HERMES

<u>H</u>azard <u>E</u>xamination and <u>R</u>econnaissance <u>M</u>essenger for <u>E</u>xtended <u>S</u>urveillance

CRITICAL DESIGN REVIEW

DECEMBER 3RD 2018

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Project Purpose and Objectives

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 inherited semi-autonomous drone from INFERNO

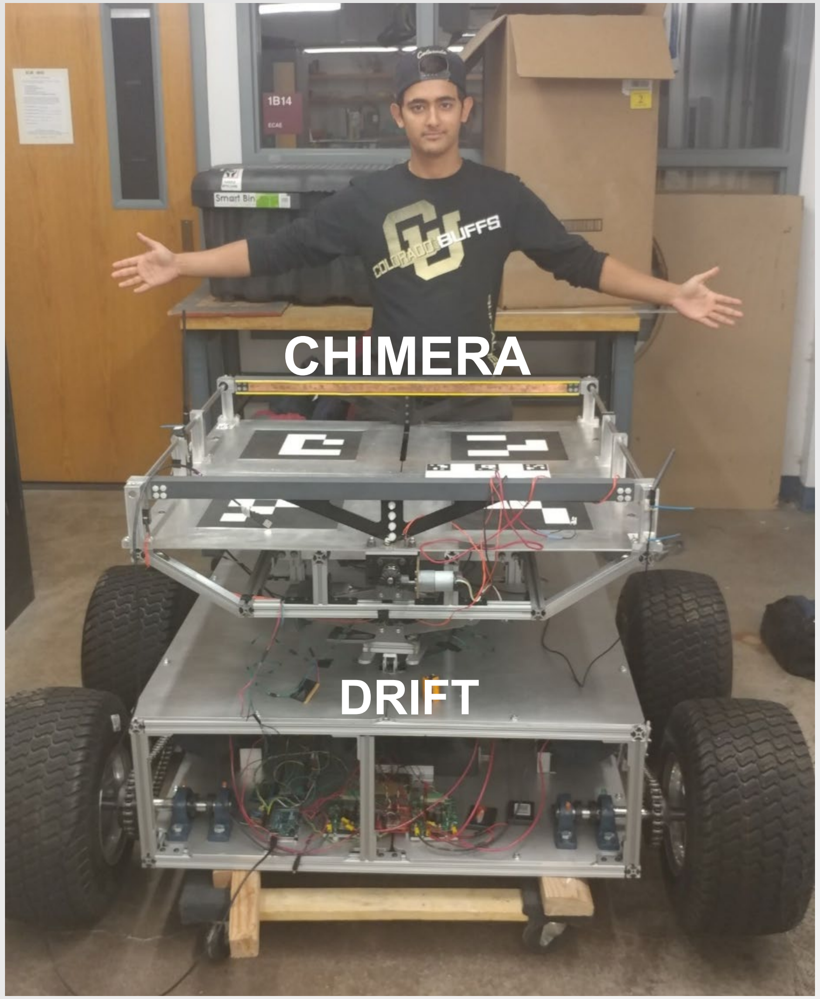
3. **DRIFT (2017-2018)**

   - Developed a **mother rover** to secure, carry, and level the semi-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.



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.

Note: Blue used for emphasis

Definitions

Pathpoint – A point after a mobility command is received and executed by the CSR.

- This point is recorded onboard the CSR and sent to the GS as a GPS coordinate.
- An operator from the ground station initially issues the command.
- *Previously referred to as 'waypoint', and changed for clarity*

Obstacle – Roots, trees, rocks, shrubs, and inclined slopes with type A terrain (only leaves are present on type A terrain)

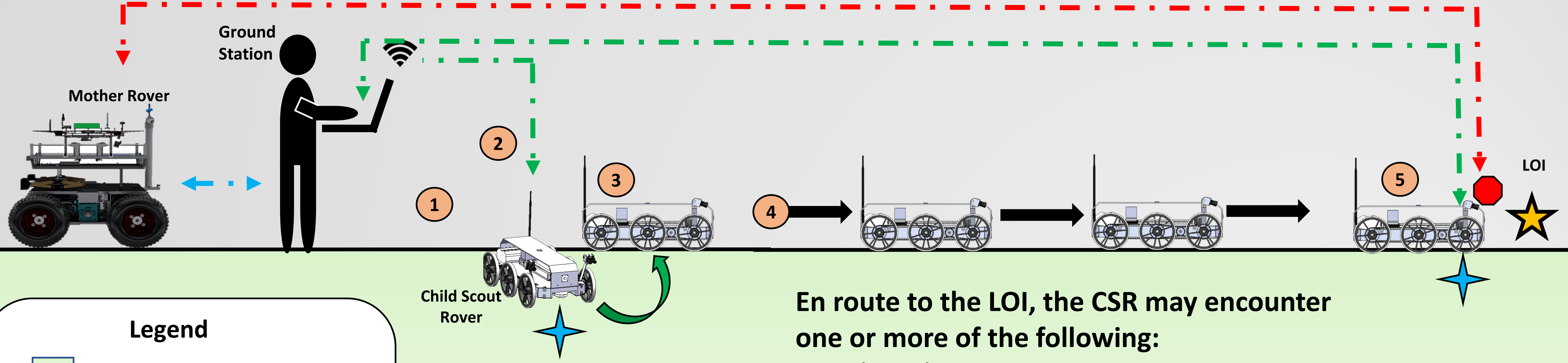
- **Traversable Obstacles**
  - Any root or rock less than 2.4 inches (6 cm) - *(6 cm is based on average root diameter from 'Tree Root Systems' from the Arboricultural Advisory and Information Service)*
- **Non-Traversable Obstacles**
  - All trees
  - All shrubs
  - All roots and rocks greater than 2.4 inches

Discontinuity – A 9 inch wide gap with a depth larger than 2.4 inches. *The width was previously 12 inches, however a model proved that the MR could only cross a 9 inch discontinuity (.229 m).*

Note: Blue used for emphasis

CONOPS: Arriving to Location of Interest

1. Deploy from Ground Station and drop a pathpoint
2. Receive Location of Interest (LOI) from GS
3. User commands CSR to point towards LOI
4. User commands CSR to travel towards the LOI in semi autonomous mode. The CSR will travel until it reaches the LOI.
5. Upon arrival it will stop, and notify the GS or MR and drop a pathpoint



En route to the LOI, the CSR may encounter one or more of the following:

1. Obstacles
2. Discontinuities
3. Slopes
4. Loss of communications

Legend

- Mission Terrain
- Pathpoint
- Stop and request user intervention
- Comm between GS and MR
- Comm between GS and CSR
- Comm between CSR and MR
- Manually controlled path
- Autonomously controlled path

Requirements

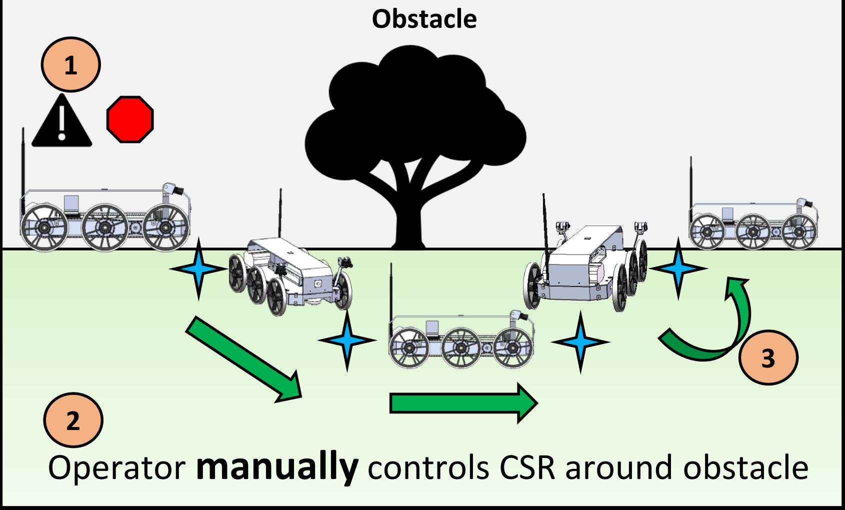
Functions

- **Up to 250 m radius (820 ft)**

CONOPS: Other Terrain

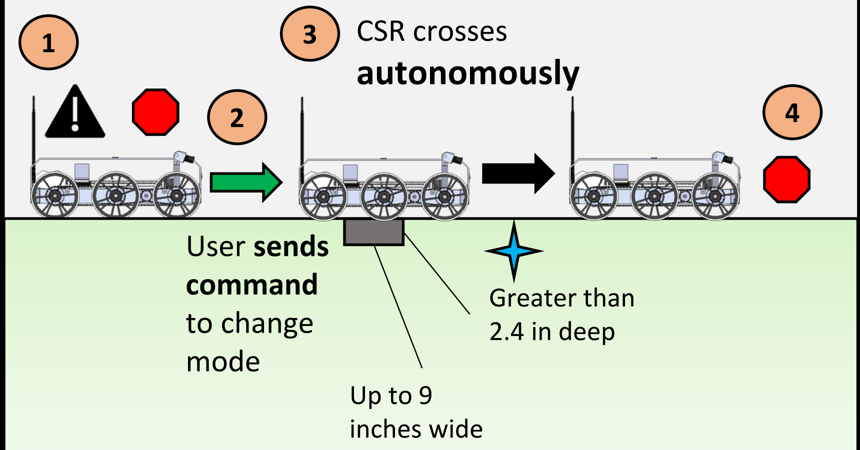
Non-Traversable Obstacles

1. If the CSR detects an obstacle**, the CSR will stop**
2. The user will take control, and **manually control the CSR around the obstacle**
   - Every time the CSR turns, a pathpoint is recorded
3. After traveling around the obstacle, **the user commands the CSR to point towards the LOI, and command it into semi- autonomous mode**



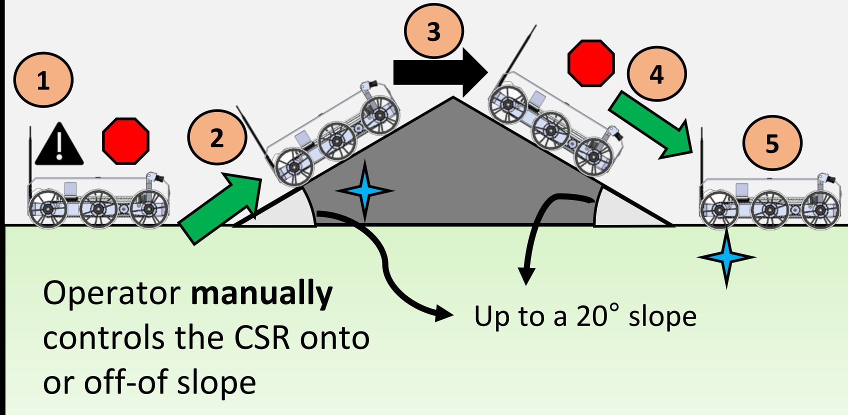
Discontinuities

1. If the CSR detects a discontinuity**, the CSR will stop**
2. The user will then **send a command** to the CSR to enter the **discontinuity traversal mode**
3. Then the CSR **autonomously** crosses the discontinuity
   - A pathpoint is recorded since a mobility command was received and executed
4. After crossing the discontinuity, the CSR **stops and requests user intervention**



Slopes

1. If the CSR detects a slope**, the CSR will stop**
2. The **user will control the CSR to get onto the slope** and command the CSR into semi autonomous mode
3. The CSR will **travel** on the slope **in semi autonomous mode**
4. Once the CSR **detects flat ground, it will stop**
5. **The user** will **control** the CSR to **return to flat ground**



= Point where sensor detects obstacle or discontinuity
= **Pathpoint**
= Stop and request user intervention
= **Manual Control**
= **Autonomous Control**

Functional Requirements

Requirement ID	Description
CSR.1	The CSR shall receive commands from the MR or the GS
CSR.2	The CSR shall send video, GPS coordinates, and sensor data to the GS or the MR through mission defined terrain
CSR.3	The CSR shall drive to a location of interest through mission defined terrain
CSR.4	The CSR shall travel back to the last reported pathpoint upon loss of communications with the MR and the GS
CSR.5	The CSR shall take video in position hold

Note: Docking/Deploying Requirement was descoped after discussions with our customer

Primary Success Levels

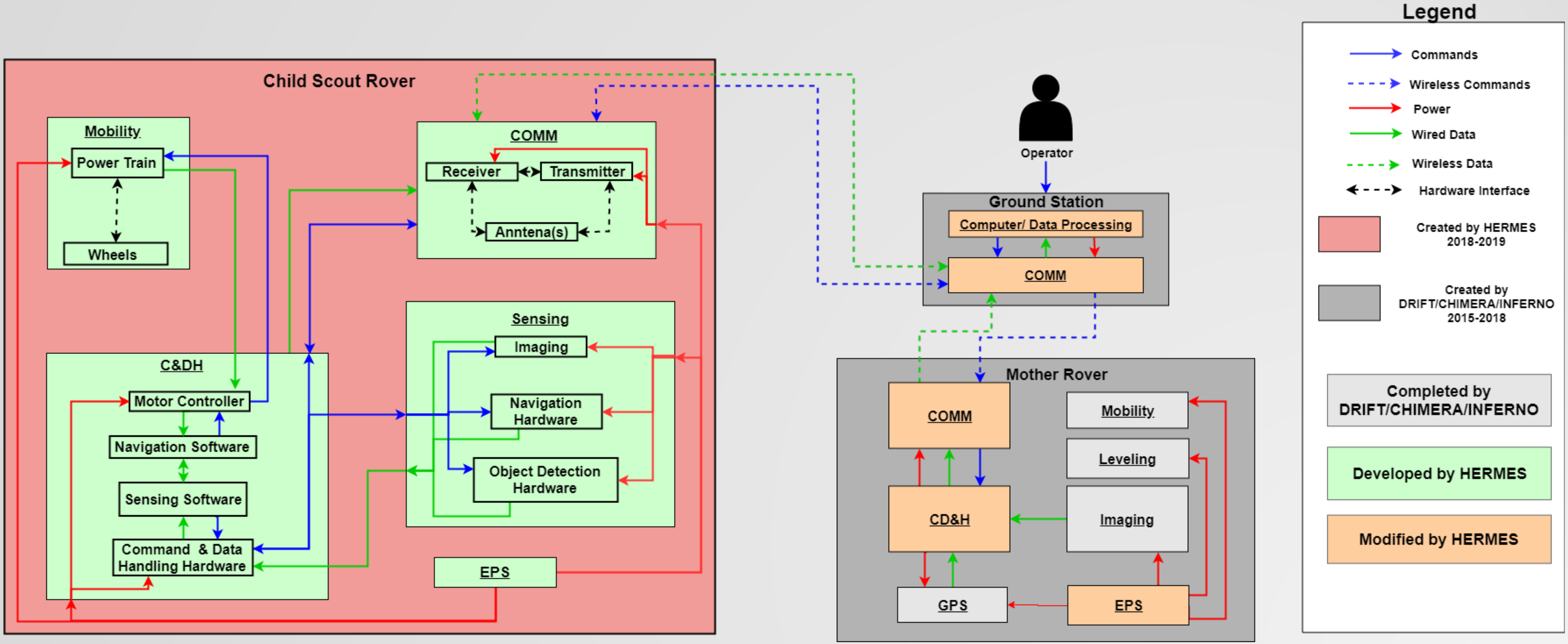
Criteria	Level 1	Level 2	Level 3
Video/ Image	• The imaging system on the CSR shall capture a FOV greater than 100° • The imaging system shall send time-stamped images to the MR/GS	• The CSR shall send videos to the MR/GS • The MR shall toggle the video capture from the CSR on or off	• The CSR shall send continuous video feed to the MR and GS
Control	• The CSR shall navigate by receiving control commands from the GS • The CSR shall perform a 360° turn • The CSR shall drive 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 **autonomously** return to the last known GPS location if connection to the GS and MR is lost.

Note: Blue used for emphasis

Note: Only main success levels are shown, the rest are in backup slides

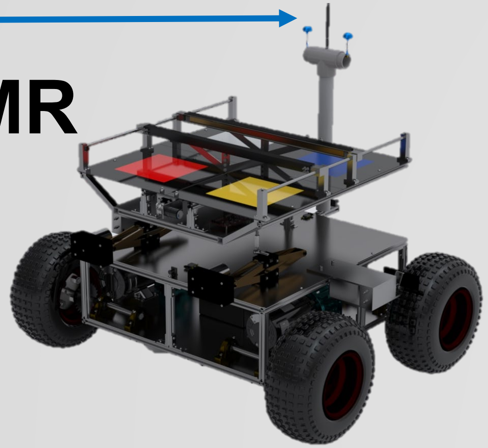
Design Solution

Functional Block Diagram



Final Design Overview: System Interface

MR

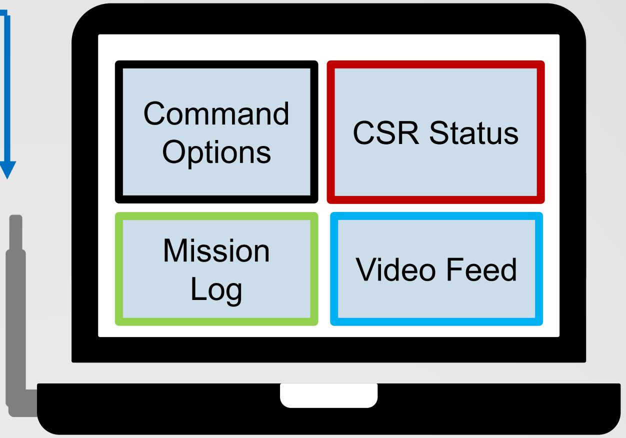


MR Comm System
1 6.5W 900MHz Ubiquiti Radio

MR Software System
- Function: ROS Slave Machine

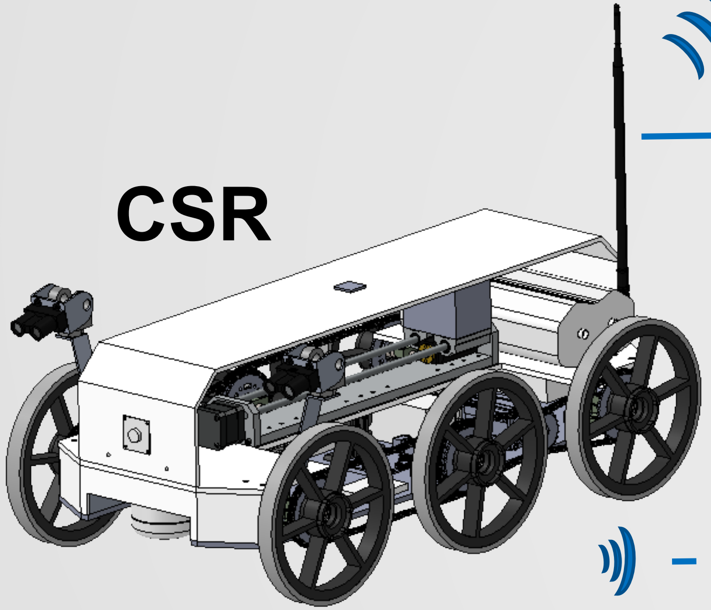
MR Comm System
1 6.5W 900MHz Ubiquiti Radio

GS Software System
- Function: ROS Host Machine
- Displays a GUI for operation



GS

CSR



MR Comm System
1 6.5W 900MHz Ubiquiti Radio

CSR Software System
- Function: ROS Slave Machine

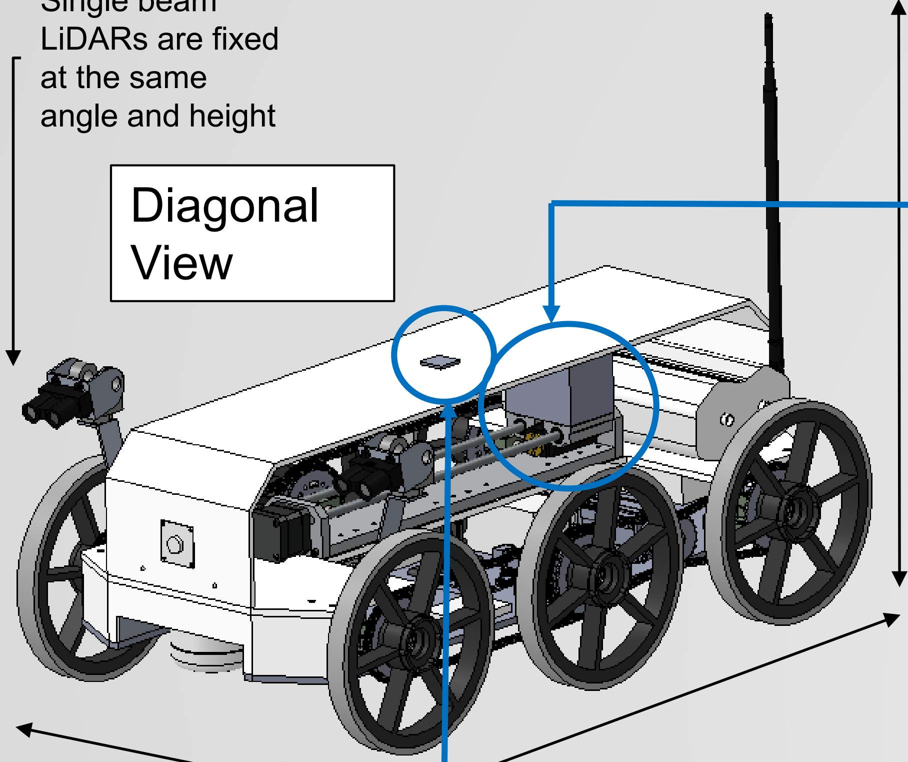
= Wireless Comms.

= Outlines components

Final Design Overview: Child Scout Rover

Single beam LiDARs are fixed at the same angle and height

Diagonal View



Mobility:

- 2 Motors with a Drive Train
- Linear Actuator with 5 kg Mass Stage

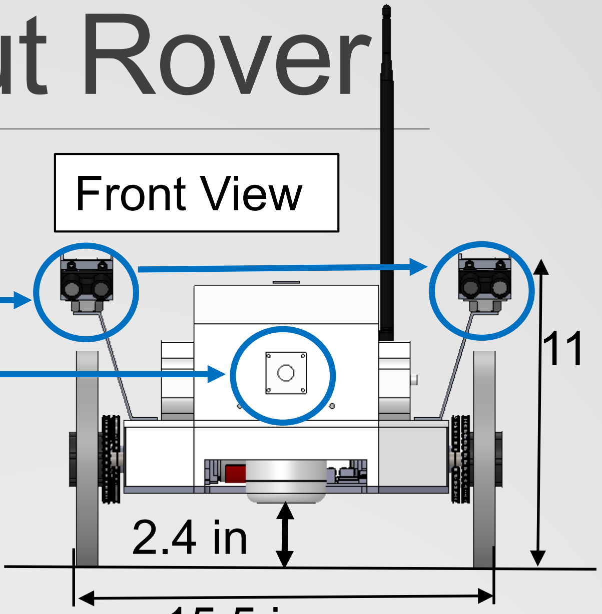
Environmental sensing:

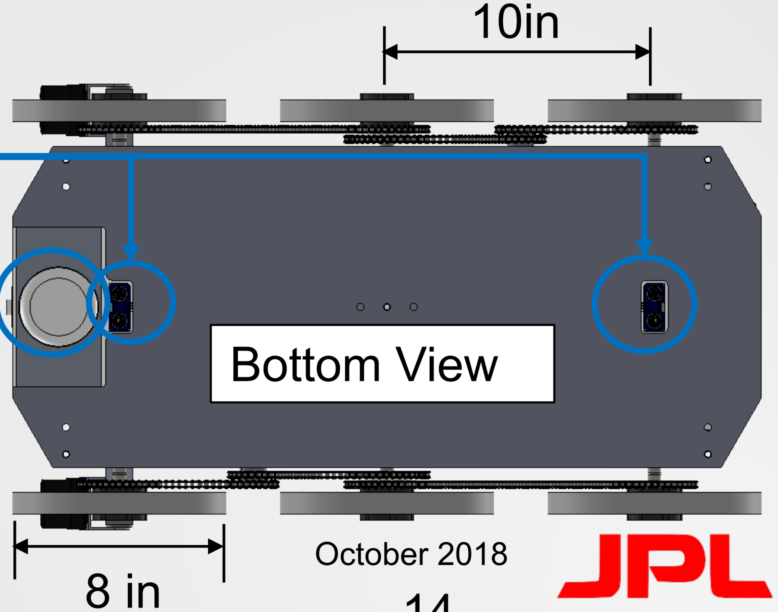
- Single beam LiDAR (right above front wheels)
- Fisheye Lens Camera
- Ultrasonic Sensors
- 360° RP LiDAR

Guidance & Navigation:

- GPS Module
- GPS Antenna
- Magnetometer/Accelerometer

Front View





Bottom View

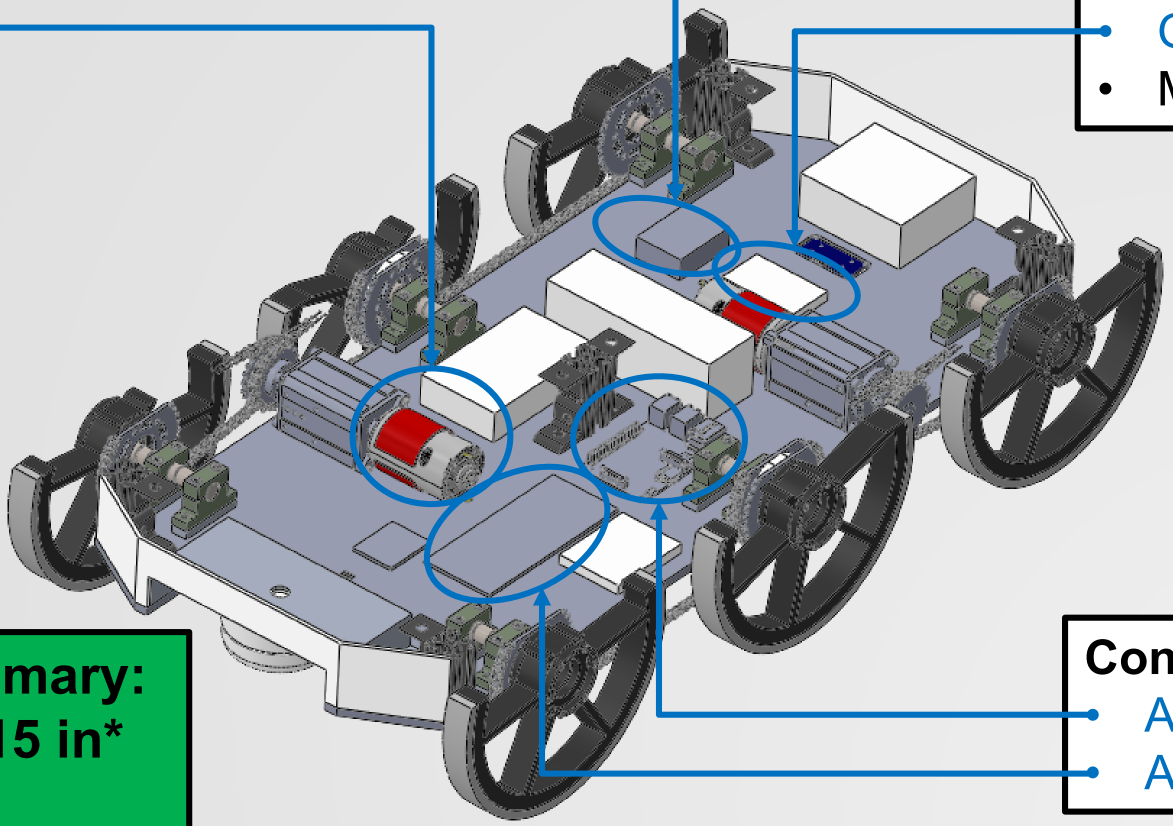
← **= Outlines components**

Note: Blue indicates component being outlined

Final Design Overview: Child Scout Rover

Mobility:
- 2 Motors with a Drive Train
- Linear Mass Stage

Guidance & Navigation:
- GPS Antenna
- GPS Module
- Magnetometer



Note: Internal components are subject to change

Controls:
- ASUS Tinker Board
- Arduino Due

CSR Physical Properties Summary:
- Overall Dimensions: **28 in x 15 in* 11 in**
- Total Mass: **17 kg**

⟵ **= Outlines components**

Note: Blue indicates component being outlined

Major Element: Control

Single Board Computer (ASUS Tinker Board):

