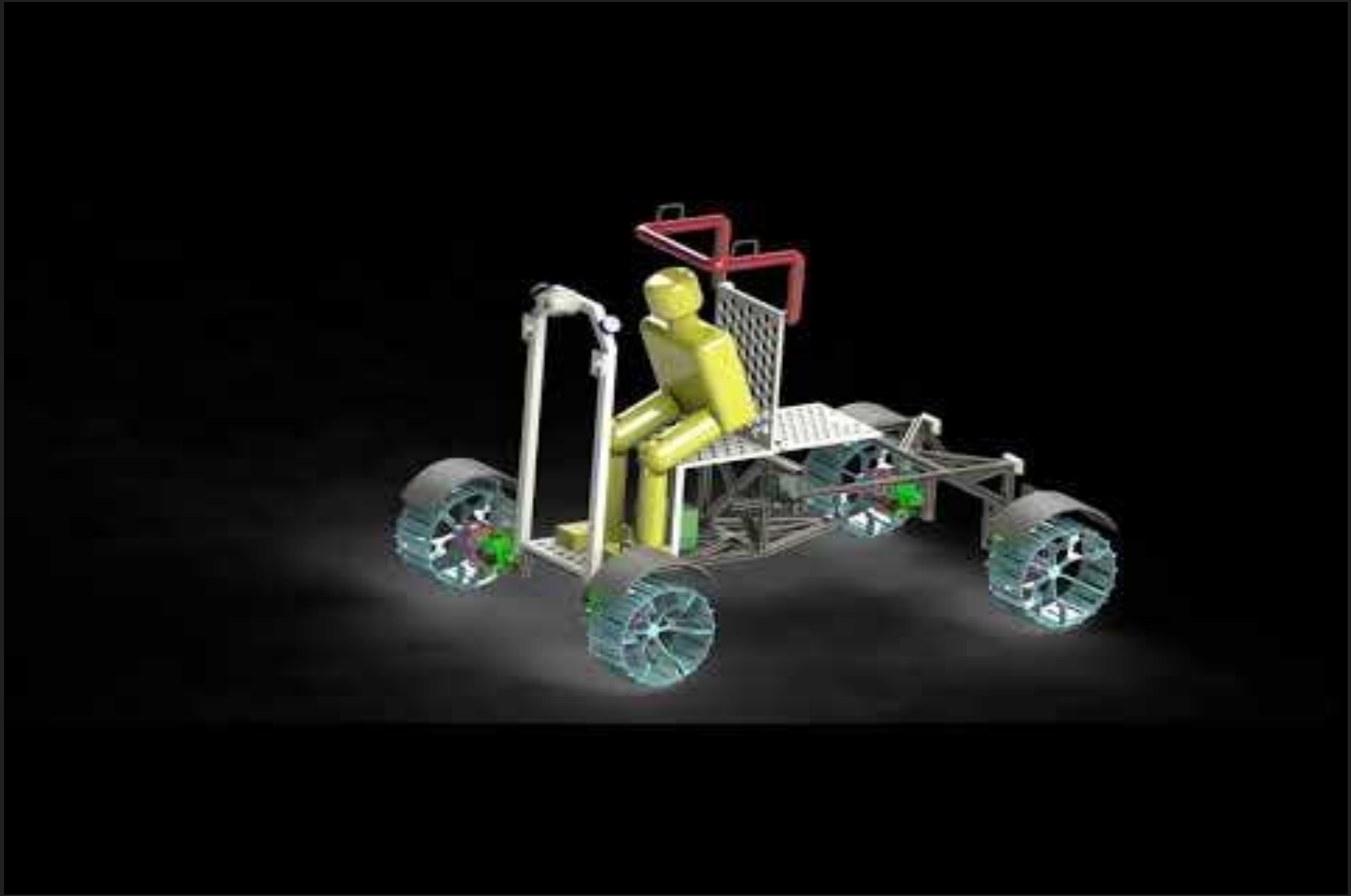
Desktop style computer:

- 64+GB RAM, 4.3GHz 8 core CPU, 8GB Graphics
- 650W
- ~6kg

Ingress and Egress

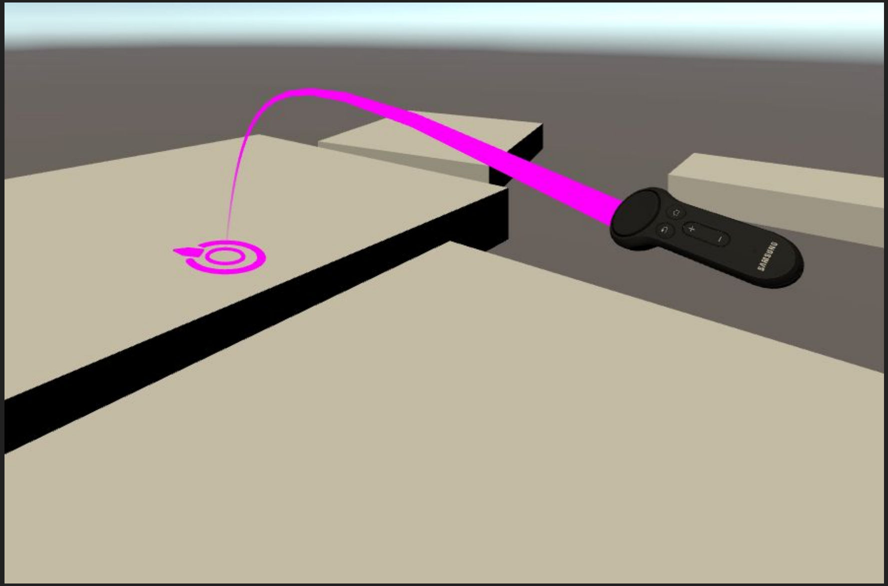


Ingress and Egress



Driving

VR Remote + AR HUD in suit



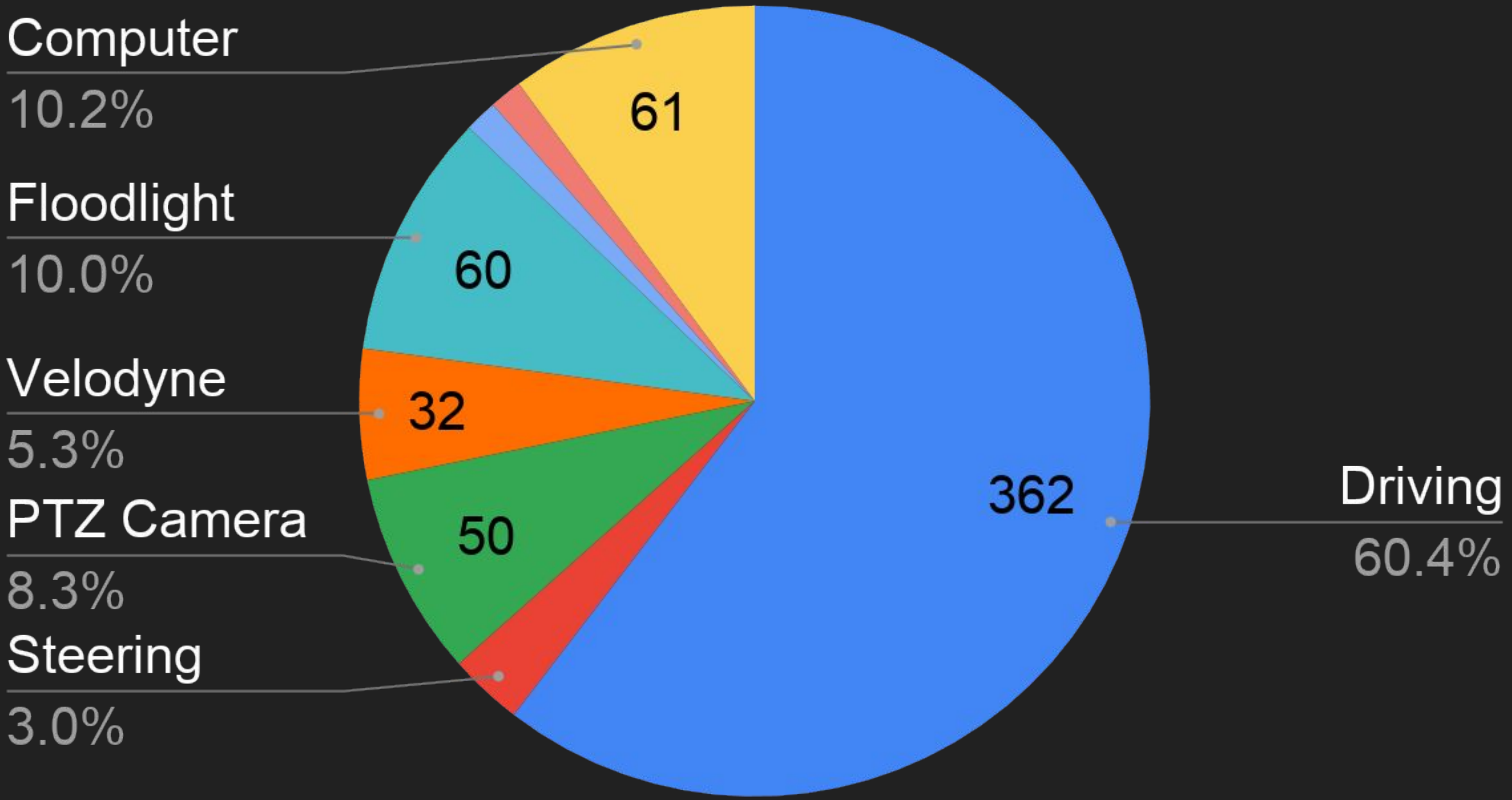
https://developer.oculus.com/blog/teleport-curves-with-the-ge
ar-vr-controller/?locale=en_US

Wireless steering wheel + control panel

https://www.logitechg.com/en-gb/products/driving/driving-force-racing-wheel.html

Power

Total Power (W)



Power

Category	Part	Individual Power (W)	# Required	Duty Cycle (%)	Total Power (W)
Driving / Steering	Driving motors	181	4	50%	362
	Steering motor	181	2	5%	18.1
					0
Sensors / Lighting	PTZ Camera	25	2	100%	50
	Velodyne Puck LITE	8	4	100%	32
	Floodlight	30	2	100%	60
	Stereo Camera	2	4	100%	8
	Omnicamera	8	1	100%	8
	Computer (Laptop sty	61	1	100%	61
				Total Power (W)	**599.1**
				Total Energy - 8 Hour Sortie (Wh)	**4792.8**
					Total Battery Mass (kg)
				@ 400Wh/kg	**11.982**
				@ 260 Wh/kg	18.43

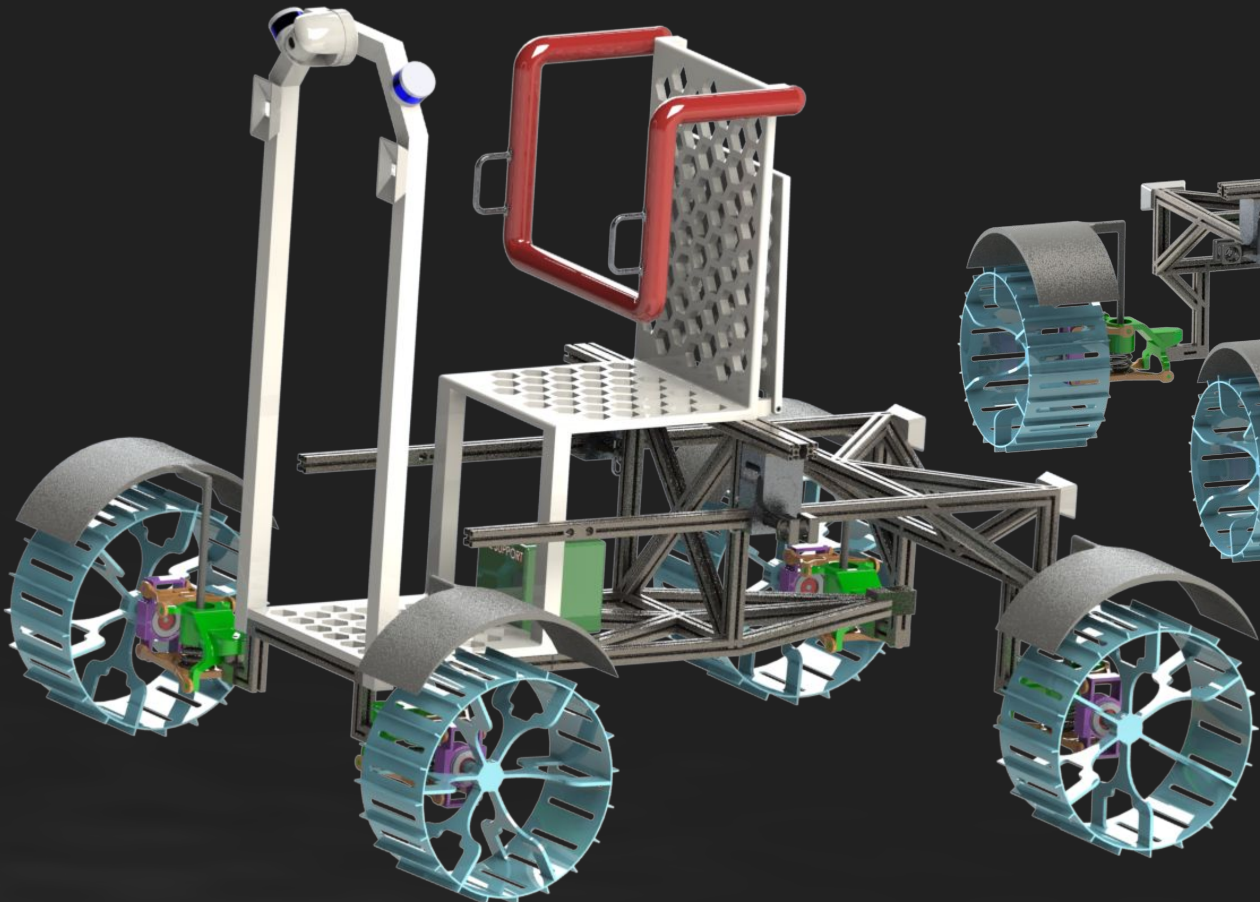
Battery

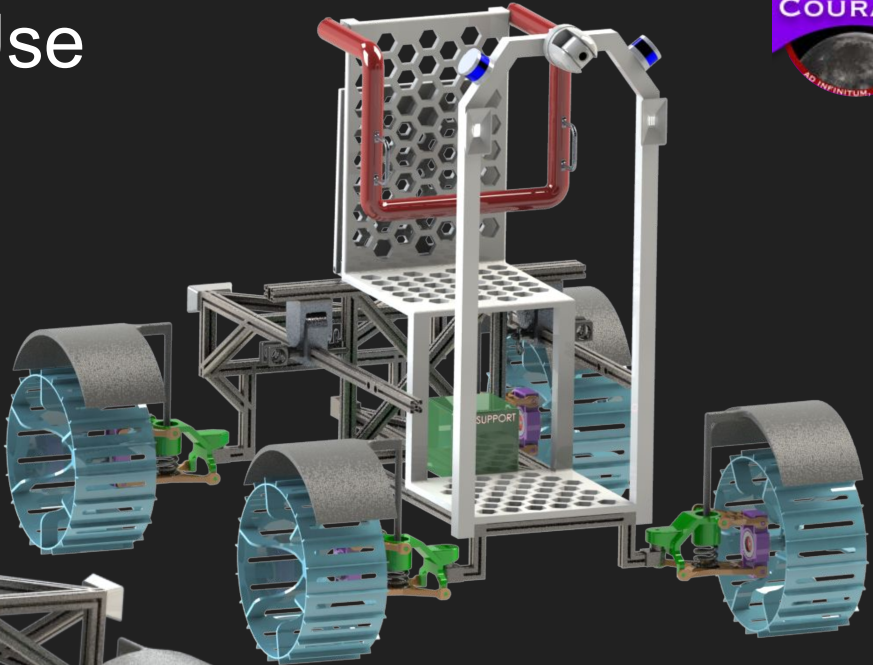
- 18.5 kg of Tesla's Model 3 Battery (260 Wh/kg)
- OR 12 kg of Tesla's planned battery (400 Wh/kg)

https://www.reuters.com/article/us-tesla-batteries/teslas-musk-hints-of-battery-capacity-jump-ahead-of-industry-event-idUSKBN25L0MC

