HERMES

Hazard Examination and Reconnaissance Messenger for Extended Surveillance

PRELIMINARY DESIGN REVIEW
OCTOBER 15, 2018

Presenters: Marcos Mejia, Chase Pellazar, Colin Chen, Junzhe He, Alexander Sandoval, Ashley Montalvo, Brandon Santori, Quinter Nyland, Alexis Sotomayor
Customer: Barbara Streiffert and Jet Propulsion Laboratory (JPL)
Advisor: Dr. Kathryn Anne Wingate
Team: Alexander Sandoval, Alexis Sotomayor, Ashley Montalvo, Brandon Santori, Brindan Adhikari, Chase Pellazar, Colin Chen, Junzhe He, Katelyn Griego, Marcos Mejia, Michely Tenardi, Quinter Nyland

Project Heritage

The Jet Propulsion Laboratory’s Fire Tracker System is a system that is designed to be a low-cost, hands-off approach to **forest fire identification.**

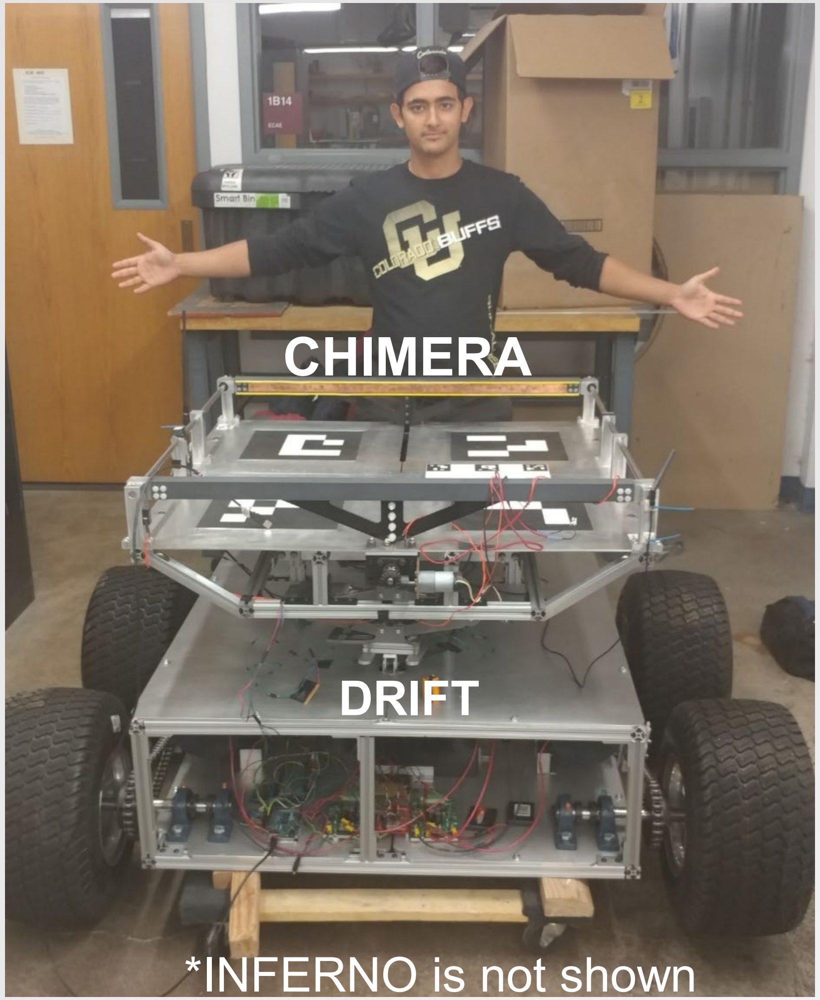
There have been **three previous years of heritage**:

1. **INFERNO (2015-2016)**
   - Built a semi-autonomous drone capable of transporting and deploying sensor packages
2. **CHIMERA (2016- 2017)**
   - Built a landing, securing, and deployment system for the autonomous drone inherited from INFERNO
3. **DRIFT (2017-2018)**
   - Developed a **mother rover** to secure, carry, and level the autonomous drone from INFERNO using the landing platform from CHIMERA

Project Motivation

The **mother rover** is large and **difficult to navigate** through forest like areas.

HERMES aims to **improve** the Fire Tracker System by **path finding** for the mother rover (MR) to **avoid potential risk** of damage by large obstacles and uneven terrain.



*INFERNO is not shown

Project Statement

The HERMES team will design, build and test a **child scout rover** (CSR) that will **deploy** on command, take **images/videos** of the surrounding terrain, **determine** a **viable** path to a location of interest (LOI), and upon arrival to the LOI, the CSR will **send** the LOI **to** the **mother rover**, and then **re-dock** on the mother rover.

Definitions

General Definitions:

- **Location of Interest (LOI)** – The final location that the CSR and MR will navigate to. This is transmitted to the CSR from the Ground Station (GS)
- **Waypoint** – Defined as a point where the CSR encounters an obstacle on the way to the LOI
- **Discontinuity** – A gap the CSR and MR must travel over. The current requirement is 1 foot wide, however the dimensions (depth and width) are subject to change based on the MR's capabilities.
- **Obstacles** – Defined by underbrush, roots, trees, and discontinuities

Terrain Definitions:

There are three main categories for varying types (A-D). The detailed terrain definition can be found in the backup slides

1) Forest

- Types vary by density of trees within a specified area

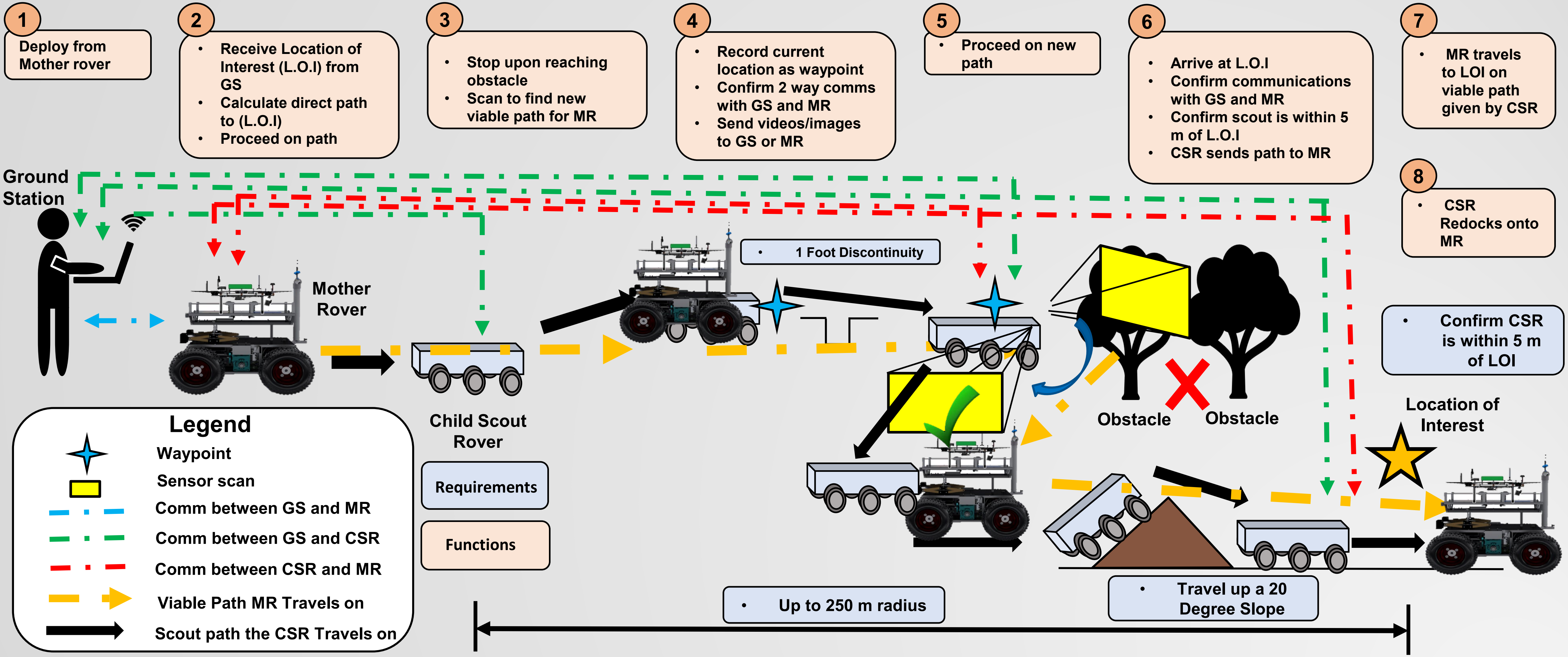
2) Ground

- Types vary by grain size

3) Underbrush

- Types vary by physical dimensions of a specified vegetation and tree root diameter

Concept of Operations



1. Deploy from Mother rover

2.
   - Receive Location of Interest (L.O.I) from GS
   - Calculate direct path to (L.O.I)
   - Proceed on path

3.
   - Stop upon reaching obstacle
   - Scan to find new viable path for MR

4.
   - Record current location as waypoint
   - Confirm 2 way comms with GS and MR
   - Send videos/images to GS or MR

5.
   - Proceed on new path

6.
   - Arrive at L.O.I
   - Confirm communications with GS and MR
   - Confirm scout is within 5 m of L.O.I
   - CSR sends path to MR

7.
   - MR travels to LOI on viable path given by CSR

8.
   - CSR Redocks onto MR

- 1 Foot Discontinuity
- Confirm CSR is within 5 m of LOI
- Up to 250 m radius
- Travel up a 20 Degree Slope

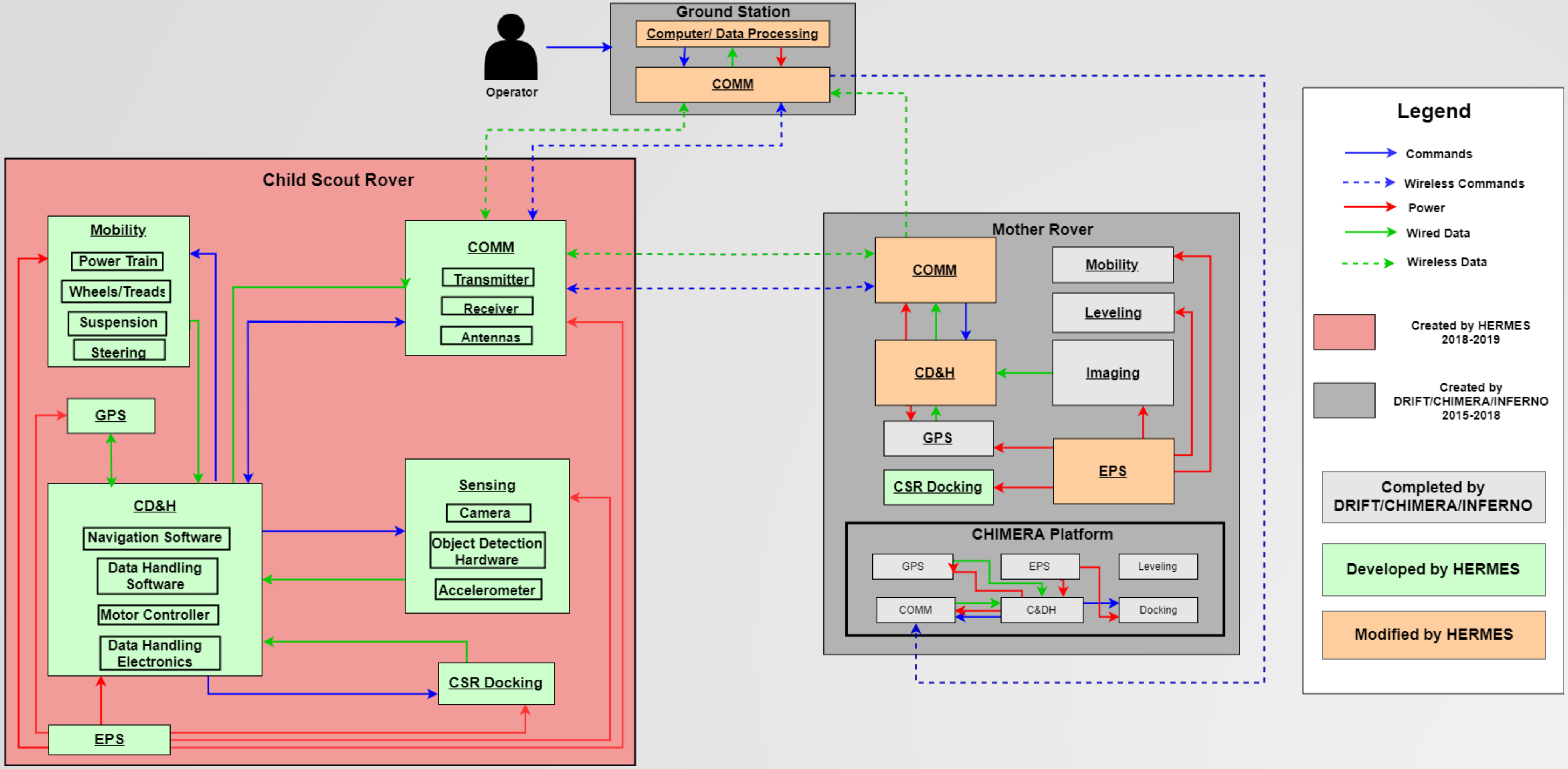
Legend

✦	Waypoint
🟨	Sensor scan
– · –	Comm between GS and MR
– · –	Comm between GS and CSR
– · –	Comm between CSR and MR
▬ ➤	Viable Path MR Travels on
➡	Scout path the CSR Travels on

Functional Requirements

Requirement ID	Description
CSR.1	**The CSR shall be able to receive commands from the MR or the GS**
CSR.2	**The CSR shall be able to send image and positioning data to the GS**
CSR.3	**The CSR shall be able to travel to a location of interest**
CSR.4	The CSR shall travel back to the last reported waypoint upon loss of communications with the MR
CSR.5	The CSR shall be able to take video while driving or in position-hold
CSR.6	The CSR shall be able to take pictures while driving or in position-hold
CSR.7	The CSR shall be able to dock from the MR
CSR.8	The CSR shall be able to deploy from the MR
MR.1	**The MR shall travel to the CSR when a path is found**

Functional Block Diagram



Baseline Design

Baseline Design

Translational System

- Allows the CSR to be able to navigate through mission defined terrain to reach the LOI

Object Detection

- Allows the CSR to avoid obstacles and aids in determining a viable path for the MR

Communication System

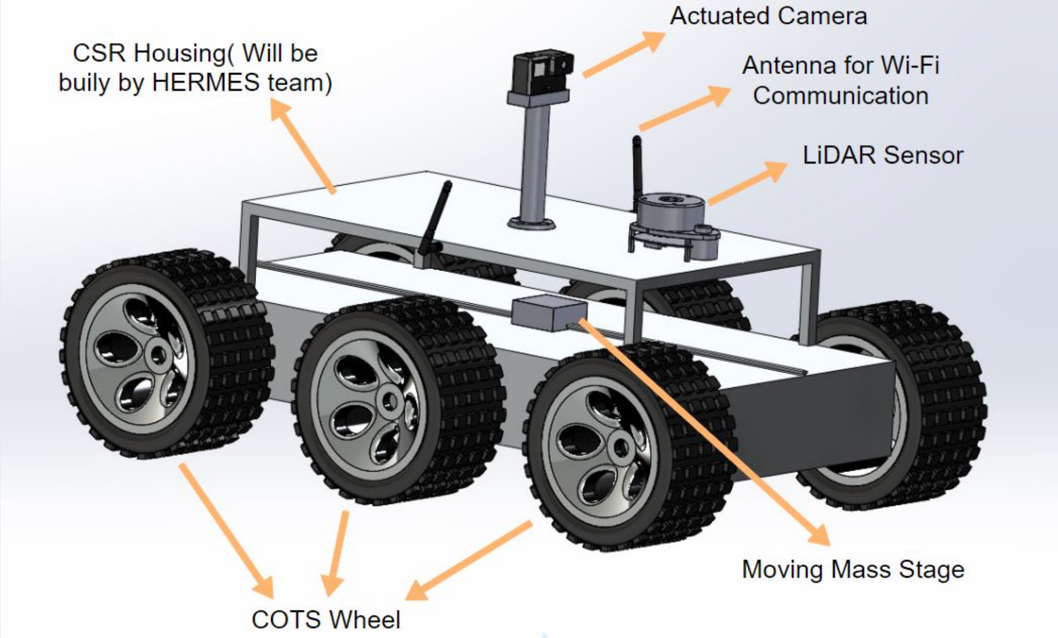
- Allows the CSR to send data (GPS, images, obstacle positions) to the GS/MR within the mission range

Docking/Deploying Mechanism

- Allows the CSR to deploy and dock from/to the MR at the beginning and end of its mission

Imaging System

- Allows the CSR to send back images and videos to the GS or MR to fulfill functional requirements



***Preliminary CAD Model of the CSR. This is a conceptual design and component placement is subject to change.**

***Not shown:**
- Docking/deploying mechanism

Translational System Baseline Design

Options Considered:

4WD with 6 Wheels, **6WD with 6 wheels**, 4WD with 4 Wheels, Tank Track, Rocker Bogie

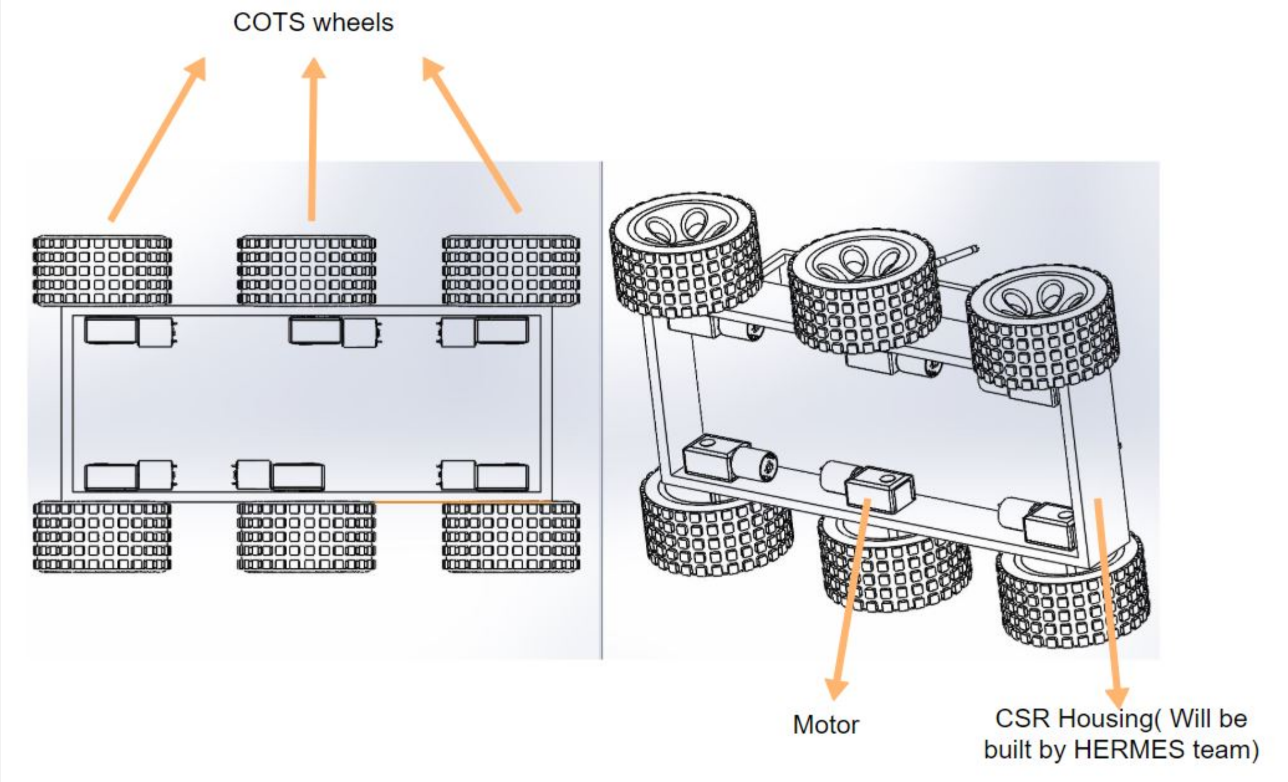
How is Translational System achieved?

6WD with 6 Wheels

- Rigid chassis with six wheels, all powered
- Skid Steering
- **Variable Center of Mass** to go over 1 ft discontinuities

Baseline Dimensions

- Distance between wheels: 0.30 m (12 in)
- Height of CSR Center of Mass: 0.25 m (10 in)
- Mass of Chassis: 15 kg
- Mass of Mass Stage: 5 kg
- Radius of each wheel: 0.2 m (4 in)
- Power required for each wheel: 24W
- Torque required for each wheel: 5 Nm



*Red means design has been changed from CDD (Conceptual Design Document)

*Green means a new design has been introduced

Object Detection Baseline Design

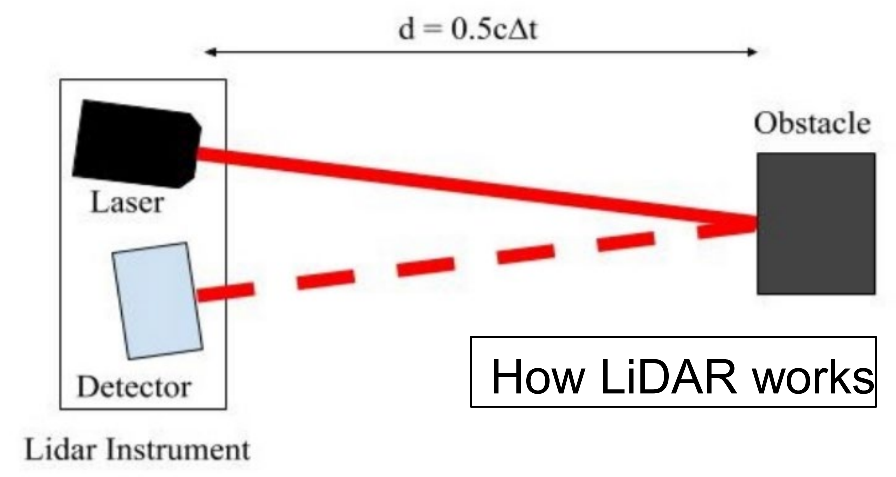
Options Considered:

- **LiDAR sensor**, ultrasonic sensor, collision sensors, and image processing

How is Object Detection Achieved?

LiDAR (Light Detection and Ranging) sensor

- Ability to create environmental maps & gather accurate distance data within a given range
- Available software & Robot Operating System (ROS) tools make the sensor possible to integrate



How LiDAR works

Solid State LiDAR [1]

- Angular resolution: <0.5°
- Field of view: 120°~130° horizontal & 5°~9° vertical
- Detecting Range: 0.1 m ~ 4 m

Solid State LiDAR sensor

Communication System Baseline Design

Options Considered:

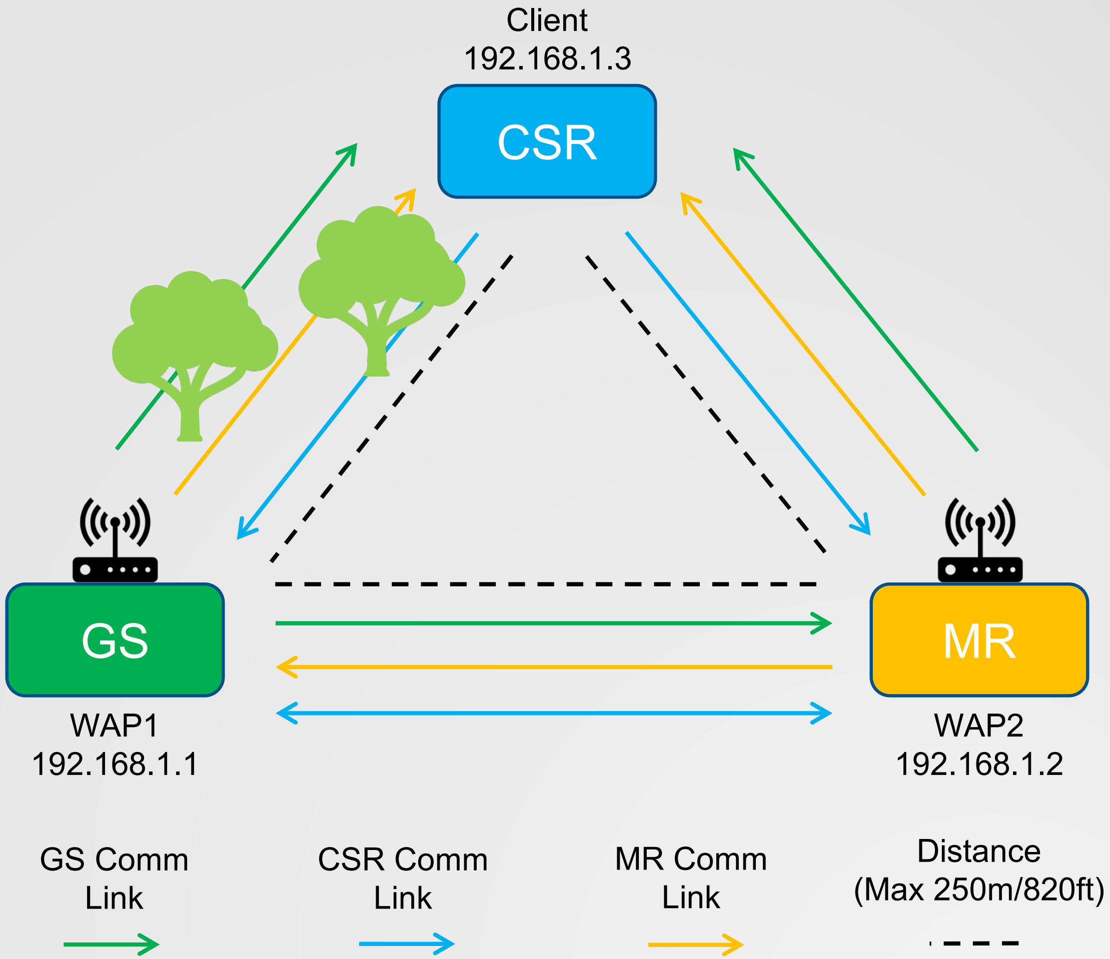
- **Wi-Fi**, Zigbee, Global System for Mobile Communications

Wi-Fi Antenna and Module:

- Antenna Gain (G): 9.5 dBi
- Directivity: Omni-Directional (360°)
- Transmission Power (Tx): 24 dBm
- Receiver Sensitivity (Rx): -86 dBm
- Frequency (f): 2400 MHz
- Data Rate (R): 1 to 300 Mbps

How is Communication Achieved?

- GS and MR create shared network with two wireless access points (WAP)
- CSR acts as a client on shared network
- Creates two possible paths for communication
  - No connection, no problem
  - Signal strength dependence

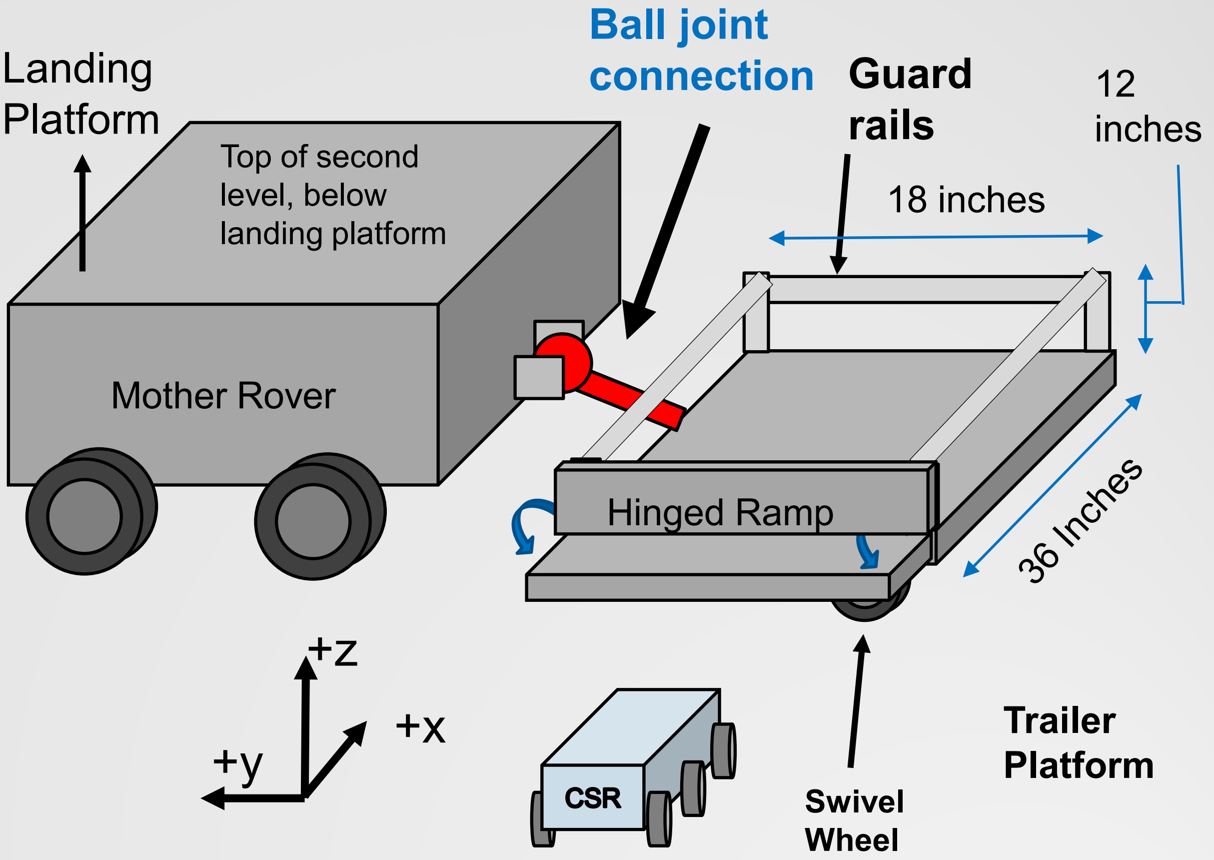


Docking/ Deploying Baseline Design

Options Considered:

- Hitch, **Trailer Platform**, On-board Ramp, On-board, Lift, On-board Lift with an Extended platform, **Ball Joint + Trailer Platform**

- **How is Docking/Deploying Achieved?**
  Ball Joint + Trailer Platform
    - A ball joint connects directly to an attached trailer platform
    - The ball joint allows for rotation around multiple axes when in uneven terrain
    - The ramp hinges towards the side of the trailer to reduce the trailer length
    - The CSR then travels up the ramp and onto the trailer



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Imaging System Baseline Design

Options Considered:

- Single fixed camera, Two fixed cameras, **Single Actuated camera**, 360° 3 DOF camera

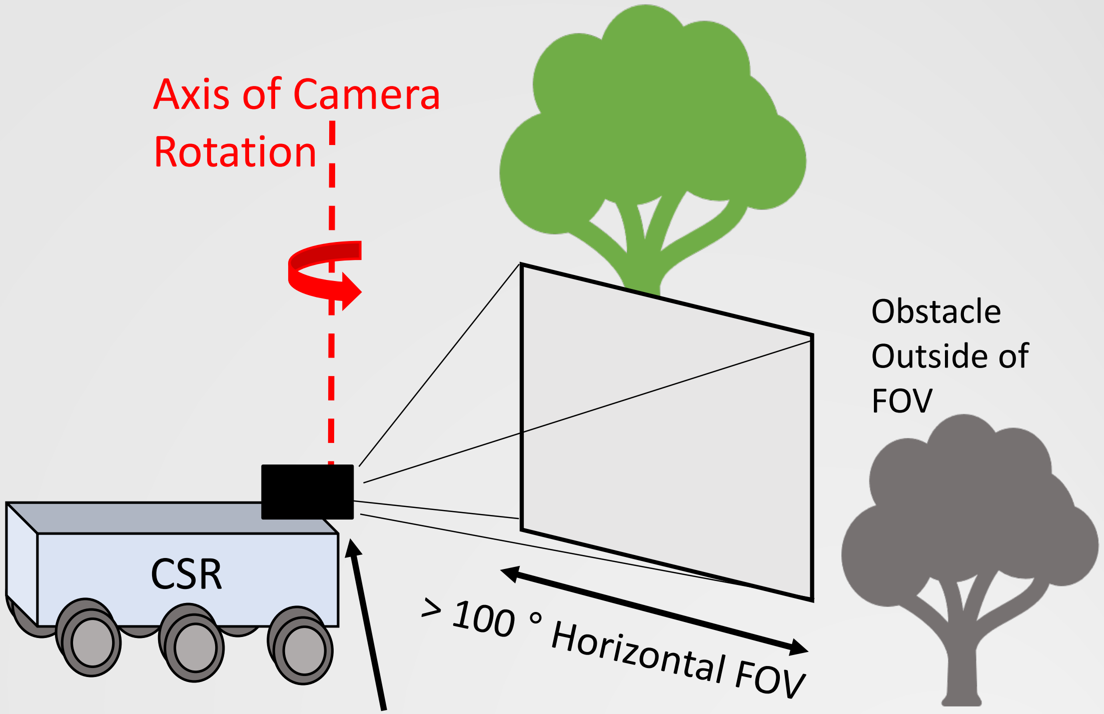
Baseline Design Selection:

Single Actuated Camera

- Allows for the CSR to remain stationary while the imaging system actuates for objects outside the FOV
- SVPro 2MPa Camera
- (800 x 600) at 30 fps Video Resolution
- 2.2 Mpa Image Resolution
- H264 Video Compression

Actuation Device

- Stepper
- 4W Power Consumption



Obstacle in FOV

Axis of Camera Rotation

Obstacle Outside of FOV

CSR

> 100 ° Horizontal FOV

Single Actuated Camera

Feasibility Analysis

Critical Project Elements

All Critical Project Elements (CPEs)

Mobility, Docking and Deploying:
The CSR must be able to travel through the defined terrain to navigate and reach an LOI. The CSR must also be able to dock/deploy to begin and end a mission.

Environment Sensing:
The CSR must be able to sense the terrain and obstacles around it to detect obstacles and determine a viable path.

Communications:
The CSR must be able to communicate with the GS and MR to send the viable path, images, and videos

Guidance, Navigation and Control:
The CSR must be able to read its own GPS data accurately to navigate and determine a viable path for the MR

Integration to Heritage Projects:
The CSR must be able to interface with previous heritage projects such as the ground station and mother rover.

Rationale:
Which CPEs relate to the most requirements?

Focus for PDR

Translational System: Mobility

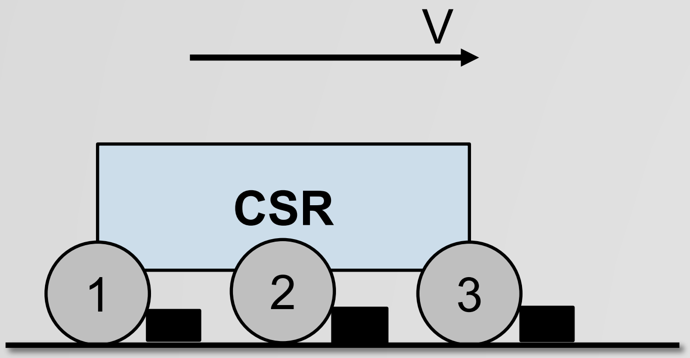
Object Detection: Environment Sensing, Guidance Navigation and Control

Communications: Communication System, Integration to Heritage Projects

Translational System Feasibility Analysis

Overcoming Obstacles

MOB.3.4 The CSR shall be able to drive in underbrush
MOB.3.4.1 The CSR shall be able to go over obstacles up to 6 cm (2.4 in) of height



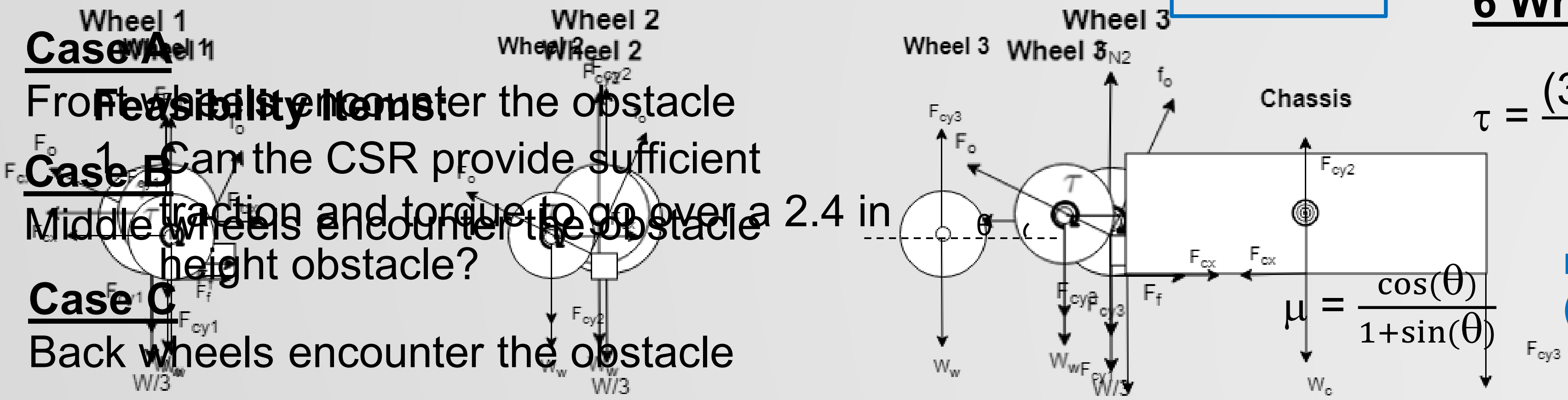
Legend:

- ▬ Obstacle
- ● Driven Wheel

r radius of the wheel
h height of the obstacle
Ww weight of the wheel pair
Wc weight of the chassis

Normal force on wheel 3 = 0

Normal force on wheel 2 = 0



Case A

Front wheels encounter the obstacle

Case B

Middle wheels encounter the obstacle

Case C

Back wheels encounter the obstacle

Feasibility Items:

1. Can the CSR provide sufficient traction and torque to go over a 2.4 in height obstacle?

$$\mu = \frac{\cos(\theta)}{1+\sin(\theta)}$$

Baseline Assumptions for Math Models:

1. Geometrically centered CoM (Center of Mass)
2. Roll no-slip
3. Steady state
4. Equal torque output on each driving wheel
5. Negligible forward velocity/kinetic energy
6. Negligible roll resistance

6 Wheel Drive (6WD) with 6 Wheels

$$\tau = 3\ Nm$$

$$\tau = \frac{(3Ww + Wc)}{2} * \frac{r\sqrt{r^2-(r-h)^2}}{2r-h} = 1\ Nm$$

$$\mu = \frac{\cos(\theta)}{1+\sin(\theta)}$$

r > 3.7 in (9.4 cm) to go over 2.4 in (6cm) obstacle with a μ of 0.7[2]

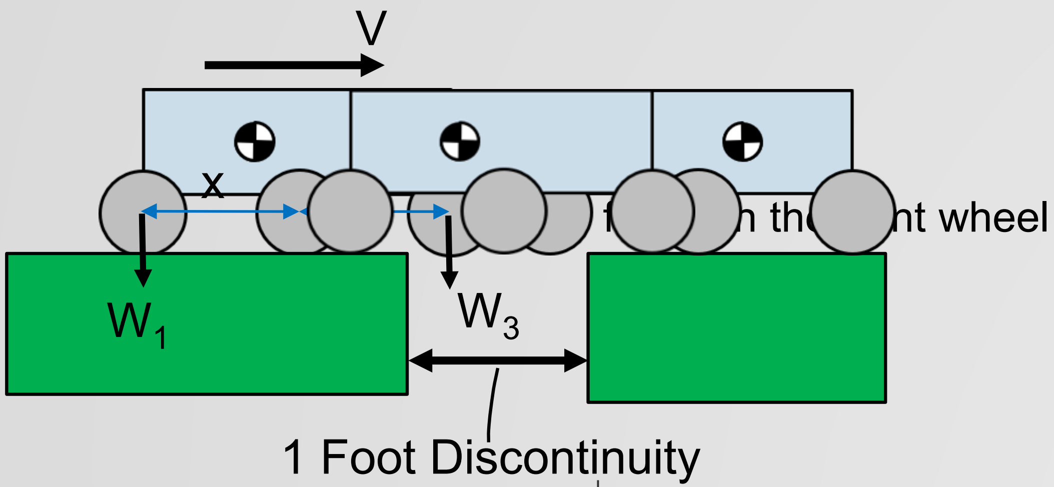
FEASIBLE

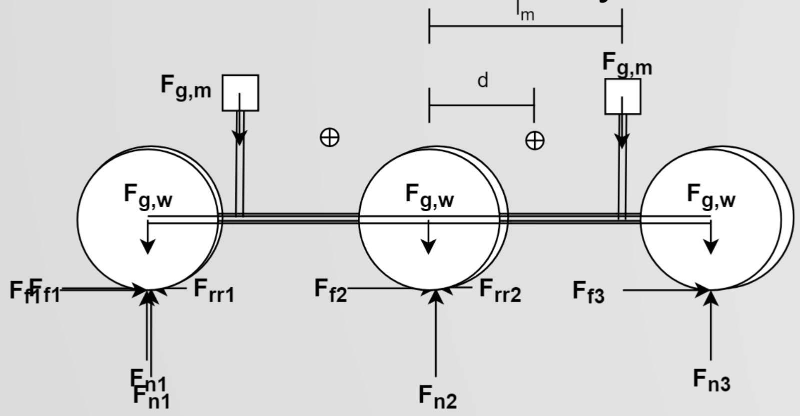
University of Colorado Boulder

JPL
Jet Propulsion Laboratory

Overcoming a 1 Foot Discontinuity

MOB.3.2 The CSR shall be able to go over discontinuities up to 1 ft (0.3 m)





Feasibility Items:

1. Can the CSR provide sufficient traction and torque to cross a 1 ft discontinuity?

Baseline Assumptions:

1. Roll no-slip
2. Negligible forward velocity
3. Equal torque across both driven wheels
4. Rigid Chassis

Results

1. Driving over a flat gap requires less torque than driving over obstacles
2. Feasibility of Case 2 obstacle proves feasibility of crossing discontinuity

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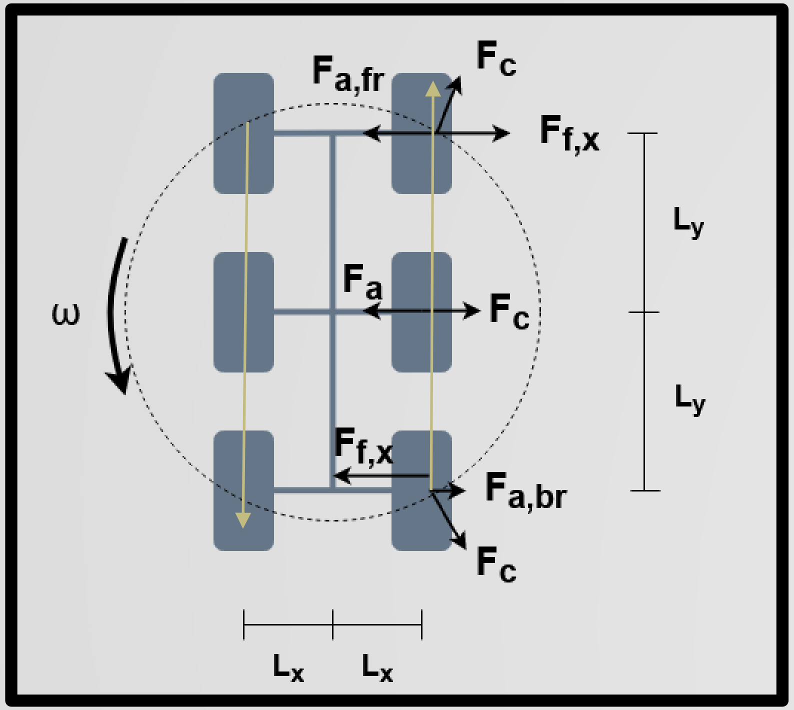
360 Degree Turn

MOB.3.1 - The CSR Mobility system shall be able to perform a 0 m (0 ft) radius turn up to 360 degrees



$$F_{a,fr} = \frac{m}{6}\left(\frac{\mu_K g L_y}{\sqrt{L_x^2 + L_y^2}} + \omega^2 L_x\right)$$

Feasibility Items:

1. Can the CSR preform up to 360 degree turns?
2. If so, what are the axial loads?

Baseline Assumptions:

1. Constant angular velocity
2. Geometrically centered CoM

Results:

1. Expect axial loads about 20N, given:
    1. Baseline Dimensions
    2. μ = 0.7 [3]
    3. Angular Velocity = 0.5 rad/s (4.25 rpm)

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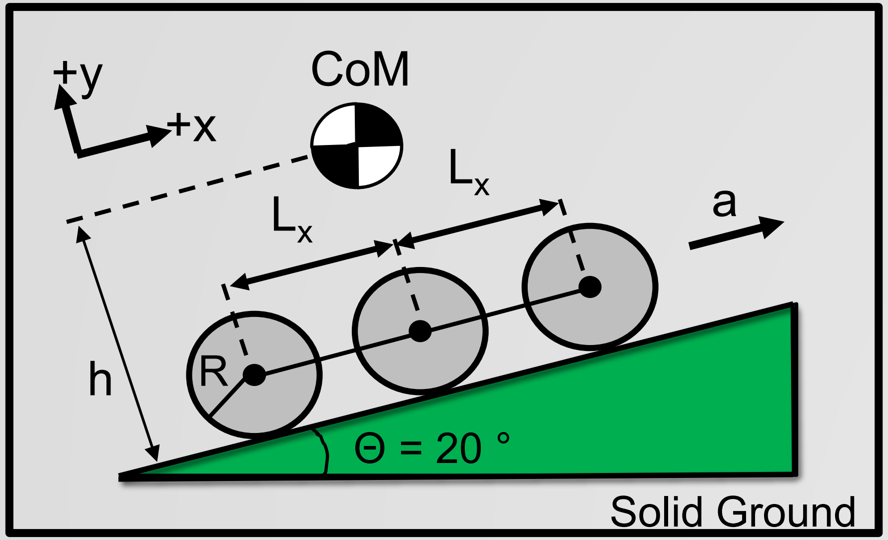
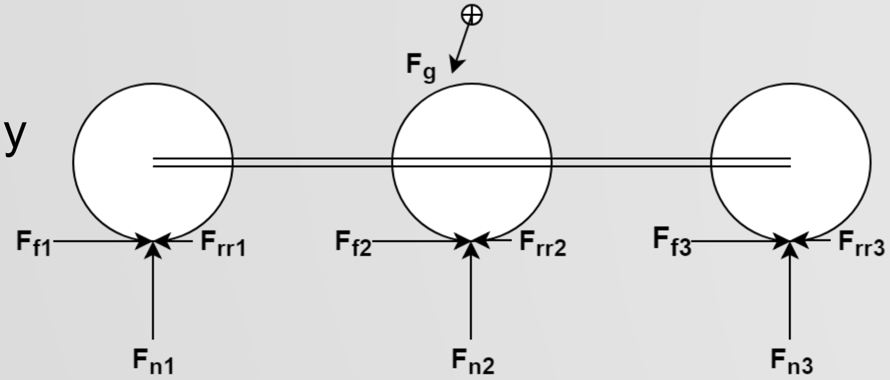
Overcoming Inclined Slopes

MOB.3.3 - The CSR shall be able to go up or down a slope up to 20 degrees



Free Body Diagram



Feasibility Items:

1. Maximum acceleration before tipping?
2. Torque and power needed to go up the slope?
3. What coefficient of friction is needed?

Baseline Assumptions:

1. Roll no-slip
2. Geometrically Centered CoM (Center of Mass)
3. Rigid Chassis

Results using Baseline Dimensions:

1. Gravel (c_{rr} = 0.02, μ[4]=0.60) ✓
   1. Required Torque per Wheel = 1.2Nm
   2. Required Power per Wheel = (12**V*) W
   3. Maximum Acceleration before slip = 1.92 m/s^2
2. Sand (c_{rr} = 0.20, μ[4]=0.60) ✓
   1. Required Torque = 2.6Nm
   2. Maximum Acceleration before slip = 0.26 m/s^2
   3. Required Power per Wheel = (22**V*) W

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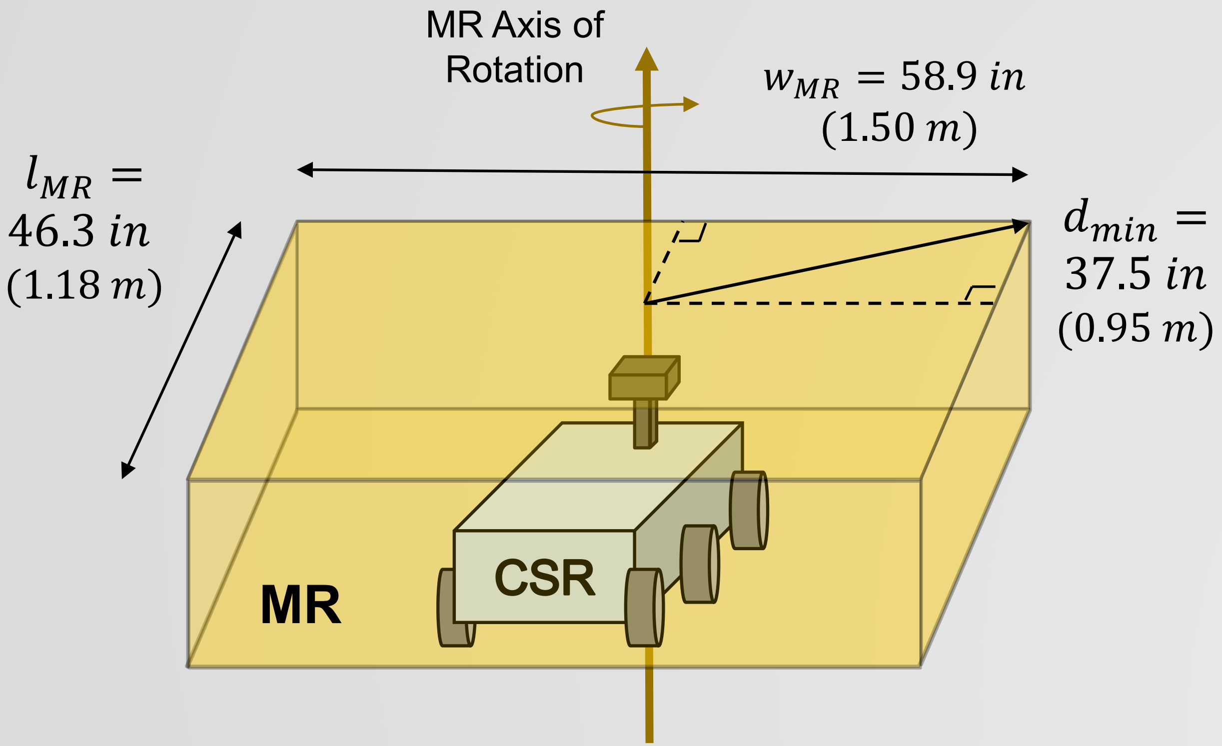
Object Detection Feasibility Analysis

Visualization of LiDAR Mounting



Description:

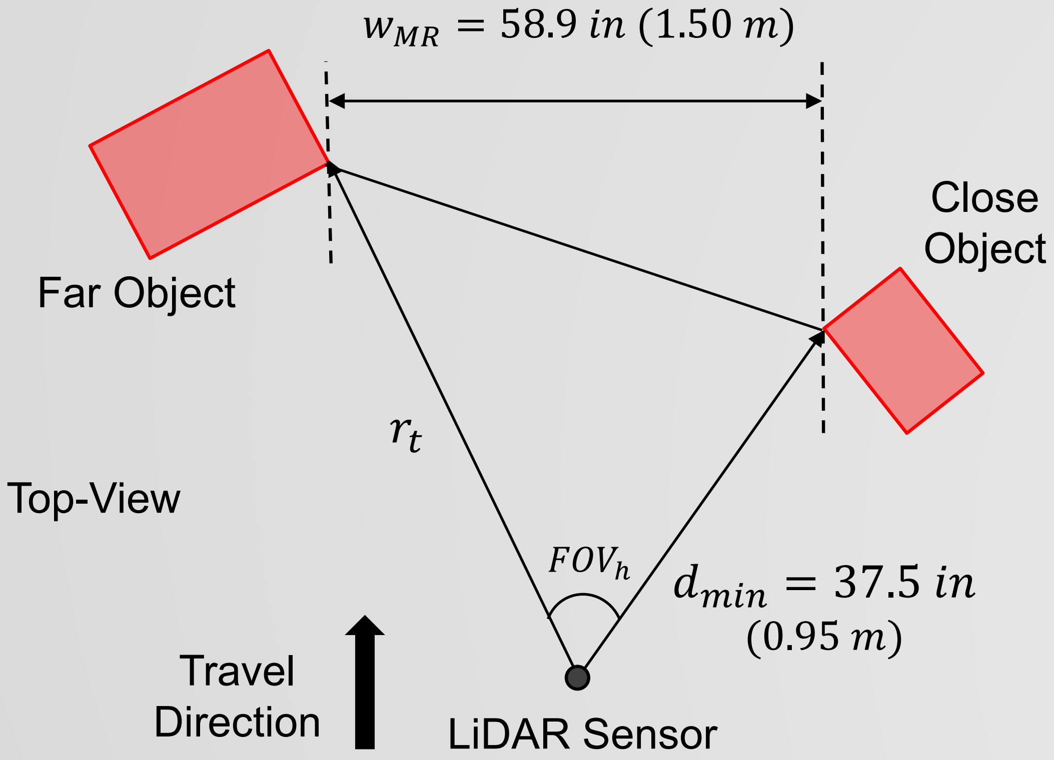
1. Object detection feasibility is based on the dimensions of the MR, not the CSR
2. The parameter d_{min} is the minimum distance the LiDAR sensor can be so that the MR will not collide with an obstacle (more information in backup slides)

Assumptions:

1. The MR is roughly a uniform rectangular box (including wheels)
2. LiDAR is mounted on the CSR, in line with the MR axis of rotation

Horizontal Field of View and Range

SENS.3.1.1 - CSR sensing system shall report objects within at least a 120 degree field of view (FOV)
SENS.3.1.2 - CSR sensing system shall report objects up to 4 m (13.123 ft) away from the CSR



Feasibility Items:

1. What is the minimum horizontal field of view (FOV_h) required?
2. What is the desired total range (r_t)?

Assumptions:

1. LiDAR sensor is located at the axis of rotation of the MR
2. The parameters w_{MR} and d_{min} are measurable lengths based on the estimated dimensions of the MR
3. The MR directly touches the obstacles it attempts to pass (no safety margin)
4. Objects consist of typical terrain obstacles: underbrush, trees, roots, etc.