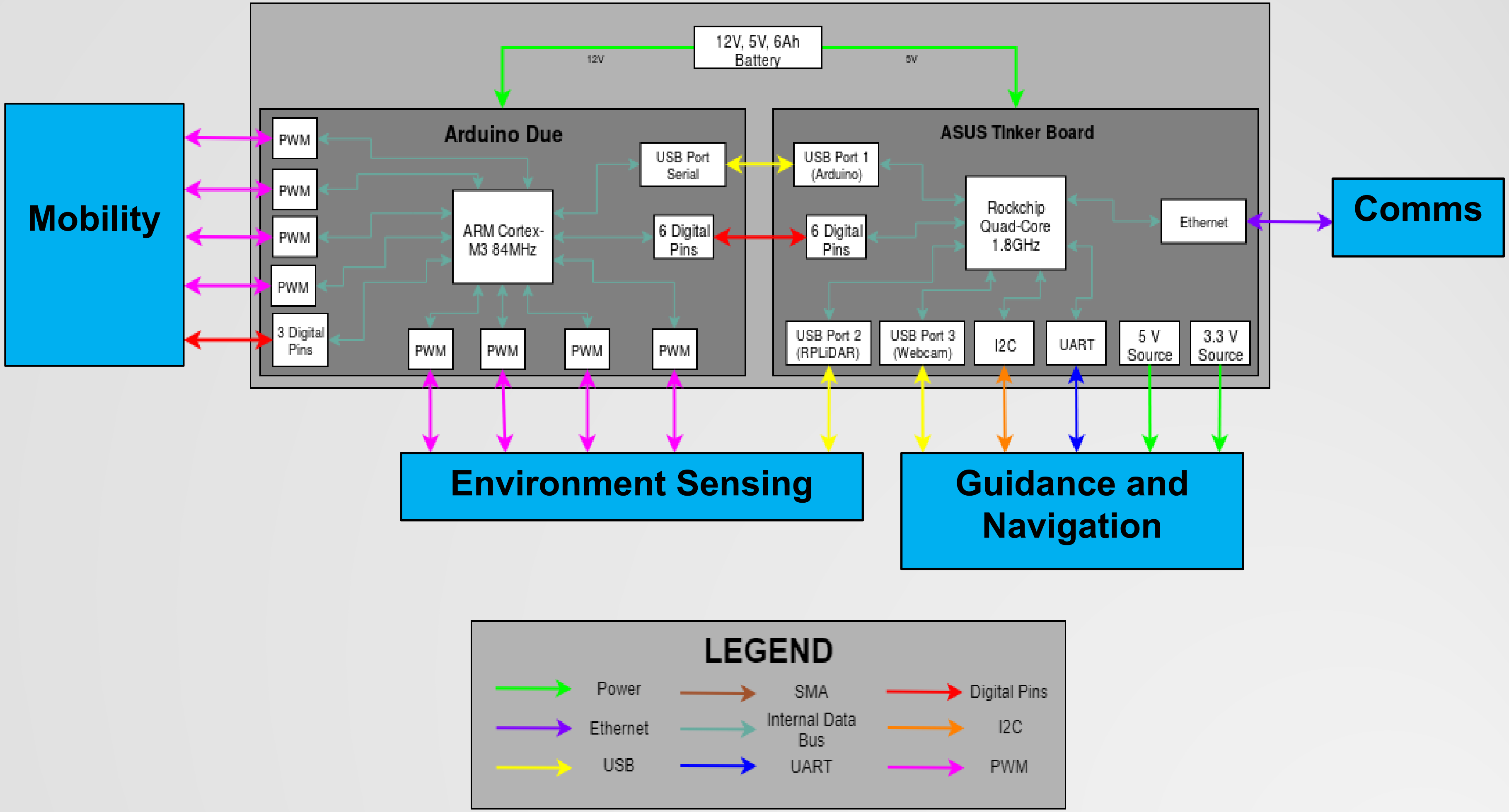
- Power: 5V, 2A
- Digital Pins: 28
- I2C Ports: 2
- UART Ports: 2
- USB Port: 4
- Supply Voltage: 3.3V/5V

ARM Microcontroller (Arduino Due):

- Power: 12V, 0.1A
- Digital Pins: 54
- Analog Pins: 12
- PWM Ports: 12
- USB Port: 1

Battery (TalentCell Lithium Ion):

- 12V, 5V, 6Ah



Major Element: Mobility

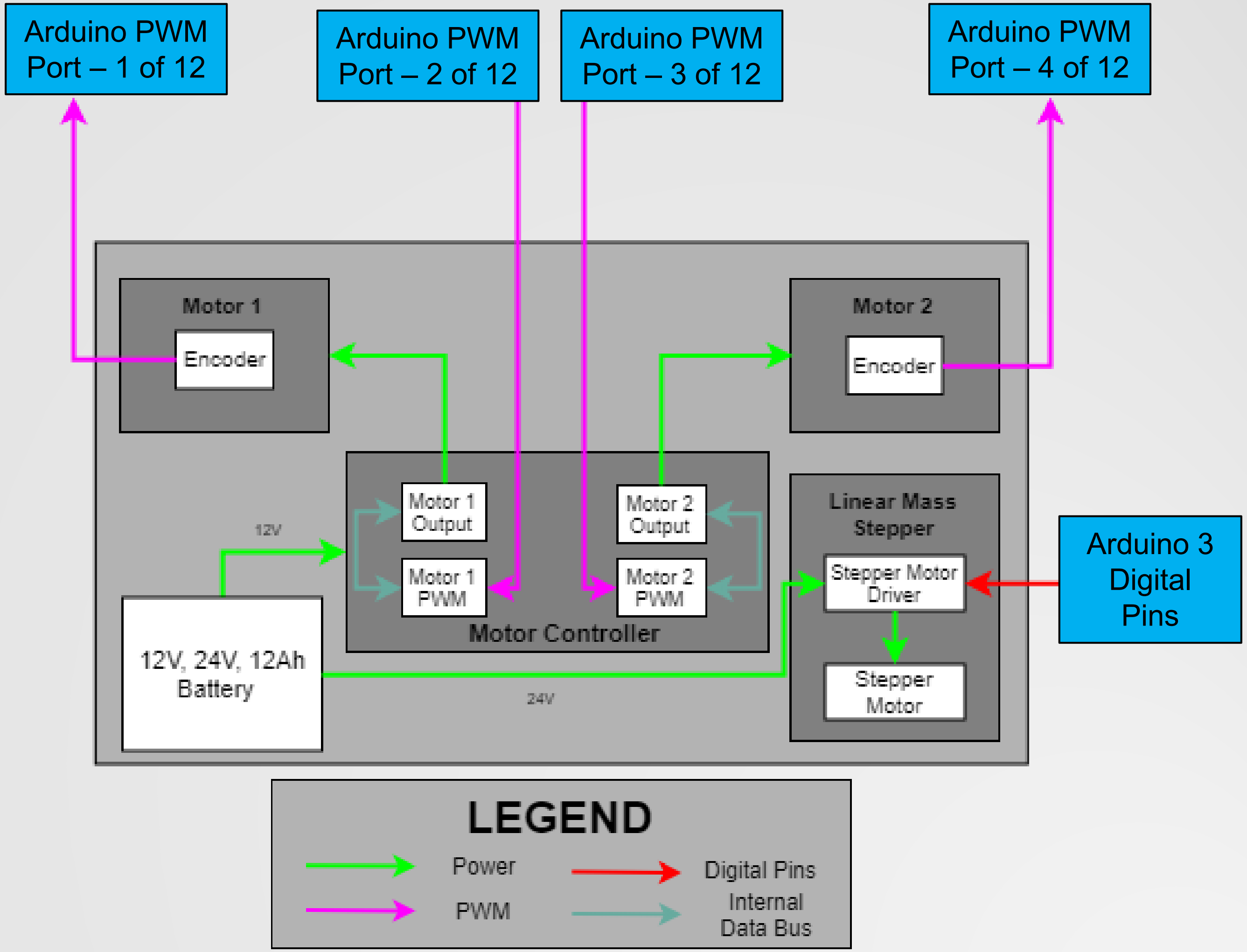
Motors (Redline 775, 57 Sport Gearmotor):
- Power: 12V, 1.5A Expected, 20A Max
- Encoders: 1 PWM Port

Motor Controller (Pololu Dual VNH5019):
- Power: 12V, 12A per motor, 30A Max
- Interface: 2 PWM Ports

Stepper Motor Driver (TB6560 Nema 23):
- Power: 24V, 3A
- Interface: 3 digital pins (step, dir, en)

Stepper Motor (Nema 23):
- Power: 24V, 3A

Battery (Gens Ace LiPo):
- 15.2V, 7.5Ah



Major Element: Communications

Radio (Ubiquiti Loco M9):

- Power: 24V, 0.27A
- Interface: Ethernet
- Specs:
  - Range: +250m
  - Bandwidth: 10-15 Mbps

Omni-Directional Antenna (Rubber Duck):

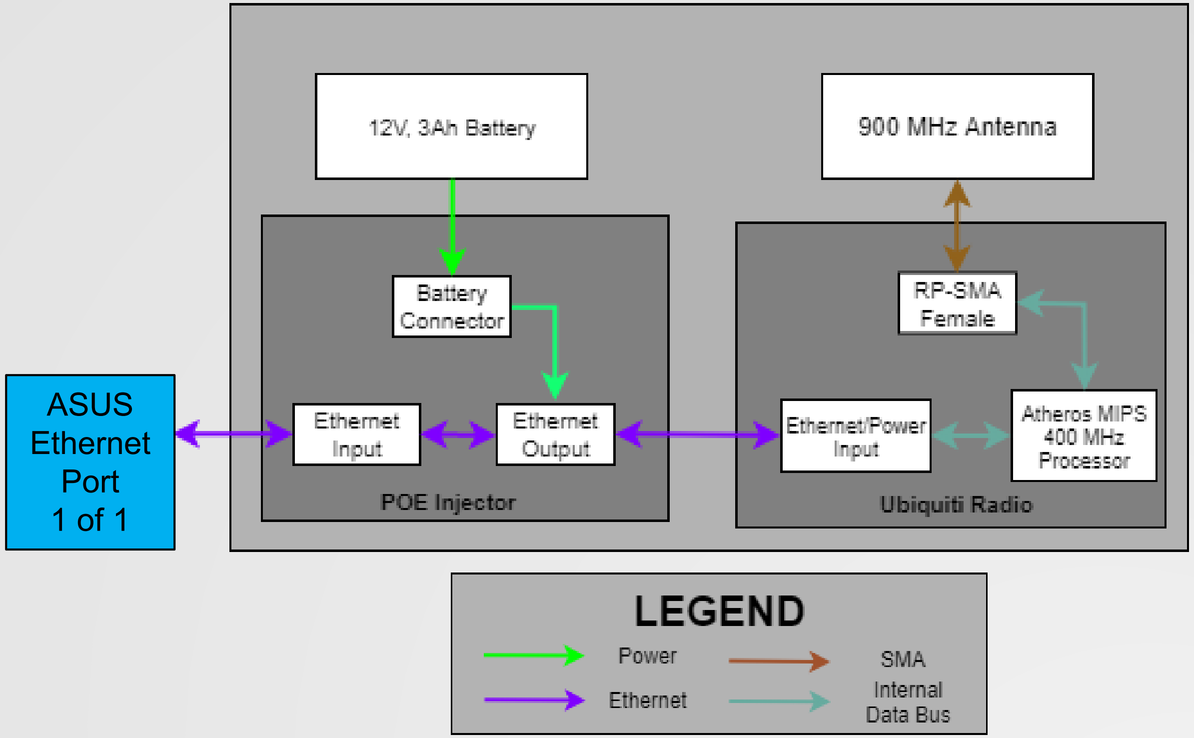
- Interface: SMA
- Frequency: 900 MHz

POE Adapter (TP-DCDC-1224):

- Interface: Ethernet
- Specs: 12V to 24V step-up

Battery (TalentCell Lithium Ion):

- 12V, 3Ah



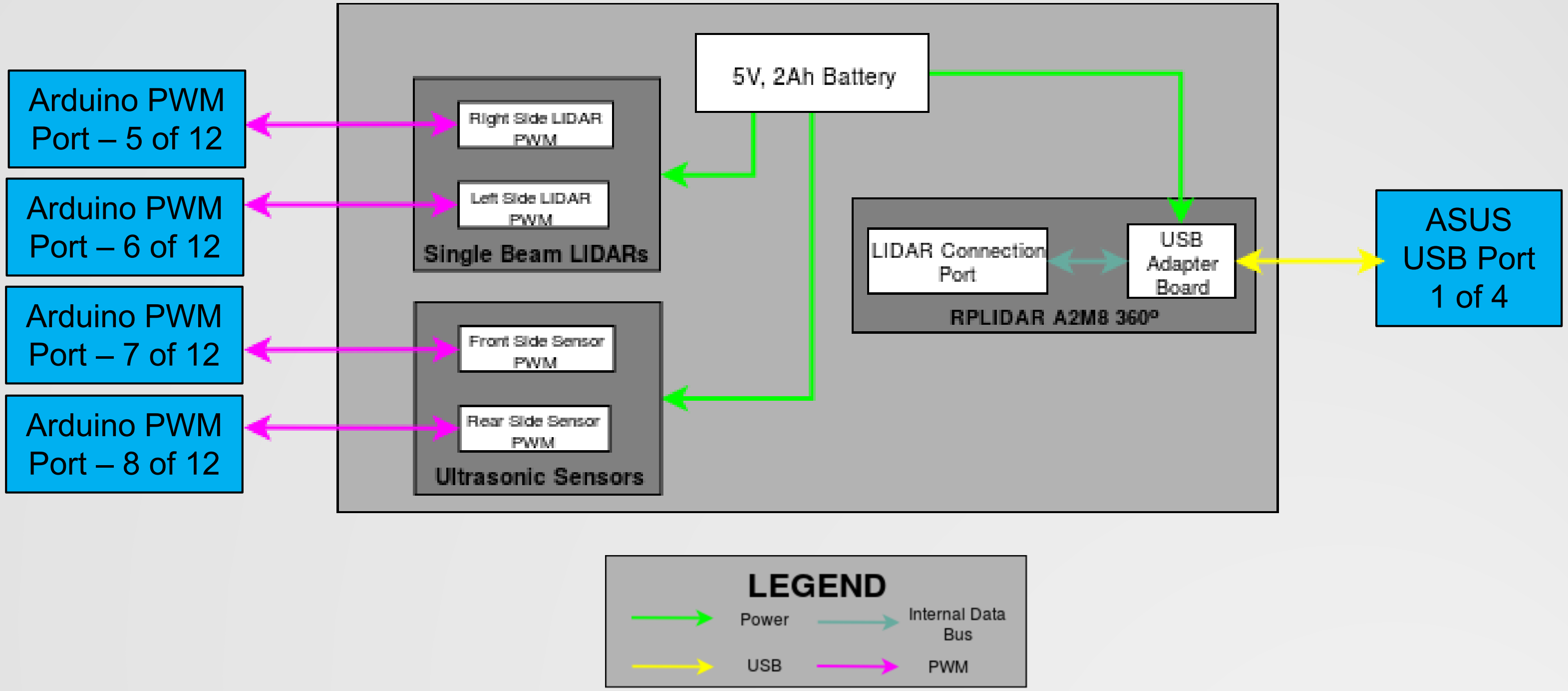
Major Element: Environment Sensing

Single Beam (LiDAR Lite v3):
- Power: 5V, 130mA
- Interface: PWM

360 LiDAR (RPLiDAR A2M8 360):
- Power: 5V, 0.6A
- Measurement Frequency: 2000-8000Hz
- Interface: USB

Ultrasonic Sensor (HC-SR04):
- Power: 5V, 15mA
- Interface: PWM

Battery (2 Lithium Ion Series):
- 3.7V, 2Ah



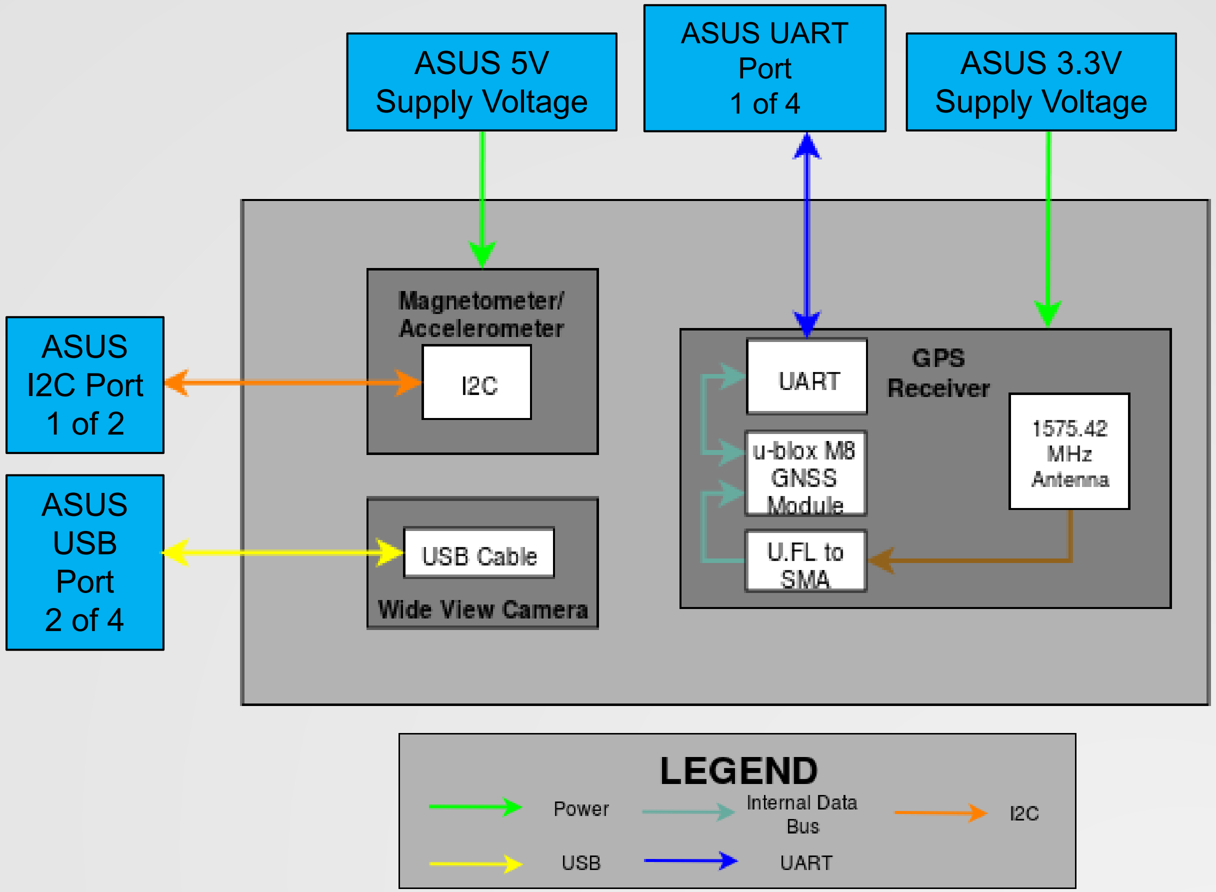
Major Element: Guidance and Navigation

Wide View Camera
(180 Fisheye lens camera):
- Power: 5V, 0.22A
- Resolution: 2 megapixel 1920x1080P
- Interface: USB 2.0

GPS Receiver
(SparkFun GPS-RTK):
- Power: 3.3V, ~35mA
- Accuracy:
  - 0.025m with RTK
- Time to First Fix: 29s (cold), 1s (hot)

GPS Antenna
(GPS/GNSS Magnetic Mount Antenna):
- Frequency Range: 1575 – 1610MHz

Magnetometer/Accelerometer
(LSM303):
- Power: 5V, 15mA
- Interface: I2C



Critical Project Elements

Critical Project Elements

Critical Project Element (CPE)	Rationale
Mobility	**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 given LOI
Communications	**The CSR must 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.
Guidance, Navigation, and Control	**The CSR must 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.
Environment Sensing	**The CSR must 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.

Note: Blue used for emphasis

Design Requirements and their Satisfaction

Mobility

DESIGN REQUIREMENTS AND THEIR SATISFACTION

Mobility Driving Requirements

Specific Requirements:

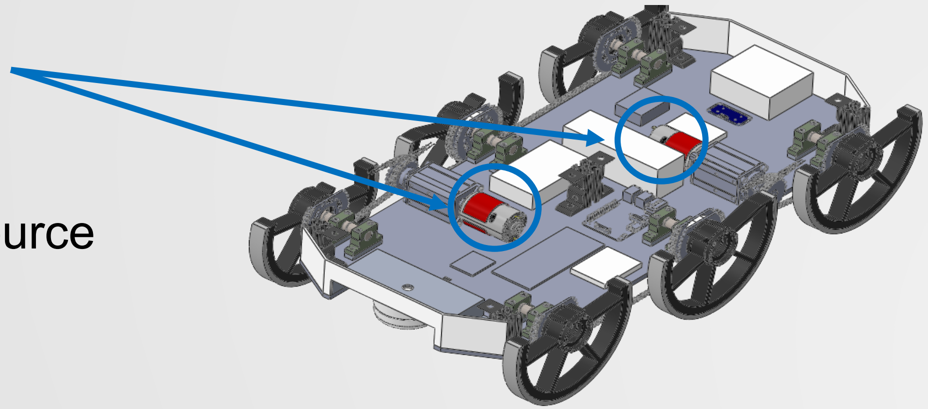
- **MOB.3.2:** The CSR shall be able to go over discontinuities up to 9 in. (0.2286 m)
- **MOB.3.3:** The CSR shall drive up or down a slope of up to 20° in type A terrain
  - Type A Terrain: 0 trees per acre, grain size of 0.00006 - 0.0039 mm, dirt with no vegetation (scattered leaves, etc).
- **MOB.3.4.1:** The CSR shall drive over a traversable obstacle up to 2.4 in. (0.06096 m) in height
- **POW.3.1:** The CSR Mobility power system shall provide at least 5400 mAh to the CSR

Major Modifications from PDR ⟶ CDR:

- 6 independent motors ⟶ 2 motors with a drivetrain

Designs Driven

- Drive motor, power train, wheels, linear mass stage, mobility power source



Note: Blue indicates component being outlined

Current Design Requirement Satisfaction

Component	Required Specifications	Achieved Specifications	Requirement Satisfied
Power Train • AndyMark 775 Redline Motor • 57 Sport 64:1 Planetary Gearbox • 1.71:1 Wheel: Gearbox Sprockets	• Torque – 12.3 Nm (9.1 ft-lbf) (Derived from obstacle mobility model)	• Torque – 40.1 Nm (29.6 ft-lbf)[1]	• MOB.3.2 • MOB.3.3 • MOB.3.4.1 • POW.3.1
Wheels • 8" Rubber Treaded Wheel	• Wheel diameter for roll no-slip – 0.094 m (3.7 in) (Derived from obstacle mobility model)	• Wheel diameter – 0.101 m (4 in)[2]	
Drive Motor Controller • Pololu Dual VNH5019 Motor Driver Shield	• Instantaneous Current – 11.4 A • Continuous Current – 1.5 A (Derived from motor data sheet [1] and mobility analysis)	• Instantaneous Current – 30 A[3] • Continuous Current – 12 A[3]	
Battery • Gens Ace LiPo, 100 C, 15.2 V, 7.5 Ah	• Instantaneous Power – 0.275 kW* • Capacity – 5400 mAh (Derived from power and mobility analysis)	• Instantaneous Power – 11.4 kW[4] • Capacity – 7500 mAh[4]	
Linear Stage Controller • TB6560 Stepper Driver	• Current – 2.8 A	• Current – 3.5 A[5]	• MOB.3.2

University of Colorado Boulder

MOB = Mobility Requirement, POW = Power Requirement

Jet Propulsion Laboratory

Mobility – Power Capacity

Projected Mission Characteristics

- Approximately **52 minutes** of flat ground (gravel/dirt)
- **6** Inclined **Slopes** at 20°: 1 minute each slope
- **30 obstacles** with height of 2.4 in: 4 seconds each obstacle traversal

Obstacle	Flat Ground	Inclined Slopes	Obstacles (2.4 [in])
Current Draw	3000 mA	11200 mA	22,860 mA
Total Time	52 min (.87 h)	6 min (.1 h)	2 min (.03 h)
Required Capacity	2600 mAh	1120 mAh	762 mAh

Total Required Capacity (with 20% inefficiency) = **5400 mAh**

↓

Mobility Battery Capacity = **7500 mAh**[4]

↓

28% Margin

Derived Power Requirement **POW.3.1** is satisfied due to this margin.