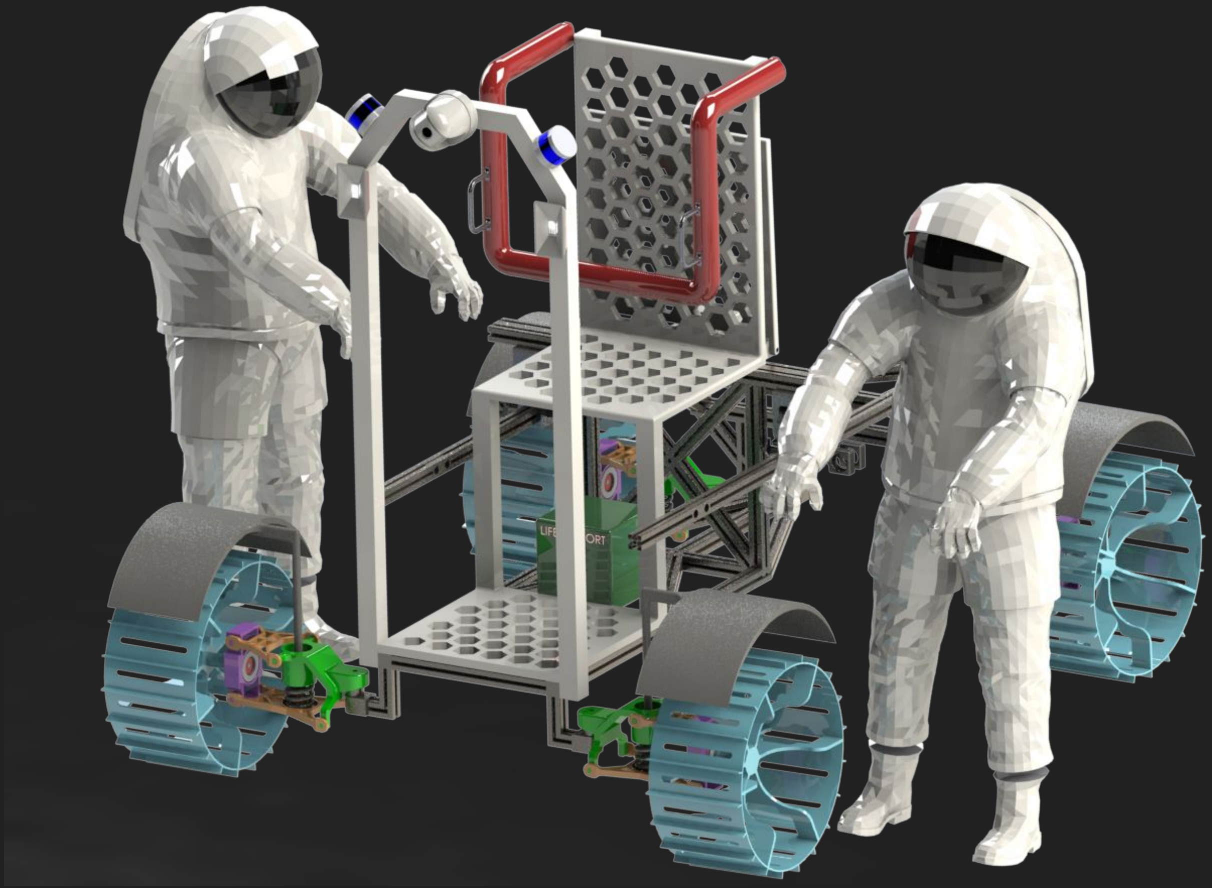
Final Design

Courage Rover - Normal Use





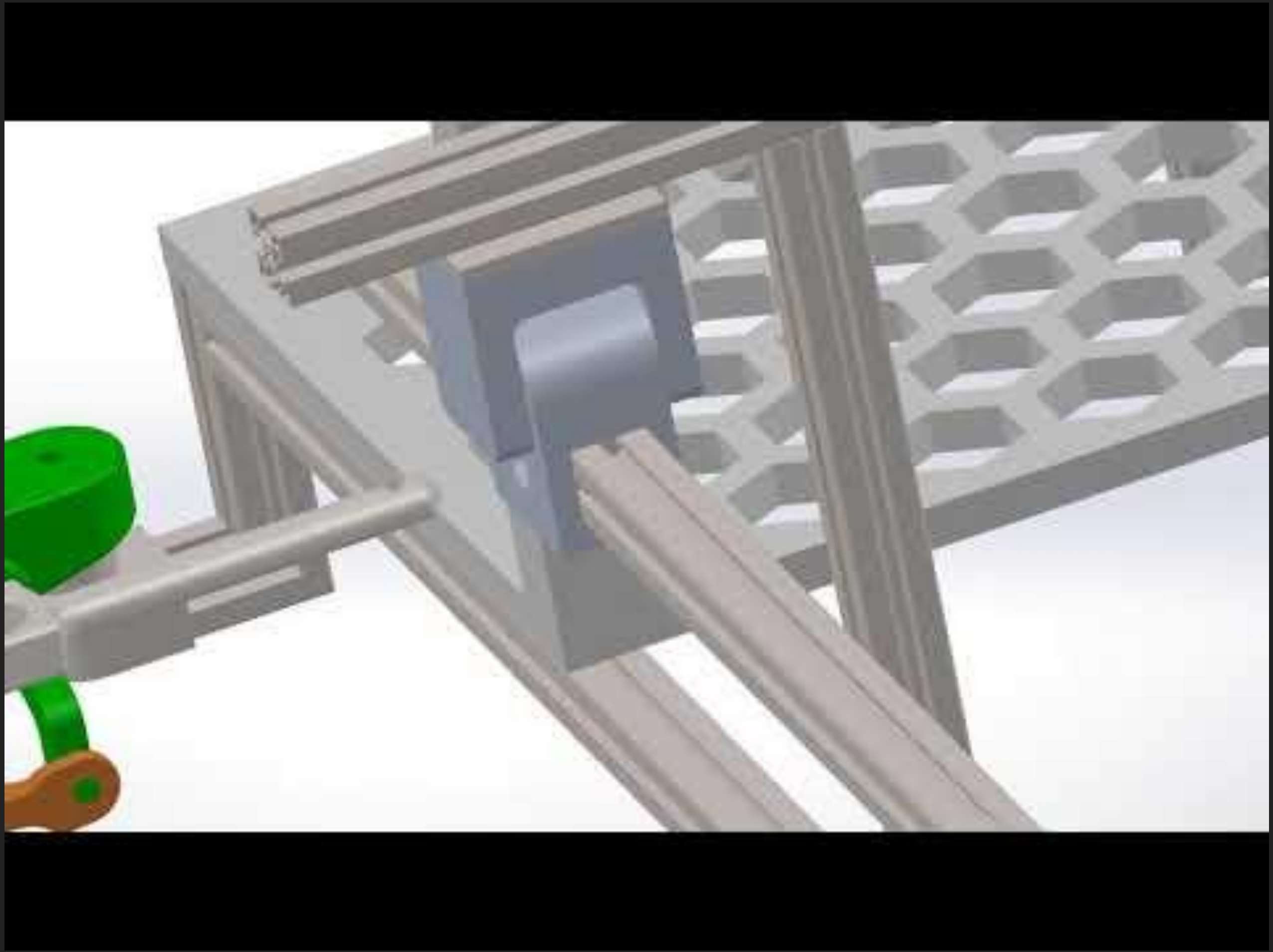
Courage Rover - Normal Use



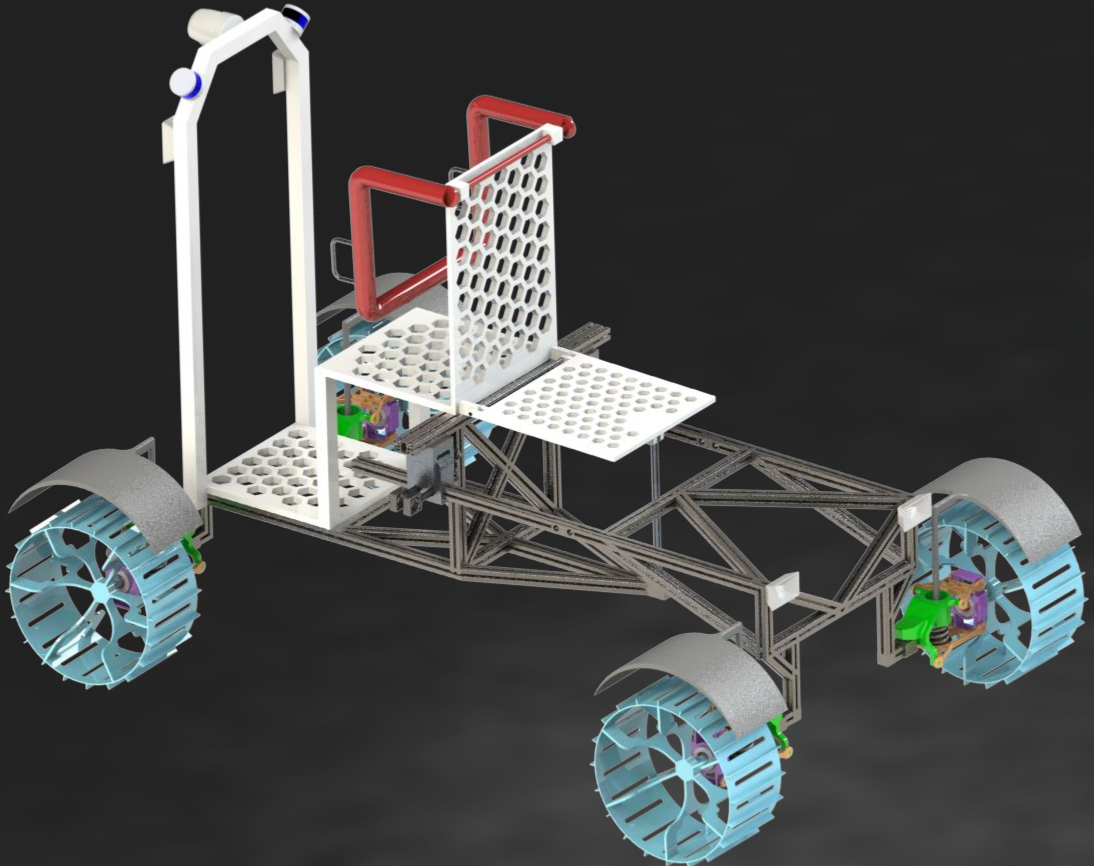
Courage Rover - Normal Use

Courage Rover - Normal Use

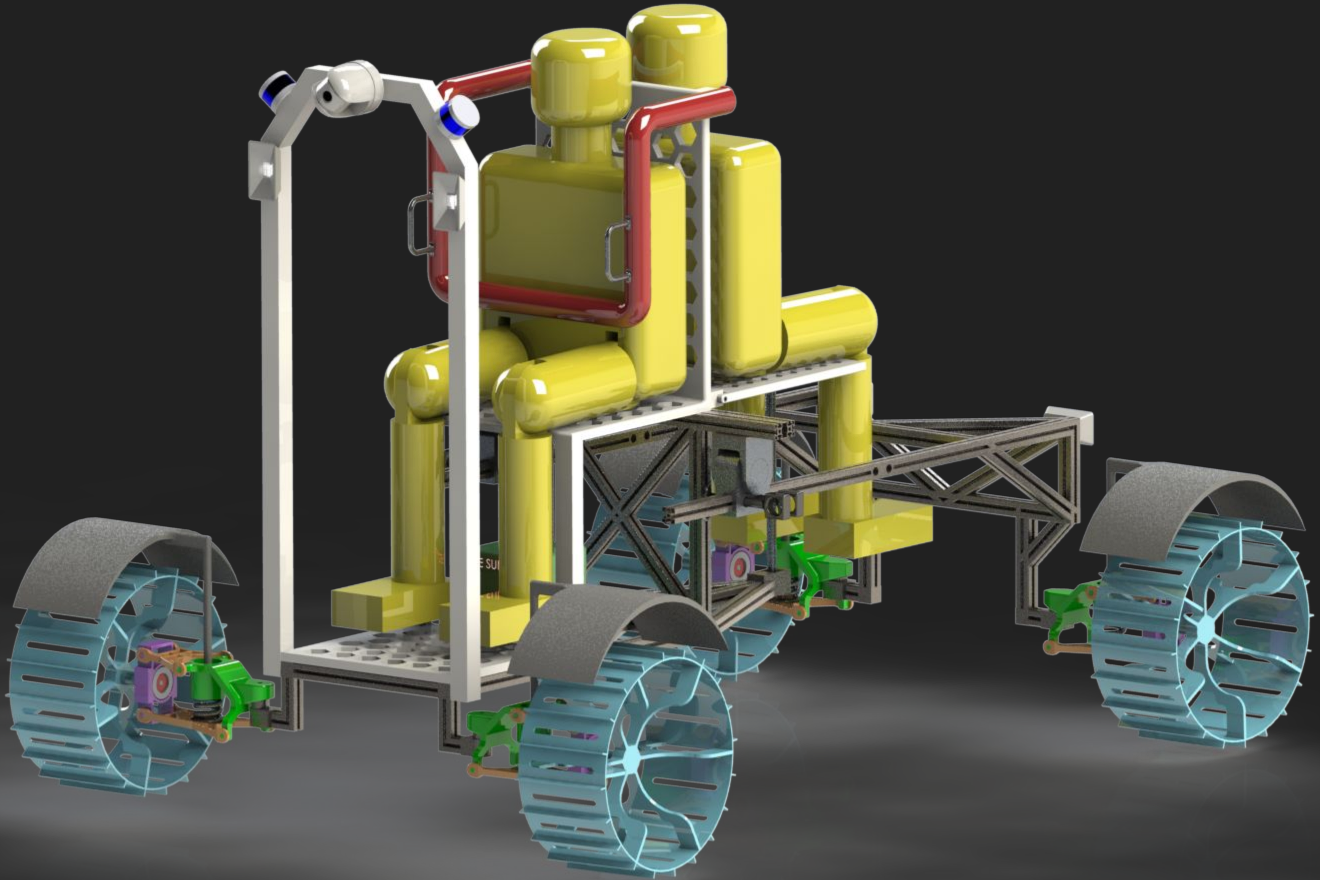
Courage Rover - Contingency Use



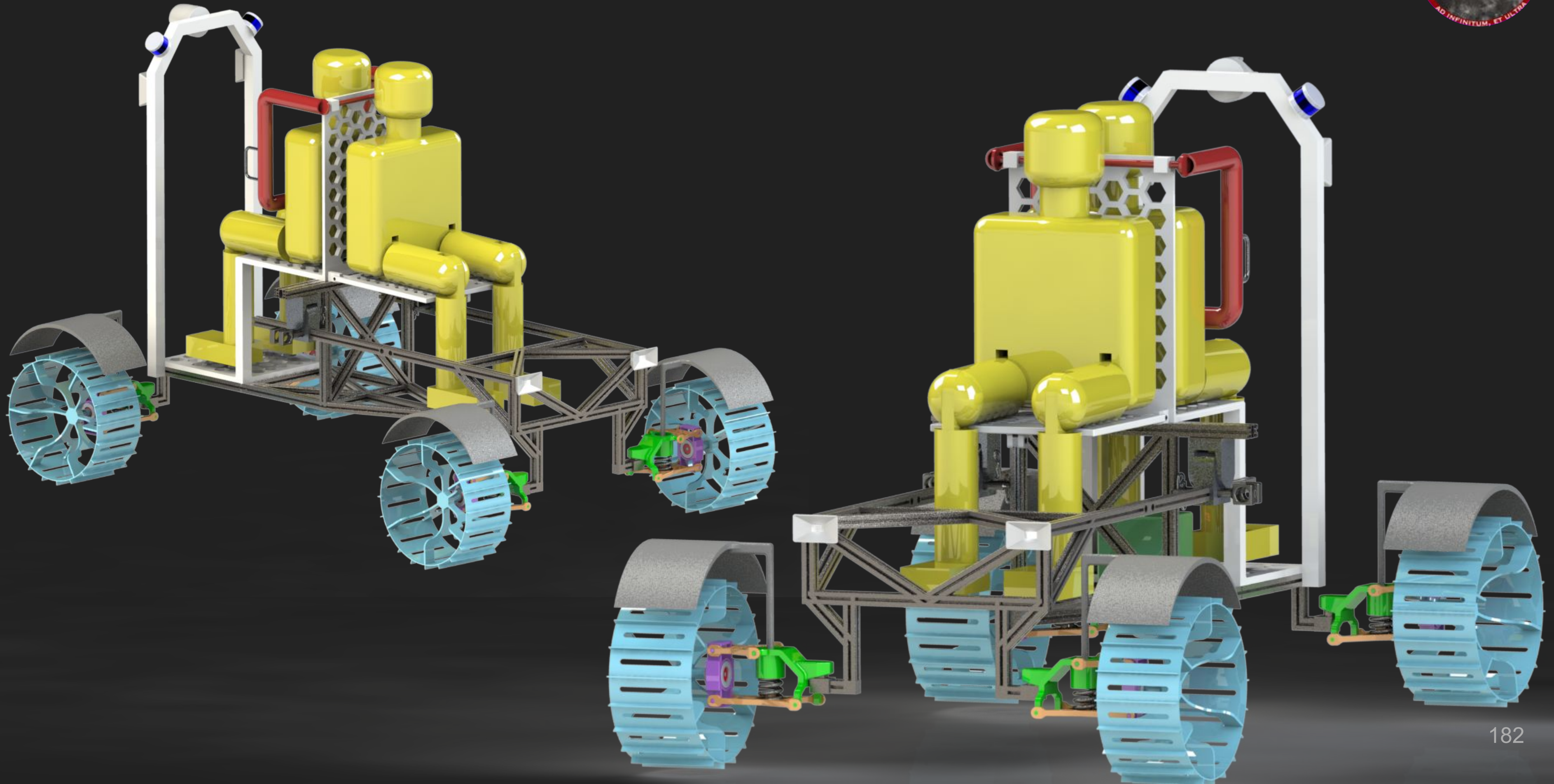
Courage Rover - Contingency Use



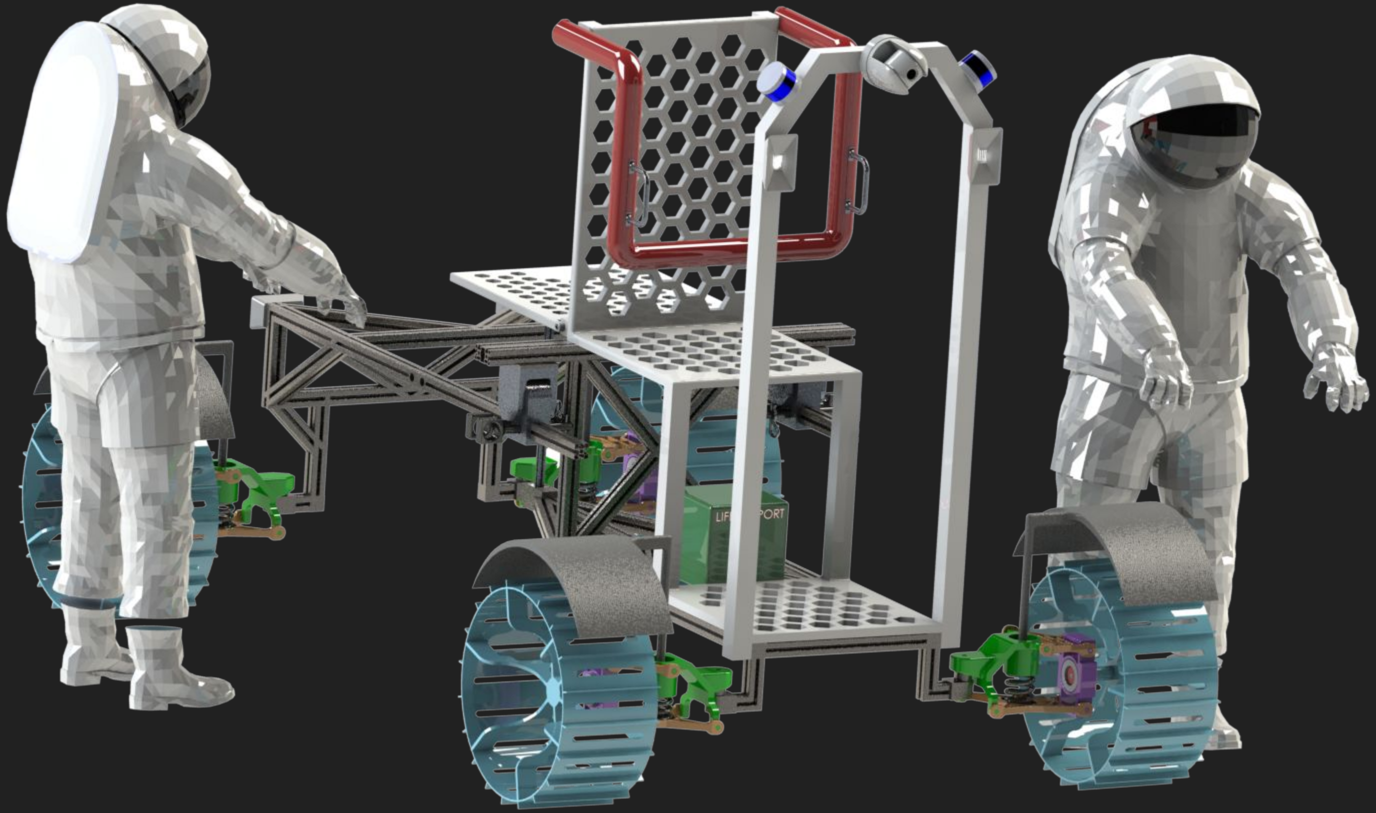
Courage Rover - Contingency Use



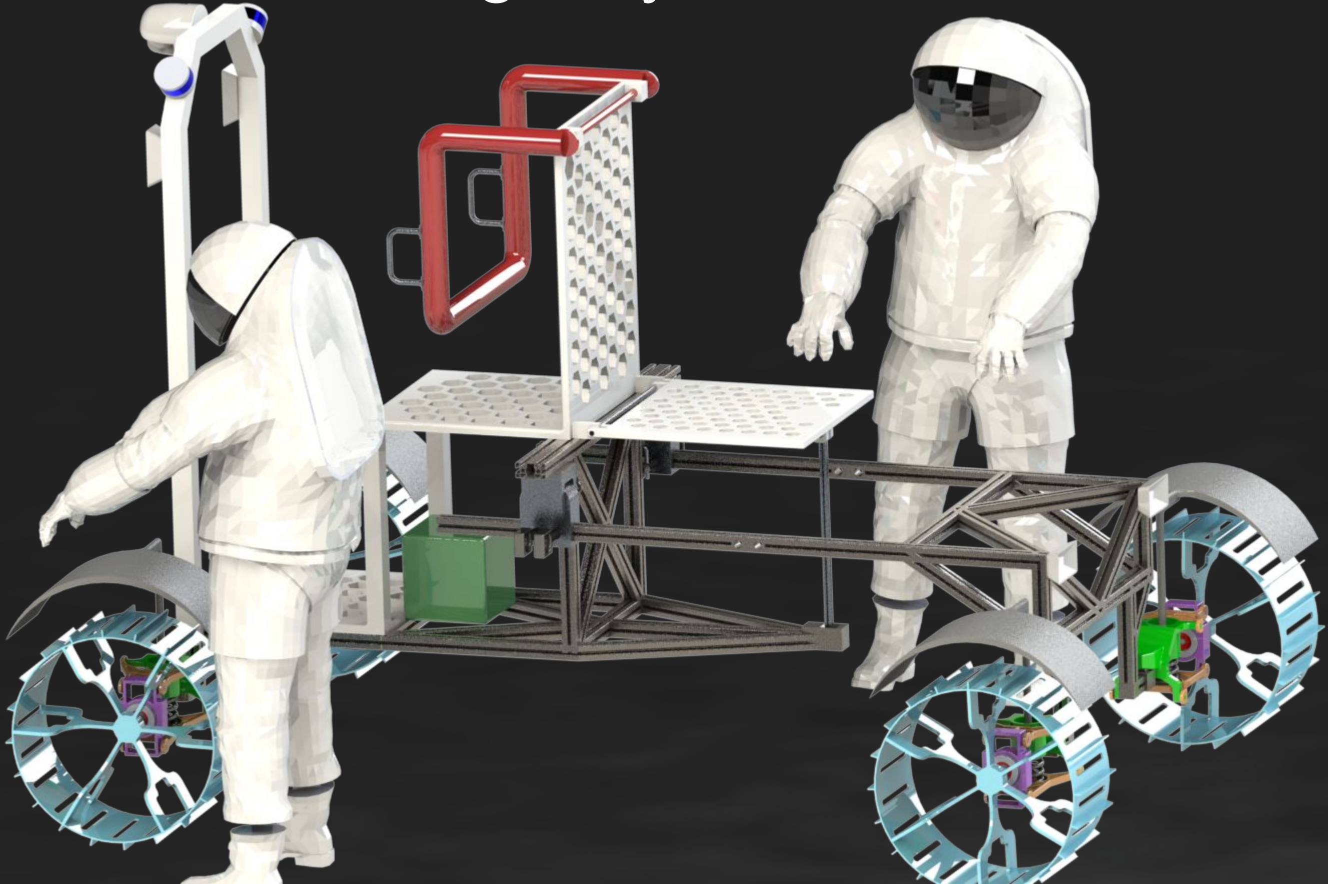
Courage Rover - Contingency Use (Rear)



Courage Rover - Contingency Use



Courage Rover - Contingency Use

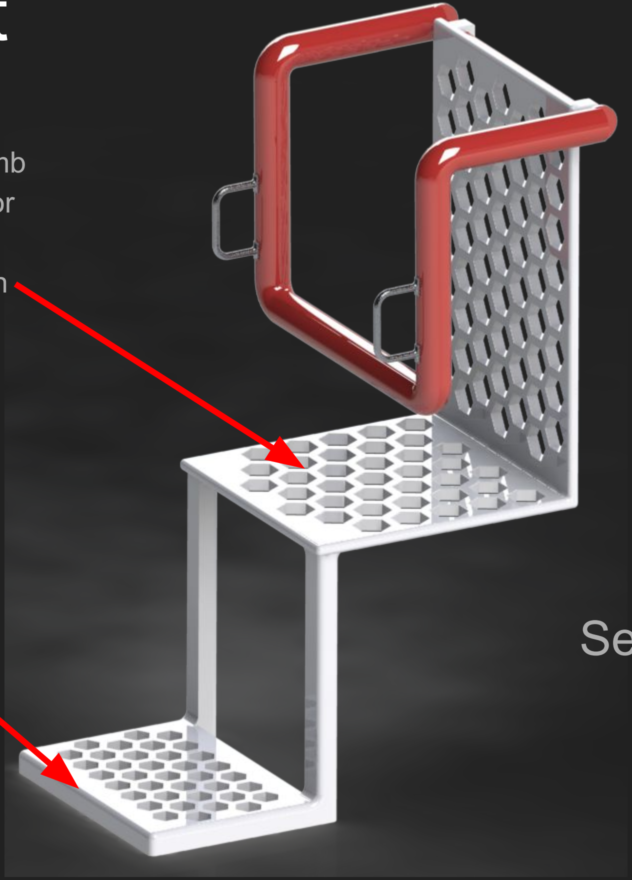


Subassemblies and Components

Seat

Honeycomb pattern for weight reduction

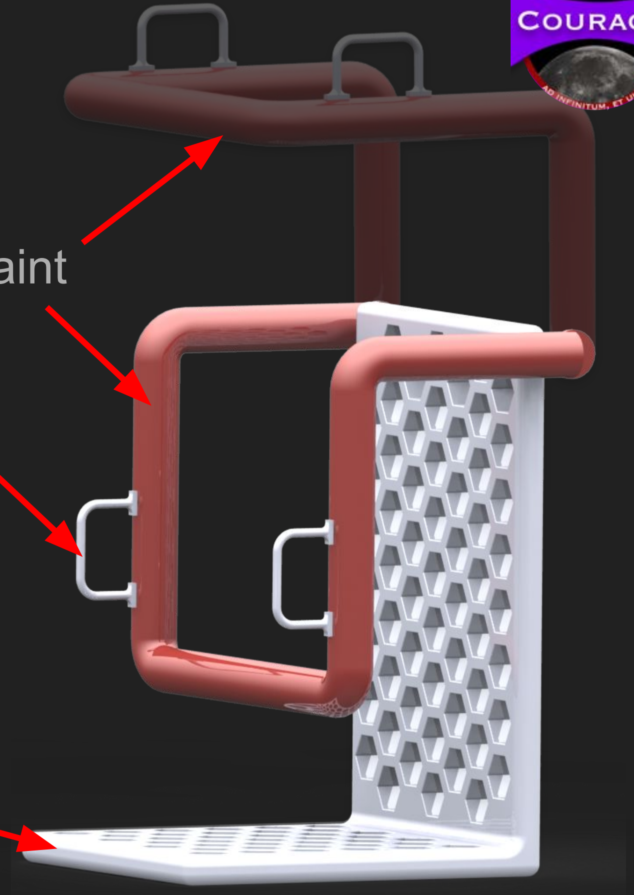
Foot rest



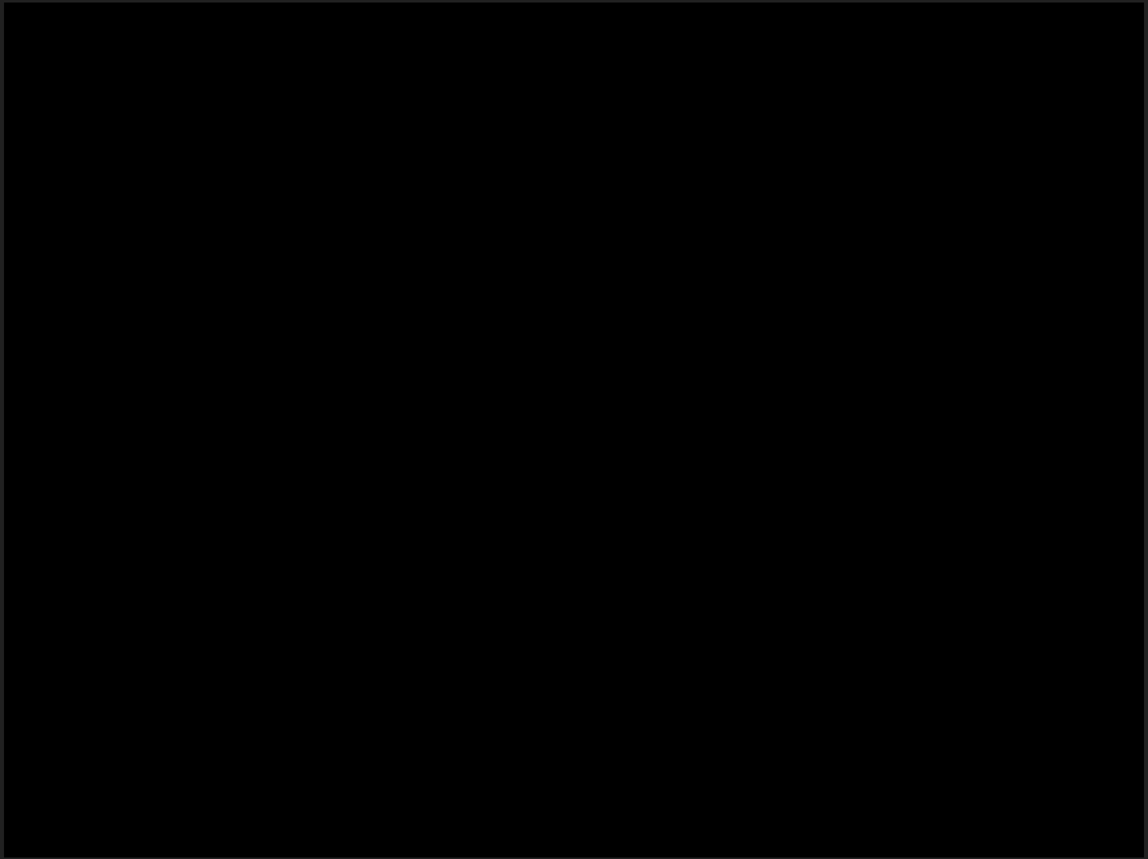
Restraint

Restraint Handles

Seat



Seat + Second Seat



Seat Restraint

Pivot Mechanism

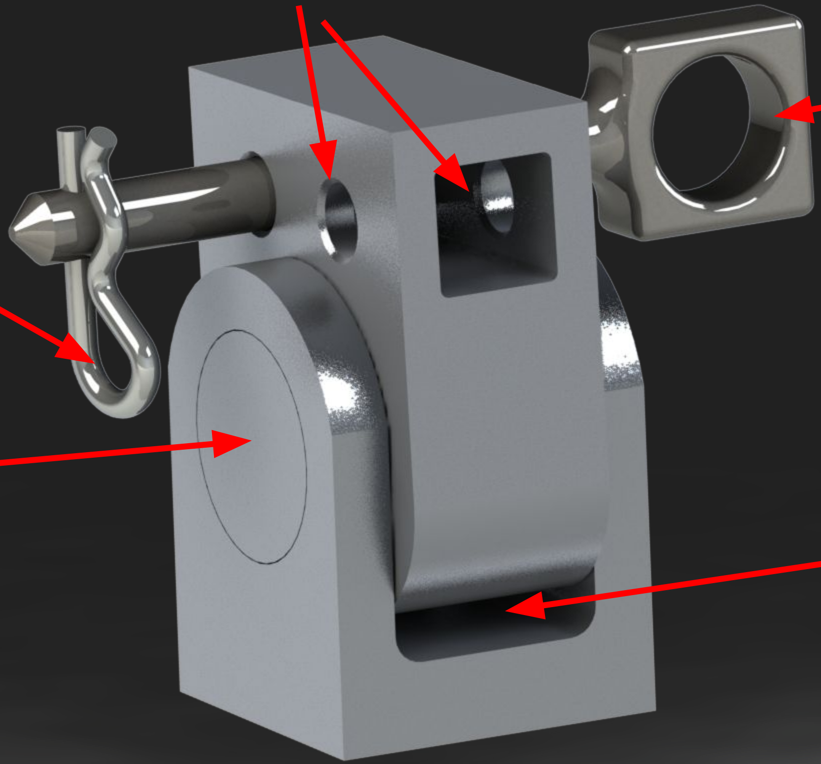
Chamfers

for easy pin insertion

Locking Pin hole

sized for gloved finger

Steel Retaining Hitch Pin

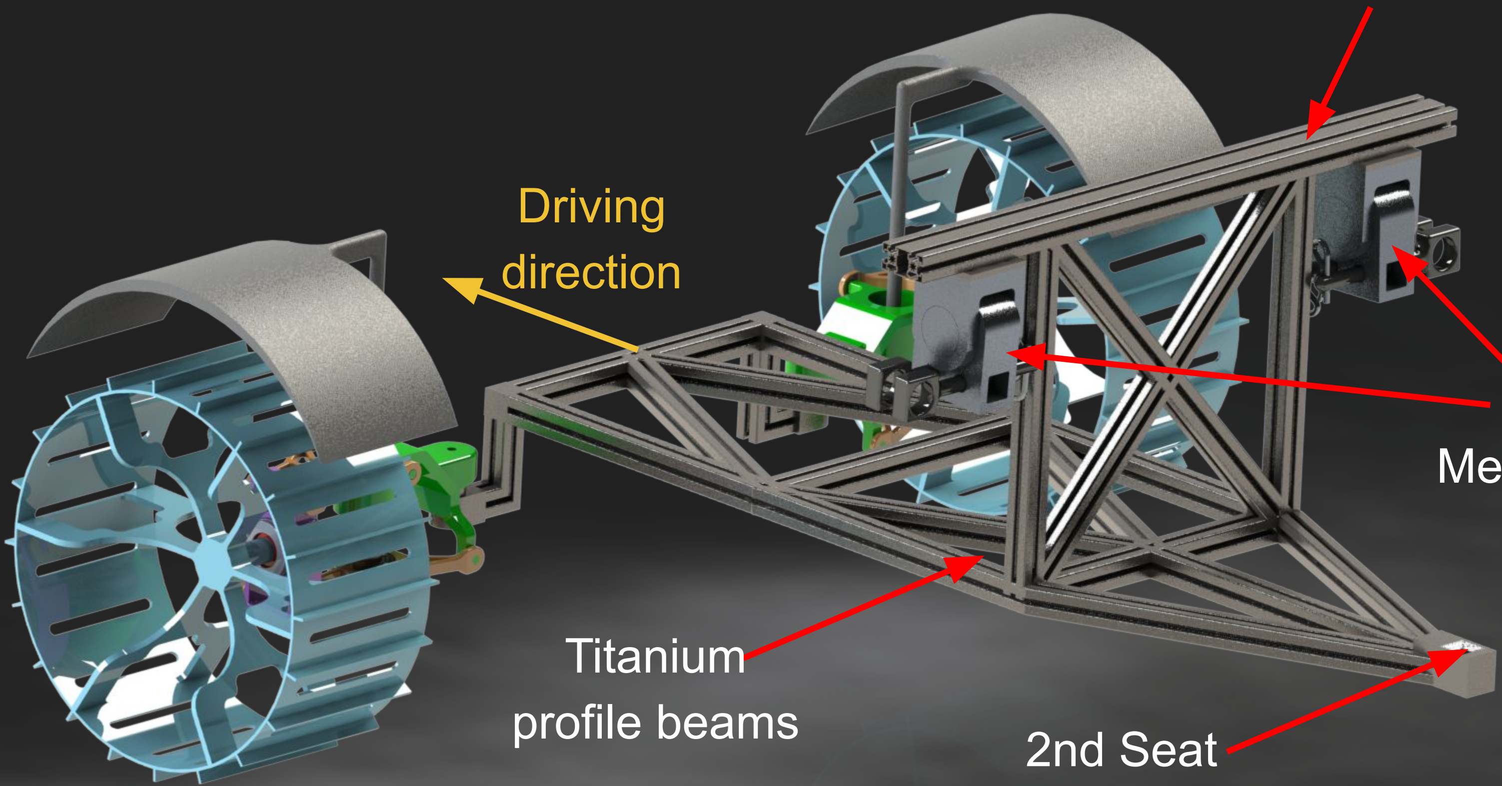


Hinge

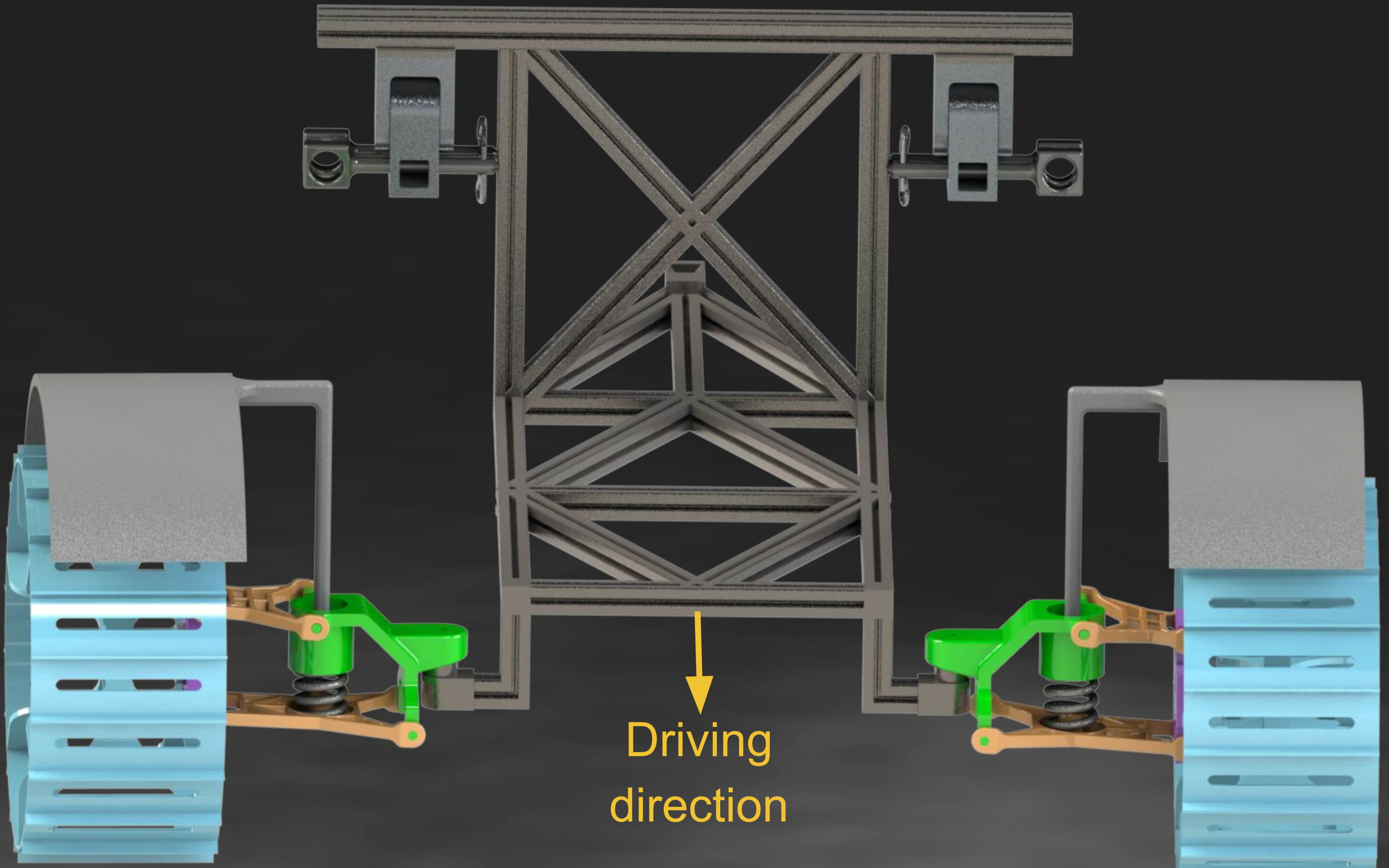
+\-20 degree mechanical stop

(not shown)

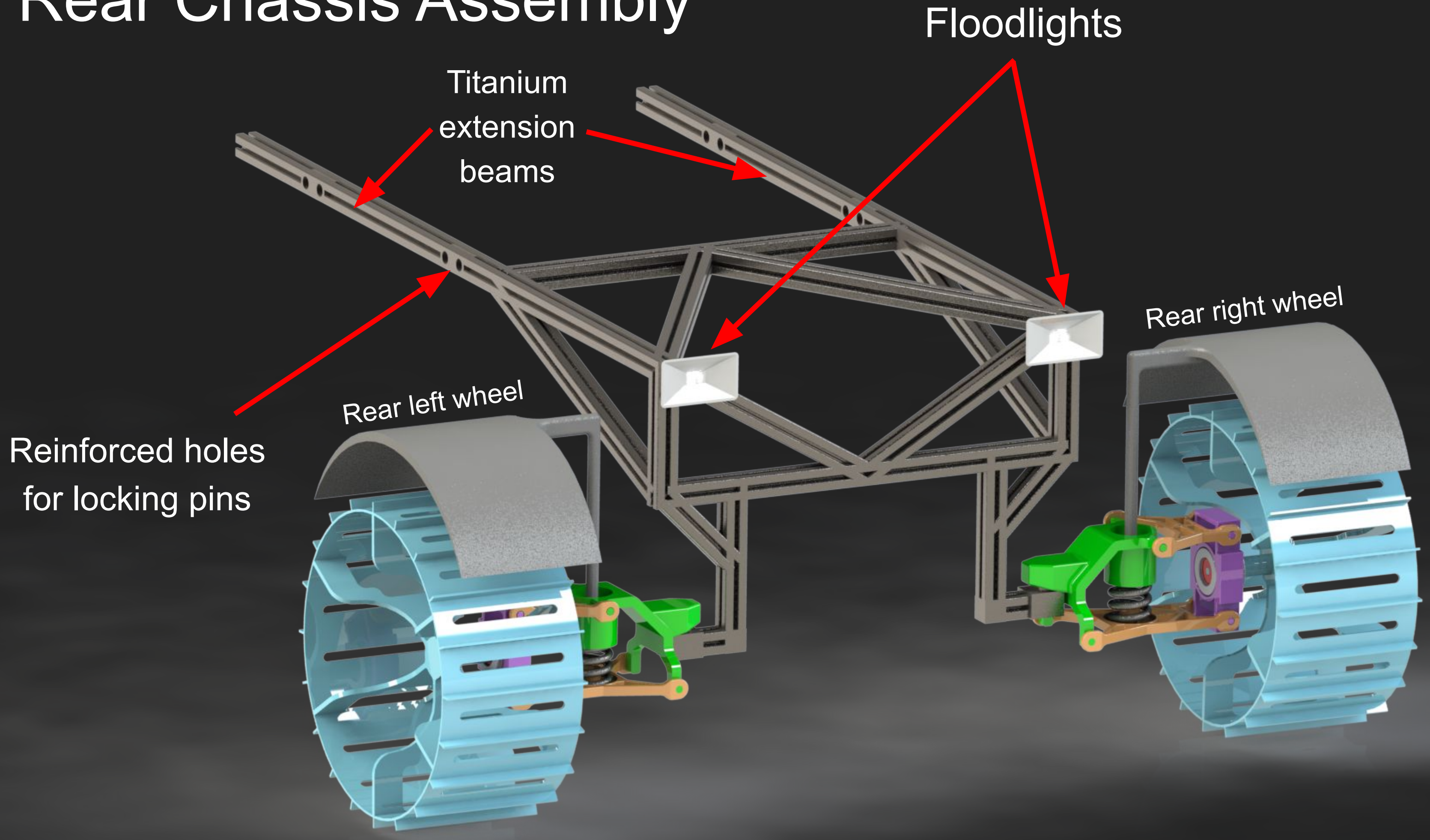
Front Chassis Assembly



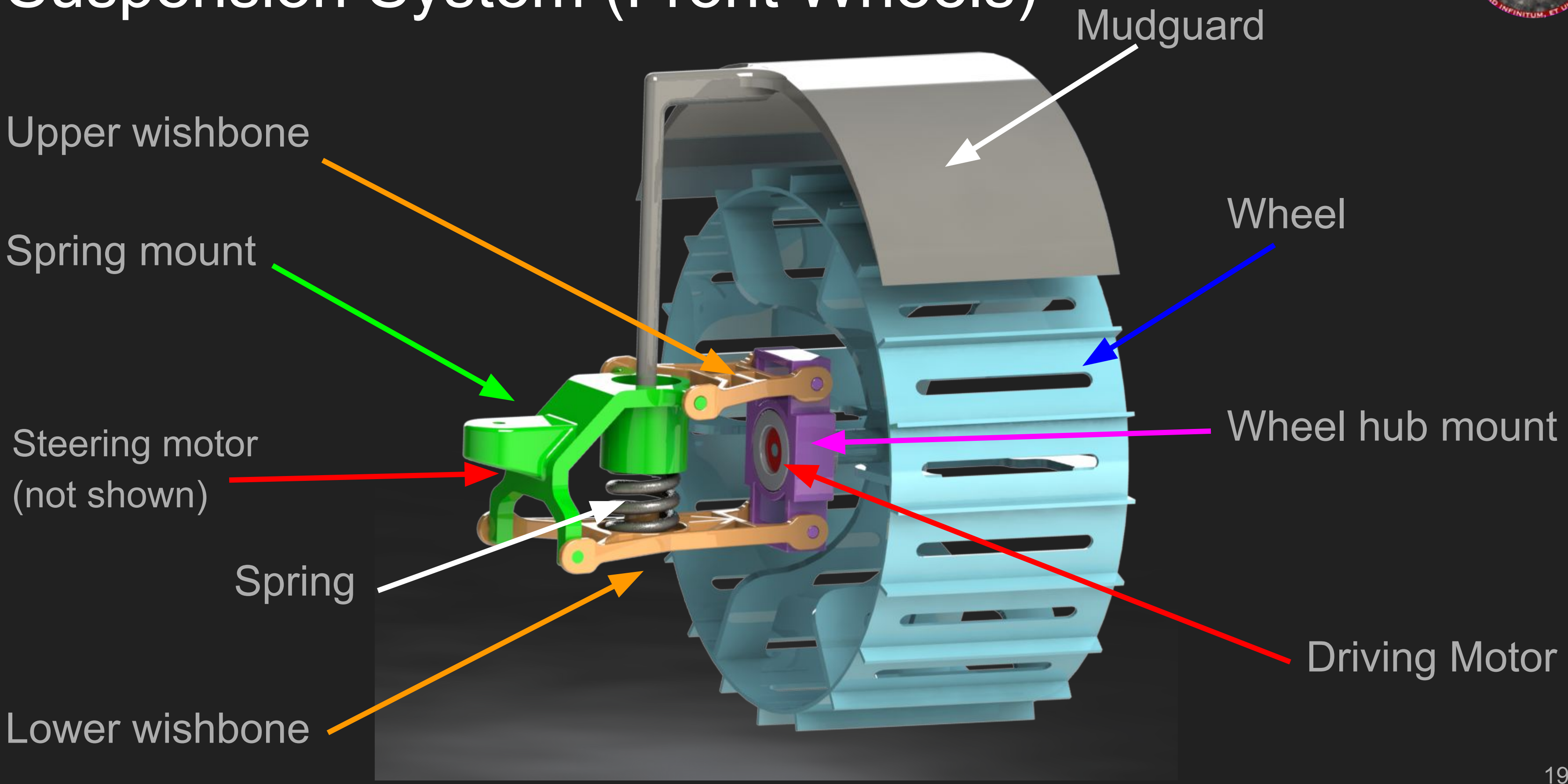
Front Chassis (Front View)