Developed a relationship between FOV_h, r_t, d_{min}, and w_{MR} (Equation in backup slides)

Horizontal Field of View and Range

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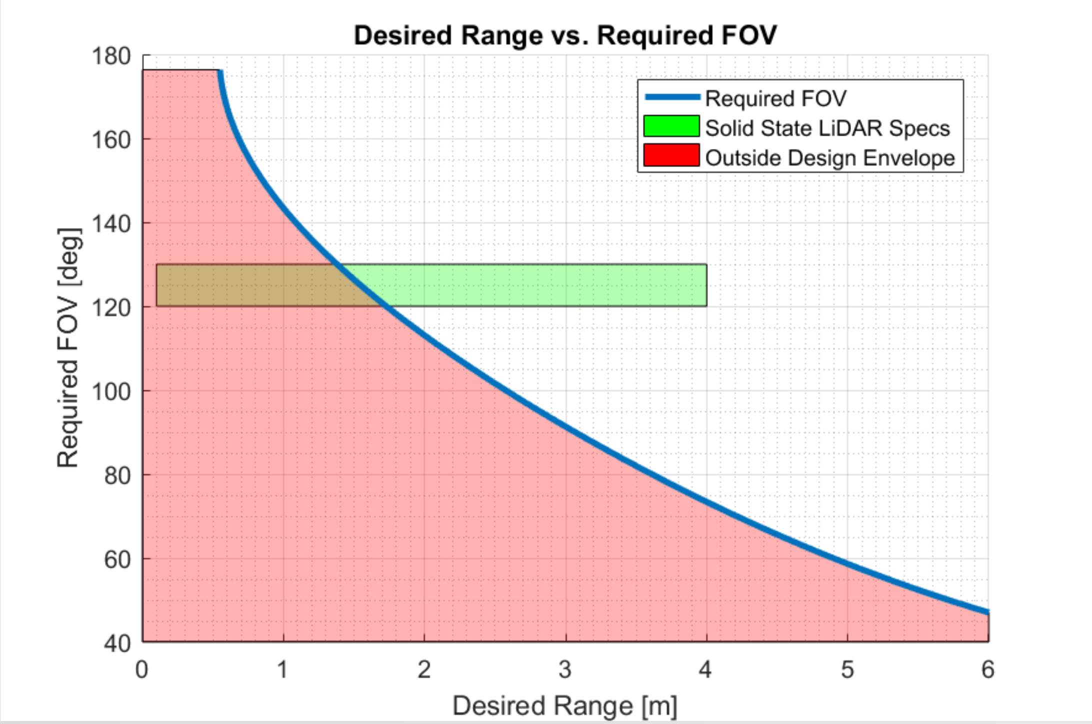

Results:

1. Required FOV_h decreases as the desired total range (r_t) of the lidar increases
2. Solid state LiDAR systems fall within the design envelope (FOV_h =120 – 140° and r_t = 0.1 – 4 m)

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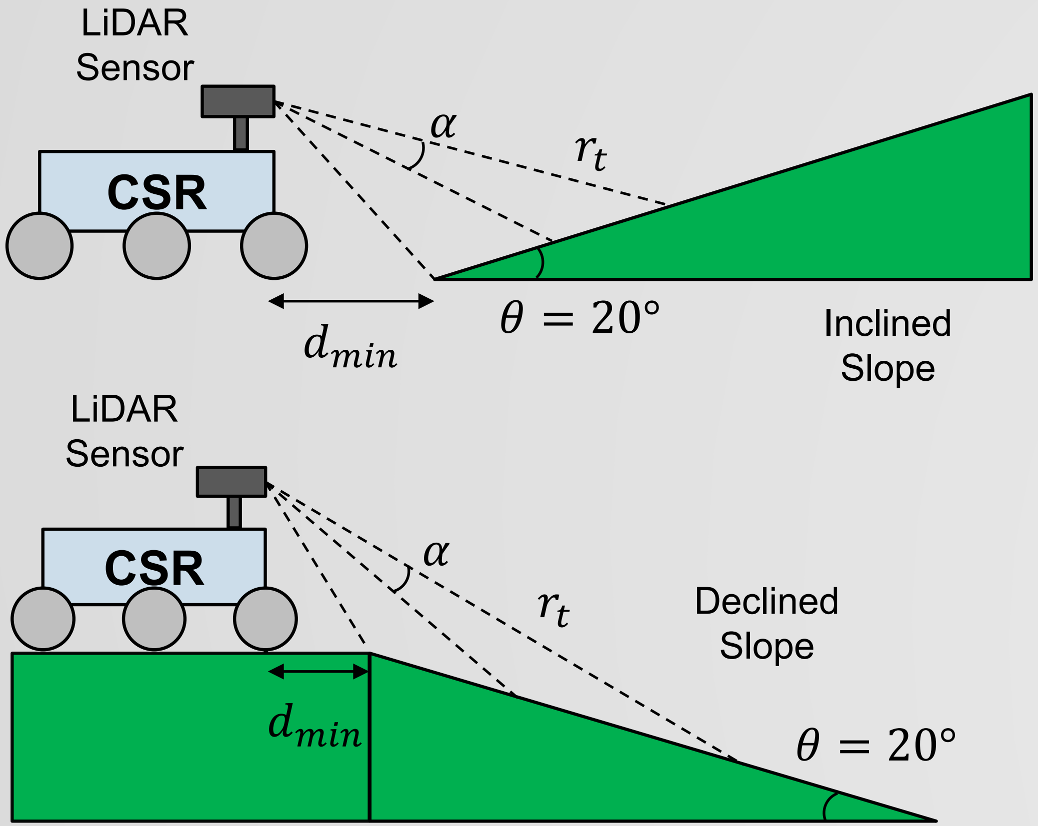
Further Analysis Required:

1. Determine the position of the LiDAR sensor on CSR to acquire more accurate values for w_{MR} and d_{min}
2. Introduce safety margins for w_{MR} and d_{min}

Range for Slope Determination

SENS.3.2 - CSR sensing system shall determine at least a 20 degree grade/incline on which the CSR is travelling
SENS.3.3 - The CSR sensing system shall determine at least a 20 degree grade/incline up to 3.125 ft (0.9525 m) away from the CSR



Feasibility Items:

1. What is the minimum range (r_t) required for slope detection?

Assumptions:

1. LiDAR sensor is located at the axis of rotation of the MR
2. The parameter d_{min} is a measurable length based on the estimated dimensions of the MR
3. Minimum range is a function of angular resolution, not FOV

Range for Slope Determination

SENS.3.2 - CSR sensing system shall determine at least a 20 degree grade/incline on which the CSR is travelling
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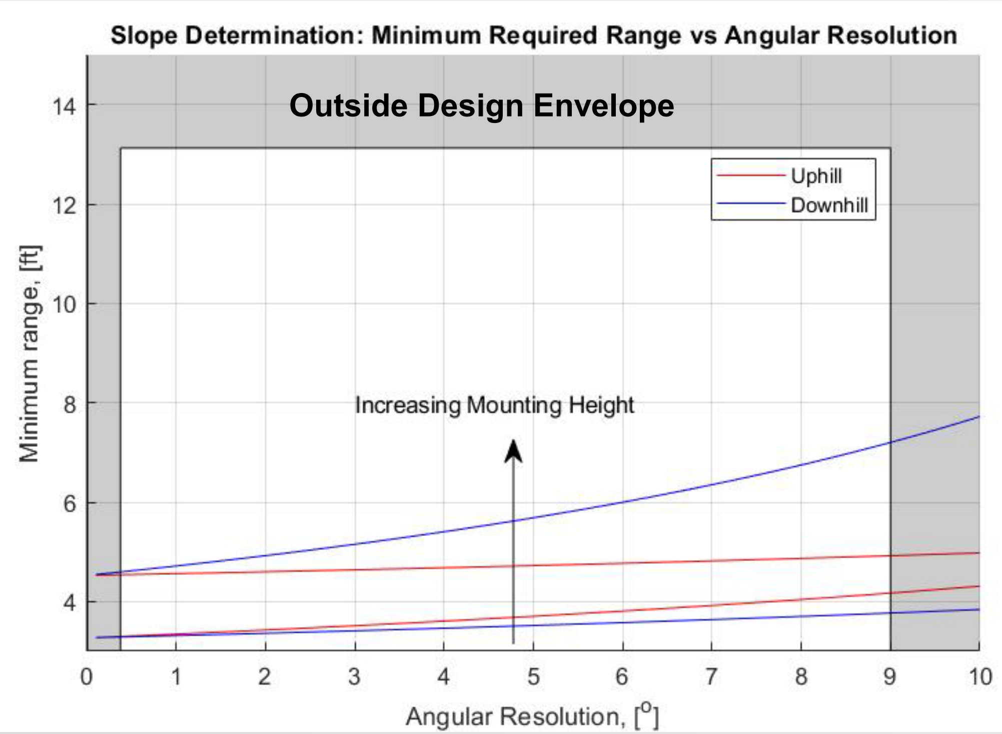

Results:

1. Minimum range and angular resolution depend on LiDAR mounting height
2. In the worst case scenario, required minimum range is 7.72 ft (2.6 m)
3. Solid state LiDAR systems fall within the design envelope ($r_t = 0.1 – 4$ m)

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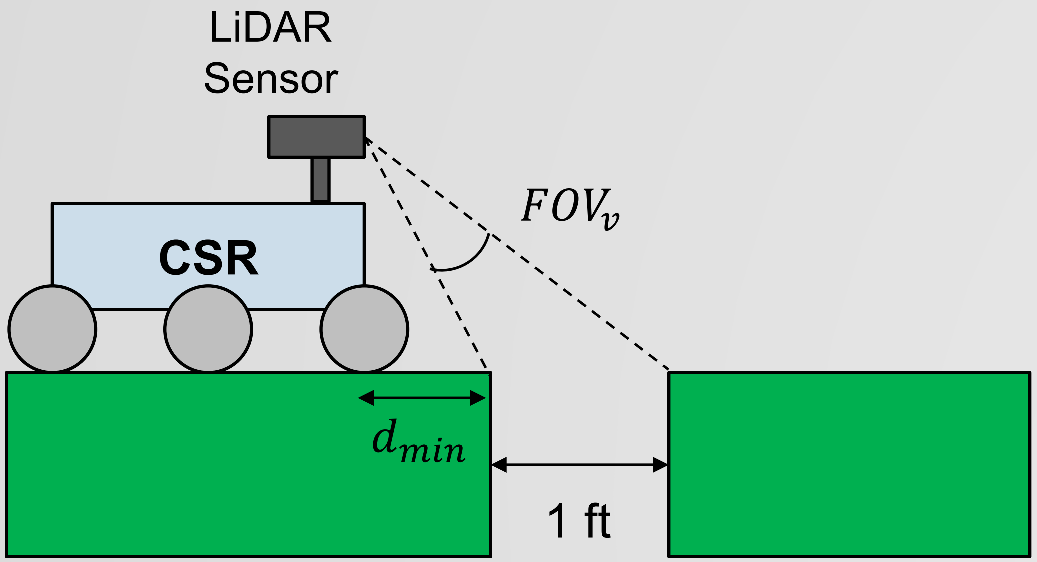
Further Analysis Required:

1. Feasibility for angular resolution to determine slopes
2. Determine mounting height and position of the LiDAR system on the CSR
3. Introduce safety margin for d_{min}

Detecting Discontinuities

SENS.3.4 - The CSR sensing system shall be capable of detecting discontinuities at least 1 ft (0.305 m) long



Feasibility Items:

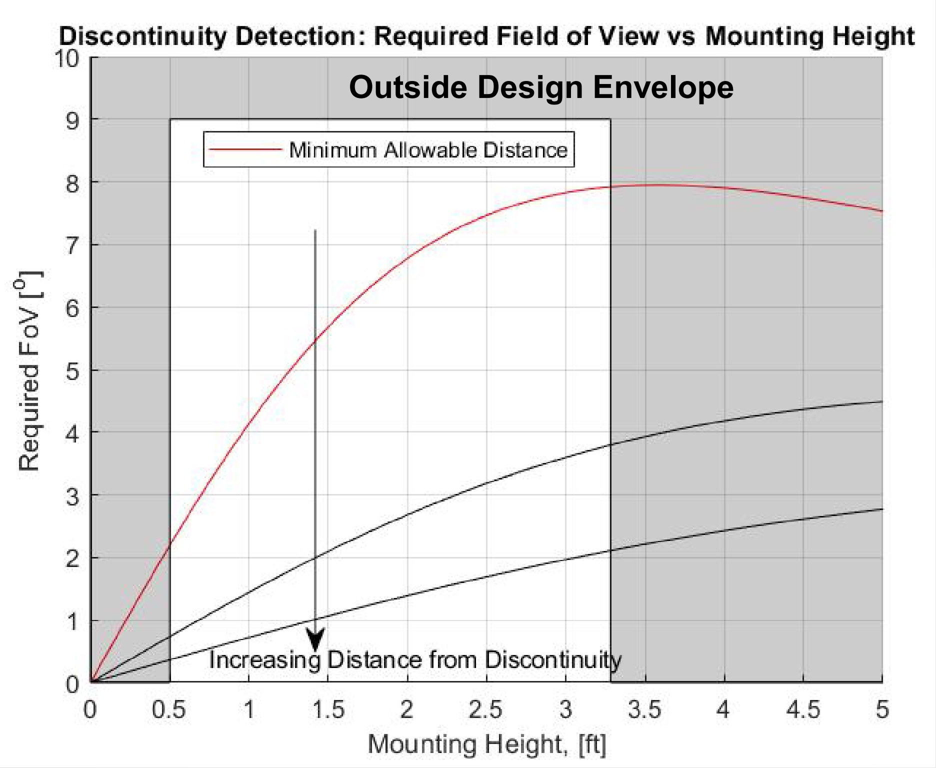
1. What is the minimum vertical field of view (FOV_v) required to detect a 1 ft horizontal discontinuity?

Assumptions:

1. Edges of discontinuity are equal in height
2. Walls of the discontinuity are perpendicular to the driving surface
3. LiDAR sensor is located at the axis of rotation of the MR
4. The parameter d_{min} is a measurable length based on the estimated dimensions of the MR

Detecting Discontinuities

SENS.3.4 - The CSR sensing system shall be capable of detecting discontinuities at least 1 ft (0.305 m) long



Results:

1. Required FOV_v is dependent on the LiDAR mounting height
2. In the worst case scenario, required FOV_v is 7.91°
3. Solid state LiDAR systems fall within the design envelope ($FOV_v = 5 – 9°$)

FEASIBLE

Further Analysis Required:

1. Feasibility of LiDAR to measure discontinuities, not just detect them
2. Determine mounting height and position of the LiDAR system on the CSR
3. Introduce safety margin for d_{min}

Communication System Feasibility Analysis

Communication Feasibility

COMM.1.1 The CSR Communication system shall receive complete command packets up to 250 m (820 ft)
COMM.2.4 The CSR Communication system shall send GPS data from up to 250 m (820 ft) to the GS
COMM.2.5 The CSR Communication system shall send obstacle position data from up to 250 m (820 ft) to the GS

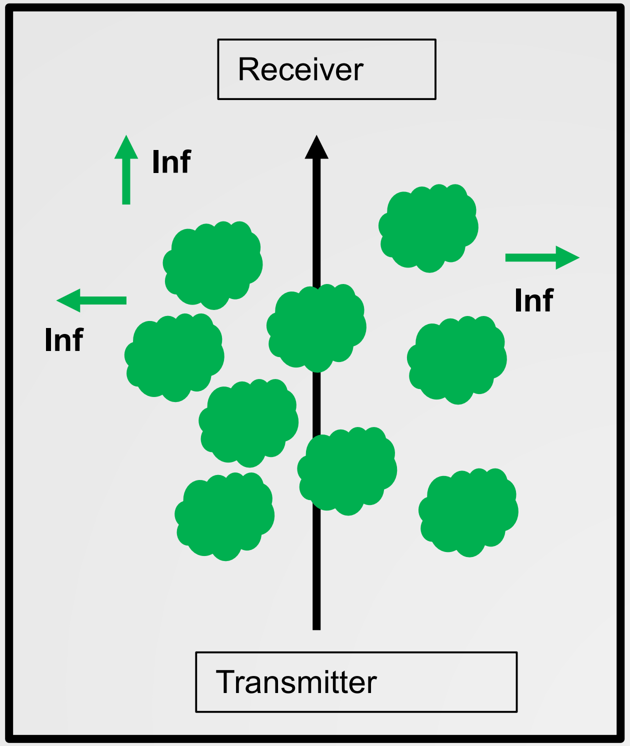
Feasibility items:

1. What is link margin for solely free space path loss?
2. What is the attenuation due to varying tree depths in this scenario?
3. Is there a link margin of at least 10 dB accounting for this attenuation?

Assumptions:

1. Radio science's model is a reliable source to calculate attenuation due to trees [5]
2. Downlink and uplink parameters will be considered as the same

Worst Case Scenario: Into Vegetation



Link Margin Calculations

Link Margin with Free Space Path Loss (FSPL)

(d): 0.25 km	(Tx): 24 dBi	(Gr/x): 9.5 dBi
(f): 2400 MHz	(Rx): -86 dBm	(L): 4 dBi

[6]

$$FSPL(dB) = 20log_{10}(d) + 20log_{10}(f) + 32.45 = 88\ dB$$

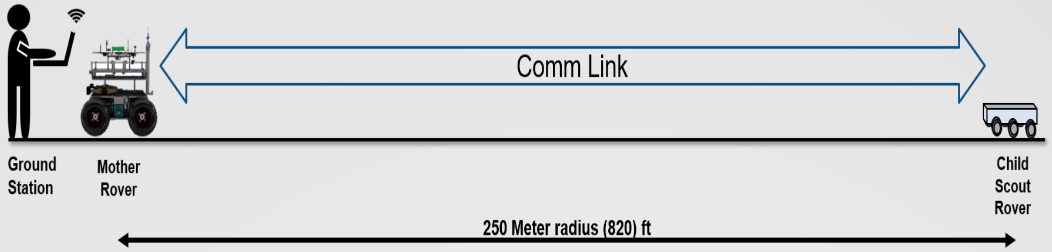
[6]

$$Link\ Margin(dB) = Tx - FSPL + Gx + Gr - Rx - L = 37\ dB$$

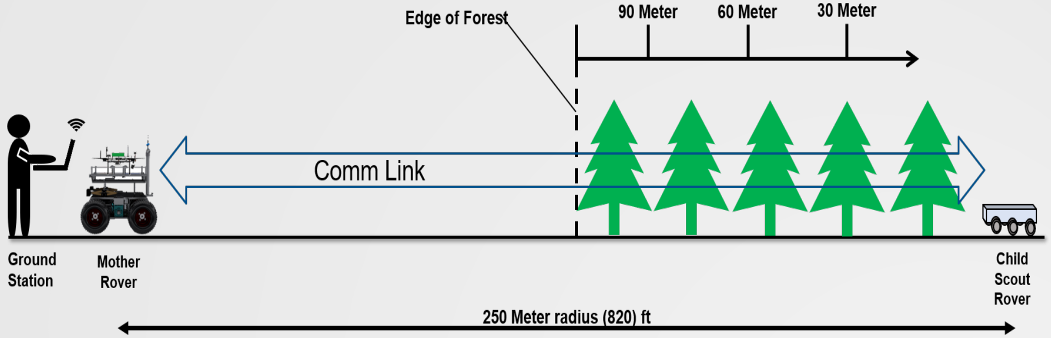
Link Margin with Attenuation

- Depends on varying tree depths
- How to determine?

$$Link\ Margin(dB) = 37\ dB\ - Attenuation\ \geq 10\ \text{dB}$$



No Attenuation

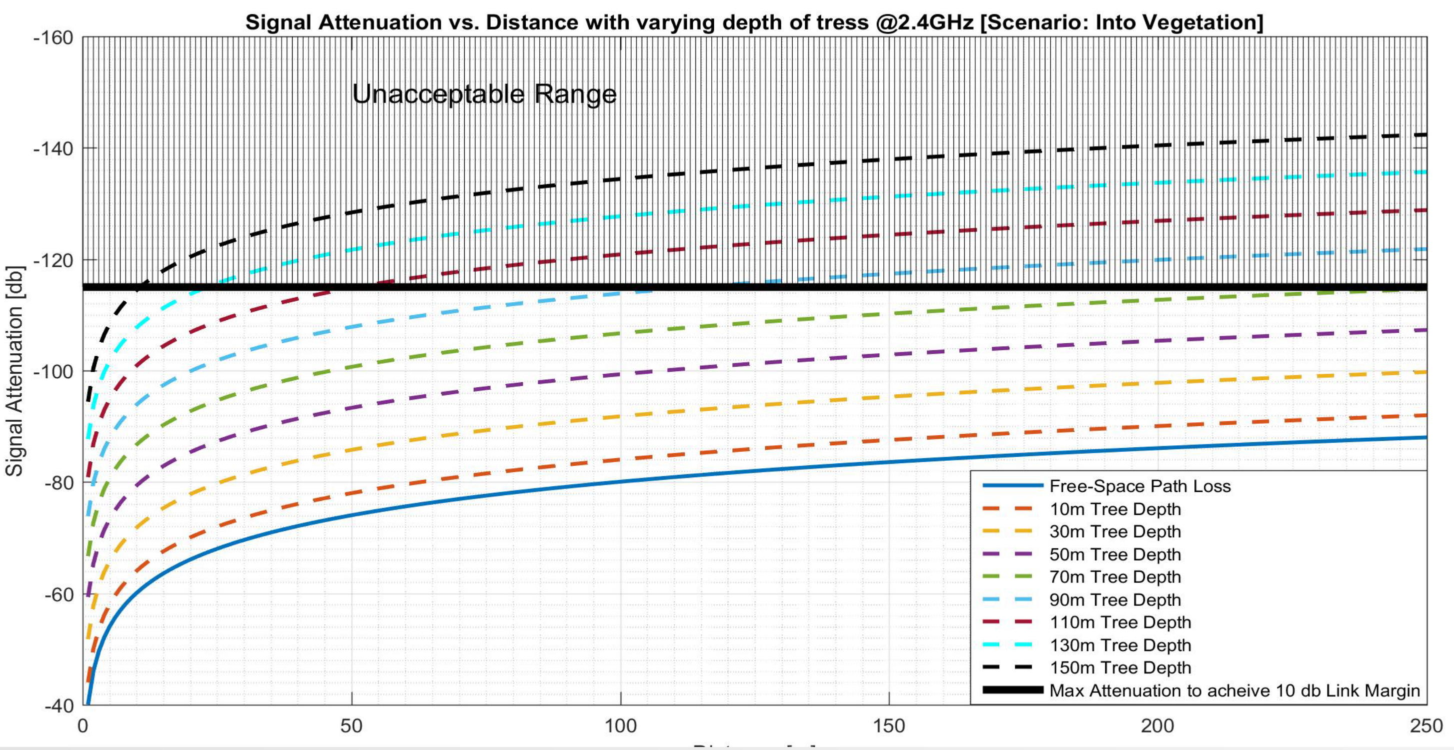


Varying Tree Depth Attenuation

Into Vegetation Signal Attenuation

$$Attenuation = R_{\infty} d + k\left[1 - exp\left(-\frac{R - R_{\infty}}{k} d\right)\right]$$ [5]

- The link margin must be ≥ 10 dB (Below the solid black line)
- The Signal attenuation increases with distance
- However, it is not a linear increase (Each line gets further apart as distance increases)



Link Budget Results

Summary

1. The link budget was calculated for the **worst** case scenario: **Into Vegetation**
2. Link margin calculated based on free-space path loss and tree attenuation

Link Budget:

Tree Depth	Attenuation (dB)	**Link Margin (dB):**
10m	-3.97	**33.01697499**
20m	-7.8816	**29.10537499**
30m	-11.737	**25.24997499**
40m	-15.539	**21.44797499**
50m	-19.289	**17.69797499**
60m	-22.989	**13.99797499**
70m	-26.642	**10.34497499**
80m	-30.248	**6.738974992**

Results:

1. Radio Science's model states that forest range can be from **62.3** m to **86.9** m (204.4 - 285.1 ft)
2. A link margin of at least **10 dBm** is required for communication to be successful but for us, this is within 60-70 m (197 – 230 ft) depth range. This fits the lower range but does not meet the higher range of forest depth
3. However, since this is the worst case scenario, communication at a distance of 250 m (820 ft) range **is feasible.** Ideally, when the tree depth is **under 70m (230 ft)**

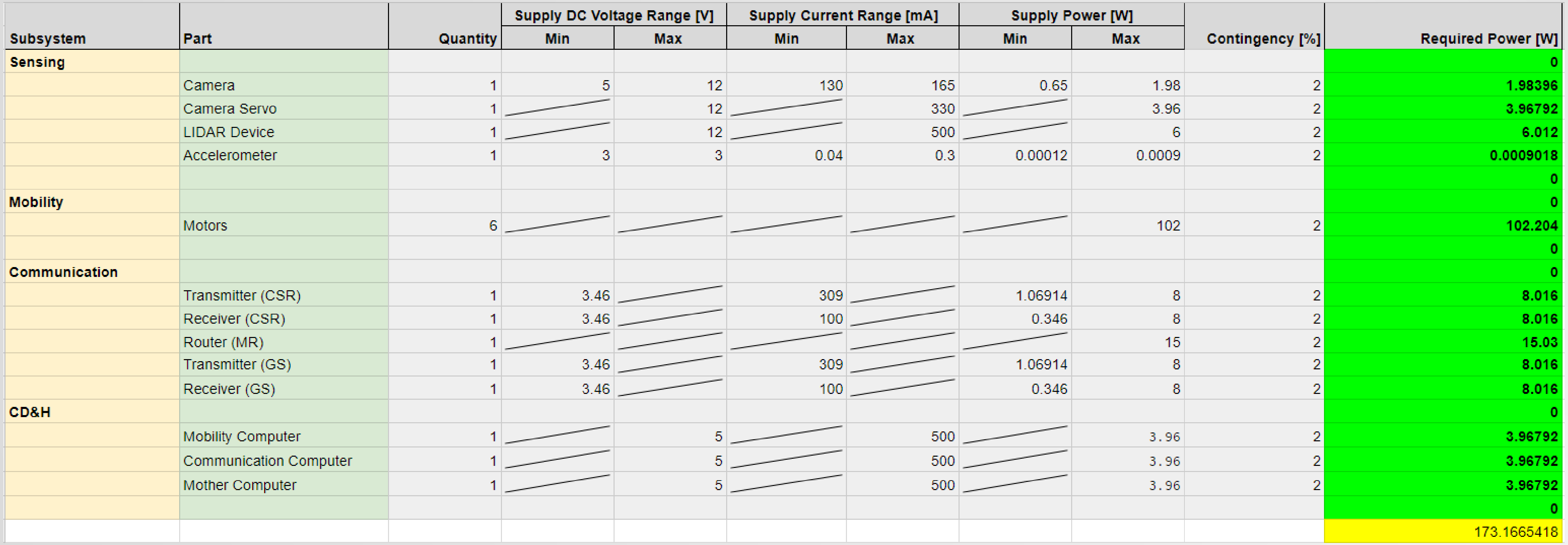
FEASIBLE

Power Feasibility

Power Budget

Required Power for the Child Scout Rover = ~173.17 W: **Feasibility Pending – Further analysis is needed**

- Feasibility dependent on many mission parameters (mission time, circuit configuration, etc.)



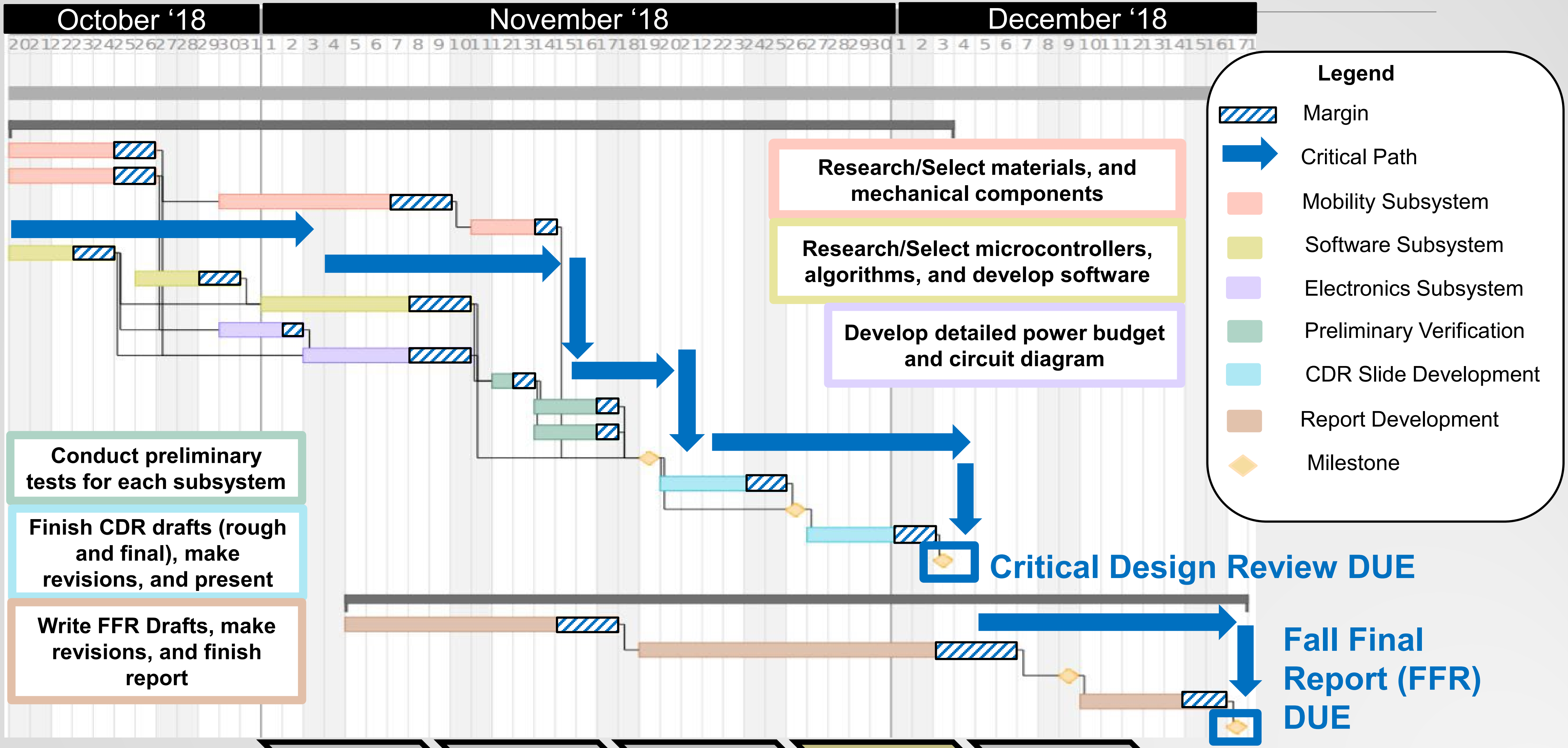
Subsystem	Part	Quantity	Supply DC Voltage Range [V]		Supply Current Range [mA]		Supply Power [W]		Contingency [%]	Required Power [W]
			Min	Max	Min	Max	Min	Max		
Sensing										**0**
	Camera	1	5	12	130	165	0.65	1.98	2	**1.98396**
	Camera Servo	1		12		330		3.96	2	**3.96792**
	LIDAR Device	1		12		500		6	2	**6.012**
	Accelerometer	1	3	3	0.04	0.3	0.00012	0.0009	2	**0.0009018**
										0
Mobility										**0**
	Motors	6						102	2	**102.204**
										0
Communication										**0**
	Transmitter (CSR)	1	3.46		309		1.06914	8	2	**8.016**
	Receiver (CSR)	1	3.46		100		0.346	8	2	**8.016**
	Router (MR)	1						15	2	**15.03**
	Transmitter (GS)	1	3.46		309		1.06914	8	2	**8.016**
	Receiver (GS)	1	3.46		100		0.346	8	2	**8.016**
CD&H										**0**
	Mobility Computer	1		5		500		3.96	2	**3.96792**
	Communication Computer	1		5		500		3.96	2	**3.96792**
	Mother Computer	1		5		500		3.96	2	**3.96792**
										0
										173.1665418

Status Summary and Strategy

Recap of Baseline Design

Baseline Design	Aspects shown to be Feasible	Continued Studies
Translational System: 6 Wheel Rover with a 6WD design and a variable center of mass	1. Obstacles up to 6 cm can be crossed 2. Discontinuities of 1 ft wide can be crossed 3. The CSR can travel up 20° inclined slopes 4. The CSR can perform up to 360° turns	1. Test MR gap traversing capability 2. Testing and modeling variable CoM performance
Object Detection: Solid State LiDAR	1. COTS LiDAR sensors exist that have the desired horizontal FOV and range needed to detect obstacles and slopes 2. COTS LiDAR sensors exist that have the desired vertical FOV to detect discontinuities	1. Determine the power consumption 2. Perform angular resolution study 3. Analyze feasibility of measuring discontinuities 4. Determine positioning of the LiDAR system on the CSR 5. Introduce safety margins into models
Communication System: Wi-Fi Communications	1. Communication at a distance of 250 m (820 ft) range is feasible when the tree depth is under 70m (230 ft).	1. Integration with software from previous years to allow for three way communication between the CSR, GS, and MR

Schedule and Gantt Chart



Research/Select materials, and mechanical components

Research/Select microcontrollers, algorithms, and develop software

Develop detailed power budget and circuit diagram

Conduct preliminary tests for each subsystem

Finish CDR drafts (rough and final), make revisions, and present

Write FFR Drafts, make revisions, and finish report

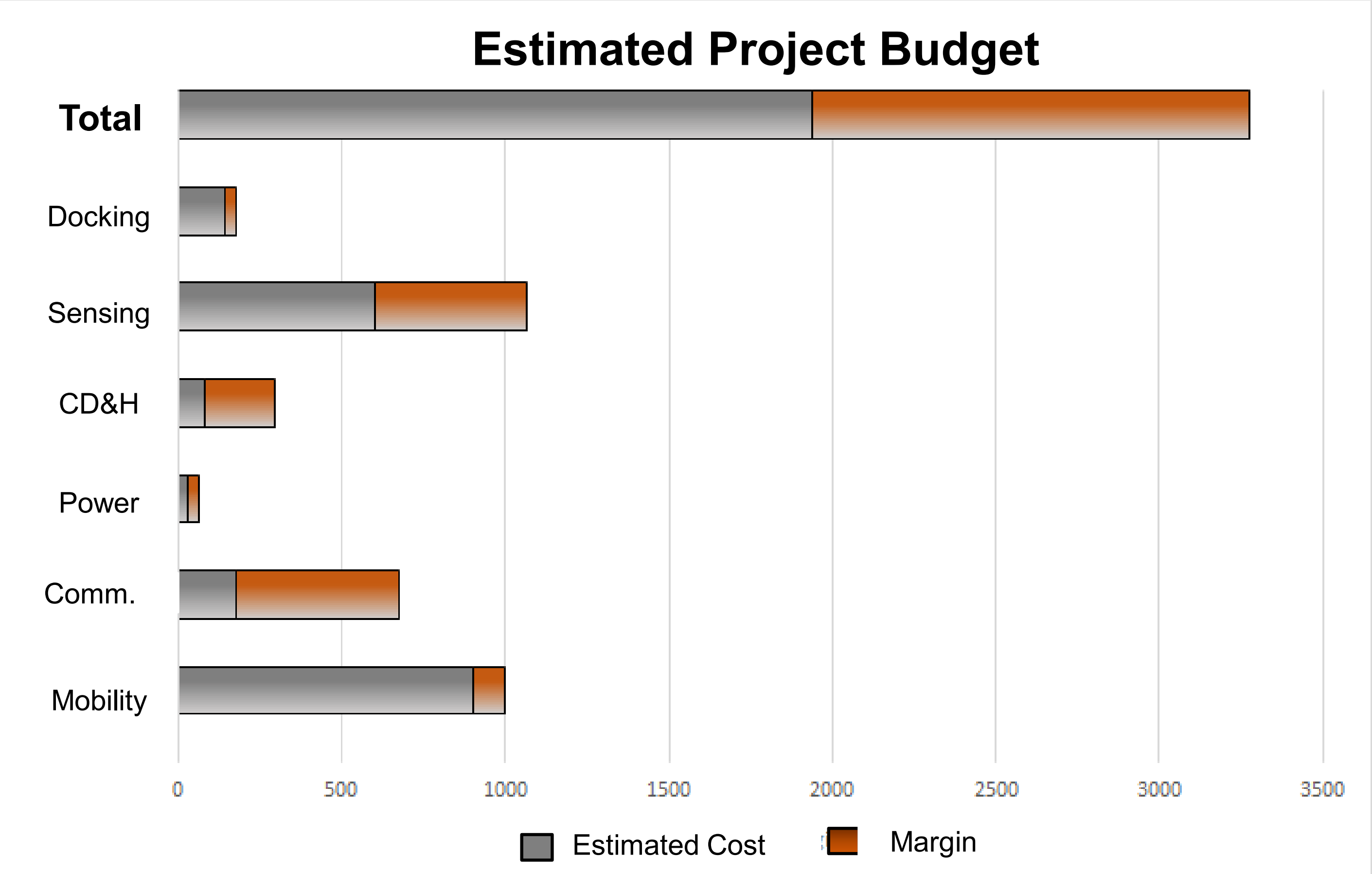
Critical Design Review DUE

Fall Final Report (FFR) DUE

Legend

- ▨ Margin
- ➡ Critical Path
- 🟥 Mobility Subsystem
- 🟨 Software Subsystem
- 🟪 Electronics Subsystem
- 🟩 Preliminary Verification
- 🟦 CDR Slide Development
- 🟫 Report Development
- ◆ Milestone

Budget



- The current budget estimate is less than $3500
- Margin of $1500 with allowable spending
- The most expensive subsystems will likely be:
  - Sensing
  - Communications
  - Mobility
- High estimates of subsystems used for total estimate

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Bobby Hodgkinson - AES

Trudy Schwartz – AES

Robert Marshall – AES

University of Colorado
Boulder

JPL
Jet Propulsion Laboratory

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3	Project Motivation
4	Project Statement
5	Definitions
6	Concept of Operations
7	Functional Requirements
8	Functional Block Diagram
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10	Baseline Design
11	Translational System Baseline Design
12	Object Detection Baseline Design
13	Communication System Baseline Design
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15	Imaging System Baseline Design
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80	Inclined Slope Model
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90	Pros/ Cons of Single Hinged Axis Trailer Platform
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Slide	Description
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[redacted]	[redacted]
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112	Hardware Specs
113	Hardware Integration
114	Wi-Fi Extra
115	Variable and Equations Descriptions
116	Scenarios
117	Communications: The Model
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Note: After slide 109 the slide numbers are 1 slide ahead of the actual presentation.

Example: Communication Systems is actually slide 110

Slide Directory

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161	Object Detection Trade Matrix
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Team Structure

Person	Position
Dr. Kathryn Wingate	Project Advisor
Marcos Mejia	Project Manager
Colin Chen	Mechanical Lead
Quinter Nyland	Integrations Lead
Katelyn Griego	Safety Lead
Brindan Adhikari	Electronics Lead
Chase Pellazar	Systems Lead
Ashley Montalvo	Test Lead
Brandon Santori	Software Lead
Alexander Sandoval	Communications and GPS Lead
Alexis Sotomayor	Finance Lead
Junzhe He	Structures Lead
Michely Tenardi	Manufacturing Lead

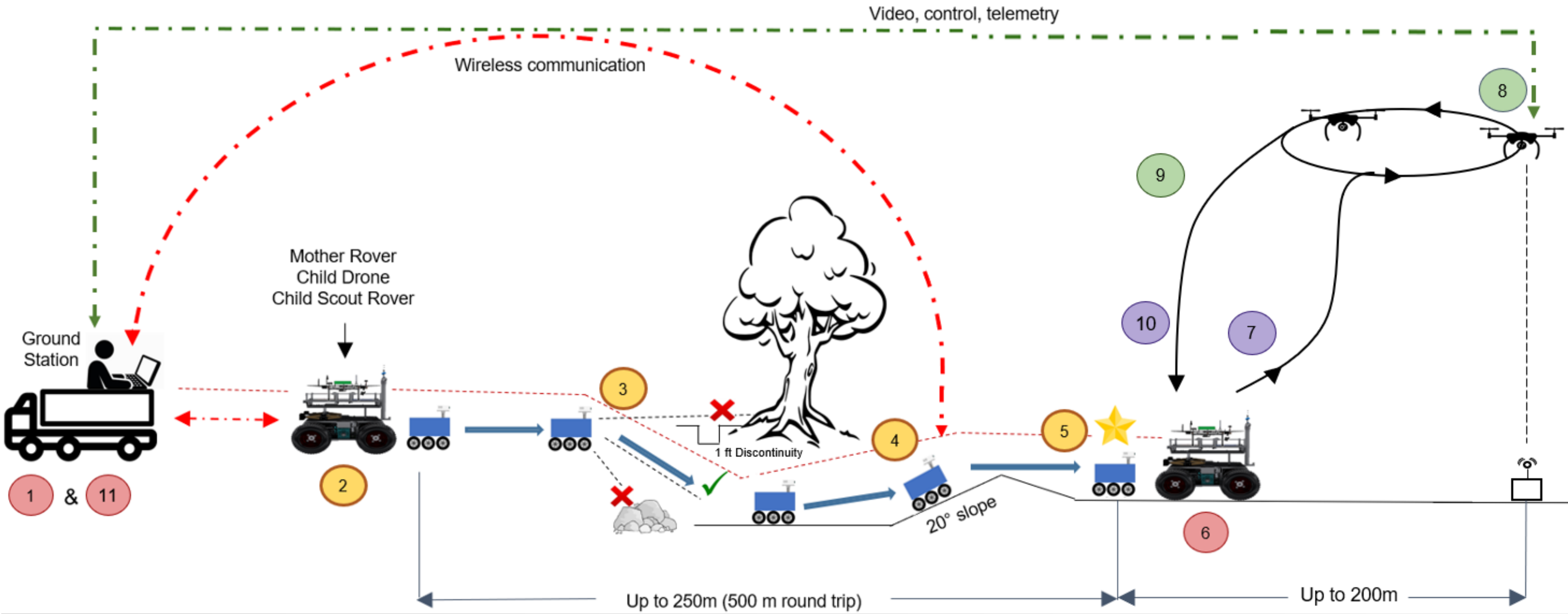
Fire tracker Concept of Operations

The overall CONOPs for the JPL Firetracker System is shown. This includes all projects, HERMES, DRIFT, CHIMERA, and INFERNO

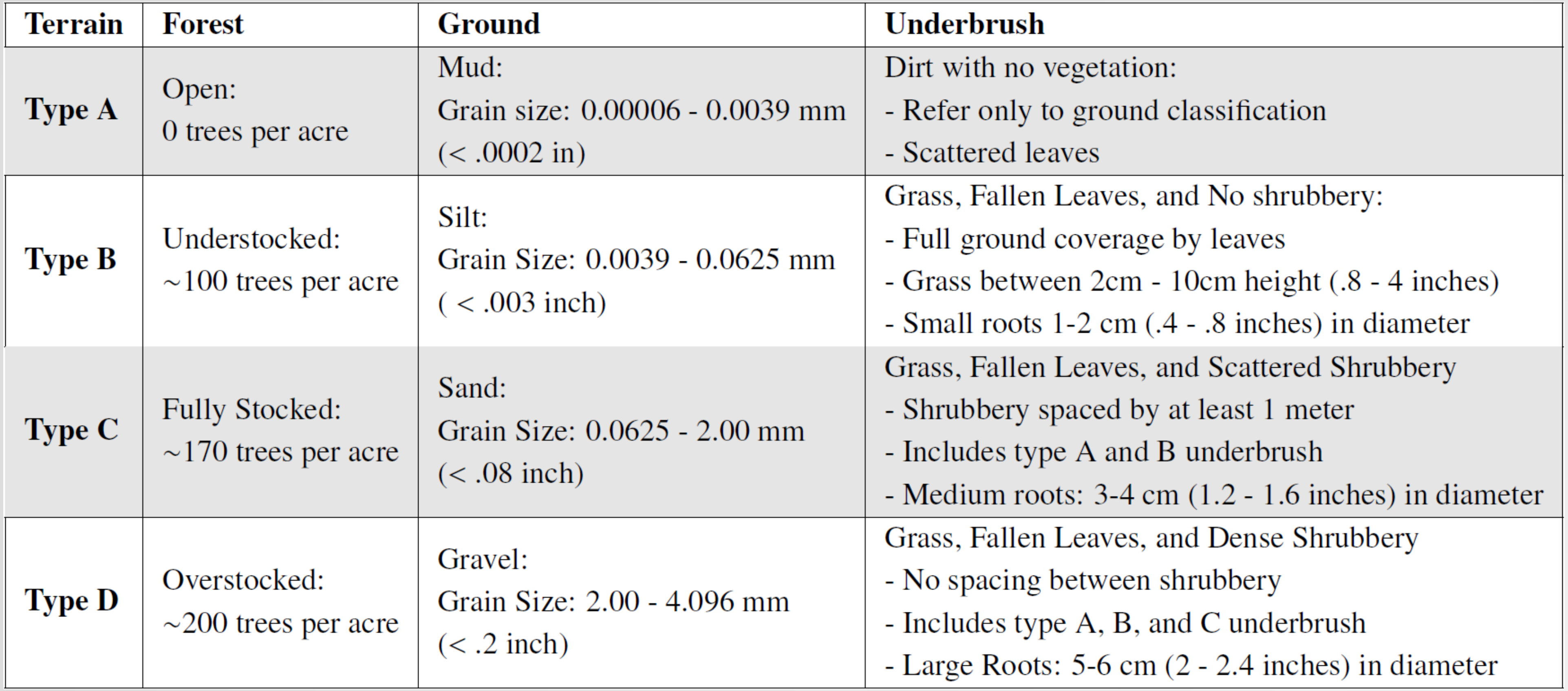
CD - Child Drone
GS - Ground Station
MR - Mother Rover
CSR – Child Scout Rover

🟡 HERMES (2018 – 2019)
🔴 DRIFT (2017 – 2018)
🟣 CHIMERA (2016 – 2017)
🟢 INFERNO (2015 – 2016)

——— CD aerial path
-·-·-·- Communications with MR
-·-·-·- Communications with GS
-------- MR ground path

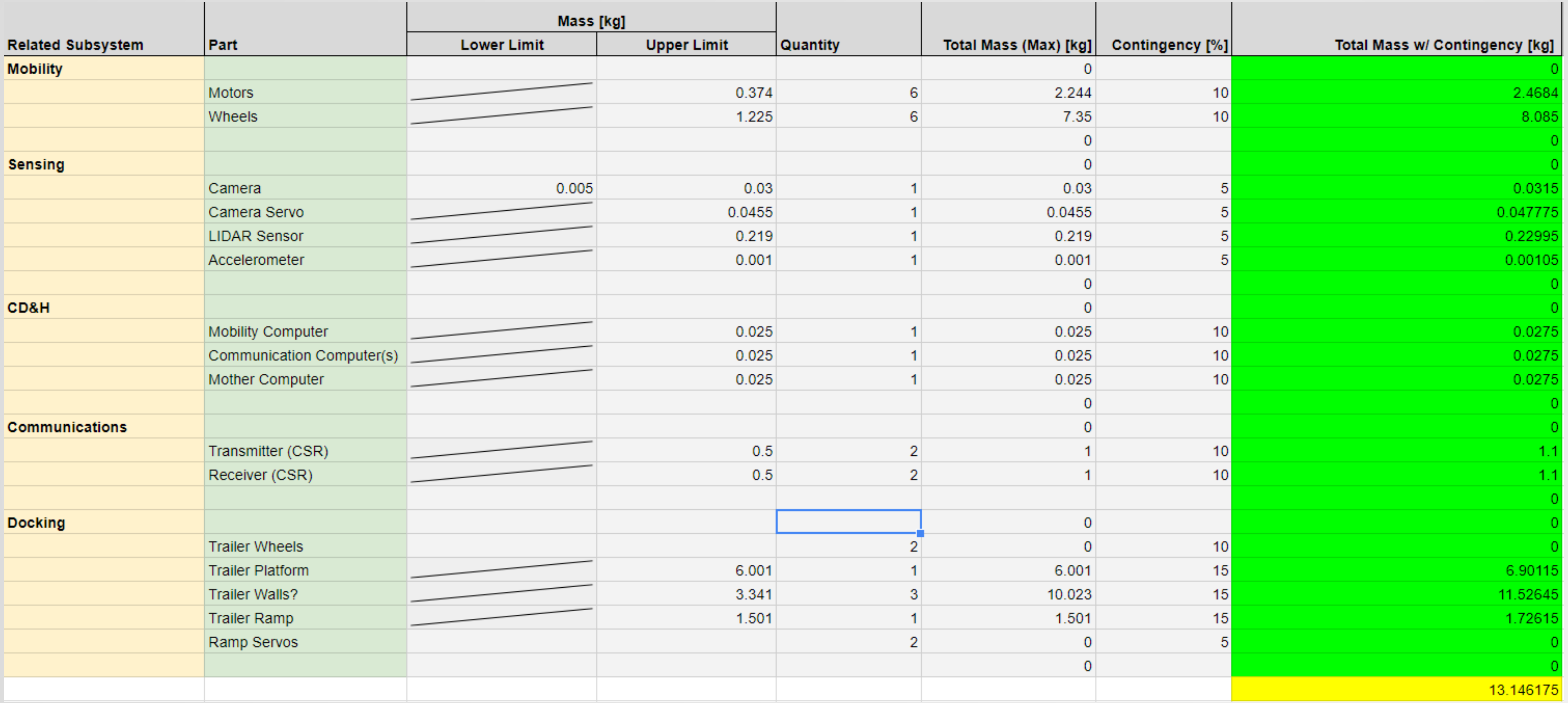


Detailed Terrain Definition



Terrain	Forest	Ground	Underbrush
Type A	Open: 0 trees per acre	Mud: Grain size: 0.00006 - 0.0039 mm (< .0002 in)	Dirt with no vegetation: - Refer only to ground classification - Scattered leaves
Type B	Understocked: ~100 trees per acre	Silt: Grain Size: 0.0039 - 0.0625 mm (< .003 inch)	Grass, Fallen Leaves, and No shrubbery: - Full ground coverage by leaves - Grass between 2cm - 10cm height (.8 - 4 inches) - Small roots 1-2 cm (.4 - .8 inches) in diameter
Type C	Fully Stocked: ~170 trees per acre	Sand: Grain Size: 0.0625 - 2.00 mm (< .08 inch)	Grass, Fallen Leaves, and Scattered Shrubbery - Shrubbery spaced by at least 1 meter - Includes type A and B underbrush - Medium roots: 3-4 cm (1.2 - 1.6 inches) in diameter
Type D	Overstocked: ~200 trees per acre	Gravel: Grain Size: 2.00 - 4.096 mm (< .2 inch)	Grass, Fallen Leaves, and Dense Shrubbery - No spacing between shrubbery - Includes type A, B, and C underbrush - Large Roots: 5-6 cm (2 - 2.4 inches) in diameter