Communication

DESIGN REQUIREMENTS AND THEIR SATISFACTION

Communications Driving Requirements

Specific Requirements:

- **CSR.1:** The CSR shall be able to receive commands from the MR or the GS
- **CSR.2:** The CSR shall send video and GPS coordinates to the GS or the MR through mission defined terrain

Major Modifications from PDR ⟶ CDR:

- Wi-Fi communication system with the MR and the GS acting as wireless access points

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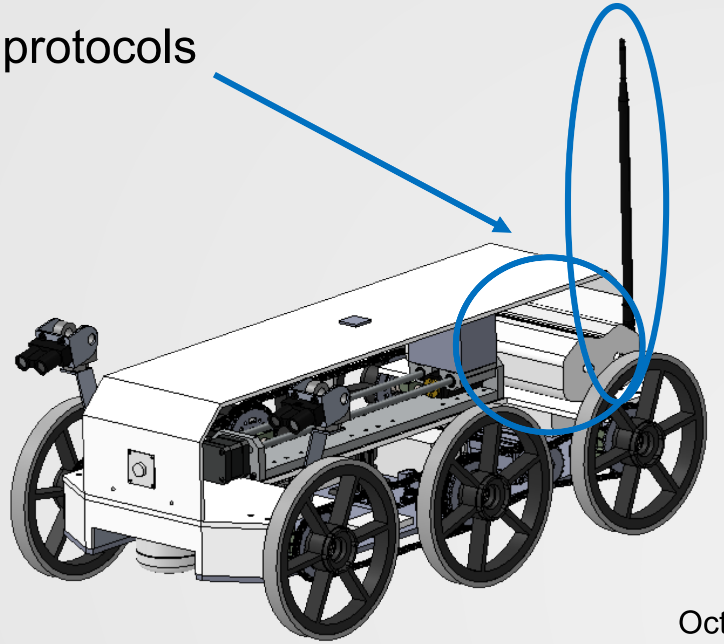
- Point to multipoint high data rate radios using IP protocols

Designs Driven:

- Radio, antennas, communication power source



Note: Blue indicates component being outlined

Communication Data Flow Diagram

900 MHz Link Radio's

- **10-15 Mbps -> Total Bandwidth**
- 28 dBm transmission power
- -96 dBm receiver sensitivity
- 360º coverage
- POE (Power over Ethernet)

Transmitted Data:

1) Continuous transmission:

- Video feed from CSR to GS ~ **9.44 Mbps** w/compression

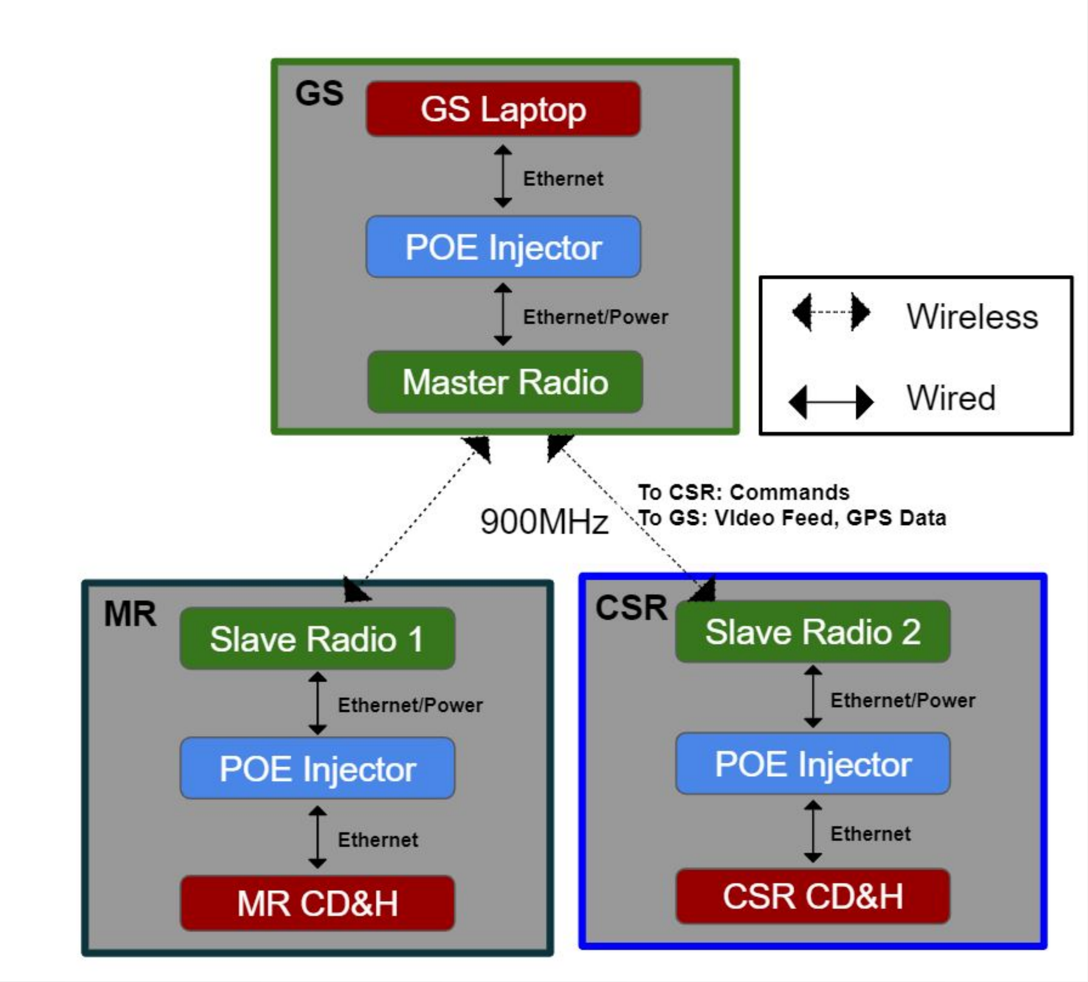
2) On command transmission:

- Commands from GS to CSR ~ 10 bit/packet = 1.25 bytes
- GPS/Magnetometer data from CSR to GS ~ 30 Bytes (String messages) *1 character = 1 byte

Maximum required Data Rate: 9.44 Mbps

Data Rate Margin: .56-5.56 Mbps

Requirements Satisfied: **CSR.1 & CSR.2** due to this margin



Guidance, Navigation and Control

DESIGN REQUIREMENTS AND THEIR SATISFACTION

GNC Driving Requirements

Specific Requirements:

- **CSR.3:** The CSR shall drive to a location of interest through mission defined terrain
- **CDH.3.3:** The CSR C&DH system shall determine if the CSR is within ± 5 meters of the location of interest
- **CDH.3.4:** The CSR C&DH system shall determine the heading of the CSR
- **MOB.3.2:** The CSR shall be able to go over discontinuities up to 9 inches
- **SENS.5.1.3:** The CSR Sensing system shall capture video with a field of view of at least 100 degrees

Major Modifications from PDR ⟶ CDR:

- N/A

Designs Driven:

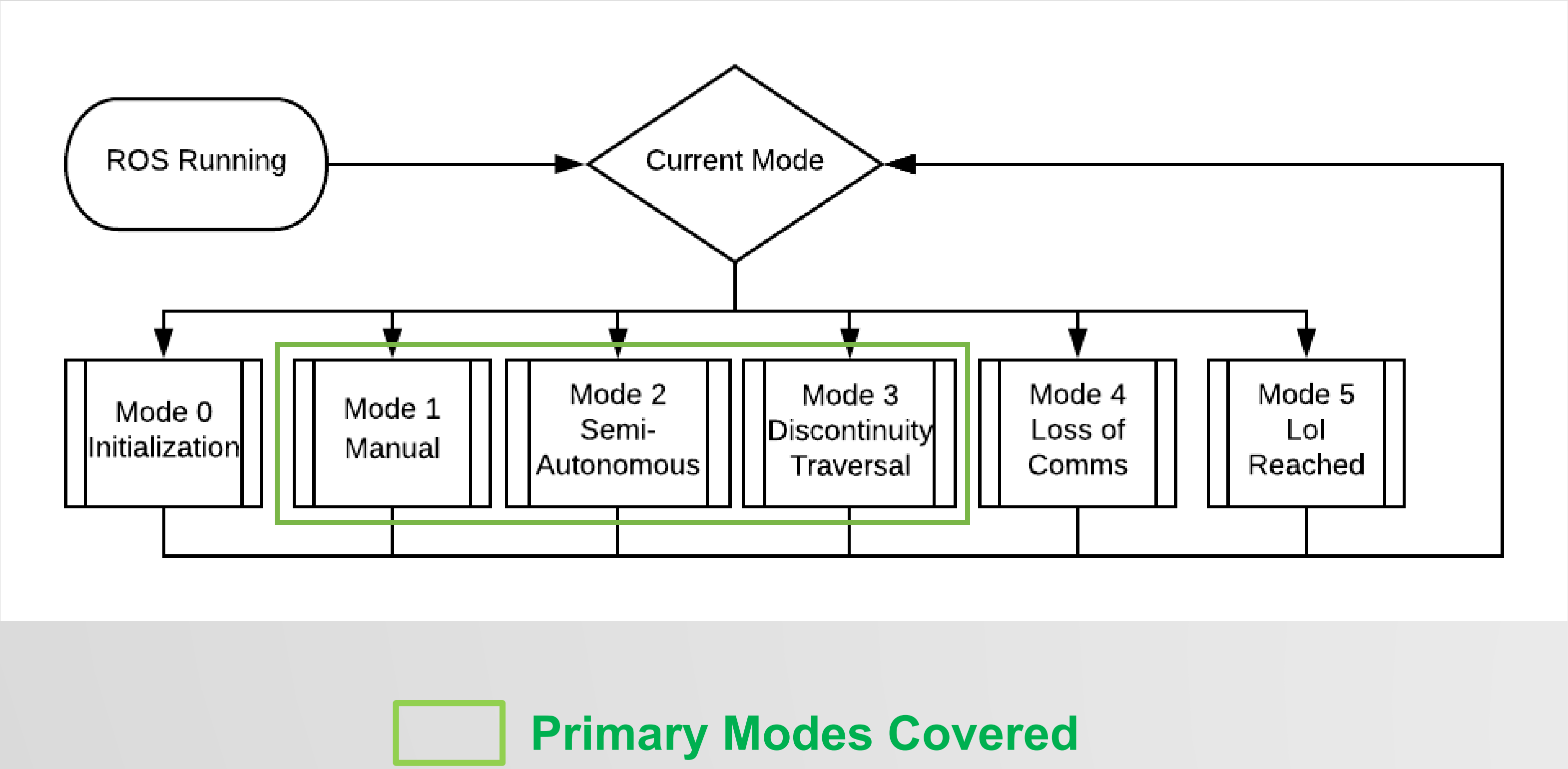
- Positioning devices used – GPS and magnetometer/accelerometer
- Imaging system used
- Control algorithms used, control hardware used, software being used

Current Design Requirement Satisfaction

Component	Required Specifications	Achieved Specifications	Requirement Satisfied
GPS • GPS-RTK Board – NEO M8P-2	• Horizontal Positioning Accuracy of ± 5 meters within LOI *(From statement of work)*	• Horizontal Positioning Accuracy: 0.025m [7]	• CDH.3 • CSR.3.3
3 axis Magnetometer/ + Accelerometer: • LSM303	• Resolution: 1 μT *(derived from 250 m range with a needed accuracy of 5 m from LOI)*	• Resolution: 0.058 μT[8]	• CDH.3.4
Imaging System • Fisheye Lens	• At least 100° FOV *(From statement of work)*	• 180° FOV	• CSR.5

CDH = C&DH Requirement, CSR = Functional Requirement

GNC CSR Software Architecture



The CSR functions in 6 different modes:

- Modes 0,5: Initialization and end of mission modes
- Modes 1-4: Traversal modes

Primary command distribution occurs within the main loop which makes calls to individual modes which further distribute commands to appropriate subsystems

The mode architecture allows for sensor data to only be processed when needed so as to reduce computational load

GNC CSR Software Functionality

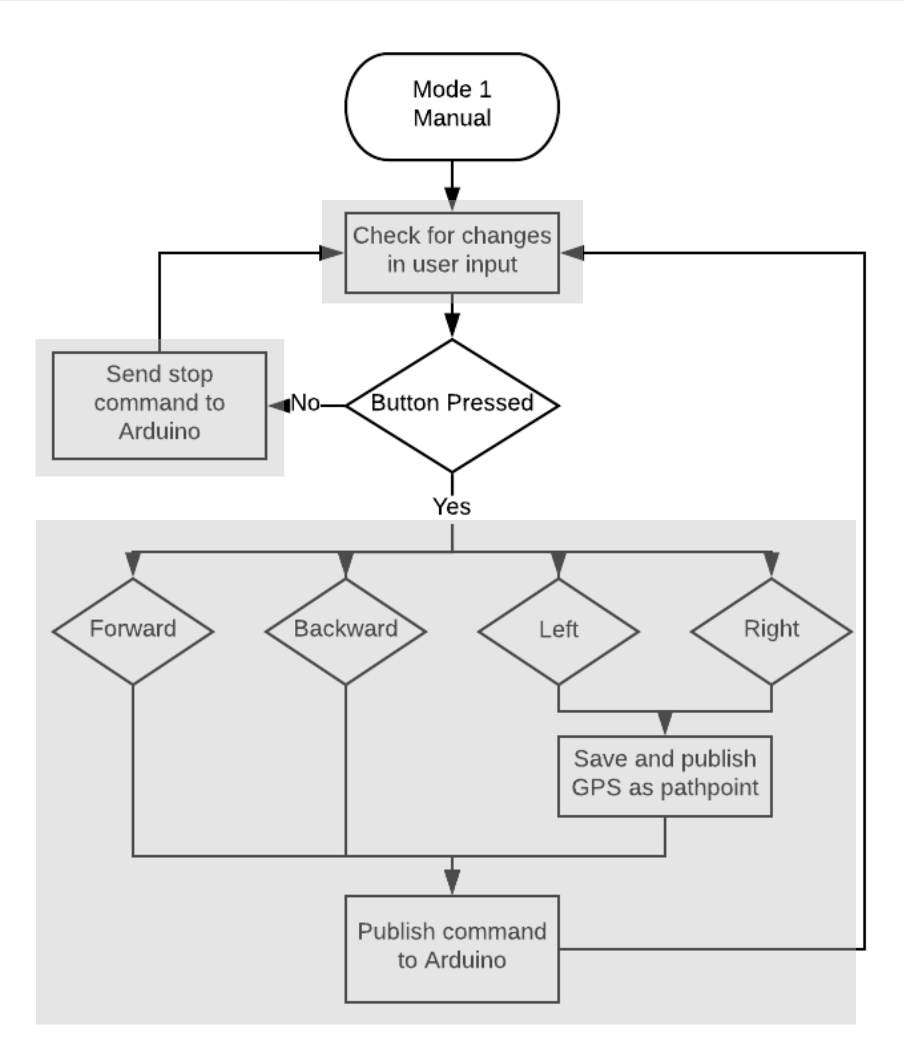
Mode Helper Functionality
This functionality only handles dealing with user input commands and interrupt signals from ROS nodes to switch the mode of operation

- Allows for the main program loop execution to be modular and simple
- Allows for the complex sensing integration to be handled elsewhere

Background ROS Nodes Functionality
This functionality allows for independent programs (nodes) to be running simultaneously outside of the main program loop for reading sensor data, comms data, navigation data, and mobility data

- Each independent node will be checking various data to signal if a mode switch is necessary
- Each independent node will only process data depending on the mode of operation

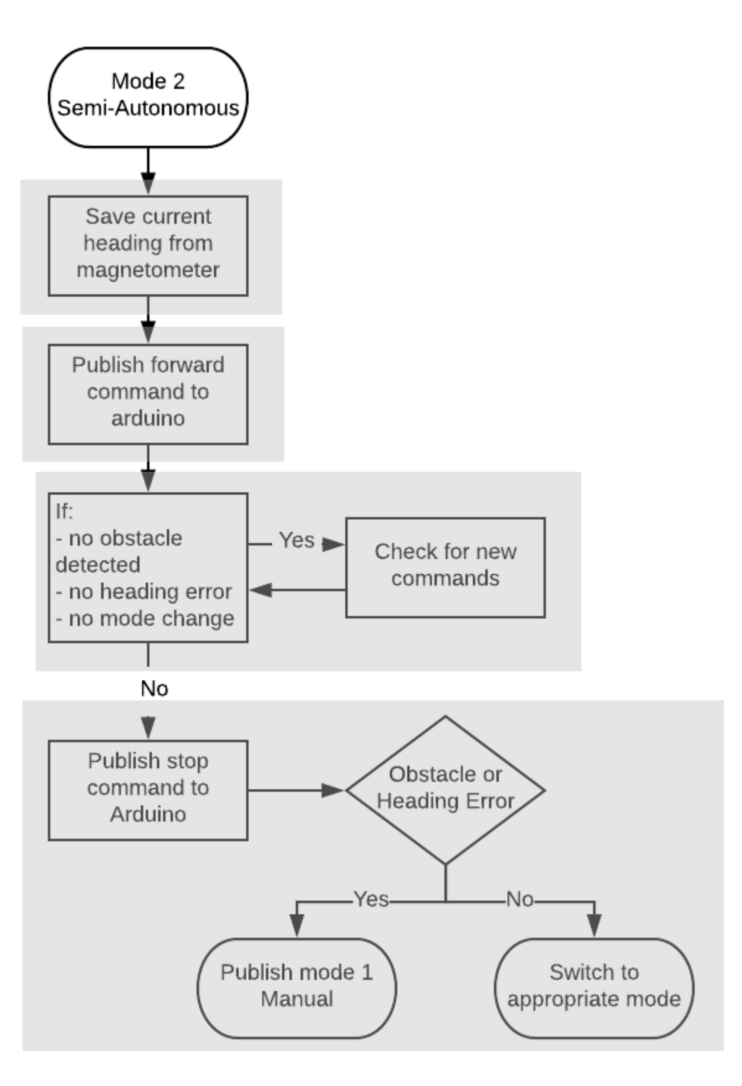
GNC CSR Manual Mode



- Upon entering manual mode, the CSR continuously checks for changes in user input
- If the user is pressing a button, the CSR determines whether or not to set a pathpoint and then sends the command to the Arduino
- The CSR then checks for a change in user input
- If no buttons are pressed, it then stops the motors and continues checking for input updates

Requirement Satisfied: **CSR.3**

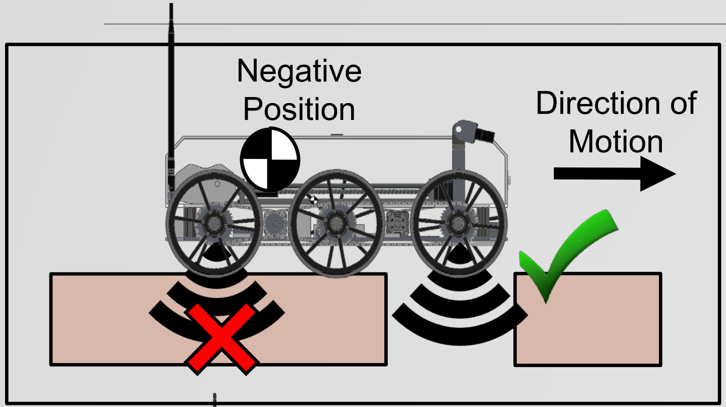
GNC CSR Semi-Autonomous Mode



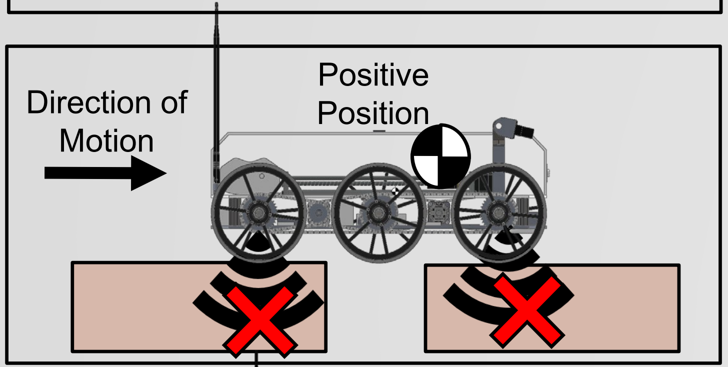
- Upon entering semi-autonomous mode, the CSR begins by saving its current heading
- A command is sent to the Arduino where it causes the motors to drive forward
- The CSR enters a while loop while checking for obstacles, heading error, and mode changes
- Upon exiting the while loop, the CSR sends a command to the Arduino to stop all motors and then either sets the mode to manual or switches to the appropriate mode if a mode change has already been made

Requirement Satisfied: **CSR.3**

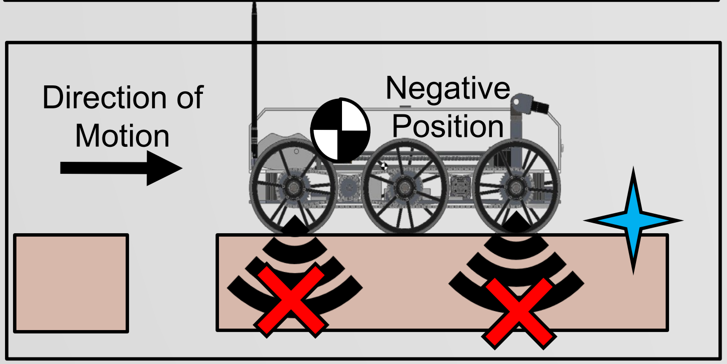
GNC CSR Discontinuity Traversal Mode



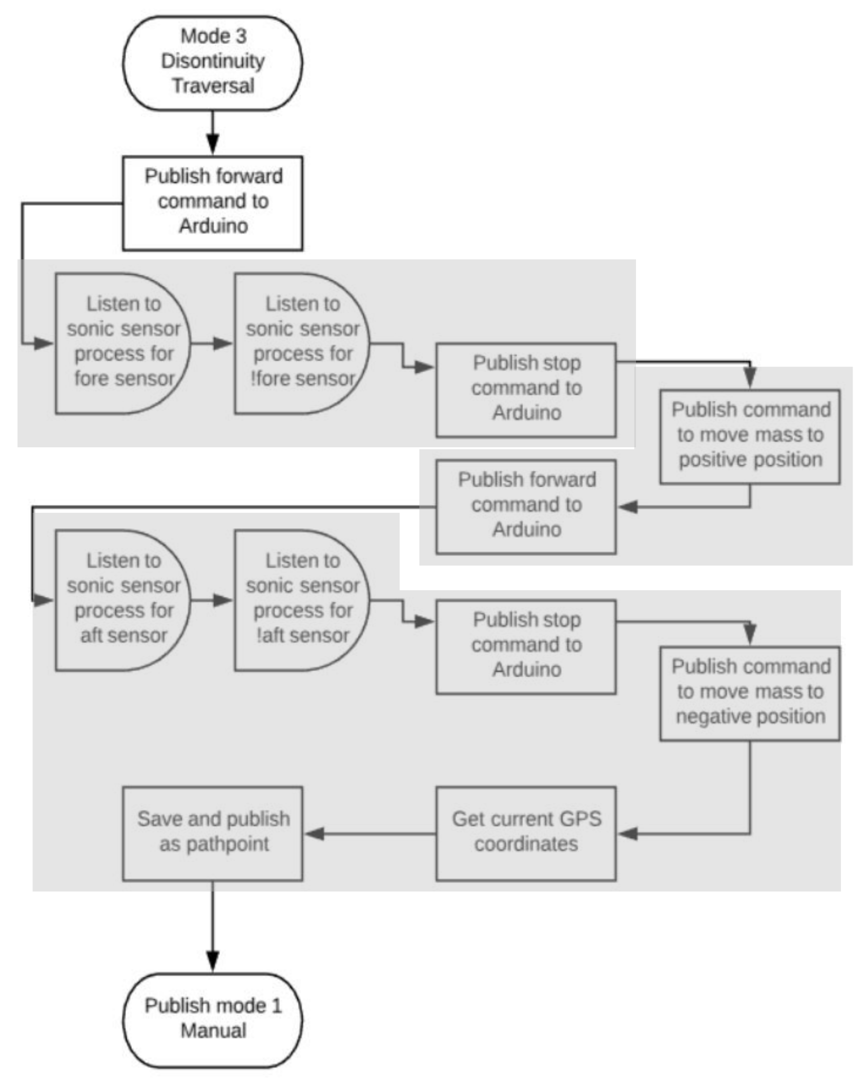
Beginning to cross the discontinuity



While crossing the discontinuity



After crossing the discontinuity



Requirement Satisfied:
MOB.3.2

= Center of Mass = Pathpoint = Ultrasonic Scan

Environment Sensing

DESIGN REQUIREMENTS AND THEIR SATISFACTION

Environment Sensing Driving Requirements

Specific Requirements:

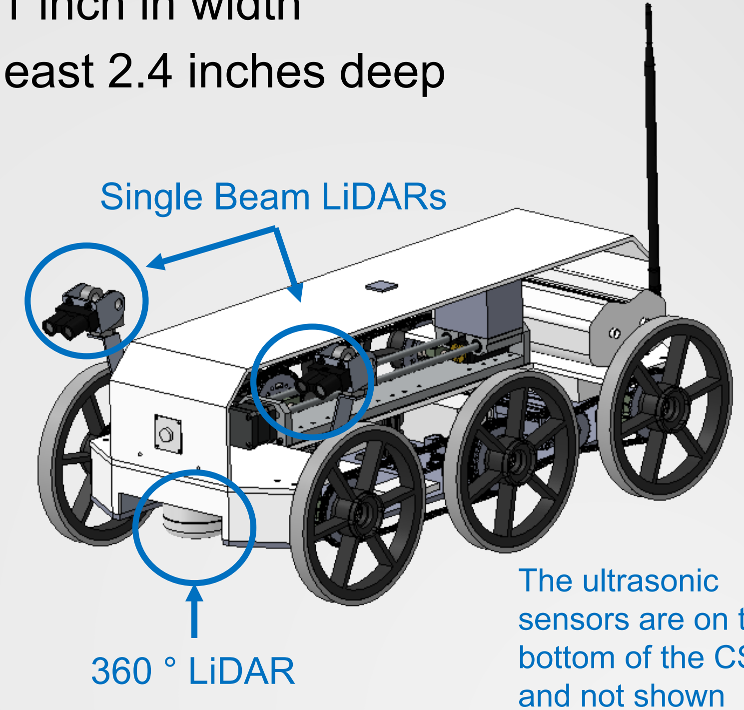
- **SENS.3.1:** The CSR Sensing system shall detect objects at least 37.5 inches (3.125 ft, 0.9525 m) from the Sensing system
- **SENS.3.1.1:** The CSR Sensing system shall detect objects within a field of view of at least 103.5° from the Sensing system
- **SENS.3.1.2:** The CSR Sensing system shall detect objects at least 1 inch in width
- **SENS.3.2:** The CSR Sensing system shall detect discontinuities at least 2.4 inches deep

Major Modifications from PDR ⟶ CDR :

- 2D solid state LiDAR ⟶ 3 independent sensing needs
  1. 360° single beam LiDAR to detect in plane objects
  2. Two fixed single beam LiDAR's to detect discontinuities
  3. Two ultrasonic sensors to complete discontinuity maneuver

Designs Driven:

- Type of sensors used, main controller(s)



The ultrasonic sensors are on the bottom of the CSR, and not shown

Note: Blue indicates component being outlined

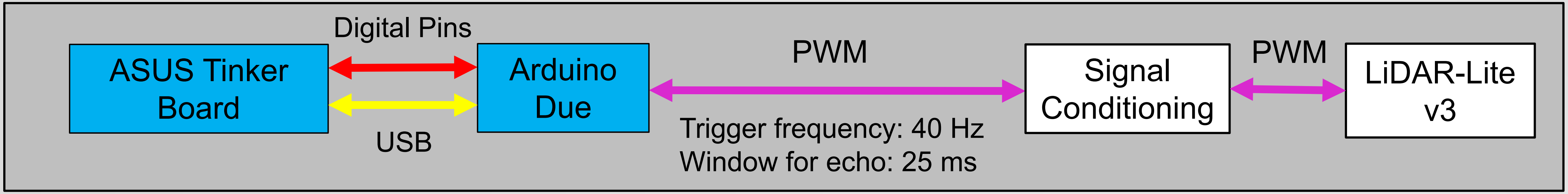
Current Design Requirement Satisfaction

	Required Specifications	Achieved Specifications	Requirements Satisfied
In-Plane Object Detection • Slamtec RPLiDAR A2M8 360° Laser Range Scanner	• Range – 3.125 ft (0.9525 m) • Field of View – 103.5° • Angular Resolution – less than 1.54°	• Range – 39.4 ft (12 m)[9] • Field of View – 360° [9] • Angular Resolution – 0.45° to 1.35° [9]	• SENS.3.1 • SENS.3.1.1 • SENS.3.1.2
Discontinuity Detection • Garmin LiDAR-Lite 3 Laser Rangefinder	• Range – 6.25 ft (1.905 m) (derived from mounting location of LiDAR-Lite 3)	• Range – 131.2 ft (40 m) [10]	• SENS.3.2
Discontinuity Depth Sensing (for Discontinuity Traversal) • Itead Studio HC-SR04 Ultrasonic Sensor	• Range – 4.8 in (0.12 m) (derived from mounting location of HC-SR04)	• Range – 19.7 in (0.5 m) [11]	

Beyond Physical Capability of Sensors:

- The sensing system must have the capability to use sensor data to detect if objects are present
- Integration of sensors with C&DH system is critical for requirement satisfaction

Discontinuity Detection – Integration

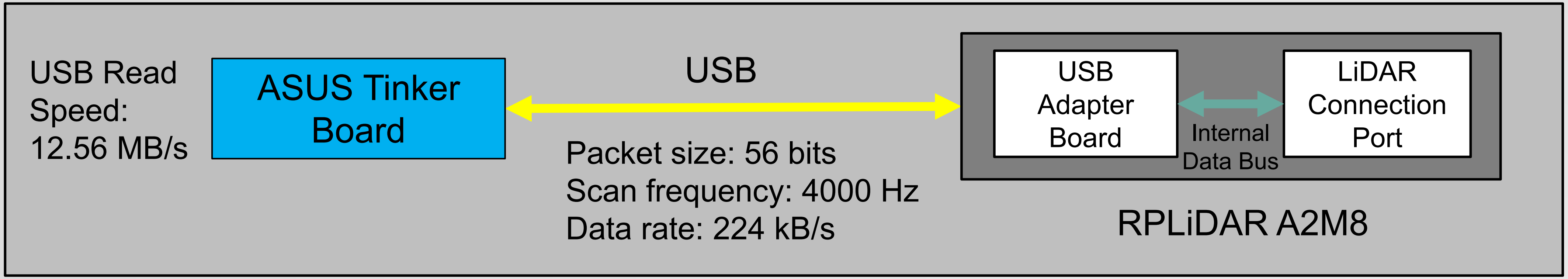


Integration Needs

- Physical hardware interface (2 PWM pins)
- Tinker Board ROS integration (software)
- Arduino sketch that controls the PWM triggers/echoes to sensor (software)
  - LIDAR-Lite v3 maximum response time is ~ 20 ms which is < 25 ms
  - LIDAR-Lite v3 has enough to time to receive trigger and return echo before next trigger is received
- Signal conditioning
  - A 1 kΩ resistor required to isolate Arduino pins for cross-talk elimination
  - Digital signaling is usually resistant to system noise, so most likely, additional filtering is not required

Note: The integration scheme for the HC-SR04 Ultrasonic sensor is almost identical to the LiDAR-Lite 3