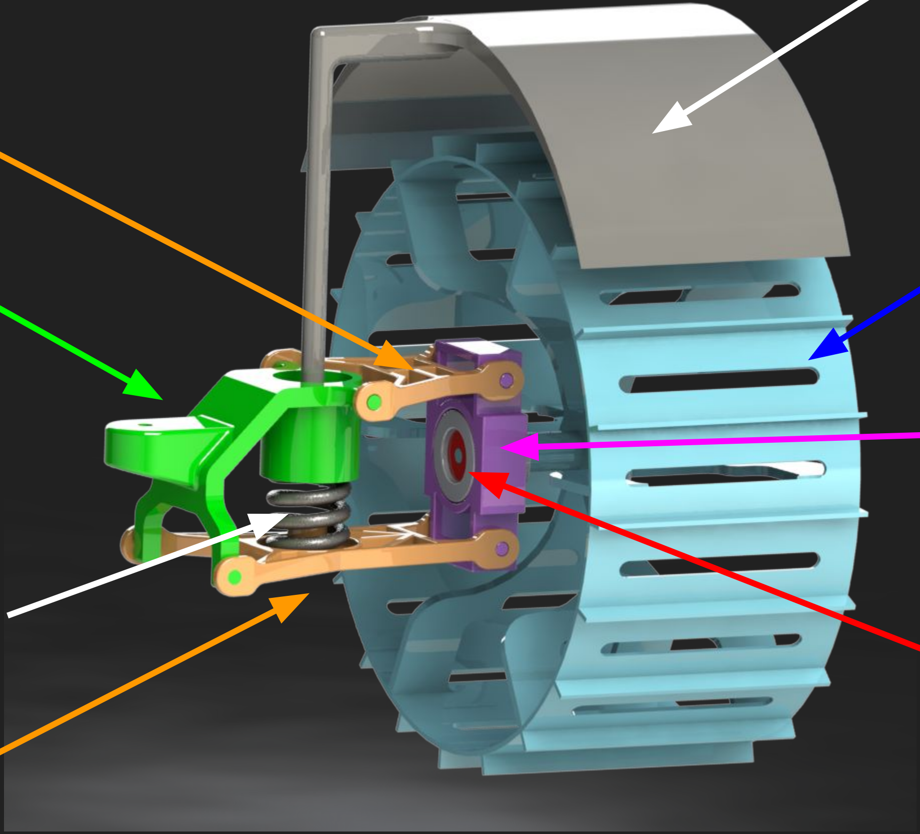
Rear Chassis Assembly



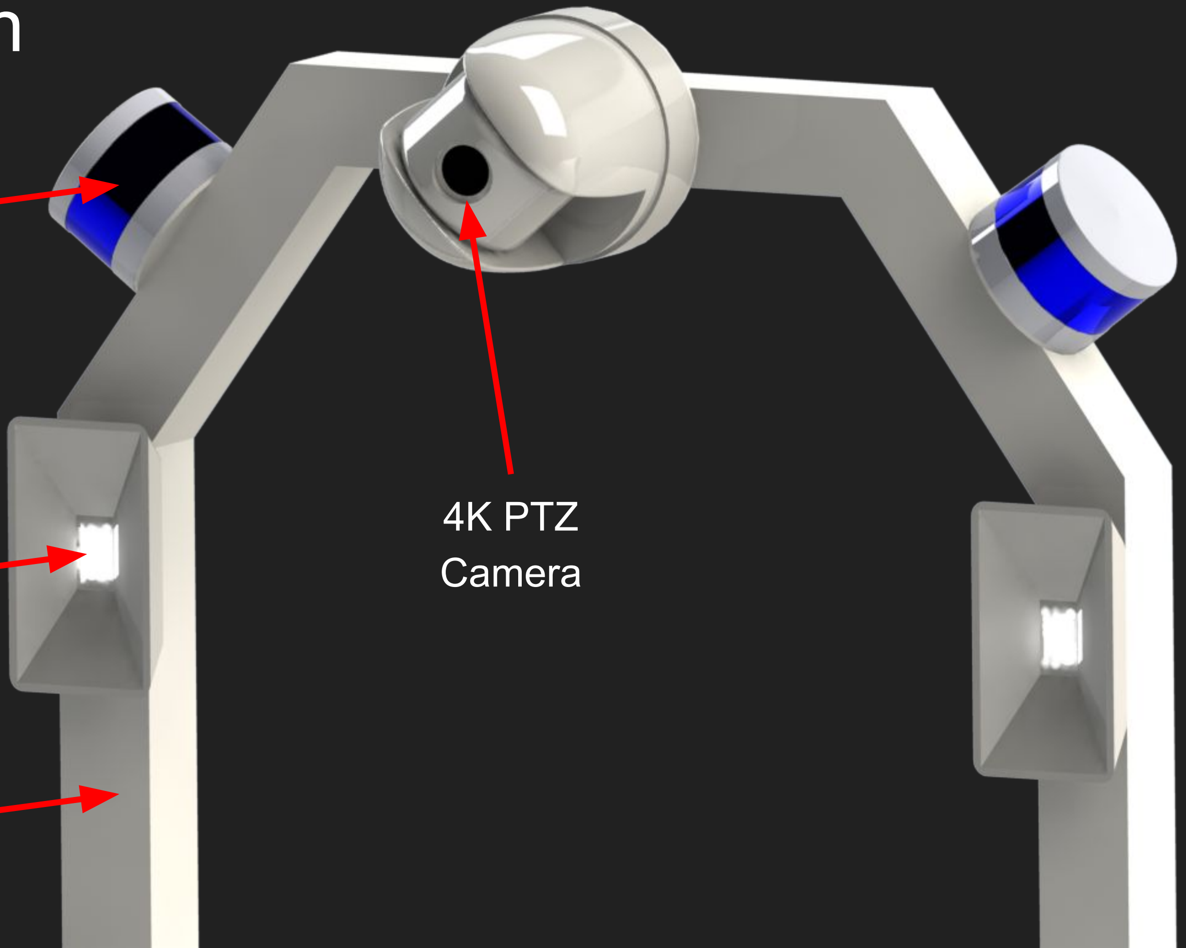
Suspension System (Front Wheels)



Suspension System (Rear Wheels)



Sensor Arch



2nd Seat Leg Structure

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

$$(170kg)(9.8\frac{m}{s^2}) = \frac{\pi^2 EI}{(0.6m)^2}$$

$$1666\frac{kgm}{s^2} = \frac{\pi^2 EI}{(0.6m)^2}$$

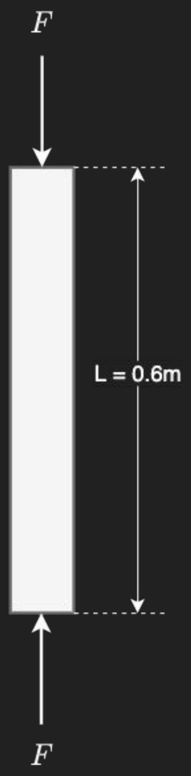
$$599.76\frac{kgm^3}{s^2} = \pi^2 EI$$

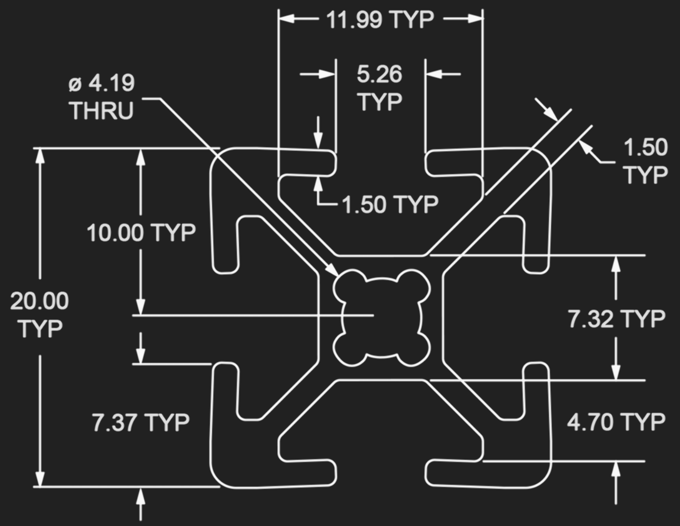
$$60.768\frac{kgm^3}{s^2} = EI$$

$$60.768\frac{kgm^3}{s^2} = 70 * 10^9\frac{N}{m^2}I$$

$$I \geq 0.08681cm^4$$

Pin-Pin Column





Use 8020’s 20-2020 beam

$I = 0.6826\ cm^4$

https://8020.net/20-2020.html

Earth & Mars Efficacy

Drawbar Pull Comparison

EARTH

$g = 9.8\ m/s^2$
$n = 0.5$
$k_c = 13190\ N/m^{1.5}$
$k_\phi = 692200\ N/m^{2.5}$
Assuming, $K_{shear} = 13190\ m$
Soil type = Clay

Drawbar pull = 6154.99 N

MARS

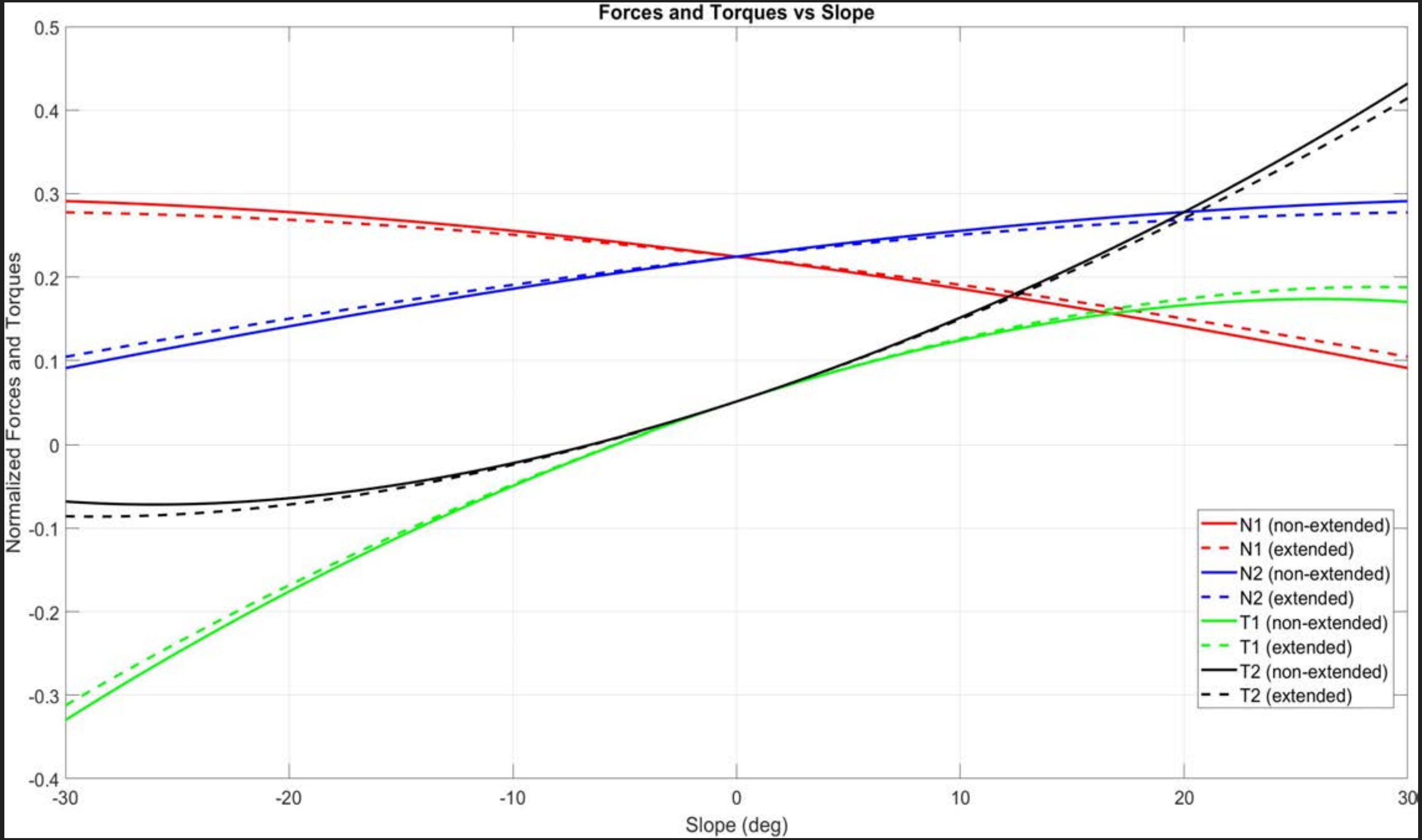
$g = 3.711\ m/s^2$
$n = 1$
$k_c = 28000\ N/m^2$
$k_\phi = 7600000\ N/m^3$
Assuming, $K_{shear} = 13190\ m$
Soil type = Sandy Loam

Drawbar pull = 968.26 N

$g = 3.711\ m/s^2$
$n = 0.8$
$k_c = 6800\ N/m^2$
$k_\phi = 210000\ N/m^3$
Assuming, $K_{shear} = 13190\ m$
Soil type = Slope soil

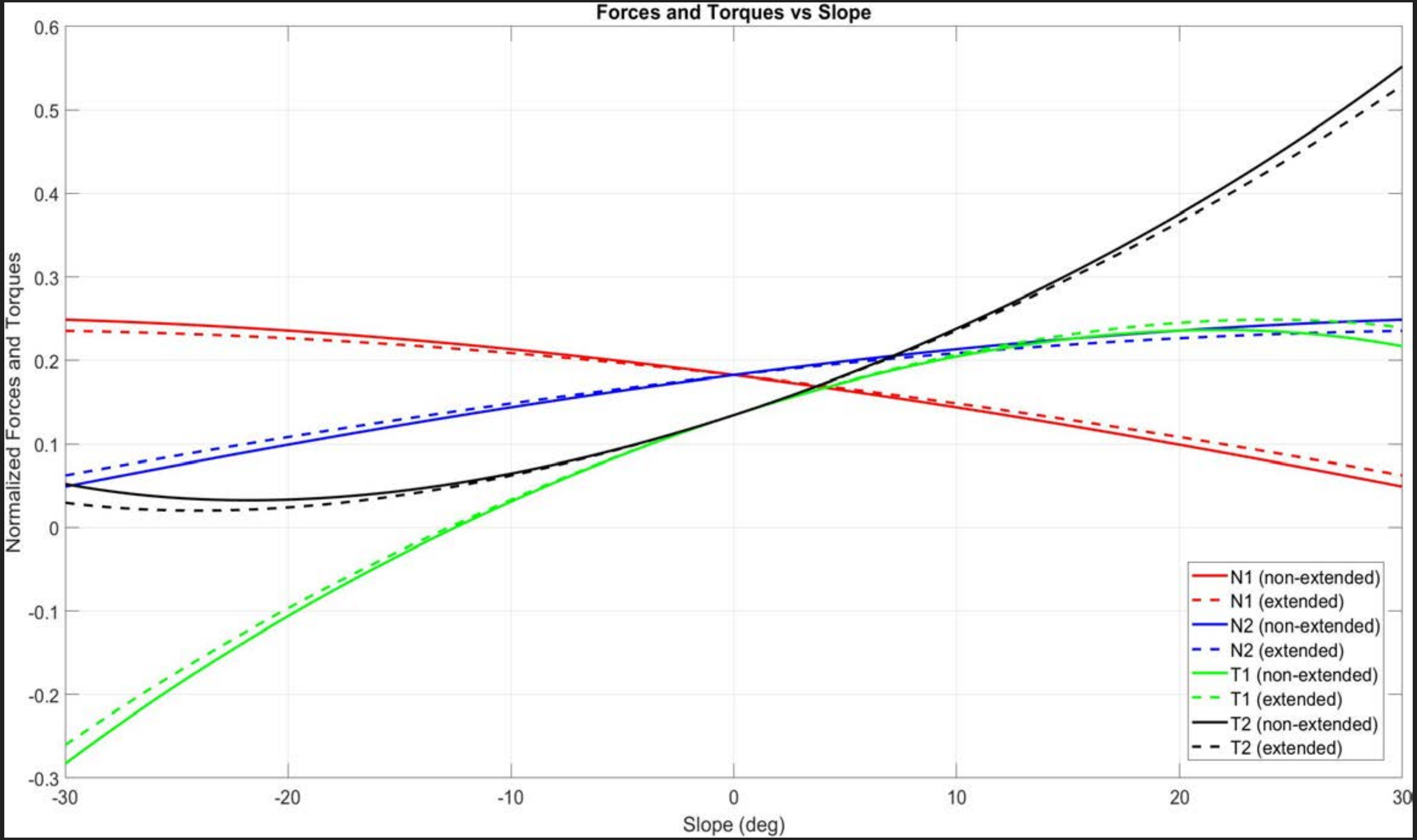
Drawbar pull = 7713.51 N

Stability check (Earth)



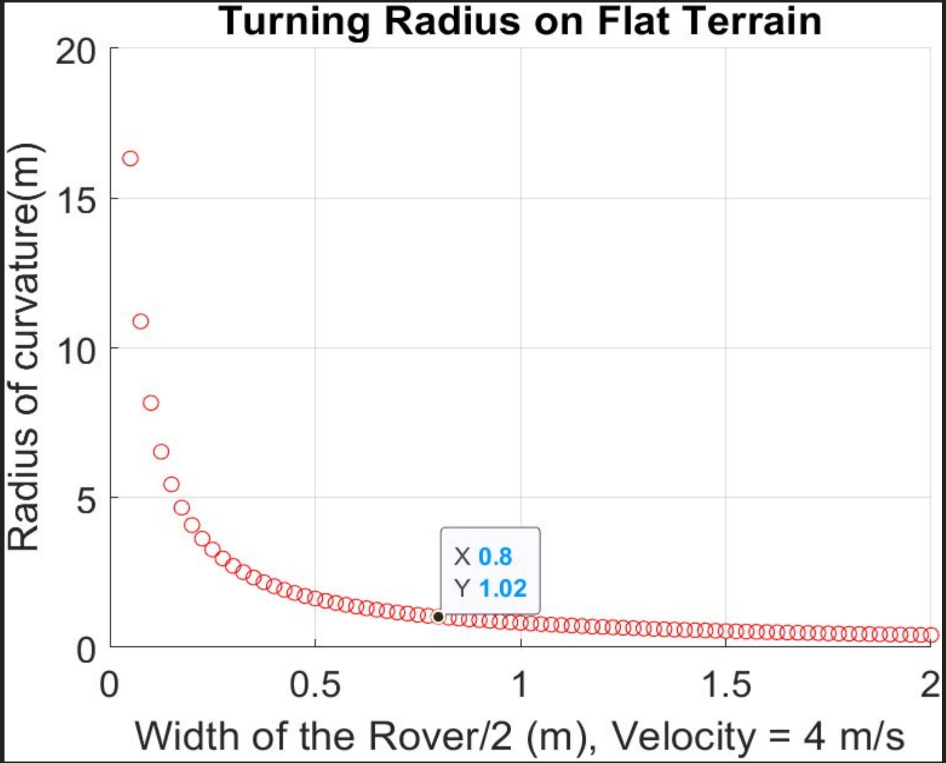
- Design is still valid for Earth environment.
- Uphill slope limit is more than 30 degrees.
- Downhill slope is less than 10 degrees.

Stability check (Mars)

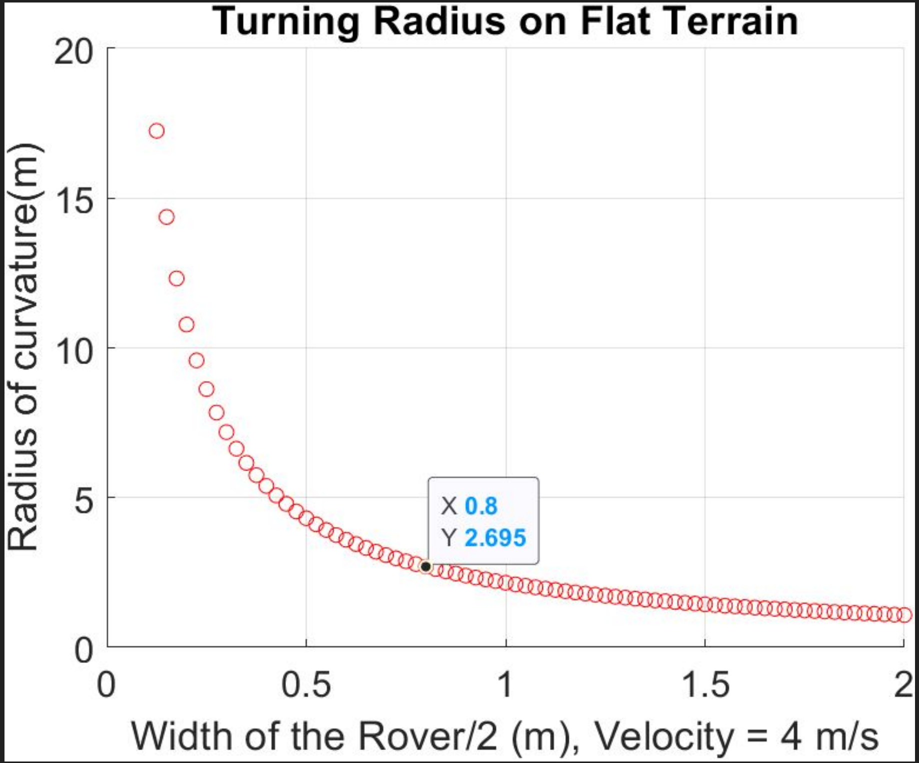


- Design is still valid for Mars environment.
- Uphill slope limit is more than 30 degrees.
- Downhill slope is more than 10 degrees.