Mass Budget



Related Subsystem	Part	Mass [kg]		Quantity	Total Mass (Max) [kg]	Contingency [%]	Total Mass w/ Contingency [kg]
		Lower Limit	Upper Limit				
Mobility					0		0
	Motors		0.374	6	2.244	10	2.4684
	Wheels		1.225	6	7.35	10	8.085
					0		0
Sensing					0		0
	Camera	0.005	0.03	1	0.03	5	0.0315
	Camera Servo		0.0455	1	0.0455	5	0.047775
	LIDAR Sensor		0.219	1	0.219	5	0.22995
	Accelerometer		0.001	1	0.001	5	0.00105
					0		0
CD&H					0		0
	Mobility Computer		0.025	1	0.025	10	0.0275
	Communication Computer(s)		0.025	1	0.025	10	0.0275
	Mother Computer		0.025	1	0.025	10	0.0275
					0		0
Communications					0		0
	Transmitter (CSR)		0.5	2	1	10	1.1
	Receiver (CSR)		0.5	2	1	10	1.1
							0
Docking					0		0
	Trailer Wheels			2	0	10	0
	Trailer Platform		6.001	1	6.001	15	6.90115
	Trailer Walls?		3.341	3	10.023	15	11.52645
	Trailer Ramp		1.501	1	1.501	15	1.72615
	Ramp Servos			2	0	5	0
					0		0
							13.146175

Testing Facilities

Terrain Testing and Mobility

- Boulder Open Space
- On campus
- ITLL

Software

- RECUV Lab in the Ideaforge
- ITLL

Sensor Calibration

- RECUV Lab in the Ideaforge

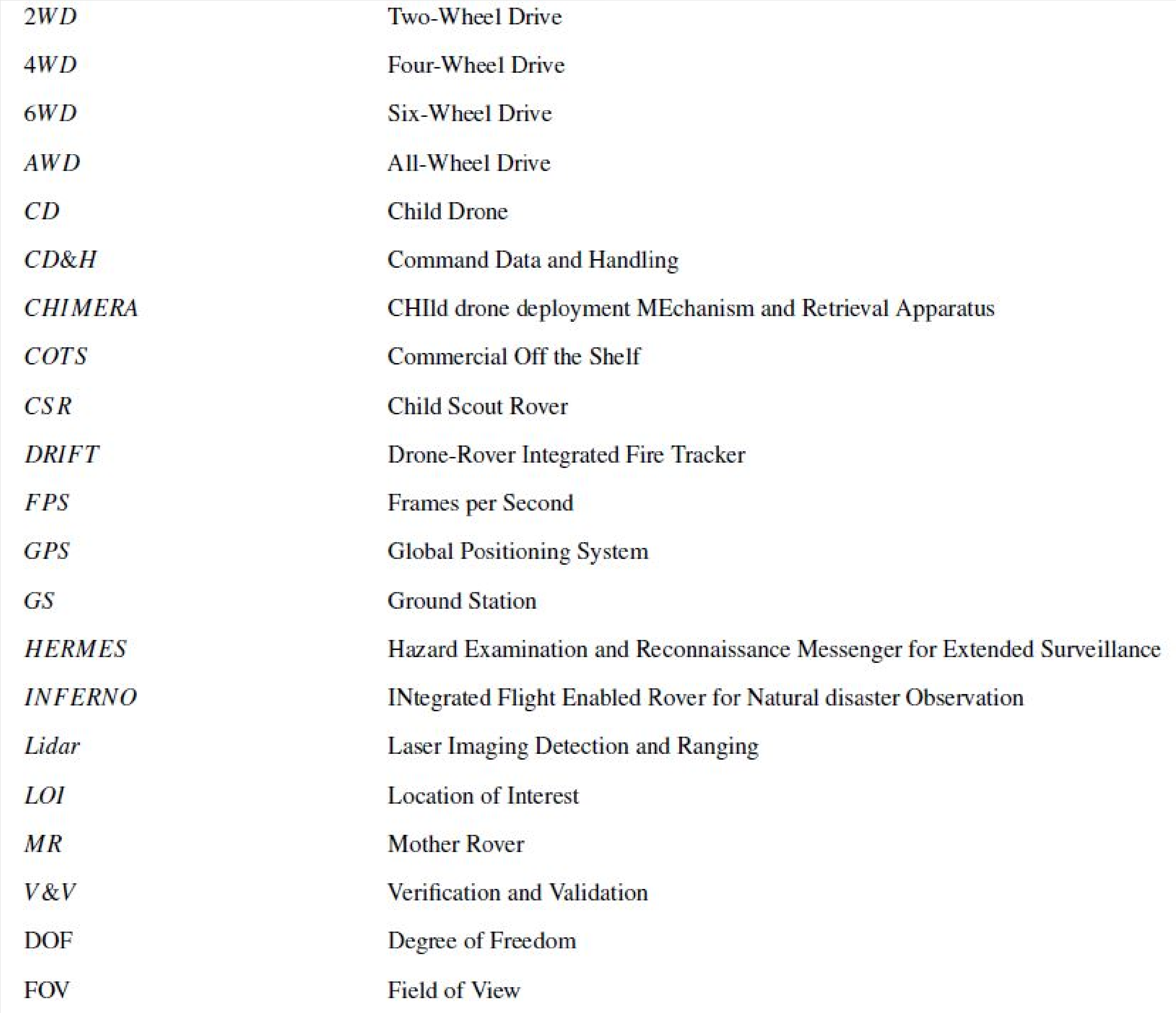
Object Detection

- RECUV Lab in the Ideaforge

Communications

- Boulder Open Space

Acronyms



2WD	Two-Wheel Drive
4WD	Four-Wheel Drive
6WD	Six-Wheel Drive
AWD	All-Wheel Drive
CD	Child Drone
CD&H	Command Data and Handling
CHIMERA	CHIld drone deployment MEchanism and Retrieval Apparatus
COTS	Commercial Off the Shelf
CSR	Child Scout Rover
DRIFT	Drone-Rover Integrated Fire Tracker
FPS	Frames per Second
GPS	Global Positioning System
GS	Ground Station
HERMES	Hazard Examination and Reconnaissance Messenger for Extended Surveillance
INFERNO	INtegrated Flight Enabled Rover for Natural disaster Observation
Lidar	Laser Imaging Detection and Ranging
LOI	Location of Interest
MR	Mother Rover
V&V	Verification and Validation
DOF	Degree of Freedom
FOV	Field of View

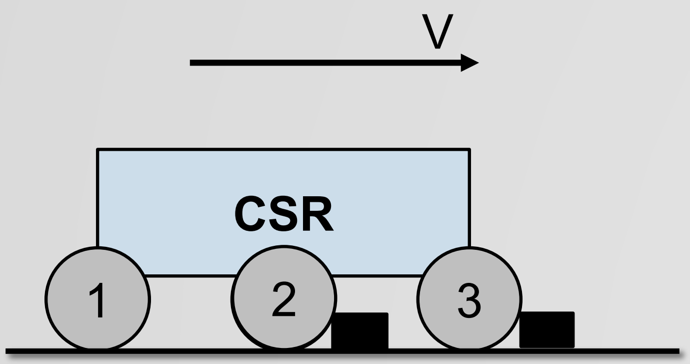
Baseline Design Summary

Translational System	Object Detection & Software	Communication System	Docking/Deploying Mechanism	Image System
4WD with 6 Wheels	**LIDAR**	**Wi-Fi**	**Trailer Platform**	**Single Actuated Camera**
4WD with 4 Wheels	Ultrasonic	Global System For Mobile Communication (GSM)	Hitch	360 ° Camera
6WD with 6 Wheels	Image Processing	Zigbee (Heritage)	On-board Ramp, Extended Platform	Single Fixed Wide FOV Camera
Tank Track	Collision Sensors		On-board Ramp	Two Fixed Wide FOV Cameras
Rocker Bogie			On board Lift, Extended Platform	
			On board lift	
			Ball Joint Trailer Platform	

Translational System

Overcoming Obstacles

MOB.3.4 The CSR shall be able to drive in underbrush
MOB.3.4.1 The CSR shall be able to go over obstacles up to 6 cm (2.4 in) of height



Legend:

- ■ Obstacle
- 🔴 Free Wheel
- ○ Driven Wheel

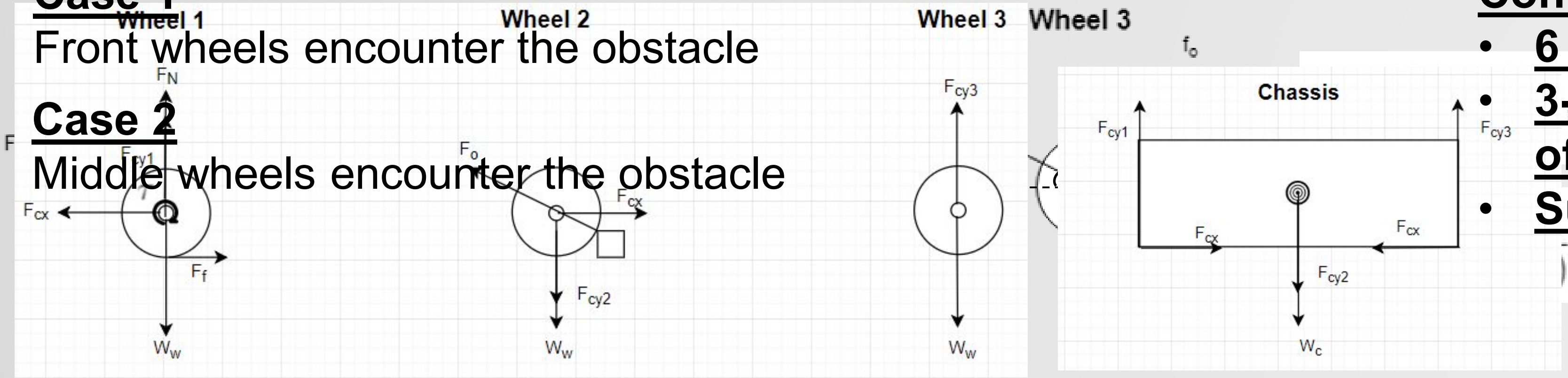
r radius of the wheel
h height of the obstacle
W_w weight of the wheel pair
W_c weight of the chassis

Normal force on wheels 1 and 3 ≡ 0

Normal force on wheel 2 ≡ 0

Baseline Assumptions for Math Models:

1. Center of mass centered at the middle
2. Roll no-slip
3. Steady state
4. Equal torque output on each driving wheel
5. Negligible forward velocity/kinetic energy



Case 1

Front wheels encounter the obstacle

Case 2

Middle wheels encounter the obstacle

4 Wheel Drive (4WD) with 6 Wheels

Continued study :

- **6 Wheel Drive (6WD) with 6 Wheels**
- **3-stage moving mass to vary location of center of mass**
- **Suspension**

Therefore, there is no traction on the wheels and the CSR can't move.

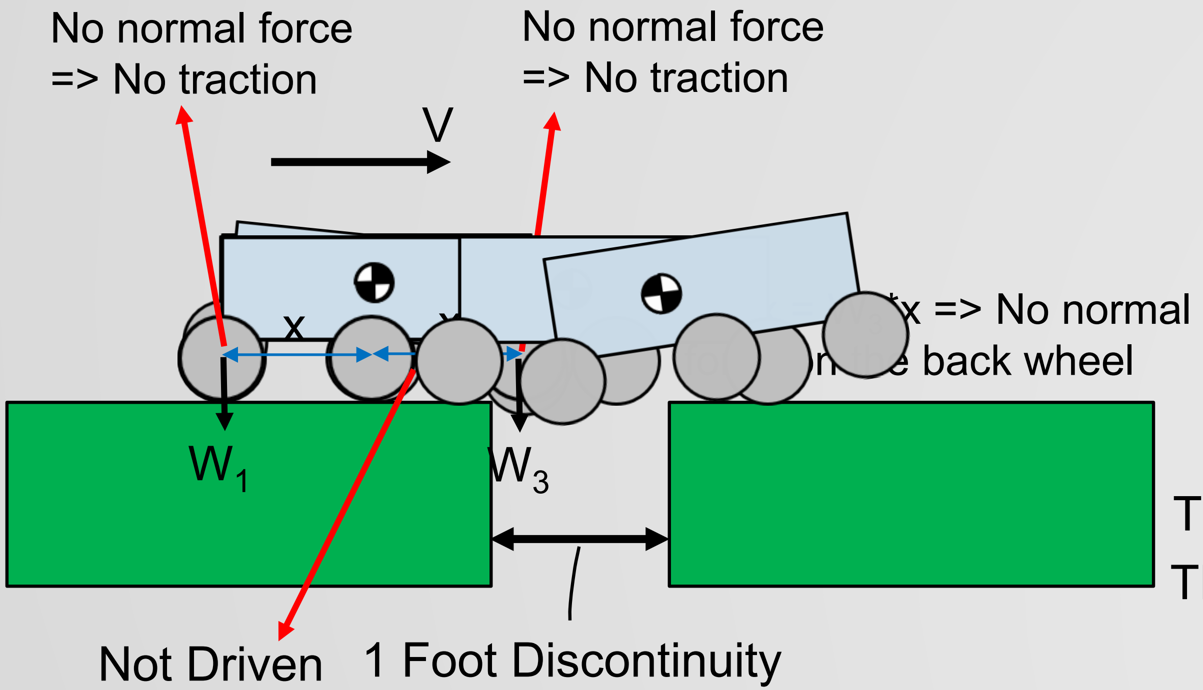
➢ 3.7in to go over 2.4in obstacle with a μ of 0.7.

NOT FEASIBLE

Overcoming a 1 Foot Discontinuity

MOB.3.2 The CSR shall be able to go over discontinuities up to 1 foot (0.3 meters)

4 Wheel Drive (4WD) with 6 Wheels
Middle wheels are not driven



Feasibility Items:
1. Can the CSR traverse a 1 ft discontinuity?

Baseline Assumptions:
1. Roll no slip
2. Insignificant Rolling Resistance
3. Velocity is small

Results?

The CSR can't move if the middle wheels are not driven NOT FEASIBLE

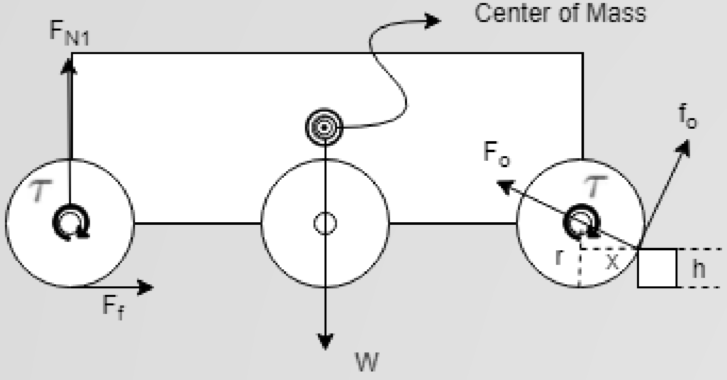
The CSR will tip and won't be able to go over the discontinuity NOT FEASIBLE

The CSR will tip and won't be able to go over the discontinuity NOT FEASIBLE

Continued study:
- **3-stage moving mass to vary location of center of mass**
- **Extended wheels**
- **8-wheel design**
- **Accelerate the CSR**

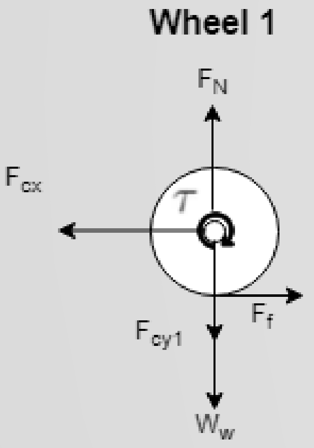
4WD

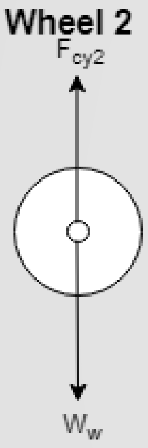
Overcoming Obstacles – Case 1

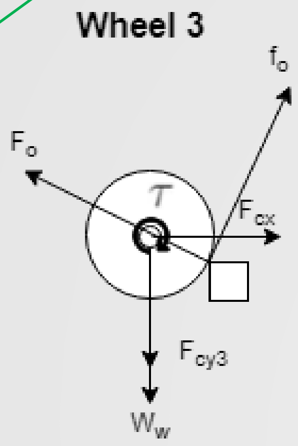


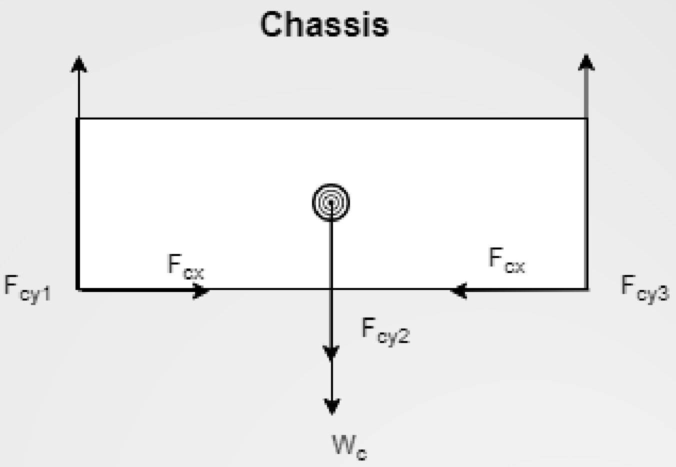
$$\tau = \frac{3W_w + W_c}{2} * \frac{r * \sqrt{r^2 - (r-h)^2}}{2r - h}$$

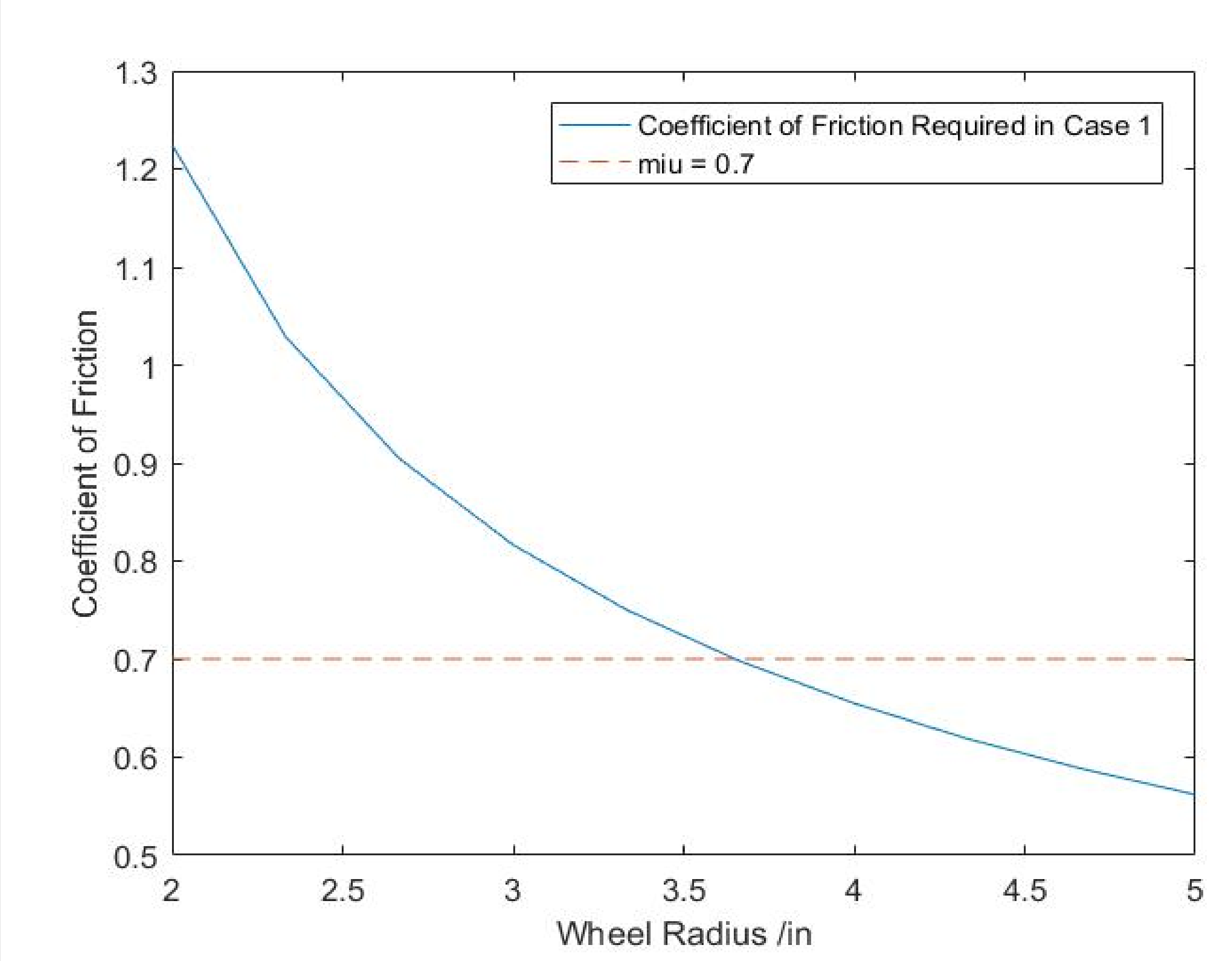
FEASIBLE







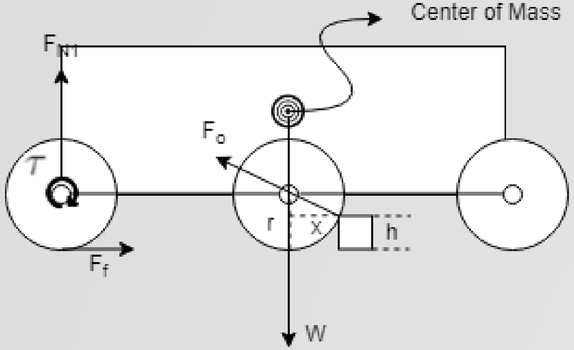




Change in μ required with the change in wheel size

Reference website

Overcoming Obstacles – Case 2

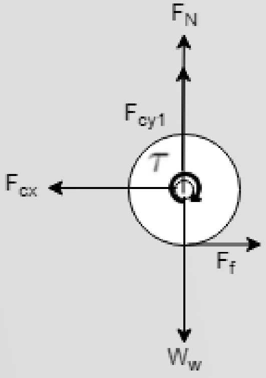


$$F_{cy1} = F_{cy3} = \frac{W}{3} => F_N = 0$$

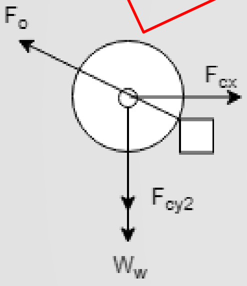
Therefore there is no fraction and the CSR can't move forward.

NOT FEASIBLE

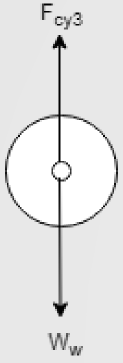
Wheel 1



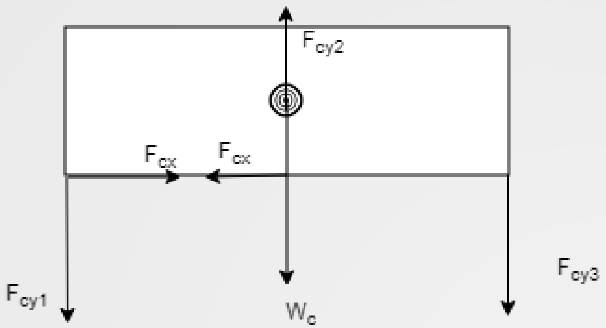
Wheel 2



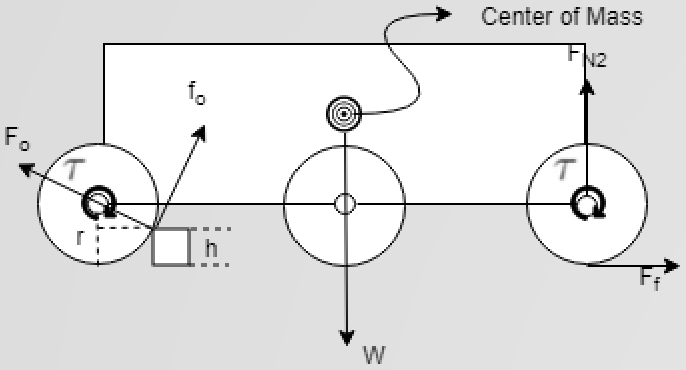
Wheel 3



Chassis

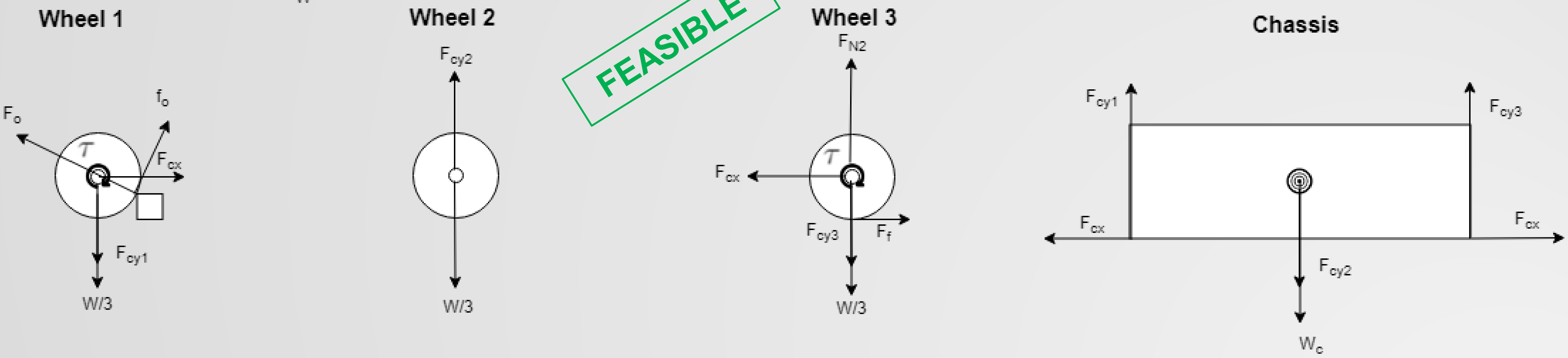


Overcoming Obstacles – Case 3



$$\tau = \frac{3W_w + W_c}{2} * \frac{r * \sqrt{r^2 - (r-h)^2}}{2r - h}$$

FEASIBLE

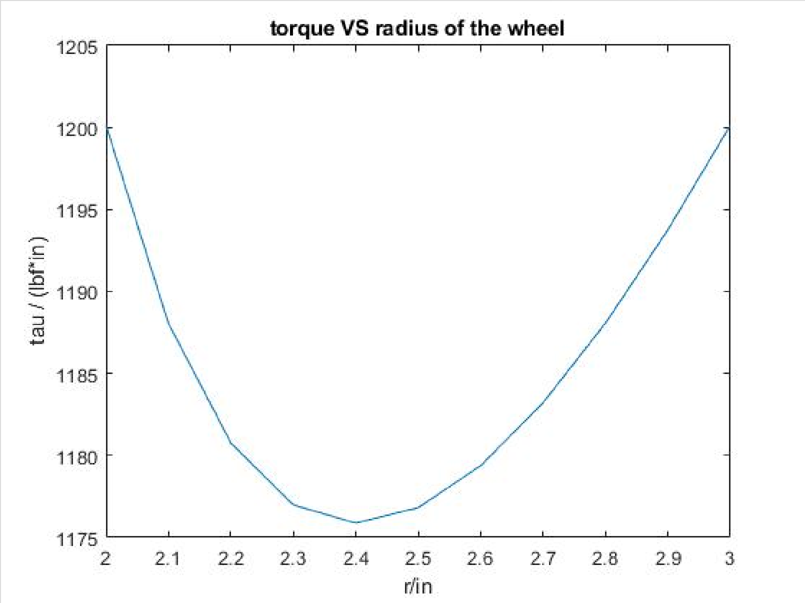

Wheel 1

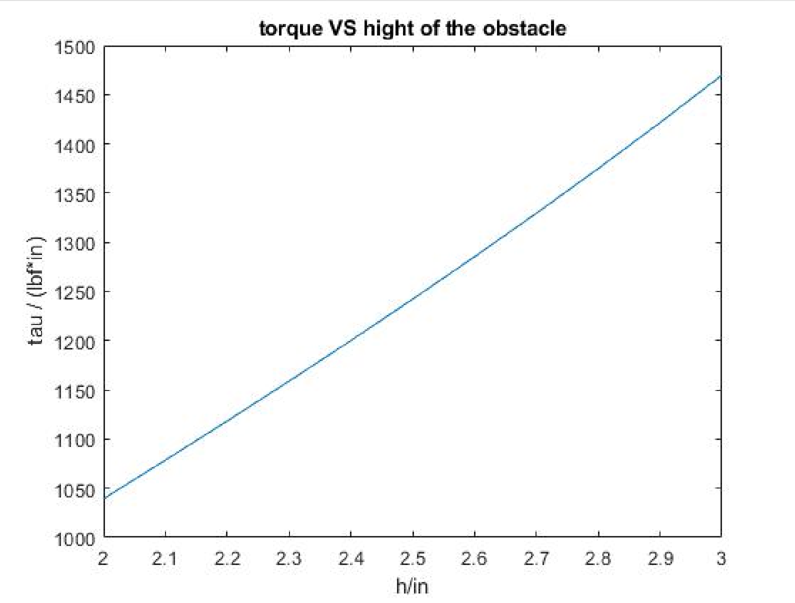
Wheel 2

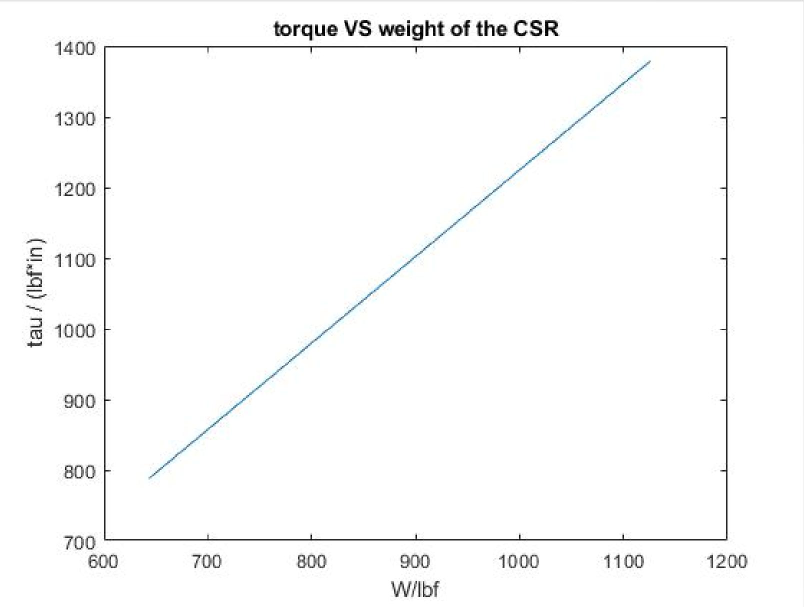
Wheel 3

Chassis

Sensitivity Analysis – Overcoming Obstacle





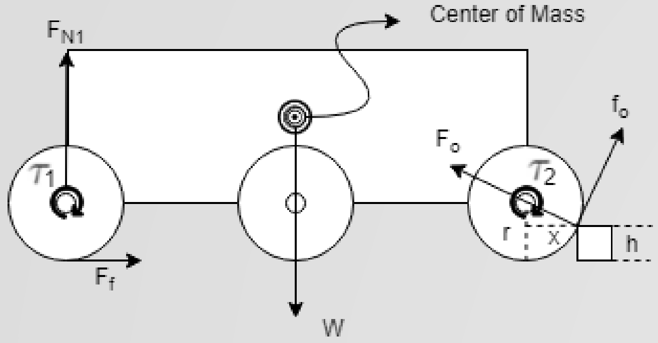


Based on the sensitivity analysis:

- Decreasing obstacle height and weight of the CSR decreases the torque required.
- Using wheels with an equal radius to the height of the obstacle requires minimum torque

6WD

Overcoming Obstacles – Case A with different torque on each motor

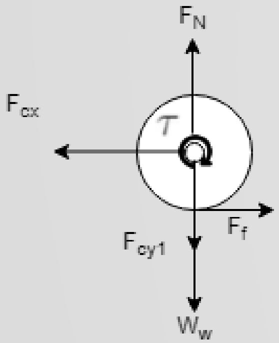


$$\tau_1 = \frac{cos(\theta) - \mu_2 sin(\theta)}{sin(\theta) + \mu_2 cos(\theta)} * \frac{W * r}{2}$$

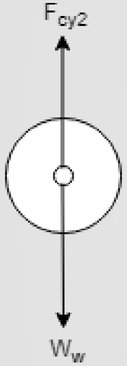
$$\tau_2 = \frac{\mu_2}{sin(\theta) + \mu_2 cos(\theta)} * \frac{W * r}{2}$$

$$\mu_1 = \frac{cos(\theta) - \mu_2 sin(\theta)}{sin(\theta) + \mu_2 cos(\theta)}$$

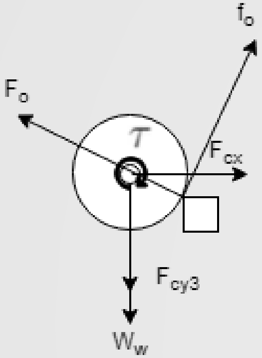
Wheel 1



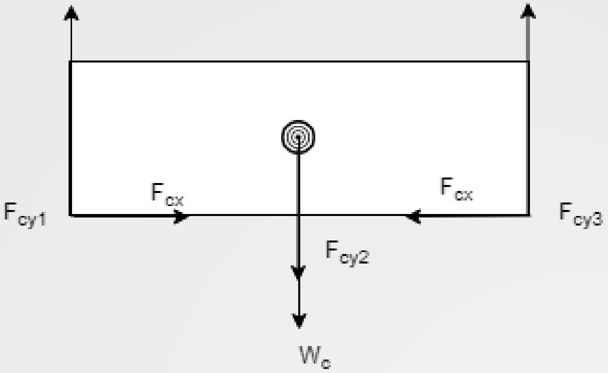
Wheel 2



Wheel 3

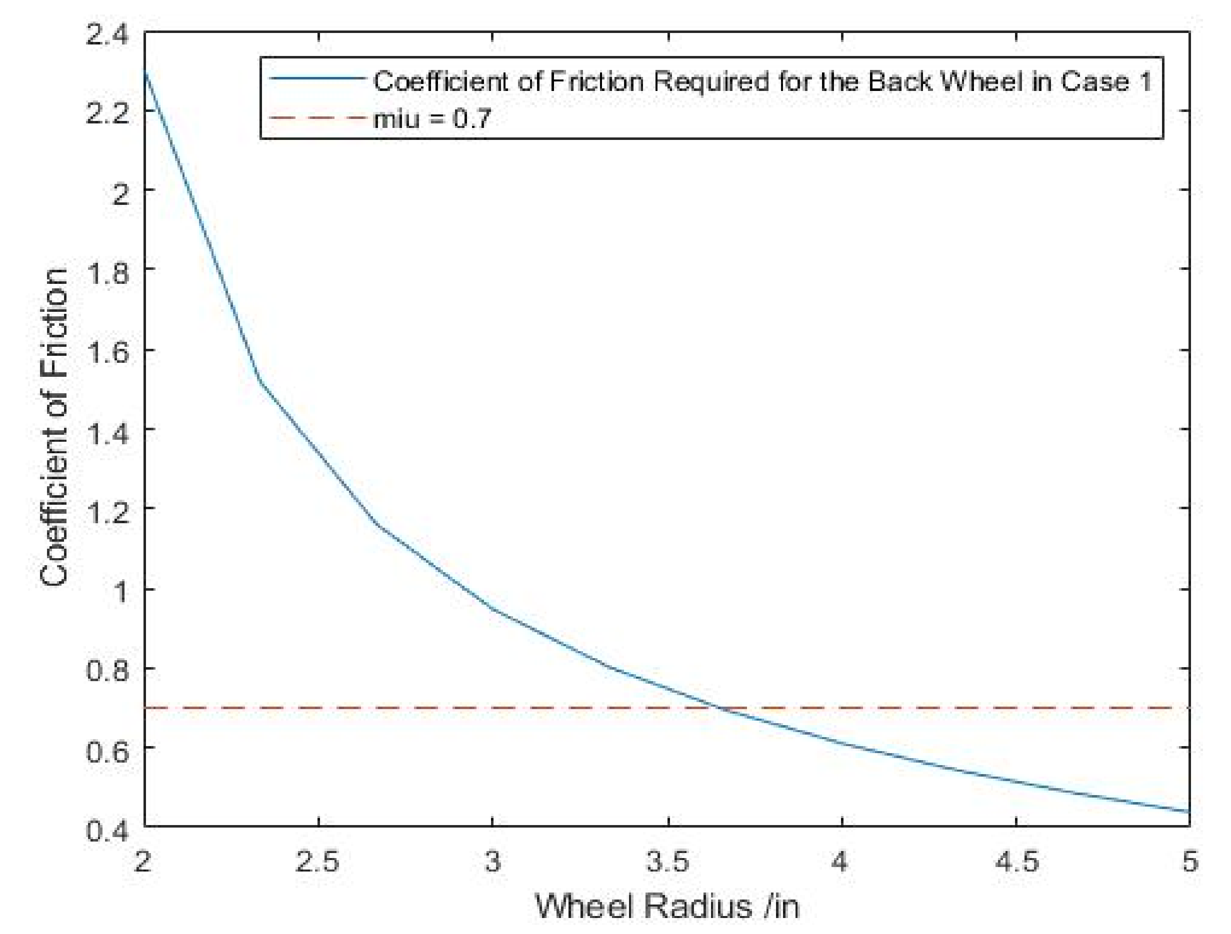


Chassis



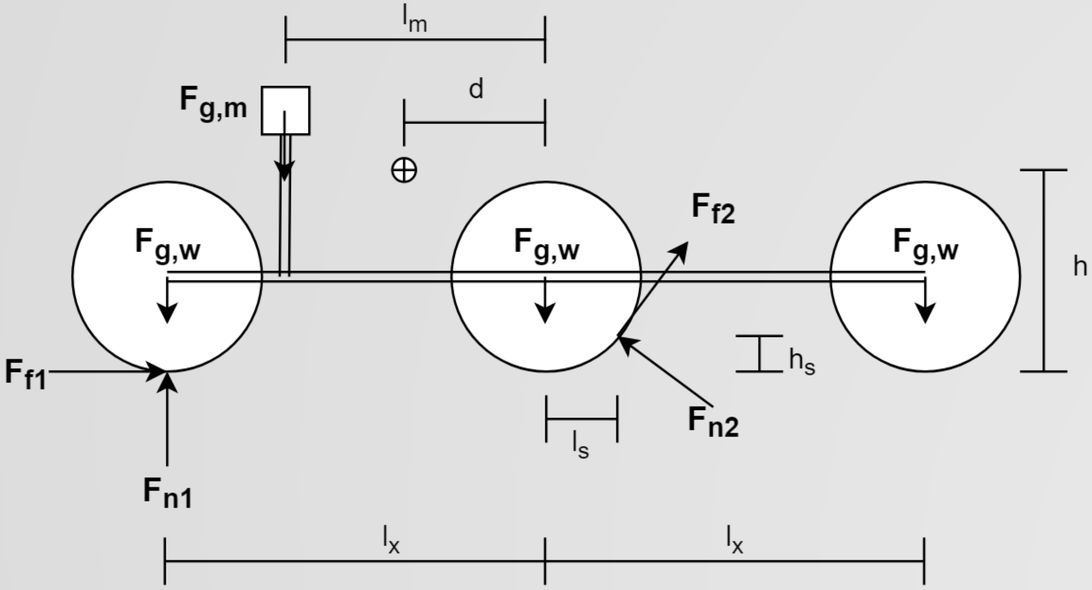
Case A Sensitivity Analysis

With μ_2 set to be 0.7, the change of μ_1 required with the change of wheel size is shown below:



Overcoming Obstacles – 6WD Case B

1) Free Body Diagram



2) Relational Equations

$$F_{g,w} = \frac{m_w g}{3}$$

$$d = \frac{m_m l_m}{m_w + m_m}$$

$$l_s = \sqrt{r^2 - (r - h_s)^2}$$

$$F_f \leq \mu F_N$$

$$\tau_{motor} = F_{f,max} r$$

3) Assume: Roll no-slip, rigid chassis, Coulomb friction model,
each wheel is of equal mass, negligible rolling resistance,
negligible forward velocity

Overcoming Obstacles – 6WD Case B

4) Summation of Forces and Moments

$$\sum F_x : 0 = F_{f1} + F_{f2} \cdot \frac{r - h_s}{r} - F_{N2} \cdot \frac{l_s}{r}$$

$$\sum F_y : 0 = F_{f2}\frac{l_s}{r} + F_{N1} + F_{N2}\frac{r - h_2}{r} - (m_w + m_m)g$$

$$\begin{aligned} \sum M_{z,CM} : 0 = hF_{f1} &+ \frac{(r - h_s)(h - h_s) + l_s(d + l_s)}{r} F_{f2} \\ &+ (d - l_x)F_{N1} + \frac{(r - h_s)(d + l_s) - l_s(h - h_s)}{r} F_{N2} - m_m g(l_m - d) \end{aligned}$$

Overcoming Obstacles – 6WD Case B

5) Convert Summation of Forces into Matrices

$$A = \begin{bmatrix} 1 & \frac{r-h_s}{r} & 0 & -\frac{l_s}{r} \\ 0 & \frac{l_s}{r} & 1 & \frac{r-h_2}{r} \\ h & \frac{(r-h_s)(h-h_s)+l_s(d+l_s)}{r} & d-l_x & \frac{(r-h_s)(d+l_s)-l_s(h-h_s)}{r} \end{bmatrix} \quad x = \begin{bmatrix} F_{f1} \\ F_{f2} \\ F_{N1} \\ F_{N2} \end{bmatrix} \quad b = \begin{bmatrix} 0 \\ (m_w+m_m)g \\ -m_m g(l_m-d) \end{bmatrix}$$

6) Augment Matrix

$$[A|b] = \left[\begin{array}{cccc|c} 1 & \frac{r-h_s}{r} & 0 & -\frac{l_s}{r} & 0 \\ 0 & \frac{l_s}{r} & 1 & \frac{r-h_2}{r} & (m_w+m_m)g \\ h & \frac{(r-h_s)(h-h_s)+l_s(d+l_s)}{r} & d-l_x & \frac{(r-h_s)(d+l_s)-l_s(h-h_s)}{r} & -m_m g(l_m-d) \end{array}\right]$$

Overcoming Obstacles – 6WD Case B

7) Reduce Augmented Matrix

$$RREF[A|b] = \left[\begin{array}{cccc|c} 1 & 0 & 0 & i & X \\ 0 & 1 & 0 & j & Y \\ 0 & 0 & 1 & k & Z \end{array}\right]$$

8) Use relation $F_f = \mu F_N$ to find normal forces associated with the maximum possible coefficient of friction allowed by a given terrain.

Set friction force on back wheel use the maximum μ

Set friction force on front wheel use the maximum μ

$$A_{\mu,max,f1} = \left[\begin{array}{ccc|c} 0 & \mu_{max} & i & X \\ 1 & 0 & j & Y \\ 0 & 1 & k & Z \end{array}\right] \; ; \quad A_{\mu,max,f2} = \left[\begin{array}{ccc|c} 1 & 0 & i & X \\ 0 & 0 & \mu_{max} + j & Y \\ 0 & 1 & k & Z \end{array}\right]$$

Overcoming Obstacles – 6WD Case 2

9) Solve the Augmented Matrices, and use normal forces to solve for effective coefficients of frictions and frictional force required for the unsolved wheel experiencing μ_{max} using relation: $F_f = \mu F_N$
If the μ required by the other wheel is greater than μ_{max}, the design is not feasable.

10) Find the maximum frictional force required between the two wheels to determine the rating required by any one motor.

11) Solve for motor torque required: $\tau_{motor} = F_{f,max} r$

6WD Case B Feasibility Analysis

Using a geometrically centered CoM with baseline dimensions, *d* = 0m:

If $\mu_1 = 0.7 \quad \mu_2 = 1.28$

If $\mu_2 = 0.7 \quad \mu_1 = 1.42$

NOT FEASIBLE

Using variable center of mass with baseline dimensions:

Set the mass stage position: $l_m = \frac{3}{4} l_x$

Provides benefit of offset center of mass, while allowing space for physical implementation.

If $\mu_1 = 0.7 \quad \mu_2 = 0.49$

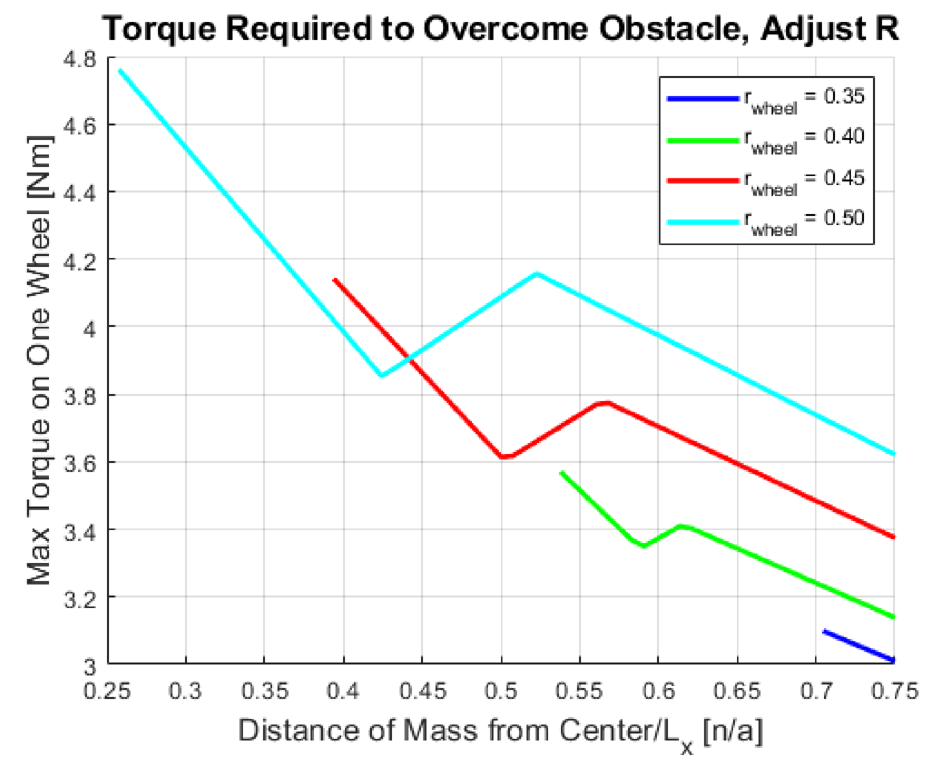
If $\mu_2 = 0.7 \quad \mu_1 = 0.54$

FEASIBLE

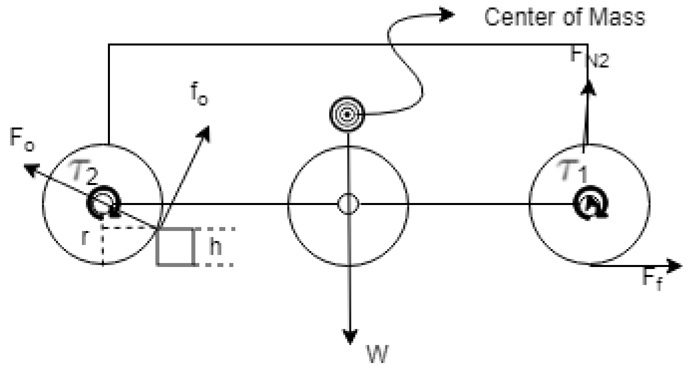
Case B Sensitivity Analysis

Using baseline CSR length and mass dimensions

Determining the distance the linear mass stage must be from the center of the CSR, and the resultant torques



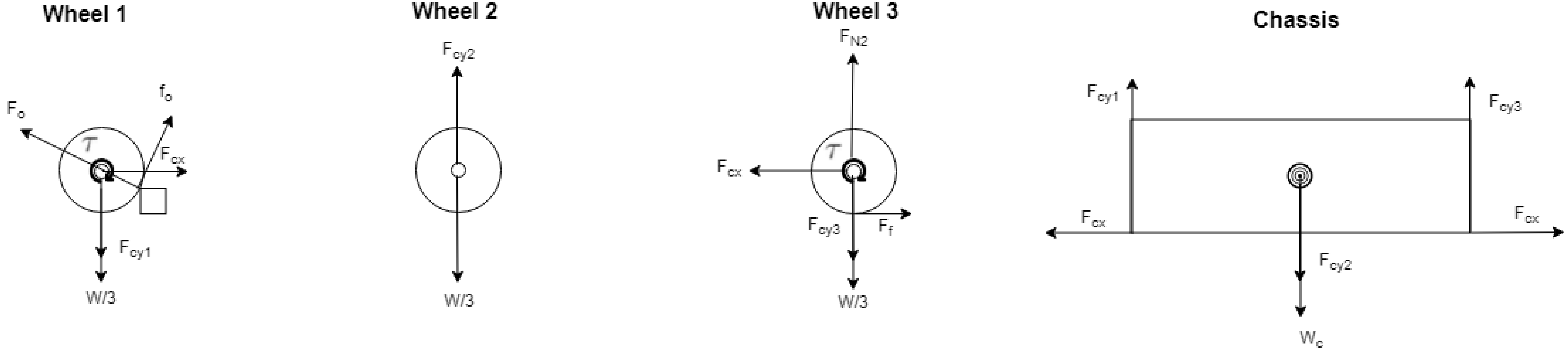
Overcoming Obstacles – Case C with different torque on each motor



$$\tau_1 = \frac{cos(\theta) - \mu_2 sin(\theta)}{sin(\theta) + \mu_2 cos(\theta)} * \frac{W * r}{2}$$

$$\tau_2 = \frac{\mu_2}{sin(\theta) + \mu_2 cos(\theta)} * \frac{W * r}{2}$$

$$\mu_1 = \frac{cos(\theta) - \mu_2 sin(\theta)}{sin(\theta) + \mu_2 cos(\theta)}$$

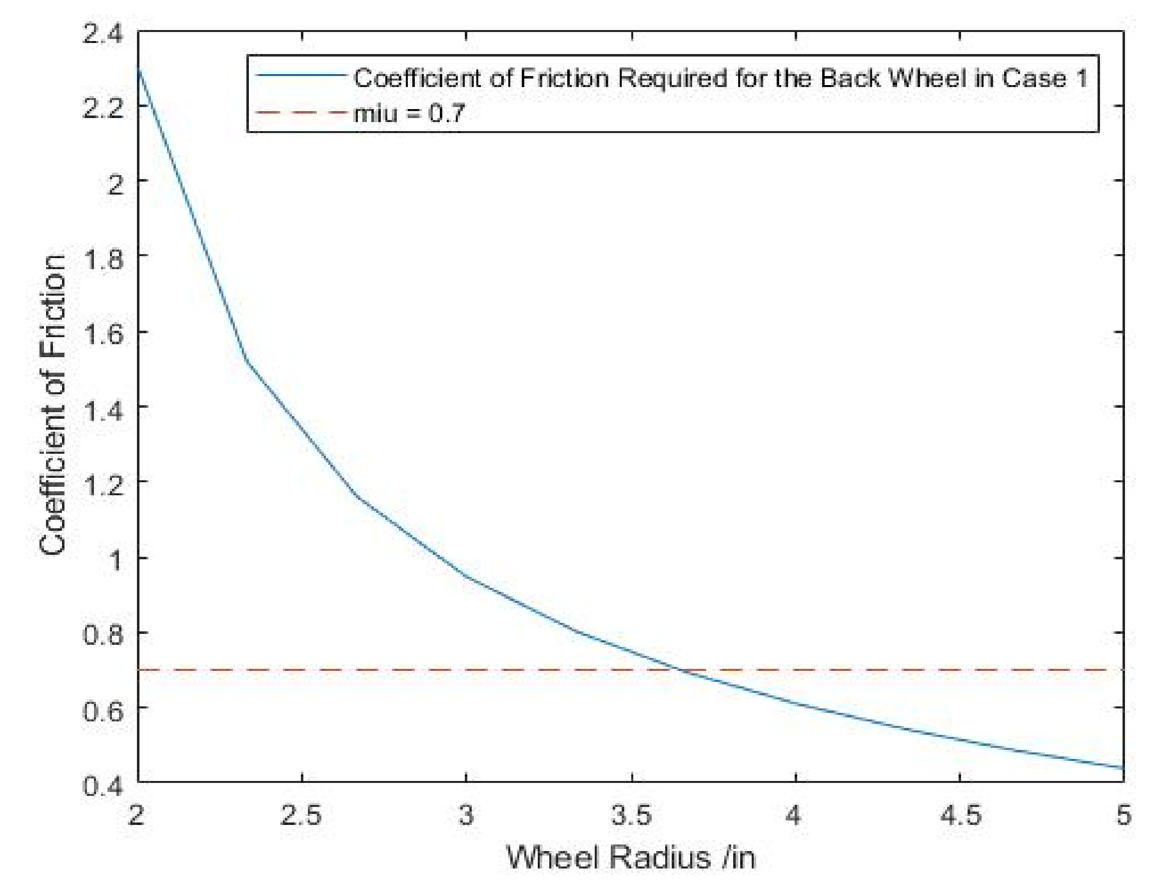


University of Colorado Boulder

Jet Propulsion Laboratory

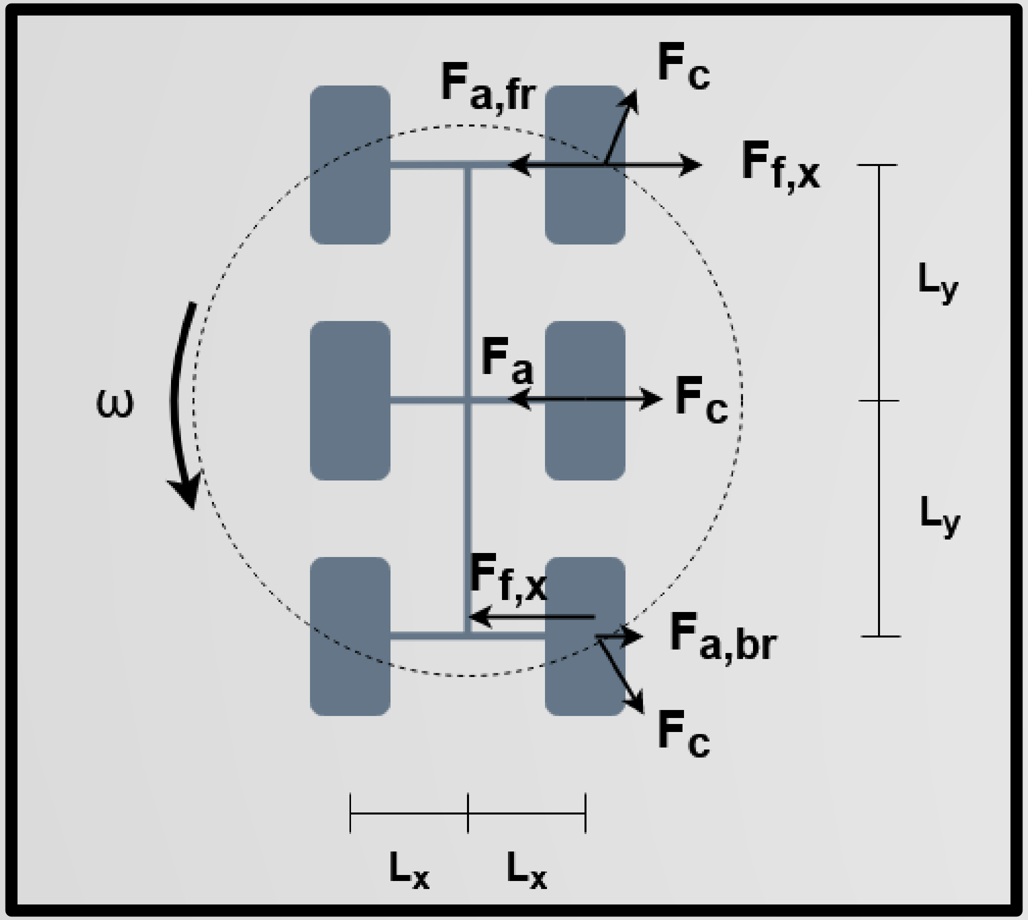
Case C Sensitivity Analysis

With μ2 set to be 0.7, the change of μ1 required with the change of wheel size is shown below:



In-Place 360° Turn Model

Compare effect of CSR dimensions and angular velocity on axial force.