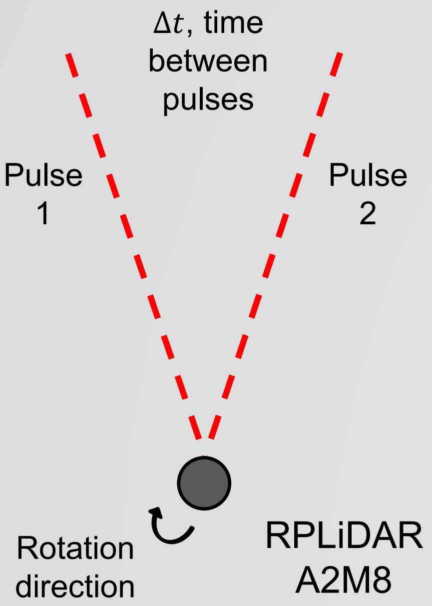
In-Plane Detection – Integration

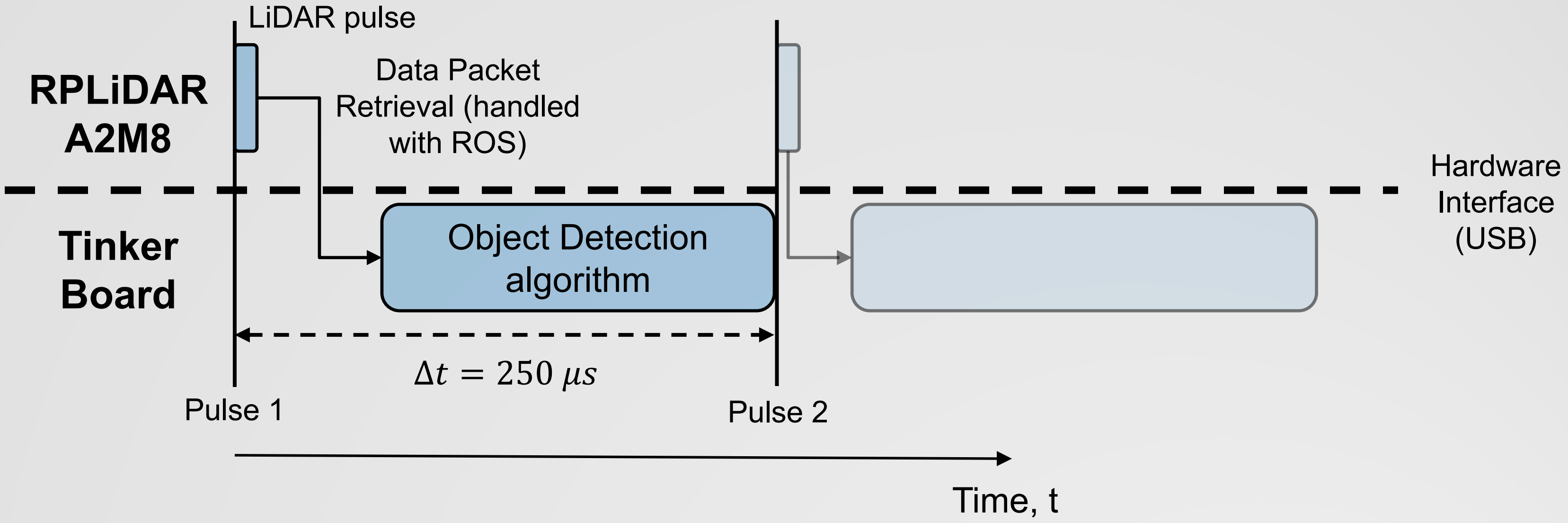


Integration Needs

- Physical hardware interface (USB)
- Tinker Board ROS node development (software)
  - Integration with ROS package
  - Implementation of Object Detection Algorithm
- Data conditioning
  - Tinker Board must process LiDAR data faster than it is sent to Tinker Board (no post-processing)
    - Object Detection Algorithm must process faster than RPLiDAR A2M8 response time
    - If it can, then data buffering is not required

In-Plane Detection – Data Processing





Scan Time and Data Flow Diagrams

- RPLiDAR sends 1 data packet per 1 pulse
- Object Detection algorithm must process data before next data packet is received

Processor Benchmark Test

- Simulated processor: Intel® Core™ i7-8550U Processor 1.8GHz
- Tinker Board Processor: Rockchip Quad-Core RK3288 processor 1.8GHz
- Expected Python sketch executes in $\sim 10\ \mu s$
- Estimated ROS data retrieval time $\sim 50\ \mu s$
- Total processing time is $\sim 60\ \mu s$ which is < $250\ \mu s$

Conclusion:
No data buffering or conditioning is required for RPLiDAR integration to satisfy requirements SENS.3.1, SENS.3.1.1, and SENS.3.1.2

Project Risks

Project Purpose and Objectives | Design Solutions | Critical Project Elements | Design Requirements and their Satisfaction | **Project Risks** | Verification and Validation | Project Planning | Backup Slides

Risk Introduction

Severity Risk Levels

Level	Technical	Schedule
1	Minimal or no impact	Minimal or no impact
2	Small reduction in technical performance	Additional activities required; able to meet key dates
3	Some reduction in technical performance	Minor schedule slip; will miss need date
4	Unacceptable; but workarounds available	Program critical path affected
5	Unacceptable; technical goals cannot be achieved	Cannot achieve key program milestone

Likelihood Risk Levels

Level	Likelihood
1	Not Likely
2	Low Likelihood
3	Likely
4	Highly Likely
5	Near Certainty

Type of Risks

Subscript	Type
T	Technical
S	Schedule

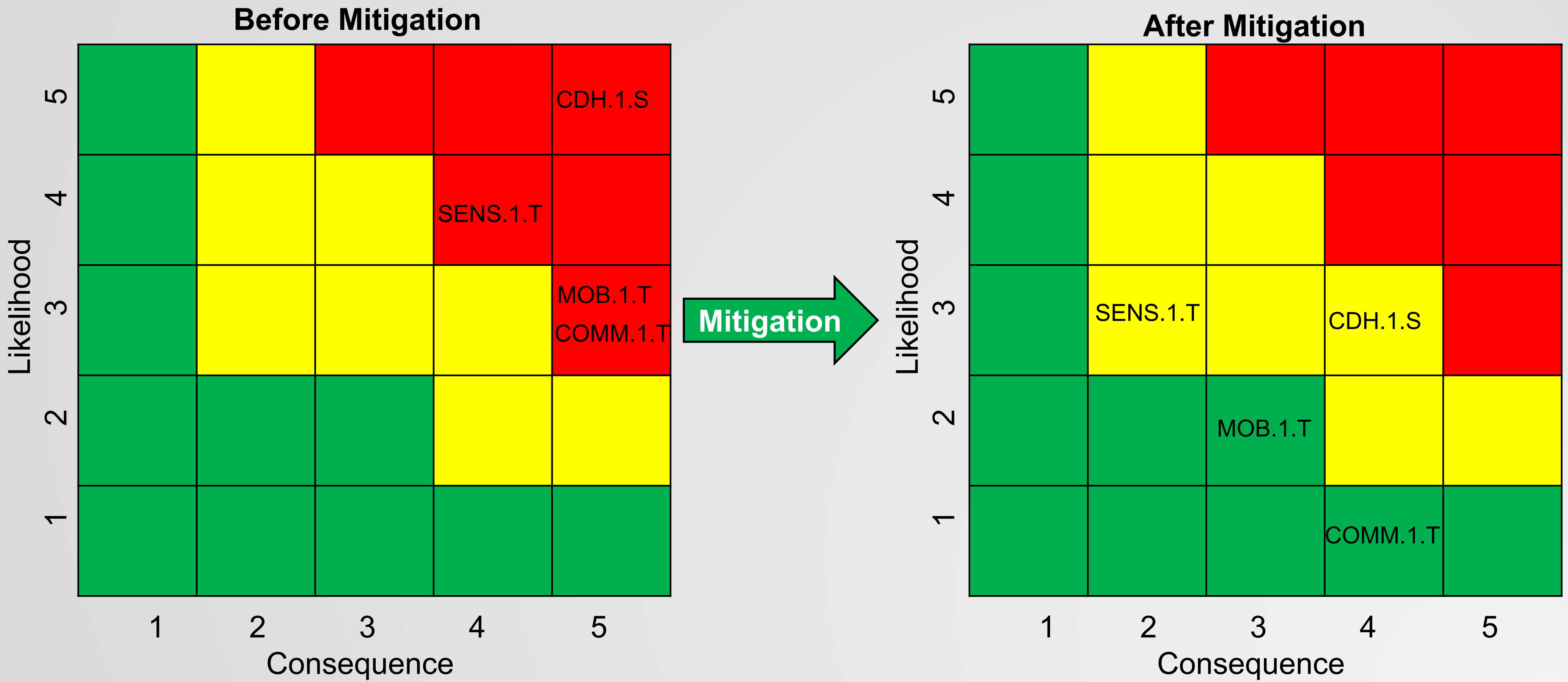
Risk Descriptions

Risk	Type	Description	Effect	Likeli hood	Severity	Total
CDH.1.S	S	**Software** development is **complex and timely**	System integration will not be possible. Functional requirements cannot be verified and validated. **Schedule will not be met.**	5	5	25
SENS.1.T	T	Integration of **360° LiDAR** is **too complex**	Solution would **require extensive time and resources**, which would affect other critical project elements.	4	4	16
MOB.1.T	T	**Motors** and motor controller **failure** due to overheating from stalling, back current, power cycling	The motor does not function properly and **cannot complete mission successfully.**	3	5	15
COMM.1.T	T	**Data budget deficit**	**Unable to send** all necessary **data** back to the GS (video/images, GPS, magnetometer)	3	5	15

Risk Mitigation

		After Mitigation		
Risk	**Mitigation Strategy**	**Likelihood**	**Severity**	**Total**
CDH.1.S	Allow enough time for software development with sufficient time margin, 5 team members assigned to software development, frequent code reviews	3	4	12
SENS.1.T	Members increase skill set with ROS early in schedule, move to off-ramp options by February 4th	3	2	6
MOB.1.T	Ensure sufficient airflow around motors and implement heat sinks; utilize current limiters and monitor current	2	3	6
COMM.1.T	Allocate a sufficient margin in data budgets; start testing components early to validate data budget	1	4	4

Risk Matrices



Verification and Validation

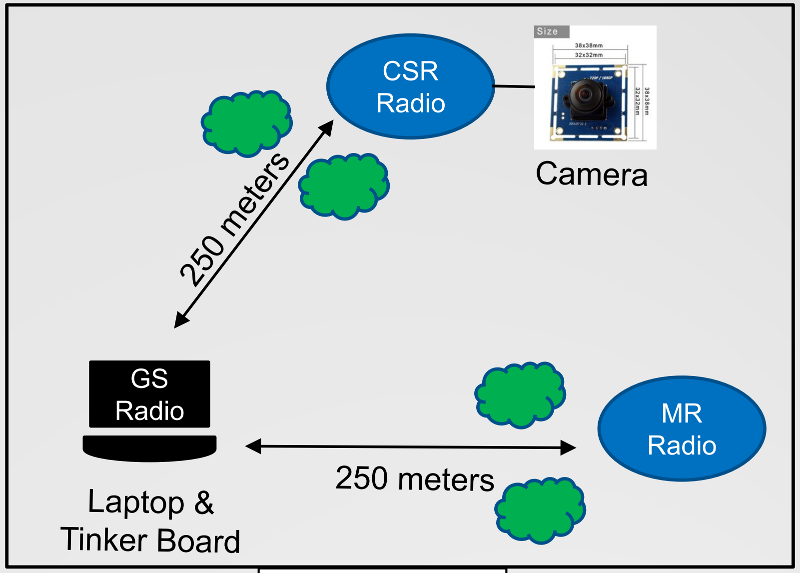
Verification Plan

Phase 1: Components and Subsystems Testing	Phase 2: Subsystem Integration	Phase 3: Full System Integration
1/14/19 - 2/24/19	**2/24/19 - 3/19/19**	**3/19/19 - 4/22/19**
Sensing Testing ➢ Object detection testing ➢ Discontinuity detection testing **Mobility Testing** ➢ Motor validation - Torque curve characterization **C&DH and Software V&V** ➢ Individual mode testing **Communications Testing** ➢ Communications testing ➢ Attenuation characterization **GNC Testing** Ø GPS accuracy Ø Magnetometer accuracy Ø Camera operations testing	**Sensing Integration** ➢ Integrating all sensors and microcontrollers **Mobility Integration & Testing** ➢ Motor mounting to chassis ➢ Drive train integration ➢ Forward & backwards motion **C&DH and Software Integration** Ø Loss of communication navigation testing	**Full System Integration** ➢ Combined Environment maneuverability and object detection integration **Full System Mobility Testing** Ø Environmental maneuverability testing Ø Endurance Testing Ø Obstacle maneuverability testing Ø Rover functional testing

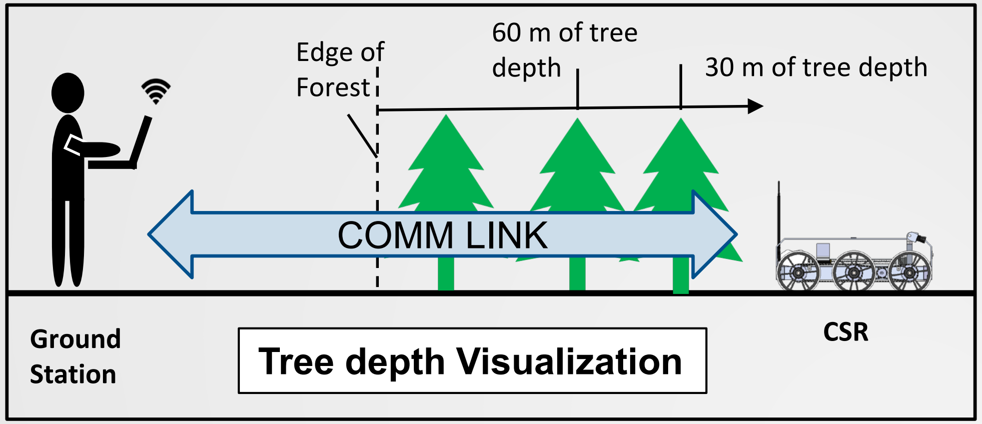
Note: Blue represents critical testing

Phase 1 – Communications Testing

Objective	• Determine largest tree depth for successful transmission and reception of data • Ensure video, GPS, and sensor data can be transmitted and received
Test Plan	<u>**Largest Tree Depth:**</u> • Send video, simulated GPS, and simulated sensor data between radios at 250 meters apart at varying levels of tree depth to determine maximum tree depth • Send constant stream of video, regular intervals of simulated magnetometer and GPS data using Linux Ping Command
Requirements Verified	COMM 1.1, COMM 2.4, COMM 2.5, COMM 2.6
Required Equipment & Software	• 2 Ubiquiti Radios • 1 Laptop • 1 ASUS Tinker Board • 1 USB Camera
Required Measurements	• Signal strength sensitivity
Test Location	• CU Boulder South Campus
Test Errors	• Measurement of tree depth and densities • Estimate of simulated data packet sizes



Test Setup

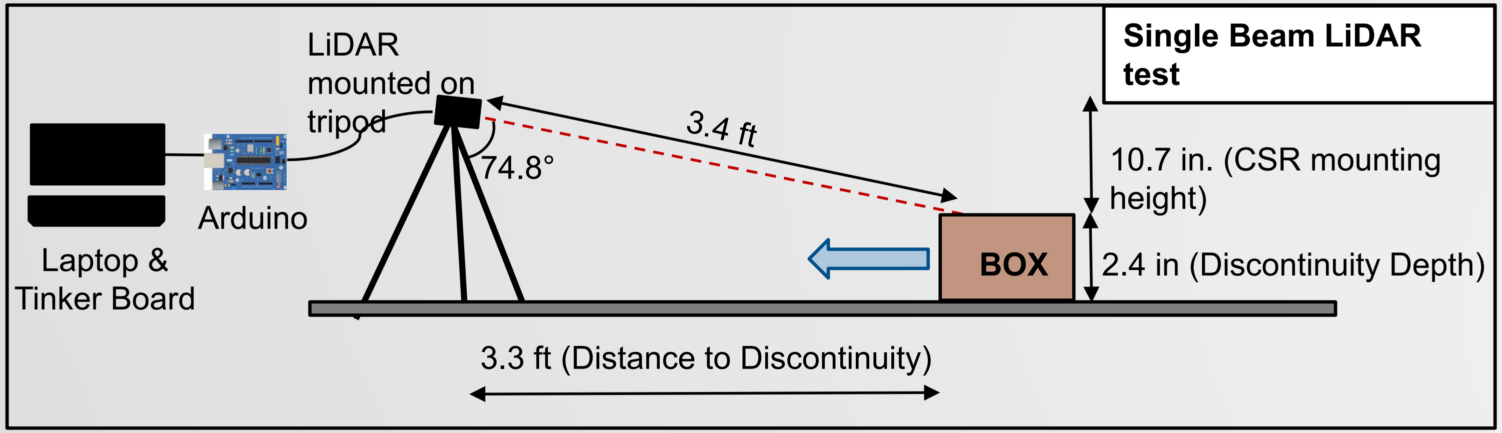


Tree depth Visualization

= Trees (Overhead view)

Phase 2 – Sensing Integration

Objective	• Integrate sensors with C&DH system • Determine if Arduino connected to single beam LiDAR sends a mode change signal when detecting a discontinuity • Determine if Arduino connected to 360° LiDAR sends a mode change signal when detecting an obstacle
Test Plan	**Single Beam LiDAR:** • Move box toward LiDAR, when LiDAR beam hits the ground the Arduino should send a "STOP" signal which alters GNC mode from 2 to 1 **360° LiDAR Sensor:** • Move 1 inch wide by 3 inch high cylinder towards the LiDAR, when the object is 1 m (3.3 ft) away from the LiDAR the Arduino should send a "STOP" signal which alters GNC mode from 2 to 1
Requirements Verified	SENS 3.1, SENS 3.3
Required Equipment & Software	• Single Beam LiDAR • Ultrasonic Sensor • Arduino Due • ASUS Tinker Board
Required Measurements	• Single beam LiDAR reading > 3.4 ft +/- error and 360° LiDAR reading = 3.3 ft +/- error
Test Location	• ITLL
Test Errors	• Sensor measurement error



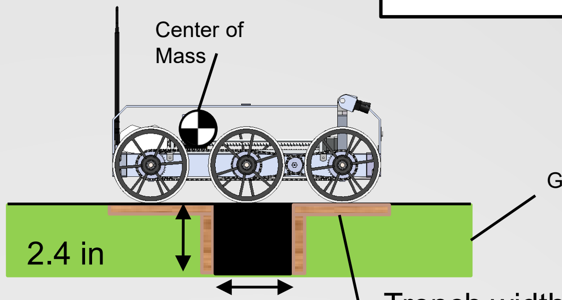
Phase 3 – Obstacle Maneuverability Testing

Objective	• Run a full system test to verify all subsystems correctly work together • Determine if CSR can traverse discontinuities • Determine if CSR can traverse up and down 20° slopes

Test Plan	**<u>Discontinuity test</u>**
	• Place CSR 1 m away from discontinuity and drive until 1st wheel crosses discontinuity
	• Move the moving mass from back to front, then cross discontinuity
	  • **Goal**: autonomous process (level 3 success)
	    Ø Deadline: **4/5/19**
	  • **Worst Case:** manually controlled process with ultrasonic sensor data (level 2 success)
	<u>20° slope test</u>
	• Manually drive CSR up and down 20° slope, successful test if CSR traverses the slope

Requirements Verified	MOB 3.2, MOB 3.3
Required Equipment & Software	• Functional CSR with mobility system and moving mass • Two 2.4 in. x CSR width planks of plywood • One 9 in. x CSR width plank of plywood • LabVIEW interface
Test Location	• Open field or backyard – self-constructed discontinuity • 20° slope hill used for DRIFT's slope test (near ITLL)

Discontinuity test



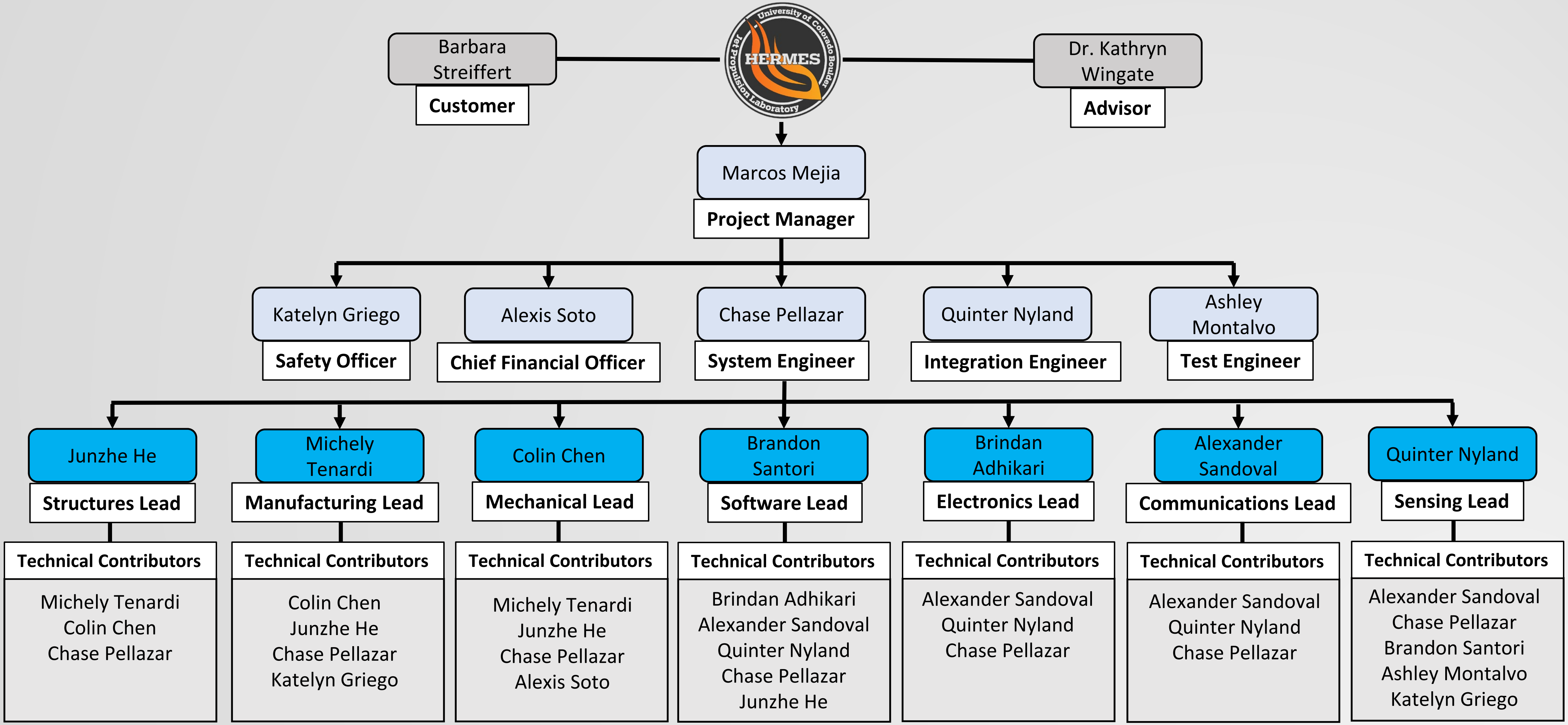
20° slope test

DRIFT's (mother rover) 20° slo pe test

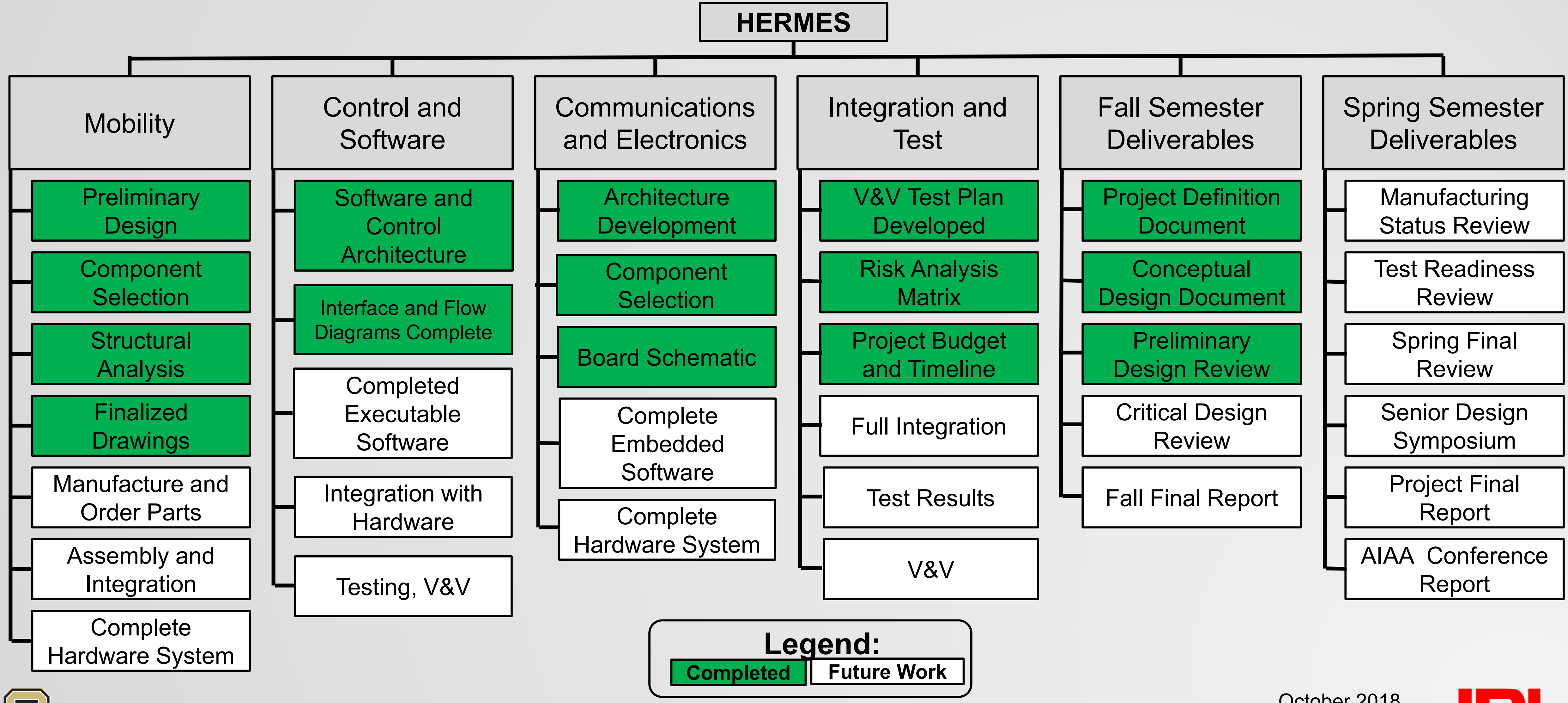
Project Planning

Project Purpose and Objectives | Design Solutions | Critical Project Elements | Design Requirements and their Satisfaction | Project Risks | Verification and Validation | **Project Planning** | Backup Slides