Turning Radius on Flat Terrain: Earth & Mars

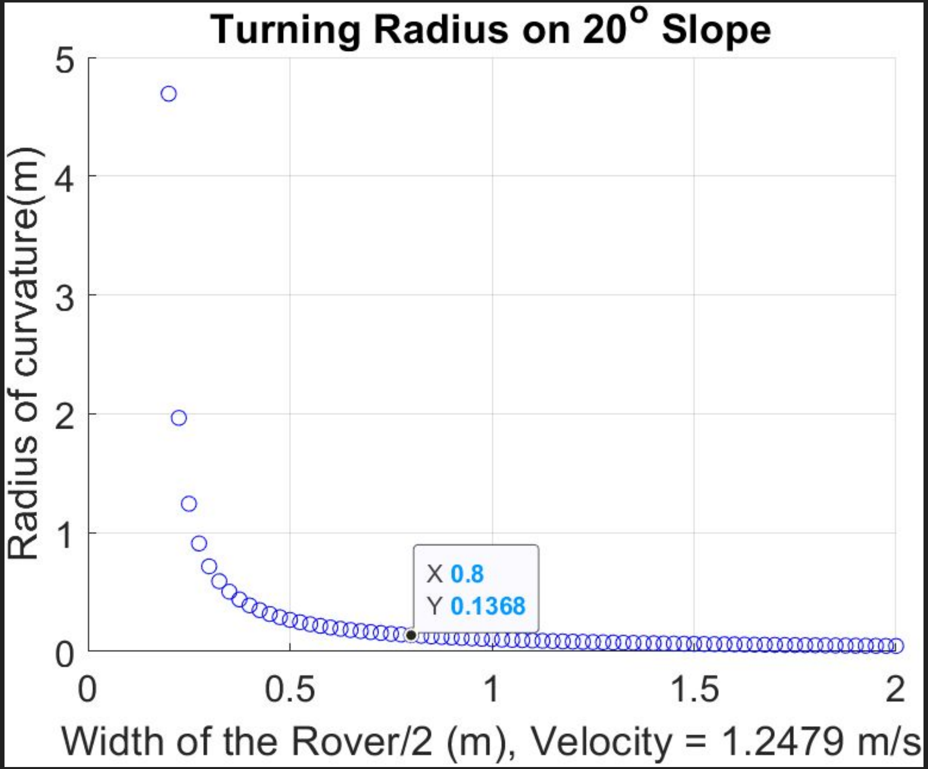


EARTH

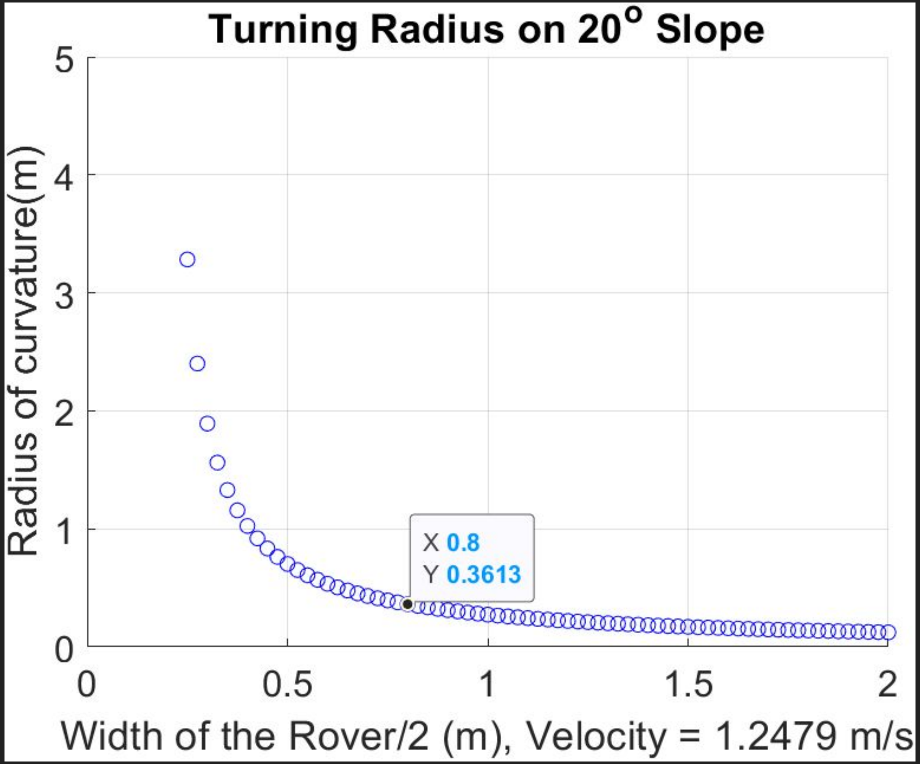


MARS

Turning Radius on 20º Slope: Earth & Mars



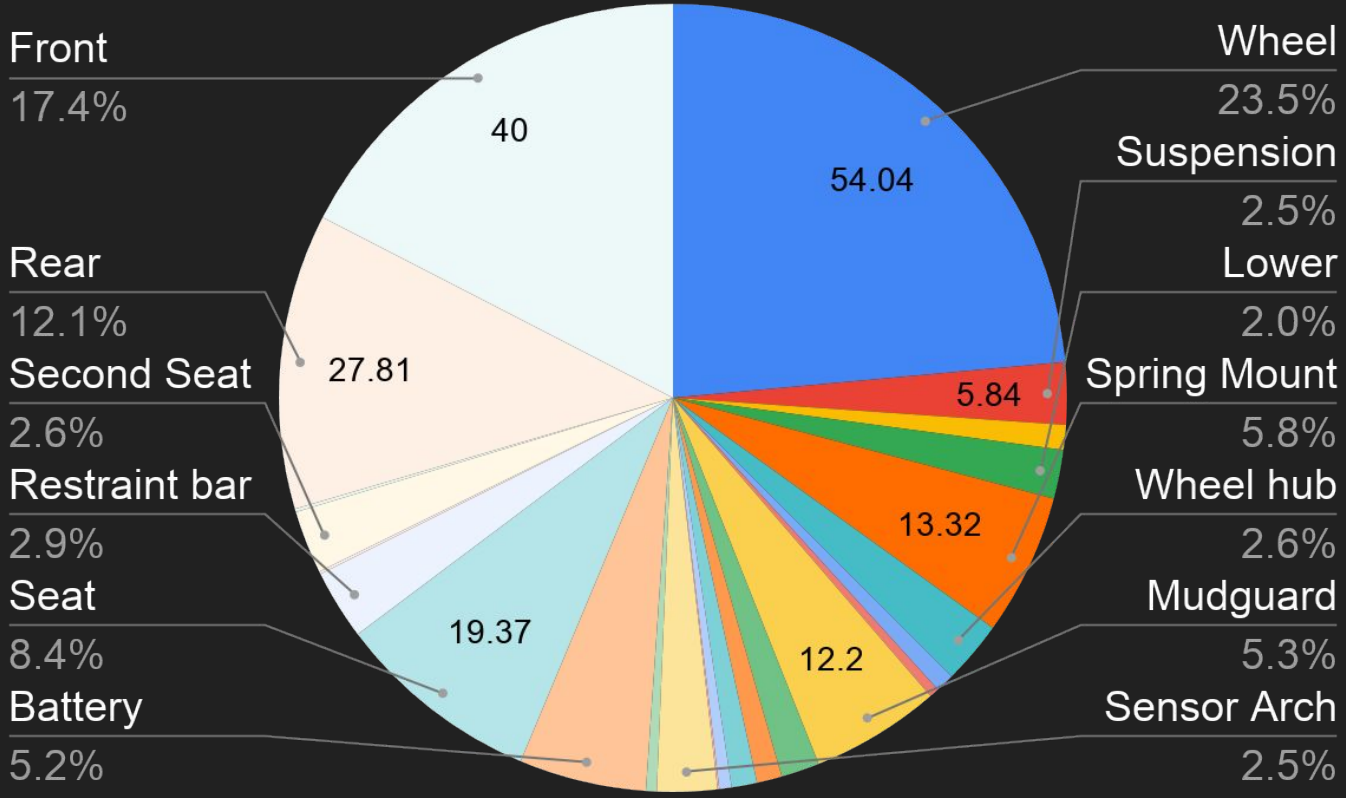
EARTH



MARS

Mass Summary

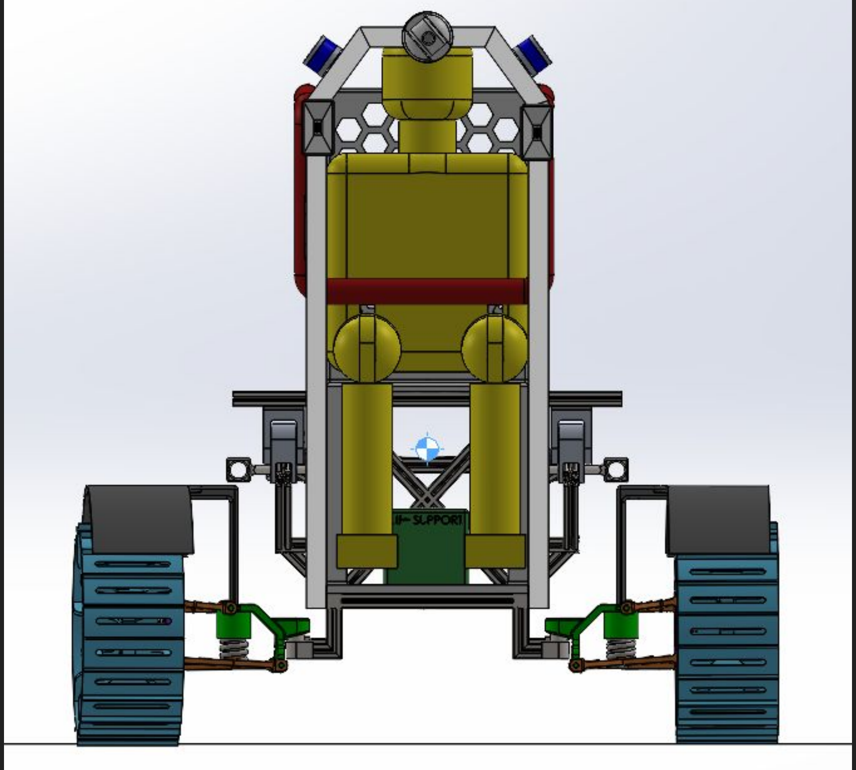
Mass Overview

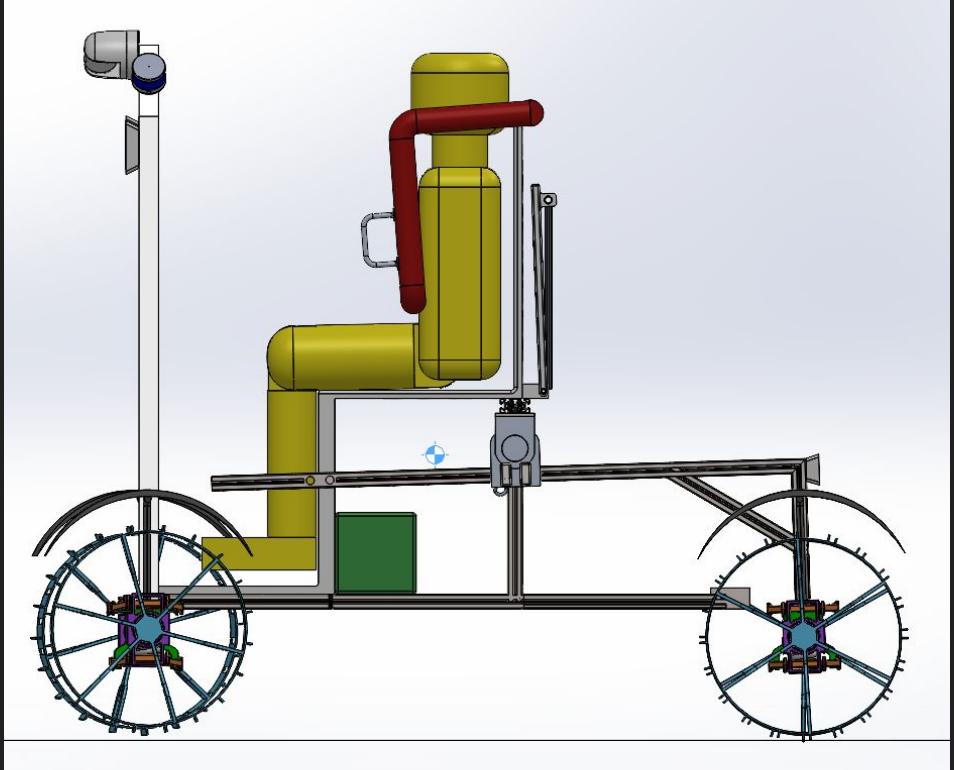


Mass Overview

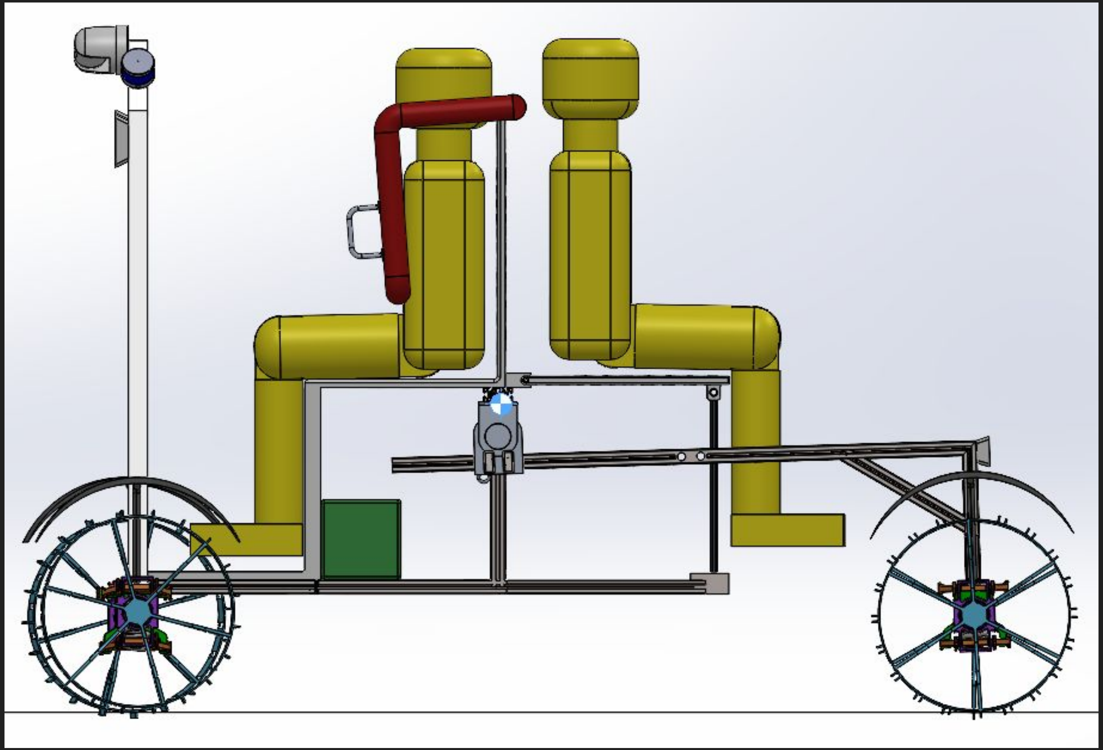
Category	Part	Material	Individual Mass (kg)	# Required	Total Mass
Suspension / Driving	Wheel	Aluminum 7075-O (SS)	13.51	4	54.04
	Suspension Spring	Stainless Steel	1.46	4	5.84
	Upper Wishbone	Aluminum 7075-O (SS)	0.59	4	2.34
	Lower wishbone	Aluminum 7075-O (SS)	1.15	4	4.6
	Spring Mount	Aluminum 7075-O (SS)	3.33	4	13.32
	Wheel hub mount	Aluminum 7075-O (SS)	1.47	4	5.88
	Driving motor	Various	0.447	4	1.788
	Steering motor	Various	0.447	2	0.894
	Mudguard	PE Low/Medium Density	3.05	4	12.2
Sensors / Lighting	PTZ Camera	Various	1.8	2	3.6
	Velodyne Puck LITE	Various	0.59	4	2.36
	Floodlight	Various	0.6	4	2.4
	Stereo Camera	Various	0.288	4	1.152
	Omnicamera	Various	0.163	1	0.163
	Sensor Arch	PVC	5.66	1	5.66
	Computer (Laptop style)	Various	1	1	1
Power	Battery (400Wh/kg)	Various	11.982	1	11.982
Seat	Seat	Very Low Density PE (SS)	19.37	1	19.37
	Restraint bar	Nylon 6/10	6.59	1	6.59
	Restraint bar handles	Aluminum 6061-T6 (SS)	0.12	2	0.24
	Second Seat	Very Low Density PE (SS)	5.94	1	5.94
	Second Seat Leg	Aluminum 6061-O (SS)	0.3	1	0.3
Chassis	Rear	Commercially Pure CP-Ti UNS R50400 (SS)	27.81	1	27.81
	Front	Commercially Pure CP-Ti UNS R50400 (SS)	40	1	40
	Hitch Pin	Chrome Stainless Steel	0.13	4	0.52
	Locking Pin	Plain Carbon Steel	1.56	4	6.24
	Pivot Mechanism	Aluminum 7075-O (SS)	7.36	2	14.72
				Total Mass (kg)	**250.95**

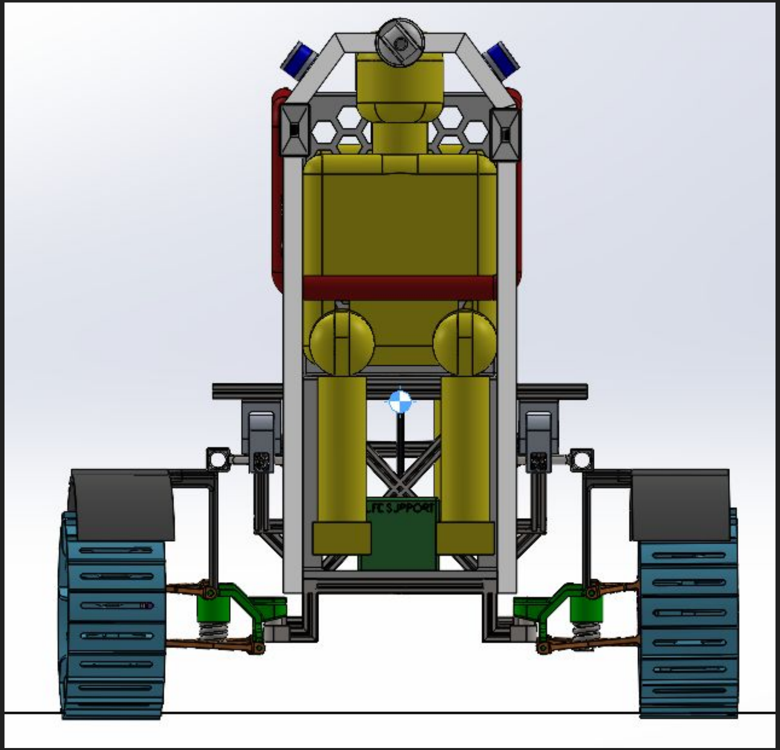
CoM Location - Unextended



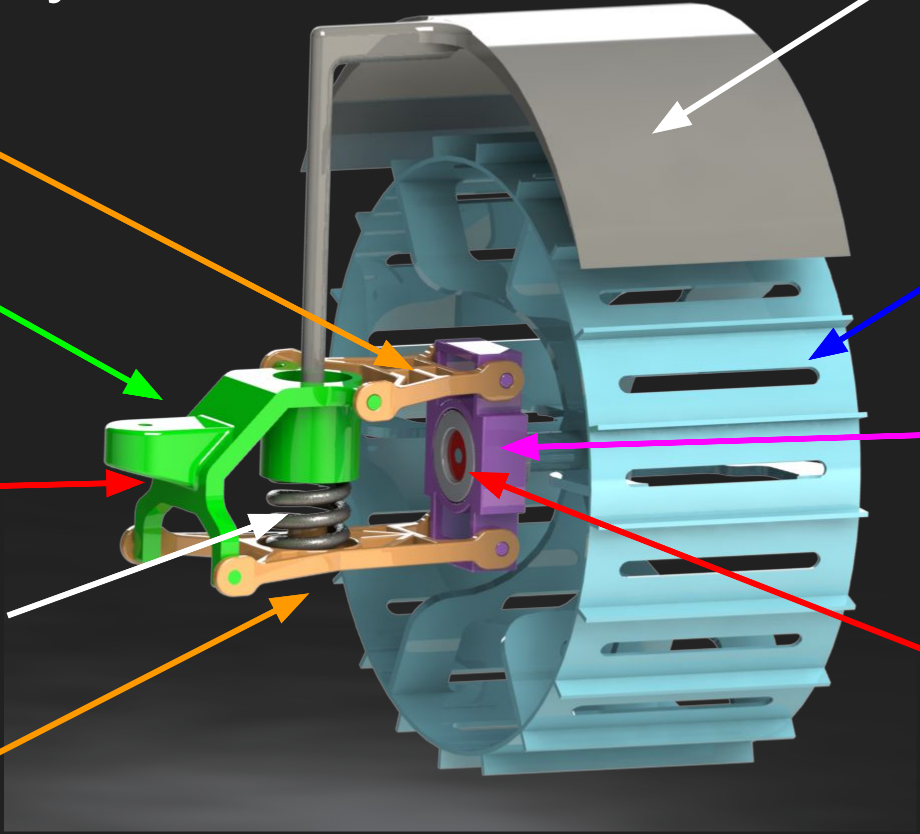


CoM Location - Extended

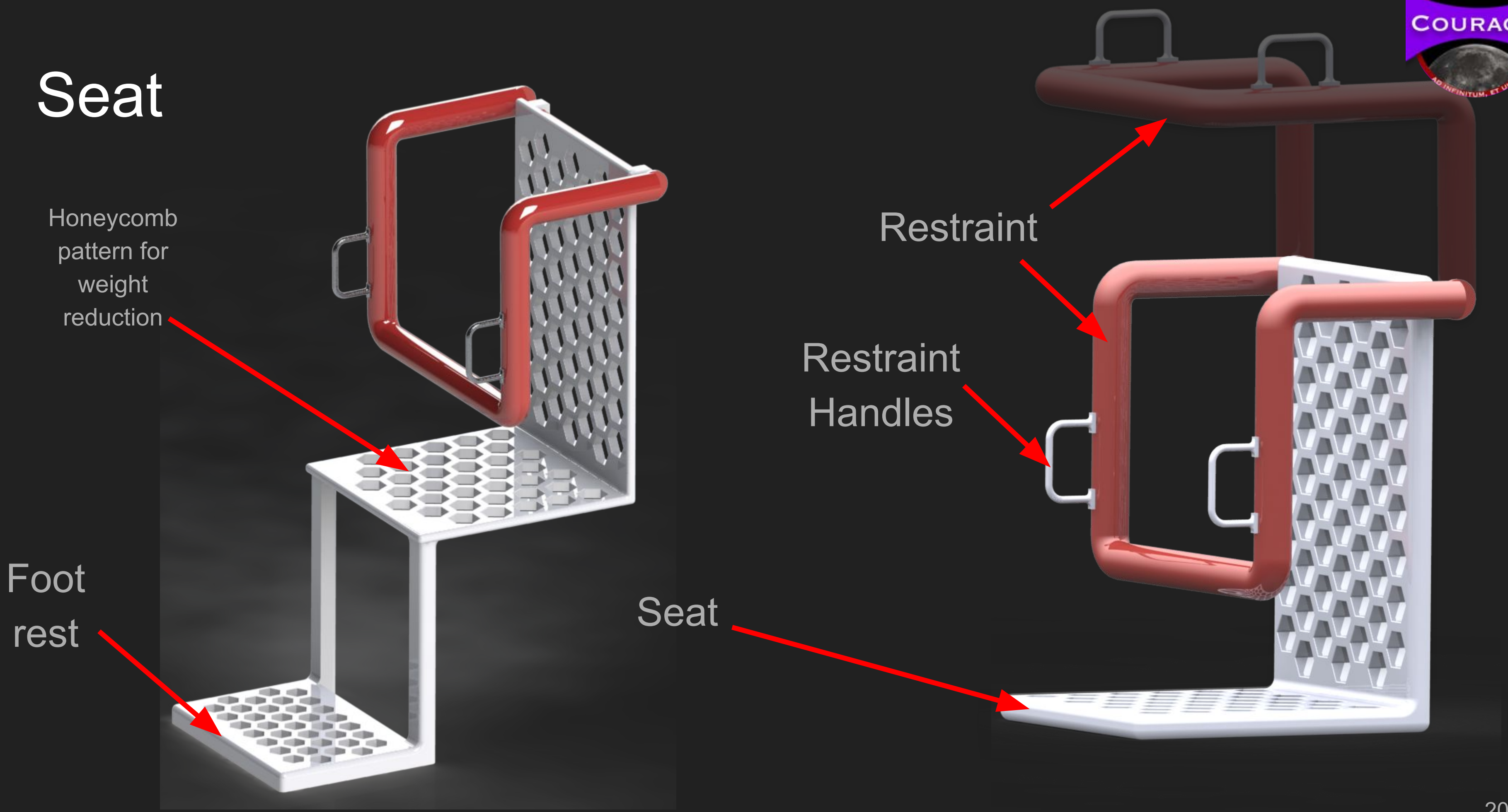




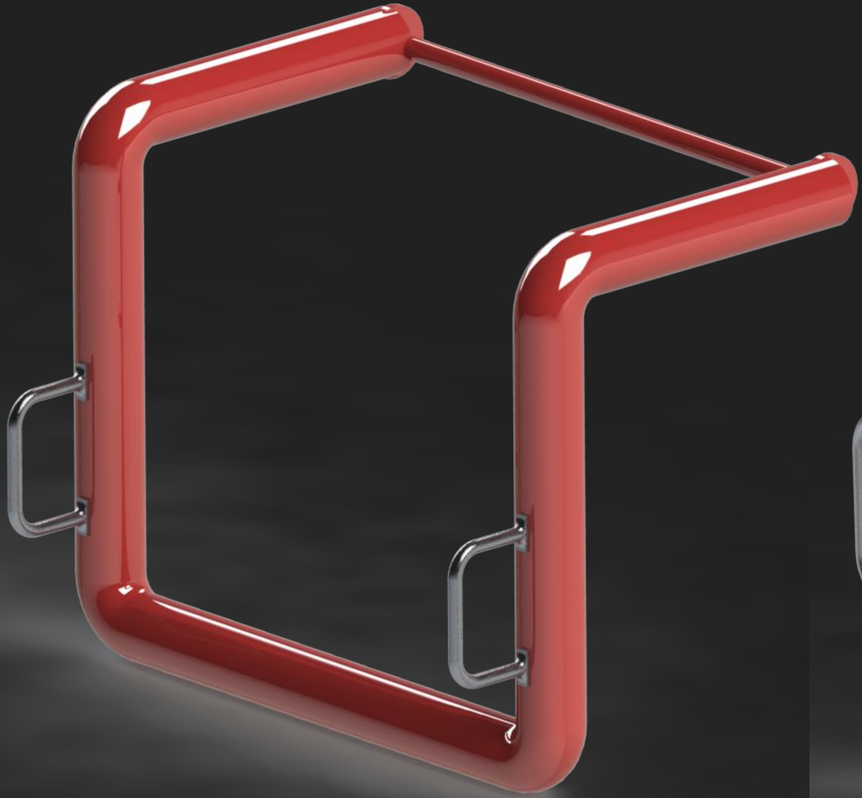
Suspension System



Seat

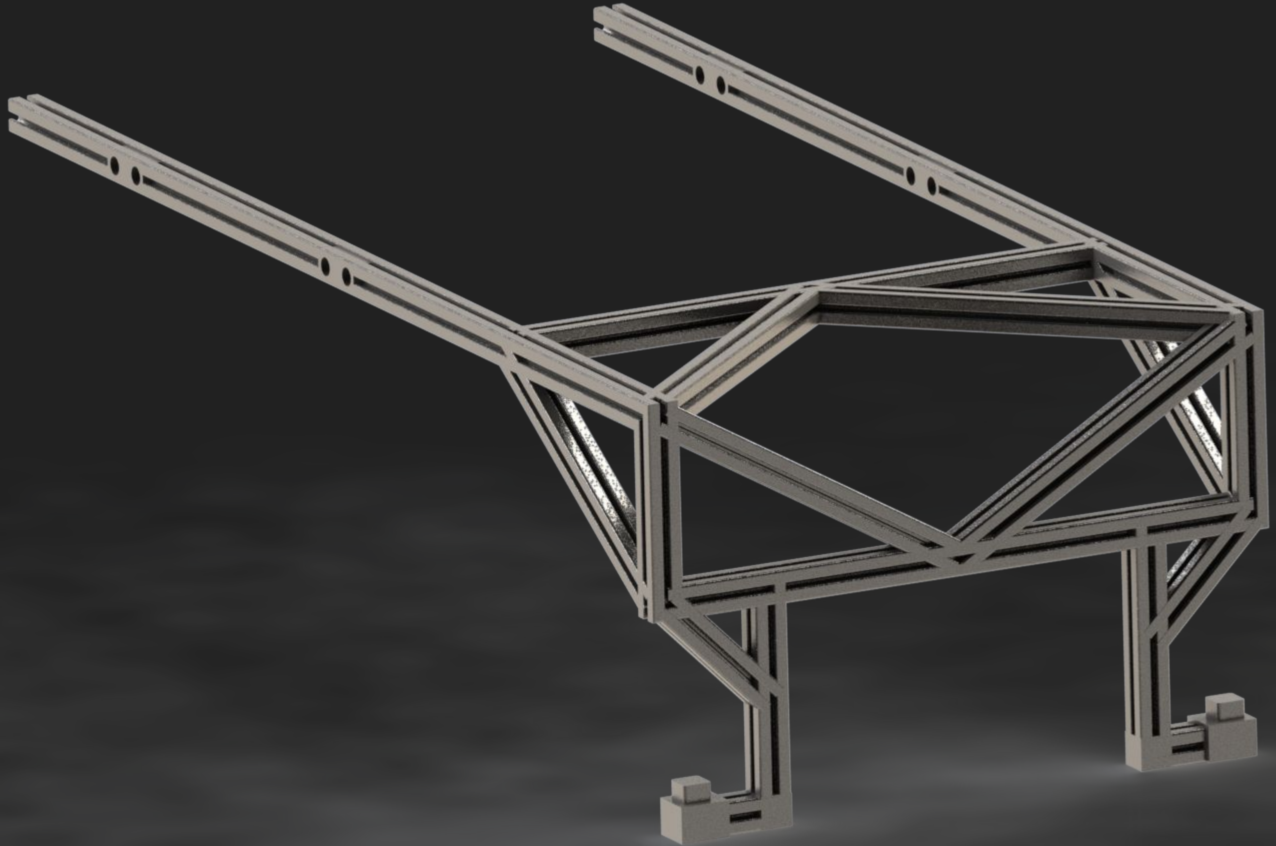

Honeycomb pattern for weight reduction
Foot rest
Restraint
Restraint Handles
Seat