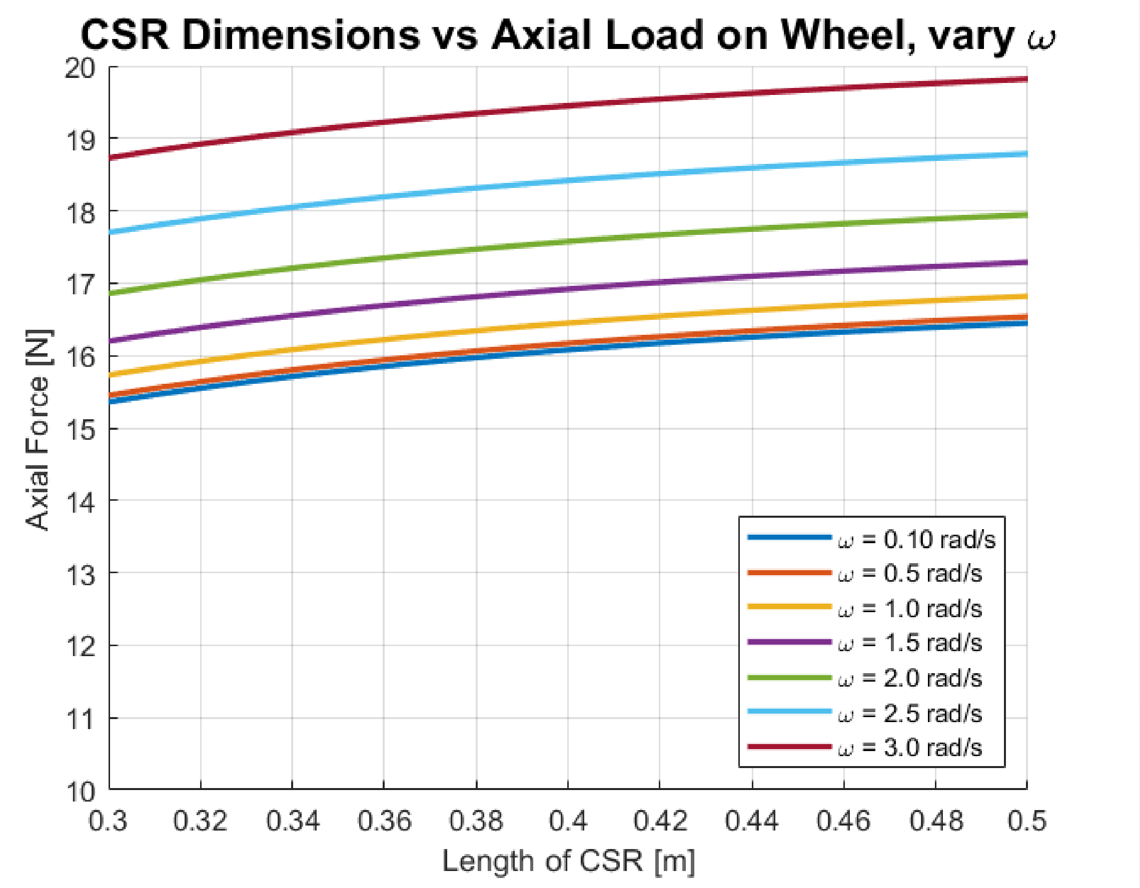
- Governing Equations:
  - Force balance equations for each wheel

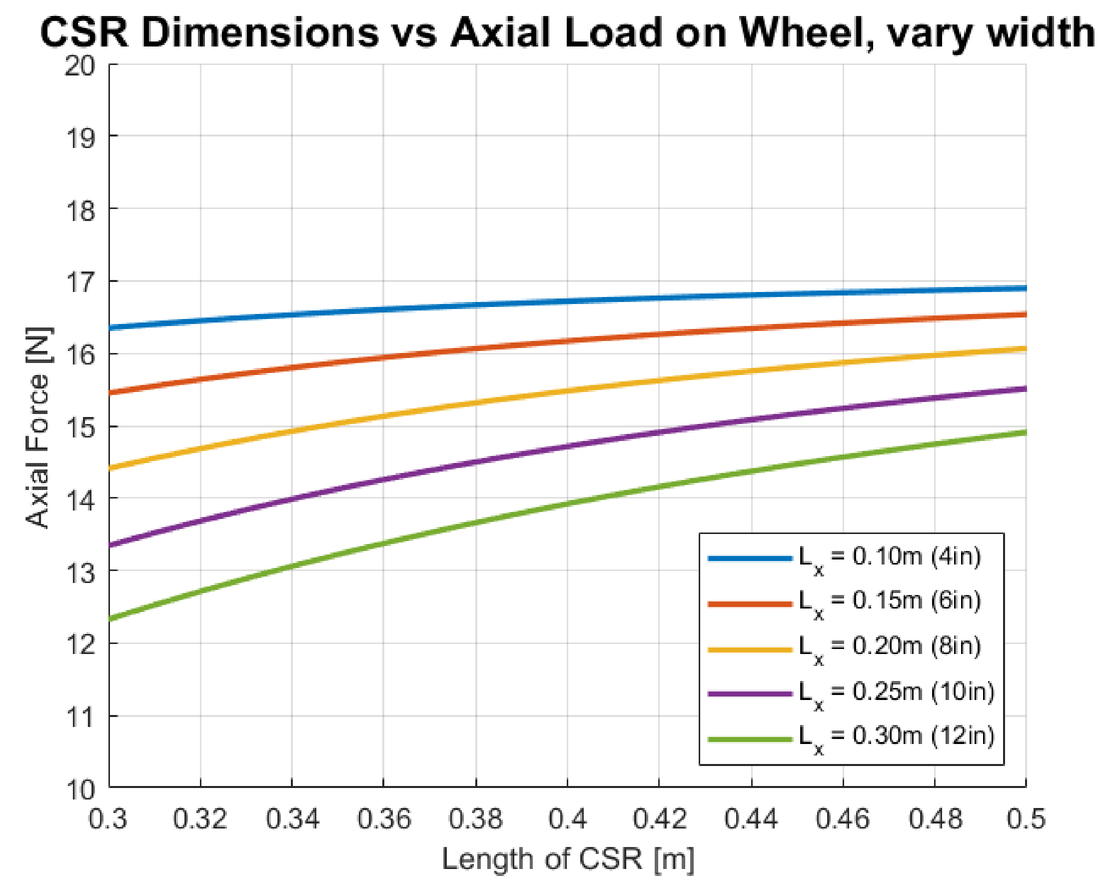
$$F_{a,fr} = \frac{m}{6}\left(\frac{\mu_K g L_y}{\sqrt{L_x^2 + L_y^2}} + \omega^2 L_x\right)$$

$$F_{a,m} = \frac{m L_x \omega^2}{6}$$

$$F_{a,br} = \frac{m}{6}\left(\frac{\mu_k g L_y}{\sqrt{L_x^2 + L_y^2}} - \omega^2 L_x\right)$$

Sensitivity analysis – In-Place Turn





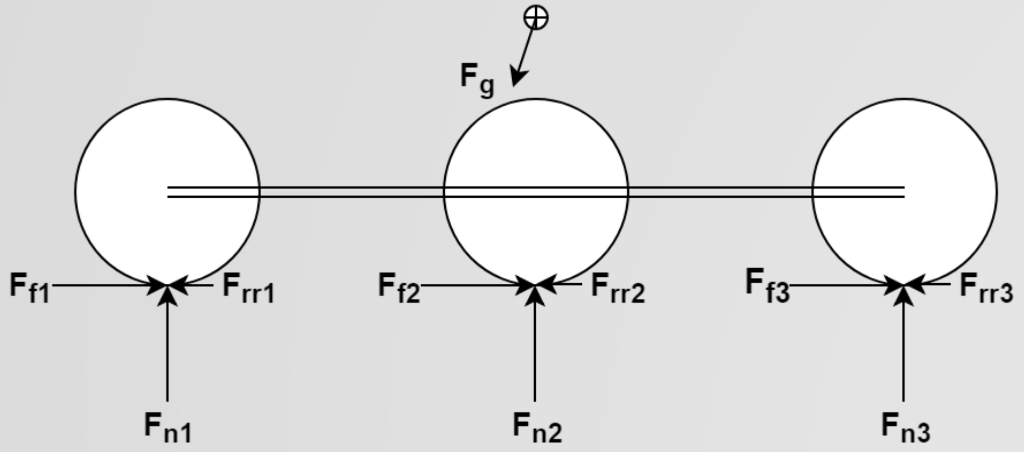
Keep L_x constant at 0.15m (6in)

Keep ω constant at 1 rad/s (9.5 rpm)

Inclined Slope Model

Compare effect of CSR dimensions and angular velocity on axial force.

1) Free Body Diagram



2) Relational Equations

$$F_f \leq \mu F_N$$

$$F_{rr} = c_{rr} F_N$$

$$F_g = mg$$

$$\tau_{motor} = F_{f,max} r$$

3) Assume: Roll no-slip, rigid chassis, geometrically centered CoM, Coulombic friction model

Inclined Slope Model

4) Summation of Forces and Moments

$$\sum F_x : ma = F_{f1} + F_{f2} + F_{f3} - (F_{rr1} + F_{rr2} + F_{rr3})$$

$$\sum F_y : 0 = F_{n1} + F_{n2} + F_{n3} - mgcos(20^o)$$

$$\sum M_{z,CM} : 0 = h(F_{f1} + F_{f2} + F_{f3} - F_{rr1} - F_{rr2} - F_{rr3}) - F_{n1}l_x + F_{n3}l_x$$

Inclined Slope Model

5) Convert Summation of Forces into Matrices

$$A = \begin{bmatrix} 1 & 1 & 1 & -c_{rr} & -c_{rr} & -c_{rr} \\ 0 & 0 & 0 & 1 & 1 & 1 \\ h & h & h & -l_x - c_{rr}h & -c_{rr}h & l_x - c_{rr}h \end{bmatrix} \quad x = \begin{bmatrix} F_{f1} \\ F_{f2} \\ F_{f3} \\ F_{N1} \\ F_{N2} \\ F_{N3} \end{bmatrix} \quad b = \begin{bmatrix} ma \\ mgcos(20^o) \\ 0 \end{bmatrix}$$

Six unknowns, three equations. Indeterminate matrix, non-unique solution

Inclined Slope Model

6) Use relation $F_f = \mu F_N$ and recreate matrices to relate the sum of the forces and moments all to the normal forces acting on the wheels

$$A = \begin{bmatrix} \mu_1 - c_{rr} & \mu_2 - c_{rr} & \mu_3 - c_{rr} \\ 1 & 1 & 1 \\ \mu_1 h - l_x - c_{rr} h & \mu_2 h - c_{rr} h & \mu_3 h + l_x - c_{rr} h \end{bmatrix} \quad x = \begin{bmatrix} F_{N1} \\ F_{N2} \\ F_{N3} \end{bmatrix} \quad b = \begin{bmatrix} ma \\ mgcos(20^o) \\ 0 \end{bmatrix}$$

Matrix equation is now solvable, given effective μ_1, μ_2, μ_3

Inclined Slope Model

7) Use guess and check, brute force algorithm to look at resultant normal forces given some combination of effective coefficients of friction that all lie below μ_{max}. If any F_N lies below 0, the combination does not work.

If a valid combination is found, the design parameters are feasible.

8) Solve for the frictional force acting on each wheel using the equations

$$F_f = \mu F_N$$

9) Find the motor torque required for any given combination of $\mu_{effective}$'s

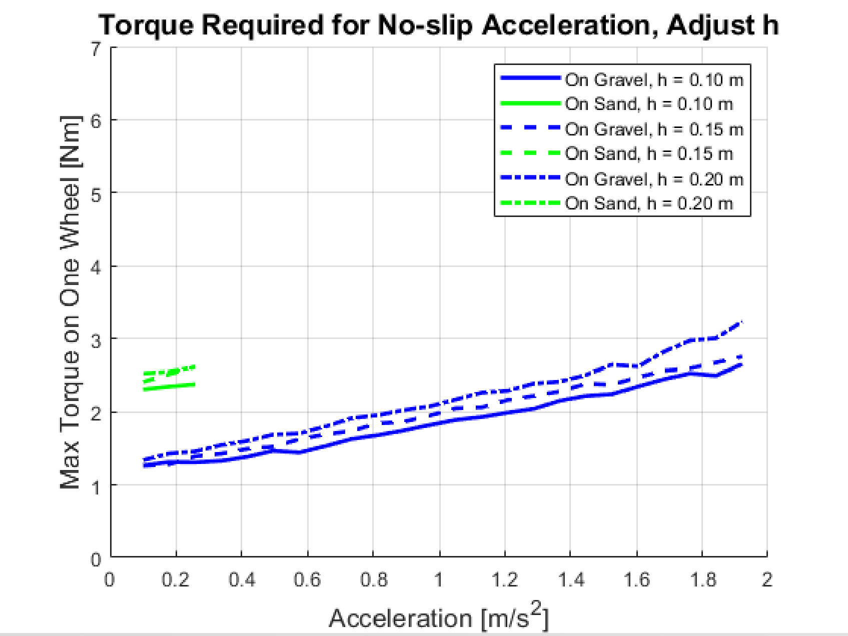
$$\tau_{motor} = F_{f,max} r$$

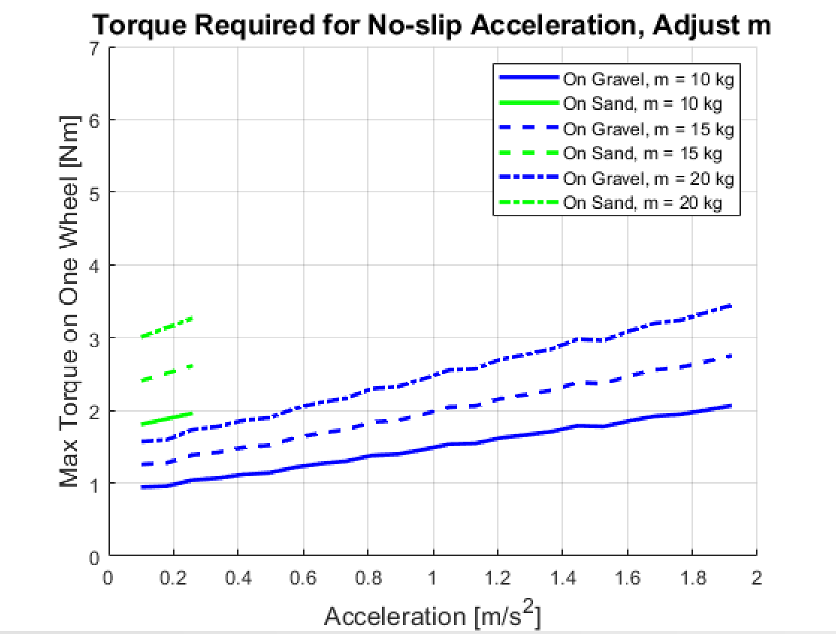
10) Select the combination of $\mu_{effective}$'s that results in the lowest τ_{motor}

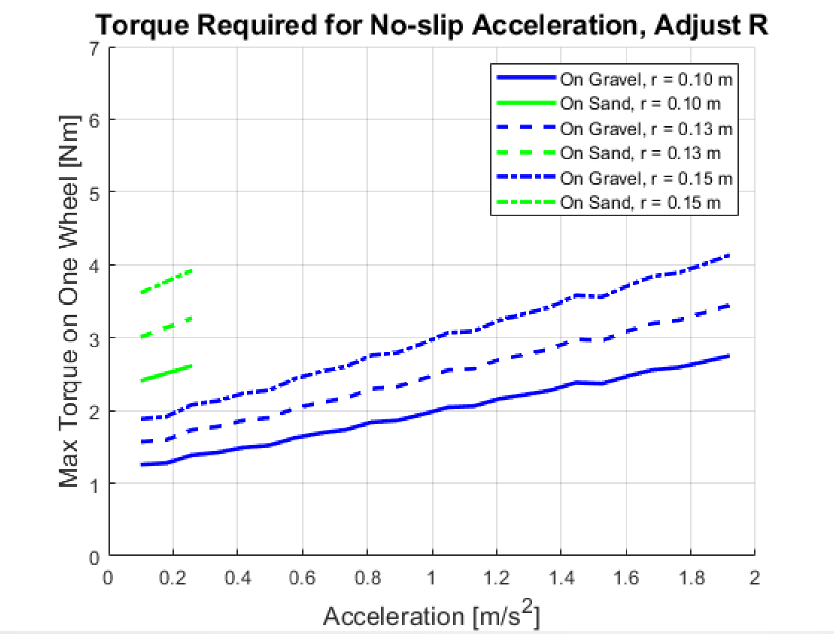
Sensitivity Analysis - Inclined Slope

Compare CSR dimensional variables height, mass, and radius, to performance in gravel (c_{rr} = 0.02) and sand (c_{rr} = 0.20)

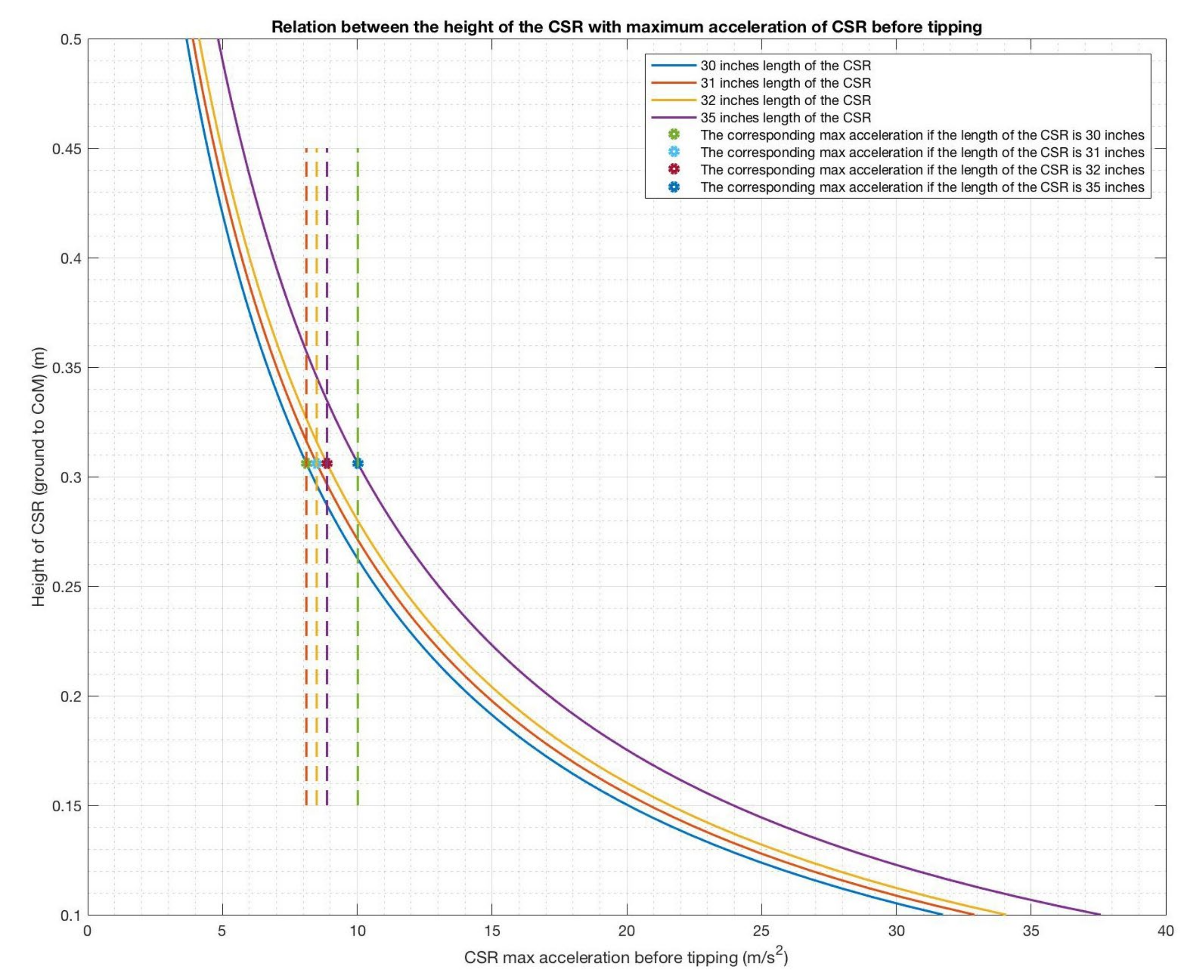
- These plots only show cases such that the combination of torques acting on each wheel cause them to not slip


Torque Required for No-slip Acceleration, Adjust h


Torque Required for No-slip Acceleration, Adjust m


Torque Required for No-slip Acceleration, Adjust R

Sensitivity Analysis – Inclined Slopes



- Sensitivity analysis for maximum acceleration before tipping in the inclined slopes.
- The final equation is:

$$a_{max} = g(\frac{l_x cos20^o}{2h} - sin20^o)$$

- Setting the length of the CSR constant which is 30 inch (0.762 meter).
- As the maximum acceleration required to tip the CSR is above the maximum acceleration possible before slipping, tipping is not a concern.

Docking/ Deployment Mechanism

Changing the baseline design

After the trade study results from CDD, there were two close options. A trailer platform and a hitch platform.

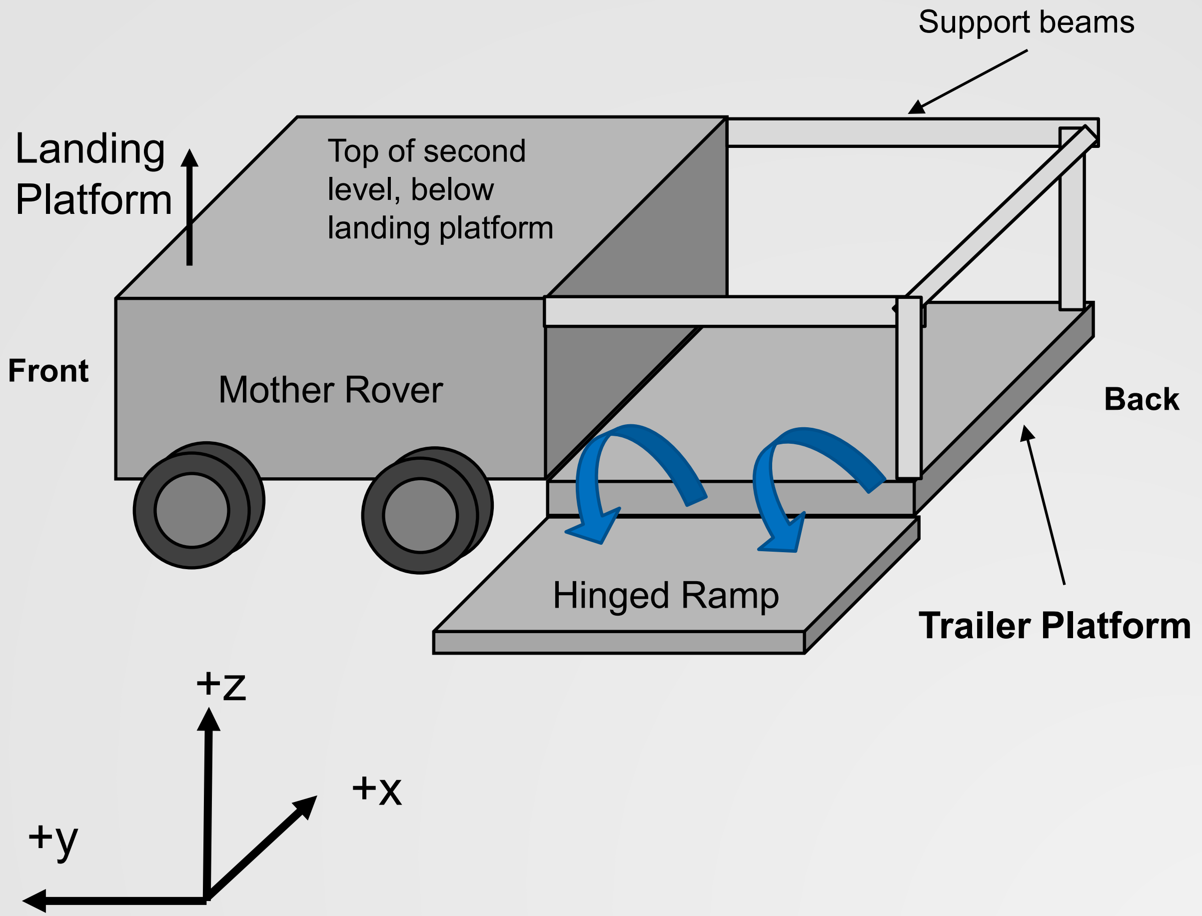
Although the baseline design that was chosen was a rigid trailer platform, further analysis was done into a **hinged trailer platform** attached by a ball joint. Another option that was considered and analyzed was a single axis hinged trailer platform.

The analysis concluded that instead of a rigid trailer platform, a hitch with a permanent platform attached by a ball joint would be the better option, so this is the new baseline design.

Diagrams and analysis of all three configurations are shown in the following slides

Rigid Trailer Platform Diagram

This platform was the initial chosen baseline design.



Pros/ Cons of Rigid Trailer Platform

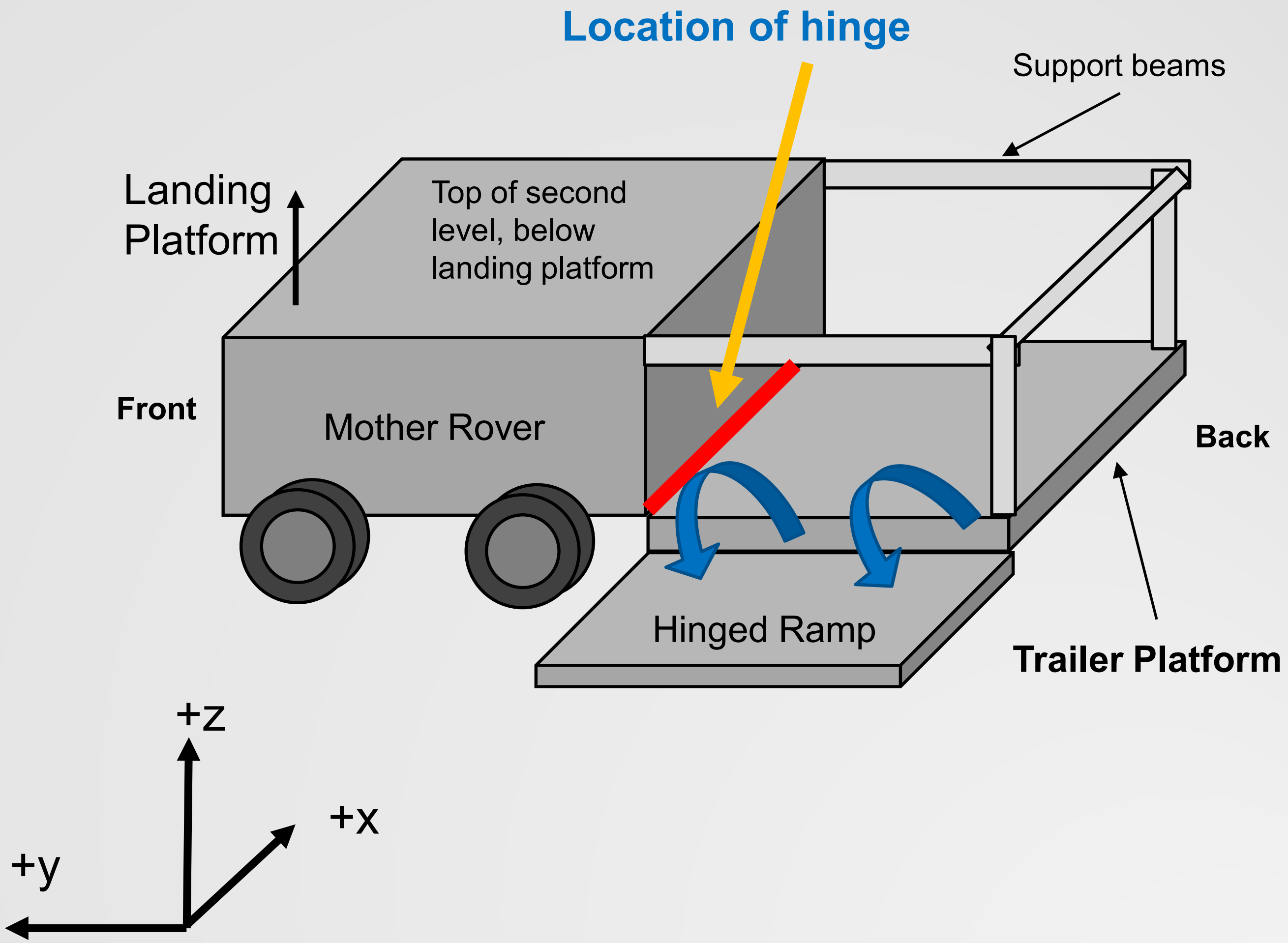
Description	Pros	Cons
Traversing from flat ground to Inclined slopes		A rigid trailer platform may not allow for clearance on this transition, and if it does the force on the back wheels would need to be analyzed.
Mobility on uneven ground		Very limited, and uneven ground may induce high stresses on
Manufacturing complexity	Easy to manufacture because more than likely it would be 8020 extensions from the MR	
Complexity of modeling force analysis		Very difficult because there are many torques and loads to consider from multiple axes
Inclined Slopes, Loss of traction on trailer wheels while going down on slopes	Since the trailer would be a fixed rigid extension of the mother rover's chassis, there is little concern of the back wheels losing traction.	

Single Hinged Axis Trailer Platform Diagram

This configuration is very similar, however there is one degree of freedom to let the trailer platform rotate due to overcoming obstacles.

This location of the hinge is outlined in red in the diagram.

The hinge would allow for rotation around the x axis.



Pros/ Cons of Single Hinged Axis Trailer Platform

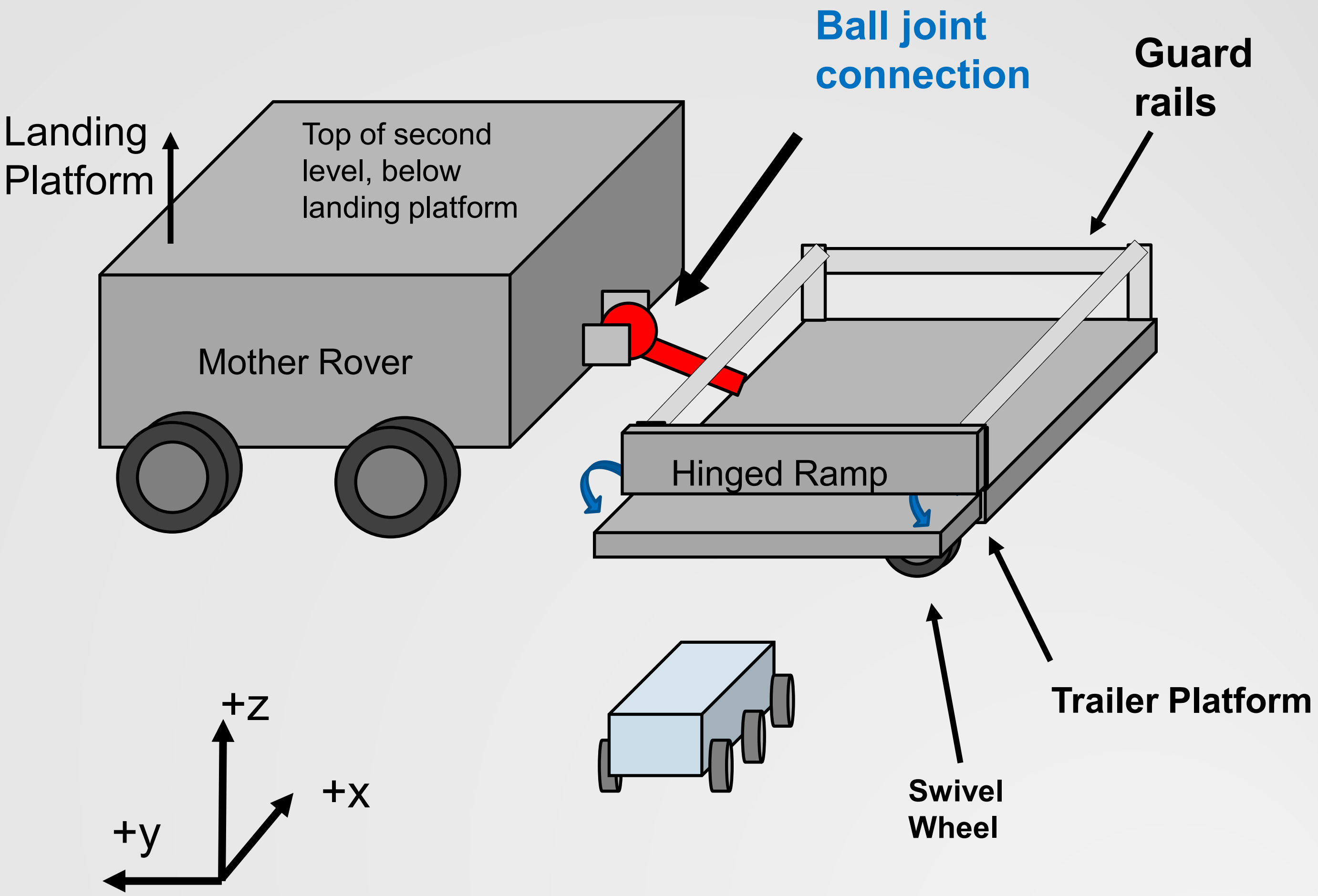
Description	Pros	Cons
Traversing from flat ground to Inclined slopes	A single hinge allows for rotation when in this situation	
Mobility on uneven ground		Limited, is there is mobility on an axis not aligned with the hinge, then the trailer may not be able to maneuver easily.
Manufacturing complexity	Will still be easy to manufacture, except more support around the hinge may be required	
Complexity of modeling force analysis		Very difficult due to torques present around the z axis.
Inclined Slopes, Loss of traction on trailer wheels while going down on slopes		Since the hinge can rotate around the x axis, there is a possibility of the trailer tipping towards the MR. This may be solved by adding stoppers

Ball Jointed Trailer Platform Diagram

The ball joint is shown in red, and allows rotation around all three axes

There will be two swivel wheels on the bottom for support and to allow the MR to perform up to 360 degree turns

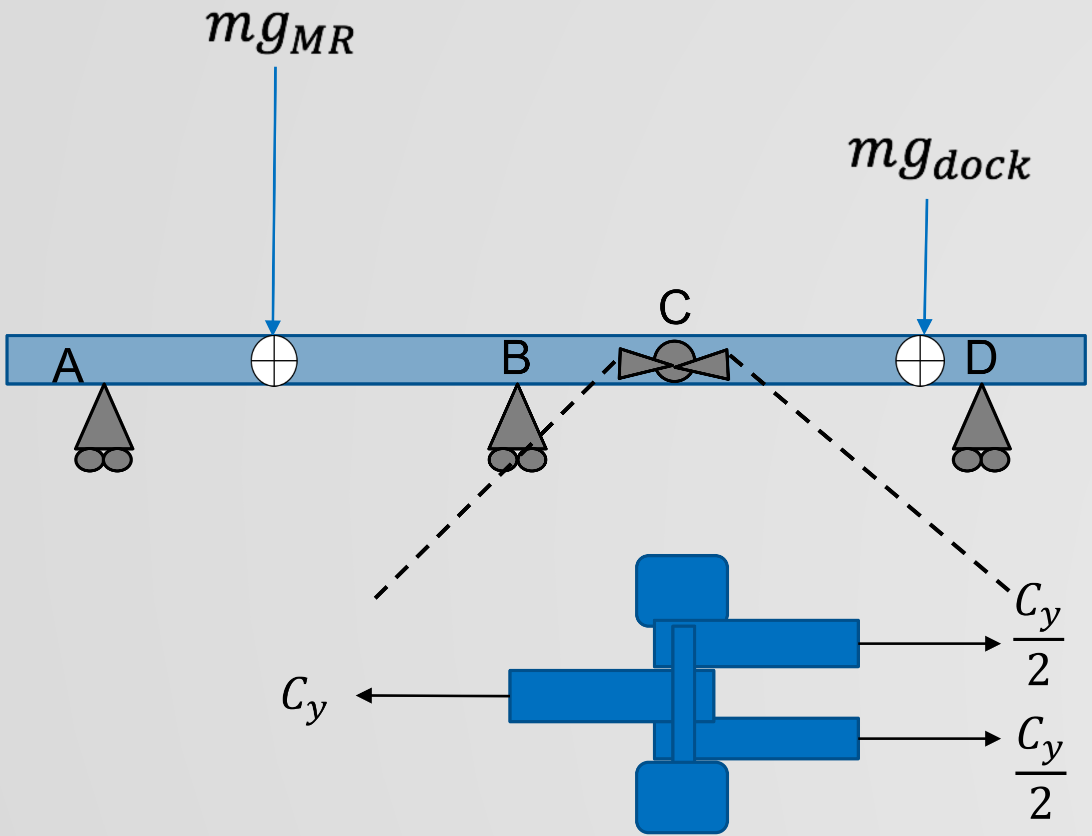
Since this was the chosen configuration, force and traction analysis was done. This is shown in the following slides



Pros/ Cons of Ball Jointed Trailer Platform

Description	Pros	Cons
Traversing from flat ground to Inclined slopes	A ball joint allows for rotation when in this situation	
Mobility on uneven ground	The ball joint allows for rotation around all axes, so this is not a concern.	
Manufacturing complexity		Will be difficult to manufacture a ball joint interface. May be solved by buying COTS parts.
Complexity of modeling force analysis		Will be difficult to model, however this may be simplified into an easier situation to model.
Inclined Slopes, Loss of traction on trailer wheels going down on slopes		Since the hinge can rotate around all axes, there is a possibility of the trailer tipping towards the MR or it's wheels. This can be solved by adding stoppers

Hitched Trailer Feasibility



Feasibility Items:

1. Can a Hitch support the reaction forces of the CSR and Trailer
2. Are the stresses and strains on the Hitch reasonable

Assumptions:

1. The MR and CSR+Trailer can be modeled as a uniform beam with two point loads at the CG of each
2. The Hitch can be modeled as a pin and the Wheels as rollers

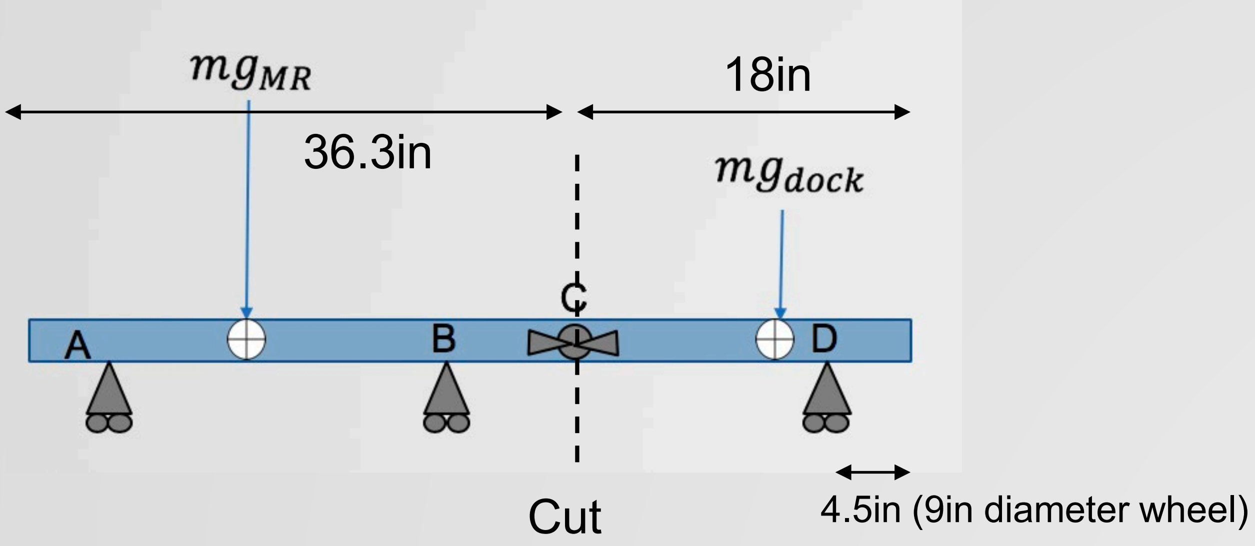
Results

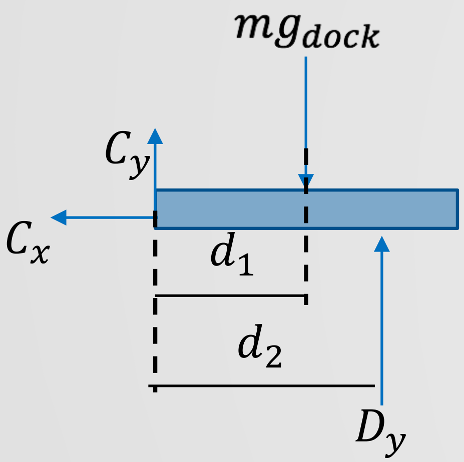
1. $C_y = \frac{1}{3} mg_{dock}$
2. $\sigma = \frac{F}{A} = \frac{\frac{4}{3} mg_{dock}}{\pi d^2}$

Stress on pin dependent on mass of docking system and the diameter of the pin, needs further analysis however with the correct materials it will be feasible

FEASIBLE

Derivation





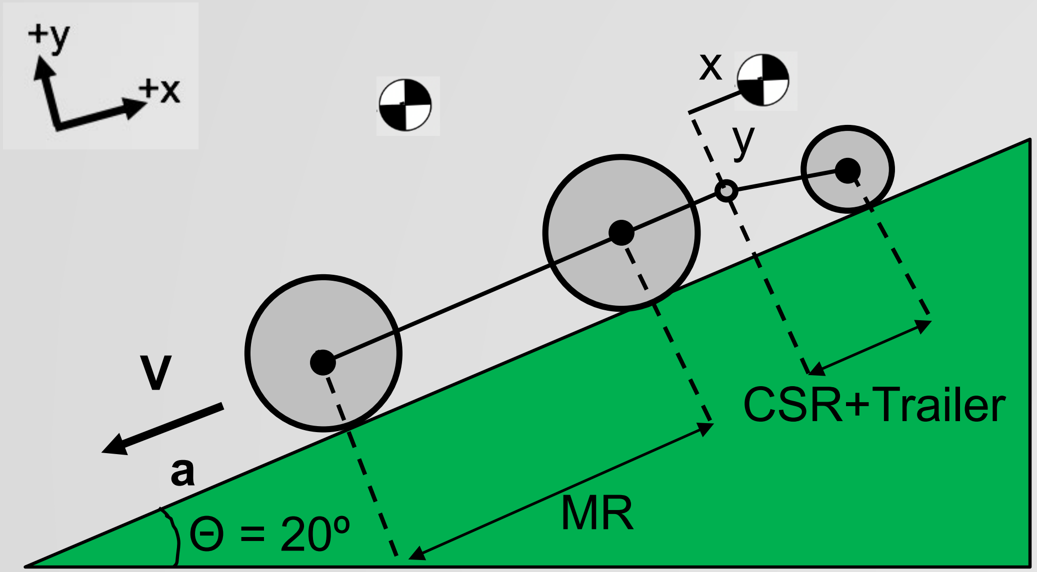
Assume mg_{dock} acts at Cg of the CSR+Trailer configuration, then:

$$d_1 = 9in$$
$$d_2 = 13.5in$$

1. $\sum F_x = 0; C_x = 0$
2. $\sum M_c = 0; mg_{dock} * d_1 - D_y * d_2$

$$D_y = \frac{2}{3} mg_{dock}$$

MR Mobility Analysis



x – distance from hitch to Cg of CSR+Trailer
y – distance from hitch to Cg of CSR+Trailer

Feasibility Items:

1. Will the trailer tip going down a 20° slope?
2. At what deceleration will the trailer begin to tip?

Assumptions:

1. Roll-no-slip
2. The Hitch can be modeled as a pin

Results

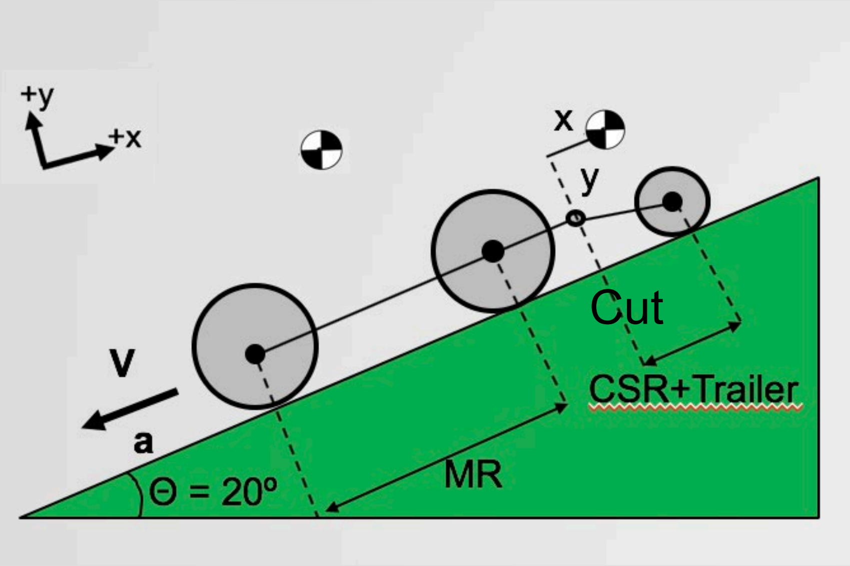
1. Trailer doesn't tip unless $\frac{y}{x} \le 2.75$
2. Deceleration at which tipping occurs

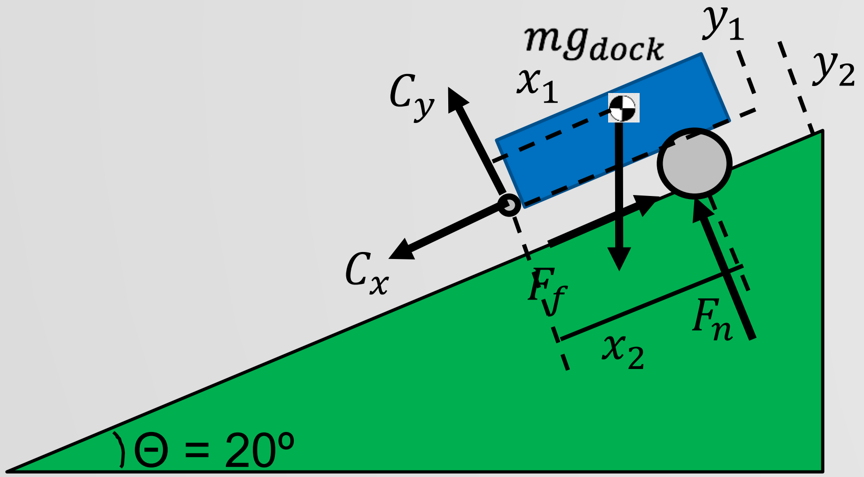
$$a = g(\frac{x}{y}\cos(\theta) - \sin(\theta))$$

Feasibility is dependent on the location of the Cg of the CSR and Trailer configuration

FEASIBLE

Tipping Derivation





$$\sum F_x = C_X - F_f + mg_{dock}sin20 = 0$$
$$\sum F_y = F_n + C_y - mg_{dock}cos20 = 0$$
$$\sum M_c = mgcos20x_1 - mgsin20y_1 - F_n d_2 - F_f d_2 =$$

0

$$\sum F_x = C_X - F_f + mg_{dock}sin20 = 0$$
$$\sum F_y = F_n + C_y - mg_{dock}cos20 = 0$$
$$\sum M_c = mgcos20x_1 - mgsin20y_1 - F_n x_2 - F_f y_2 = 0$$
$$\sum M_c = mgcos20x_1 - mgsin20y_1 - F_n x_2 - \mu F_n y_2 = 0$$
$$F_n = \frac{mg_{dock}(x_1 cos\theta - y_1 sin\theta)}{x_2 + \mu y_2}$$