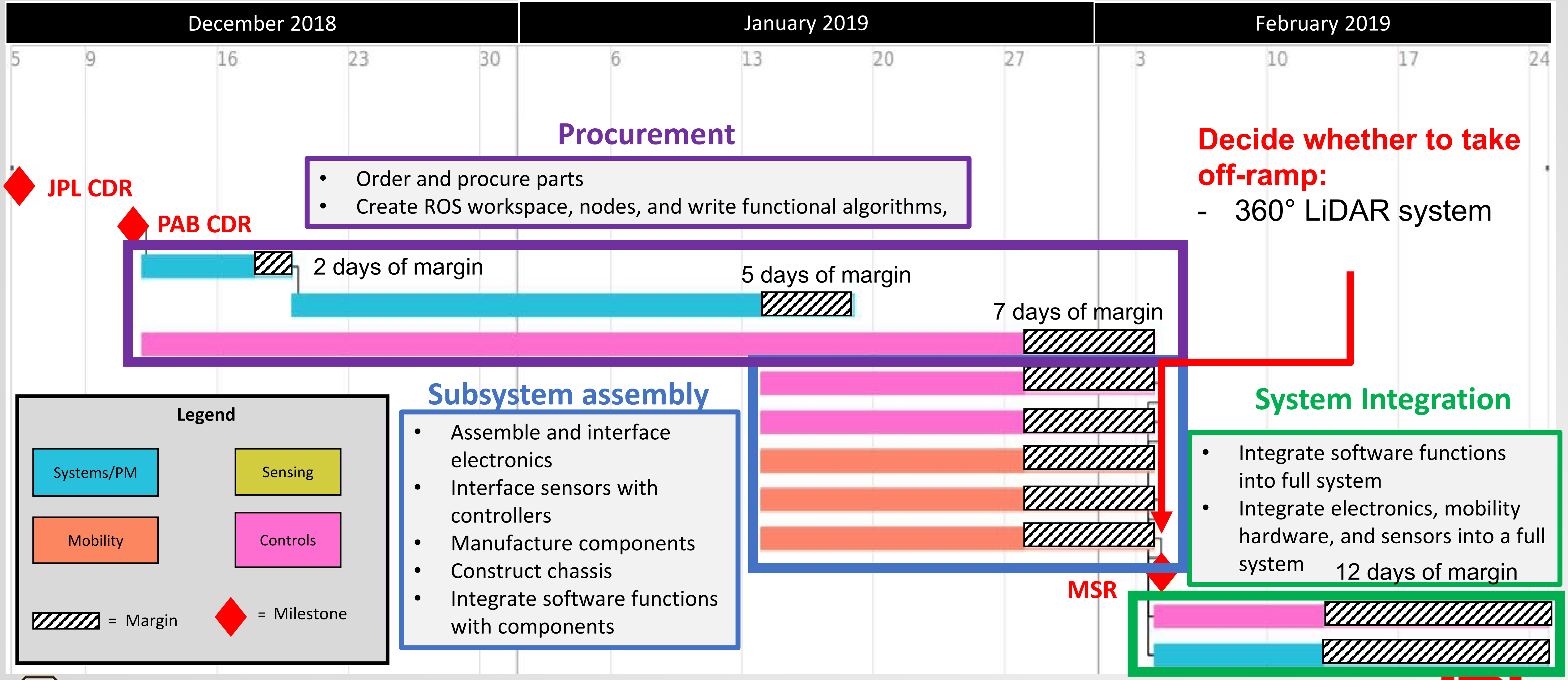
Organizational Chart



Work Breakdown Structure

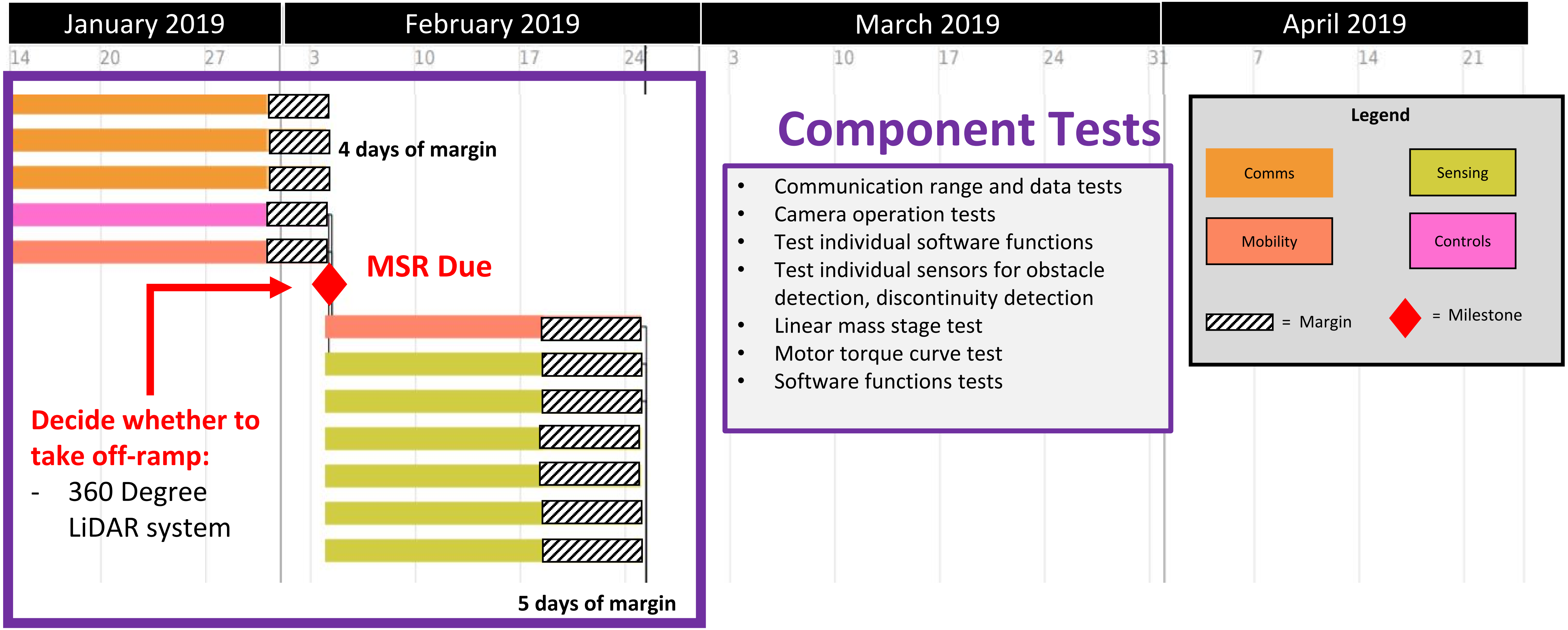


Work Plan

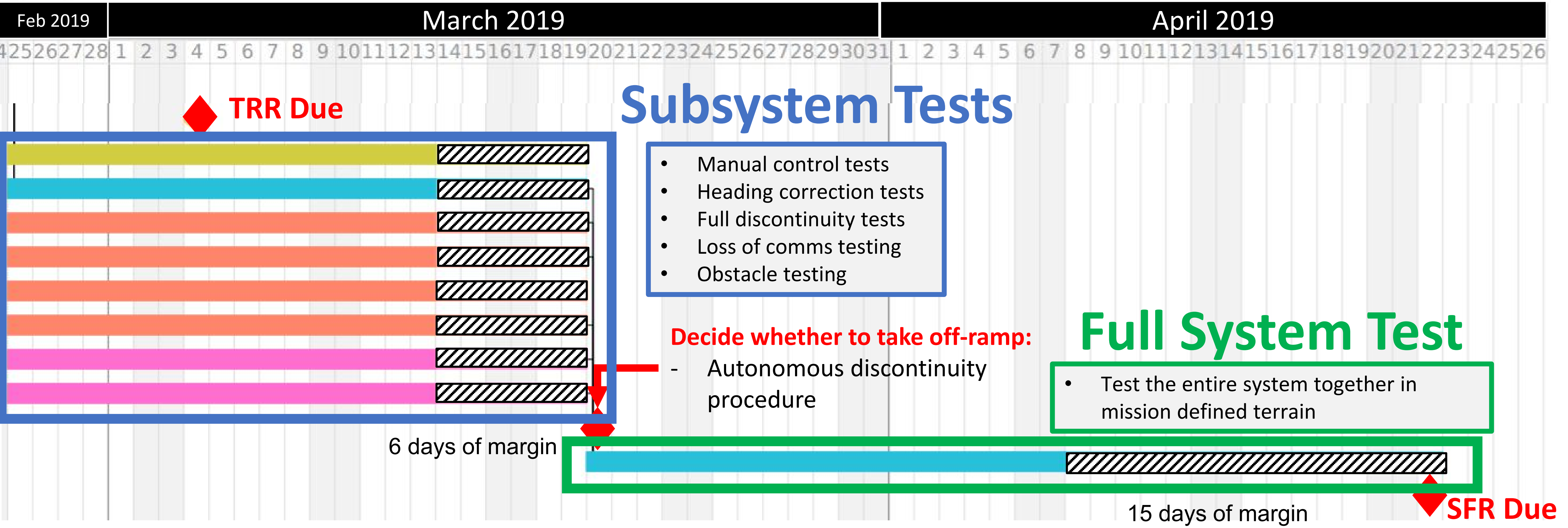


December 2018
January 2019
February 2019
5
9
16
23
30
6
13
20
27
3
10
17
24
Procurement
• Order and procure parts
• Create ROS workspace, nodes, and write functional algorithms,
JPL CDR
PAB CDR
2 days of margin
5 days of margin
7 days of margin
Decide whether to take off-ramp:
- 360° LiDAR system
Subsystem assembly
• Assemble and interface electronics
• Interface sensors with controllers
• Manufacture components
• Construct chassis
• Integrate software functions with components
System Integration
• Integrate software functions into full system
• Integrate electronics, mobility hardware, and sensors into a full system
12 days of margin
MSR
Legend
Systems/PM
Sensing
Mobility
Controls
= Margin
= Milestone

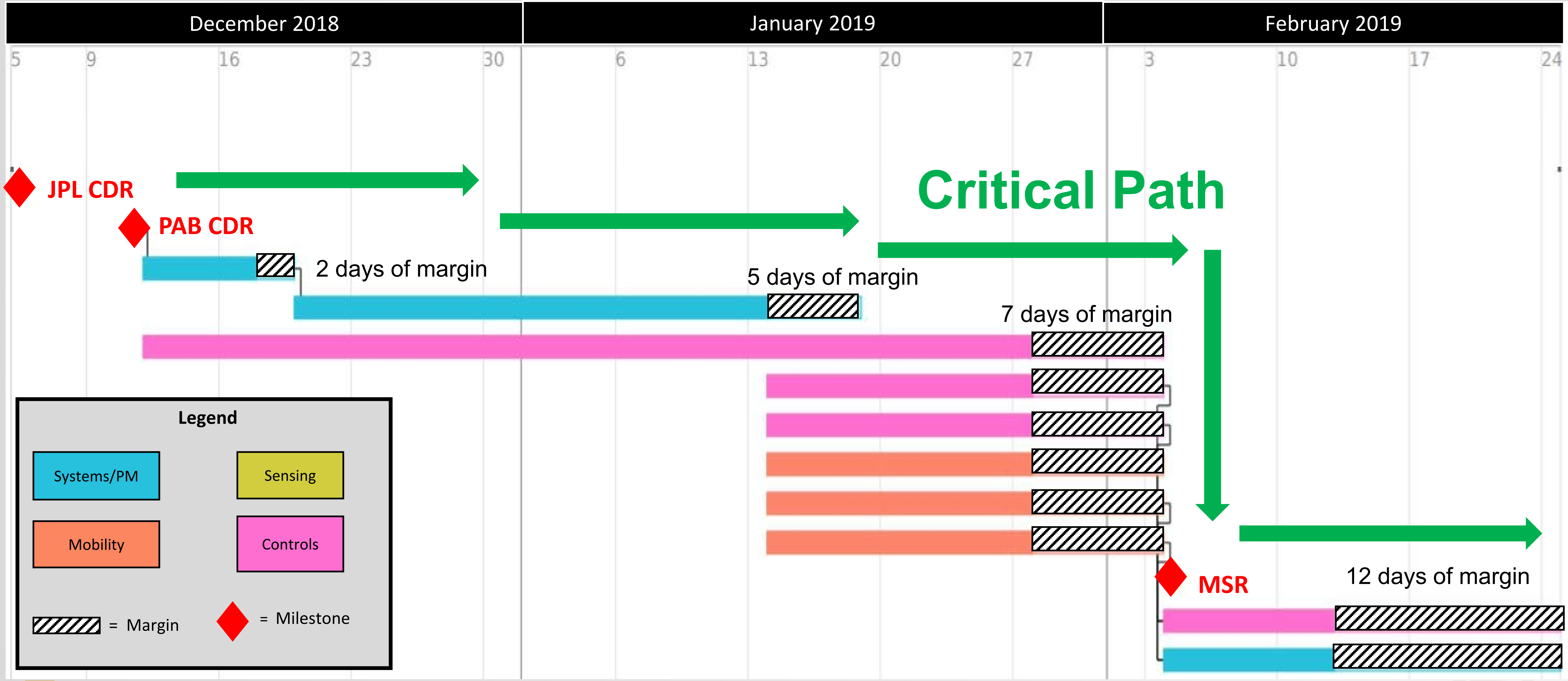
Work Plan


January 2019
February 2019
March 2019
April 2019
14
20
27
3
10
17
24
3
10
17
24
31
7
14
21
4 days of margin
MSR Due
Decide whether to take off-ramp:
- 360 Degree LiDAR system
5 days of margin
Component Tests
• Communication range and data tests
• Camera operation tests
• Test individual software functions
• Test individual sensors for obstacle detection, discontinuity detection
• Linear mass stage test
• Motor torque curve test
• Software functions tests
Legend
Comms
Sensing
Mobility
Controls
= Margin
= Milestone

Work Plan


Feb 2019
March 2019
April 2019
TRR Due
Subsystem Tests
• Manual control tests
• Heading correction tests
• Full discontinuity tests
• Loss of comms testing
• Obstacle testing
Decide whether to take off-ramp:
- Autonomous discontinuity procedure
6 days of margin
Full System Test
• Test the entire system together in mission defined terrain
15 days of margin
SFR Due

Work Plan



December 2018
January 2019
February 2019
5
9
16
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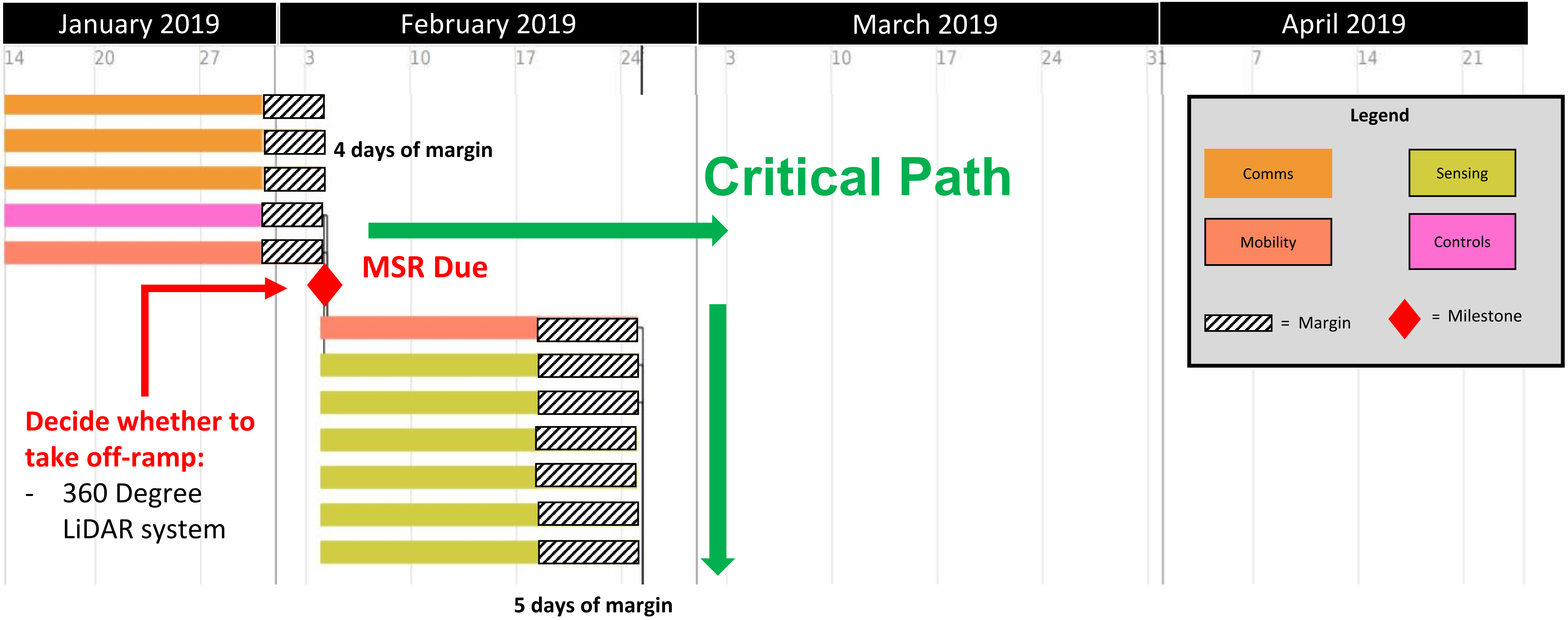
17
24
JPL CDR
PAB CDR
Critical Path
2 days of margin
5 days of margin
7 days of margin
MSR
12 days of margin
Legend
Systems/PM
Sensing
Mobility
Controls
= Margin
= Milestone

Work Plan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4 days of margin
Critical Path
MSR Due
Decide whether to take off-ramp:
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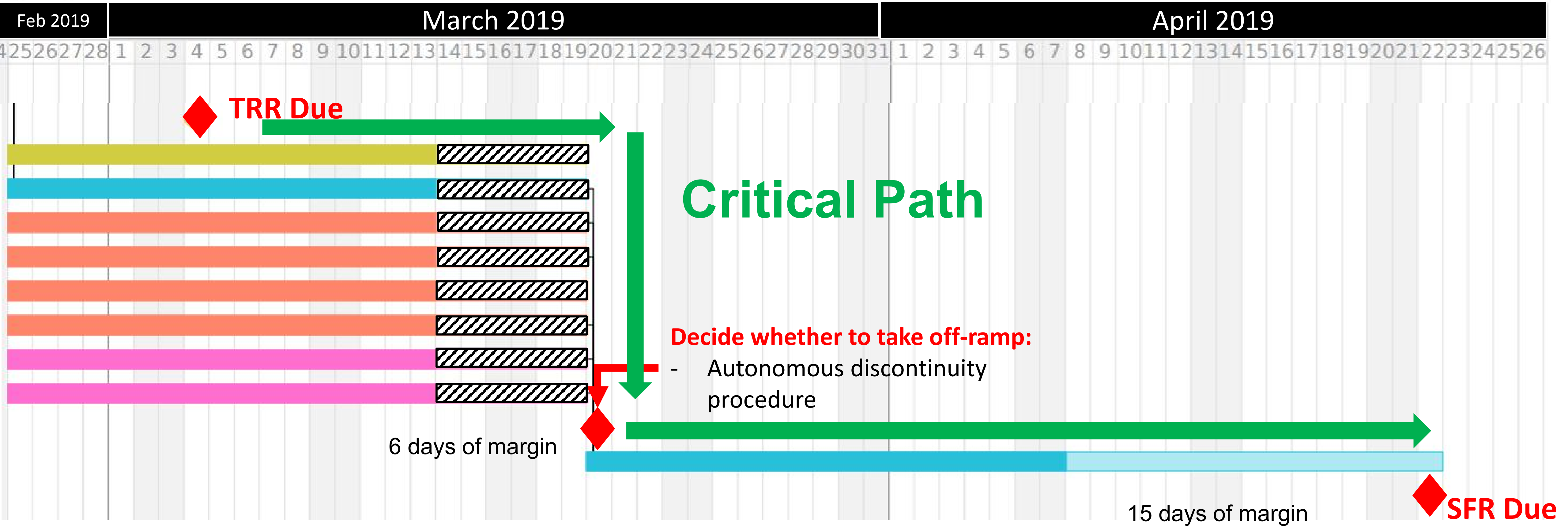
Legend
Comms
Sensing
Mobility
Controls
= Margin
= Milestone

Work Plan



Feb 2019
March 2019
April 2019
TRR Due
Critical Path
Decide whether to take off-ramp:
- Autonomous discontinuity procedure
6 days of margin
15 days of margin
SFR Due

Test Plan

Major Test	Phase/Date	Testing Facility	Subsystem
Object detection testing	Phase 1: 1/22	CU business field	Sensing
Discontinuity detection testing	Phase 1: 1/29	Open field	Sensing
Camera operations testing	Phase 1: 2/5	CU Boulder South	Sensing
Motor validation - Torque curve characterization	Phase 1: 2/12	ITLL	Mobility
Communications Testing	Phase 1: 2/19	CU Boulder South	Comms
C&DH Testing & Integration	Phase 2: 2/24-3/19	ITLL	C&DH
Sensing Integration	Phase 2: 2/24-3/19	Senior Project Room	Sensing, C&DH
Rover functional testing	Phase 3: 3/19	Parking lot – flat ground	Mobility
Environmental maneuverability testing	Phase 3: 3/26	CU Boulder South	Mobility
Obstacle maneuverability testing	Phase 3: 4/7	20° slope next to ITLL	Mobility

Note: Tests in Phase 1 are not dependent on each other

Cost Plan

Most Expensive Subsystems:
1. Mobility
2. Sensing
3. Communication
4. Navigation

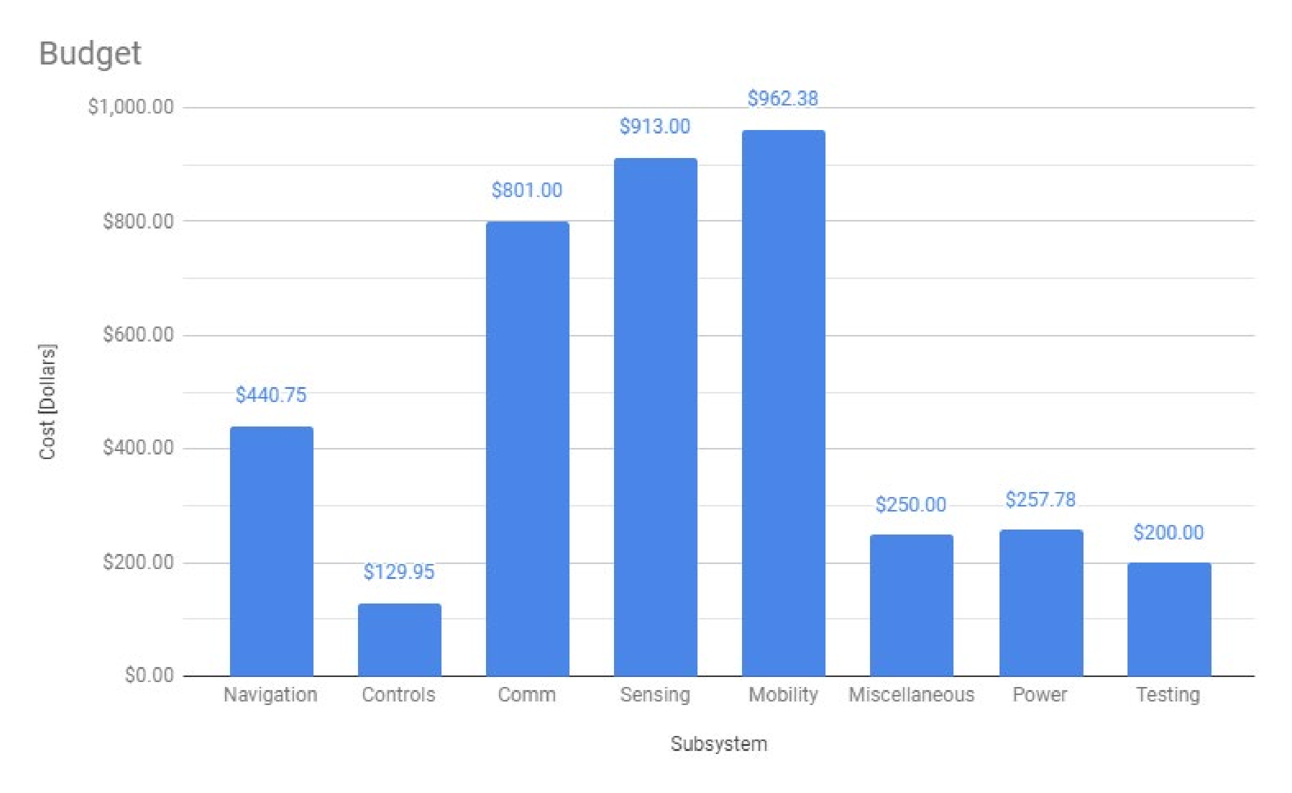
Current Budget Without Margin: $3,954.86

15% Margin: $593.23

Total Budget with Margin: **$4548.09**

Remaining Funds: **$451.91**

*current budget includes items from BoM, shipping costs, and electronic wiring



University of Colorado Boulder

HERMES

University of Colorado Boulder · Jet Propulsion Laboratory

JPL

Jet Propulsion Laboratory

Backup Slides

References

1. "AndyMark Redline Motor", Retrieved November 13, 2018, from http://www.andymark.com/RedLine-Motor-p/am-3775.htm. NOTE: No motor curve longer on website, is shown
2. "57 Sport", Retrieved Number 13, 2018, from https://www.andymark.com/products/57-sport-options
3. "8 in. Rubber Treaded Wheel", Retrieved November 14, 2018 from https://www.andymark.com/products/8-in-rubber-treaded-wheel
4. "Pololu Dual VNH5019 Motor Driver Shield for Arduino", Retrieved November 13, 2018 from https://www.pololu.com/product/2507
5. "Gens Ace 4S LiHV 100C LiPo Battery Pack (15.2V/7500mAh)", Retrieved November 13, 2018 from https://www.amainhobbies.com/gens-ace-4s-lihv-100c-lipo-battery-pack-15.2v-7500mah-ga-b1102/p779337
6. "CNC Router Single Axis 3.5A TB6560 Stepper Stepping Motor Driver 16 Microstep Factory price MD430" Retrieved November 28, 2018 from https://www.aliexpress.com/store/product/CNC-Router-Single-Axis-3-5A-TB6560-Stepper-Stepping-Motor-Driver-16-Microstep-Factory-price-MD430/907217_2041316513.html
7. “NEO-M8P u-blox M8 High Precisions GNSS Modules”, Retrieved November 20, 2018, from “https://cdn.sparkfun.com/assets/2/f/6/8/3/NEO-M8P_DataSheet__UBX-15016656_.pdf”
8. “LSM202DLHC”, Retrieved November 27, 2018, from “https://cdn-shop.adafruit.com/datasheets/LSM303DLHC.PDF”
9. “RPLIDAR A2M8 360 Degree Laser", Retrieve November 15 from "https://www.slamtec.com/en/Lidar/A2Spec"
10. “LIDAR-Lite v3”, Retrieved November 15 2018, from “https://www.sparkfun.com/products/14032?_ga=2.41586212.746972706.1541356129-811093297.1535990000&_gac=1.6416262.1540966863.EAIaIQobChMIhbz-8YSw3gIVDr7ACh2ERQD2EAAYASAAEgL7LPD_BwE”
11. “Ultrasonic Sensor – HC-SR04” Retrieved November 15, 2018, from “https://www.sparkfun.com/products/13959”
12. “Qwiic Magnetometer (MLX90393) Hookup Guide” Sparkfun, Retrieved November 20, 2018, from https://learn.sparkfun.com/tutorials/qwiic-magnetometer-mlx90393-hookup-guide?_ga=2.194486825.504201191.1543446845-811093297.1535990000&_gac=1.245508400.1540966863.EAIaIQobChMIhbz-8YSw3gIVDr7ACh2ERQD2EAAYASAAEgL7LPD_BwE#example-code.
13. “COMPASS HEADING USING MAGNETOMETERS” Honeywell, Retrieved November 20, 2018, from https://aerocontent.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures-documents/Magnetic__Literature_Application_notes-documents/AN203_Compass_Heading_Using_Magnetometers.pdf

Slide Directory

Main Slide Directory

Project Definition

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

Success Levels

Criteria	Level 1	Level 2	Level 3
Control	• The CSR shall navigate by received control commands from the GS • The CSR shall perform a 360 degree turn • The CSR shall drive 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 **autonomously** return to the last known GPS location if connection to the GS and MR is lost.
Communication	• 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 record and send waypoint locations after encountering an obstacle	• The CSR shall transmit continuous video feed. • The CSR shall verify its location from the LOI within +/- 5 meters • The CSR shall communicate through type D terrain up to a 250 meter radius from the deployment point

Note: Blue used for emphasis

Success Levels Continued

Criteria	Level 1	Level 2	Level 3
Environment	• The CSR shall traverse the following: 1. Open areas 2. Up to 20 degree incline slopes	• The CSR shall traverse the following: 1. Type A underbrush 2. Roots up to a 2.4 inch(6 cm) diameter	• The CSR shall traverse the following: 1. Type D underbrush 2. Up to a 9 inch wide discontinuities with depths greater than 2.4 inches (6 cm)
Range	• The CSR shall drive up to a 250 meter radius from the deployment point on flat terrain	• The CSR shall 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 degree inclined slope
Video/ Image	• The imaging system on the CSR shall capture a FOV greater than 100 degrees • The imaging system shall send time-stamped images to the MR/GS	• The CSR shall send videos to the MR/GS • The MR shall toggle the video capture from the CSR on or off	• The CSR shall send continuous video feed to the MR and GS

CONOPS: Loss of Comms

1
- CSR detects no comms

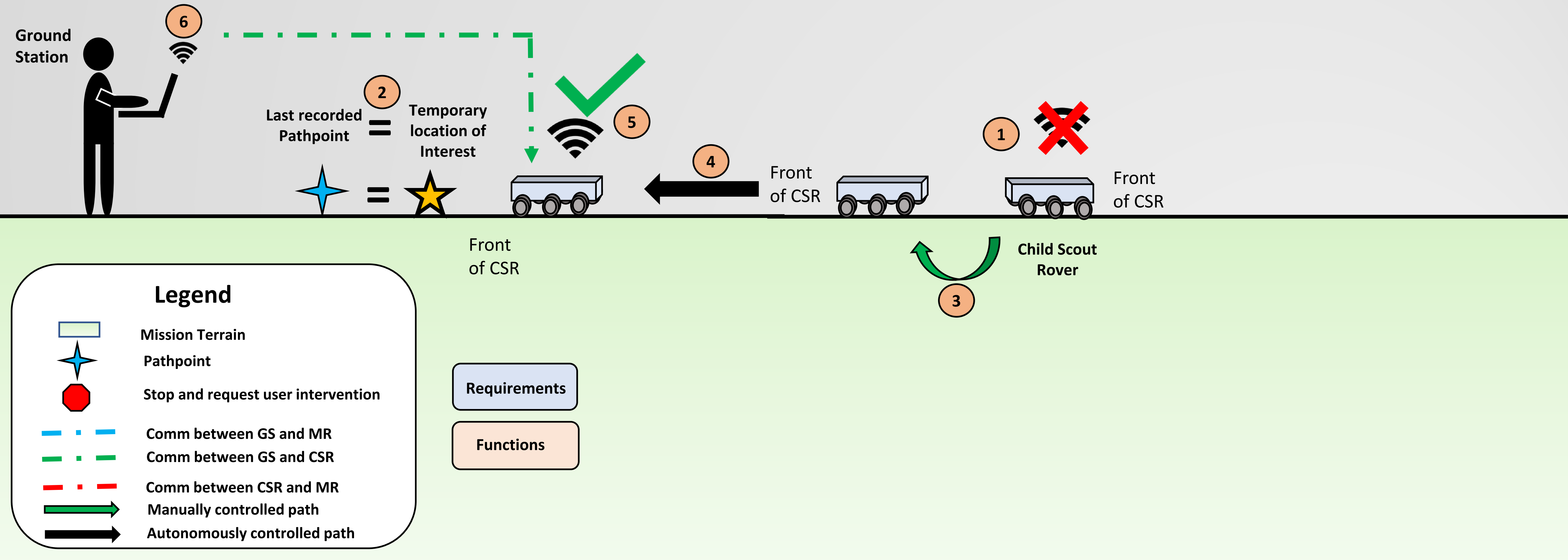
2
- CSR initiates last recorded pathpoint as a new temporary LOI