Seat Restraint



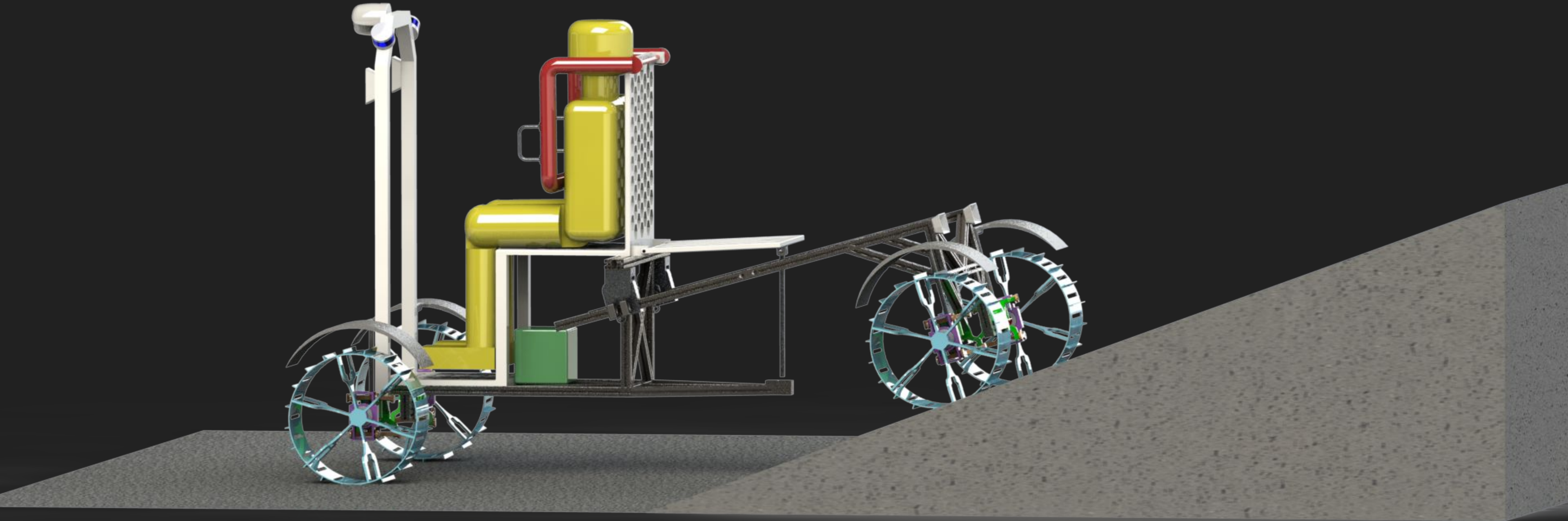
Front Chassis

Rear Chassis

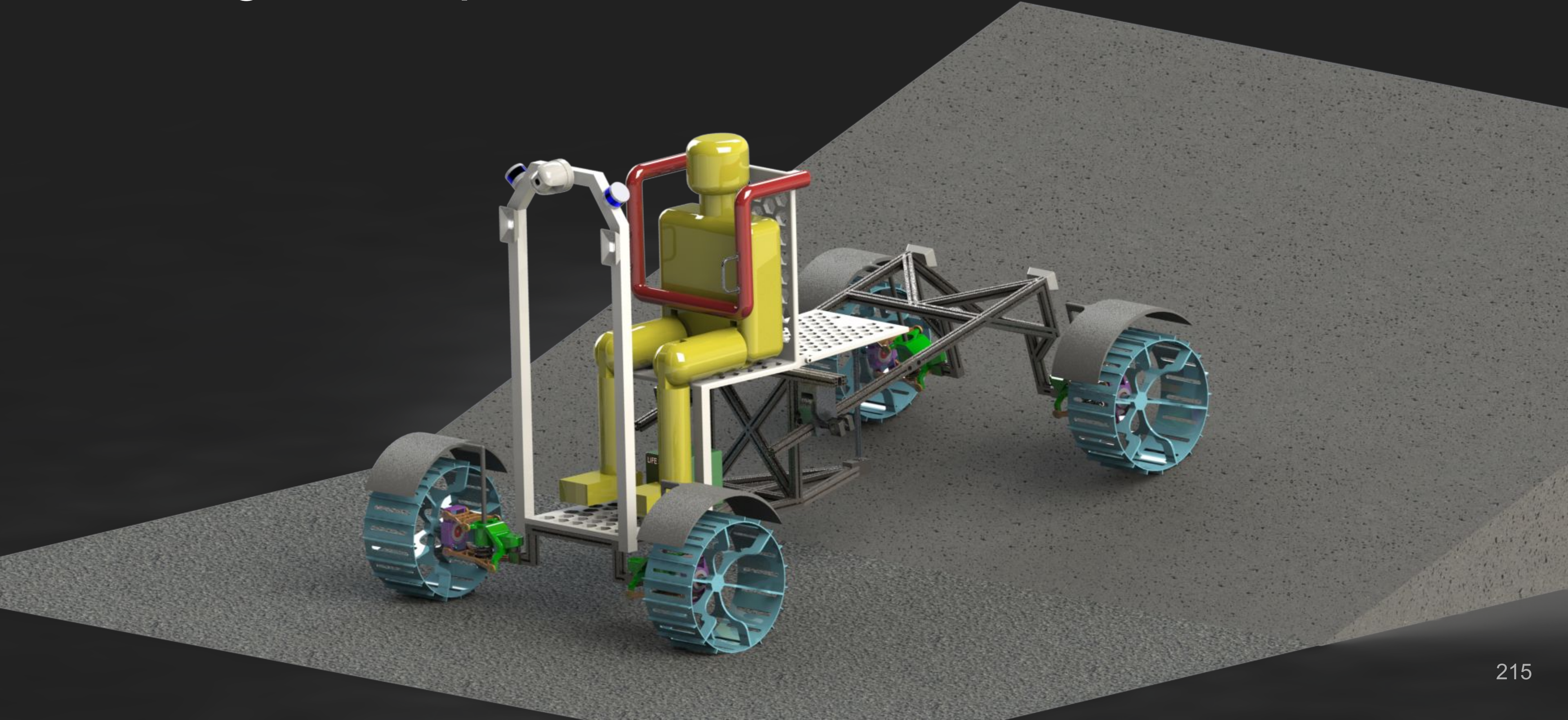


Trafficability

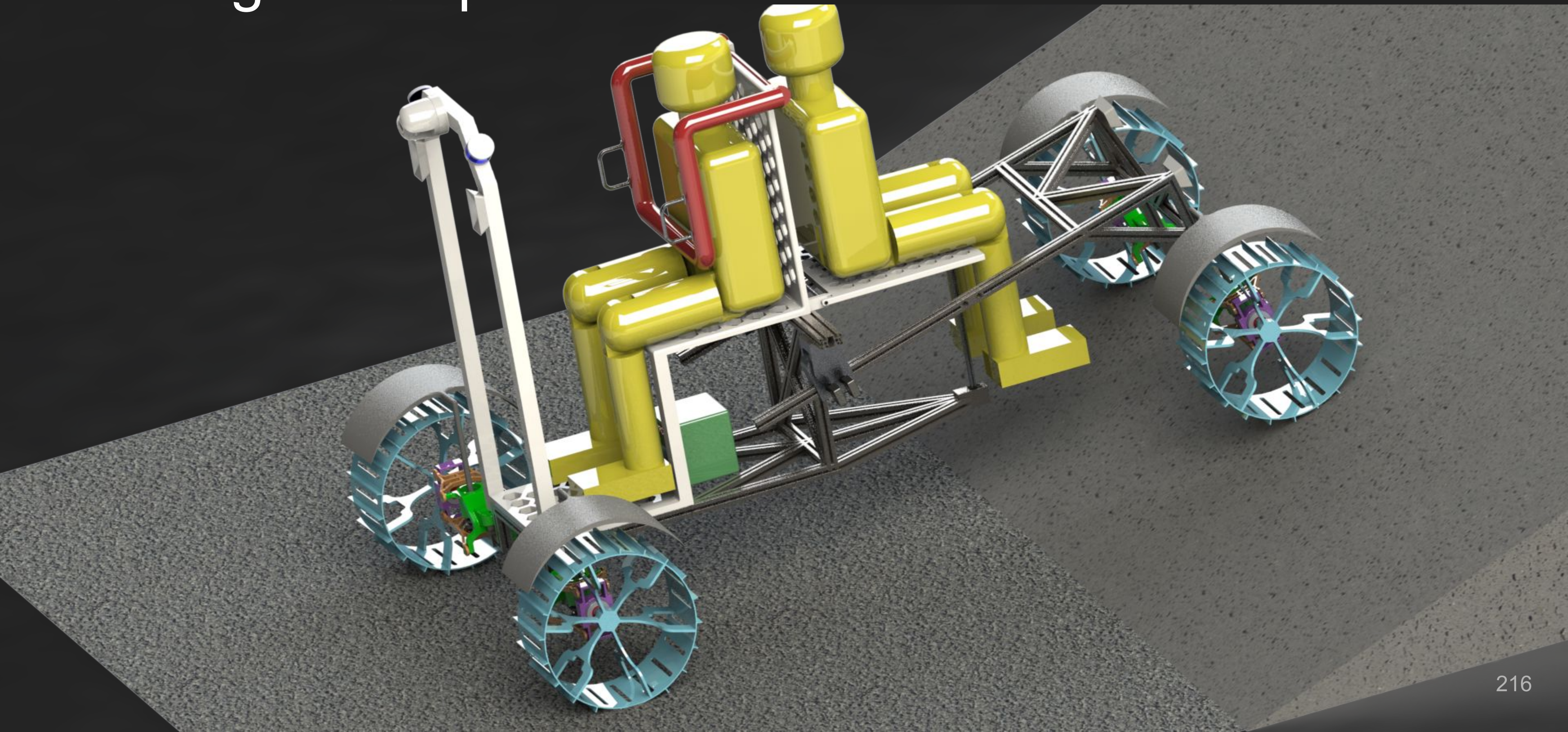
20 Degree Slope - Downhill



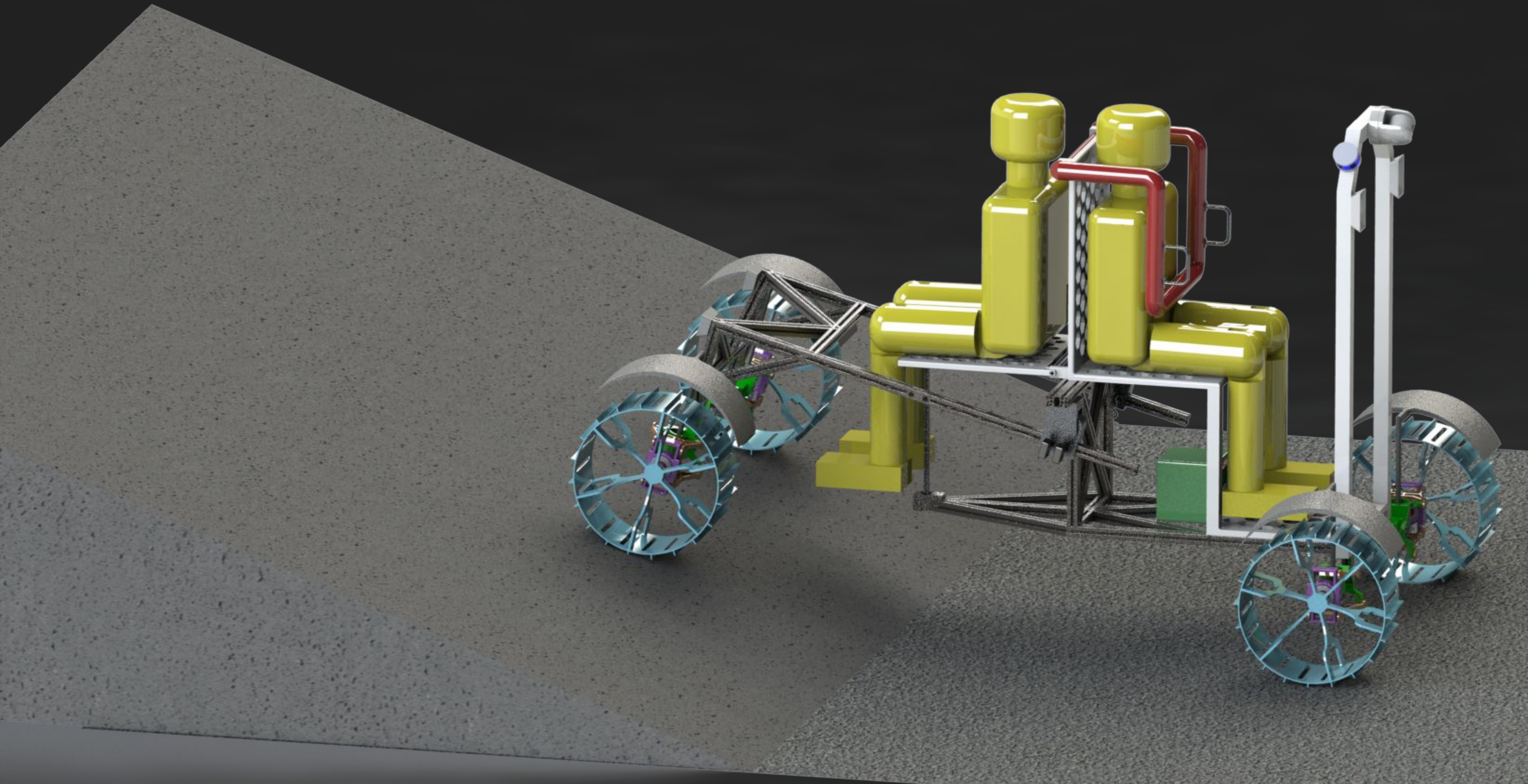
20 Degree Slope - Downhill



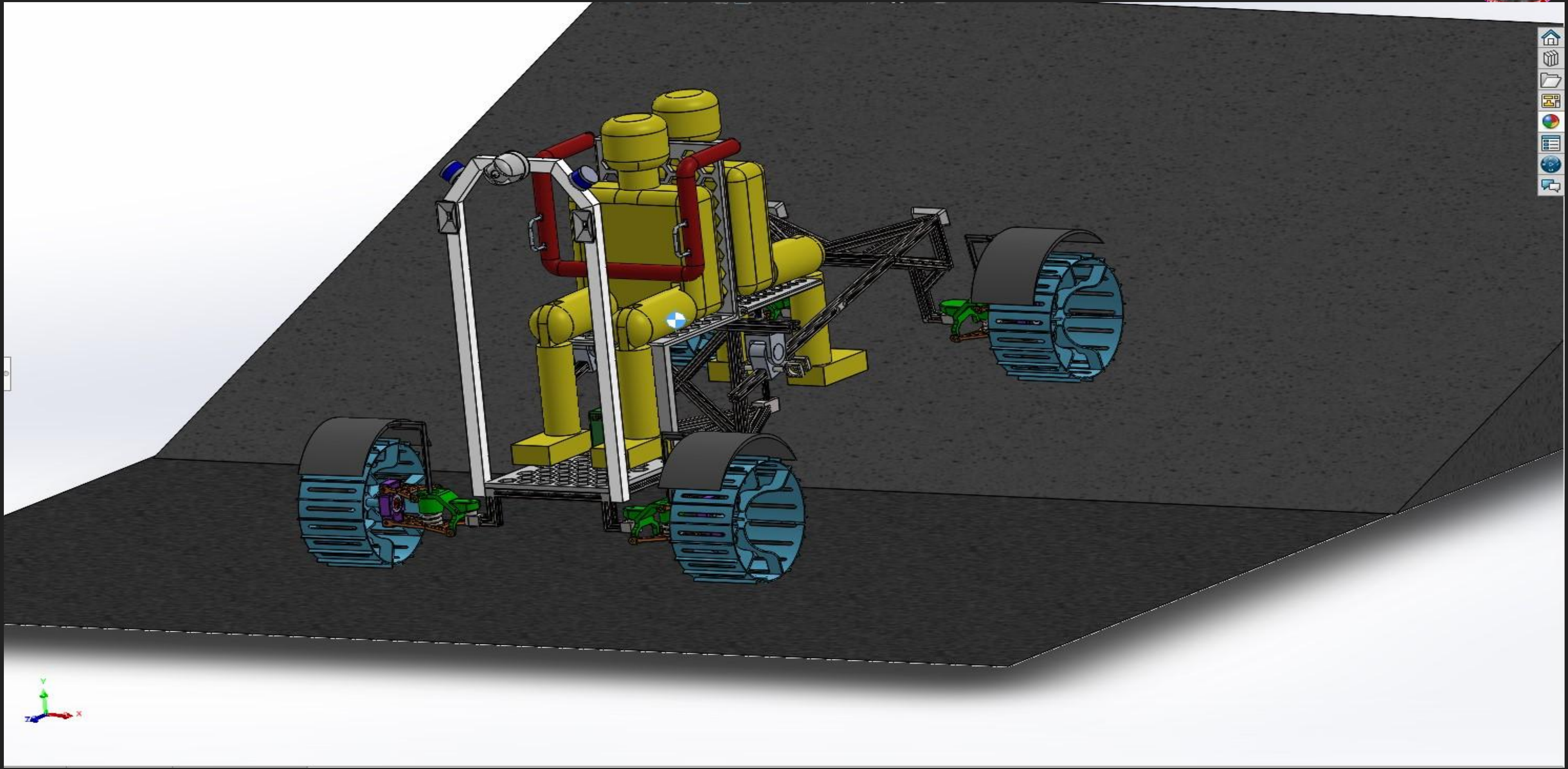
20 Degree Slope - Downhill



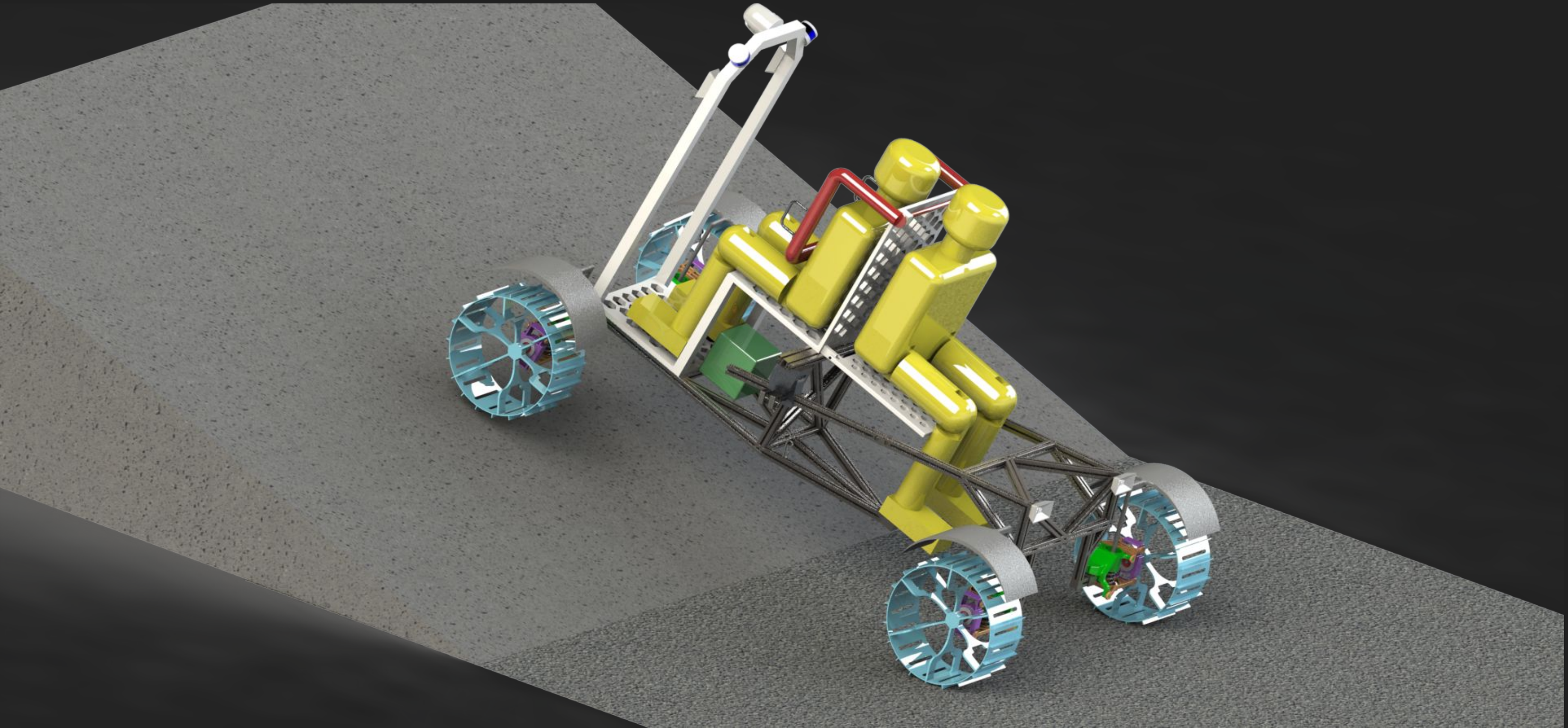
20 Degree Slope - Downhill



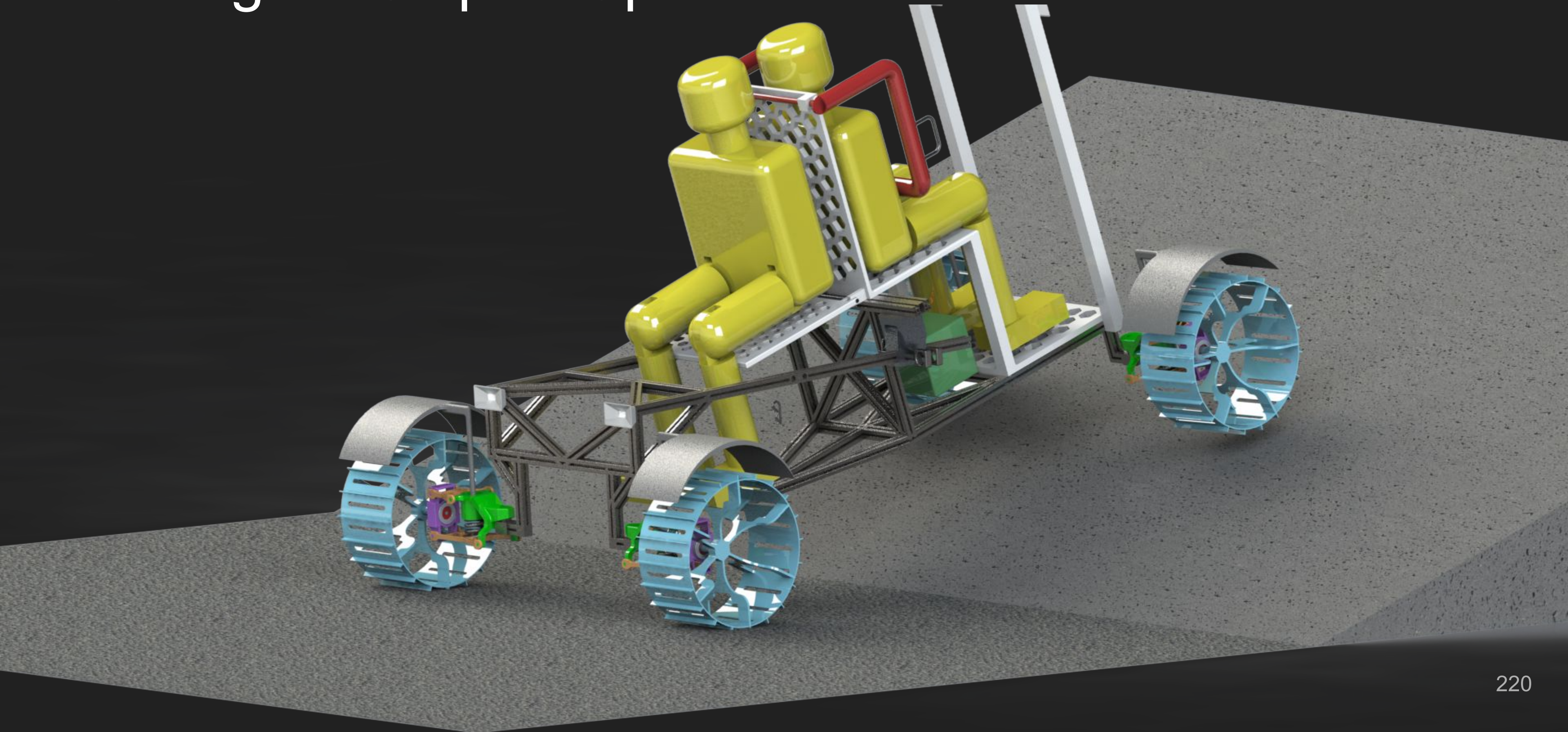
20 Degree Slope - CoM



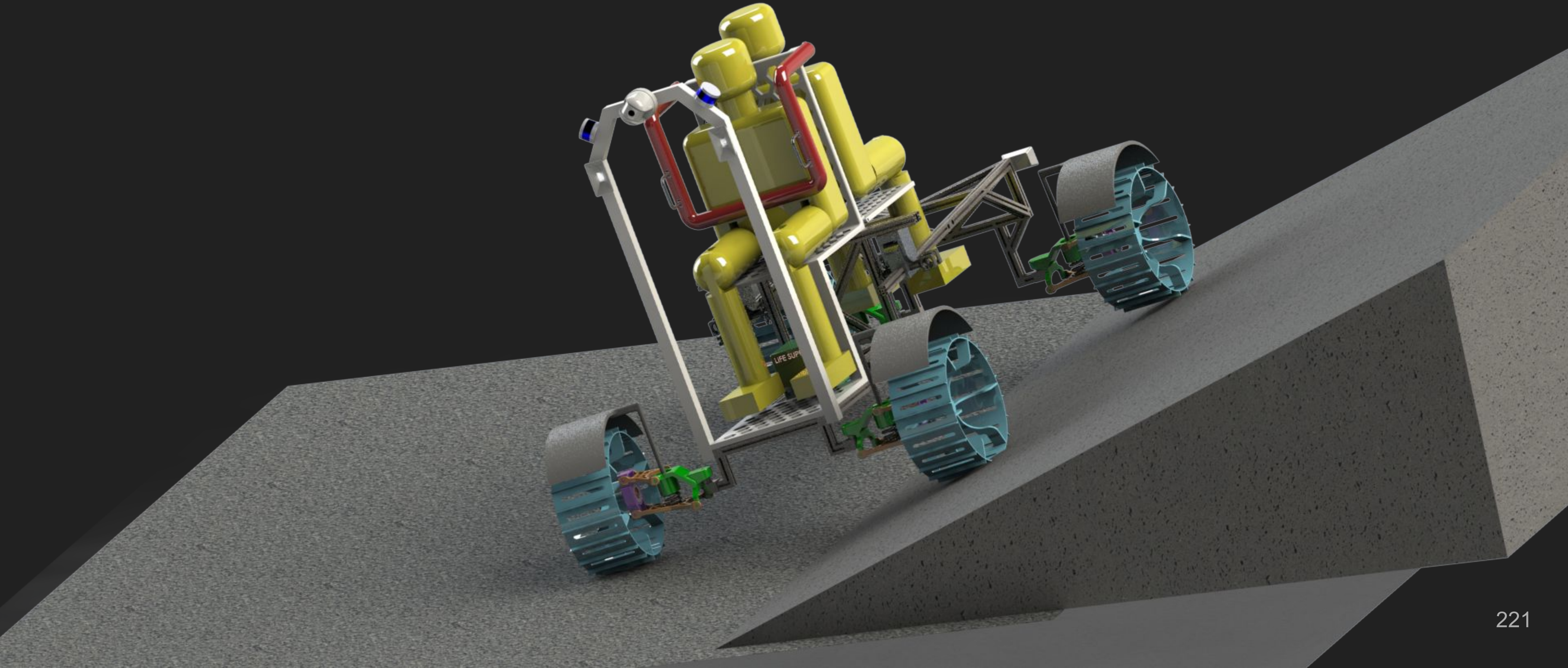
20 Degree Slope - Uphill



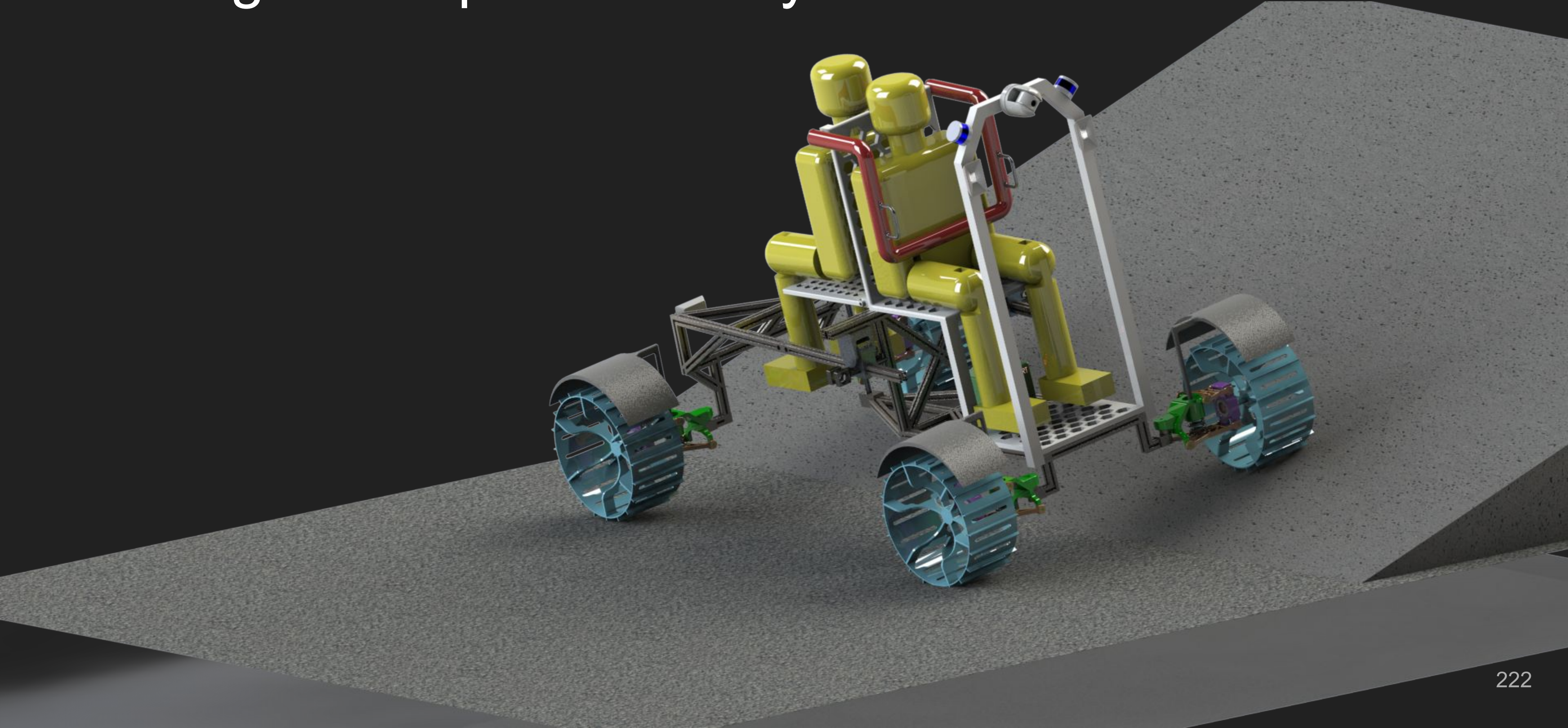
20 Degree Slope - Uphill



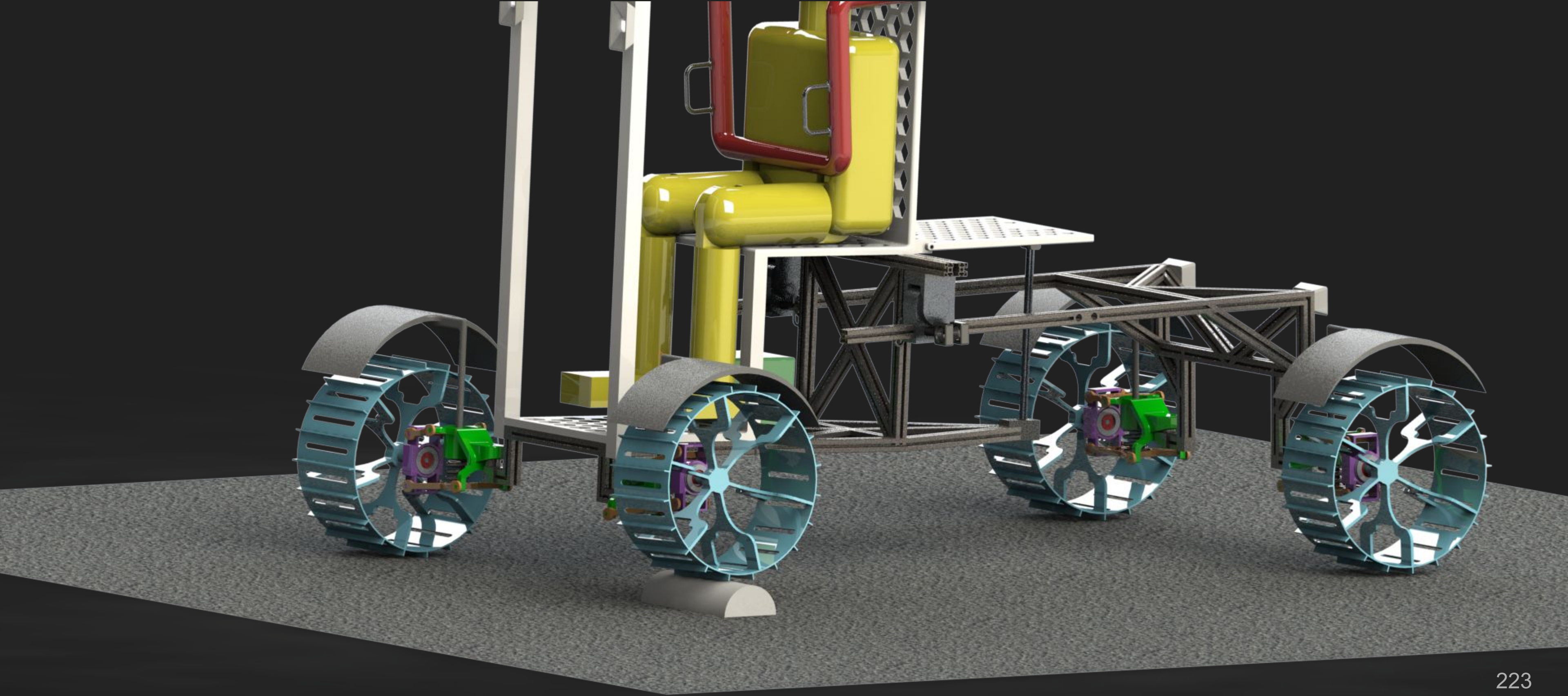
20 Degree Slope - Sideways



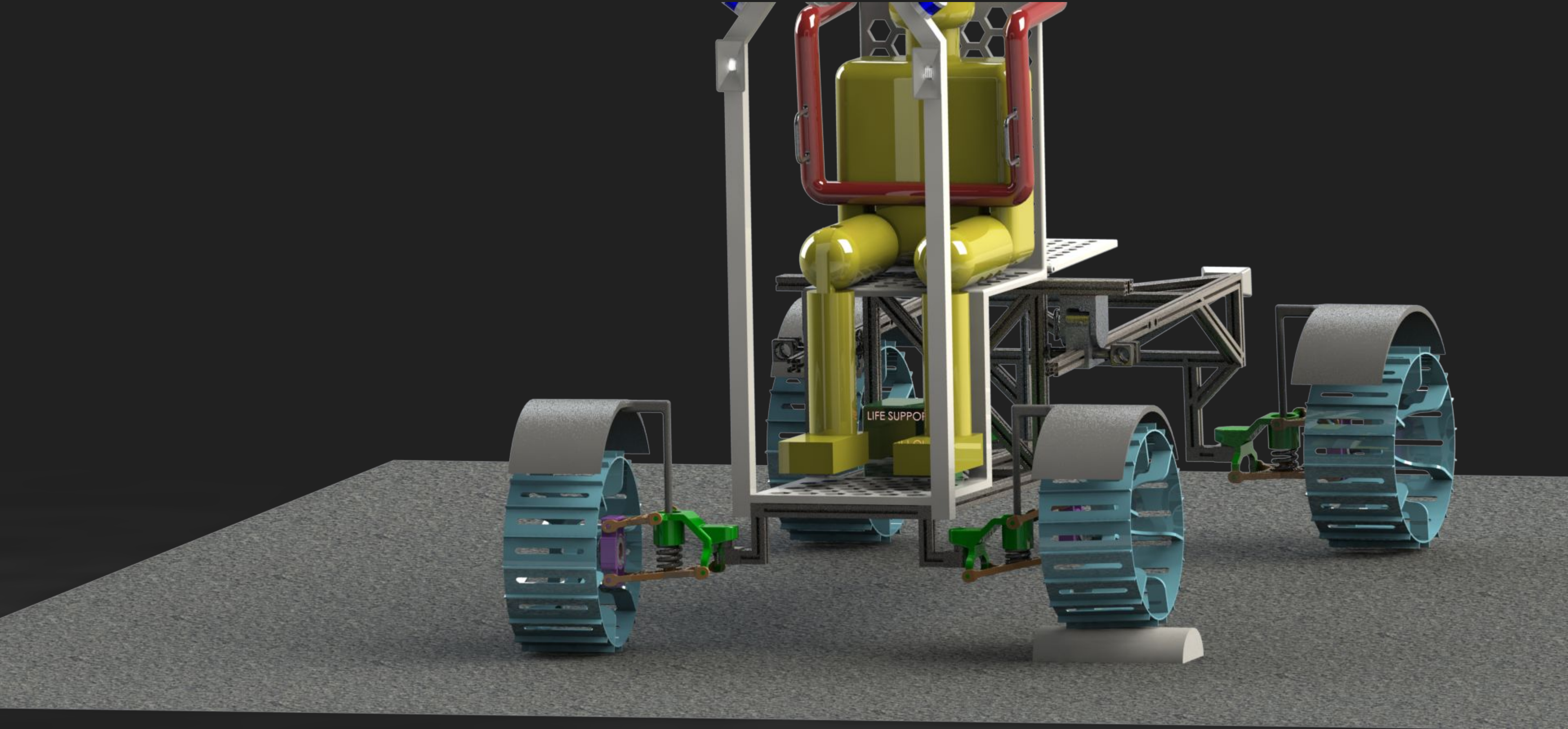
20 Degree Slope - Sideways



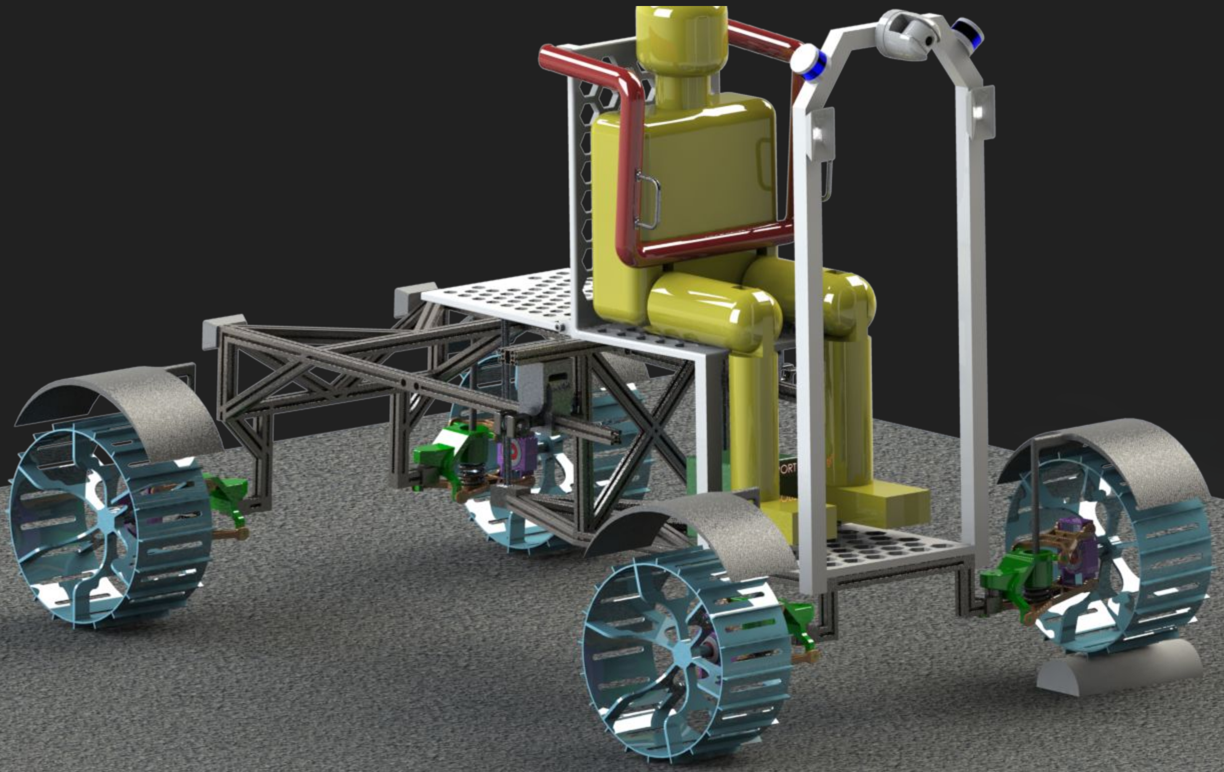