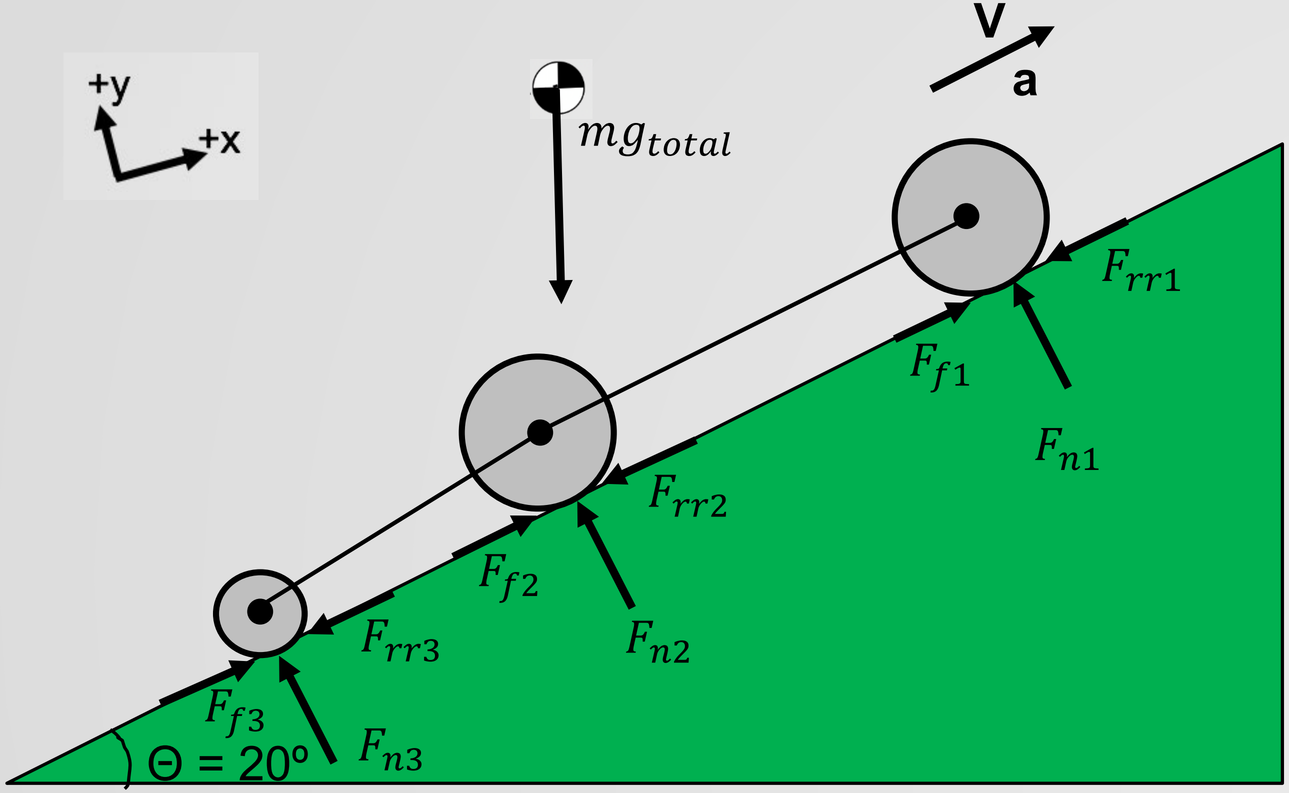
If F_n=0:

$$y_1 \leq 2.7474x_1$$

For deceleration:

$$F_n = 0 \; so \; F_f = 0$$
$$\sum F_x = ma = C_x - mg_{dock}sin20$$
$$\sum F_y = C_y - mg_{dock}cos20 = 0$$
$$\sum M_{cg} = C_x y_1 + C_y x_1$$
$$a = g(\frac{x_1}{y_1}cos\theta - sin\theta)$$

Power Analysis of MR + CSR + Trailer



Feasibility Items

1. Does the MR have enough power to pull the trailer + CSR?

Baseline Assumptions:

1. Roll no-slip
2. Rigid Chassis
3. Trailer+CSR weight = 150lbs

Results using Baseline Dimensions:

Use same technique as before with Matrix Manipulation

1. Gravel (c_{rr} = 0.02, μ=0.60) ✓
    1. Required Torque per Wheel = 1030lbf*ft

Further analysis and research into MR's motors required

FEASIBLE

Object Detection System

Object Detection Docking Method

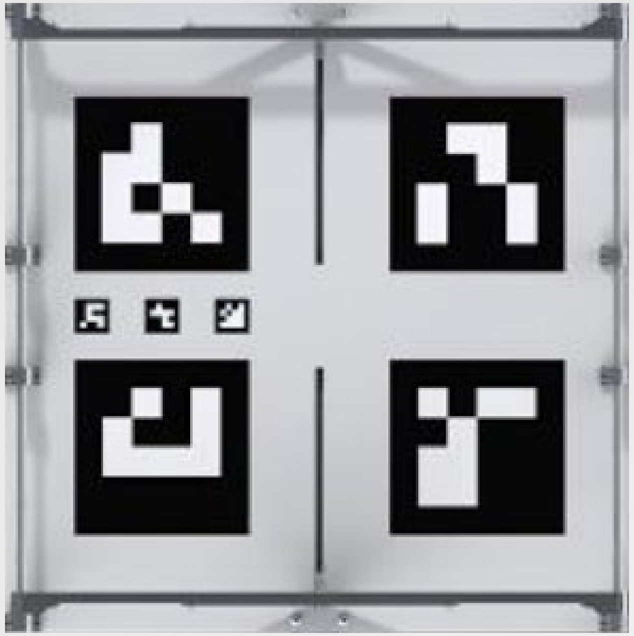
CSR.7 - The CSR shall be able to dock to the MR
SENS.7.1 - CSR sensing system shall report orientation with respect to MR docking system

Results:

- Image recognition software will be used with Augmented Reality (AR) tag on the mother rover's trailer platform
- This method was similarly used and verified for the landing of the child drone (INFERNO) on the mother rover
- LiDAR processing software will be switched to image processing software once in close proximity (test determined)

Further Analysis:

1. Determine the distance in which the image recognition software will be able to recognize the AR tag



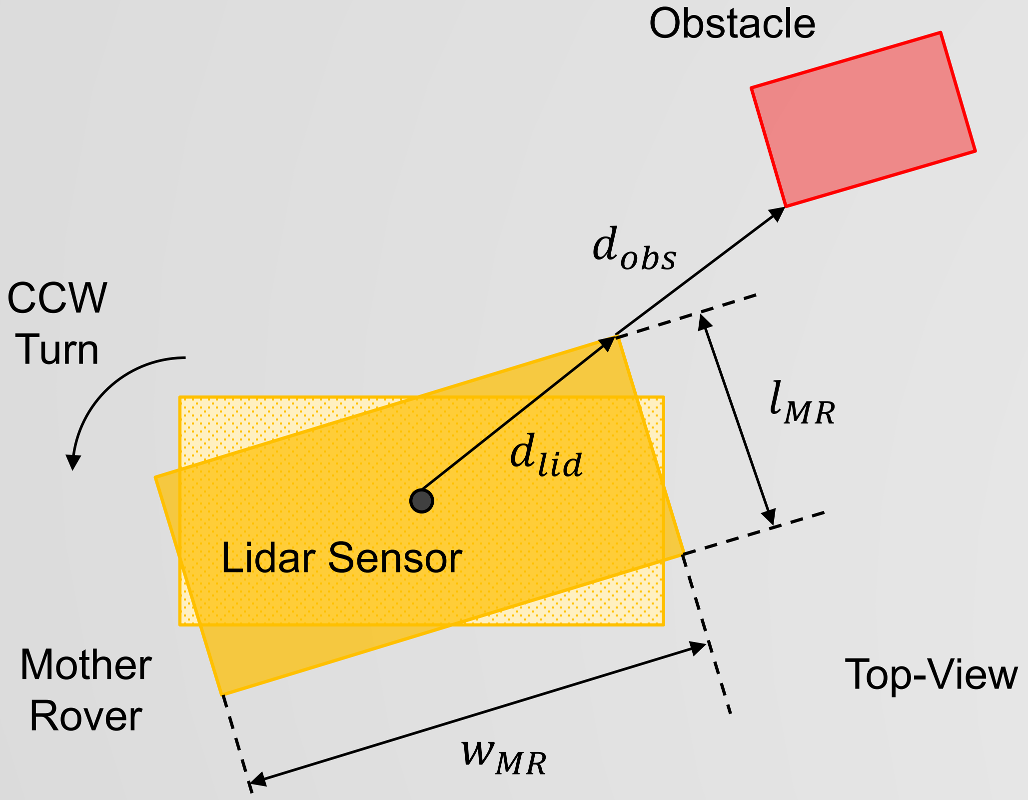
Is image recognition software available and can it be modified to recognize AR tags? YES

FEASIBLE

Determination of d_{min}

SENS.3.1.1 - CSR sensing system shall report objects within a field of view (FOV)

SENS.3.1.2 - CSR sensing system shall report objects up to a maximum range from the CSR



- Assuming lidar is at the center of MR

$$d_{lid} = \sqrt{({}^{w_{MR}}/_{2})^2 + ({}^{l_{MR}}/_{2})^2}$$

$$d_{min} = d_{lid} + d_{obs}$$

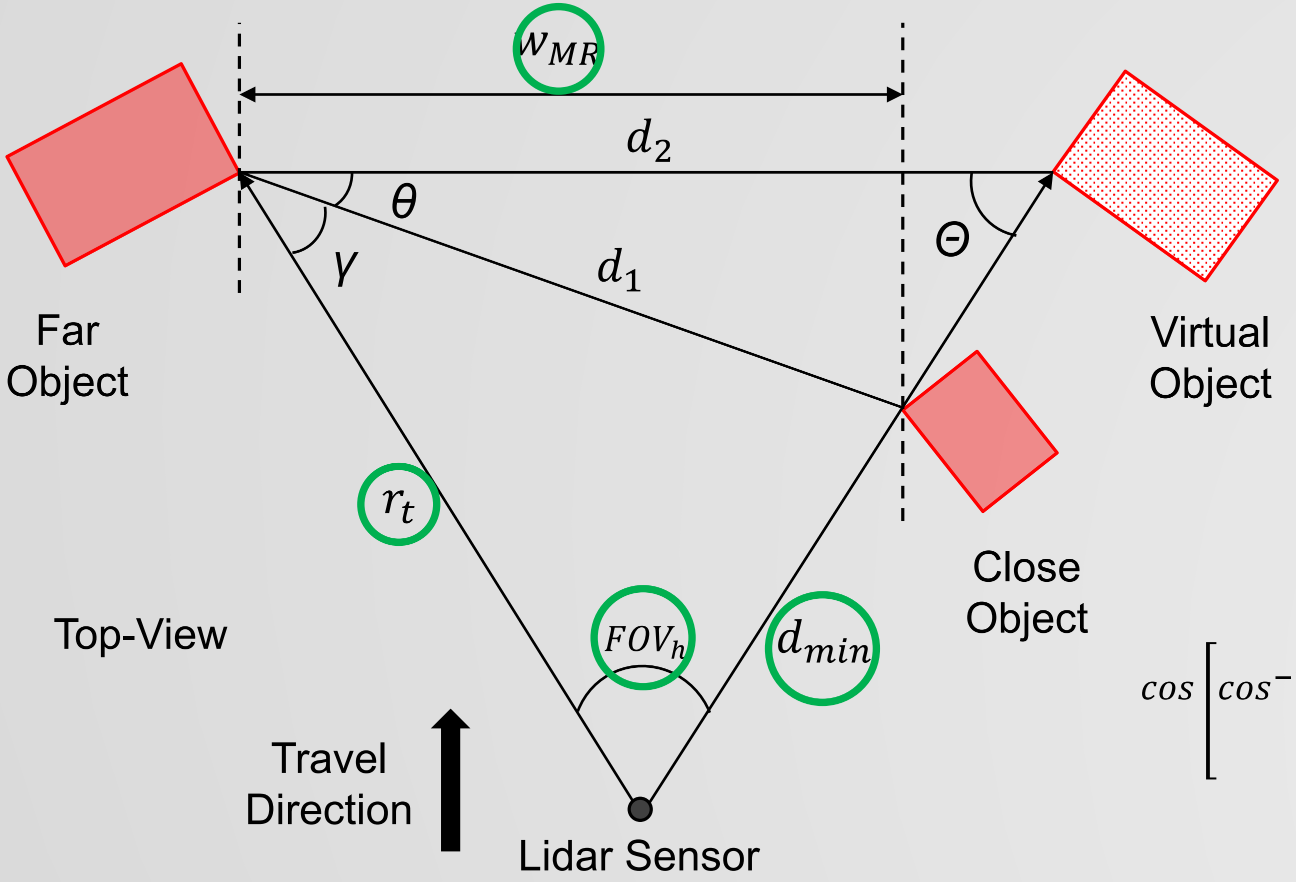
- If a safety margin is used, $d_{obs} = k \cdot d_{lid}$, specify a safety margin (SM) that defines d_{min}

$$d_{min} = SM \cdot d_{lid}$$
$$SM = 1 + k$$

Horizontal FOV and Range Model

SENS.3.1.1 - CSR sensing system shall report objects within a field of view (FOV)

SENS.3.1.2 - CSR sensing system shall report objects up to a maximum range from the CSR

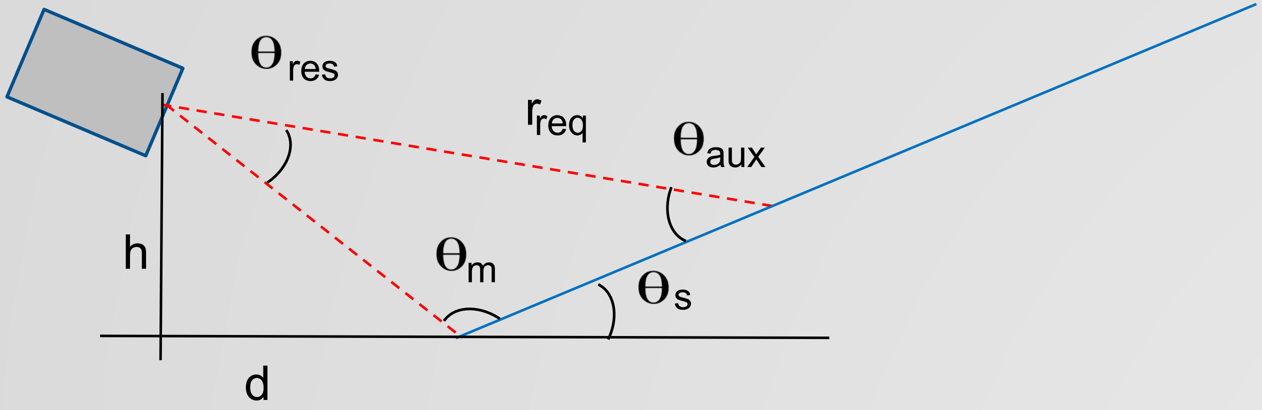


Controllable Variables

- d_{min}: Minimum distance desired between lidar sensor and closest obstacle
- r_t: Total (desired) range of the lidar sensor
- w_{MR}: Width of the Mother Rover
- FOV_h: Horizontal field of view of the lidar sensor

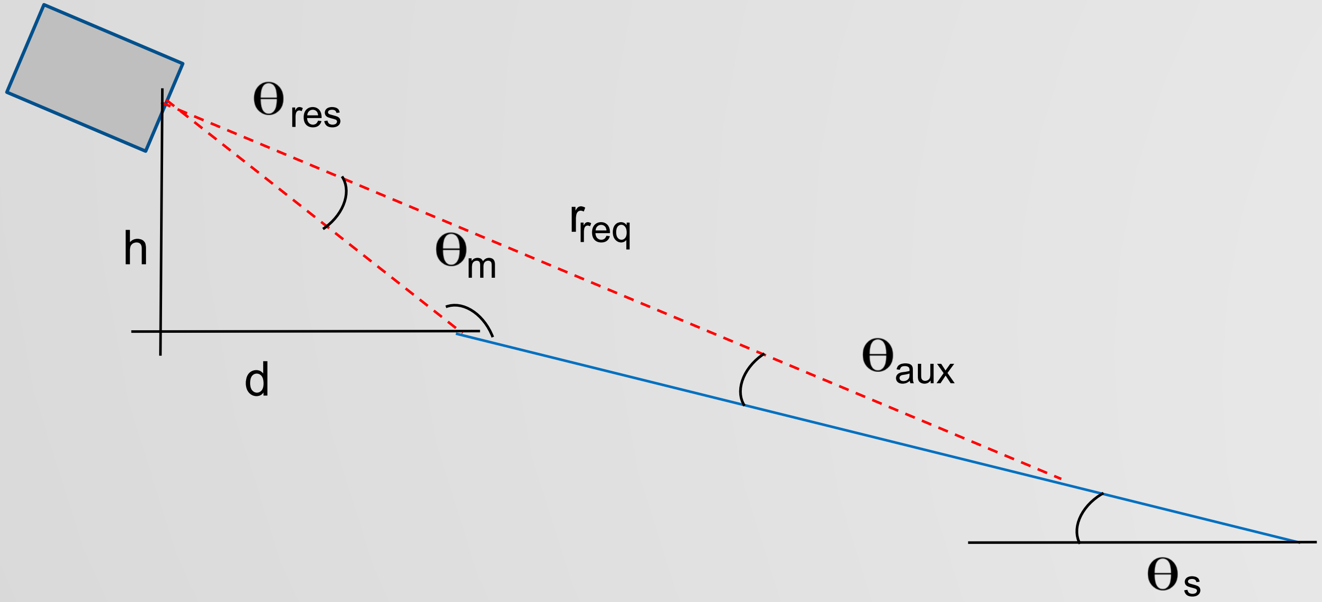
$$w_{MR} = \sqrt{r_t{}^2 + d_{min}{}^2 - 2r_t d_{min}\cos(FOV_h)} \cdot cos\left[cos^{-1}\left(\frac{1}{2}\sqrt{2(1-\cos(FOV_h))}\right) + cos^{-1}\left(\frac{r_t - d_{min}cos(FOV_h)}{\sqrt{r_t{}^2 + d_{min}{}^2 - 2r_t d_{min}cos(FOV_h)}}\right)\right]$$

Slope Determination



$$\theta_m = 180 - tan^{-1}(\tfrac{h}{d})$$

$$r_{req} = \frac{sin(\theta_m)}{sin(180-\theta_{res}-\theta_m)}\sqrt{h^2+d^2}$$

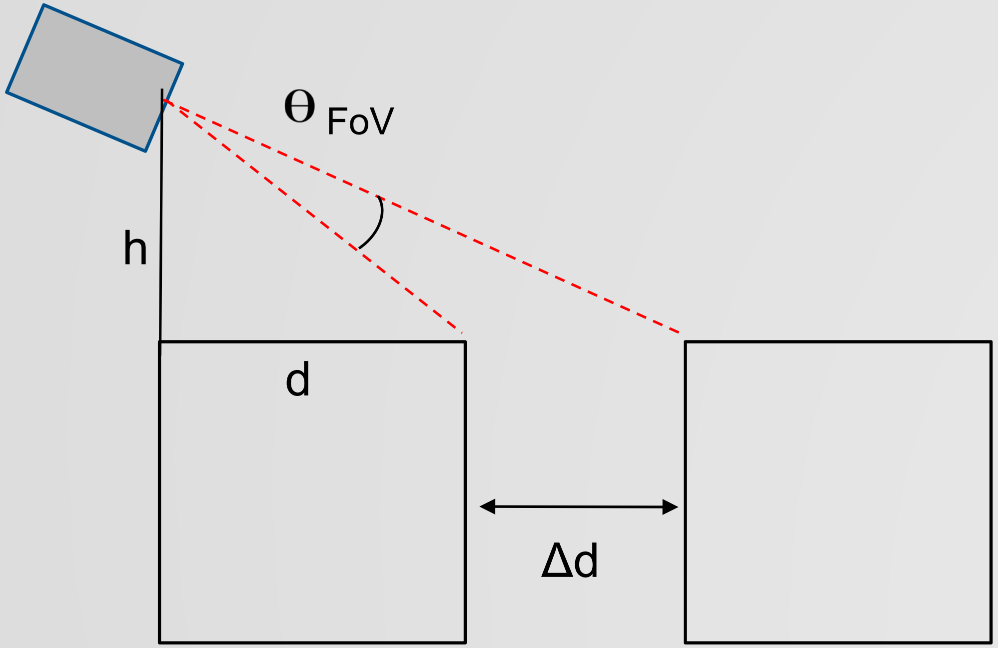


$$\theta_m = 180 - tan^{-1}(\tfrac{d}{h}) + \theta_s$$

$$\theta_{aux} = tan^{-1}(\tfrac{d}{h}) - \theta_s - \theta_{res}$$

$$r_{req} = \frac{sin(\theta_m)}{sin(\theta_{aux})}\sqrt{h^2+d^2}$$

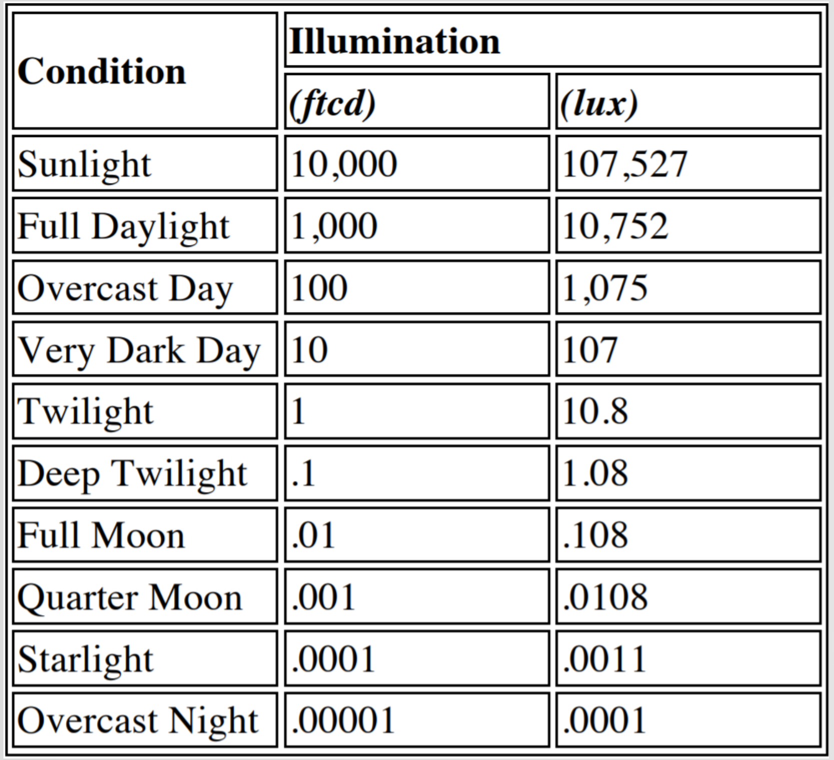
1 Foot Discontinuity Determination



$$\theta_{FoV} = tan^{-1}\left(\frac{d+\Delta d}{h}\right) - tan^{-1}\left(\frac{d}{h}\right)$$

LiDAR Brightness Feasibility

Common Outdoor Light Levels [8]



Condition	Illumination	
	(ftcd)	*(lux)*
Sunlight	10,000	107,527
Full Daylight	1,000	10,752
Overcast Day	100	1,075
Very Dark Day	10	107
Twilight	1	10.8
Deep Twilight	.1	1.08
Full Moon	.01	.108
Quarter Moon	.001	.0108
Starlight	.0001	.0011
Overcast Night	.00001	.0001

Feasibility Items:

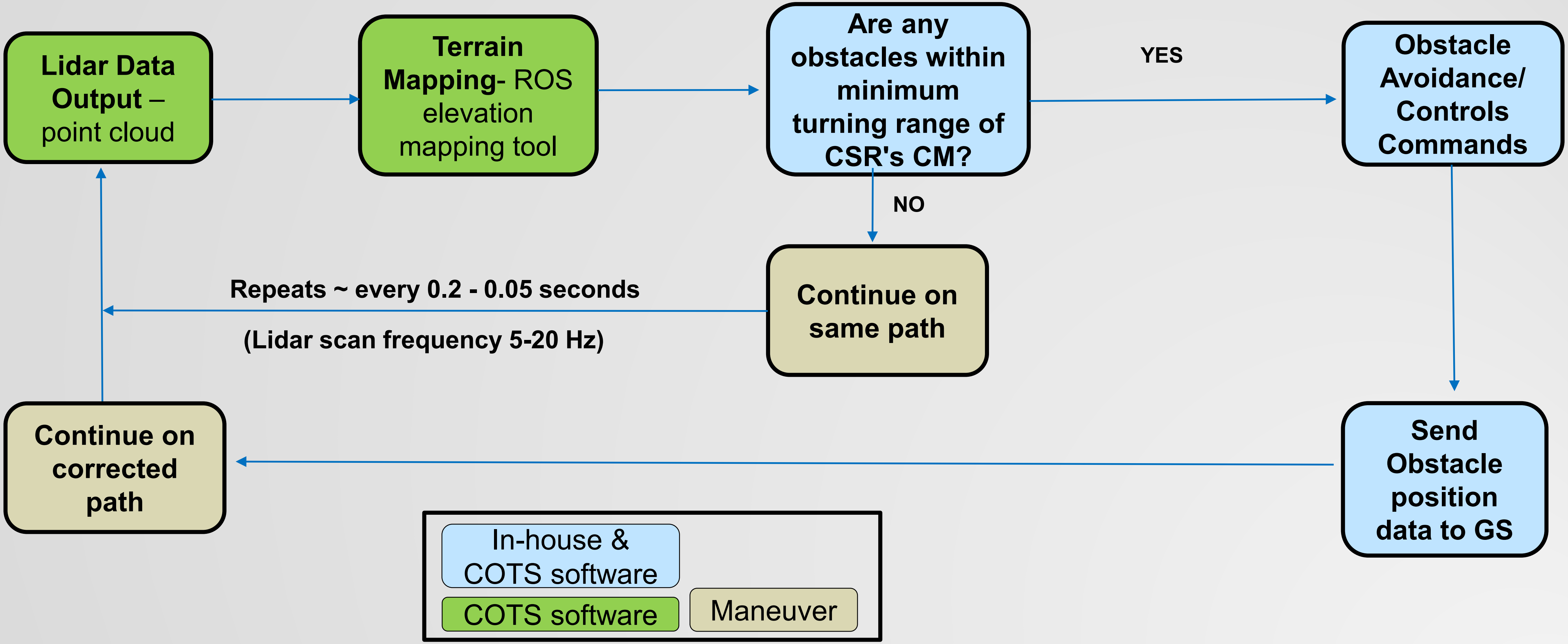
1. Will the LiDAR system operate in an outdoor environment?

Results:

1. Outdoor operation requires the LiDAR to operate over a specific illuminance with enough ambient light resistance
2. Based on the chart to the left, it is reasonable that a resistance of 10,752 lux (full daylight) represents feasibility
3. The solid state LiDAR chosen has an ambient light resistance of 60,000 lux

60,000 lux > 10,752 lux, so **FEASIBLE**

Object Detection Software Feasibility



Lidar Data Output – point cloud

Terrain Mapping- ROS elevation mapping tool

Are any obstacles within minimum turning range of CSR's CM?

YES

Obstacle Avoidance/ Controls Commands

NO

Continue on same path

Repeats ~ every 0.2 - 0.05 seconds

(Lidar scan frequency 5-20 Hz)

Send Obstacle position data to GS

Continue on corrected path

In-house & COTS software

COTS software

Maneuver

Lidar Trade Study

SENS.3.1 - The CSR sensing system shall be capable of object detection

Criteria	1	2	3	4	5
Cost	>$700	$500-$700	$300-$500	$100-$300	<$100
Data Rate	>200 kHz	50-200 kHz	1-50 kHz	10-1000 Hz	<10 Hz
Angular Resolution	No angular resolution	N/A	>0.5°	N/A	<0.5°
Slope Determination	Vertical and horizontal actuation or CSR movement required	N/A	Vertical Actuation required	N/A	No CSR movement or LiDAR actuation required
Field of View	No field of view	<120° horizontal No vertical FoV	>120° horizontal No vertical FoV	>120° horizontal <5° Vertical FoV	>120° horizontal >5° Vertical FoV
Environmental Vulnerability	High vulnerability to impact and bright light.	High vulnerability to either impact or bright light	Low vulnerability to impact and bright light.	Low vulnerability to either impact or bright light	Little to no vulnerability to bright light or impacts

Lidar Trade Study

SENS.3.1 - The CSR sensing system shall be capable of object detection

Criteria	Weight	Single Beam	360° Rotating Single Beam	Solid State Lidar
Cost	5%	4	3	1
Data Rate	10%	5	3	2
Environmental Vulnerability	15%	5	2	5
Angular Resolution	20%	1	5	5
Slope Determination	25%	1	3	5
Field of View	25%	1	3	5
Total	**100%**	**2.15**	**3.05**	**4.35**


Single Beam LiDAR


360° Rotating Single Beam LiDAR


Solid State LiDAR

Lidar Trade Study Rationale

Criteria	Weight	Rationale
Cost	5%	Cost must be considered in order to remain within designated budge. However, as the LiDAR is crucial to success, a higher cost is largely justifiable.
Data Rate	10%	The more data produced per second increases the computational load of data processing and thus may necessitate more powerful microprocessors.
Environmental Vulnerability	15%	The LiDAR system may be exposed to bright light or impacts. Thus, it is important that it remain functional in these conditions in order for the CSR to complete it's mission.
Angular Resolution	20%	A higher angular resolution may allow soft obstacles such as grass to be differentiated from hard obstacles like trees.
Slope Determination	25%	Slope determination is important as it may facilitate differentiation between trees and ground as well as allowing the CSR to find a traversable path.
Field of View	25%	A larger field of view allows the CSR to analyze a greater amount of terrain without requiring CSR maneuvering or actuation.

Communication System

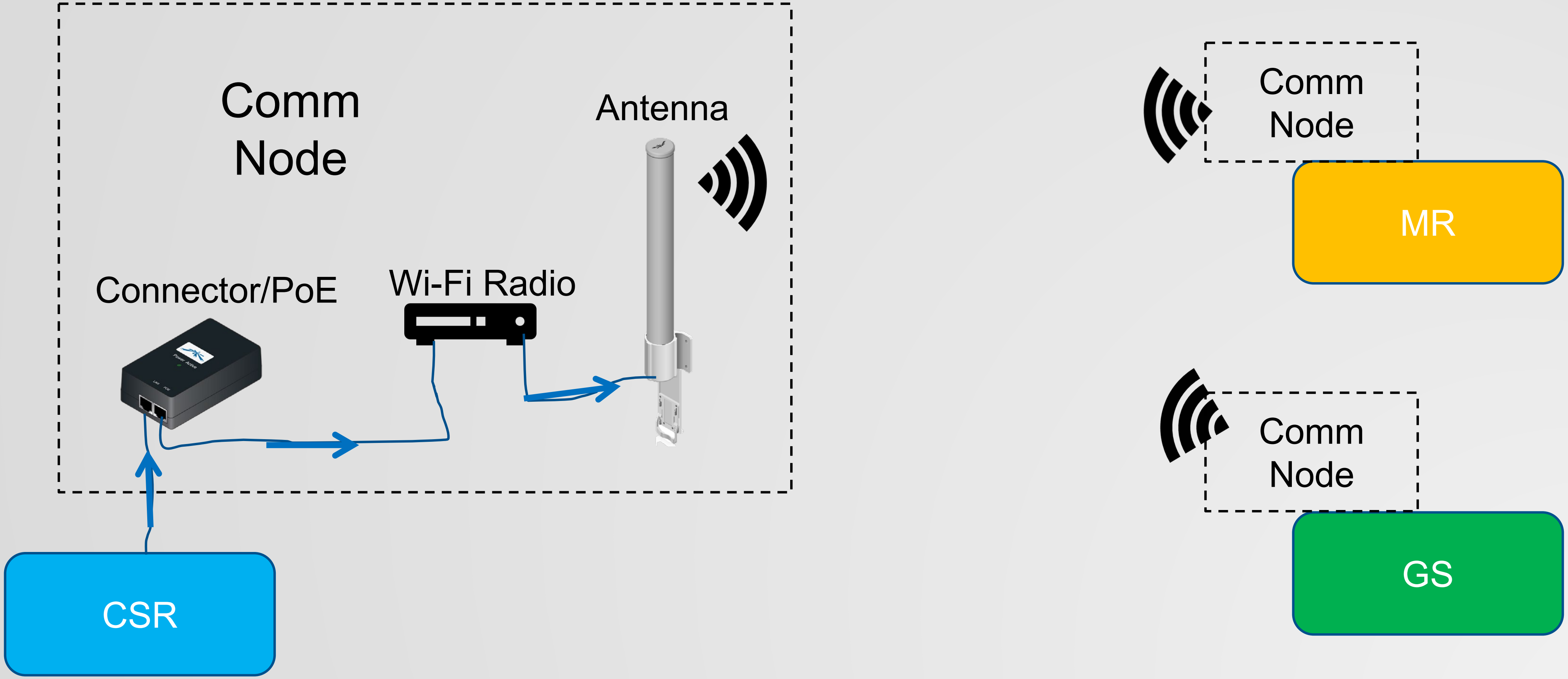
BASELINE DESIGN AND FEASIBILITY ANALYSIS

Hardware Specs

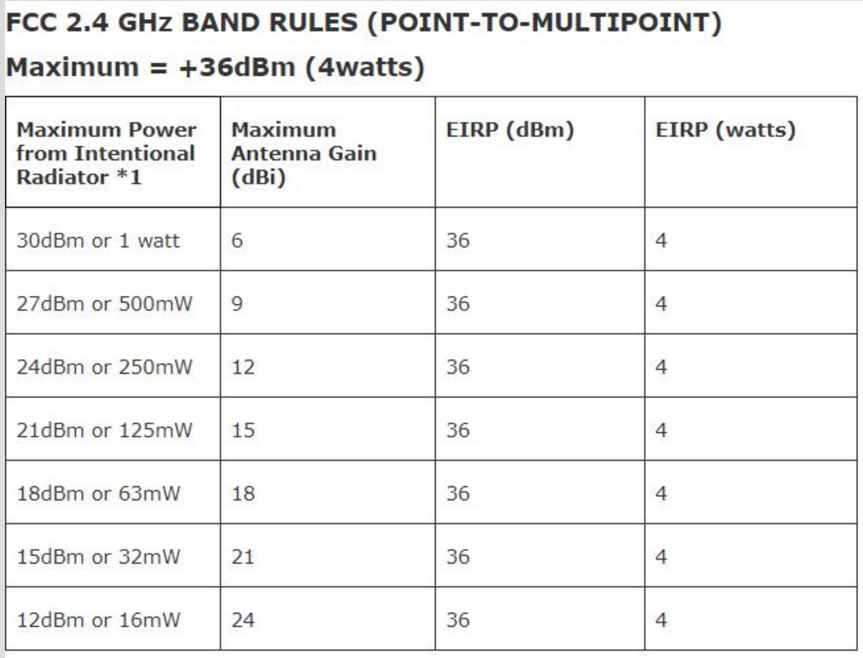
	Model	Connection	Connection Loss (dBm)	Frequency (GHz)	Gain (dBi)	Dimensions (in)	Direction	**Cost ($)**
Antenna Extensions	A8EX	N-Type Female	2	2.4	8.00	20 x 3 x 3	Omni-Directional 360 (outdoor)	89.32
	TL-ANT2408CL	RP-SMA Female	2	2.4	8.00	14 x 3.2 x 0.8	Omni-Directional 360 (indoor)	10.56
	TL-ANT2409A	RP-SMA Female	2	2.4	9.00	4.72 x 4.72 x 1.57	Directional 60 (outdoor)	24.49
	TECHTOO1	RP-SMA Female	2	2.4	9.00	15.3 x 0.7 x 0.7	Omni-Directional (indoor)	13.99
	TECHTOO2	RP-SMA Female	2	2.4	12.00	10 x 6 x 2.7	Omni-Directional(indoor)	29.99
	ANRD2405	RP-SMA Female	2	2.4	9.00	15 x 0.7 x 0.7	Omni-Directional(indoor)	17.99
	TL-ANT2412D	Female N-Connector	2	2.4	12.00	47 x 3.54 x 2.56	Omni-Directional 360 (outdoor)	36.61
	HA09SIP	RP-SMA, N-Plug	2	2.4	9.00	24.45 x 1.77 x 1.77	Omni-Directional 360 (outdoor)	73.99
Averages			2	2.4	9.5	18.8 x 2.95 x 1.725		37.1175

	Model	Connection	Frequency (GHz)	Data Rate (Mbps)	Transmission Power (dBm)	**Receiver Sensitivity (dBm)**	Power Consumption (W/V)	Cost ($)
Standalone Wi-Fi Modules	Xbee Wi-Fi S6B	Pins, RP-SMA	2.4	1/72	16	-82	?/3.3	43.95
	TL-WN722N	USB, RP-SMA	2.4	11/150	20	-88	N/A	14.99
	M2	Ethernet, POE, RP-SMA	2.4	10/100	28	-88	6.5/24	89.00
	M5	Ethernet, POE, RP-SMA	5	10/100	27	-88	8/24	89.00
	BM2HP	Ethernet, POE, Type N	2.4	6/24	28	-88	7/24	79.00
	BM5HP	Ethernet, POE, Type N	5	10/100	25	-88	6/24	79.00
	LocoM2	Ethernet, POE (Has Antenna)	2.4	1/54	20	78	5.5/24	48.53
	TL-WA7210N	Ethernet, POE, Type N (Has Antenna)	2.4	11/150	27	-88	12/12	53.00
	CPE210	Ethernet, POE, (Own Antenna)	2.4	36/300	27	-88	6/24	39.98
Averages			2.4		24.22222222	86		59.60555556

Hardware Integration



Wi-Fi Extra



FCC 2.4 GHz BAND RULES (POINT-TO-MULTIPOINT)

Maximum = +36dBm (4watts)

Maximum Power from Intentional Radiator *1	Maximum Antenna Gain (dBi)	EIRP (dBm)	EIRP (watts)
30dBm or 1 watt	6	36	4
27dBm or 500mW	9	36	4
24dBm or 250mW	12	36	4
21dBm or 125mW	15	36	4
18dBm or 63mW	18	36	4
15dBm or 32mW	21	36	4
12dBm or 16mW	24	36	4

https://www.air802.com/fcc-rules-and-regulations.html

Variable and Equations Descriptions

Receive sensitivity
The minimum level of a received signal required for a device to understand the signal.

Access point
A device that allows wireless devices to connect to a wired network using Wi-Fi.

dBm
An abbreviation for the power ratio in decibels (dB) of the power referenced to one milliwatt (mW). 0 dBm is equal to 1 milliwatt.

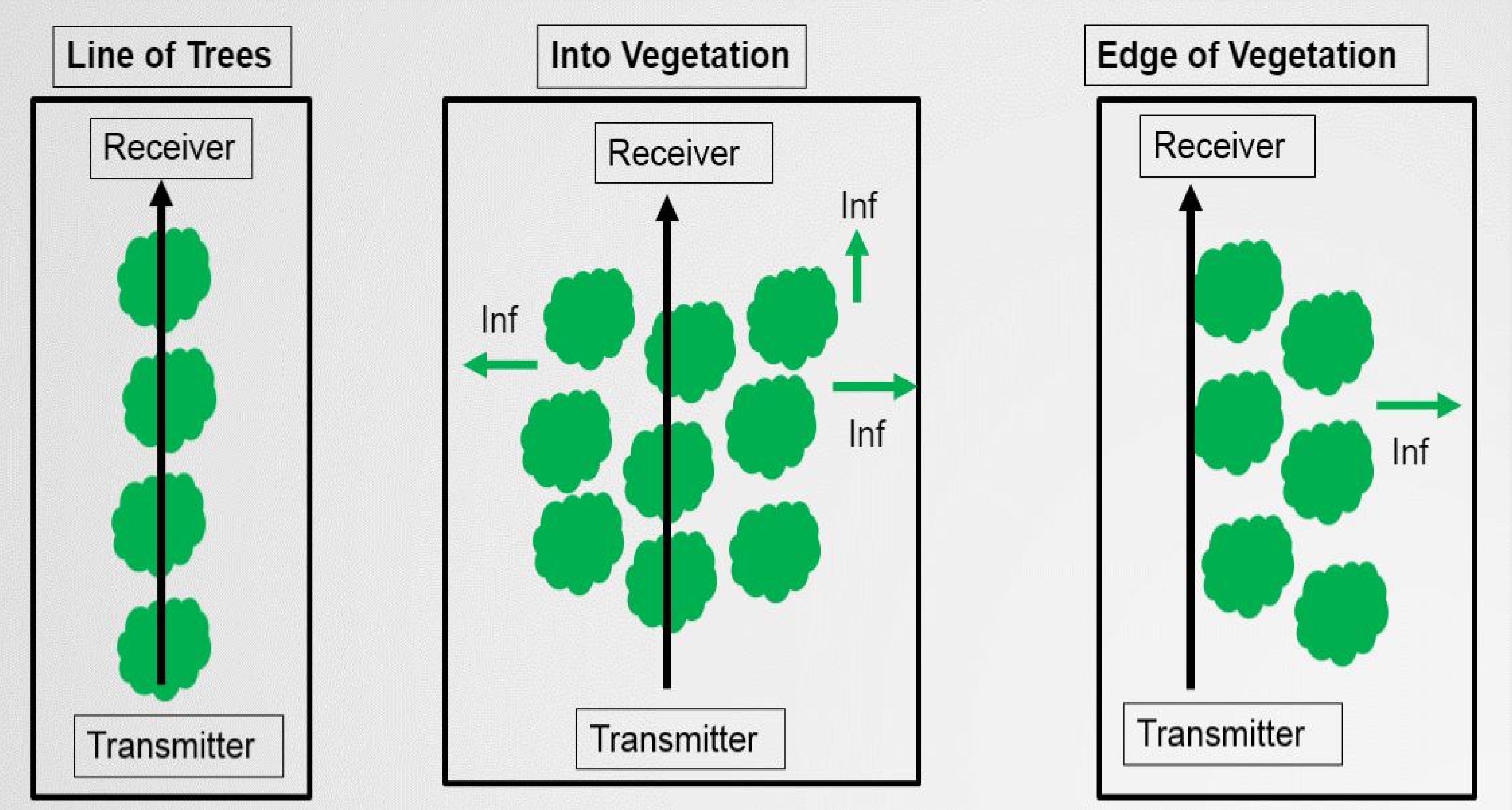
Gradient
Analysis is a research approach for study of spatial patterns of vegetation.

Non-Zero Gradient Model:

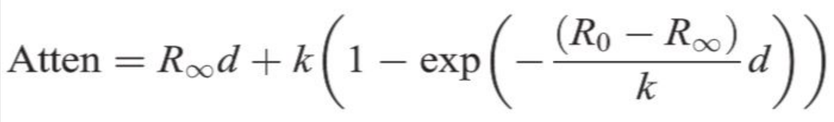
-R: Initial Gradient
-R∞: Final Gradient
-k: Offset Final Gradient
-d: Vegetation depth in meters
-Assuming 2.4 GHz

$$Attentuation = R_{\infty}d + k(1 - \exp(-\frac{R - R_{\infty}}{k}d))$$

Scenarios


Line of Trees
Receiver
Transmitter
Into Vegetation
Receiver
Inf
Inf
Inf
Transmitter
Edge of Vegetation
Receiver
Inf
Transmitter

Communications: The Model



$$\text{Atten} = R_{\infty} d + k\left(1 - \exp\left(-\frac{(R_0 - R_{\infty})}{k} d\right)\right)$$

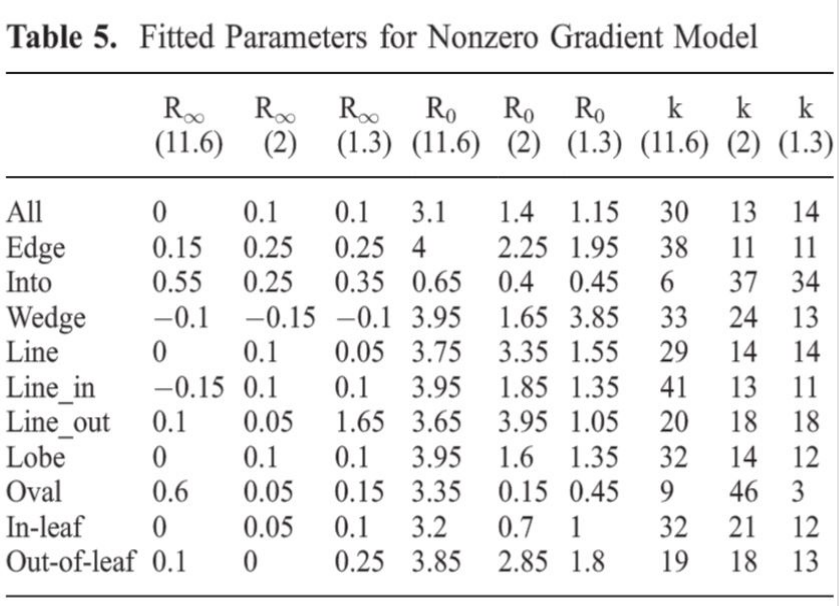


Table 5. Fitted Parameters for Nonzero Gradient Model

	R_{∞} (11.6)	R_{∞} (2)	R_{∞} (1.3)	R_0 (11.6)	R_0 (2)	R_0 (1.3)	k (11.6)	k (2)	k (1.3)
All	0	0.1	0.1	3.1	1.4	1.15	30	13	14
Edge	0.15	0.25	0.25	4	2.25	1.95	38	11	11
Into	0.55	0.25	0.35	0.65	0.4	0.45	6	37	34
Wedge	−0.1	−0.15	−0.1	3.95	1.65	3.85	33	24	13
Line	0	0.1	0.05	3.75	3.35	1.55	29	14	14
Line_in	−0.15	0.1	0.1	3.95	1.85	1.35	41	13	11
Line_out	0.1	0.05	1.65	3.65	3.95	1.05	20	18	18
Lobe	0	0.1	0.1	3.95	1.6	1.35	32	14	12
Oval	0.6	0.05	0.15	3.35	0.15	0.45	9	46	3
In-leaf	0	0.05	0.1	3.2	0.7	1	32	21	12
Out-of-leaf	0.1	0	0.25	3.85	2.85	1.8	19	18	13

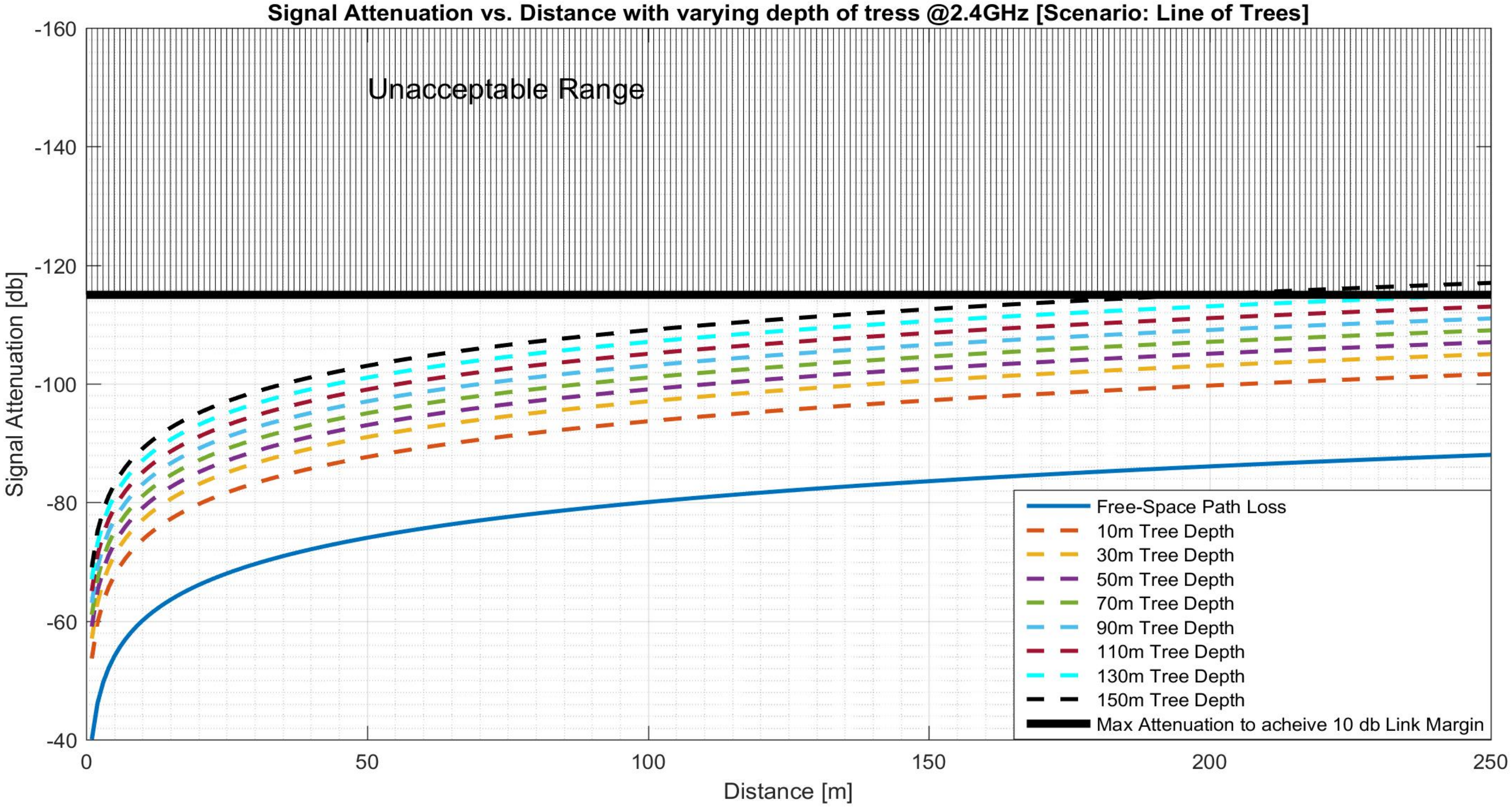
Pros:

1. A very accurate model and simple to calculate.
2. A practical model based on normal forest conditions.

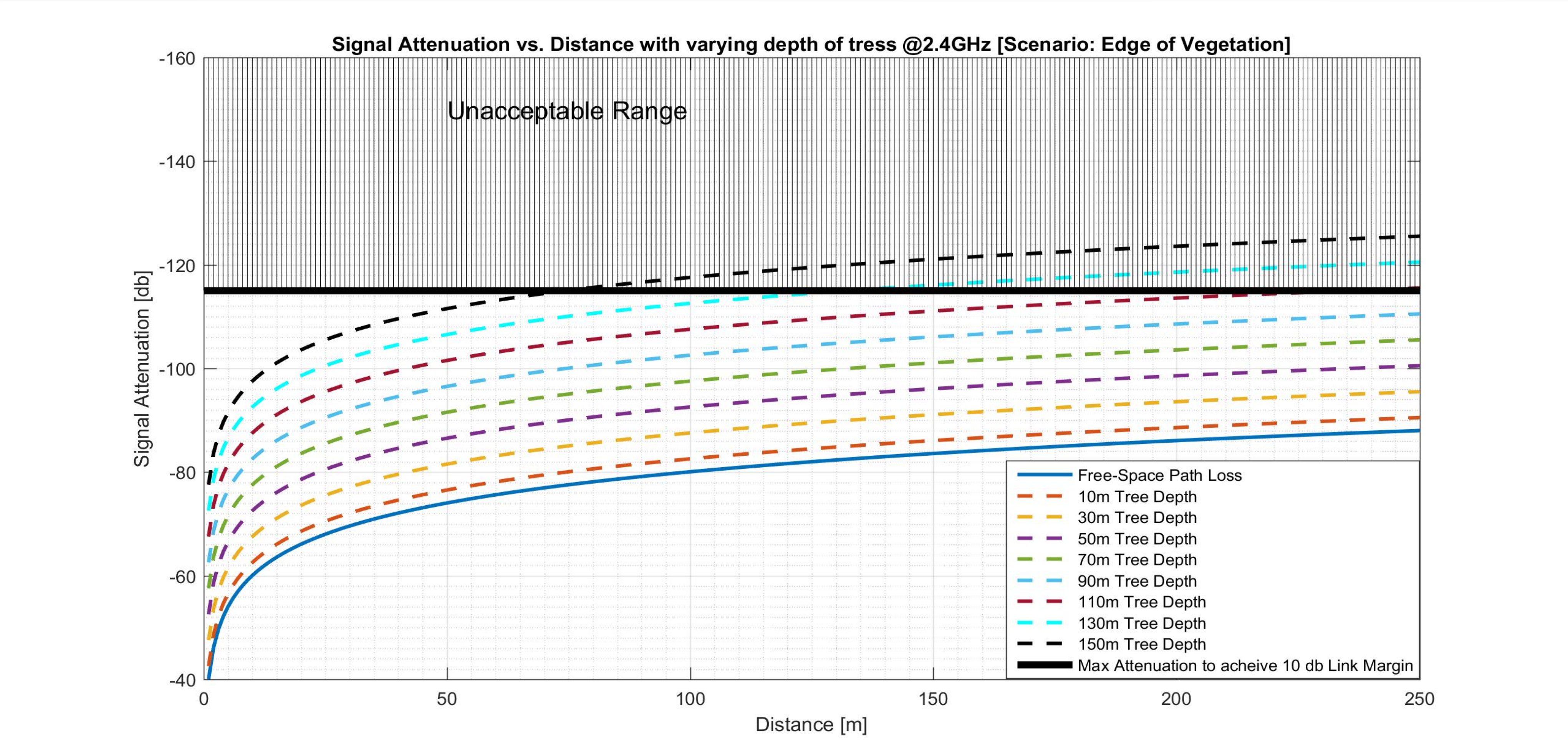
Cons:

1. The calculation of the variables are not for a specific density of trees but an average values of a found forest range.
2. Limits us on knowing exactly how many trees we're dealing in the area.