3
- CSR turns to point towards new temporary LOI

4
- CSR proceeds to travel towards new LOI

5
- Upon arrival it will stop, and wait for acquisition of communications

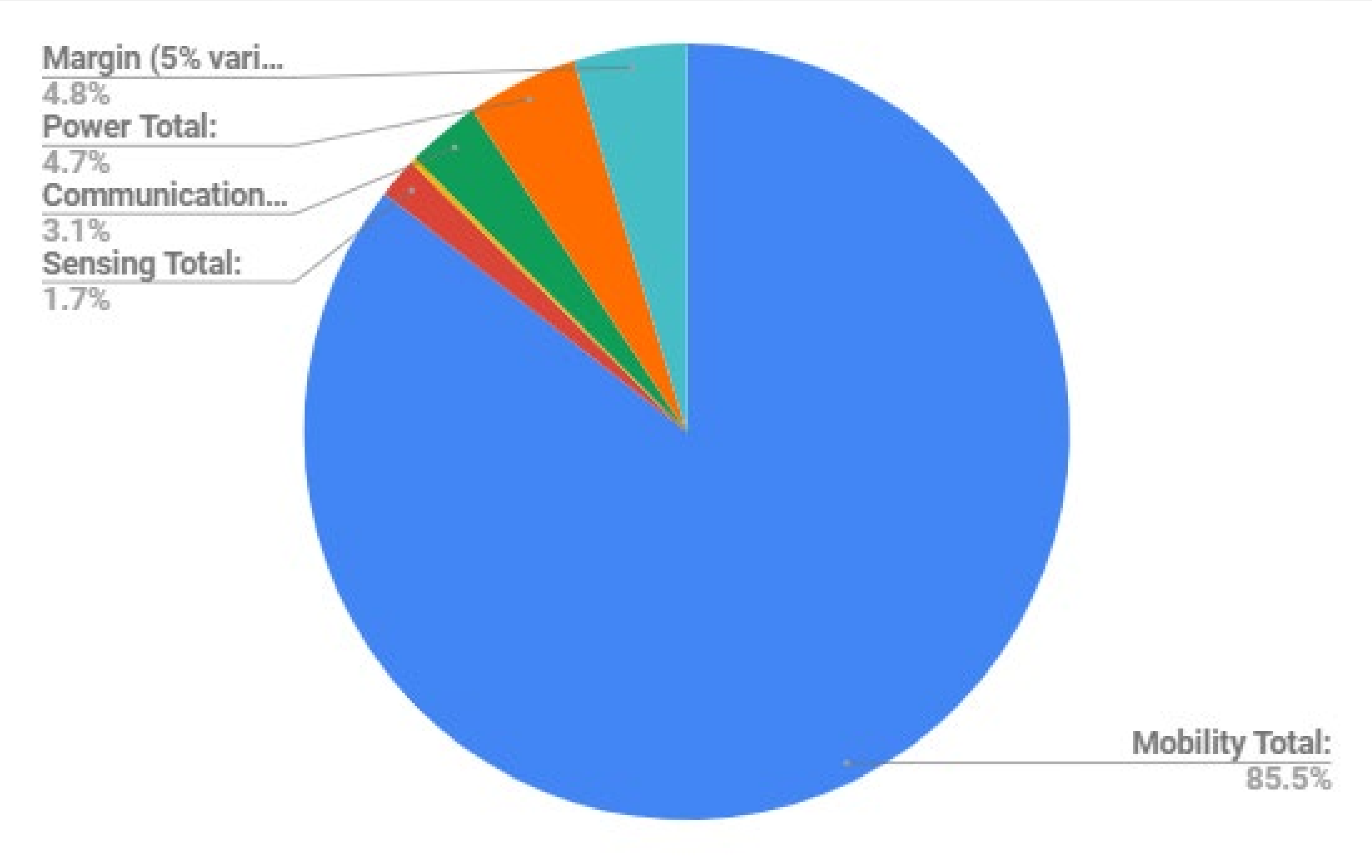
6
- Upon acquisition of signal, the operator takes control of the CSR



Systems

Mass Budget

Total Mass [lbs]	
Mobility Total:	46.342
Sensing Total:	0.916
C&DH Total:	0.135
Communications Total:	1.67
Power Total:	2.545
Margin (5% variation):	2.58
CSR Total:	54.188



Requirements

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 command packets up to 250 meters in Mission Defined Terrain with no more than a 10 dB loss *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 C&DH software shall identify the intended receiving subsystem (i.e. Mobility, Sensing, Communication) for received commands *Motivation - Since the CSR system will have multiple subsystems it is necessary that the CD&H subsystem distributes commands to the intended subsystem*	Test - Communication Demonstration
CDH.1.2	The CSR C&DH software shall distribute commands to the intended receiving subsystem (i.e. Mobility, Sensing, Communication) *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
CDH.1.3	The CSR C&DH system shall interface with the CSR Communication system receiver on a hardware and software level *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

Requirements

COMM.2.1	The CSR Communication system shall send GPS data packets to the GS or the MR through mission defined terrain (See Terrain Definition) upon request from the user *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 video frames at a frequency of at least 30 Hz *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.2.3	The CSR Communication system shall send video from up to 250 meters (820 ft) to the GS or the MR *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 Analysis
COMM.2.4	The CSR Communication system shall send GPS data from up to 250 meters (820 ft) to the GS or the MR *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 Analysis
COMM.2.5	The CSR Communication system shall send sensor data from up to 250 meters (820 ft) to the GS or the MR *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 Analysis

Requirements

CDH.2.1	The CSR C&DH system software shall time stamp collected GPS, obstacle position, and imaging data *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 C&DH system shall interface with the CSR Communication system transmitter on a hardware and software level *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

Requirements

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 - CSR Functional Demonstration Analysis
MOB.3.2	The CSR shall be able to go over discontinuities up to 9 inches *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 - Discontinuity Operation Demonstration Analysis
MOB.3.3	The CSR shall drive up or down a slope of 20 ^{o} in type A forest and underbrush terrain (See Terrain Definition) from position hold *Motivation - Since the MR can drive up and down slopes of this degree, the CSR needs to have the capability too*	Test - Inclinations Demonstration Analysis
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

Requirements

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 detect objects at least 37.5 inches (3.125 ft, 0.9525 m) from the Sensing system *Motivation - In order for the CSR to navigate itself through an unknown environment it needs a way to sense obstacles*	Test - Obstacle Detection Demonstration Analysis
SENS.3.1.1	The CSR Sensing system shall report objects within a field of view of at least 103.5° of the CSR *Motivation - Available commercial of the shelf devices have a 2D field of view at a minimum of TBD°*	Test - Obstacle Detection Demonstration Analysis
SENS.3.1.2	The CSR Sensing system shall detect objects at least 1 inch in width *Motivation - Available commercial of the shelf devices have a 2D range up to 4 meters*	Test - Obstacle Detection Demonstration Analysis

Requirements

SENS.3.2	The CSR Sensing system shall detect discontinuities at least 2.4 inches deep *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
CDH.3.1	The CSR C&DH shall interface with the Mobility system's power train on a hardware and software level *Motivation - For the CSR to drive commands must be sent to the power train*	Demonstration
CDH.3.2	The CSR C&DH system software shall store the Location of Interests GPS coordinates in memory. *Motivation - The MR has a width limitation of 5 ft (1.524 meters)*	Test - Obstacle Detection Analysis Demonstration

Requirements

CDH.3.3	The CSR C&DH system shall determine if the CSR is within +/- 5 meters of the location of interest *Motivation - In order for the CSR to remain on course with the Location of Interest the location must be stored in memory*	Demonstration
CDH.3.4	The CSR C&DH system shall determine the heading of the CSR *Motivation - In order for the user to correct the heading of the CSR to be towards the LOI the CSR's current heading must be known*	Demonstration
POW.3.1	The CSR Power system shall provide at least 69.03 Wh to the CSR *Motivation - To fulfill its mission the CSR must house enough power to do so*	Inspection

Requirements

CSR.4 : The CSR shall travel back to the last recorded waypoint upon loss of communications with the GS		
Requirement ID	**Description**	**V&V**
CDH.4.1	The CSR C&DH software shall store the last recorded node in memory *Motivation - nodes must be stored in memory to be used in the event of off-nominal communication*	Test - Off-Nominal Communication Navigation Demonstration
CDH.4.2	The CSR C&DH software shall detect loss of communications with the MR and the GS *Motivation - In order to react to a loss of comms the CSR must be monitoring communications*	Test - Off-Nominal Communication Navigation Demonstration
CDH.4.3	The CSR C&DH software shall establish a temporary Location of Interest at the last node *Motivation - To autonomously travel back to the last recorded node the CSR must know which direction to travel*	Test - Off-Nominal Communication Navigation Demonstration

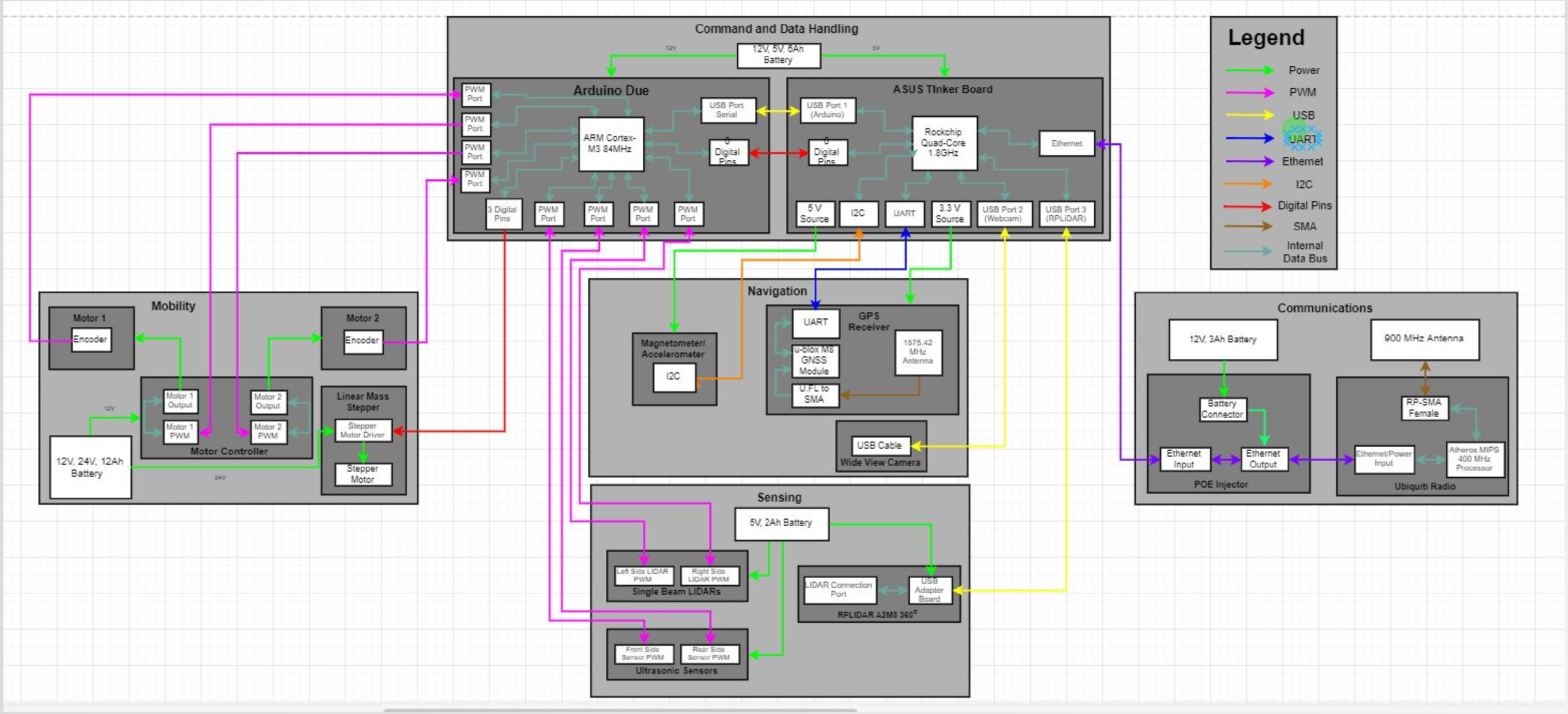
Requirements

CSR.4 : The CSR shall travel back to the last recorded waypoint upon loss of communications with the MR		
Requirement ID	**Description**	**V&V**
CDH.4.1	The CSR C&DH software shall store the last recorded node in memory *Motivation - nodes must be stored in memory to be used in the event of off-nominal communication*	Test - Off-Nominal Communication Navigation Demonstration
CDH.4.2	The CSR C&DH software shall detect loss of communications with the MR and the GS *Motivation - In order to react to a loss of comms the CSR must be monitoring communications*	Test - Off-Nominal Communication Navigation Demonstration
CDH.4.3	The CSR C&DH software shall establish a temporary Location of Interest at the last node *Motivation - To autonomously travel back to the last recorded node the CSR must know which direction to travel*	Test - Off-Nominal Communication Navigation Demonstration

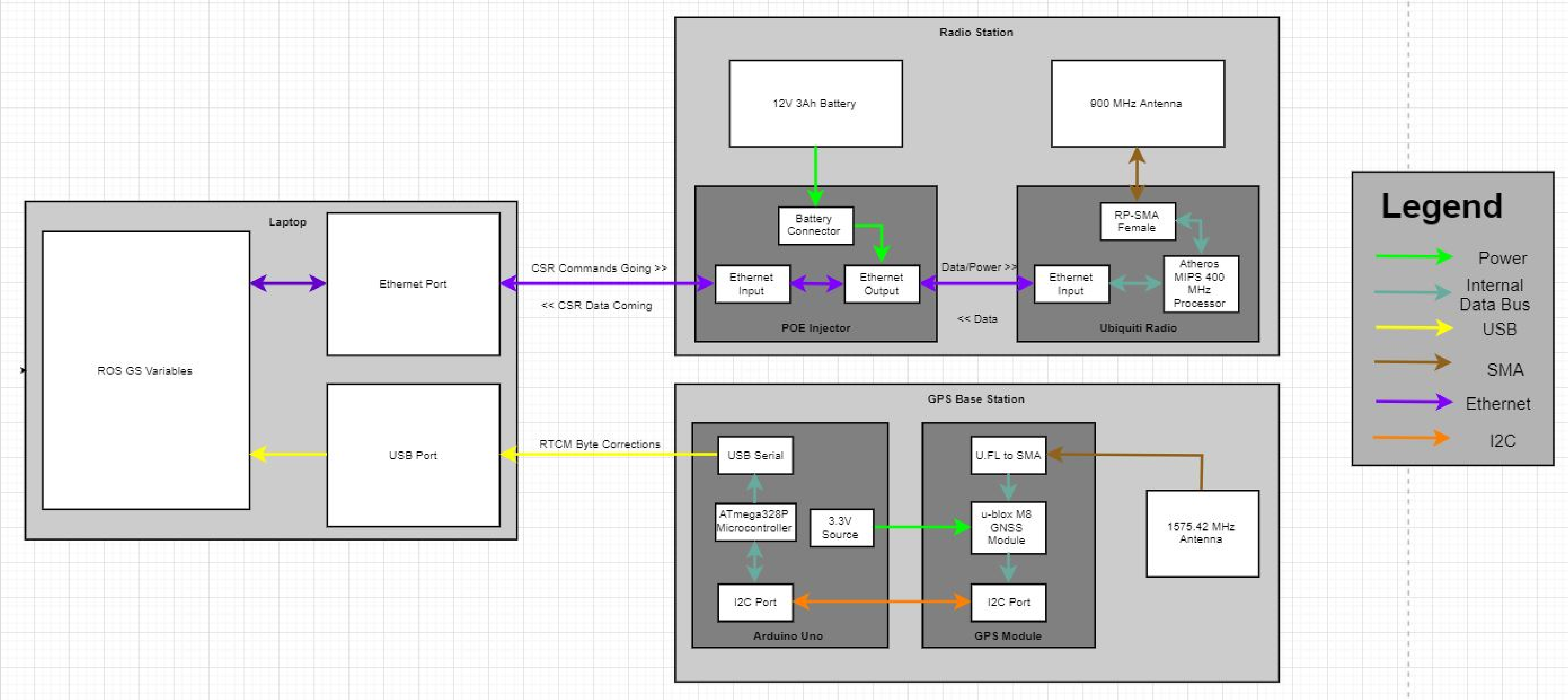
Requirements

CSR.5 : The CSR shall capture 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 INFERNO's frame rate.* [11]	Test - Camera Operation Inspection Demonstration
SENS.5.1.2	The CSR Sensing system shall take video at at least 800 x 600 pixels *Motivation - The video quality is being based on INFERNO's frame resolution.* [11]	Test - Camera Operation Inspection Demonstration
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 Demonstration

Hardware Architecture Diagram: CSR



Hardware Architecture Diagram: GS



Bill of Materials

Subsystem	Subassembly	Part Name	Description	Qty	Source	Unit Cost	Total Cost
Mechanical	Chassis	chassis_bot	Aluminum Chassis Base Plate	1	https://www.mcmaster.	$69.02	$69.02
Mechanical	Chassis	chassis_top	Acrylic Top Plate (Cut from 0.25"x12"x48" sheet)	1	https://www.mcmaster.	$39.86	$39.86
Mechanical	Chassis	chassis_housing	Acrylic Housing (Cut from 0.25"x12"x48" sheet)	1	https://www.mcmaster.	$39.86	$39.86
Mechanical	Chassis	80/20 Framing	Support struts for top plate (Part: 5 struts, 2.2 in height. Component: 2 ft)	1	https://www.mcmaster.	$7.79	$7.79
Mechanical	Chassis	80/20 Brackets	Support brackets for 80/20 framing and housing (12 for struts).	12	https://www.mcmaster.	$5.21	$62.52
Mechanical	Chassis	80/20 Fasteners	Fasteners for 80/20 struts (Need 12, Comes in pack of 4)	3	https://www.mcmaster.	$2.30	$6.90
Mechanical	Chassis	1" 1/4-20 Screws	Plate-Strut Fastener. Need 9, comes in pack of 50	1	https://www.mcmaster.	$8.14	$8.14
Mechanical	Chassis	14-20 Nuts	Plate-Strut-Bracket Fastener. Need 10, comes in pack of 50	1	https://www.mcmaster.	$4.60	$4.60
Mechanical	Chassis	1/4" Washer	Washers for 1/4-20 Screws. Need 19, comes in pack of 100	1	https://www.mcmaste	$3.37	$3.37
Mechanical	Chassis	0.75" 1/4-20 Screws	Screws for Plate-Strut-Bracket Fastener. Need 10, comes in pack of 50	1	https://www.mcmaste	$7.48	$7.48
Mechanical	Chassis	General Purpose Corner Brackets	Corner brackets to support the acrylic housing and walls	12	https://www.mcmaste	$1.00	$12.00
Mechanical	Chassis	0.5" 10-32 Screws	Screws to fix corner brackets interfaces. (Need 20, Comes in pack 100)	1	https://www.mcmaster.	$9.60	$9.60
Mechanical	Chassis	10-32 Nuts	Fastener for corner bracket interfaces. (Need 20, Comes in pack of 100)	1	https://www.mcmaster.	$3.77	$3.77
Mechanical	Chassis	Shaft Mount	Part: 12 of 2"x0.5"x1.5" aluminum blocks. Stock: 1 of 2"x0.5"x24"	1	https://www.mcmaster.	$17.86	$17.86
Mechanical	Chassis	1" 1/4-20 Screws	Screws to mount shaft mount to base plate (Need 12, use from line 8).	12	Line 8	$0.00	$0.00
Mechanical	Chassis	1/4-20 Helicoils	Helicoil Inserts for shaft mount (Need 24, Comes in pack of 10)	3	https://www.mcmaster.	$6.15	$18.45
Mechanical	Chassis	0.5" 10-32 Screws	Screws to mount the gearbox to the base plate (Need 8, use from line 13)	8	Line 13	$0.00	$0.00
Mechanical	Chassis	#10 Washers	Washers for gearbox screws (Need 8, Comes in pack of 100)	1	https://www.mcmaster.	$2.33	$2.33
Mechanical	Drive Train	AndyMark 775 RedLine Motor	Drive Motor	2	ıark.com/RedLine-Motc	$18.00	$36.00
Mechanical	Drive Train	57 Sport 64:1 Gearbox	Drive train gearbox	2	http://www.andymark.	$96.00	$192.00

Bill of Materials

Mechanical	Drive Train	AndyMark Motor Vent Spacer	Drive Motor Ventilation Spacer	2	https://www.andymark	$5.00	$10.00
Mechanical	Drive Train	Wheel Sprocket (#25-38t)	Sprocket to fix to wheel	8	https://www.vexrobotic	$11.99	$95.92
Mechanical	Drive Train	Gearbox Sprocket (#25-22t)	Sprocket to fix to gearbox	4	https://www.vexrobotic	$9.99	$39.96
Mechanical	Drive Train	10-24 Wheel Set Screws	Screws fixing sprocket to wheel. Need 36. Comes in set of 50.	1	https://www.andymark	$8.50	$8.50
Mechanical	Drive Train	Chains	5 ft, 1/4 in pitch chains for drive train	1	https://www.mcmaster.	$25.70	$25.70
Mechanical	Drive Train	Shaft	Part: 6 of 3.75", 1/2"OD Shaft. Stock: 1 of 24", 1/2" OD Shaft	1	https://www.mcmaster.	$17.21	$17.21
Mechanical	Drive Train	Wheels	8" Rubber Treaded Wheels	6	https://www.andymark	$12.00	$72.00
Mechanical	Drive Train	Bearings	1/2" ID Wheel Bearings	6	https://www.andymark	$3.00	$18.00
Mechanical	Drive Train	Shaft Collars	1/2" ID Shaft collars to ensure wheels stay on shafts	12	https://www.mcmaster.	$2.51	$30.12
Mechanical	Linear Mass Stage	Linear Stage	Actuated Linear Stage to vary CoM	1	https://www.amazon.c	$98.99	$98.99
Mechanical	Linear Mass Stage	Linear Mass	Mass used to vary CoM	1	https://www.mcmaster.	$39.49	$39.49
SUBTOTAL							$997.44
Subsystem	**Subassembly**	**Part Name**	**Description**	**Qty**	**Source**	**Unit Cost**	**Total Cost**
Power	Power	Sensing Battery	Sensing Battery	1	https://www.adafruit.c	$12.50	$12.50
Power	Power	Motor Battery	Motor Battery	1	https://www.amainhob	$139.99	$139.99
Power	Power	Communication Battery	Communication Battery	1	https://www.amazon.c	$24.79	$24.79
Power	Power	Computer Battery	Computer Battery	1	https://www.amazon.c	$34.00	$34.00
SUBTOTAL							$211.28

Bill of Materials

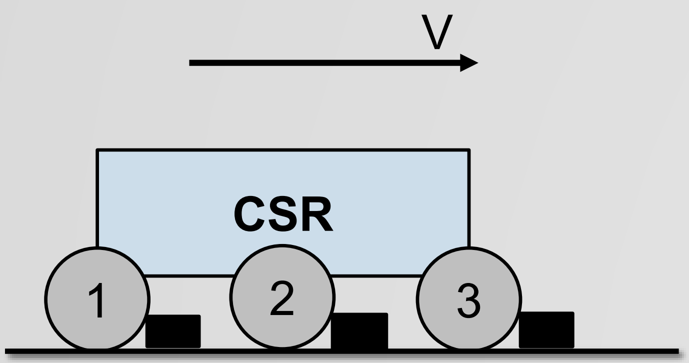
Subsystem	Subassembly	Part Name	Description	Qty	Source	Unit Cost	Total Cost
C&DH	C&DH	ASUS Tinker Board	ASUS Tinker Board	1	https://www.asus.com	$80.00	$80.00
C&DH	C&DH	Arduino Due	Arduino Due	1	https://www.sparkfun.	$49.95	$49.95
SUBTOTAL							$129.95
Subsystem	**Subassembly**	**Part Name**	**Description**	**Qty**	**Source**	**Unit Cost**	**Total Cost**
Comms	Comms	Ubiquiti Radio	Ubiquiti Radio	3	https://www.amazon.c	$118.95	$356.85
Comms	Comms	POE Adapter	POE Adapter	3	https://www.amazon.c	$44.90	$134.70
Comms	Comms	900 MHz Antenna	900 MHz Antenna	6	http://www.l-com.com	$26.84	$161.04
SUBTOTAL							$652.59
Subsystem	**Subassembly**	**Part Name**	**Description**	**Qty**	**Source**	**Unit Cost**	**Total Cost**
GNC	Motor Controls	Drivetrain Motor Controller	Drivetrain Motor Controller	1	www.pololu.com/produ	$49.95	$49.95
GNC	Motor Controls	Linear Stage Stepper Controller	Linear Stage Stepper Controller	1	l198988&hvpos=1o1&h	$13.99	$13.99
GNC	Sensing	360 Degree Lidar	360 Degree Lidar	1	w.sparkfun.com/produ	$319.95	$319.95
GNC	Sensing	Ultrasonic Range	Ultrasonic Range	2	w.sparkfun.com/produ	$3.95	$7.90
GNC	Sensing	Single Beam Lidar	Single Beam Lidar	2	.1535990000&_gac=1.	$129.99	$259.98
GNC	Sensing	180 degree Fisheye Lens	180 degree Fisheye Lens	1	MZJNR1X3E&pd_rd_v	$45.00	$45.00
GNC	Nav	GPS Module	GPS Module	2	w.sparkfun.com/produ	$199.95	$399.90
GNC	Nav	GPS Antenna	GPS Antenna	2	https://www.sparkfun.	$12.95	$25.90
GNC	Nav	Magnetometer/Accelerometer	Magnetometer/Accelerometer	1	ww.adafruit.com/prod	$14.95	$14.95
SUBTOTAL							$1,137.52
	TOTAL						$3,128.78

Note: This bill of materials does not include electronics, shipping, and testing materials.
But the cost plan includes all of these.

Mobility

Mobility – Obstacle Model

MOB.3.4 The CSR shall be able to drive in underbrush
MOB.3.4.1 The CSR shall drive over a traversable obstacle up to 2.4 inches (0.06096 m) in height



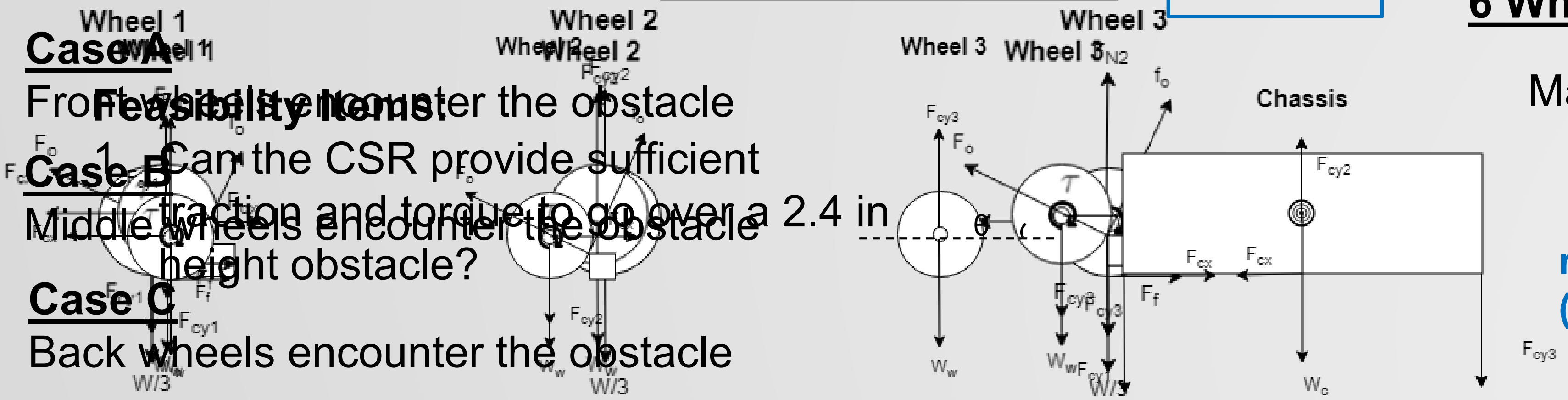
Legend:

- 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?