0.1m Obstacle



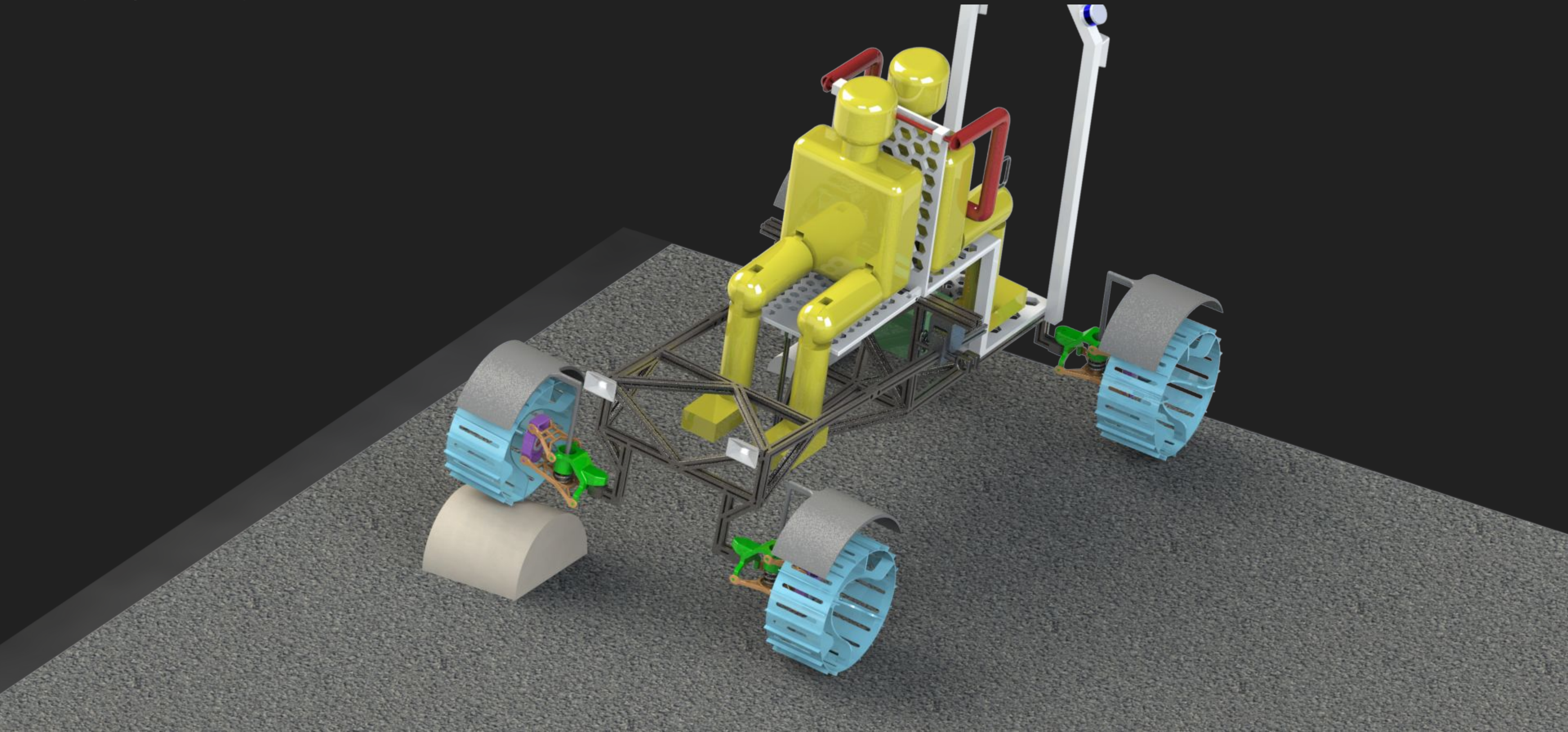
0.1m Obstacle



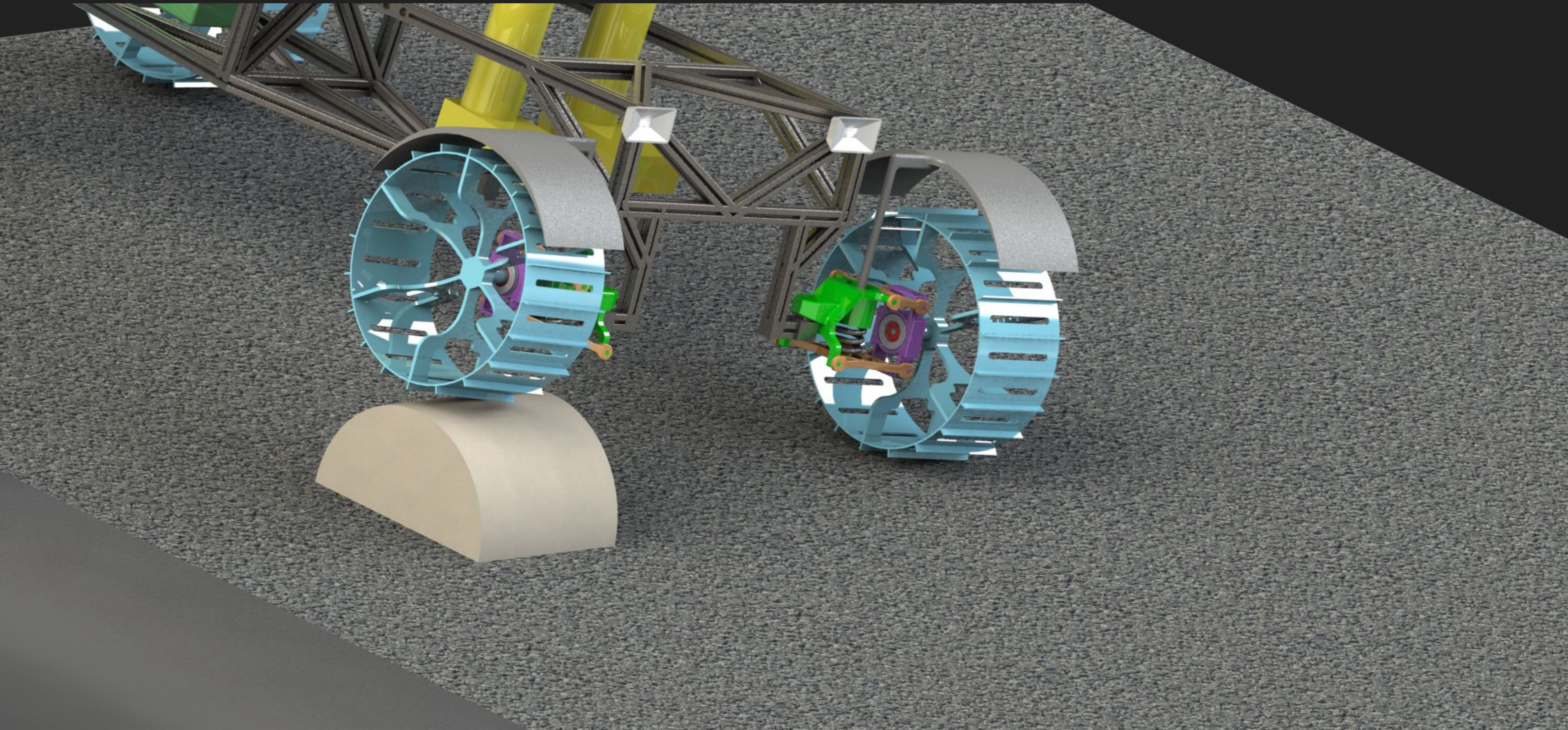
0.1m Obstacle



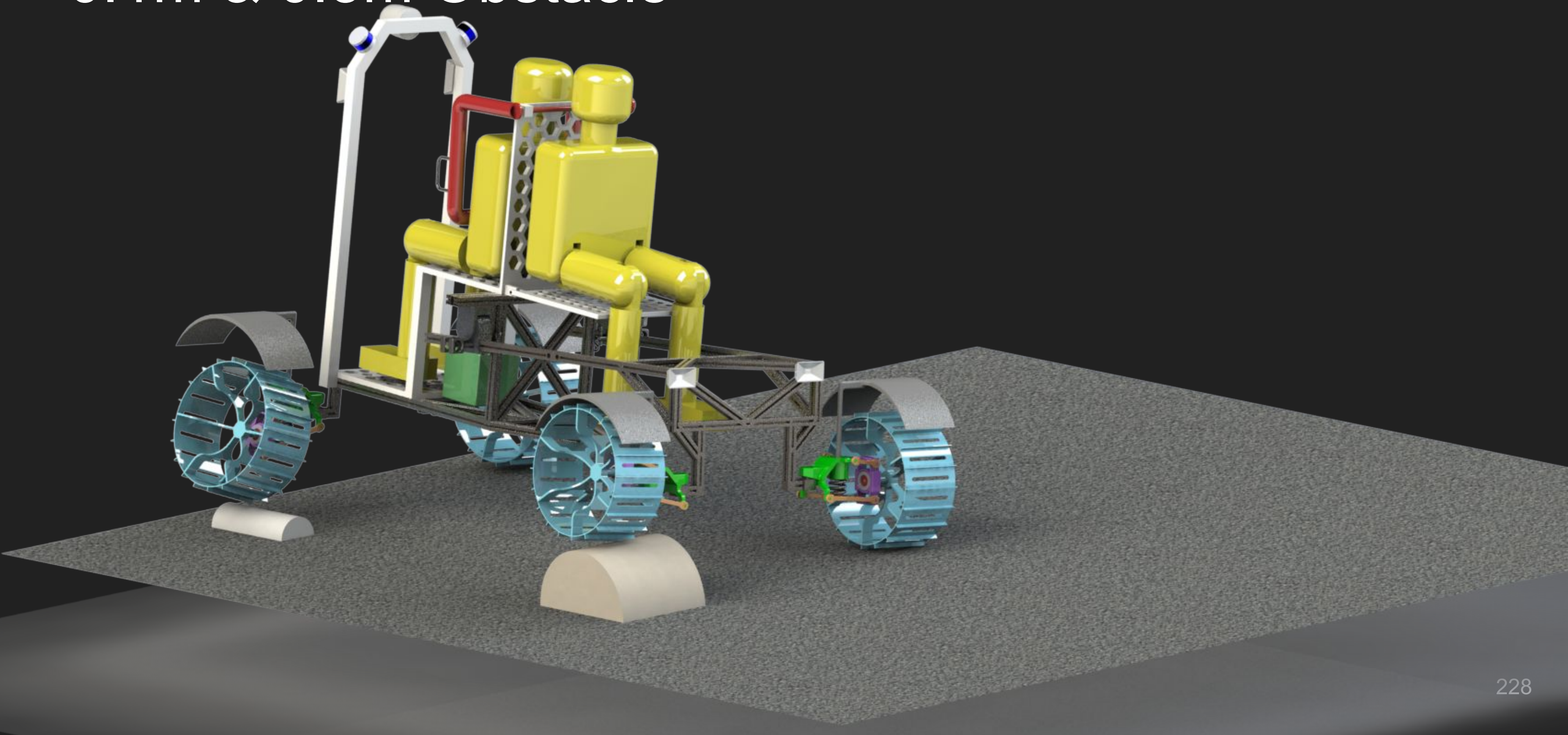
0.3m Obstacle



0.3m Obstacle



0.1m & 0.3m Obstacle



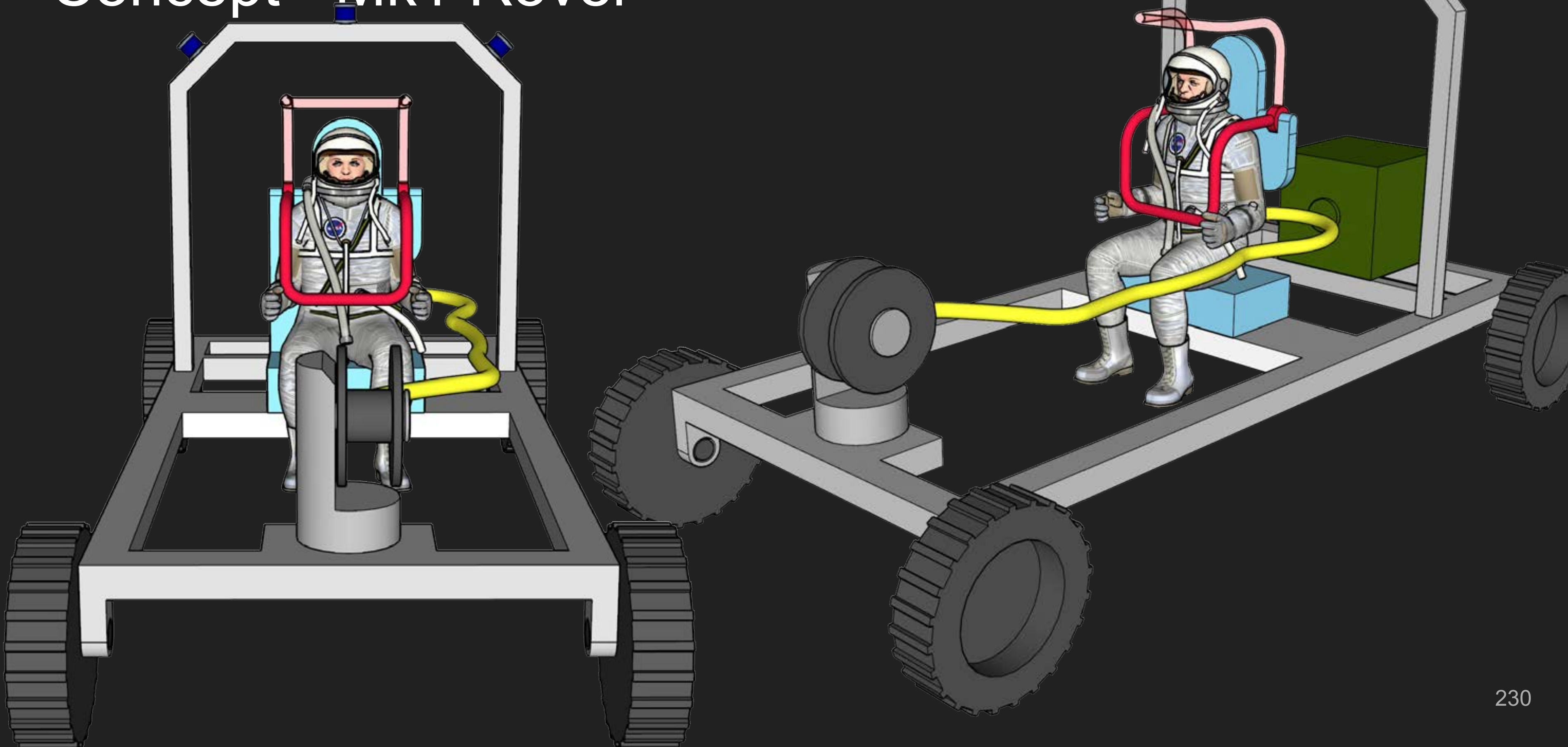
Design Evolution

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."

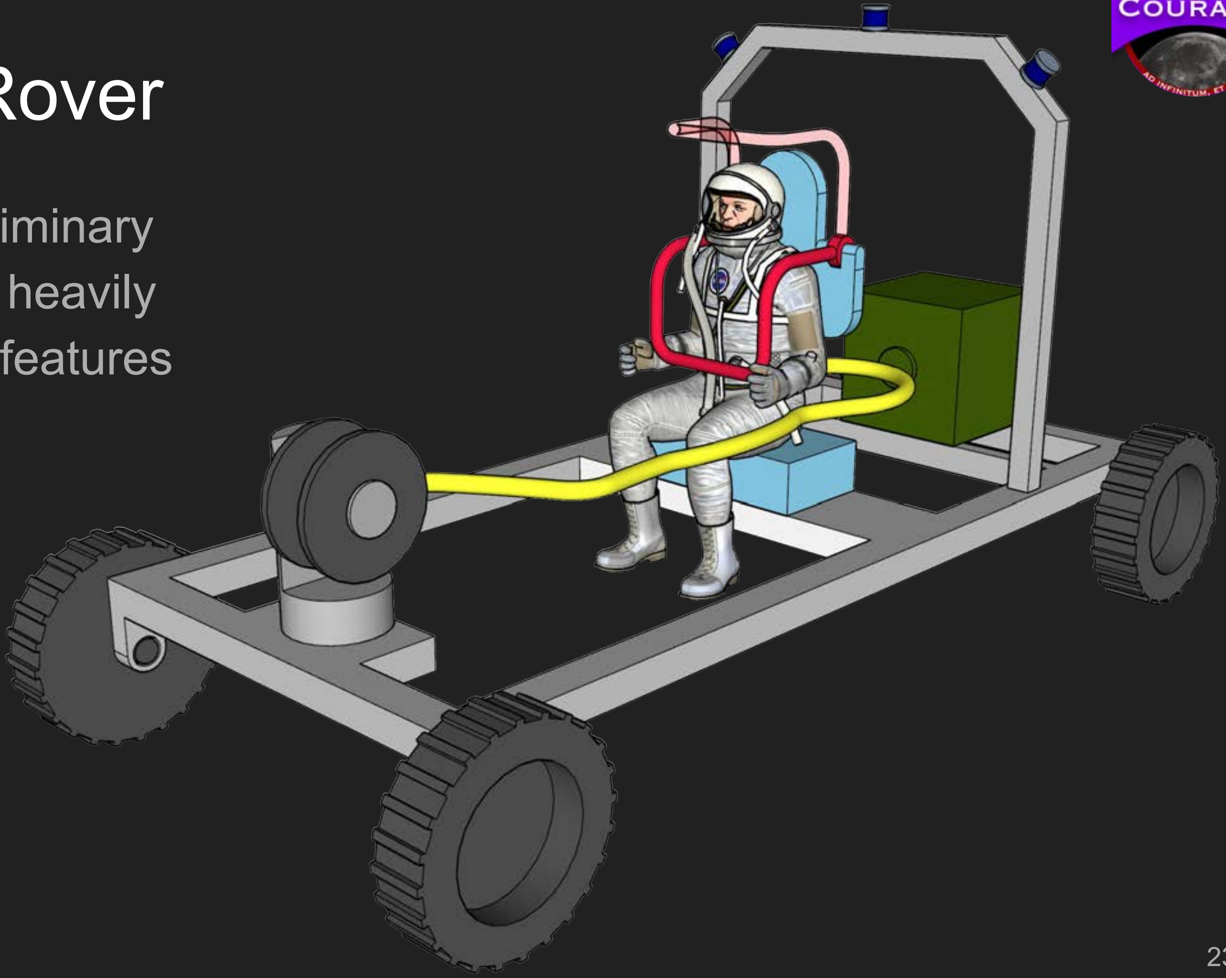
-Akin's Laws of Spacecraft Design

Concept - Mk1 Rover



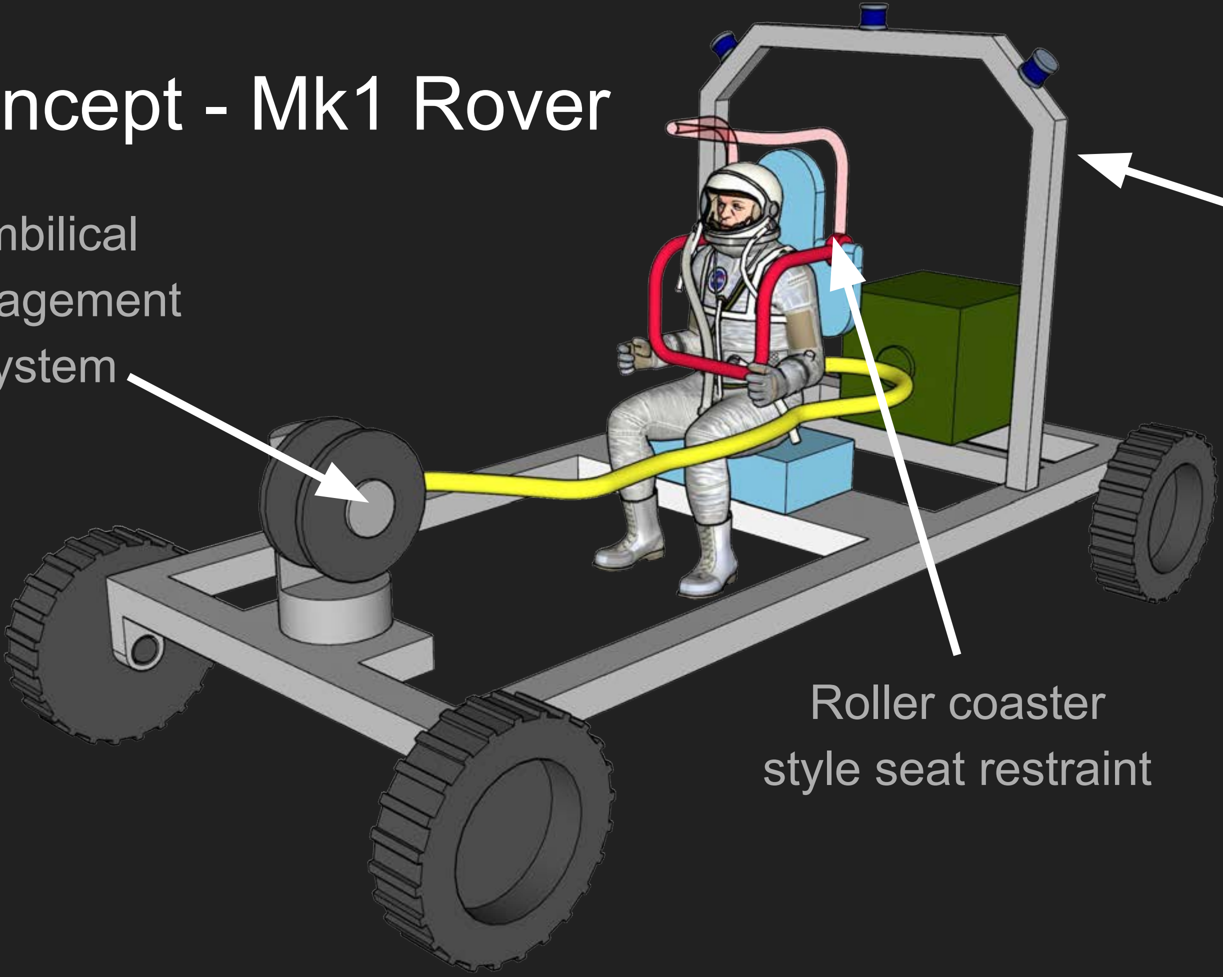
Concept - Mk1 Rover

The Mk1 rover was a preliminary layout prototype. It draws heavily from the Apollo LRV, and features 4 wheels with individual suspension.



Concept - Mk1 Rover

Umbilical management system



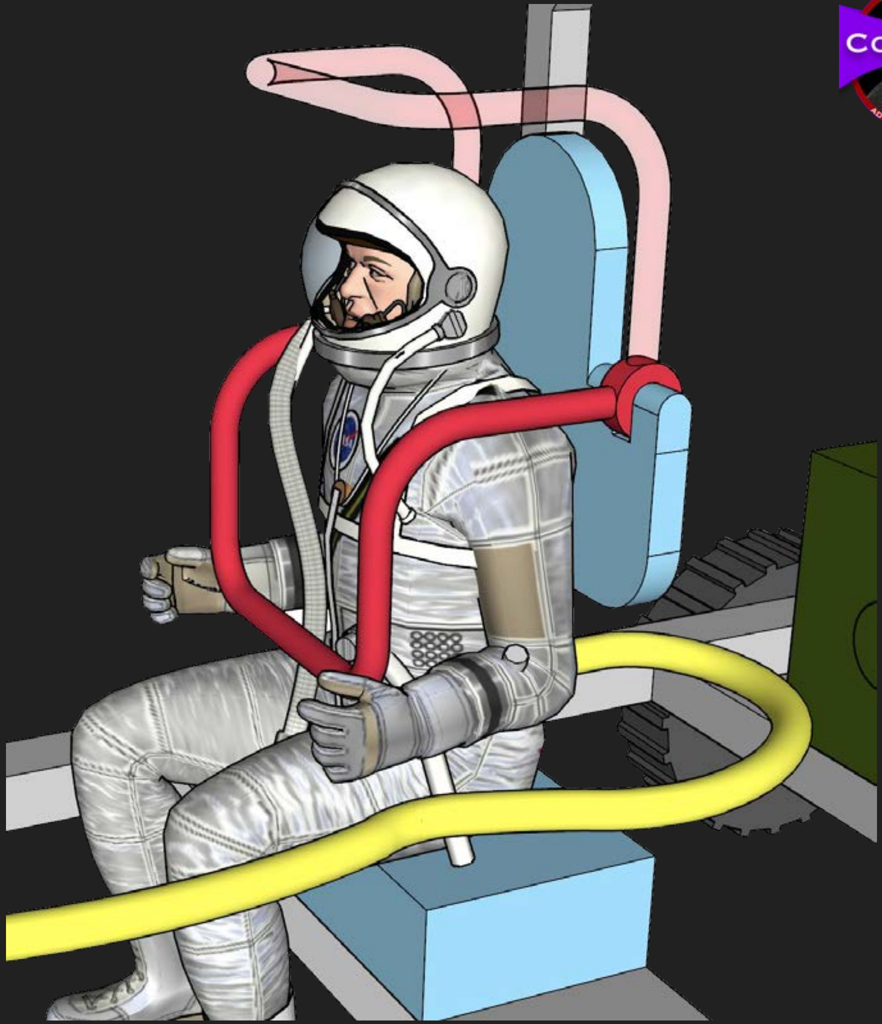
Sensor arch with Velodyne LiDAR pucks, flood lights, and several PTZ cameras (not shown).