Line of Trees



Edge of Vegetation

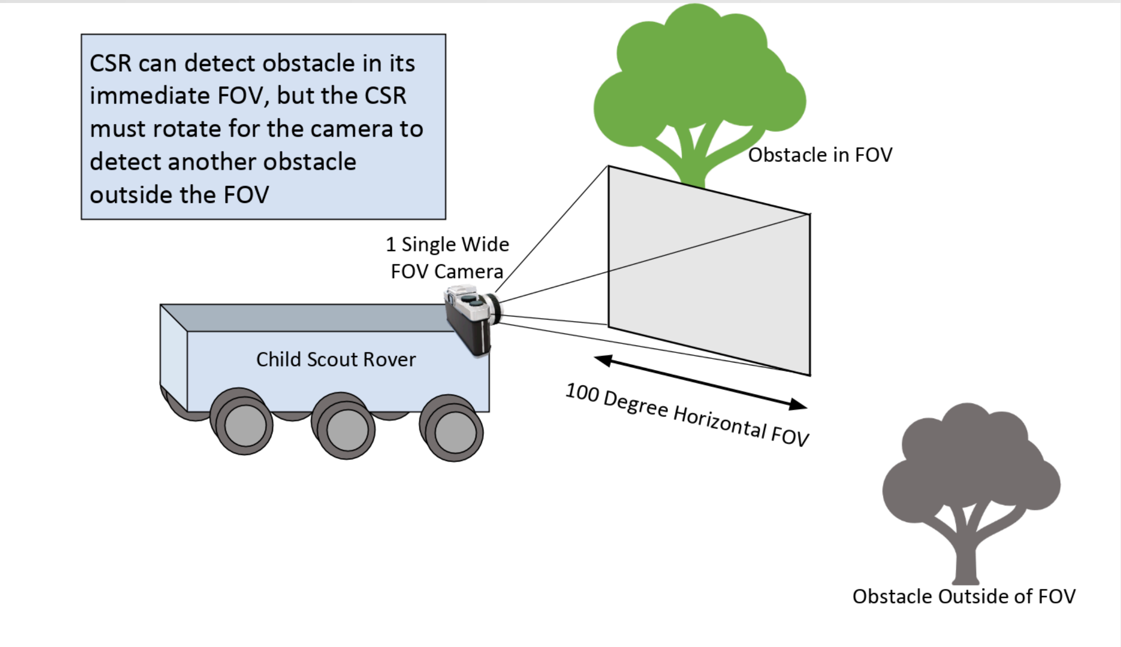


Imaging System

BASELINE DESIGN AND FEASIBILITY ANALYSIS

Imaging System Baseline Design

- Imaging system needed to satisfy major requirements for images/video feed
- Single actuated camera chosen as baseline selection



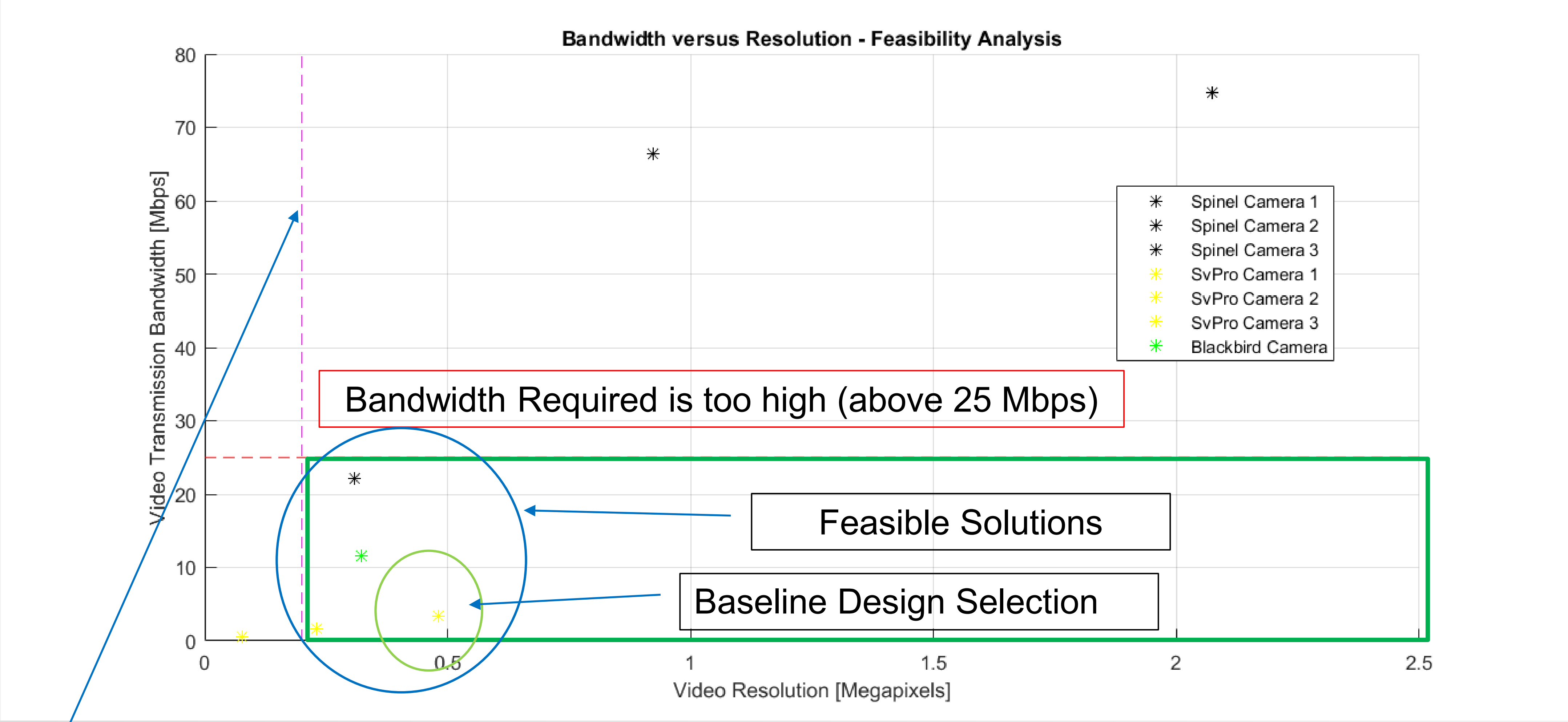
CSR can detect obstacle in its immediate FOV, but the CSR must rotate for the camera to detect another obstacle outside the FOV

Camera Types and Specifications

SENS.5.1 The CSR Sensing system shall capture video
SENS.6.1 The CSR Sensing system shall capture images

Camera	Field of View	Average Video Resolution	Cost	Power	Frame Rate	Projected Bandwidth (with compress)
Spinel 2MP (UC03MPA)	100 deg (no distortion)	(640 x 480)	$50	.7 W	60 fps	22 Mbps
SvPro	100 deg (no distortion)	(320 x 240)	$53	.83 W	30 fps	1.66 Mbps
Blackbird 1D 3D FPV	54 deg (no distortion)	(656 x 442)	$90	1.1 W	30 fps	11.6 Mbps

Camera Feasibility



Bandwidth Required is too high (above 25 Mbps)

Feasible Solutions

Baseline Design Selection

Minimum Video Resolution at Standard Definition (0.2 Mpa)

FEASIBLE

University of Colorado
Boulder

October 2018

Jet Propulsion Laboratory

Actuation System

	Pros	Cons	Cost	Power
Servo	High Resolution High Efficiency Closed Loop	Complexity High Bandwidth No Position Hold	~$12.00	10.9 W
Stepper	Low Torque (for our case) Low Complexity Position Hold/ Low Vibration	Open Loop	~$15.00	3.96 W

Power is << than total Power Budget

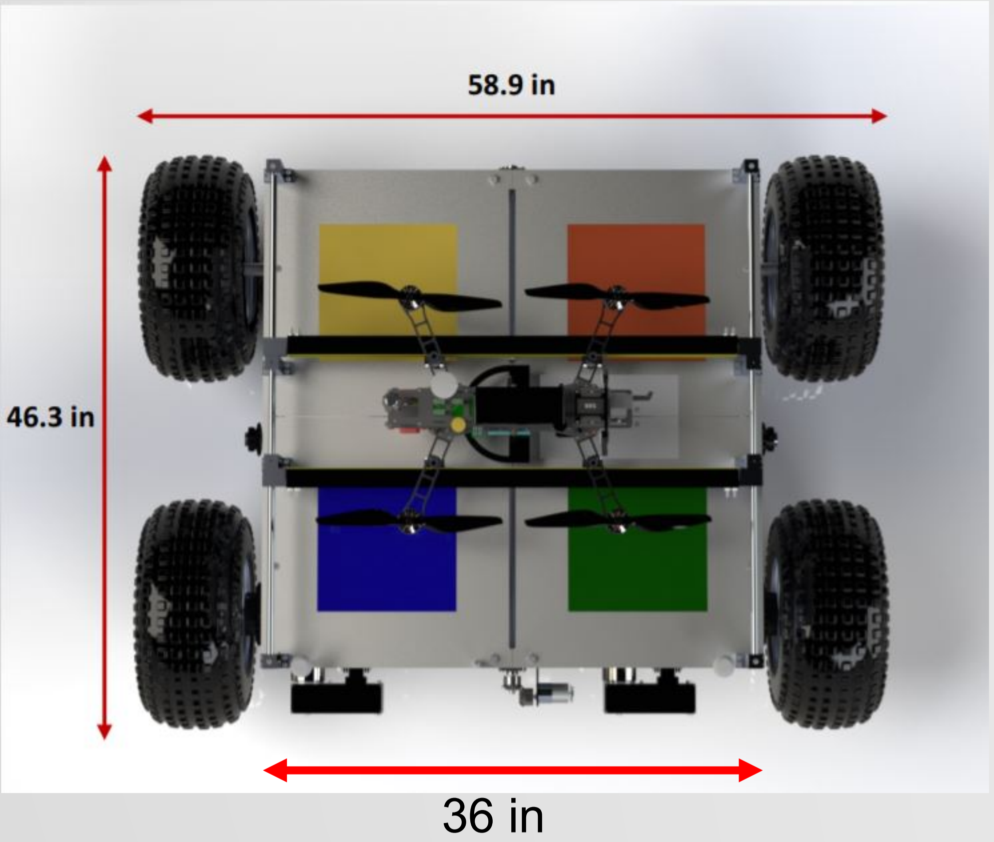
FEASIBLE

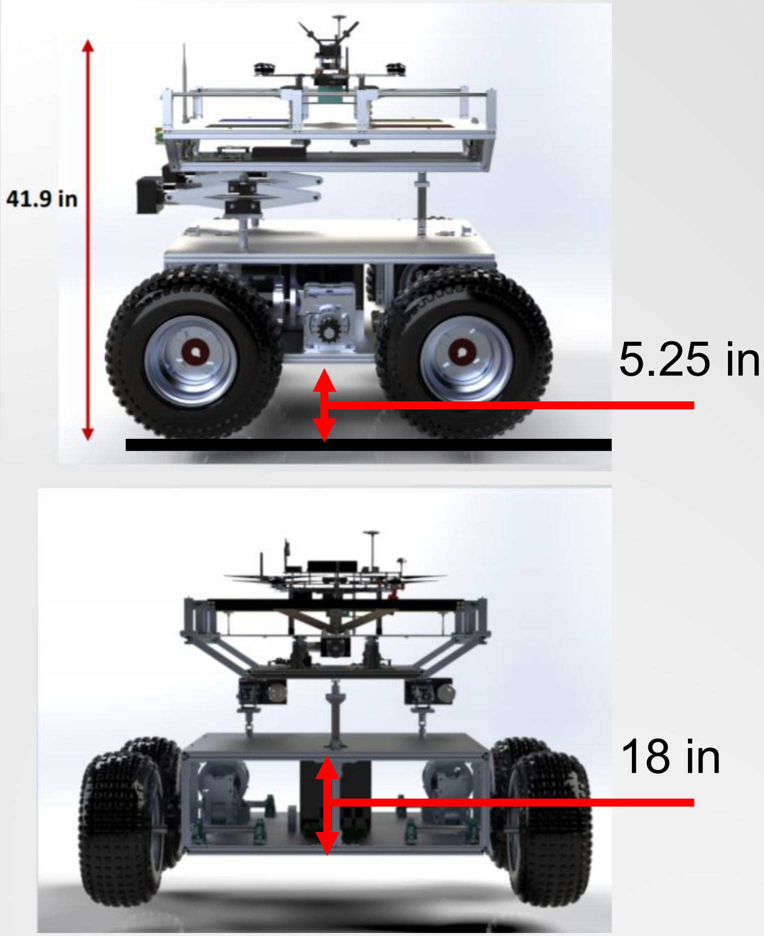
Dimensions

MOTHER ROVER, CHILD SCOUT ROVER, TRAILER

Mother Rovers Dimensions

Dimensions have not been confirmed with actual measurements





State of the Mother rover

It works!

We met up with DRIFT members who showed us what the correct code was needed to command the MR wirelessly, or plugged in. We were able to have the wheels turn, go forward and in reverse, however the MR does not stop after commanding it to stop. Further debugging needs to be done.

Construction quality will need to be improved, and then there is a slight right offset when driving.

Two DC60-4Q 24V 20A Motor Drivers – Motor Control

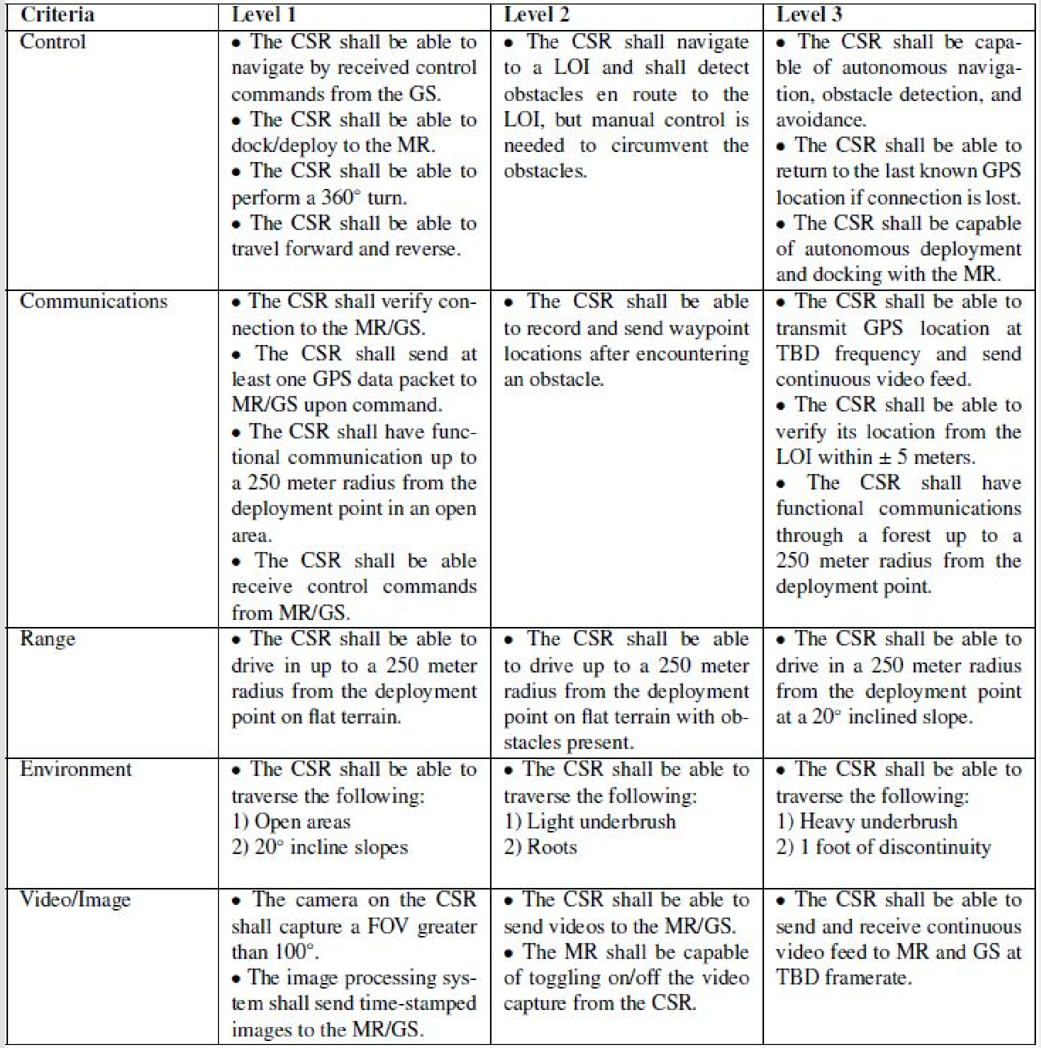
Two MCP4131 Digital Potentiometers – Variable Speed Control

Two Brushed DC Marathon Gear Motors with Reducer Producing 535 in-lb each

Two 12V 100Ah Lead Acid Marine Batteries

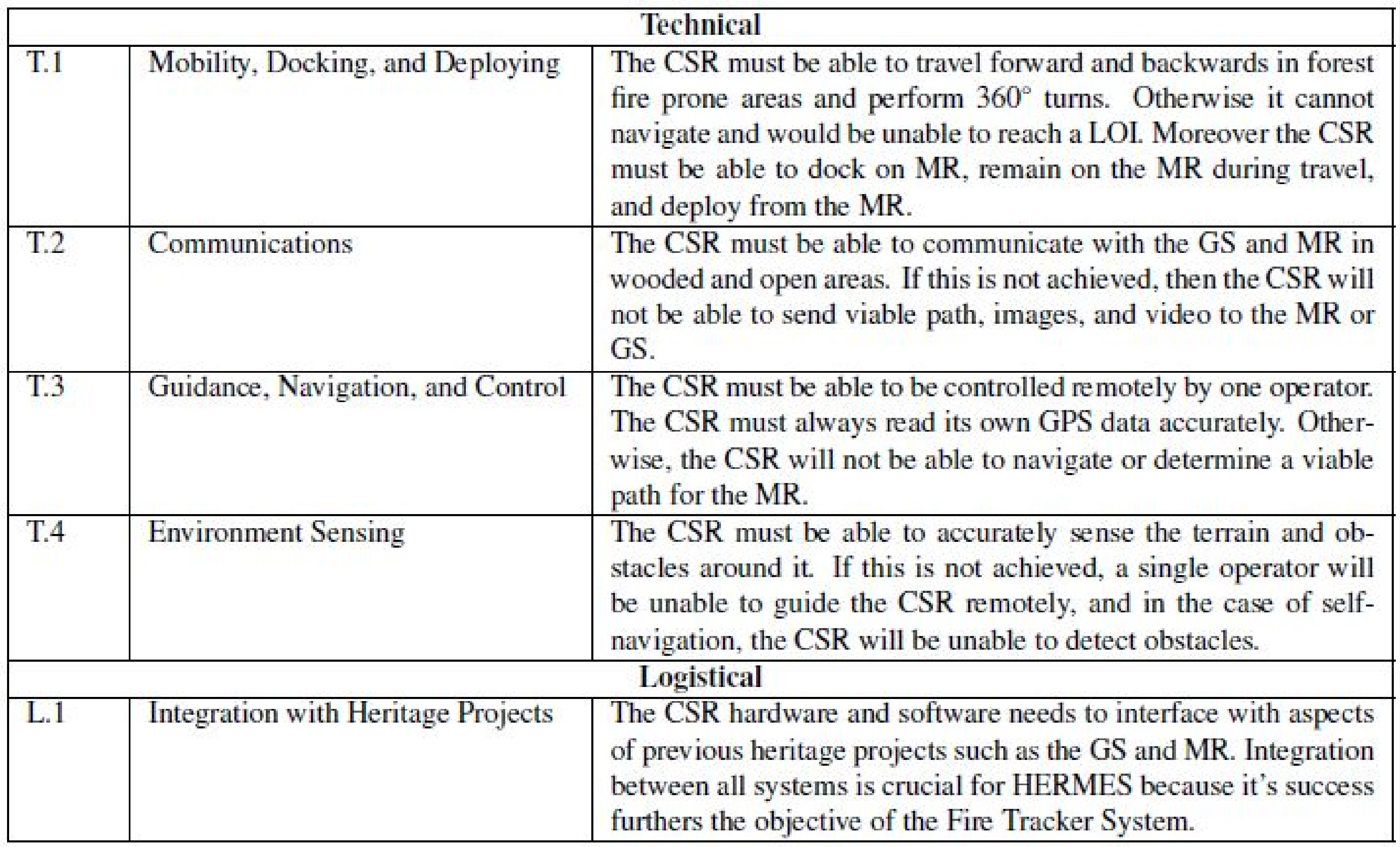
One 60A Time Delay Fuse – Current limiter for motor driver

Levels of Success from PDD



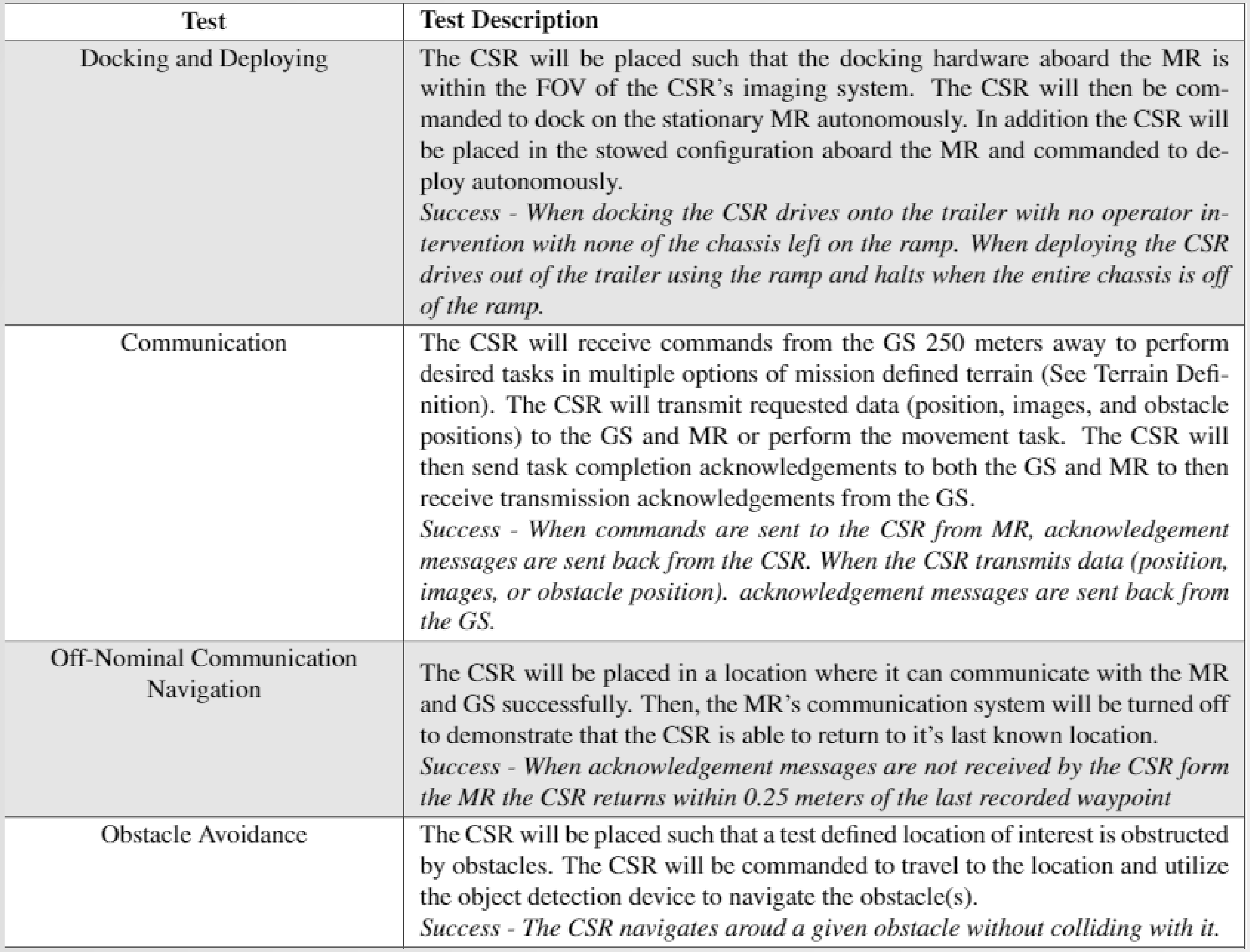
Criteria	Level 1	Level 2	Level 3
Control	• The CSR shall be able to navigate by received control commands from the GS. • The CSR shall be able to dock/deploy to the MR. • The CSR shall be able to perform a 360° turn. • The CSR shall be able to travel forward and reverse.	• The CSR shall navigate to a LOI and shall detect obstacles en route to the LOI, but manual control is needed to circumvent the obstacles.	• The CSR shall be capable of autonomous navigation, obstacle detection, and avoidance. • The CSR shall be able to return to the last known GPS location if connection is lost. • The CSR shall be capable of autonomous deployment and docking with the MR.
Communications	• The CSR shall verify connection to the MR/GS. • The CSR shall send at least one GPS data packet to MR/GS upon command. • The CSR shall have functional communication up to a 250 meter radius from the deployment point in an open area. • The CSR shall be able receive control commands from MR/GS.	• The CSR shall be able to record and send waypoint locations after encountering an obstacle.	• The CSR shall be able to transmit GPS location at TBD frequency and send continuous video feed. • The CSR shall be able to verify its location from the LOI within ± 5 meters. • The CSR shall have functional communications through a forest up to a 250 meter radius from the deployment point.
Range	• The CSR shall be able to drive in up to a 250 meter radius from the deployment point on flat terrain.	• The CSR shall be able to drive up to a 250 meter radius from the deployment point on flat terrain with obstacles present.	• The CSR shall be able to drive in a 250 meter radius from the deployment point at a 20° inclined slope.
Environment	• The CSR shall be able to traverse the following: 1) Open areas 2) 20° incline slopes	• The CSR shall be able to traverse the following: 1) Light underbrush 2) Roots	• The CSR shall be able to traverse the following: 1) Heavy underbrush 2) 1 foot of discontinuity
Video/Image	• The camera on the CSR shall capture a FOV greater than 100°. • The image processing system shall send time-stamped images to the MR/GS.	• The CSR shall be able to send videos to the MR/GS. • The MR shall be capable of toggling on/off the video capture from the CSR.	• The CSR shall be able to send and receive continuous video feed to MR and GS at TBD framerate.

Critical Project Elements from PDD



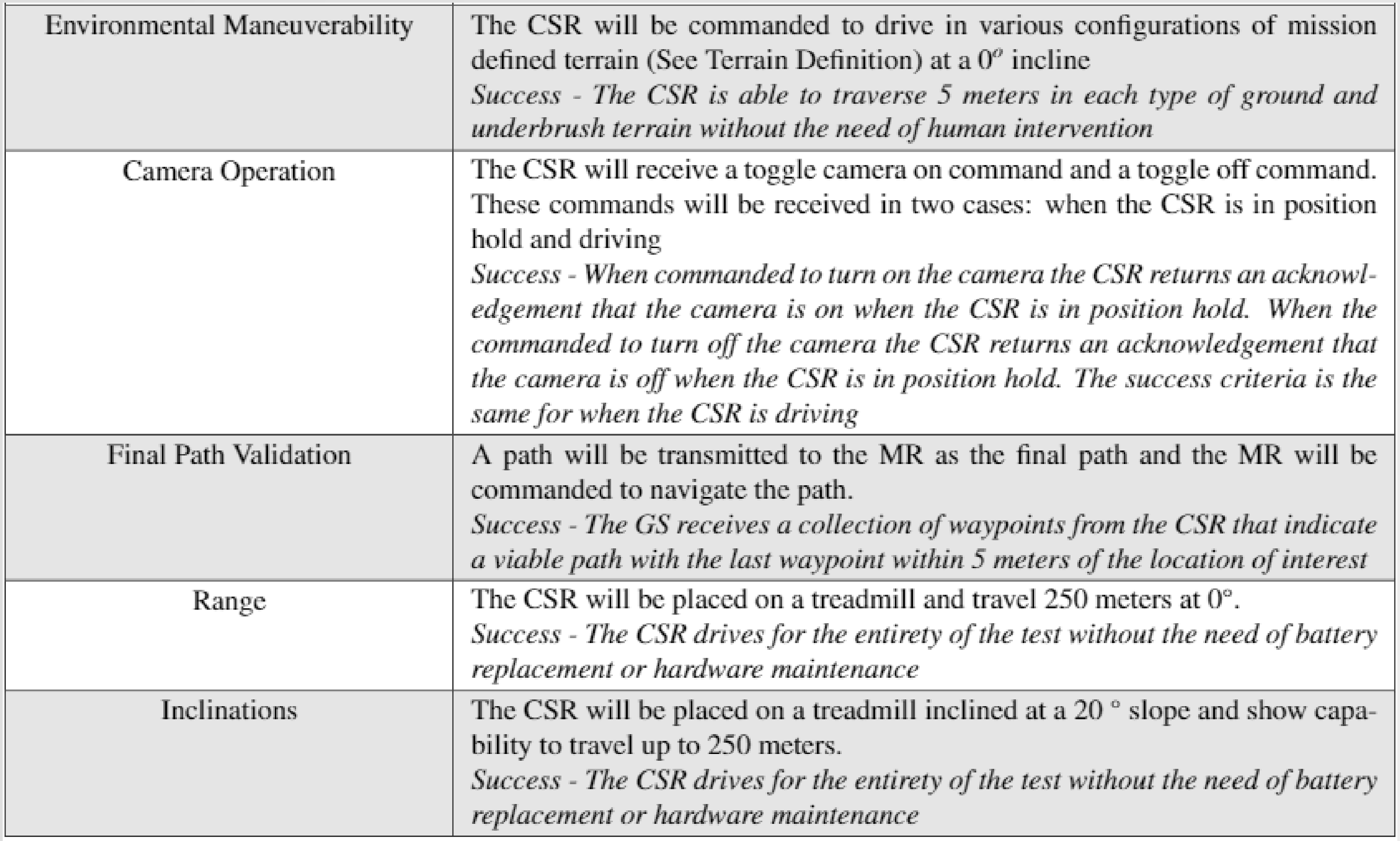
	Technical	
T.1	Mobility, Docking, and Deploying	The CSR must be able to travel forward and backwards in forest fire prone areas and perform 360° turns. Otherwise it cannot navigate and would be unable to reach a LOI. Moreover the CSR must be able to dock on MR, remain on the MR during travel, and deploy from the MR.
T.2	Communications	The CSR must be able to communicate with the GS and MR in wooded and open areas. If this is not achieved, then the CSR will not be able to send viable path, images, and video to the MR or GS.
T.3	Guidance, Navigation, and Control	The CSR must be able to be controlled remotely by one operator. The CSR must always read its own GPS data accurately. Otherwise, the CSR will not be able to navigate or determine a viable path for the MR.
T.4	Environment Sensing	The CSR must be able to accurately sense the terrain and obstacles around it. If this is not achieved, a single operator will be unable to guide the CSR remotely, and in the case of self-navigation, the CSR will be unable to detect obstacles.
	Logistical	
L.1	Integration with Heritage Projects	The CSR hardware and software needs to interface with aspects of previous heritage projects such as the GS and MR. Integration between all systems is crucial for HERMES because it's success furthers the objective of the Fire Tracker System.

Verification and Validation Definition



Test	Test Description
Docking and Deploying	The CSR will be placed such that the docking hardware aboard the MR is within the FOV of the CSR's imaging system. The CSR will then be commanded to dock on the stationary MR autonomously. In addition the CSR will be placed in the stowed configuration aboard the MR and commanded to deploy autonomously. *Success - When docking the CSR drives onto the trailer with no operator intervention with none of the chassis left on the ramp. When deploying the CSR drives out of the trailer using the ramp and halts when the entire chassis is off of the ramp.*
Communication	The CSR will receive commands from the GS 250 meters away to perform desired tasks in multiple options of mission defined terrain (See Terrain Definition). The CSR will transmit requested data (position, images, and obstacle positions) to the GS and MR or perform the movement task. The CSR will then send task completion acknowledgements to both the GS and MR to then receive transmission acknowledgements from the GS. *Success - When commands are sent to the CSR from MR, acknowledgement messages are sent back from the CSR. When the CSR transmits data (position, images, or obstacle position). acknowledgement messages are sent back from the GS.*
Off-Nominal Communication Navigation	The CSR will be placed in a location where it can communicate with the MR and GS successfully. Then, the MR's communication system will be turned off to demonstrate that the CSR is able to return to it's last known location. *Success - When acknowledgement messages are not received by the CSR form the MR the CSR returns within 0.25 meters of the last recorded waypoint*
Obstacle Avoidance	The CSR will be placed such that a test defined location of interest is obstructed by obstacles. The CSR will be commanded to travel to the location and utilize the object detection device to navigate the obstacle(s). *Success - The CSR navigates aroud a given obstacle without colliding with it.*

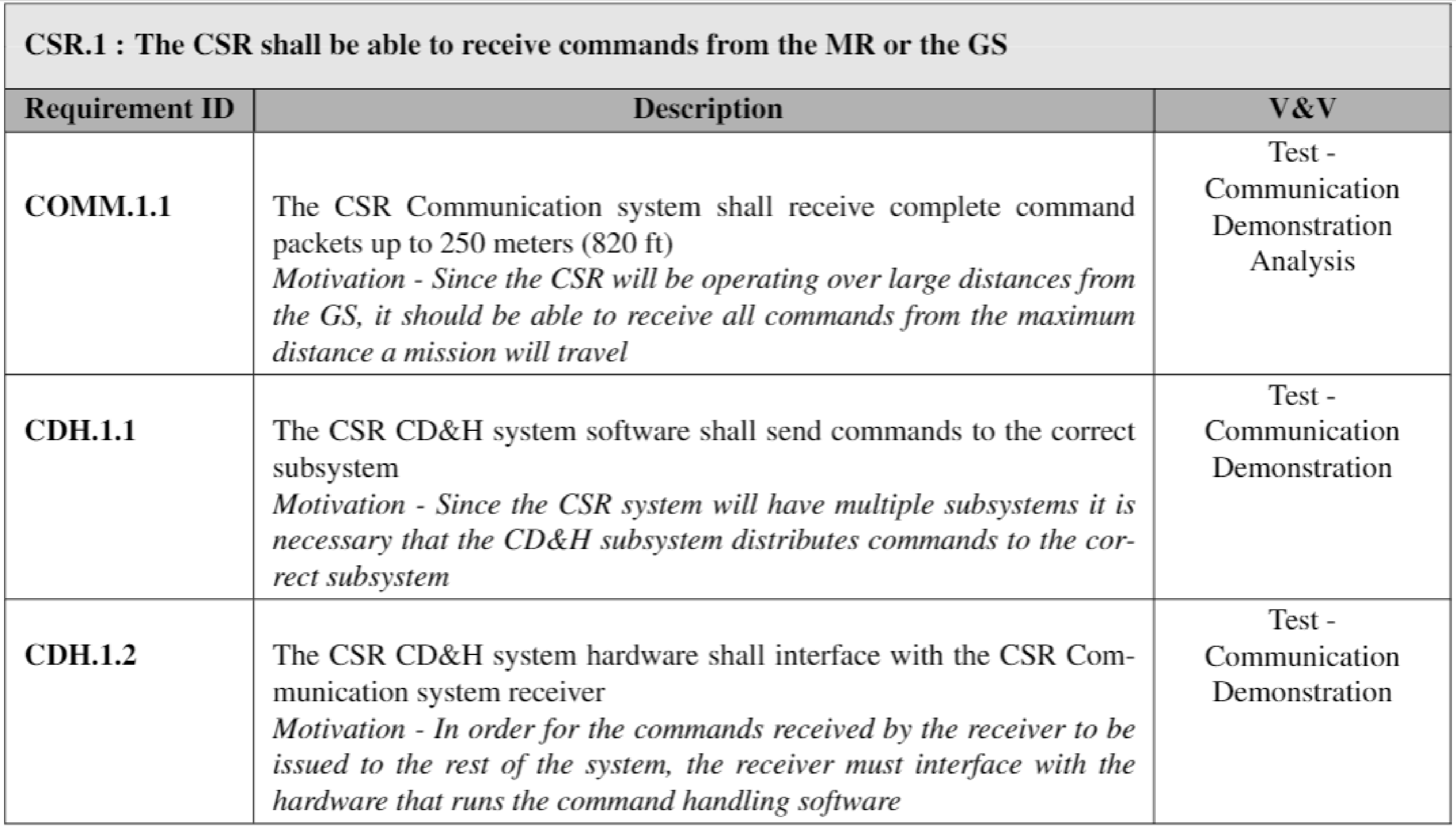
Verification and Validation Definition



Environmental Maneuverability	The CSR will be commanded to drive in various configurations of mission defined terrain (See Terrain Definition) at a 0^o incline *Success - The CSR is able to traverse 5 meters in each type of ground and underbrush terrain without the need of human intervention*
Camera Operation	The CSR will receive a toggle camera on command and a toggle off command. These commands will be received in two cases: when the CSR is in position hold and driving *Success - When commanded to turn on the camera the CSR returns an acknowledgement that the camera is on when the CSR is in position hold. When the commanded to turn off the camera the CSR returns an acknowledgement that the camera is off when the CSR is in position hold. The success criteria is the same for when the CSR is driving*
Final Path Validation	A path will be transmitted to the MR as the final path and the MR will be commanded to navigate the path. *Success - The GS receives a collection of waypoints from the CSR that indicate a viable path with the last waypoint within 5 meters of the location of interest*
Range	The CSR will be placed on a treadmill and travel 250 meters at 0°. *Success - The CSR drives for the entirety of the test without the need of battery replacement or hardware maintenance*
Inclinations	The CSR will be placed on a treadmill inclined at a 20 ° slope and show capability to travel up to 250 meters. *Success - The CSR drives for the entirety of the test without the need of battery replacement or hardware maintenance*

Derived Requirements

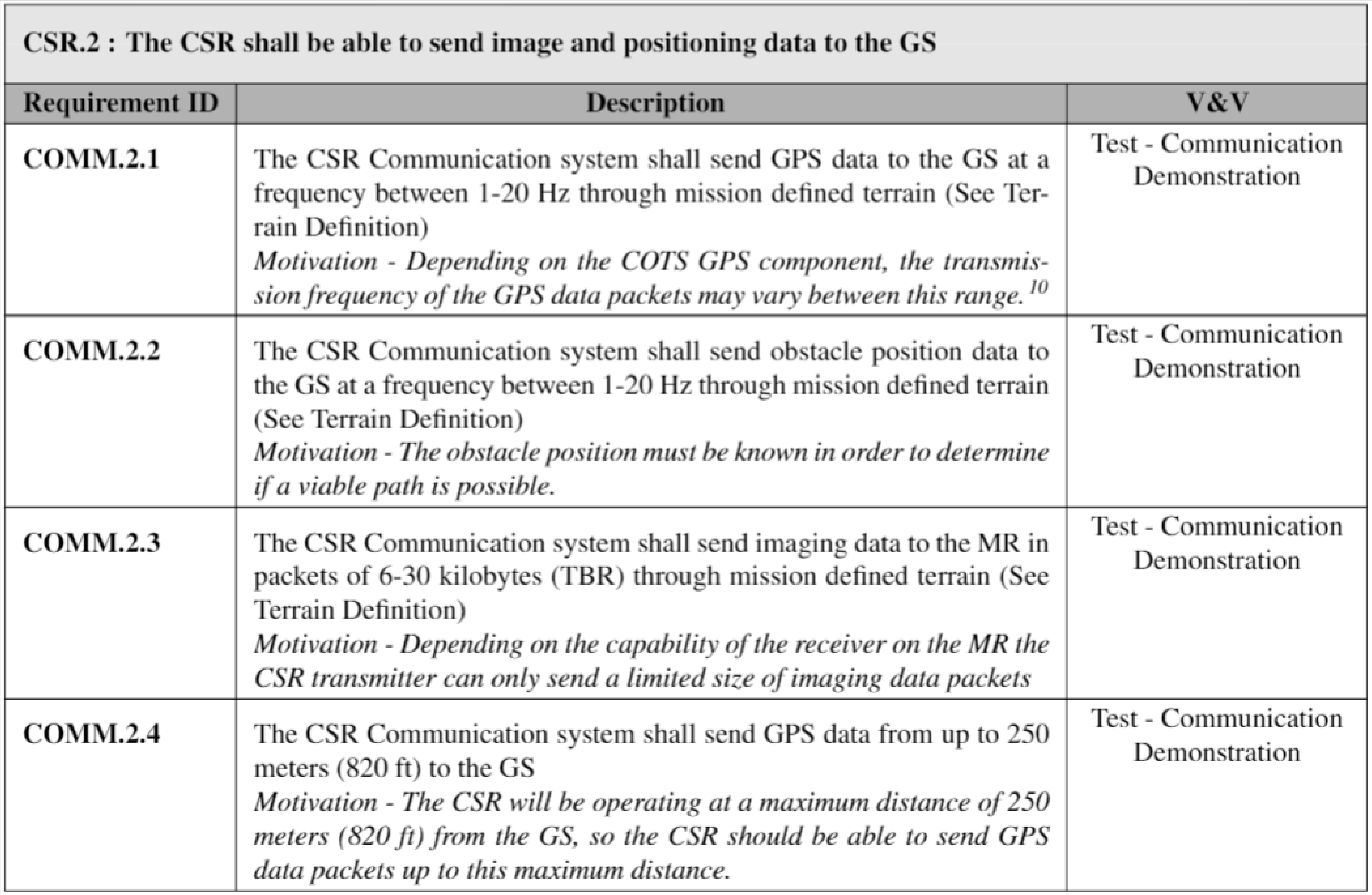
Derived Requirements - CSR.1



CSR.1 : The CSR shall be able to receive commands from the MR or the GS

Requirement ID	Description	V&V
COMM.1.1	The CSR Communication system shall receive complete command packets up to 250 meters (820 ft) *Motivation - Since the CSR will be operating over large distances from the GS, it should be able to receive all commands from the maximum distance a mission will travel*	Test - Communication Demonstration Analysis
CDH.1.1	The CSR CD&H system software shall send commands to the correct subsystem *Motivation - Since the CSR system will have multiple subsystems it is necessary that the CD&H subsystem distributes commands to the correct subsystem*	Test - Communication Demonstration
CDH.1.2	The CSR CD&H system hardware shall interface with the CSR Communication system receiver *Motivation - In order for the commands received by the receiver to be issued to the rest of the system, the receiver must interface with the hardware that runs the command handling software*	Test - Communication Demonstration

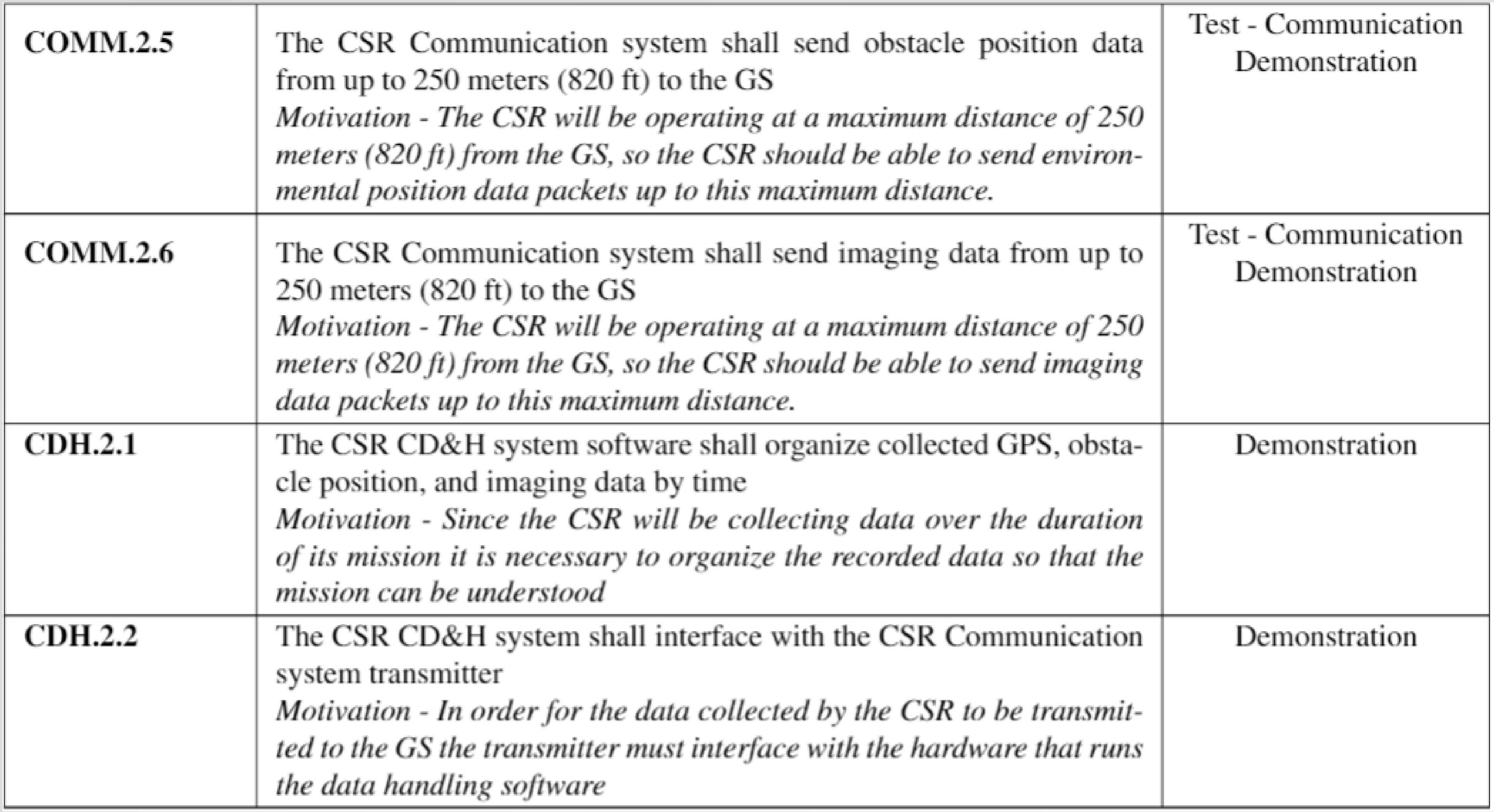
Derived Requirements - CSR.2



CSR.2 : The CSR shall be able to send image and positioning data to the GS

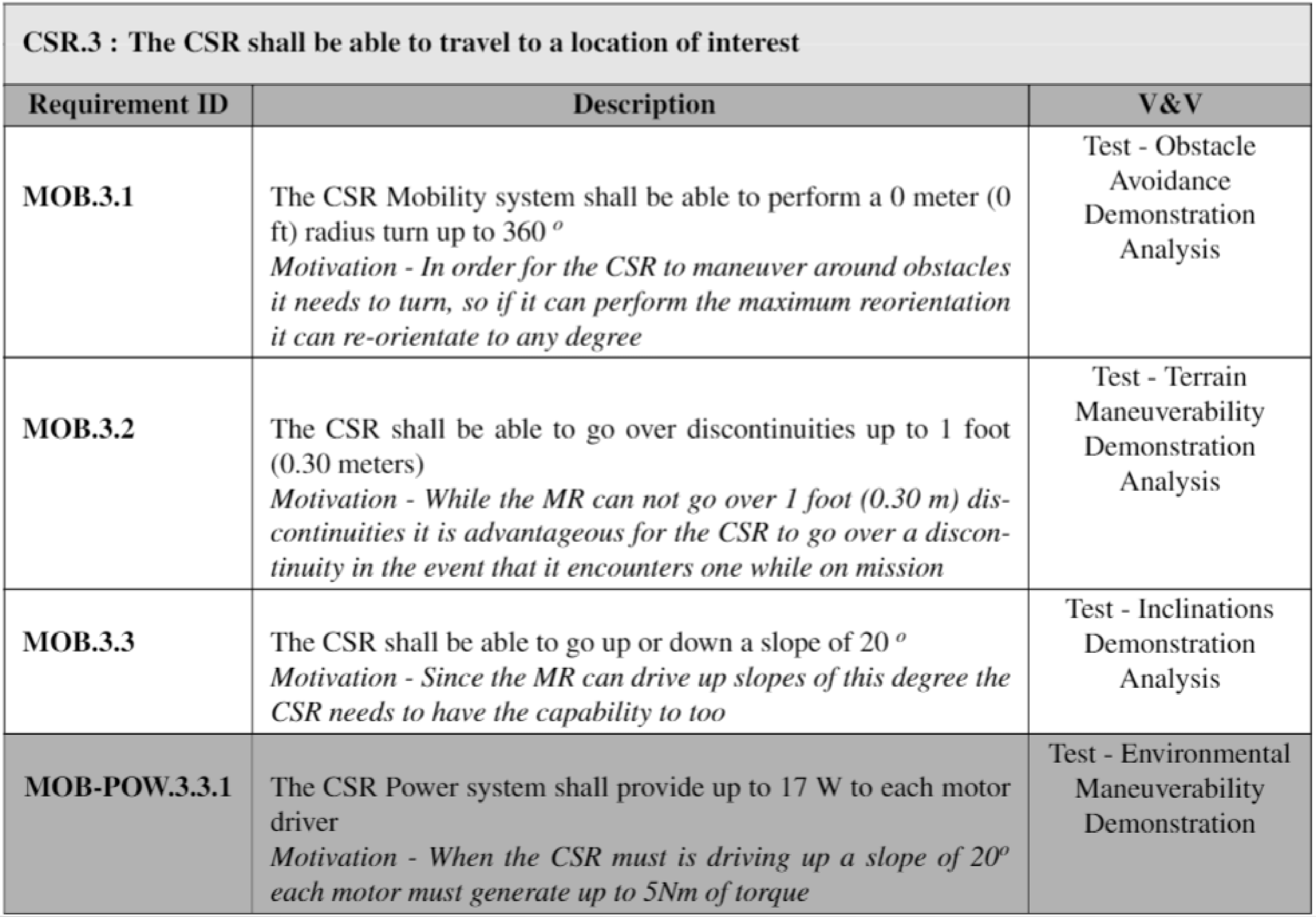
Requirement ID	Description	V&V
COMM.2.1	The CSR Communication system shall send GPS data to the GS at a frequency between 1-20 Hz through mission defined terrain (See Terrain Definition) *Motivation - Depending on the COTS GPS component, the transmission frequency of the GPS data packets may vary between this range.*[10]	Test - Communication Demonstration
COMM.2.2	The CSR Communication system shall send obstacle position data to the GS at a frequency between 1-20 Hz through mission defined terrain (See Terrain Definition) *Motivation - The obstacle position must be known in order to determine if a viable path is possible.*	Test - Communication Demonstration
COMM.2.3	The CSR Communication system shall send imaging data to the MR in packets of 6-30 kilobytes (TBR) through mission defined terrain (See Terrain Definition) *Motivation - Depending on the capability of the receiver on the MR the CSR transmitter can only send a limited size of imaging data packets*	Test - Communication Demonstration
COMM.2.4	The CSR Communication system shall send GPS data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send GPS data packets up to this maximum distance.*	Test - Communication Demonstration

Derived Requirements - CSR.2



COMM.2.5	The CSR Communication system shall send obstacle position data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send environmental position data packets up to this maximum distance.*	Test - Communication Demonstration
COMM.2.6	The CSR Communication system shall send imaging data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send imaging data packets up to this maximum distance.*	Test - Communication Demonstration
CDH.2.1	The CSR CD&H system software shall organize collected GPS, obstacle position, and imaging data by time *Motivation - Since the CSR will be collecting data over the duration of its mission it is necessary to organize the recorded data so that the mission can be understood*	Demonstration
CDH.2.2	The CSR CD&H system shall interface with the CSR Communication system transmitter *Motivation - In order for the data collected by the CSR to be transmitted to the GS the transmitter must interface with the hardware that runs the data handling software*	Demonstration