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

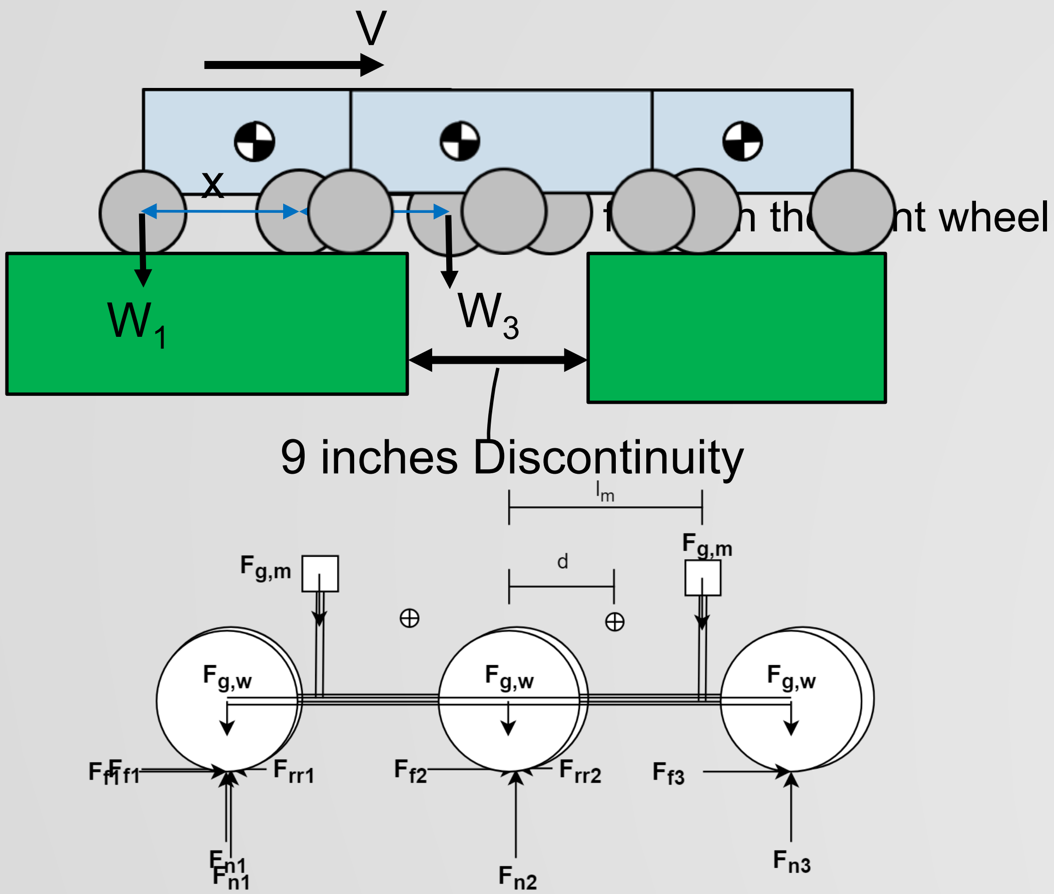
Maximum torque required: 12.3 Nm

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

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

Mobility - Discontinuity Model

MOB.3.2 The CSR shall be able to go over discontinuities up to 9 inches (0.2286 m)



Feasibility Items:

1. Can the CSR provide sufficient traction and torque to cross a 9 inches discontinuity?

Baseline Assumptions:

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

Results

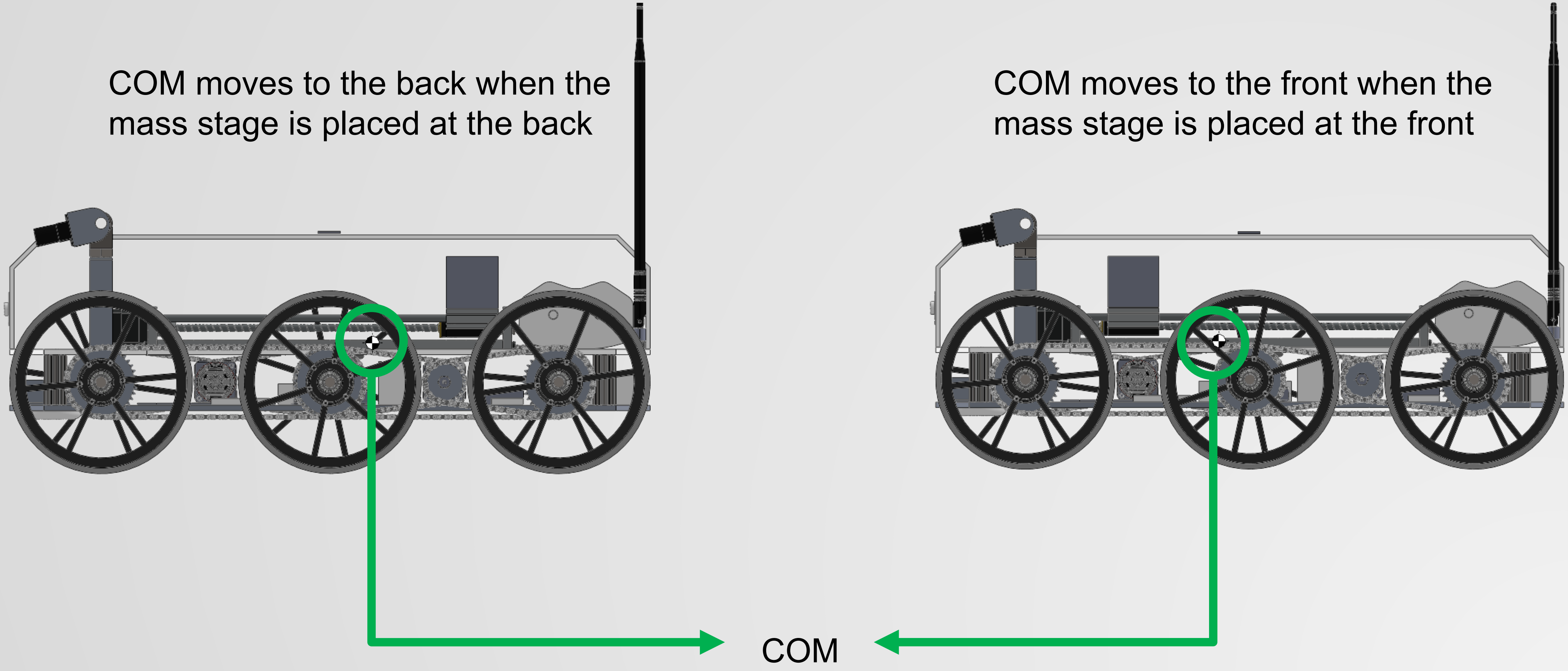
1. Driving over a flat gap requires less torque than driving over obstacles
2. Feasibility of Case 2 obstacle proves feasibility of crossing discontinuity

FEASIBLE

Mobility – Center of Mass

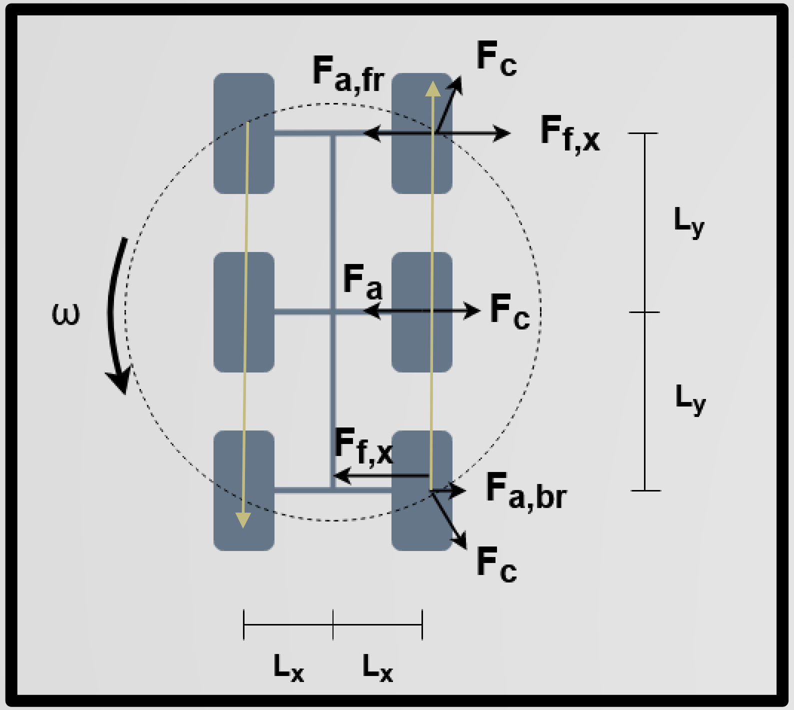
COM moves to the back when the mass stage is placed at the back

COM moves to the front when the mass stage is placed at the front



Mobility - 360 Degree Turn / Skid Steering

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. Angular Velocity = 0.5 rad/s (4.25 rpm)

FEASIBLE

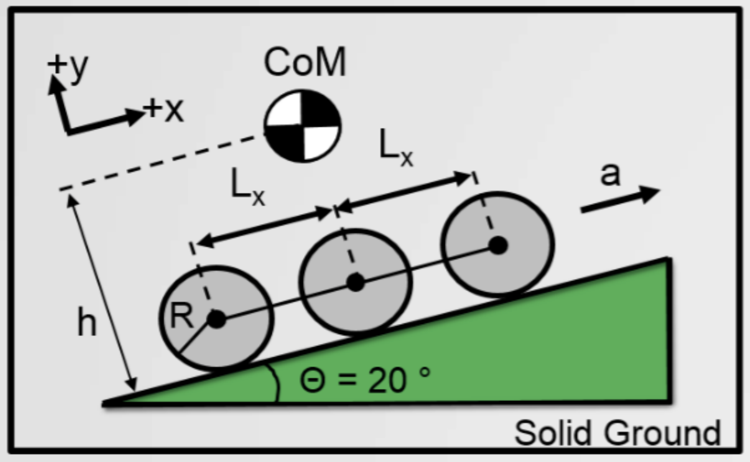
Mobility – Slope Model

MOB.3.3 - The CSR shall drive up or down a slope of up to 20 degrees in type A terrain (See Terrain Definition)

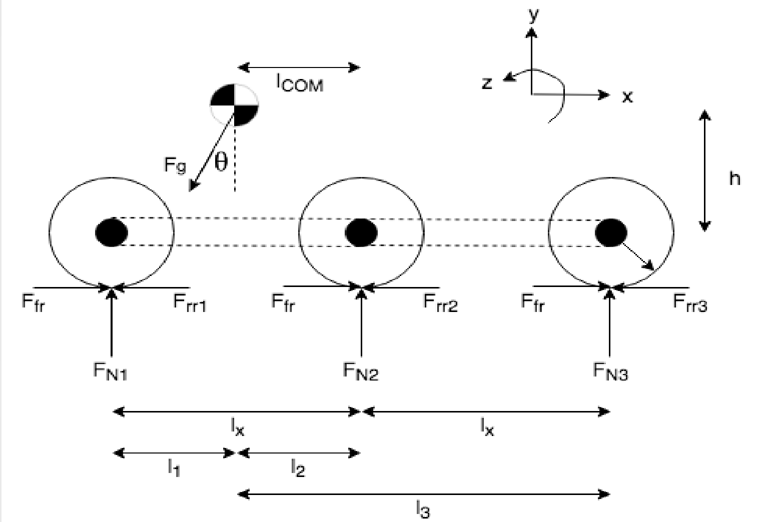
Feasibility Items:
1. Instantaneous power required
2. Torque required by a single motor

Baseline Assumptions:
1. Roll no-slip
2. Weights act as single point forces CoM (Center of Mass)
3. CoM is not the moving mass location
4. Rigid Chassis

Results using Baseline Dimensions:
1. Gravel (Crr = 0.02, μ = 0.60)
   2. Torque required by a single motor = 3.6702 Nm
2. Sand (Crr = 0.20, μ = 0.60)
   2. Torque required by a single motor = 5.3908 Nm



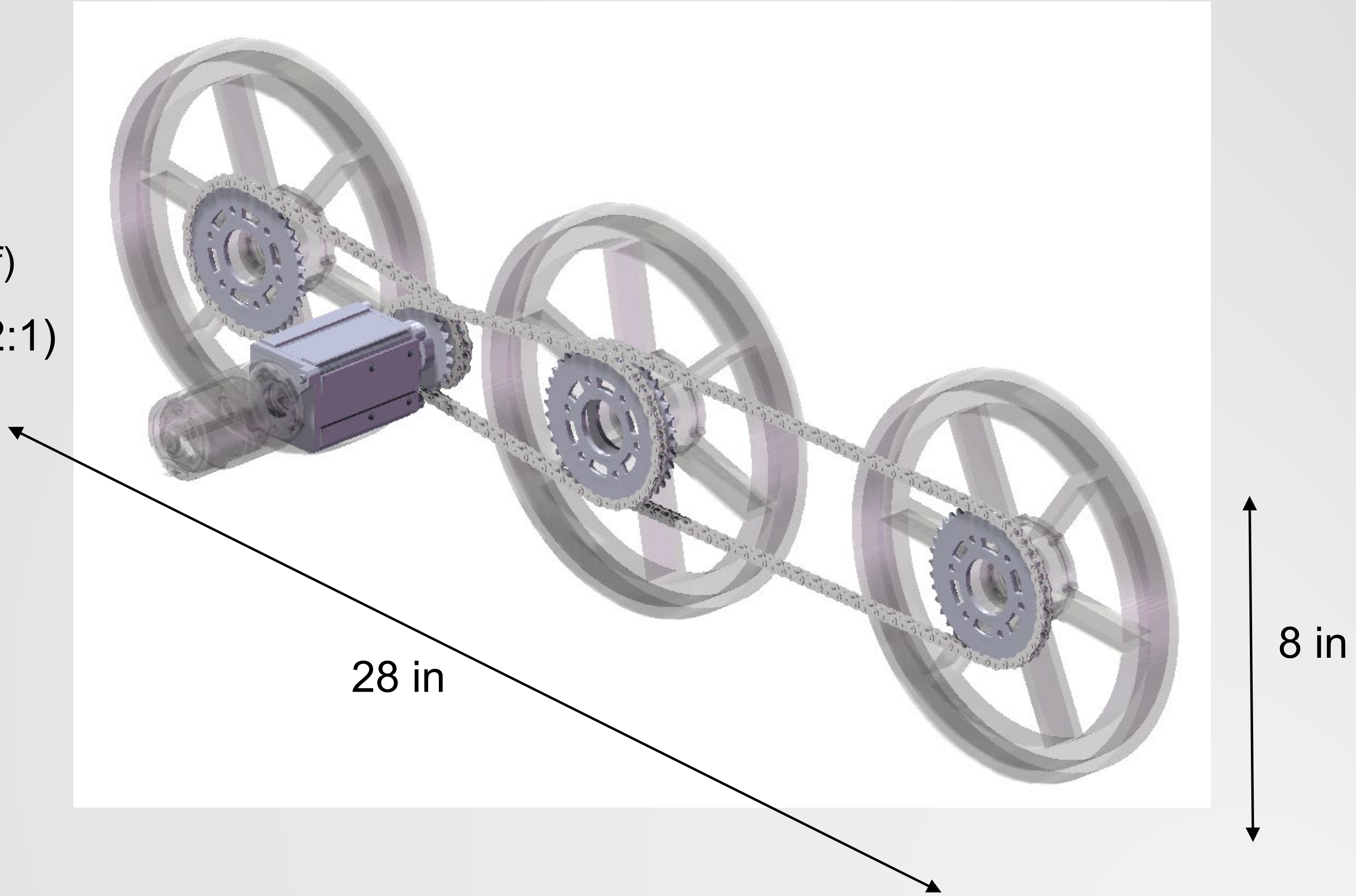
Free Body Diagram



Mobility – Hardware Specifications

Gear Train:

- 57 Sport Planetary Gearbox (64:1)
  - Gear Ratio = 64:1
  - Maximum Torque: 40.1 Nm (29.6 ft-lbf)
- 38:22 Tooth Sprocket Assembly (1.72:1)
- Effective Gear Ratio (110:1)

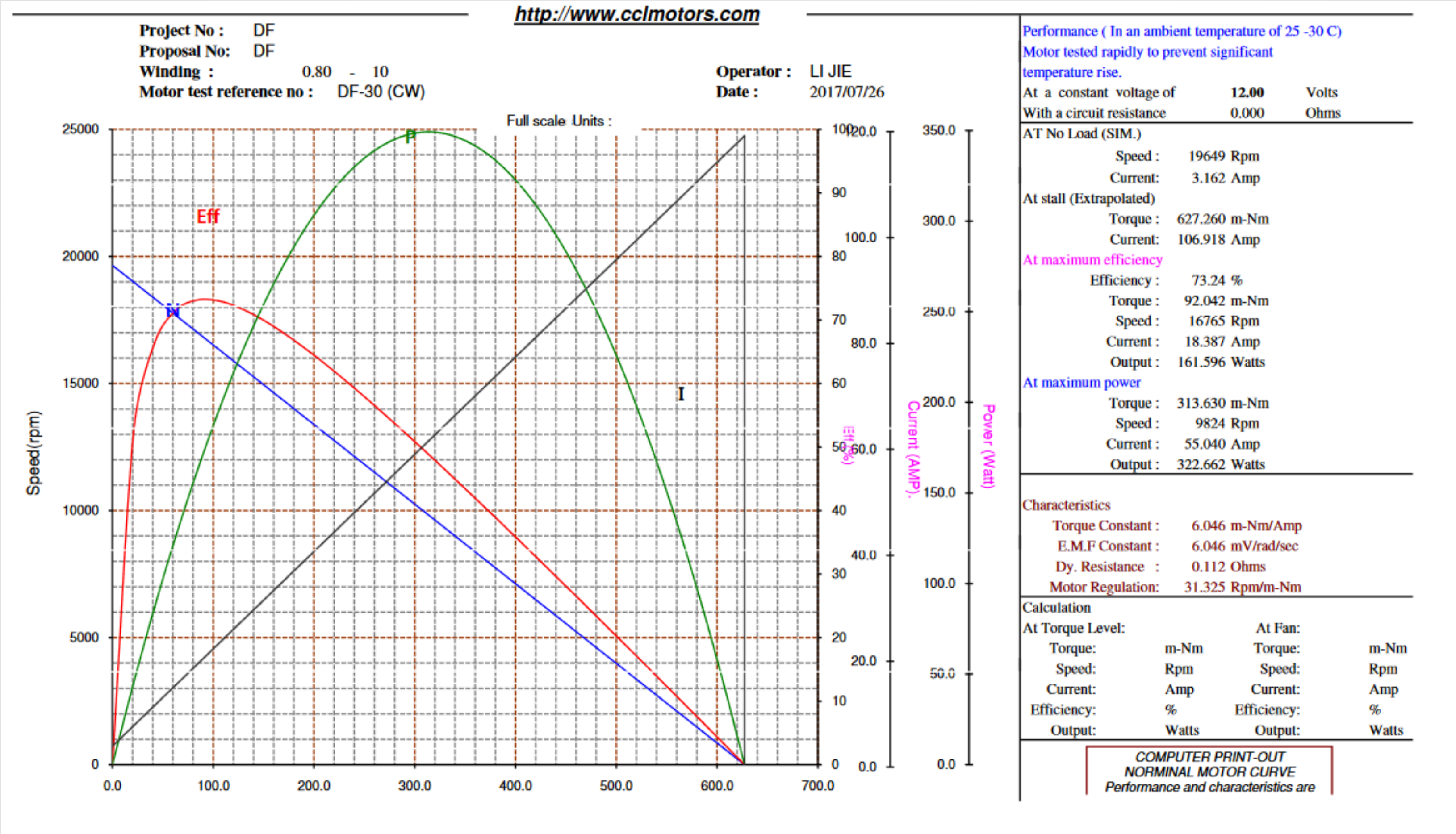


Mobility – Hardware Specifications

AndyMark 755 Redline Motor:

Using 64:1 Gearbox and 38:22 tooth gear train (n = 110:1) at peak expected torque (11.1 Nm)

- Motor Torque: 101 mNm
- Motor Max Loaded RPM: 16500 rpm
- CSR Max Speed: 1.76 m/s
- Pulse Current: 20 A
- Effective Current at 1 m/s: 11.4 A



Mobility – Hardware Specifications

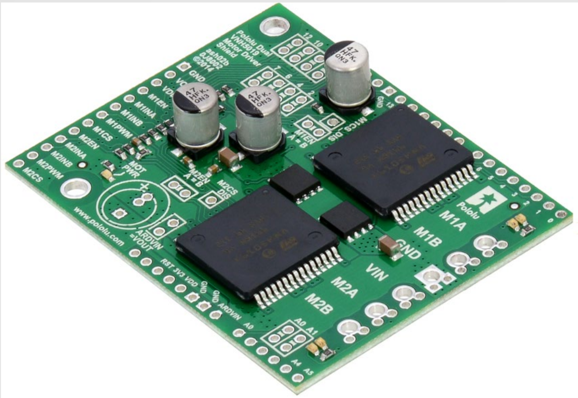
Pololu Dual VNH5019 Motor Driver:

Expected Current Loads:

- Slope:
  - Peak Current Draw: 11 A
  - Max Speed: 1.95 m/s
  - Expected Current Draw: 5.6 A
- Obstacle:
  - Peak Current Draw: 20 A each motor
  - Max Speed: 1.75 m/s
  - Expected Current Draw: 11.43
- Nominal (Gravel):
  - Peak Current Draw: 3.2 A each motor
  - Max Speed: 2.1 m/s
  - Expected Current Draw: 1.5 A each motor

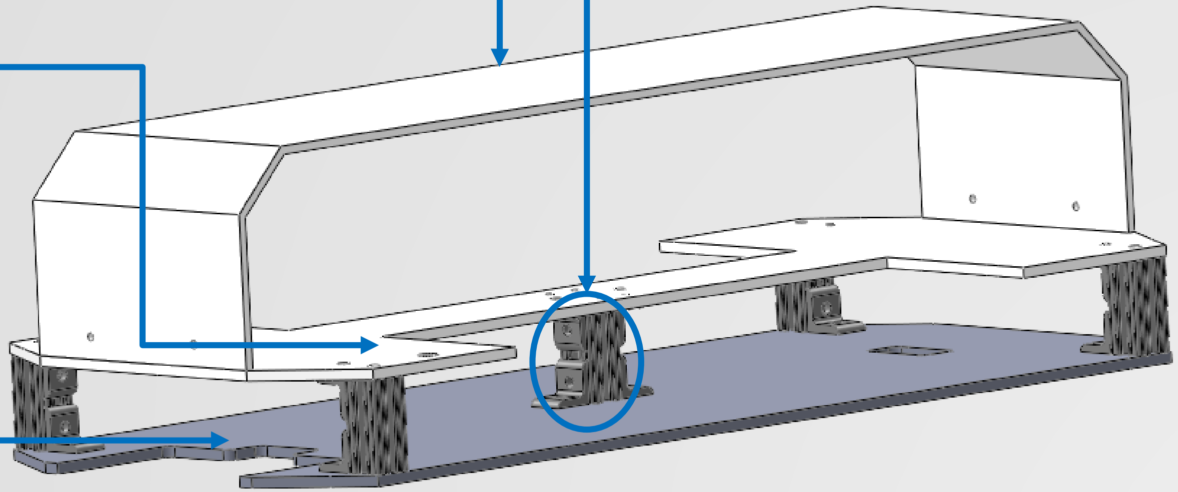
Driver Capacity:

- 12 A Continuous Draw
- 30 A Instantaneous Draw



Final Design Overview: Child Scout Rover

CSR structure:
- 80-20 supports
- Acrylic housing
- Acrylic top platform with 0.25' thickness
- Aluminum bottom platform with 0.25' thickness
- Pillow blocks for the shafts
- Shaft with 0.5' diameter



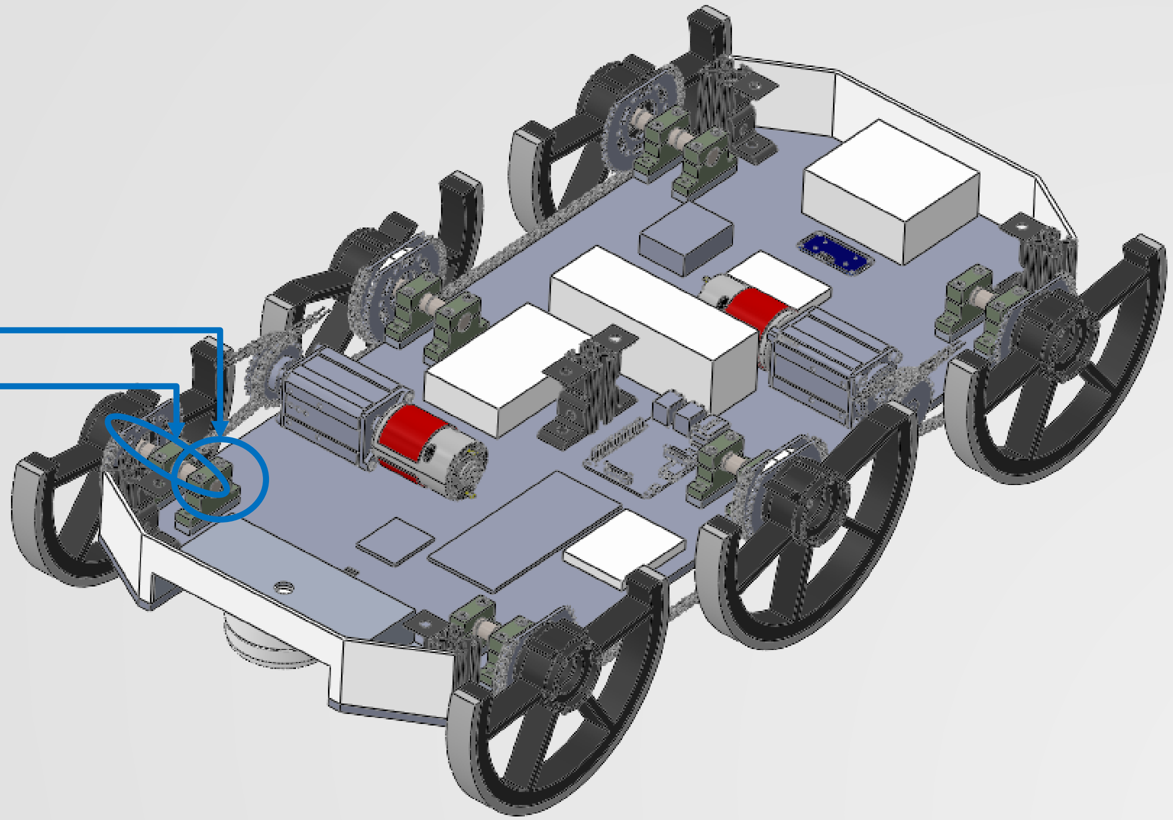
Section Cut View

← **= Outlines components**

Note: Green indicates component being outlined

Final Design Overview: Child Scout Rover

CSR structure:
- 80-20 supports
- Acrylic housing
- Acrylic top platform
- Aluminum bottom platform
- Pillow blocks for shafts
- Shaft

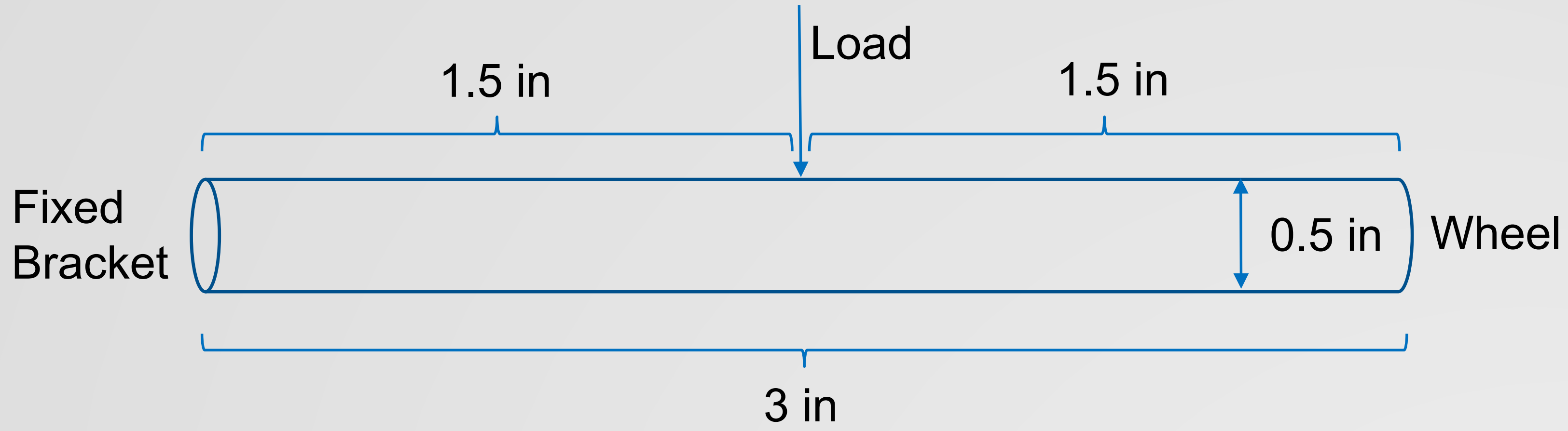


Section Cut View

= **Outlines components**

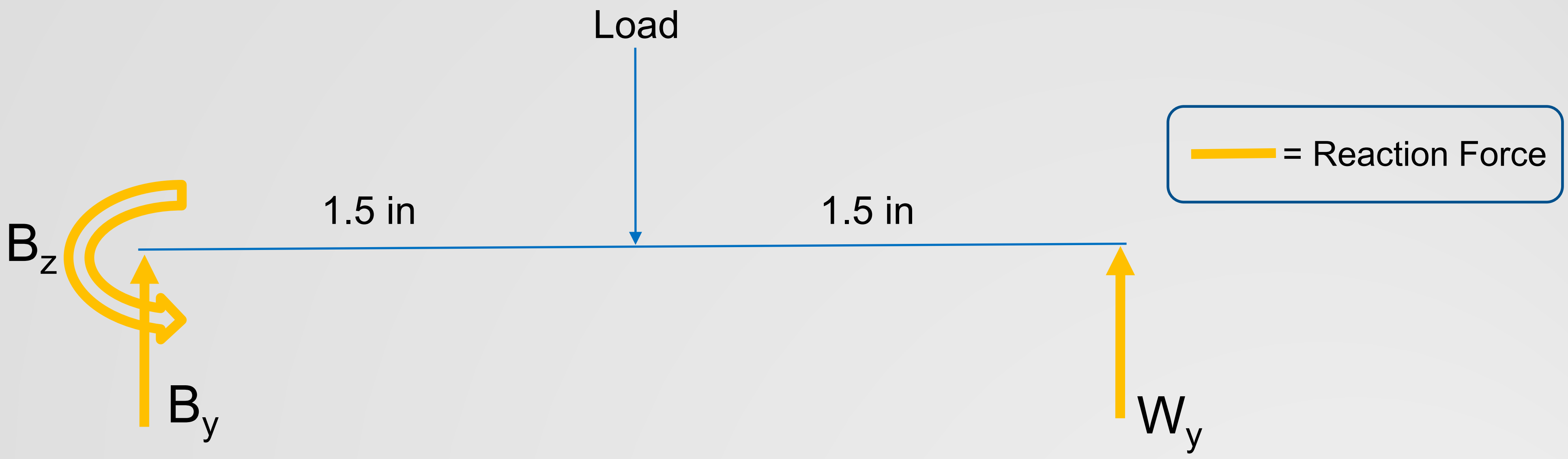
Note: Green indicates component being outlined

Force Analysis of the Shaft



- The shaft is supporting the chassis right in the middle
- Having 6 shafts, each shaft supports 1/6 weight of the chassis in regular condition
- Material: 303 Stainless Steel
- Yield Strength: 45,000 psi

Force Analysis of the Shaft



- Bracket is fixed
- Neglecting the force in the X direction of the wheel because it is a lot smaller compare to gravity force.
- Since a lot of forces are neglected, the factor of safety is 3 for the calculation.