Configurations with 2 or 3 sensor arches are also possible with this design

Roller coaster style seat restraint

Concept CAD: Seat Restraint

The astronaut is secured in their seat with a rollercoaster style over the shoulder restraint. This restraint includes handlebars and can be released via a foot pedal

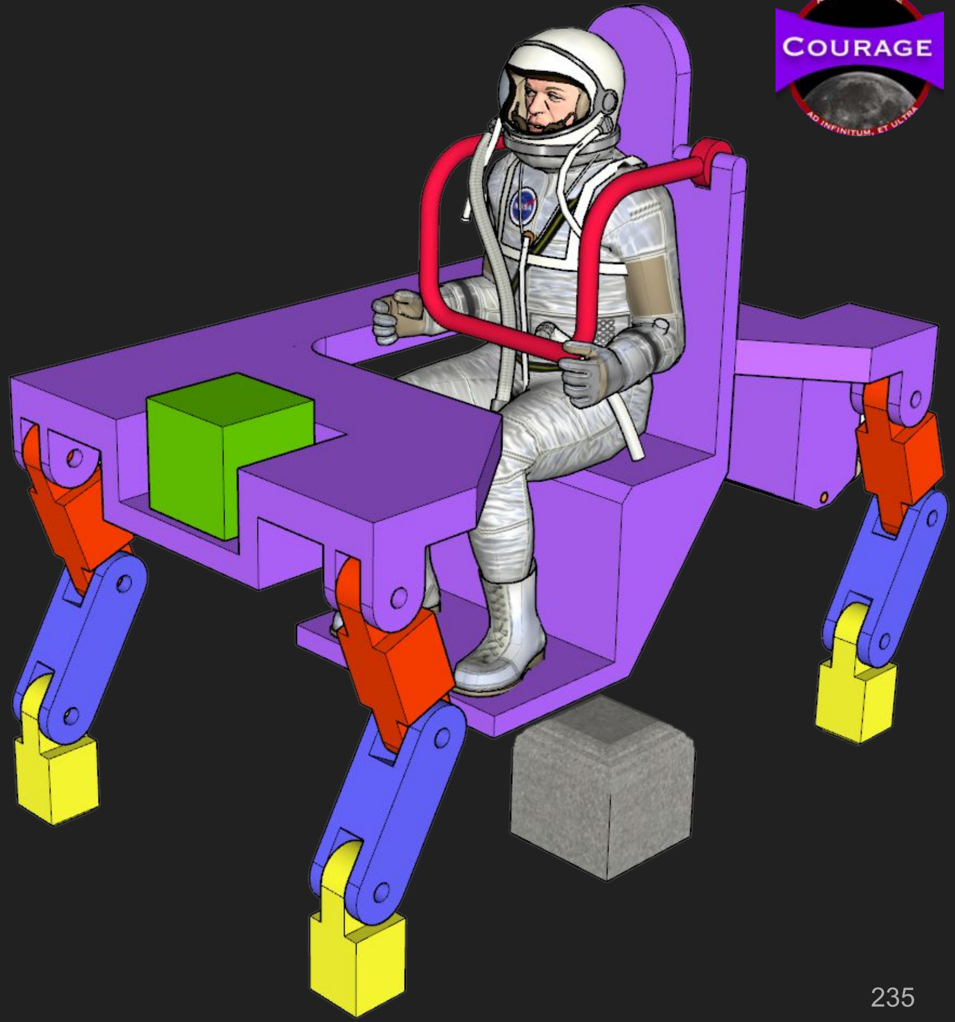


Preliminary CAD: Seat Restraint

The astronaut is secured in their seat with a rollercoaster style over the shoulder restraint. This restraint includes handlebars and can be released via a foot pedal

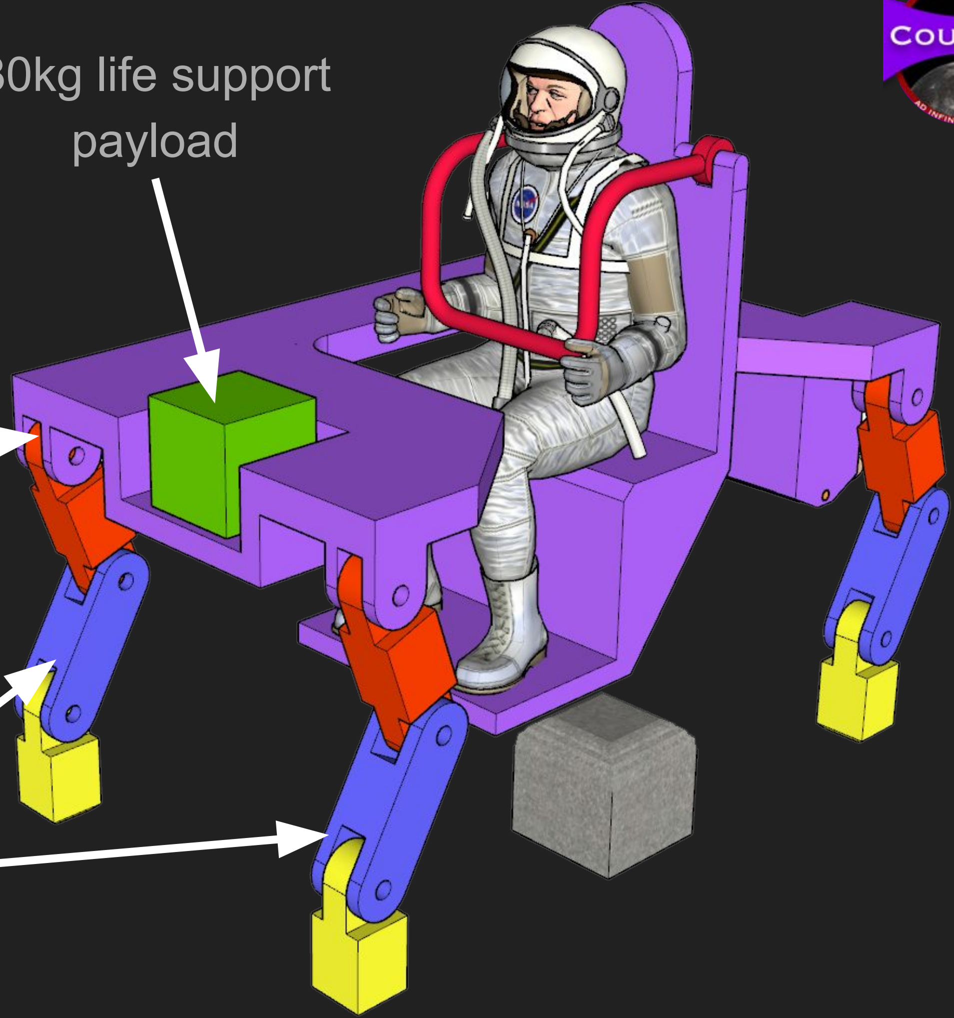
Concept - Horsebot

The Horsebot is a bio-inspired concept that utilizes four 4 Degree of Freedom legs to walk over varied terrain.

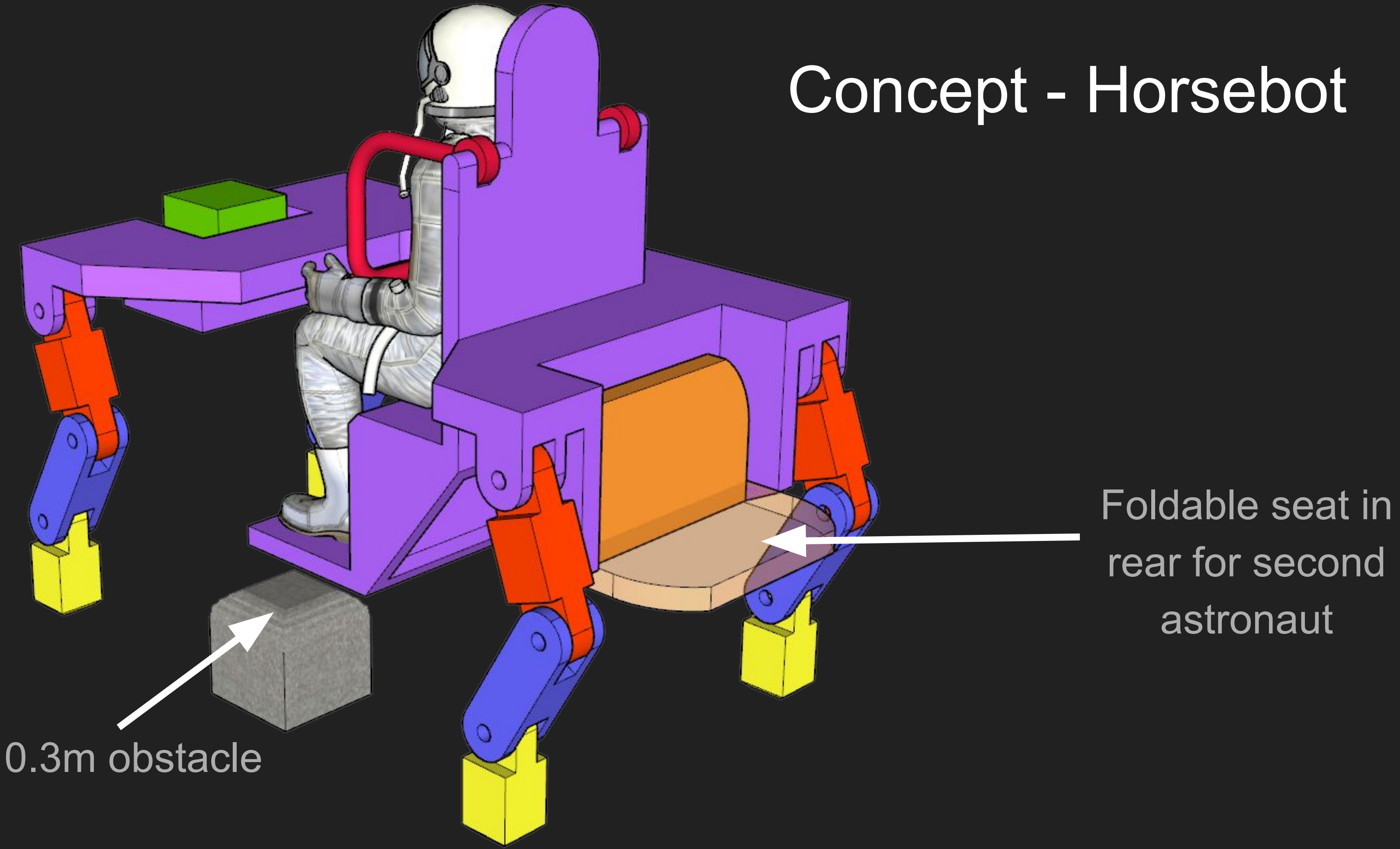


Concept - Horsebot

- Bio-inspired legged locomotion

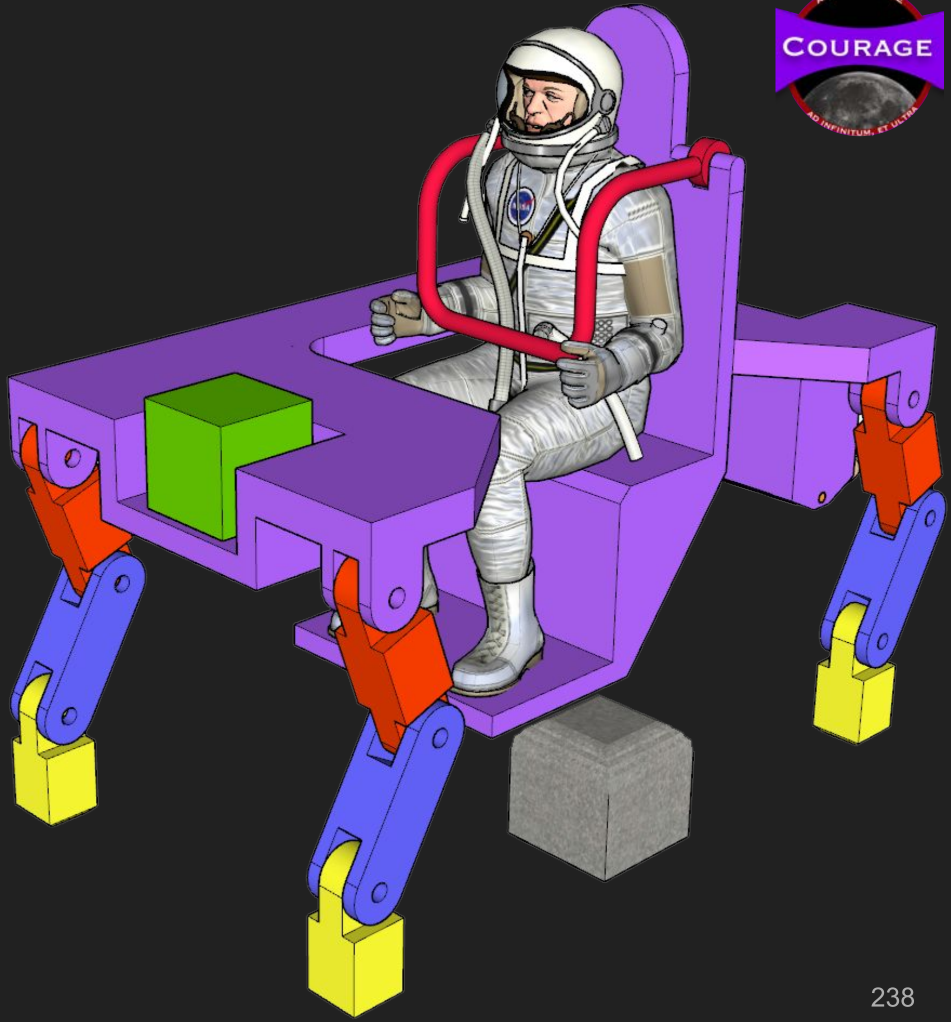


Concept - Horsebot



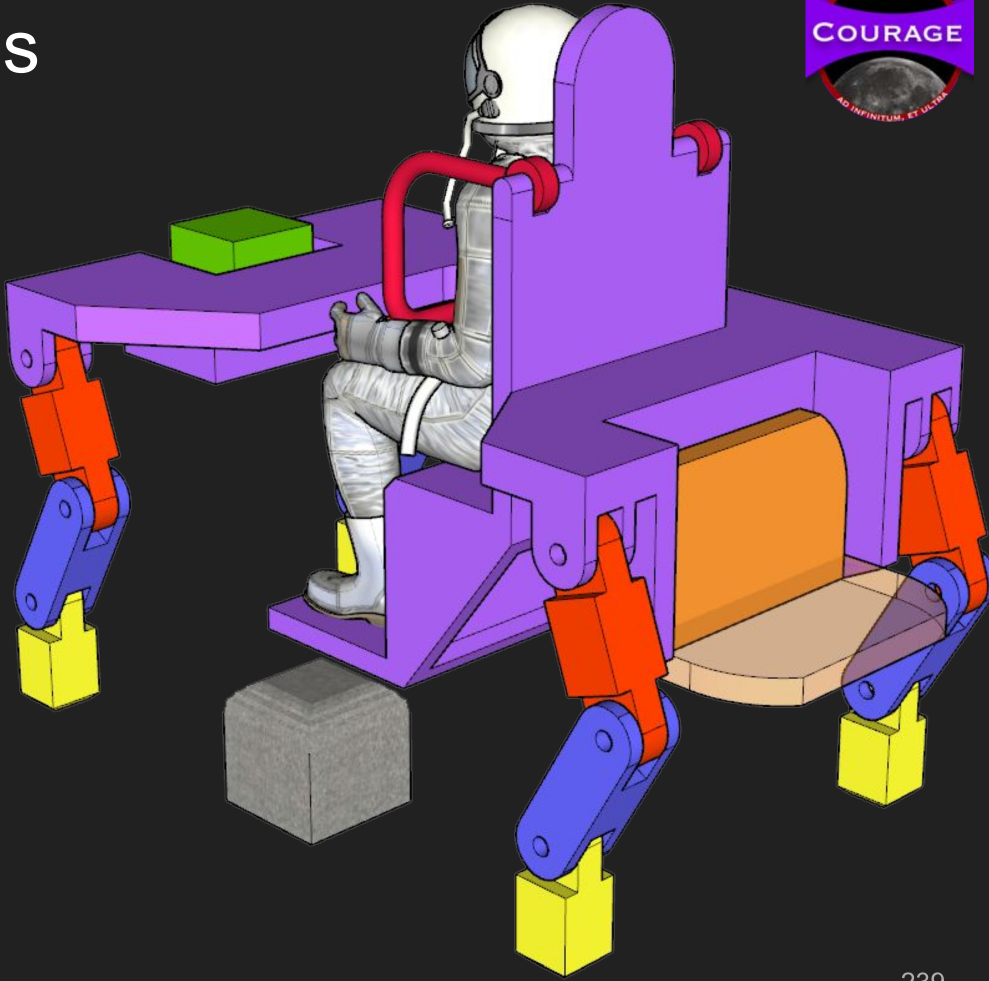
Concept - Horsebot - Pros

- Legged locomotion easily clears any obstacle
- Works well on rugged/uneven terrain
- 360° rotation hip joint allows Horsebot to walk sideways (or at arbitrary angle) with its standard gait
- Easy to incorporate second rider
- Seat position keeps center of mass relatively low
- Novel and interesting



Concept - Horsebot - Cons

- Legs are more complex than wheels (more ways to fail)
- Legs require more actuators (more weight)
- 4 m/s would require a medium trot/slow gallop gait, which are only dynamically stable
- Trot/Gallop gait requires much faster and higher torque motors (more weight, more power)
- Additional DoFs (ex: hip abduction, ankle pronation) might be needed for walking on slopes



Concept - Wheeled Horsebot

Similar to the Horsebot shown in previous slides, this concept 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.

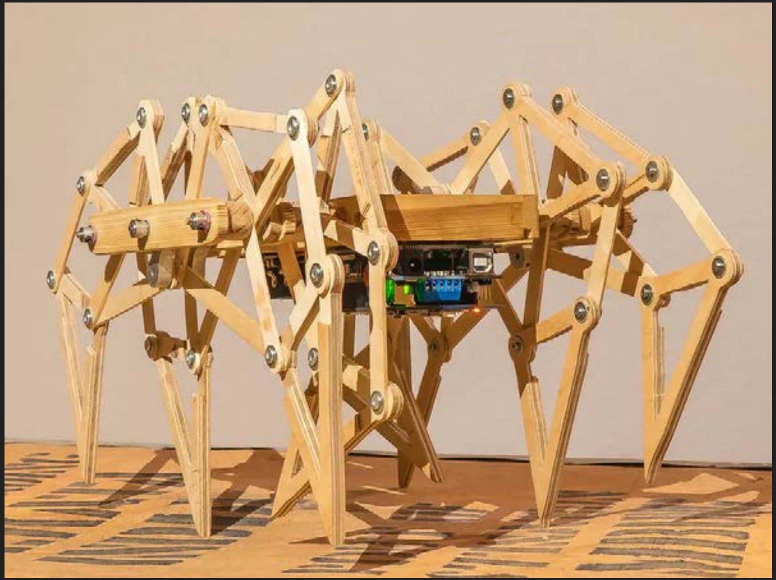
The increased weight from the extra motors makes this concept impractical for this mission

Concept - Strandbeest Locomotion

Locomotion inspired by Theo Jansen's Strandbeests and other similar designs

https://www.newmobility.com/2018/09/spider-chair/

https://www.newmobility.com/2013/07/walking-wheelchair-with-12-legs/



https://www.hackster.io/fx4u/strandbeest-a-robotic-project-7e1e23

Concept - Strandbeest Locomotion - Pros

- Legs can be actuated with very few motors
- Chair centric design is compact and relatively lightweight (center photo on previous slide is 96 kg)
- Novel and interesting design

https://theawesomer.com/the-walking-chair/539767/

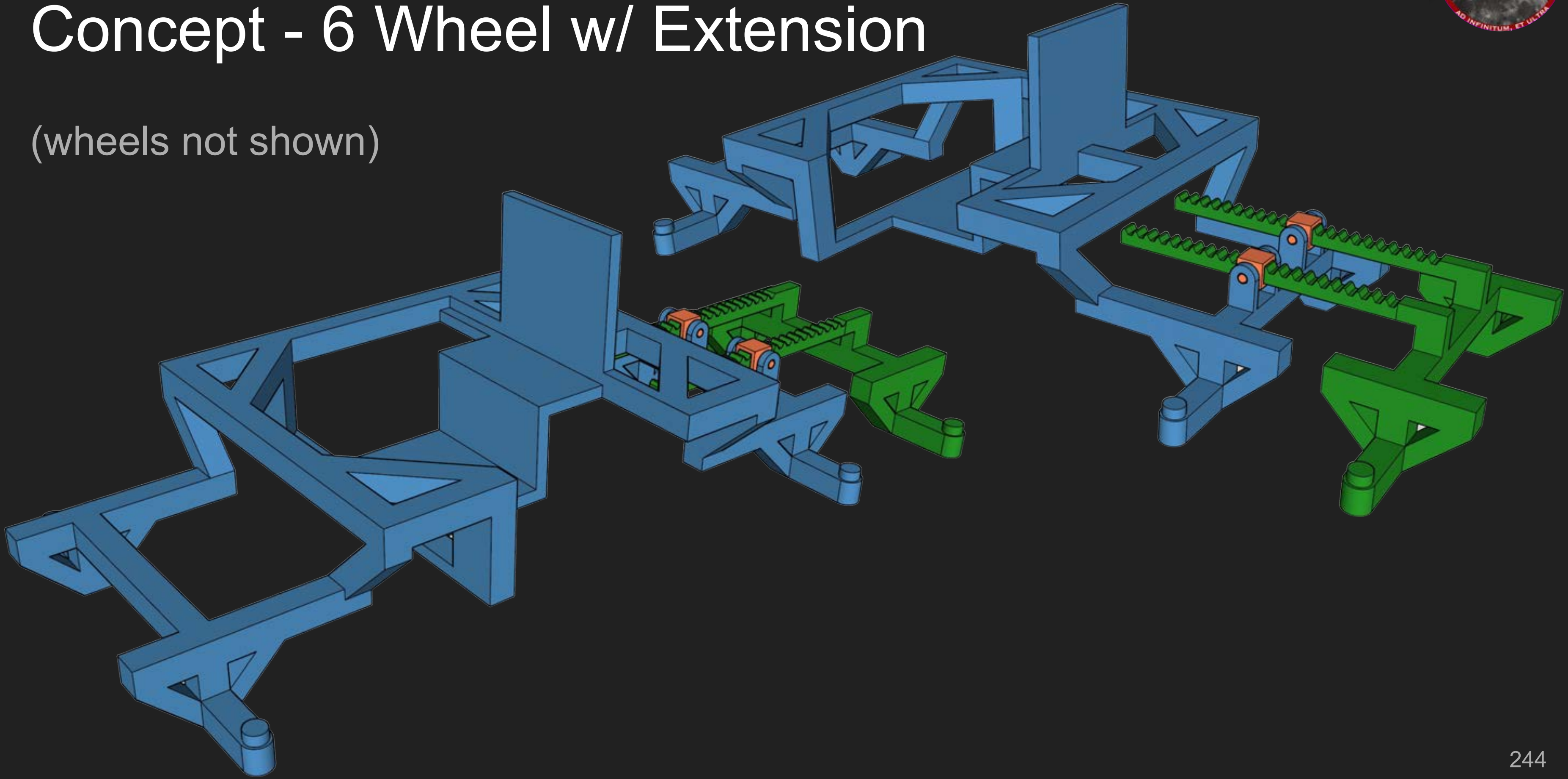
https://mikeshouts.com/bicycle-with-mechanical-walking-legs-by-the-q/

Concept - Strandbeest Locomotion - Cons

- Very high mechanical complexity (*many* ways to fail)
- Well tested on sand, but not well tested on rugged/uneven terrain
- Largely incompatible with stair climbing (due to leg lengths)

Concept - 6 Wheel w/ Extension

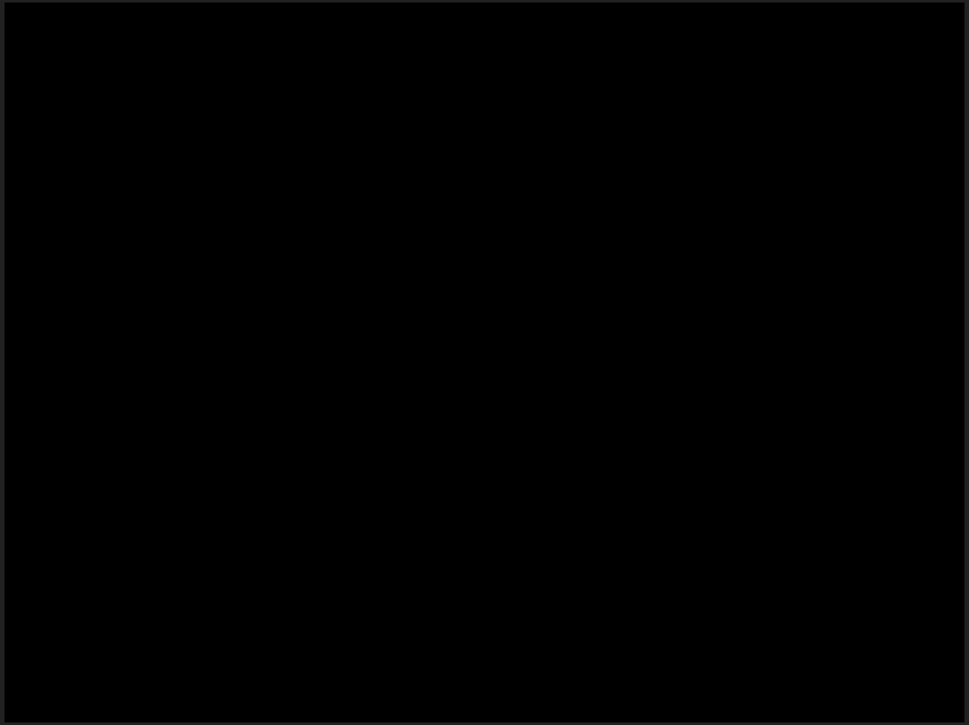
(wheels not shown)



Concept - 6 Wheels w/ Extension

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 wider 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 on the previous slide) for improved stability, as well as an additional pivot (orange, on the previous slide), allowing for the rear wheels to not be coplanar with the rest of the rover (ex: exiting a hill)

Crank Actuated Extension



Structure

Strength Analysis - Rear Arch Cross Beam

$F = 670kg * 1.62 m/s^2 * 0.5$

$$\delta_{max} = \frac{Fa}{24EI}(3L^2 - 4a^2)$$

L=1.5m
a=0.25m

https://mechanicalc.com/reference/beam-analysis

45-9090 Type Aluminum Extrusion

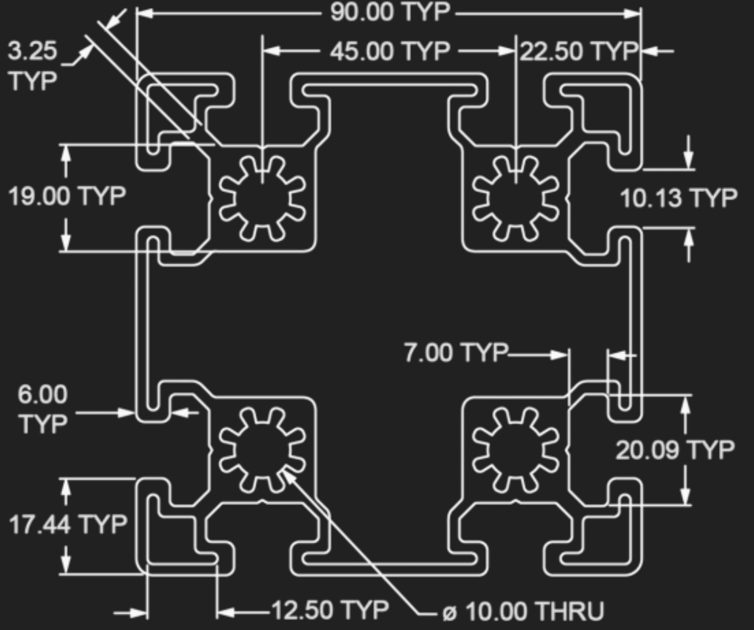
Young's Modulus=$70*10^9$ Pa

I = 179.4968 cm^4

A = 20.014 cm^2

Total Mass: **8.104 kg**

Max Deflection (@x=L/2): **0.29 mm**



https://8020.net/45-9090.html#

45-4545 Lite *Titanium* Extrusion

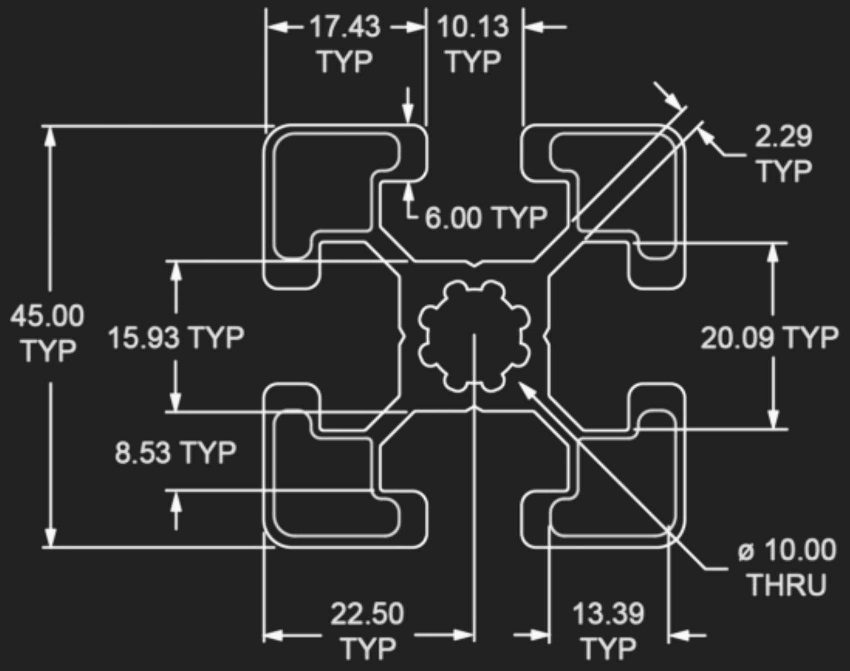
Young's Modulus=$170*10^9$ Pa

I = 9.2029 cm^4

A = 5.167 cm^2

Total Mass: **3.49 kg**

Max Deflection (@x=L/2): **3.3mm**

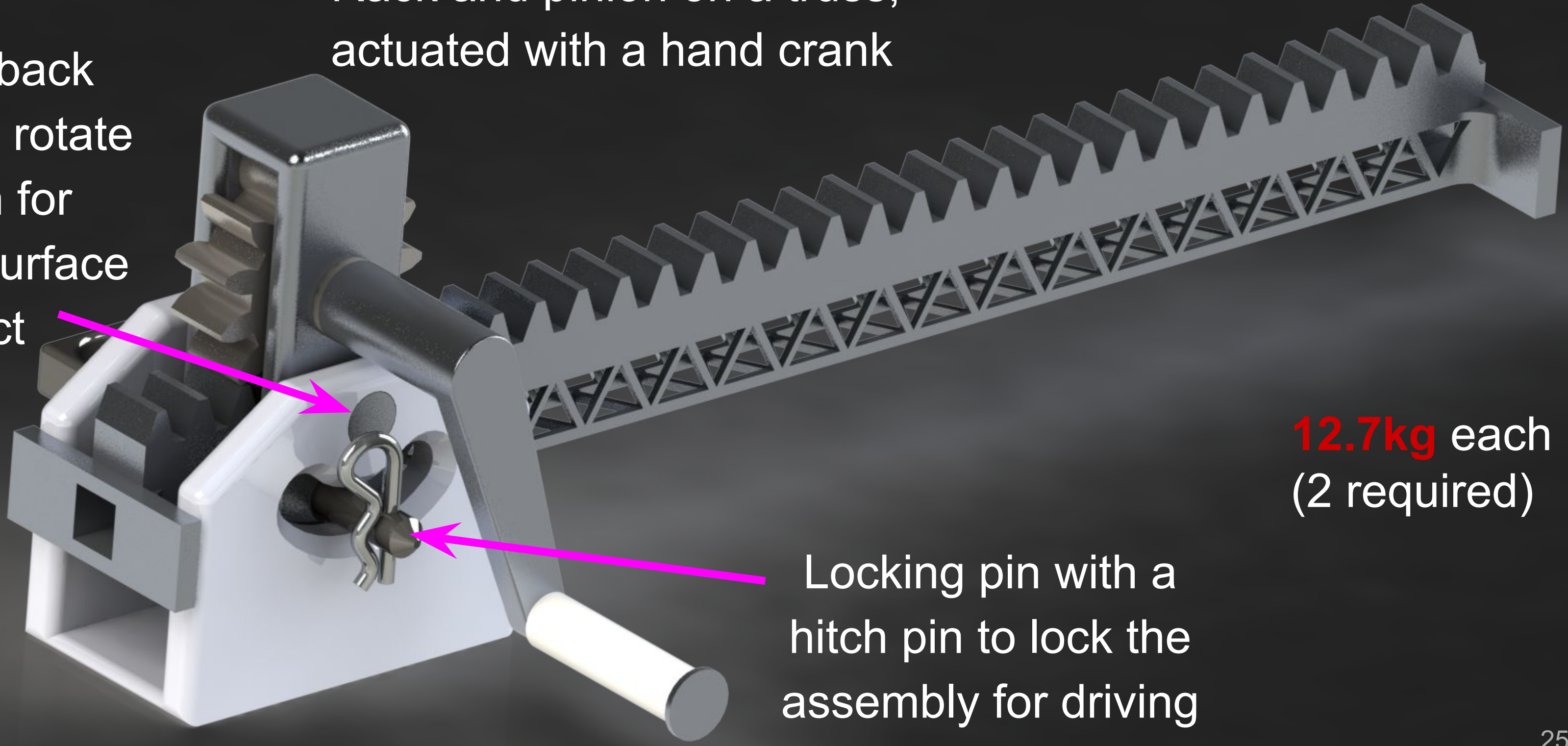


https://8020.net/45-4545-lite.html

Extension Mechanism - Original

Rack and pinion on a truss, actuated with a hand crank

Hinged - back wheels can rotate up/down for improved surface contact



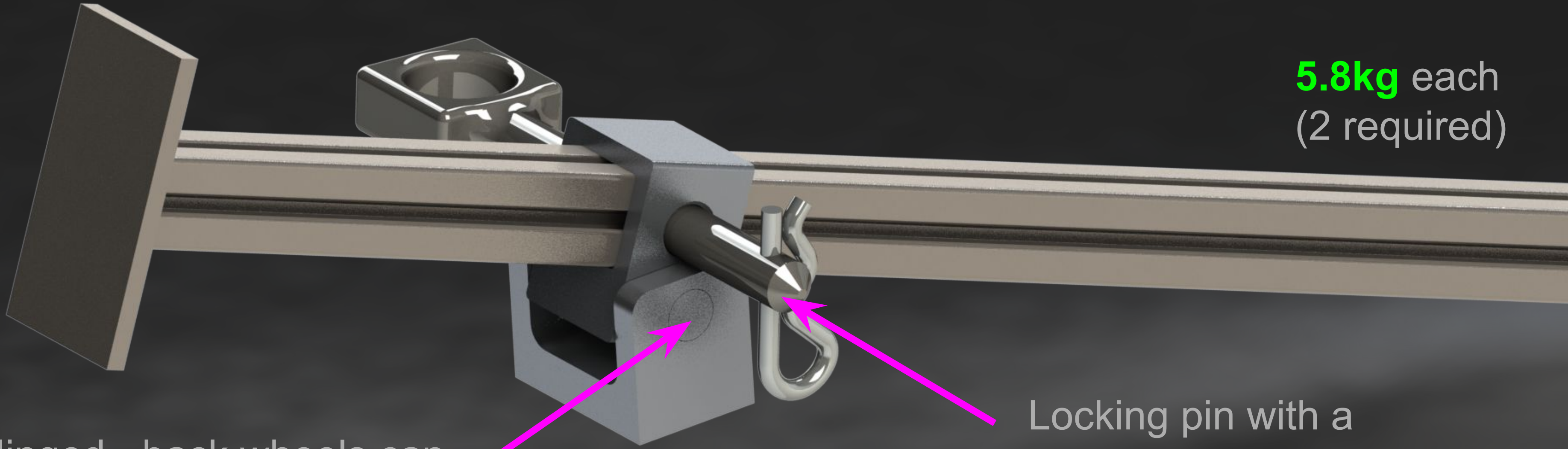
Locking pin with a hitch pin to lock the assembly for driving