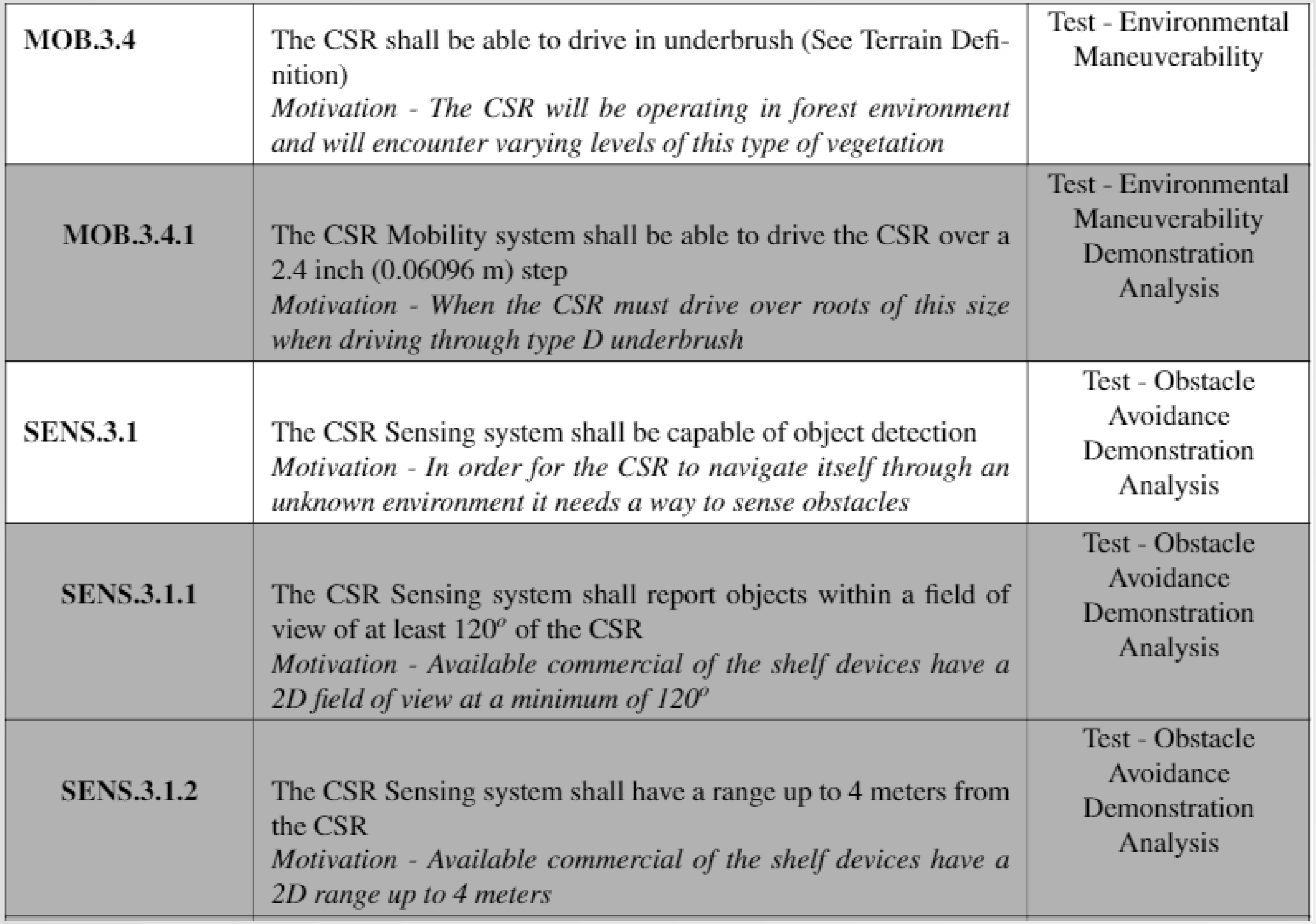
Derived Requirements - CSR.3



CSR.3 : The CSR shall be able to travel to a location of interest

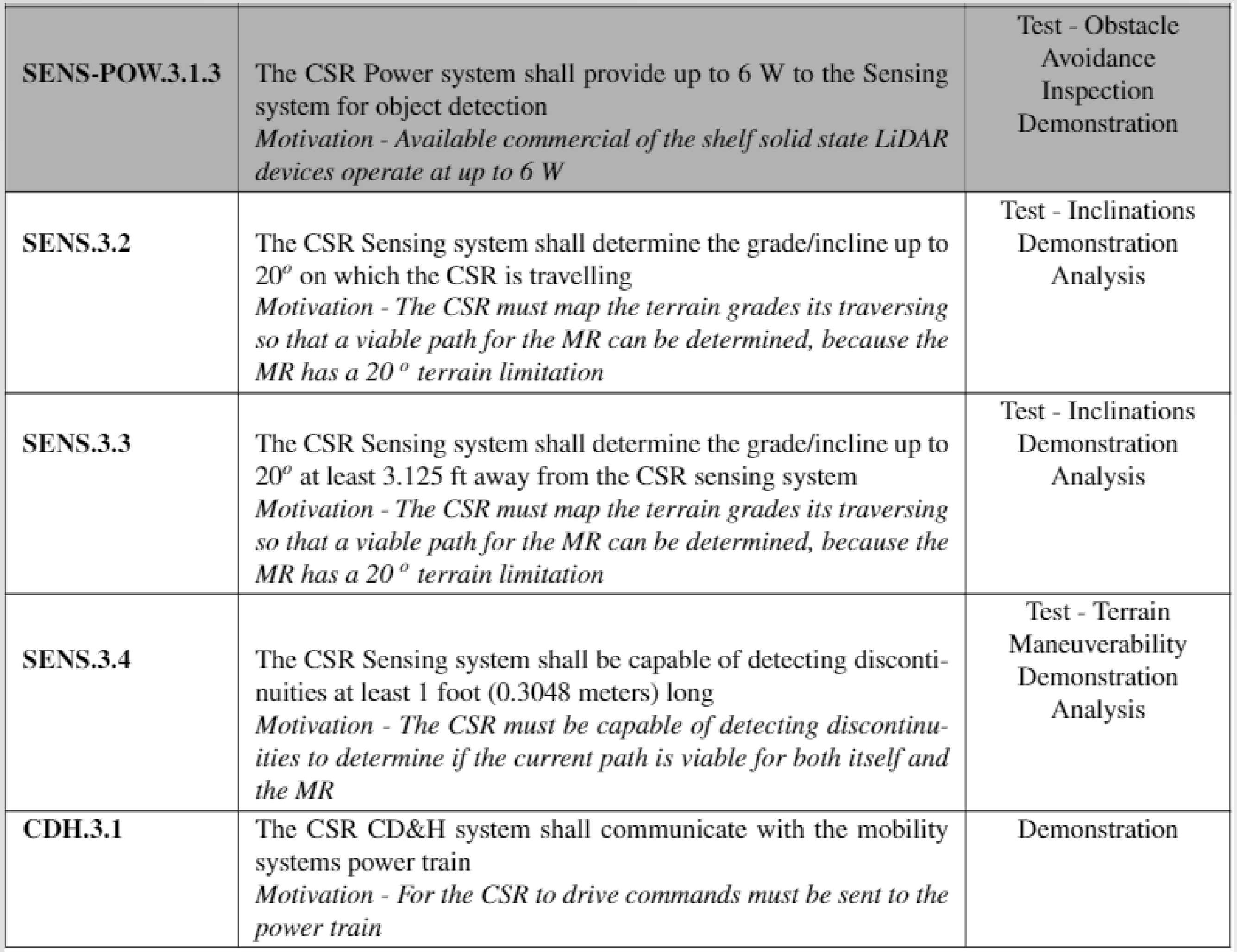
Requirement ID	Description	V&V
MOB.3.1	The CSR Mobility system shall be able to perform a 0 meter (0 ft) radius turn up to 360 ^{o} *Motivation - In order for the CSR to maneuver around obstacles it needs to turn, so if it can perform the maximum reorientation it can re-orientate to any degree*	Test - Obstacle Avoidance Demonstration Analysis
MOB.3.2	The CSR shall be able to go over discontinuities up to 1 foot (0.30 meters) *Motivation - While the MR can not go over 1 foot (0.30 m) discontinuities it is advantageous for the CSR to go over a discontinuity in the event that it encounters one while on mission*	Test - Terrain Maneuverability Demonstration Analysis
MOB.3.3	The CSR shall be able to go up or down a slope of 20 ^{o} *Motivation - Since the MR can drive up slopes of this degree the CSR needs to have the capability to too*	Test - Inclinations Demonstration Analysis
MOB-POW.3.3.1	The CSR Power system shall provide up to 17 W to each motor driver *Motivation - When the CSR must is driving up a slope of 20^o each motor must generate up to 5Nm of torque*	Test - Environmental Maneuverability Demonstration

Derived Requirements - CSR.3



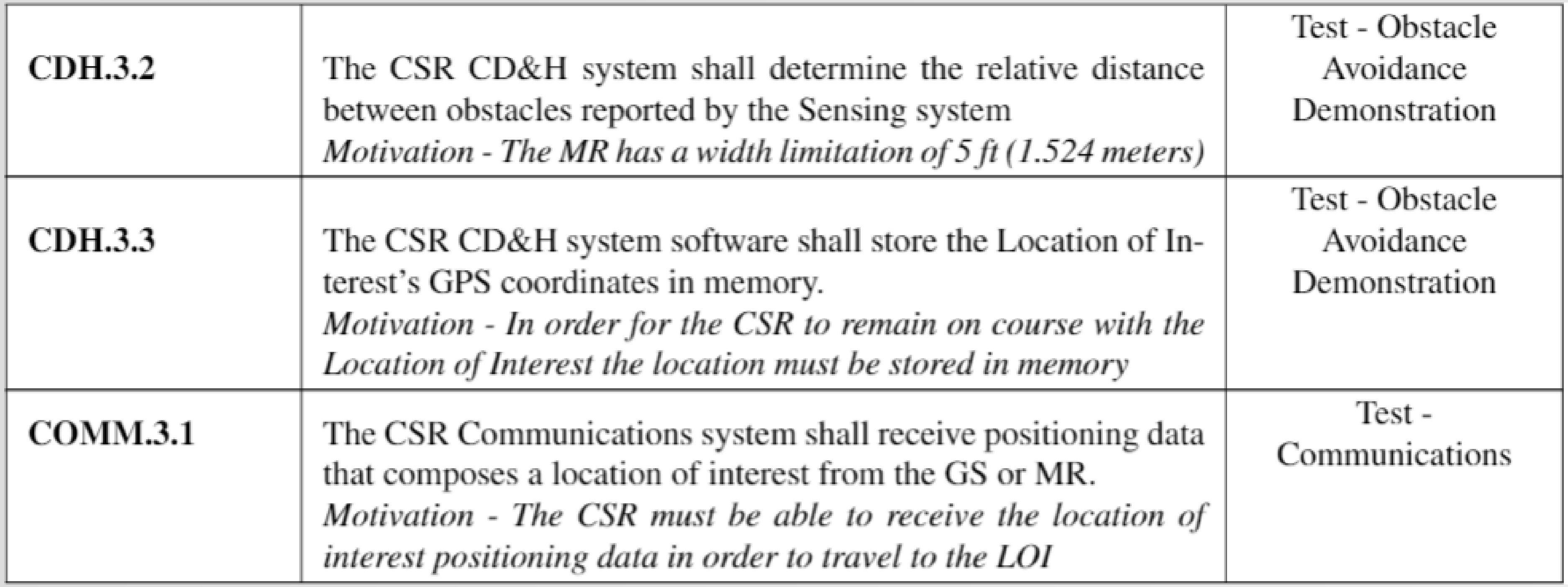
MOB.3.4	The CSR shall be able to drive in underbrush (See Terrain Definition) *Motivation - The CSR will be operating in forest environment and will encounter varying levels of this type of vegetation*	Test - Environmental Maneuverability
MOB.3.4.1	The CSR Mobility system shall be able to drive the CSR over a 2.4 inch (0.06096 m) step *Motivation - When the CSR must drive over roots of this size when driving through type D underbrush*	Test - Environmental Maneuverability Demonstration Analysis
SENS.3.1	The CSR Sensing system shall be capable of object detection *Motivation - In order for the CSR to navigate itself through an unknown environment it needs a way to sense obstacles*	Test - Obstacle Avoidance Demonstration Analysis
SENS.3.1.1	The CSR Sensing system shall report objects within a field of view of at least 120^o of the CSR *Motivation - Available commercial of the shelf devices have a 2D field of view at a minimum of 120^o*	Test - Obstacle Avoidance Demonstration Analysis
SENS.3.1.2	The CSR Sensing system shall have a range up to 4 meters from the CSR *Motivation - Available commercial of the shelf devices have a 2D range up to 4 meters*	Test - Obstacle Avoidance Demonstration Analysis

Derived Requirements - CSR.3



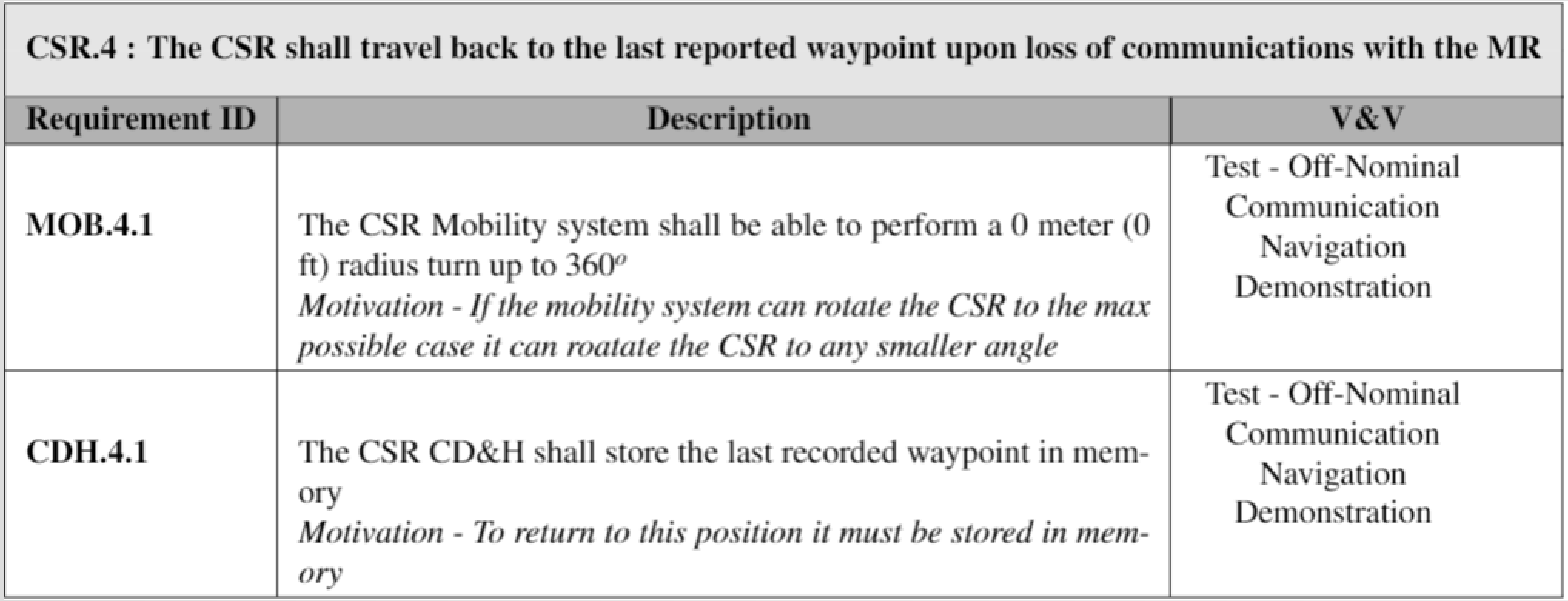
SENS-POW.3.1.3	The CSR Power system shall provide up to 6 W to the Sensing system for object detection *Motivation - Available commercial of the shelf solid state LiDAR devices operate at up to 6 W*	Test - Obstacle Avoidance Inspection Demonstration
SENS.3.2	The CSR Sensing system shall determine the grade/incline up to 20^o on which the CSR is travelling *Motivation - The CSR must map the terrain grades its traversing so that a viable path for the MR can be determined, because the MR has a* 20^o *terrain limitation*	Test - Inclinations Demonstration Analysis
SENS.3.3	The CSR Sensing system shall determine the grade/incline up to 20^o at least 3.125 ft away from the CSR sensing system *Motivation - The CSR must map the terrain grades its traversing so that a viable path for the MR can be determined, because the MR has a* 20^o *terrain limitation*	Test - Inclinations Demonstration Analysis
SENS.3.4	The CSR Sensing system shall be capable of detecting discontinuities at least 1 foot (0.3048 meters) long *Motivation - The CSR must be capable of detecting discontinuities to determine if the current path is viable for both itself and the MR*	Test - Terrain Maneuverability Demonstration Analysis
CDH.3.1	The CSR CD&H system shall communicate with the mobility systems power train *Motivation - For the CSR to drive commands must be sent to the power train*	Demonstration

Derived Requirements - CSR.3



CDH.3.2	The CSR CD&H system shall determine the relative distance between obstacles reported by the Sensing system *Motivation - The MR has a width limitation of 5 ft (1.524 meters)*	Test - Obstacle Avoidance Demonstration
CDH.3.3	The CSR CD&H system software shall store the Location of Interest's GPS coordinates in memory. *Motivation - In order for the CSR to remain on course with the Location of Interest the location must be stored in memory*	Test - Obstacle Avoidance Demonstration
COMM.3.1	The CSR Communications system shall receive positioning data that composes a location of interest from the GS or MR. *Motivation - The CSR must be able to receive the location of interest positioning data in order to travel to the LOI*	Test - Communications

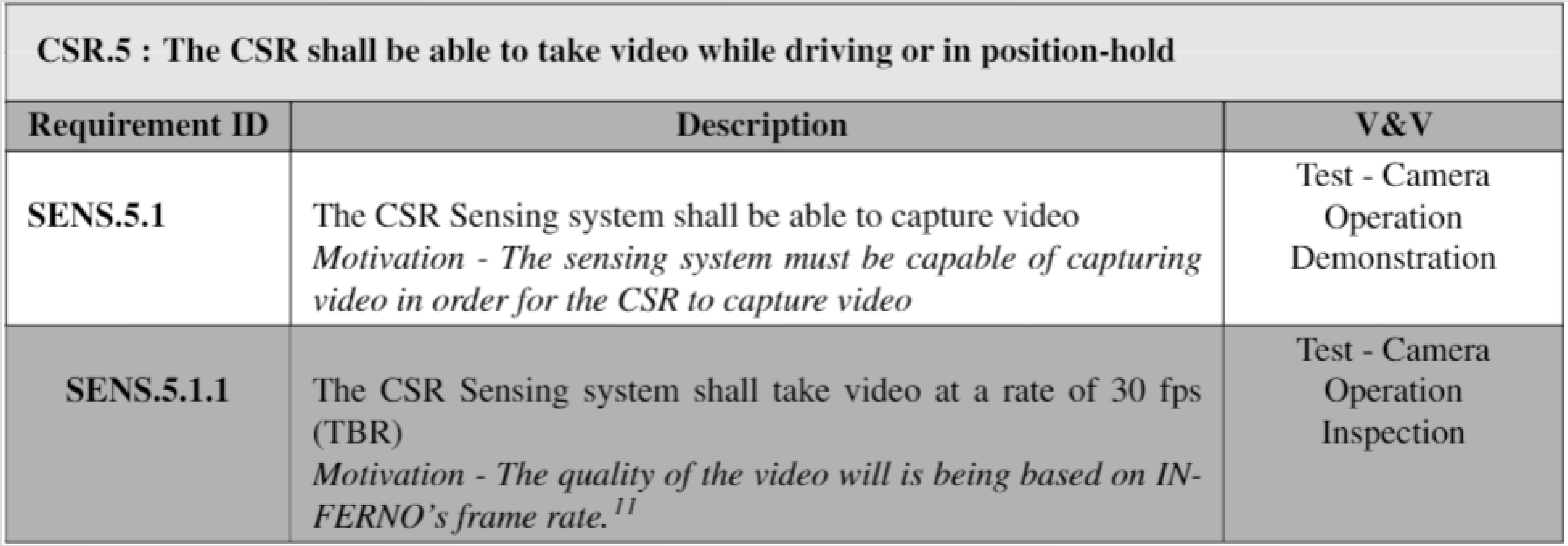
Derived Requirements - CSR.4



CSR.4 : The CSR shall travel back to the last reported waypoint upon loss of communications with the MR

Requirement ID	Description	V&V
MOB.4.1	The CSR Mobility system shall be able to perform a 0 meter (0 ft) radius turn up to 360^o *Motivation - If the mobility system can rotate the CSR to the max possible case it can roatate the CSR to any smaller angle*	Test - Off-Nominal Communication Navigation Demonstration
CDH.4.1	The CSR CD&H shall store the last recorded waypoint in memory *Motivation - To return to this position it must be stored in memory*	Test - Off-Nominal Communication Navigation Demonstration

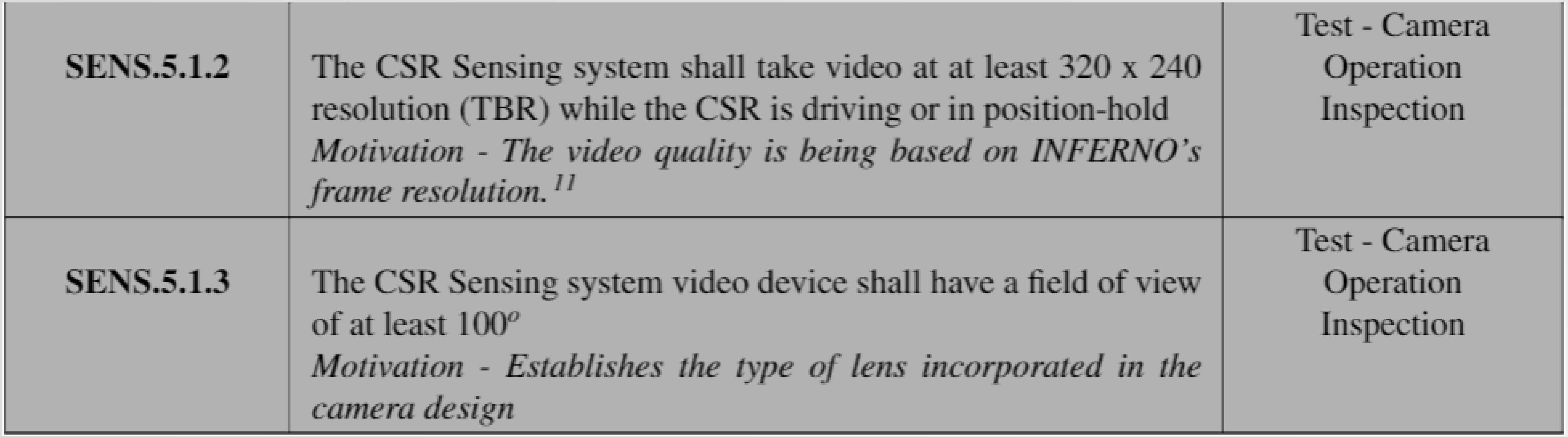
Derived Requirements - CSR.5



CSR.5 : The CSR shall be able to take video while driving or in position-hold

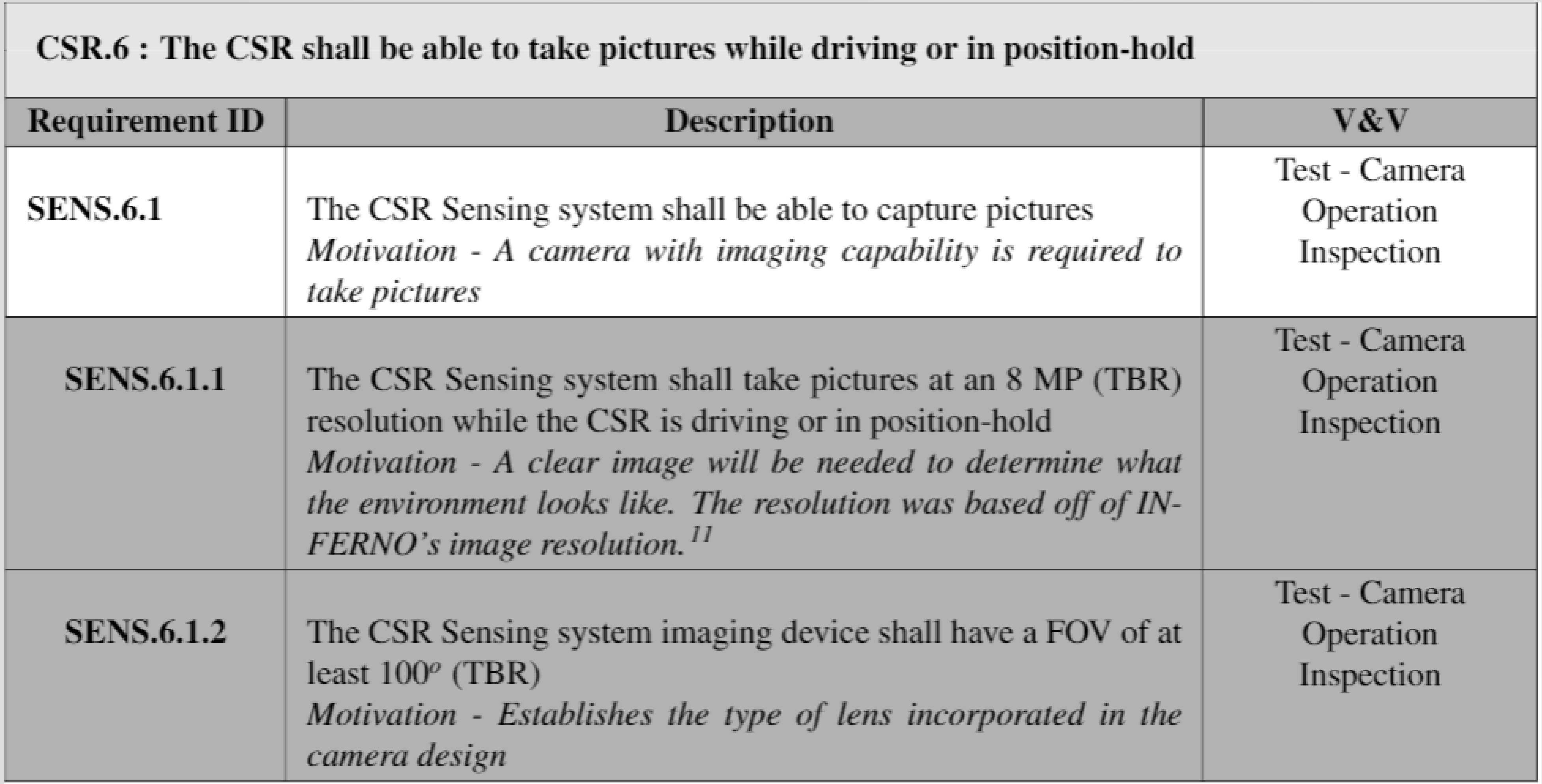
Requirement ID	Description	V&V
SENS.5.1	The CSR Sensing system shall be able to capture video *Motivation - The sensing system must be capable of capturing video in order for the CSR to capture video*	Test - Camera Operation Demonstration
SENS.5.1.1	The CSR Sensing system shall take video at a rate of 30 fps (TBR) *Motivation - The quality of the video will is being based on IN-FERNO's frame rate.*[11]	Test - Camera Operation Inspection

Derived Requirements - CSR.5



SENS.5.1.2	The CSR Sensing system shall take video at at least 320 x 240 resolution (TBR) while the CSR is driving or in position-hold *Motivation - The video quality is being based on INFERNO's frame resolution.*[11]	Test - Camera Operation Inspection
SENS.5.1.3	The CSR Sensing system video device shall have a field of view of at least 100^o *Motivation - Establishes the type of lens incorporated in the camera design*	Test - Camera Operation Inspection

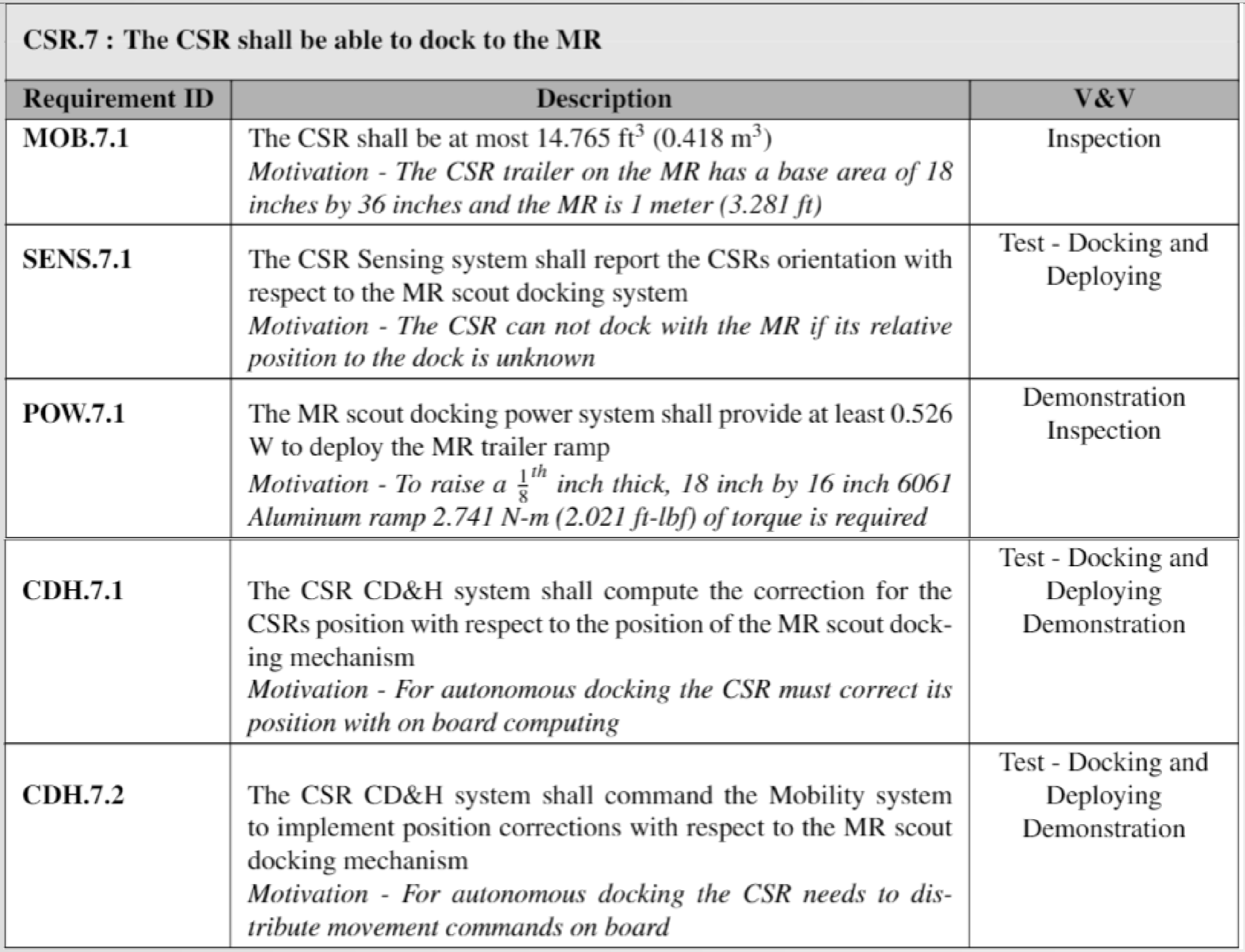
Derived Requirements - CSR.6



CSR.6 : The CSR shall be able to take pictures while driving or in position-hold

Requirement ID	Description	V&V
SENS.6.1	The CSR Sensing system shall be able to capture pictures *Motivation - A camera with imaging capability is required to take pictures*	Test - Camera Operation Inspection
SENS.6.1.1	The CSR Sensing system shall take pictures at an 8 MP (TBR) resolution while the CSR is driving or in position-hold *Motivation - A clear image will be needed to determine what the environment looks like. The resolution was based off of IN-FERNO's image resolution.*[11]	Test - Camera Operation Inspection
SENS.6.1.2	The CSR Sensing system imaging device shall have a FOV of at least 100^o (TBR) *Motivation - Establishes the type of lens incorporated in the camera design*	Test - Camera Operation Inspection

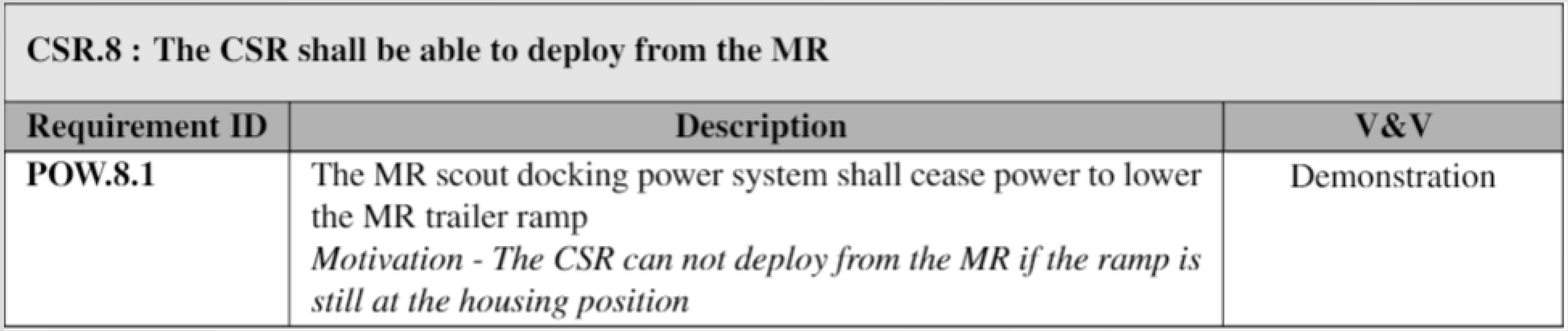
Derived Requirements - CSR.7



CSR.7 : The CSR shall be able to dock to the MR

Requirement ID	Description	V&V
MOB.7.1	The CSR shall be at most 14.765 ft^3 (0.418 m^3) *Motivation - The CSR trailer on the MR has a base area of 18 inches by 36 inches and the MR is 1 meter (3.281 ft)*	Inspection
SENS.7.1	The CSR Sensing system shall report the CSRs orientation with respect to the MR scout docking system *Motivation - The CSR can not dock with the MR if its relative position to the dock is unknown*	Test - Docking and Deploying
POW.7.1	The MR scout docking power system shall provide at least 0.526 W to deploy the MR trailer ramp *Motivation - To raise a $\frac{1}{8}^{th}$ inch thick, 18 inch by 16 inch 6061 Aluminum ramp 2.741 N-m (2.021 ft-lbf) of torque is required*	Demonstration Inspection
CDH.7.1	The CSR CD&H system shall compute the correction for the CSRs position with respect to the position of the MR scout docking mechanism *Motivation - For autonomous docking the CSR must correct its position with on board computing*	Test - Docking and Deploying Demonstration
CDH.7.2	The CSR CD&H system shall command the Mobility system to implement position corrections with respect to the MR scout docking mechanism *Motivation - For autonomous docking the CSR needs to distribute movement commands on board*	Test - Docking and Deploying Demonstration

Derived Requirements - CSR.8

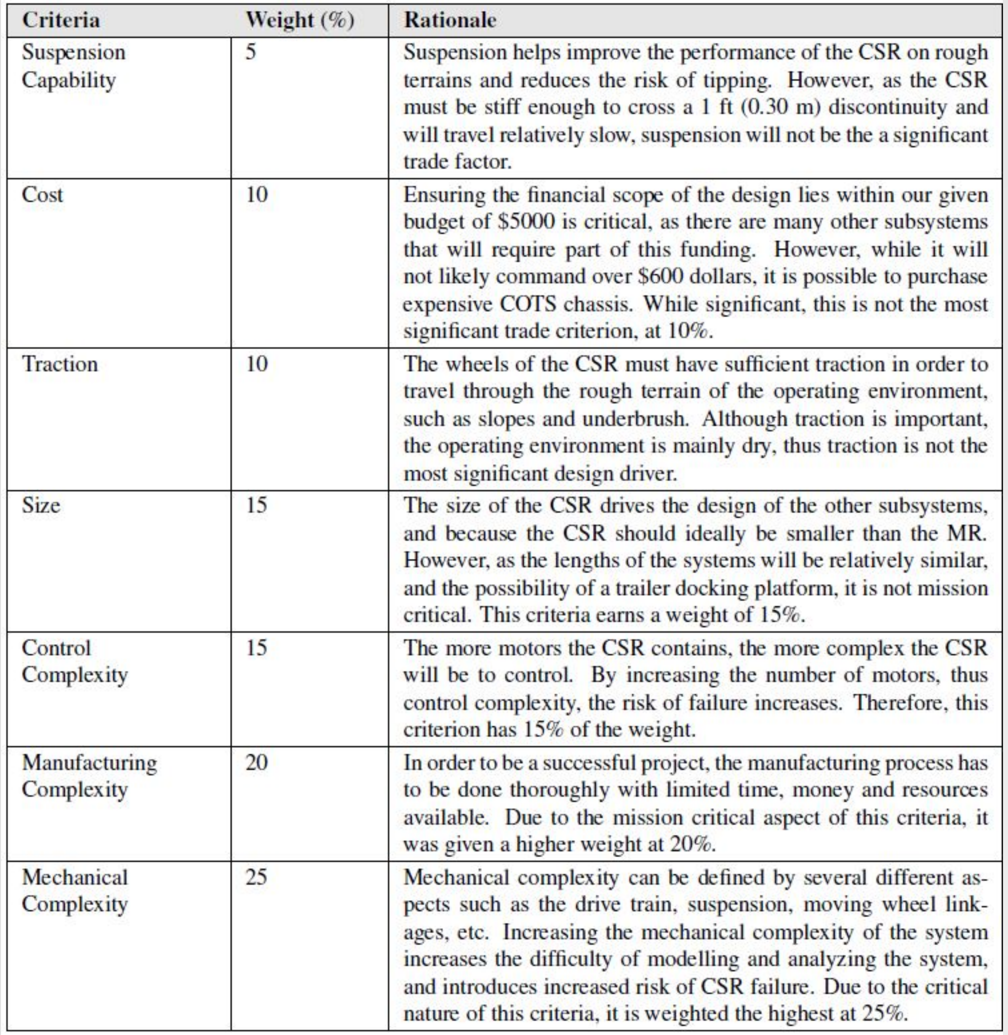


CSR.8 : The CSR shall be able to deploy from the MR

Requirement ID	Description	V&V
POW.8.1	The MR scout docking power system shall cease power to lower the MR trailer ramp *Motivation - The CSR can not deploy from the MR if the ramp is still at the housing position*	Demonstration

Weighting and Criteria for Trade Matrices

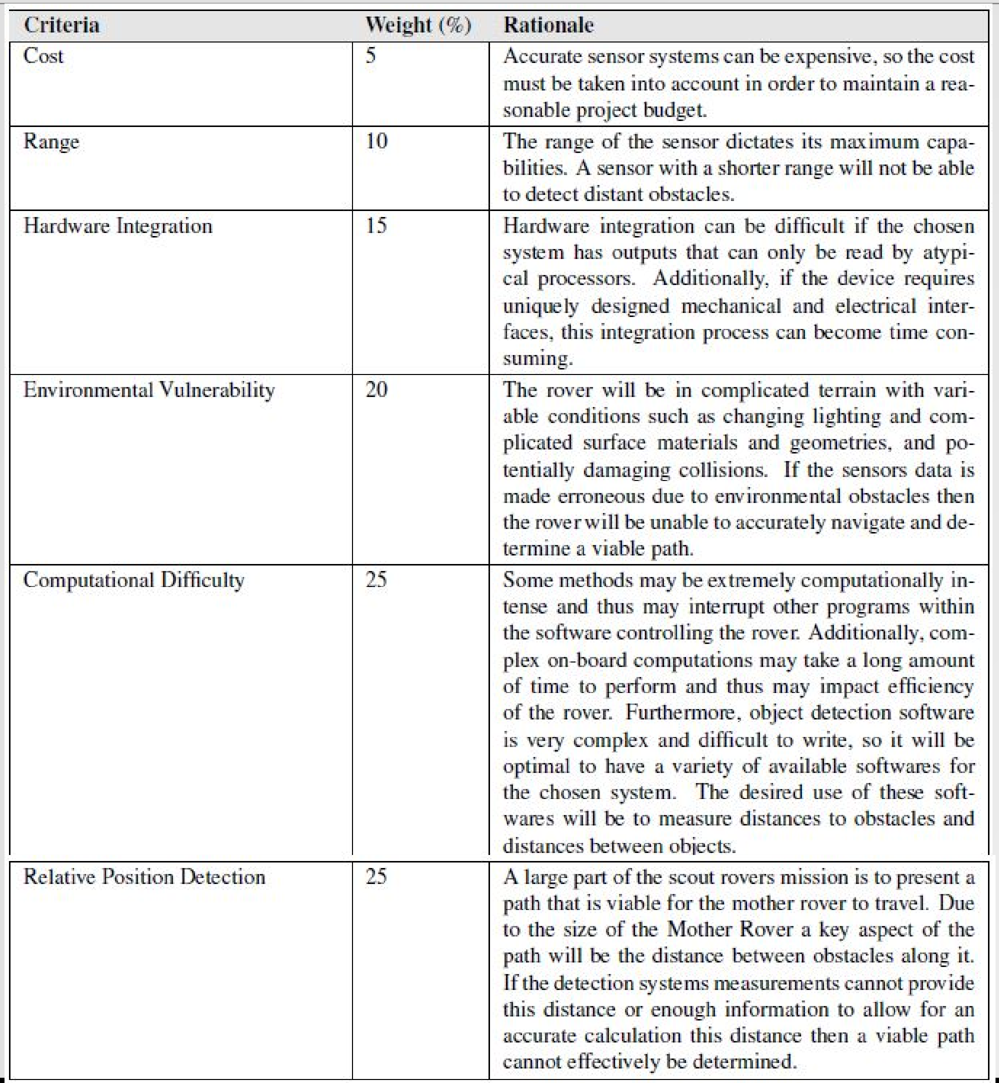
Translational System Weighing and Criteria



Criteria	Weight (%)	Rationale
Suspension Capability	5	Suspension helps improve the performance of the CSR on rough terrains and reduces the risk of tipping. However, as the CSR must be stiff enough to cross a 1 ft (0.30 m) discontinuity and will travel relatively slow, suspension will not be the a significant trade factor.
Cost	10	Ensuring the financial scope of the design lies within our given budget of \$5000 is critical, as there are many other subsystems that will require part of this funding. However, while it will not likely command over \$600 dollars, it is possible to purchase expensive COTS chassis. While significant, this is not the most significant trade criterion, at 10%.
Traction	10	The wheels of the CSR must have sufficient traction in order to travel through the rough terrain of the operating environment, such as slopes and underbrush. Although traction is important, the operating environment is mainly dry, thus traction is not the most significant design driver.
Size	15	The size of the CSR drives the design of the other subsystems, and because the CSR should ideally be smaller than the MR. However, as the lengths of the systems will be relatively similar, and the possibility of a trailer docking platform, it is not mission critical. This criteria earns a weight of 15%.
Control Complexity	15	The more motors the CSR contains, the more complex the CSR will be to control. By increasing the number of motors, thus control complexity, the risk of failure increases. Therefore, this criterion has 15% of the weight.
Manufacturing Complexity	20	In order to be a successful project, the manufacturing process has to be done thoroughly with limited time, money and resources available. Due to the mission critical aspect of this criteria, it was given a higher weight at 20%.
Mechanical Complexity	25	Mechanical complexity can be defined by several different aspects such as the drive train, suspension, moving wheel linkages, etc. Increasing the mechanical complexity of the system increases the difficulty of modelling and analyzing the system, and introduces increased risk of CSR failure. Due to the critical nature of this criteria, it is weighted the highest at 25%.

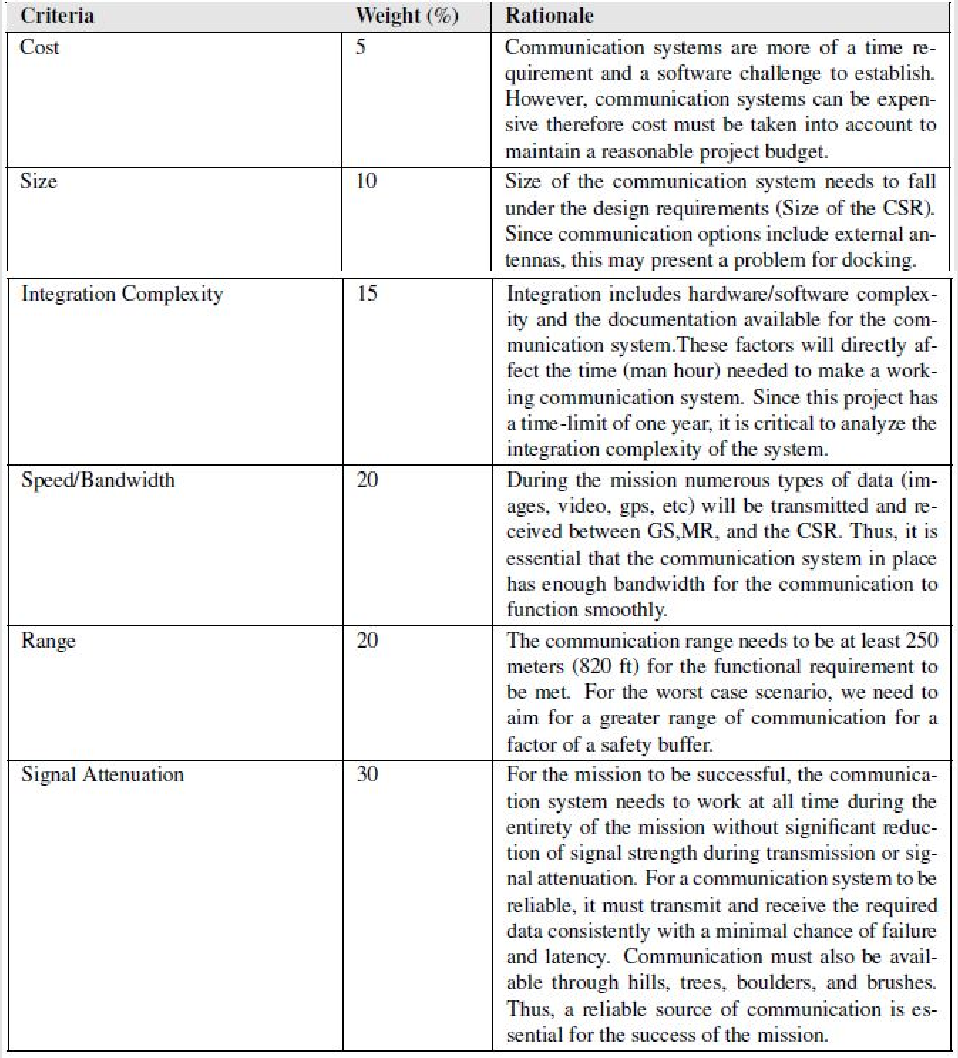
Table 34. Translational System Weighting Criteria and Rationale

Object Detection Weighing and Criteria



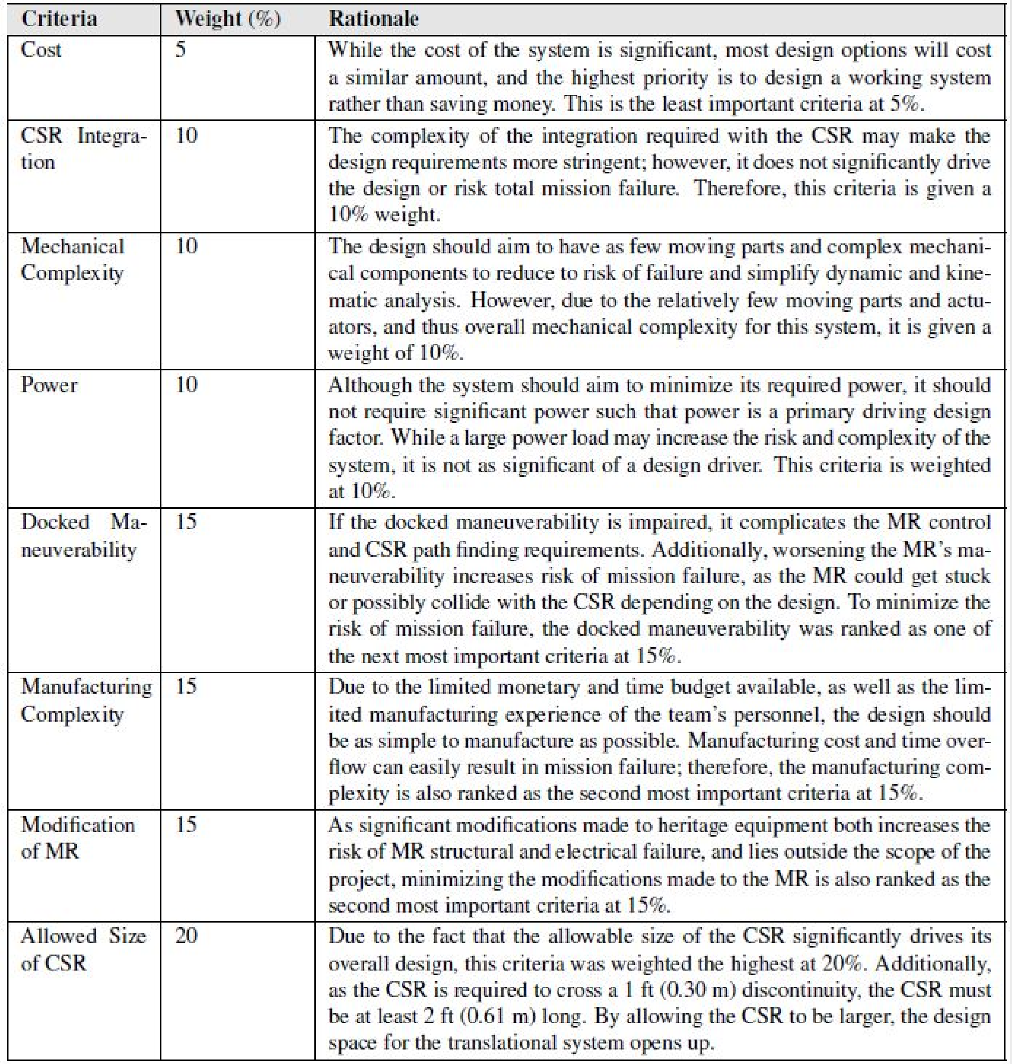
Criteria	Weight (%)	Rationale
Cost	5	Accurate sensor systems can be expensive, so the cost must be taken into account in order to maintain a reasonable project budget.
Range	10	The range of the sensor dictates its maximum capabilities. A sensor with a shorter range will not be able to detect distant obstacles.
Hardware Integration	15	Hardware integration can be difficult if the chosen system has outputs that can only be read by atypical processors. Additionally, if the device requires uniquely designed mechanical and electrical interfaces, this integration process can become time consuming.
Environmental Vulnerability	20	The rover will be in complicated terrain with variable conditions such as changing lighting and complicated surface materials and geometries, and potentially damaging collisions. If the sensors data is made erroneous due to environmental obstacles then the rover will be unable to accurately navigate and determine a viable path.
Computational Difficulty	25	Some methods may be extremely computationally intense and thus may interrupt other programs within the software controlling the rover. Additionally, complex on-board computations may take a long amount of time to perform and thus may impact efficiency of the rover. Furthermore, object detection software is very complex and difficult to write, so it will be optimal to have a variety of available softwares for the chosen system. The desired use of these softwares will be to measure distances to obstacles and distances between objects.
Relative Position Detection	25	A large part of the scout rovers mission is to present a path that is viable for the mother rover to travel. Due to the size of the Mother Rover a key aspect of the path will be the distance between obstacles along it. If the detection systems measurements cannot provide this distance or enough information to allow for an accurate calculation this distance then a viable path cannot effectively be determined.

Communication Weighing and Criteria



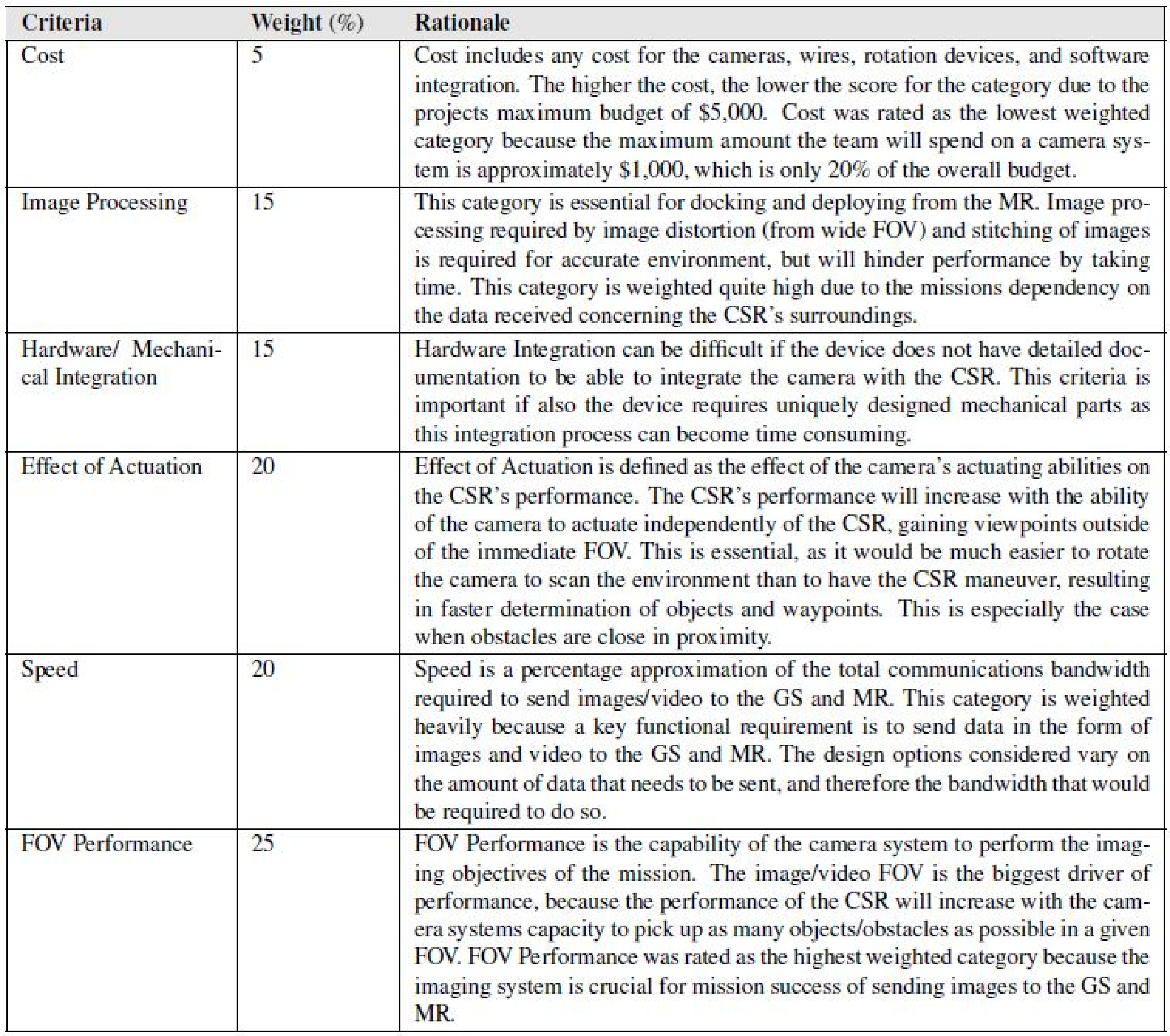
Criteria	Weight (%)	Rationale
Cost	5	Communication systems are more of a time requirement and a software challenge to establish. However, communication systems can be expensive therefore cost must be taken into account to maintain a reasonable project budget.
Size	10	Size of the communication system needs to fall under the design requirements (Size of the CSR). Since communication options include external antennas, this may present a problem for docking.
Integration Complexity	15	Integration includes hardware/software complexity and the documentation available for the communication system.These factors will directly affect the time (man hour) needed to make a working communication system. Since this project has a time-limit of one year, it is critical to analyze the integration complexity of the system.
Speed/Bandwidth	20	During the mission numerous types of data (images, video, gps, etc) will be transmitted and received between GS,MR, and the CSR. Thus, it is essential that the communication system in place has enough bandwidth for the communication to function smoothly.
Range	20	The communication range needs to be at least 250 meters (820 ft) for the functional requirement to be met. For the worst case scenario, we need to aim for a greater range of communication for a factor of a safety buffer.
Signal Attenuation	30	For the mission to be successful, the communication system needs to work at all time during the entirety of the mission without significant reduction of signal strength during transmission or signal attenuation. For a communication system to be reliable, it must transmit and receive the required data consistently with a minimal chance of failure and latency. Communication must also be available through hills, trees, boulders, and brushes. Thus, a reliable source of communication is essential for the success of the mission.

Docking/Deploying Weighing and Criteria



Criteria	Weight (%)	Rationale
Cost	5	While the cost of the system is significant, most design options will cost a similar amount, and the highest priority is to design a working system rather than saving money. This is the least important criteria at 5%.
CSR Integration	10	The complexity of the integration required with the CSR may make the design requirements more stringent; however, it does not significantly drive the design or risk total mission failure. Therefore, this criteria is given a 10% weight.
Mechanical Complexity	10	The design should aim to have as few moving parts and complex mechanical components to reduce to risk of failure and simplify dynamic and kinematic analysis. However, due to the relatively few moving parts and actuators, and thus overall mechanical complexity for this system, it is given a weight of 10%.
Power	10	Although the system should aim to minimize its required power, it should not require significant power such that power is a primary driving design factor. While a large power load may increase the risk and complexity of the system, it is not as significant of a design driver. This criteria is weighted at 10%.
Docked Maneuverability	15	If the docked maneuverability is impaired, it complicates the MR control and CSR path finding requirements. Additionally, worsening the MR's maneuverability increases risk of mission failure, as the MR could get stuck or possibly collide with the CSR depending on the design. To minimize the risk of mission failure, the docked maneuverability was ranked as one of the next most important criteria at 15%.
Manufacturing Complexity	15	Due to the limited monetary and time budget available, as well as the limited manufacturing experience of the team's personnel, the design should be as simple to manufacture as possible. Manufacturing cost and time overflow can easily result in mission failure; therefore, the manufacturing complexity is also ranked as the second most important criteria at 15%.
Modification of MR	15	As significant modifications made to heritage equipment both increases the risk of MR structural and electrical failure, and lies outside the scope of the project, minimizing the modifications made to the MR is also ranked as the second most important criteria at 15%.
Allowed Size of CSR	20	Due to the fact that the allowable size of the CSR significantly drives its overall design, this criteria was weighted the highest at 20%. Additionally, as the CSR is required to cross a 1 ft (0.30 m) discontinuity, the CSR must be at least 2 ft (0.61 m) long. By allowing the CSR to be larger, the design space for the translational system opens up.

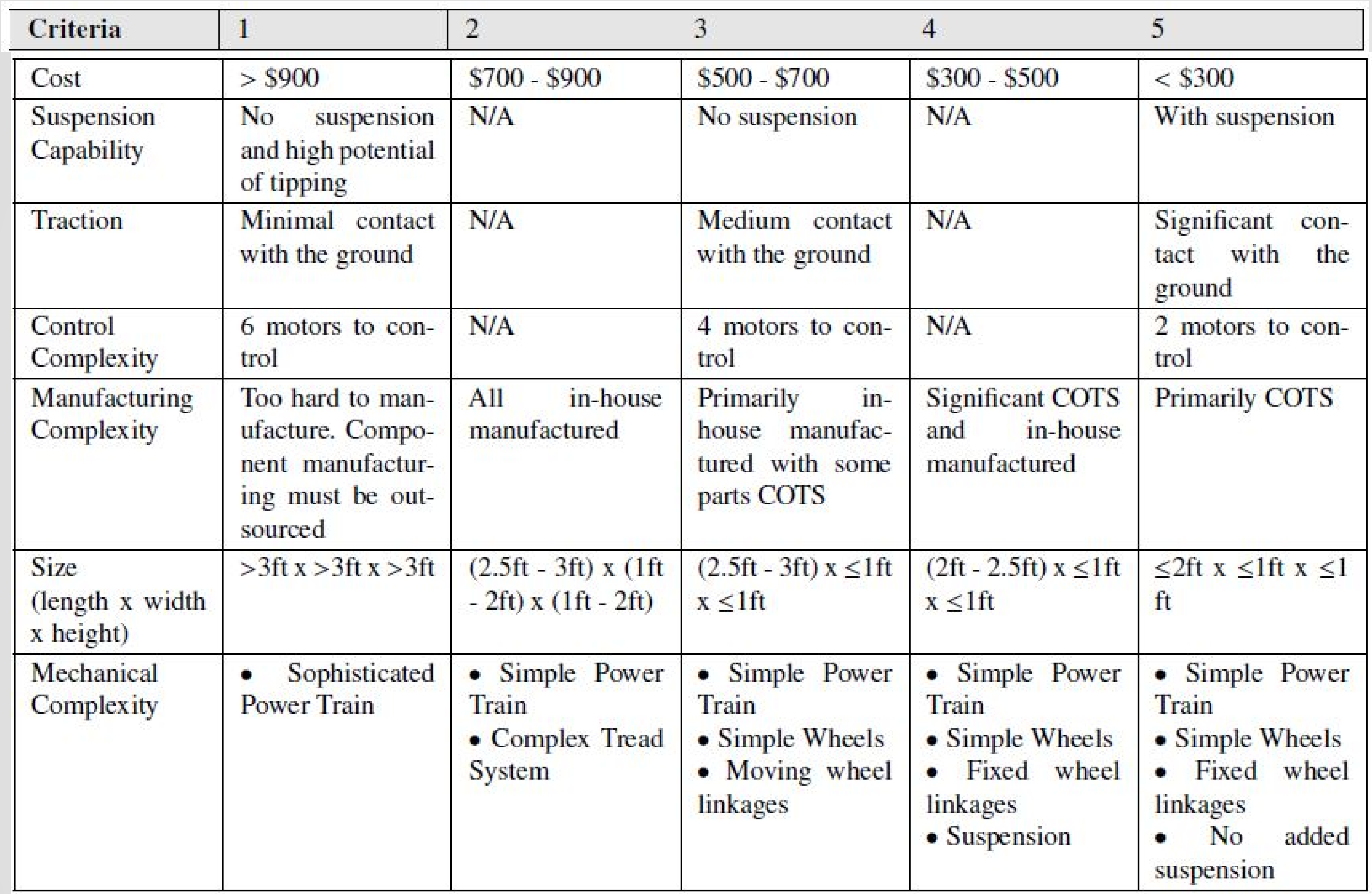
Imaging System Weighing and Criteria



Criteria	Weight (%)	Rationale
Cost	5	Cost includes any cost for the cameras, wires, rotation devices, and software integration. The higher the cost, the lower the score for the category due to the projects maximum budget of $5,000. Cost was rated as the lowest weighted category because the maximum amount the team will spend on a camera system is approximately $1,000, which is only 20% of the overall budget.
Image Processing	15	This category is essential for docking and deploying from the MR. Image processing required by image distortion (from wide FOV) and stitching of images is required for accurate environment, but will hinder performance by taking time. This category is weighted quite high due to the missions dependency on the data received concerning the CSR's surroundings.
Hardware/ Mechanical Integration	15	Hardware Integration can be difficult if the device does not have detailed documentation to be able to integrate the camera with the CSR. This criteria is important if also the device requires uniquely designed mechanical parts as this integration process can become time consuming.
Effect of Actuation	20	Effect of Actuation is defined as the effect of the camera's actuating abilities on the CSR's performance. The CSR's performance will increase with the ability of the camera to actuate independently of the CSR, gaining viewpoints outside of the immediate FOV. This is essential, as it would be much easier to rotate the camera to scan the environment than to have the CSR maneuver, resulting in faster determination of objects and waypoints. This is especially the case when obstacles are close in proximity.
Speed	20	Speed is a percentage approximation of the total communications bandwidth required to send images/video to the GS and MR. This category is weighted heavily because a key functional requirement is to send data in the form of images and video to the GS and MR. The design options considered vary on the amount of data that needs to be sent, and therefore the bandwidth that would be required to do so.
FOV Performance	25	FOV Performance is the capability of the camera system to perform the imaging objectives of the mission. The image/video FOV is the biggest driver of performance, because the performance of the CSR will increase with the camera systems capacity to pick up as many objects/obstacles as possible in a given FOV. FOV Performance was rated as the highest weighted category because the imaging system is crucial for mission success of sending images to the GS and MR.

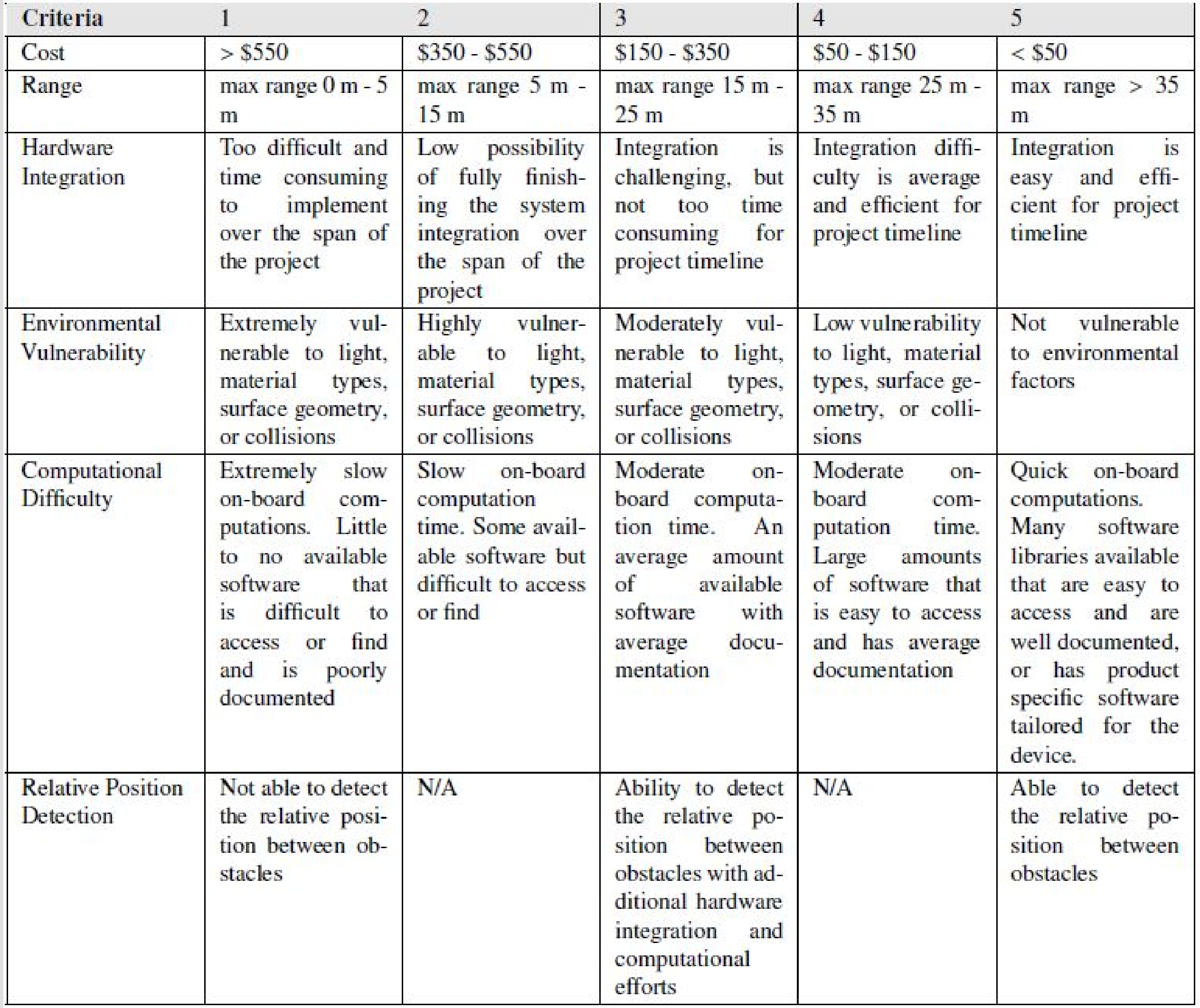
Scale Levels for Trade Matrices

Translational System Scale Leveling



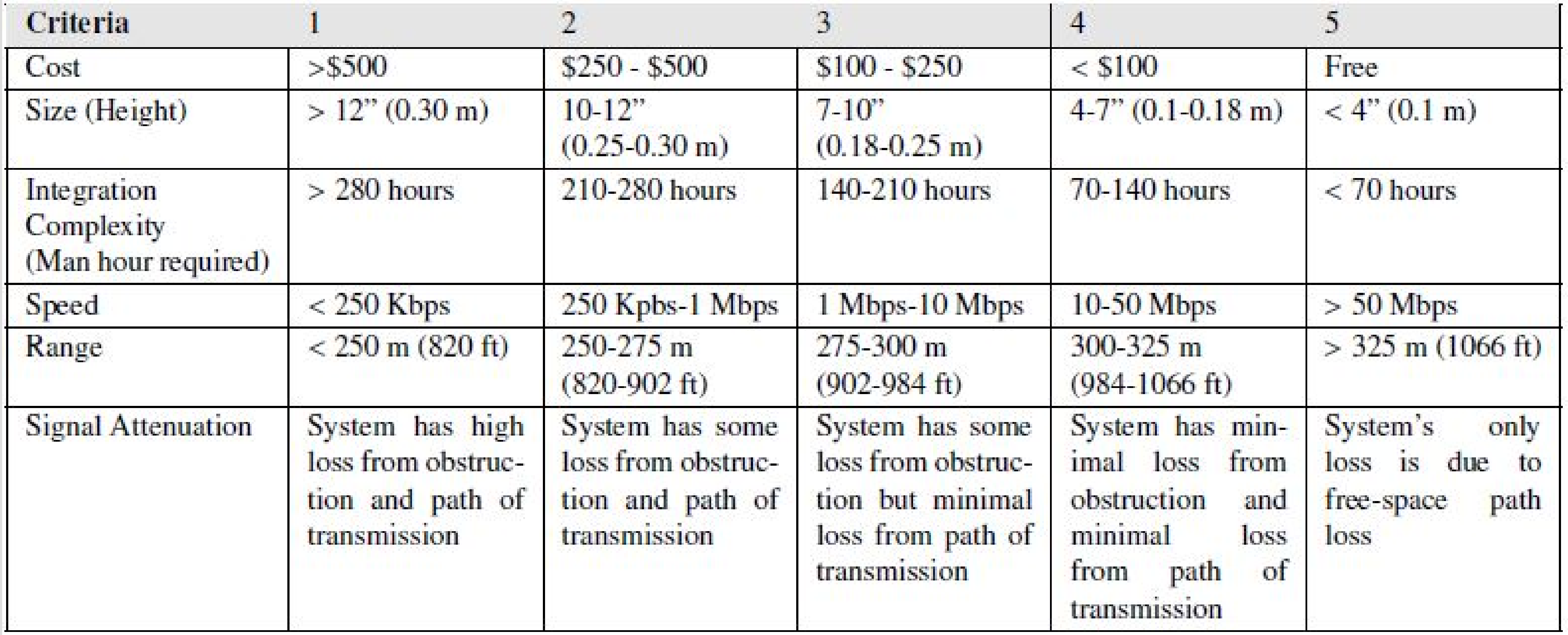
Criteria	1	2	3	4	5
Cost	> $900	$700 - $900	$500 - $700	$300 - $500	< $300
Suspension Capability	No suspension and high potential of tipping	N/A	No suspension	N/A	With suspension
Traction	Minimal contact with the ground	N/A	Medium contact with the ground	N/A	Significant contact with the ground
Control Complexity	6 motors to control	N/A	4 motors to control	N/A	2 motors to control
Manufacturing Complexity	Too hard to manufacture. Component manufacturing must be outsourced	All in-house manufactured	Primarily in-house manufactured with some parts COTS	Significant COTS and in-house manufactured	Primarily COTS
Size (length x width x height)	>3ft x >3ft x >3ft	(2.5ft - 3ft) x (1ft - 2ft) x (1ft - 2ft)	(2.5ft - 3ft) x ≤1ft x ≤1ft	(2ft - 2.5ft) x ≤1ft x ≤1ft	≤2ft x ≤1ft x ≤1 ft
Mechanical Complexity	• Sophisticated Power Train	• Simple Power Train • Complex Tread System	• Simple Power Train • Simple Wheels • Moving wheel linkages	• Simple Power Train • Simple Wheels • Fixed wheel linkages • Suspension	• Simple Power Train • Simple Wheels • Fixed wheel linkages • No added suspension

Object Detection Scale Leveling



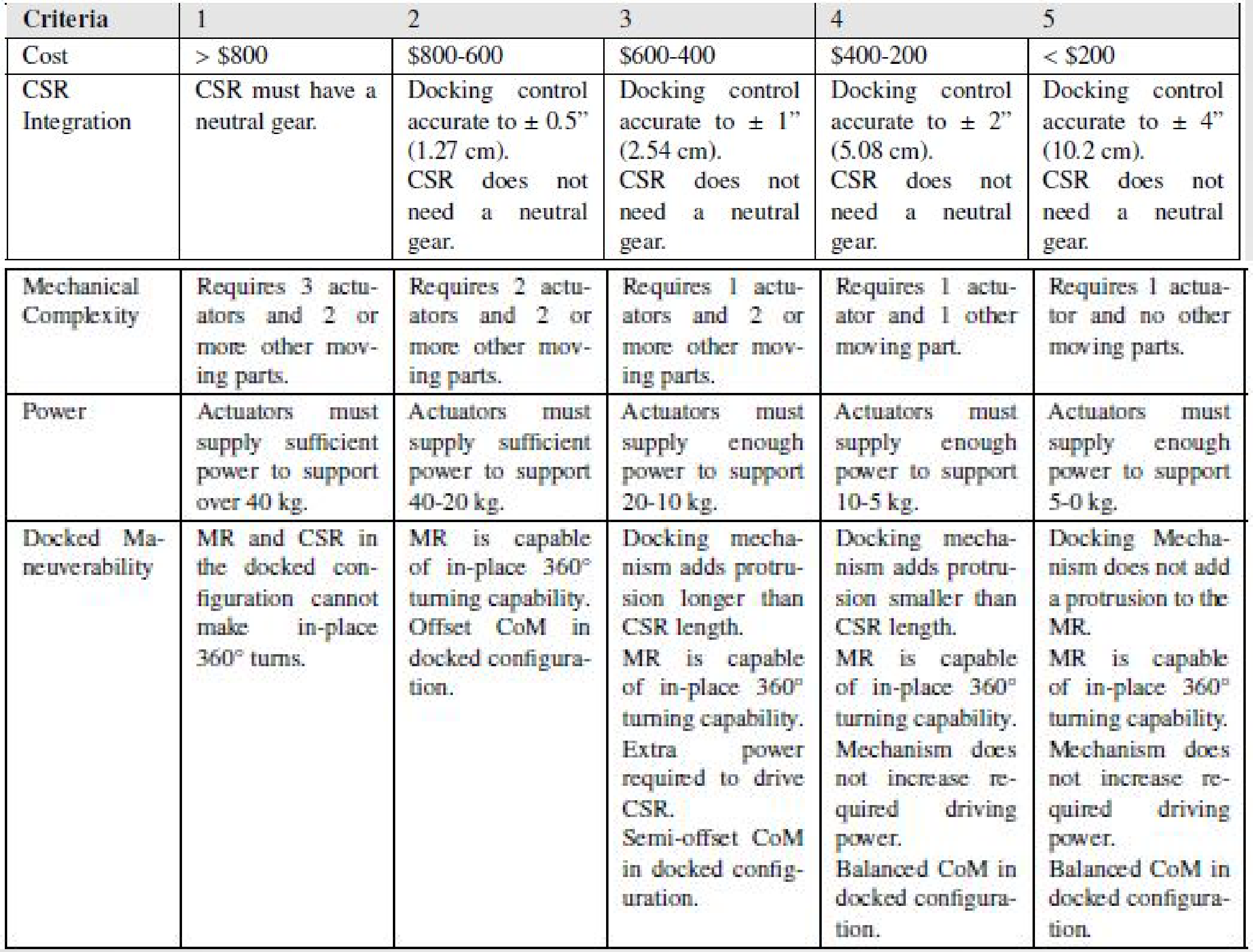
Criteria	1	2	3	4	5
Cost	> $550	$350 - $550	$150 - $350	$50 - $150	< $50
Range	max range 0 m - 5 m	max range 5 m - 15 m	max range 15 m - 25 m	max range 25 m - 35 m	max range > 35 m
Hardware Integration	Too difficult and time consuming to implement over the span of the project	Low possibility of fully finishing the system integration over the span of the project	Integration is challenging, but not too time consuming for project timeline	Integration difficulty is average and efficient for project timeline	Integration is easy and efficient for project timeline
Environmental Vulnerability	Extremely vulnerable to light, material types, surface geometry, or collisions	Highly vulnerable to light, material types, surface geometry, or collisions	Moderately vulnerable to light, material types, surface geometry, or collisions	Low vulnerability to light, material types, surface geometry, or collisions	Not vulnerable to environmental factors
Computational Difficulty	Extremely slow on-board computations. Little to no available software that is difficult to access or find and is poorly documented	Slow on-board computation time. Some available software but difficult to access or find	Moderate on-board computation time. An average amount of available software with average documentation	Moderate on-board computation time. Large amounts of software that is easy to access and has average documentation	Quick on-board computations. Many software libraries available that are easy to access and are well documented, or has product specific software tailored for the device.
Relative Position Detection	Not able to detect the relative position between obstacles	N/A	Ability to detect the relative position between obstacles with additional hardware integration and computational efforts	N/A	Able to detect the relative position between obstacles

Communication Scale Leveling



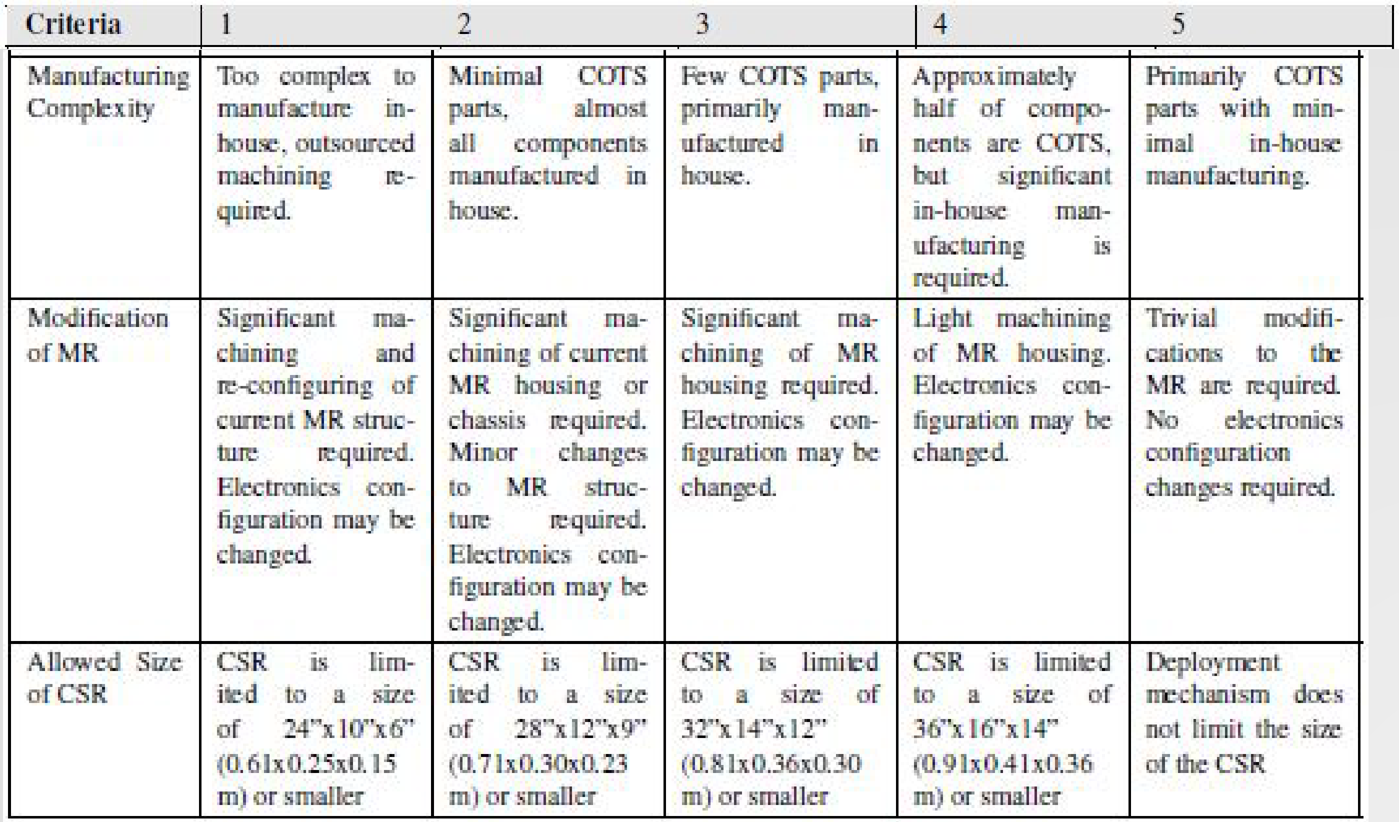
Criteria	1	2	3	4	5
Cost	>$500	$250 - $500	$100 - $250	< $100	Free
Size (Height)	> 12" (0.30 m)	10-12" (0.25-0.30 m)	7-10" (0.18-0.25 m)	4-7" (0.1-0.18 m)	< 4" (0.1 m)
Integration Complexity (Man hour required)	> 280 hours	210-280 hours	140-210 hours	70-140 hours	< 70 hours
Speed	< 250 Kbps	250 Kpbs-1 Mbps	1 Mbps-10 Mbps	10-50 Mbps	> 50 Mbps
Range	< 250 m (820 ft)	250-275 m (820-902 ft)	275-300 m (902-984 ft)	300-325 m (984-1066 ft)	> 325 m (1066 ft)
Signal Attenuation	System has high loss from obstruction and path of transmission	System has some loss from obstruction and path of transmission	System has some loss from obstruction but minimal loss from path of transmission	System has minimal loss from obstruction and minimal loss from path of transmission	System's only loss is due to free-space path loss

Docking/Deploying Scale Leveling



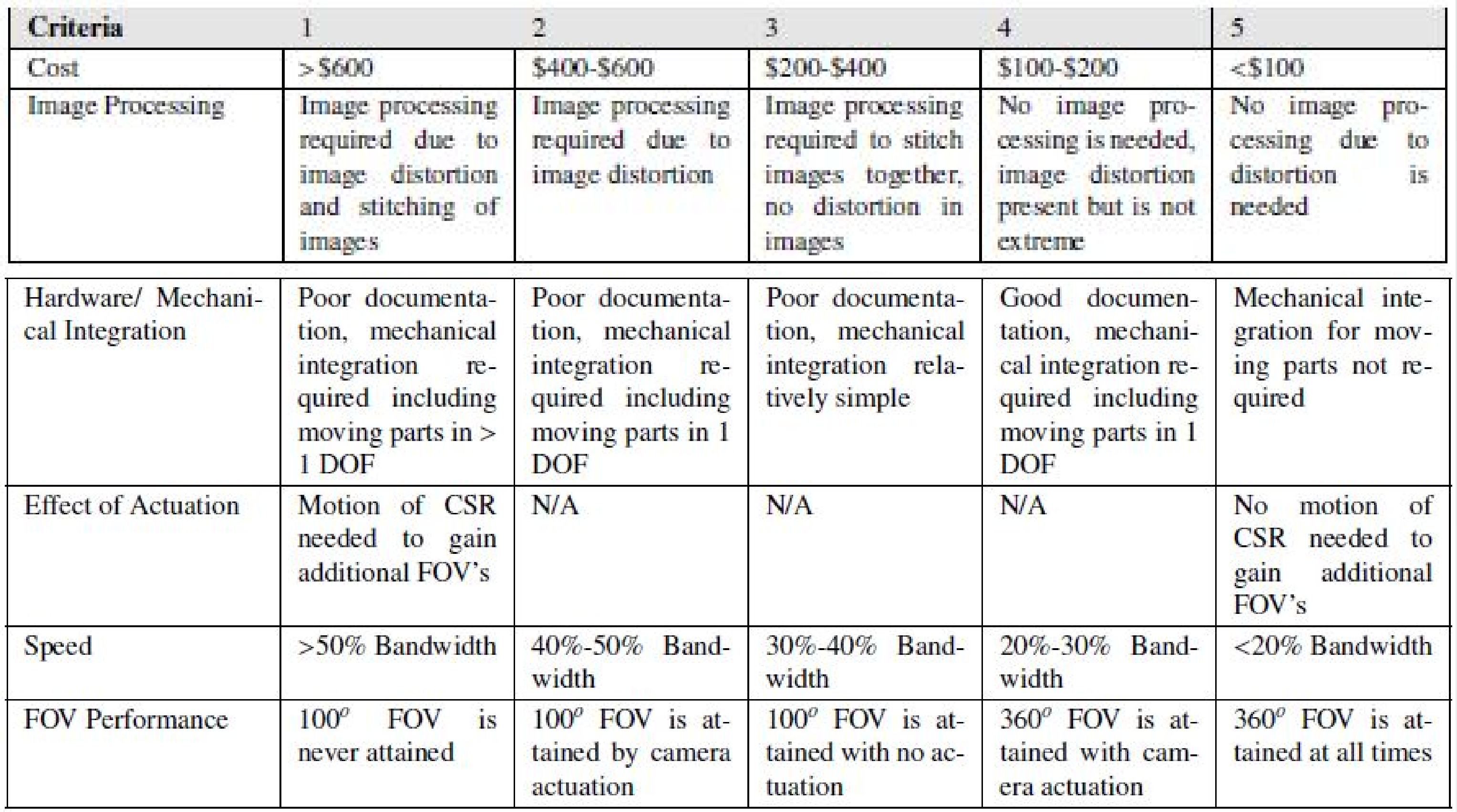
Criteria	1	2	3	4	5
Cost	> $800	$800-600	$600-400	$400-200	< $200
CSR Integration	CSR must have a neutral gear.	Docking control accurate to ± 0.5" (1.27 cm). CSR does not need a neutral gear.	Docking control accurate to ± 1" (2.54 cm). CSR does not need a neutral gear.	Docking control accurate to ± 2" (5.08 cm). CSR does not need a neutral gear.	Docking control accurate to ± 4" (10.2 cm). CSR does not need a neutral gear.
Mechanical Complexity	Requires 3 actuators and 2 or more other moving parts.	Requires 2 actuators and 2 or more other moving parts.	Requires 1 actuators and 2 or more other moving parts.	Requires 1 actuator and 1 other moving part.	Requires 1 actuator and no other moving parts.
Power	Actuators must supply sufficient power to support over 40 kg.	Actuators must supply sufficient power to support 40-20 kg.	Actuators must supply enough power to support 20-10 kg.	Actuators must supply enough power to support 10-5 kg.	Actuators must supply enough power to support 5-0 kg.
Docked Maneuverability	MR and CSR in the docked configuration cannot make in-place 360° turns.	MR is capable of in-place 360° turning capability. Offset CoM in docked configuration.	Docking mechanism adds protrusion longer than CSR length. MR is capable of in-place 360° turning capability. Extra power required to drive CSR. Semi-offset CoM in docked configuration.	Docking mechanism adds protrusion smaller than CSR length. MR is capable of in-place 360° turning capability. Mechanism does not increase required driving power. Balanced CoM in docked configuration.	Docking Mechanism does not add a protrusion to the MR. MR is capable of in-place 360° turning capability. Mechanism does not increase required driving power. Balanced CoM in docked configuration.

Docking/Deploying Scale Leveling



Criteria	1	2	3	4	5
Manufacturing Complexity	Too complex to manufacture in-house, outsourced machining required.	Minimal COTS parts, almost all components manufactured in house.	Few COTS parts, primarily manufactured in house.	Approximately half of components are COTS, but significant in-house manufacturing is required.	Primarily COTS parts with minimal in-house manufacturing.
Modification of MR	Significant machining and re-configuring of current MR structure required. Electronics configuration may be changed.	Significant machining of current MR housing or chassis required. Minor changes to MR structure required. Electronics configuration may be changed.	Significant machining of MR housing required. Electronics configuration may be changed.	Light machining of MR housing. Electronics configuration may be changed.	Trivial modifications to the MR are required. No electronics configuration changes required.
Allowed Size of CSR	CSR is limited to a size of 24”x10”x6” (0.61x0.25x0.15 m) or smaller	CSR is limited to a size of 28”x12”x9” (0.71x0.30x0.23 m) or smaller	CSR is limited to a size of 32”x14”x12” (0.81x0.36x0.30 m) or smaller	CSR is limited to a size of 36”x16”x14” (0.91x0.41x0.36 m) or smaller	Deployment mechanism does not limit the size of the CSR

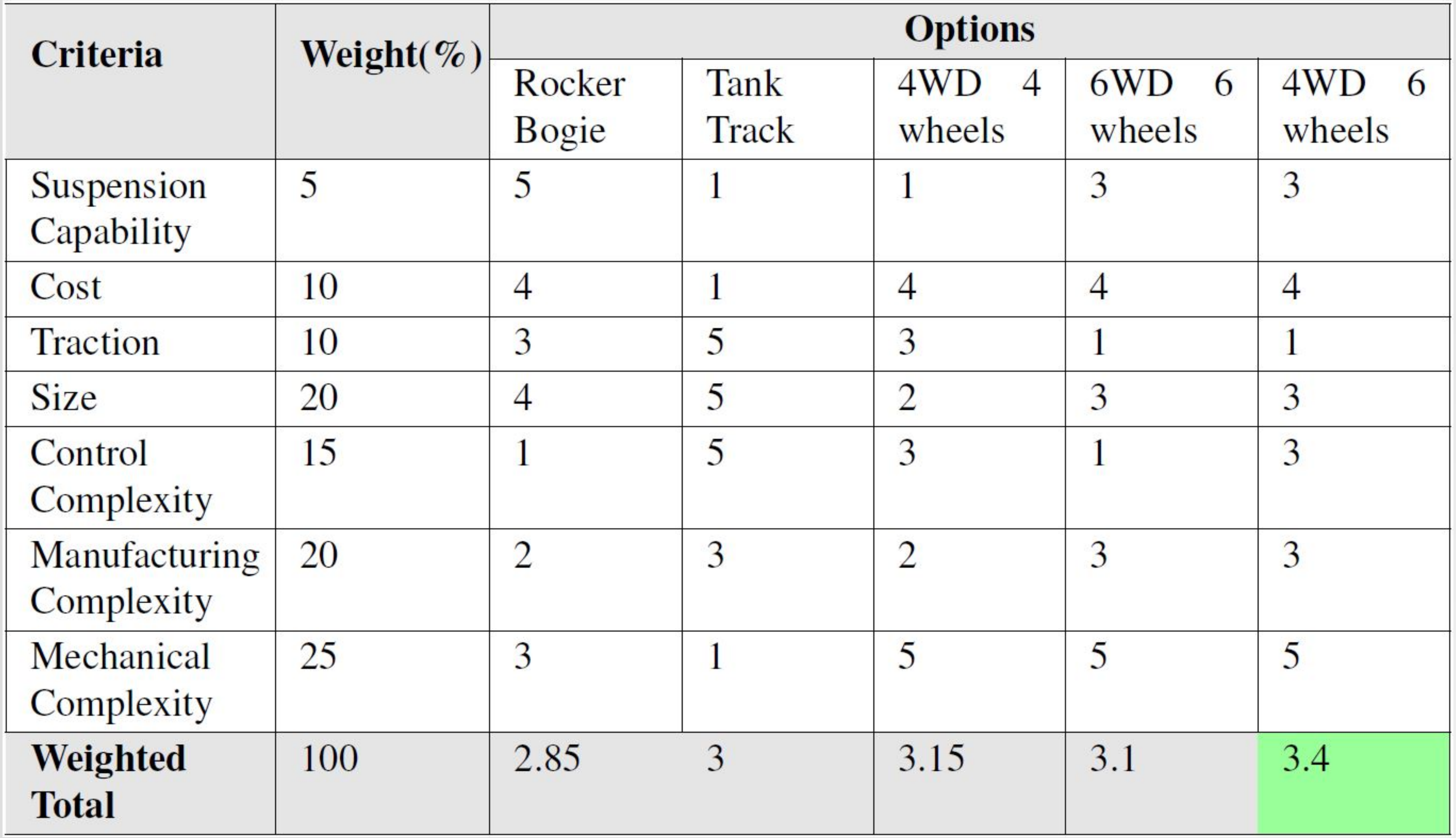
Imaging Scale Leveling



Criteria	1	2	3	4	5
Cost	>$600	$400-$600	$200-$400	$100-$200	<$100
Image Processing	Image processing required due to image distortion and stitching of images	Image processing required due to image distortion	Image processing required to stitch images together, no distortion in images	No image processing is needed, image distortion present but is not extreme	No image processing due to distortion is needed
Hardware/ Mechanical Integration	Poor documentation, mechanical integration required including moving parts in > 1 DOF	Poor documentation, mechanical integration required including moving parts in 1 DOF	Poor documentation, mechanical integration relatively simple	Good documentation, mechanical integration required including moving parts in 1 DOF	Mechanical integration for moving parts not required
Effect of Actuation	Motion of CSR needed to gain additional FOV's	N/A	N/A	N/A	No motion of CSR needed to gain additional FOV's
Speed	>50% Bandwidth	40%-50% Bandwidth	30%-40% Bandwidth	20%-30% Bandwidth	<20% Bandwidth
FOV Performance	100^{o} FOV is never attained	100^{o} FOV is attained by camera actuation	100^{o} FOV is attained with no actuation	360^{o} FOV is attained with camera actuation	360^{o} FOV is attained at all times

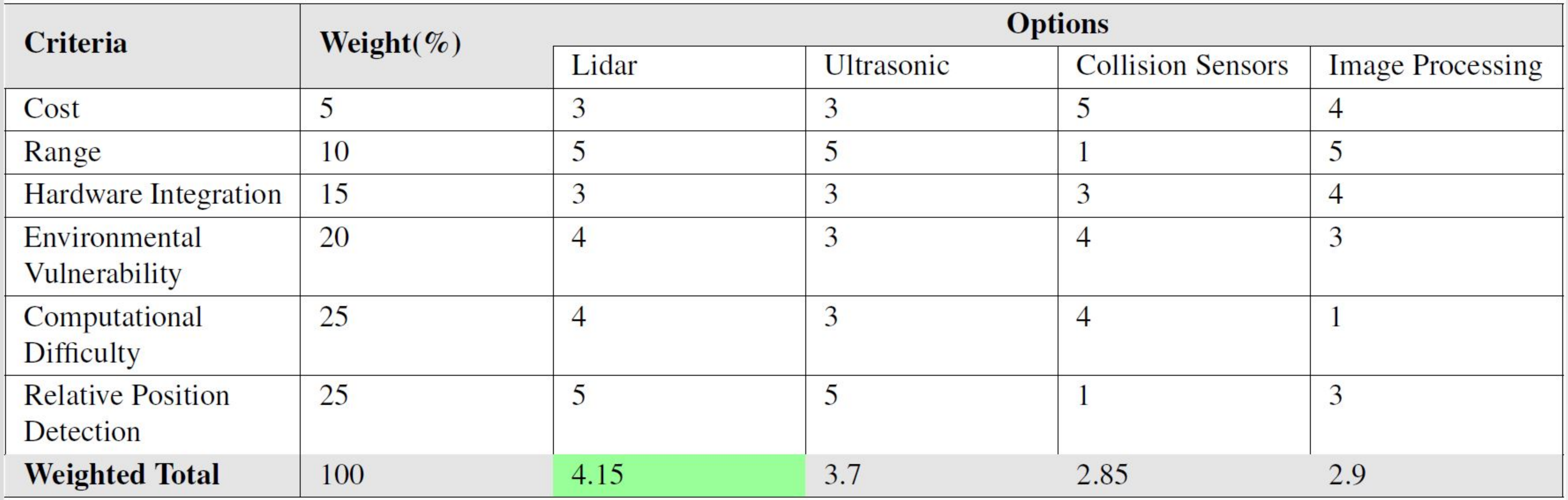
Trade Matrices

Translational System Trade Matrix



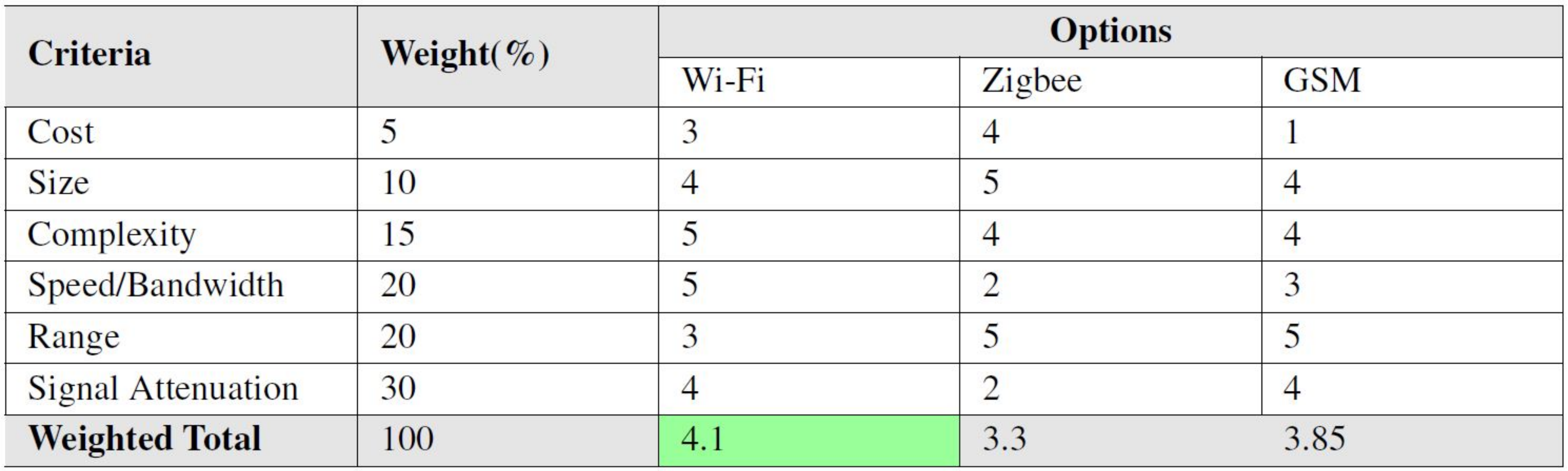
Criteria	**Weight(%)**	**Options**				
		Rocker Bogie	Tank Track	4WD 4 wheels	6WD 6 wheels	4WD 6 wheels
Suspension Capability	5	5	1	1	3	3
Cost	10	4	1	4	4	4
Traction	10	3	5	3	1	1
Size	20	4	5	2	3	3
Control Complexity	15	1	5	3	1	3
Manufacturing Complexity	20	2	3	2	3	3
Mechanical Complexity	25	3	1	5	5	5
Weighted Total	100	2.85	3	3.15	3.1	3.4

Object Detection Trade Matrix



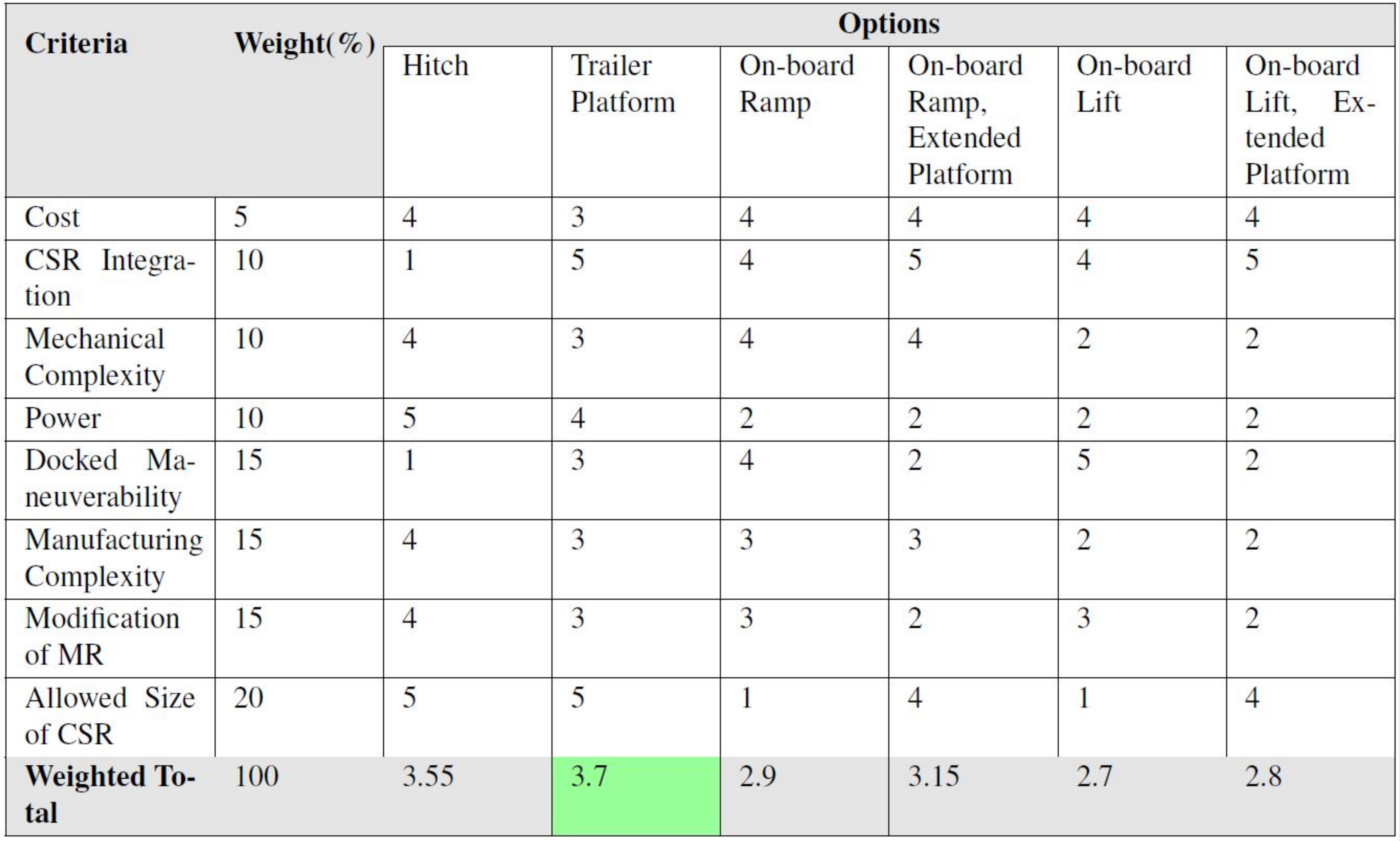
Criteria	**Weight(%)**	**Options**			
		Lidar	Ultrasonic	Collision Sensors	Image Processing
Cost	5	3	3	5	4
Range	10	5	5	1	5
Hardware Integration	15	3	3	3	4
Environmental Vulnerability	20	4	3	4	3
Computational Difficulty	25	4	3	4	1
Relative Position Detection	25	5	5	1	3
Weighted Total	100	4.15	3.7	2.85	2.9

Communication System Trade Matrix



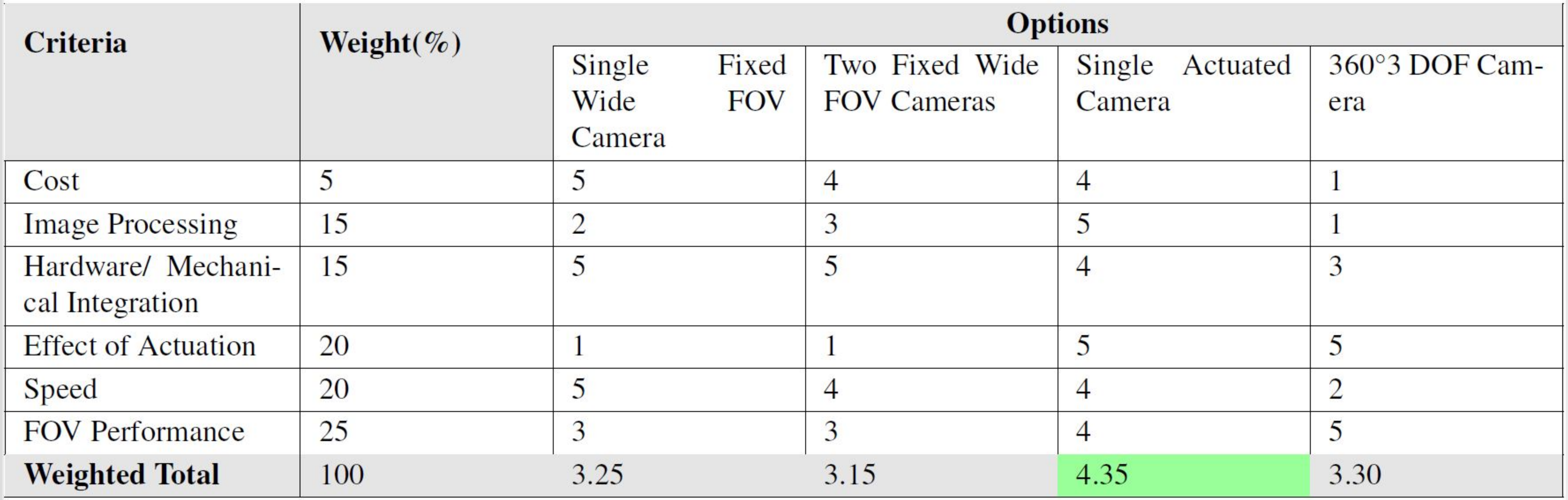
Criteria	**Weight(%)**	**Options**		
		Wi-Fi	Zigbee	GSM
Cost	5	3	4	1
Size	10	4	5	4
Complexity	15	5	4	4
Speed/Bandwidth	20	5	2	3
Range	20	3	5	5
Signal Attenuation	30	4	2	4
Weighted Total	100	🟩 4.1	3.3	3.85

Docking/Deployment Trade Matrix



Criteria	**Weight(%)**	**Options**					
		Hitch	Trailer Platform	On-board Ramp	On-board Ramp, Extended Platform	On-board Lift	On-board Lift, Extended Platform
Cost	5	4	3	4	4	4	4
CSR Integration	10	1	5	4	5	4	5
Mechanical Complexity	10	4	3	4	4	2	2
Power	10	5	4	2	2	2	2
Docked Maneuverability	15	1	3	4	2	5	2
Manufacturing Complexity	15	4	3	3	3	2	2
Modification of MR	15	4	3	3	2	3	2
Allowed Size of CSR	20	5	5	1	4	1	4
Weighted Total	100	3.55	3.7	2.9	3.15	2.7	2.8

Imaging System Trade Matrix



Criteria	**Weight(%)**	**Options**			
		Single Fixed Wide FOV Camera	Two Fixed Wide FOV Cameras	Single Actuated Camera	360°3 DOF Camera
Cost	5	5	4	4	1
Image Processing	15	2	3	5	1
Hardware/ Mechanical Integration	15	5	5	4	3
Effect of Actuation	20	1	1	5	5
Speed	20	5	4	4	2
FOV Performance	25	3	3	4	5
Weighted Total	100	3.25	3.15	4.35	3.30