12.7kg each (2 required)

Extension Mechanism - Simplified for Weight

Sliding 45-4545-Lite Titanium beam on rollers, actuated by reversing rear wheels

5.8kg each
(2 required)



Hinged - back wheels can rotate up/down for improved surface contact

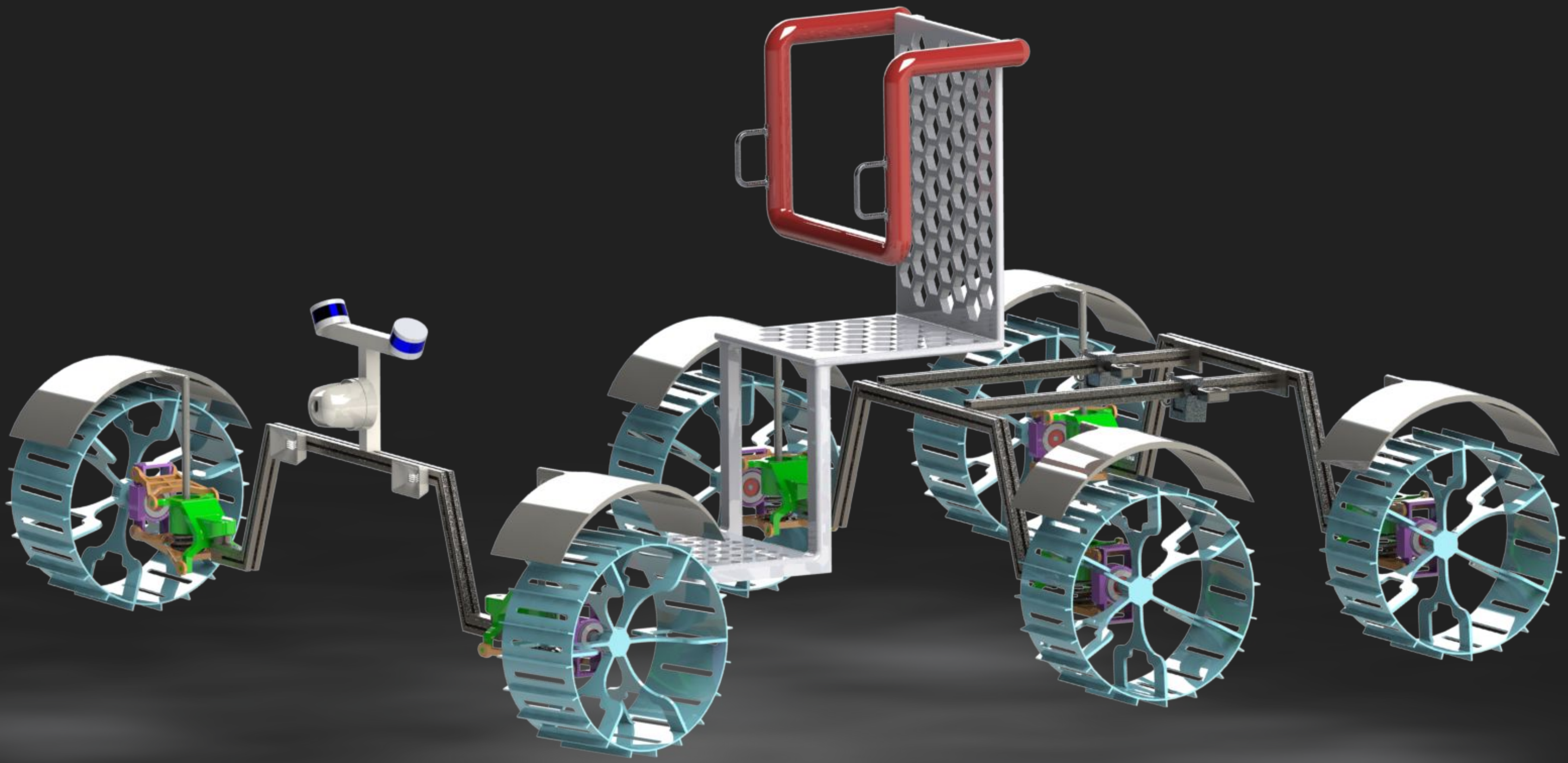
Locking pin with a hitch pin to lock the assembly for driving

Extension Mechanism

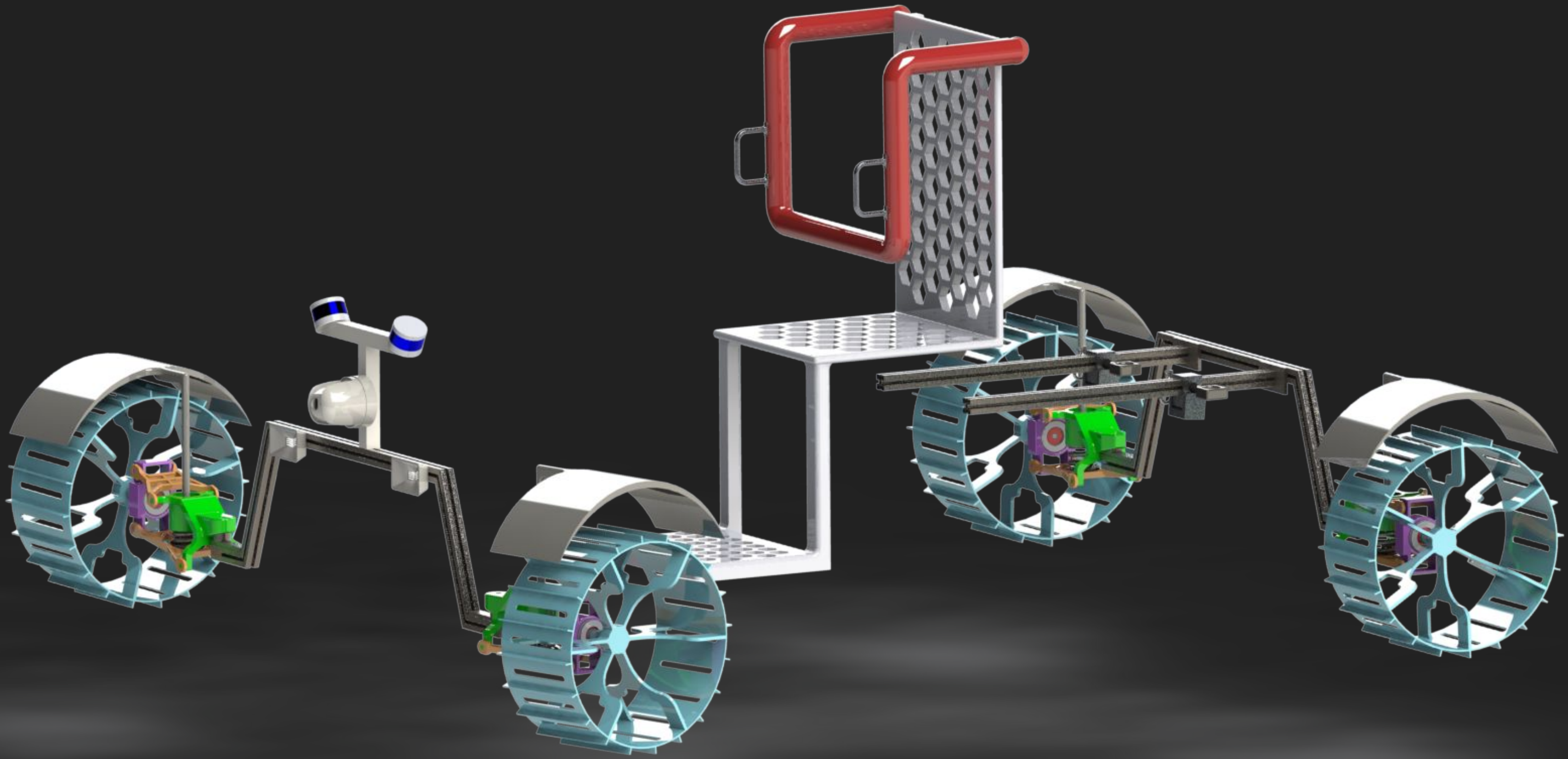
This extension mechanism revision was done when the rover still had arched chasses. The benefit of the weight savings in switching profiles and materials far exceeded the small decrease in structural strength. The sliding mechanism is now actuated by driving the rear wheels in reverse (and/or also driving the front wheels forward) to separate the two chassis halves.

Later revisions on this concept continue to use the titanium sliding beam, but offer additional reinforcement elsewhere in the structure (various braces and cross beams) and a much stronger pivot mechanism. The sliding box includes small rollers on the inside (like a skate wheel conveyor) to minimize friction.

6 Wheel Rover, Chassis Arches



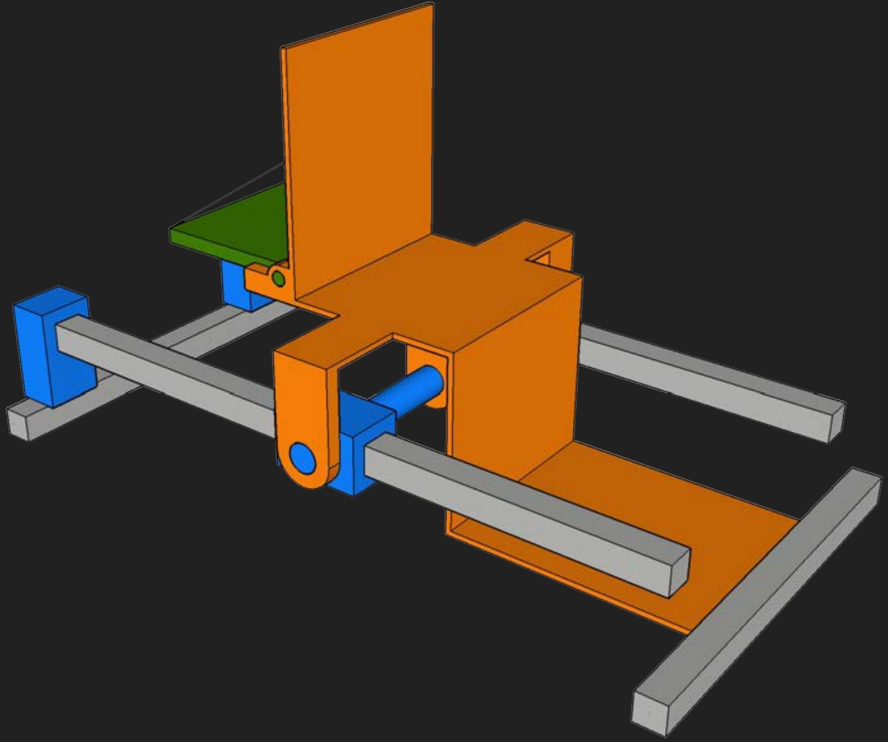
4 Wheel Rover, Chassis Arches

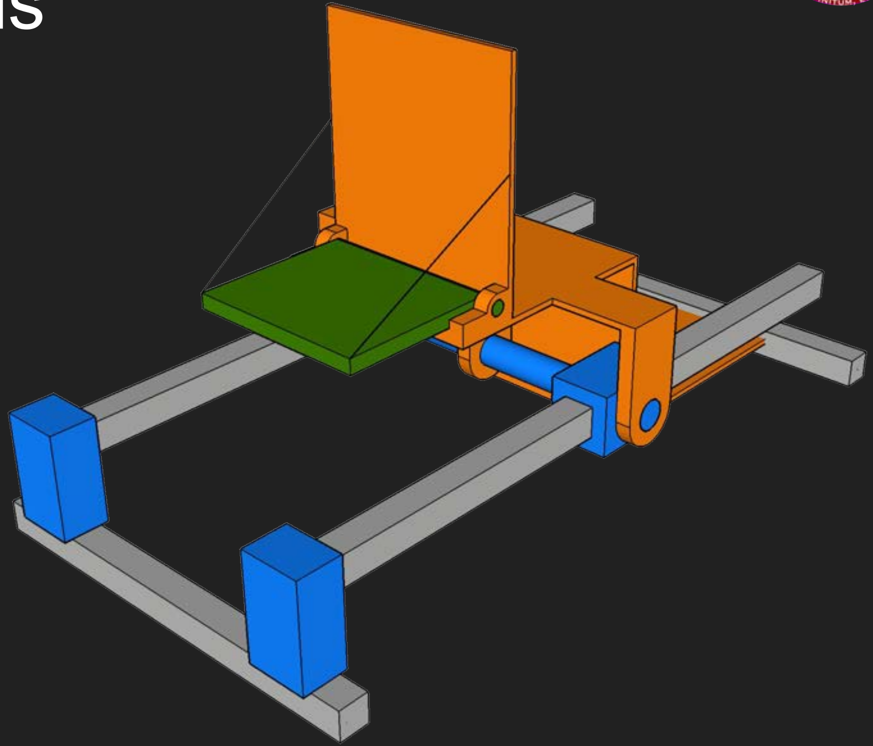


4 Wheel Rover, Chassis Arches

The middle two wheels in the 6 wheel design were excluded were 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.

4 Wheel Rover, Flat Chassis

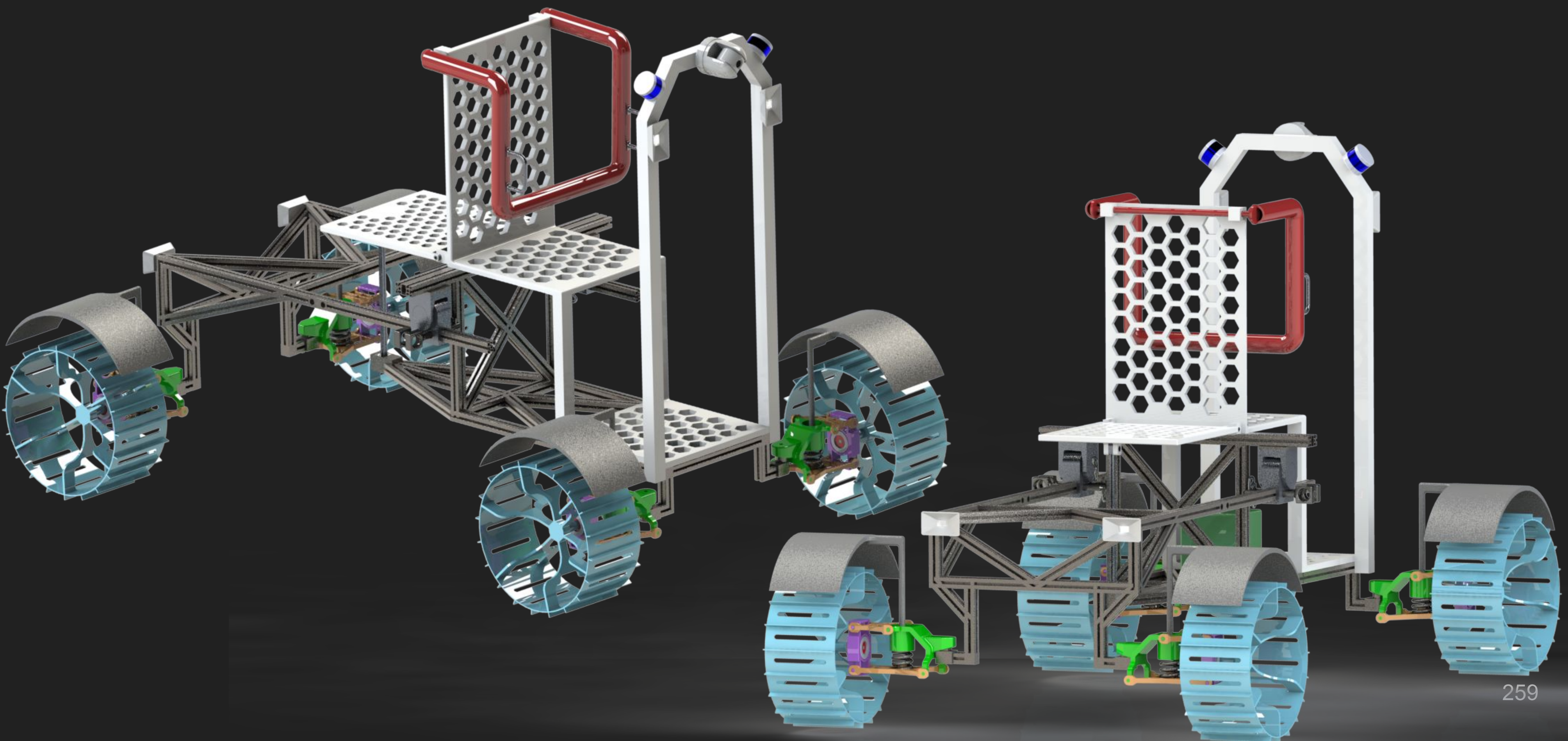




4 Wheel Rover, Flat Chassis

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.

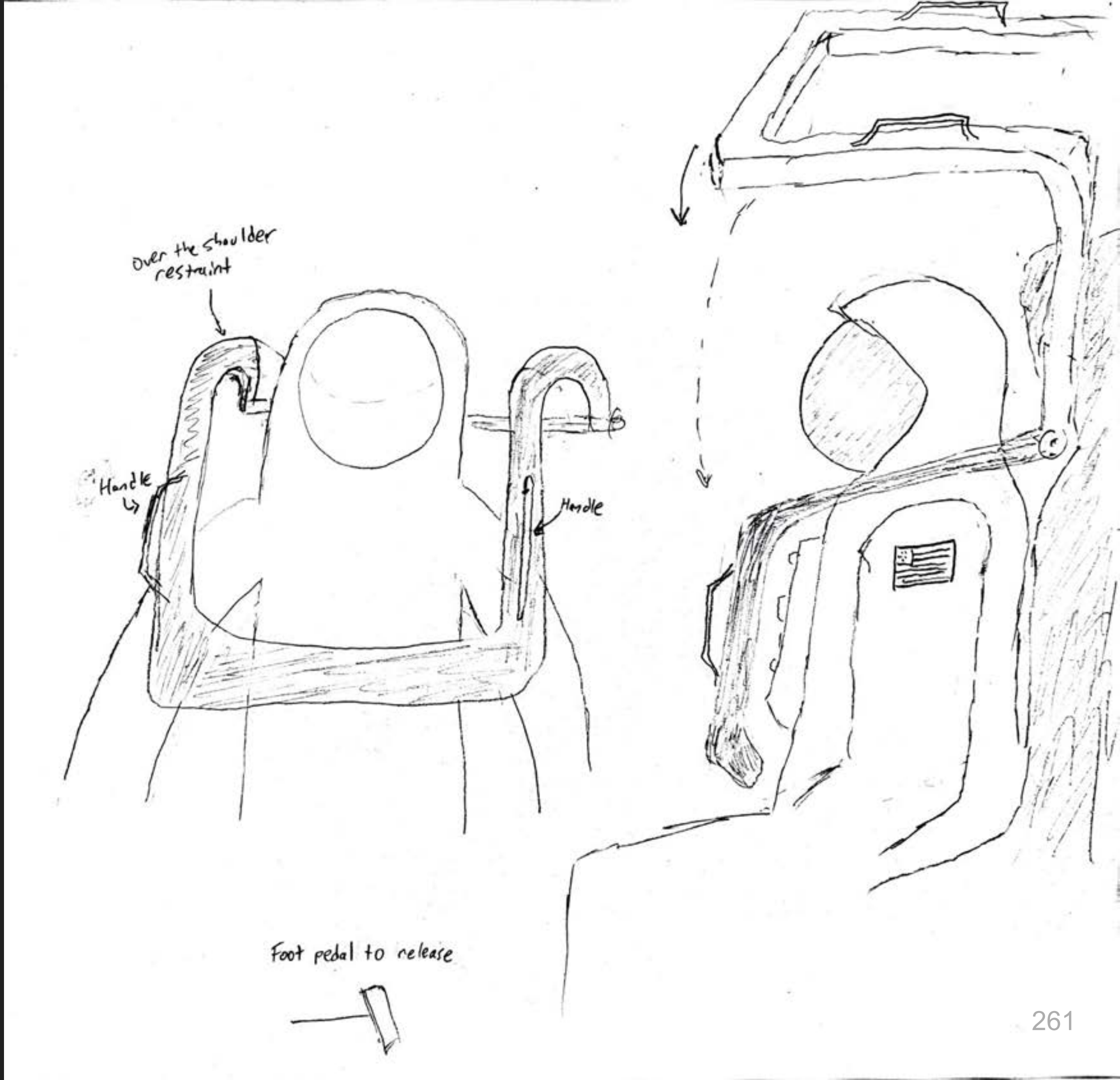
4 Wheel Rover, Flat Chassis (Final)



Sketches and Additional Concepts

Concept Sketch: Seat Restraint

The astronaut is secured in their seat with a rollercoaster style over the shoulder restraint. This restraint includes handlebars and can be released via a foot pedal

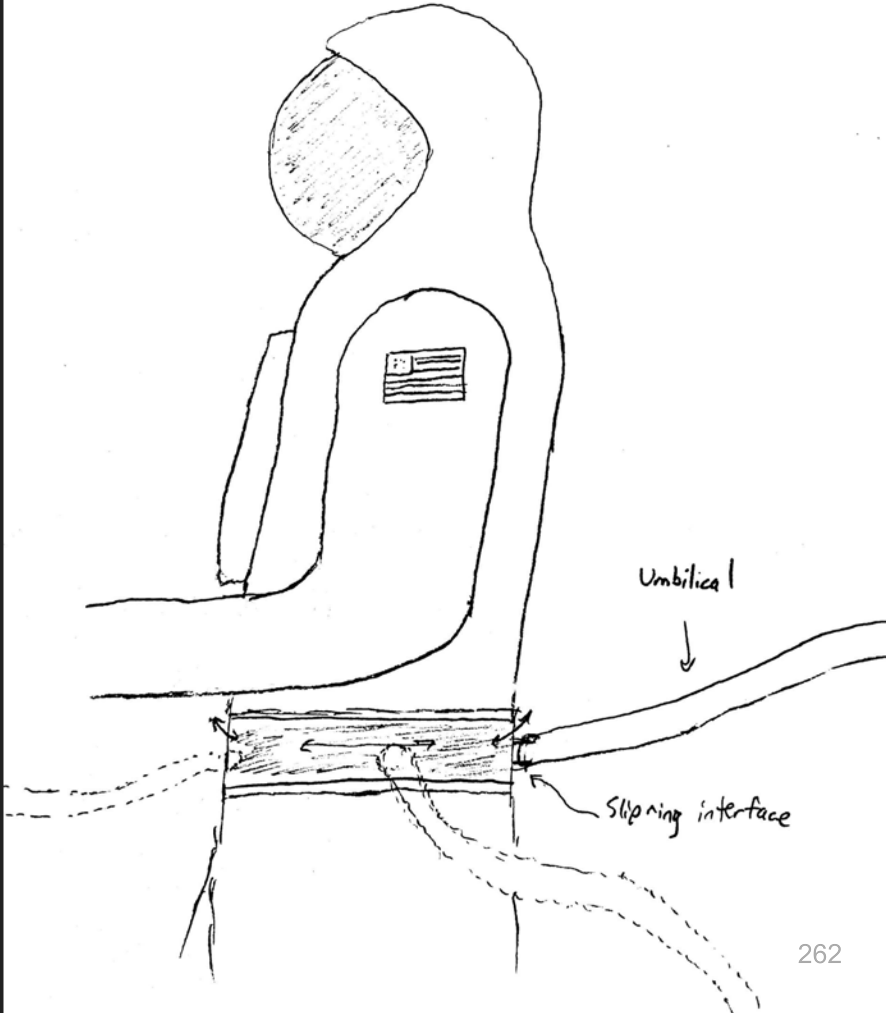


Concept Sketch: Umbilical Interface

The astronaut's umbilical hose connects to their EVA suit via a slip ring interface at their waist, which allows the hose to rotate freely around the astronaut as they move.

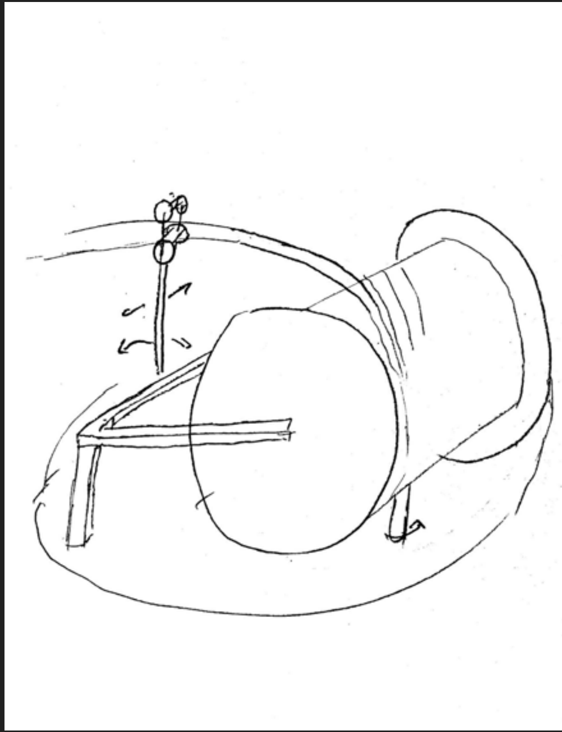
To enter the Hab:

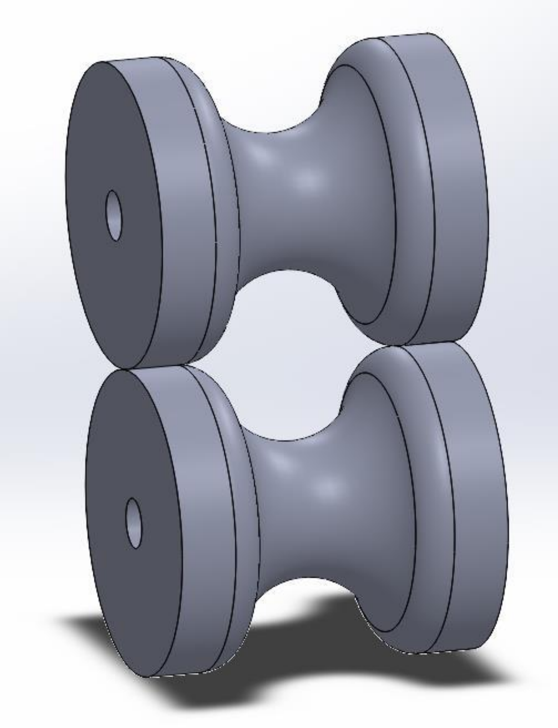
1. Enter airlock (door open, still connected to rover hose)
2. Connect Hab umbilical hose to second waist port
3. Wait for system confirmation of successful connection
4. Disconnect rover hose
5. Close airlock door and begin decompression



Concept Sketch: Umbilical Hose Management

Umbilical spool sits on a lazy susan and can spin freely to 'face' the astronaut. The spool can be unwound as the astronaut walks and is rewound by a motor. The hose is fed through double rollers for reduced friction/snagging





Concept - Multiple Treads

https://www.kimpex.com/en-us/products/atv/winter-accessories/atv-utv-tracks/commander-wss4-track-kit-4-seasons

Concept - High DoF Articulated Suspension

https://www.therobotreport.com/energid-to-provide-sdk-to-help-power-motivs-robomantis-platform/

https://spinoff.nasa.gov/Spinoff2019/ps_3.html

Concept - Enormous Wheels (Lunar Monster Truck)

https://www.pinterest.com/pin/827747606488888555/

https://www.beautifullife.info/automotive-design/best-all-terrain-vehicles-for-sale/

Future Work

Larger Suspension assembly to handle larger obstacles

Safety covering over extender beams to protect against pinched fingers/toes/extremities

Fold out stairs on side for easy ingress/egress to second seat

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/

Check Mark from http://www.clker.com/clipart-transparent-green-checkmark.html