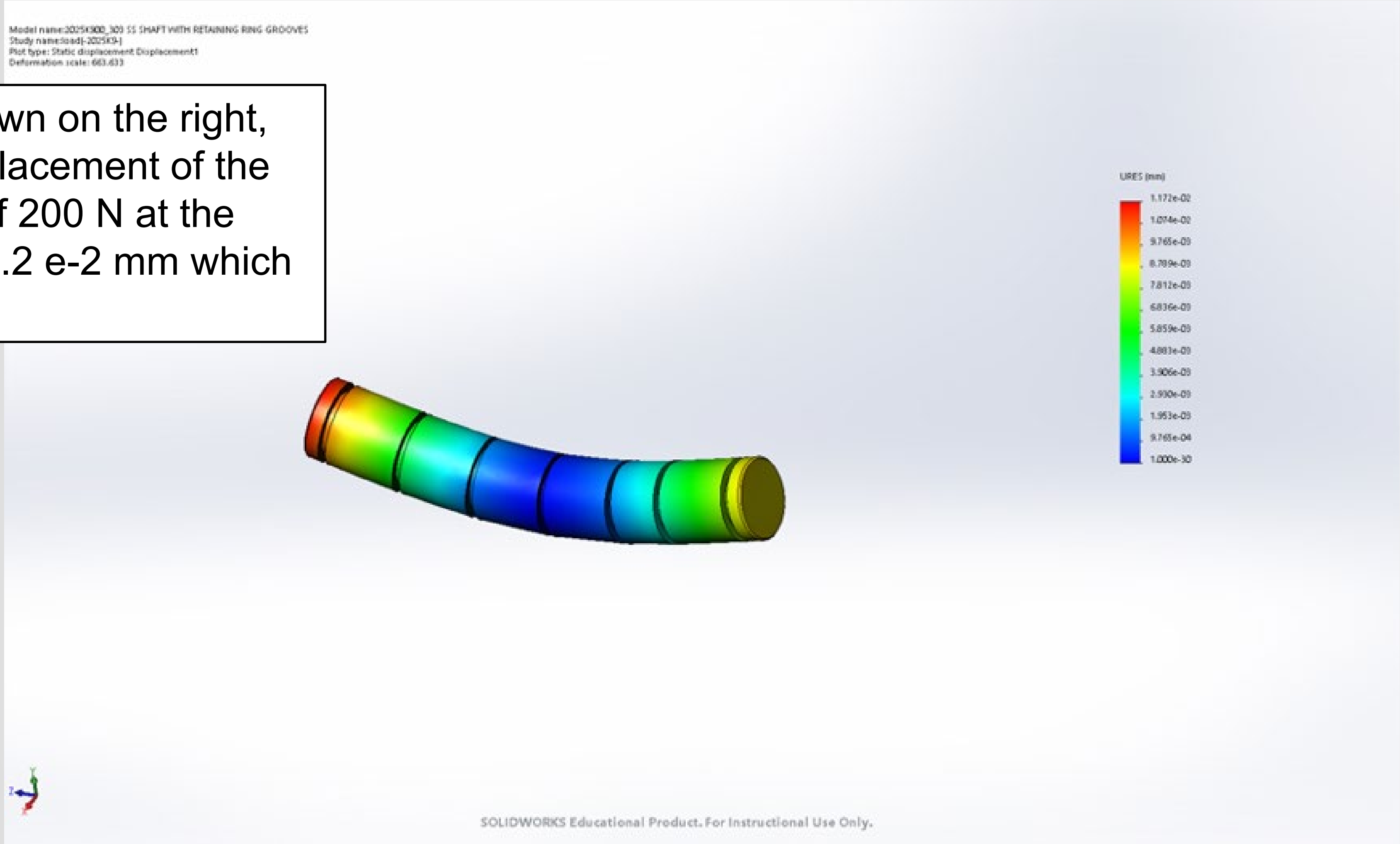
Force Analysis of the Shaft

	1/6 $W_{chassis}$	¼ $W_{chassis}$	½ $W_{chassis}$	Capability
Maximum Shear Stress	2,468.53 psi	3,703.6 psi	7,407.11 psi	Yield Strength 45,000 psi
Maximum Bending Moment	397.2 lbf in	595.8 lbf in	1,192 lbf in	26,595 lbf in

- Safety Factor of 3
- Wheel shafts are not experiencing torsion because the wheels are coupled to the shaft through bearings. The sprockets are fixed to the wheels, which are driving the wheels. Thus, no calculation needed for torsion.
- Only the gearbox shaft that is experiencing torsion. Full gearbox assembly is rated 3 times of our expected load (40Nm vs 12Nm), thus the requirement is still satisfied.

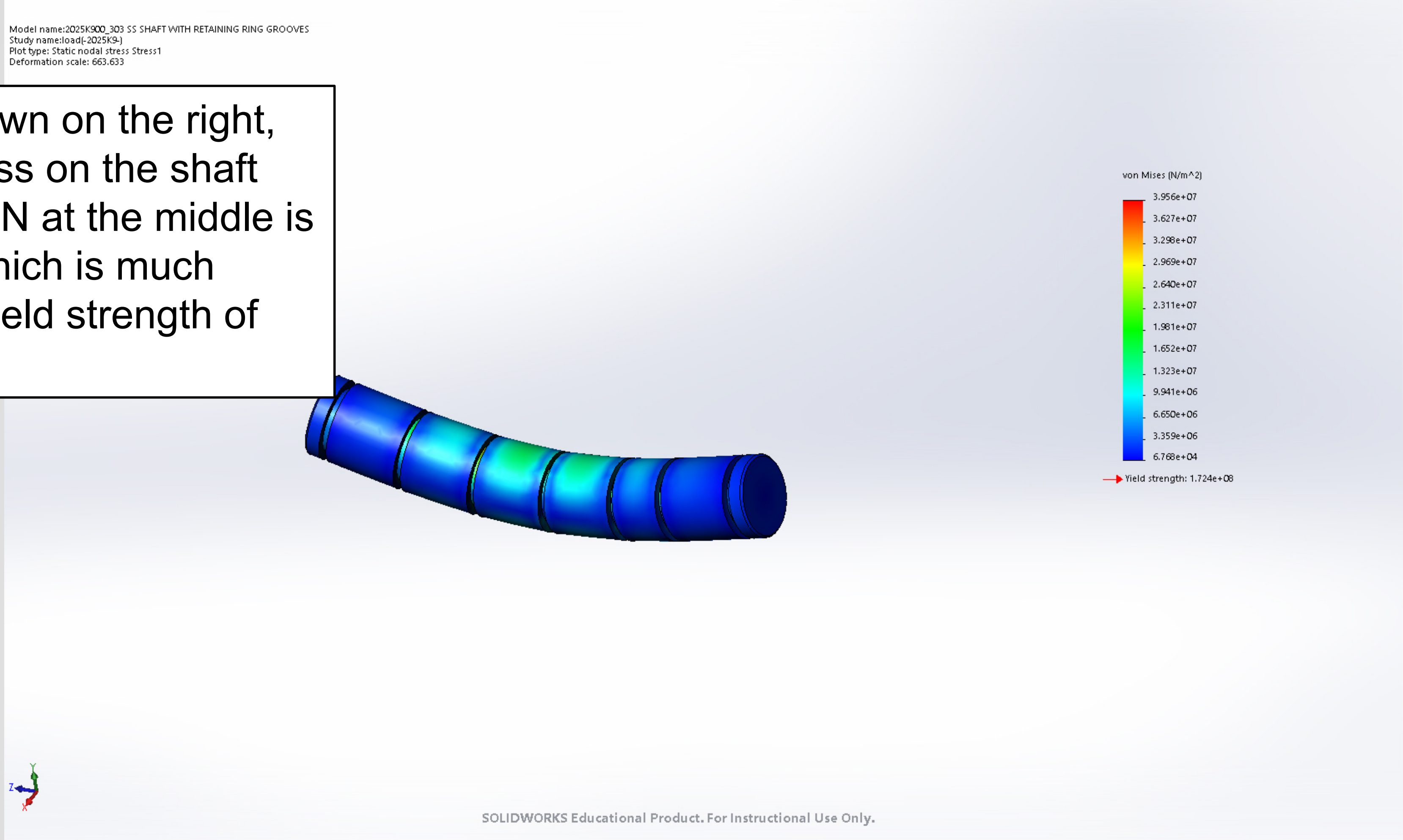
Mobility – Shaft FEA Tests : Displacement

From the FEA shown on the right, the maximum displacement of the shaft with a load of 200 N at the middle is around 1.2 e-2 mm which is negligible.



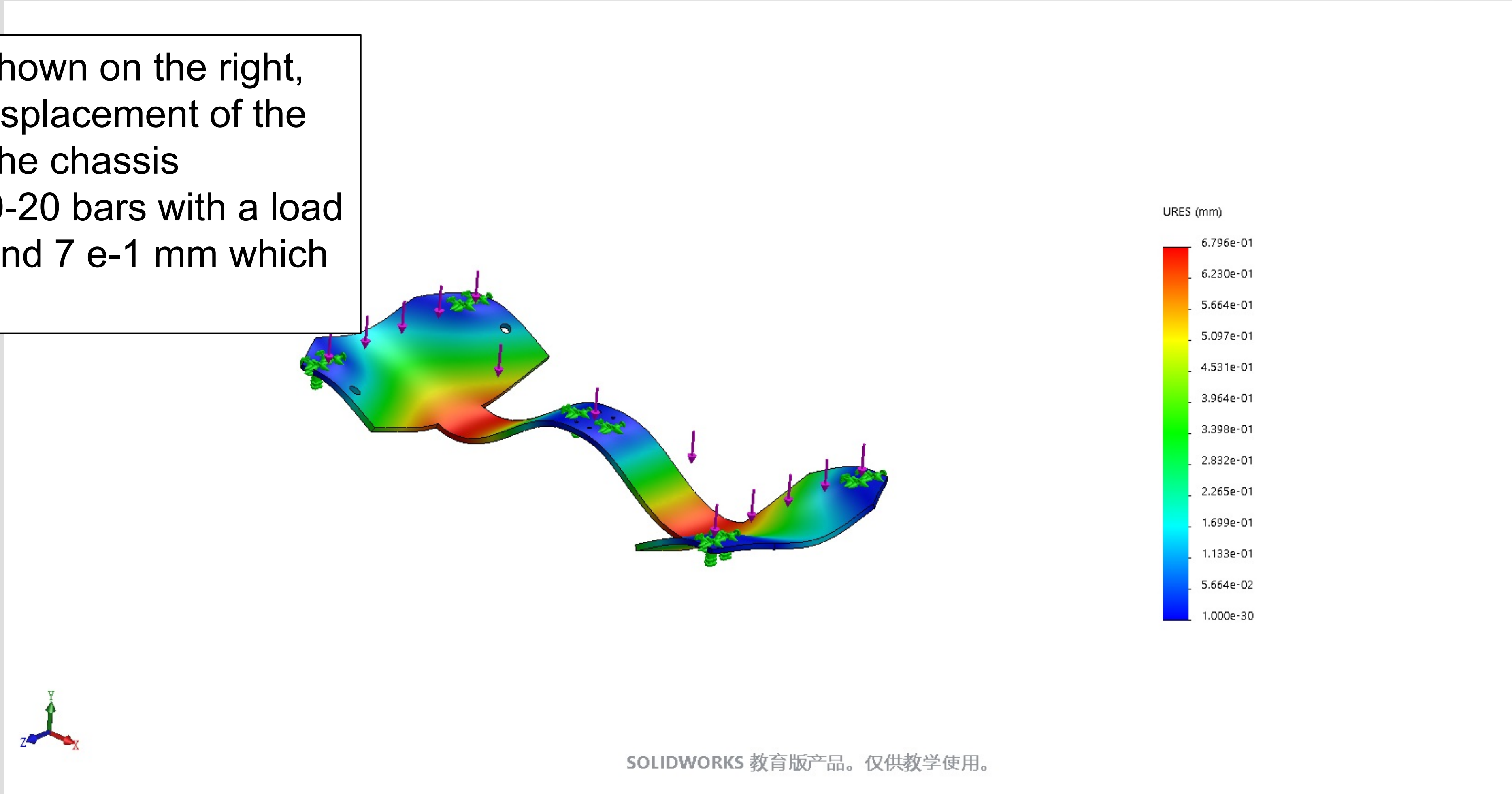
Mobility – Shaft FEA Tests: Stress

From the FEA shown on the right, the maximum stress on the shaft with a load of 200 N at the middle is around 4 e7 Pa which is much smaller than the yield strength of the shaft.



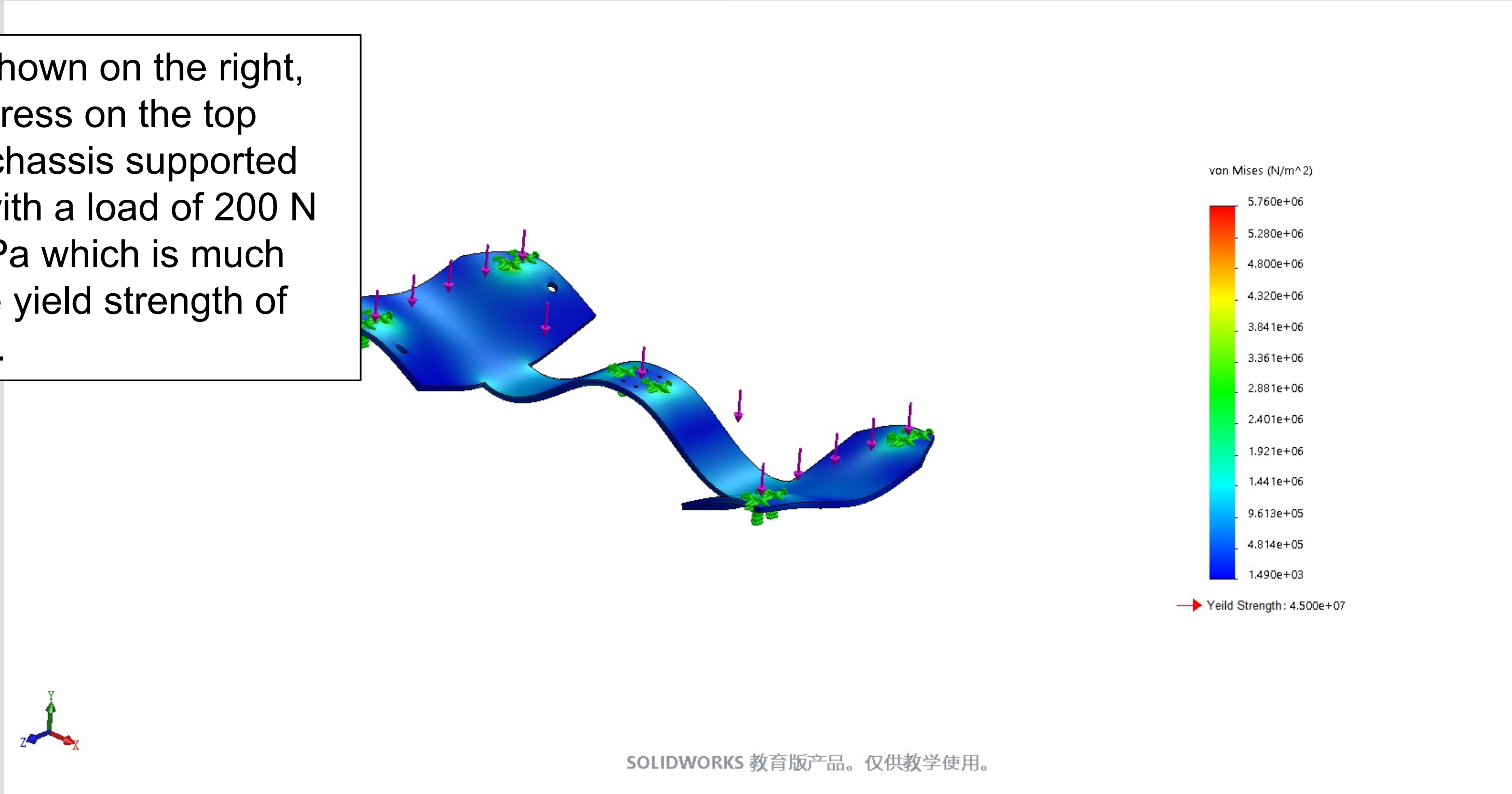
Mobility – Chassis FEA Tests :

From the FEA shown on the right, the maximum displacement of the top platform of the chassis supported by 80-20 bars with a load of 200 N is around 7 e-1 mm which is negligible.



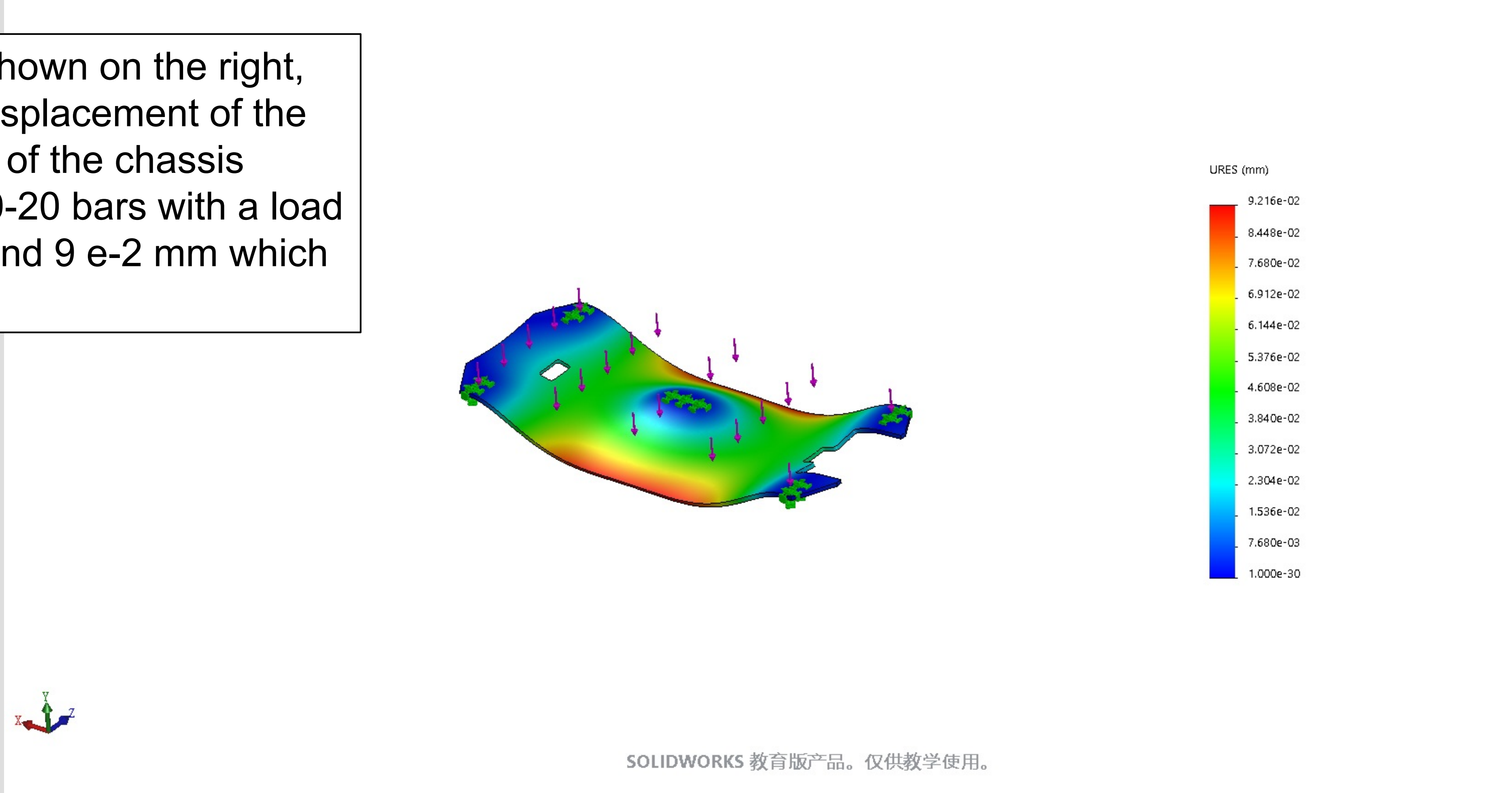
Mobility – Chassis FEA Tests :

From the FEA shown on the right, the maximum stress on the top platform of the chassis supported by 80-20 bars with a load of 200 N is around 6 e6 Pa which is much smaller than the yield strength of the top platform.



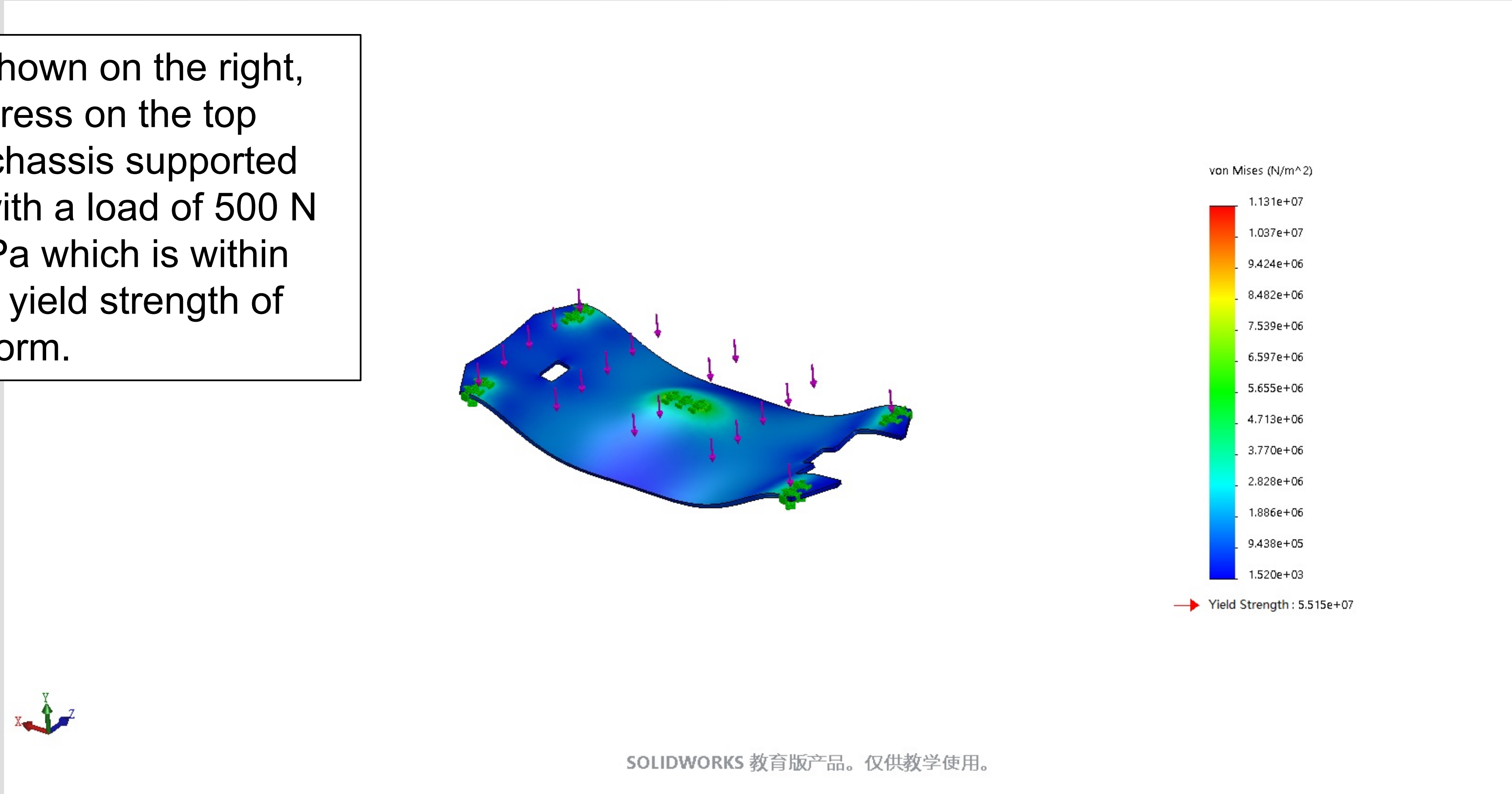
Mobility – Chassis FEA Tests :

From the FEA shown on the right, the maximum displacement of the bottom platform of the chassis supported by 80-20 bars with a load of 500 N is around 9 e-2 mm which is negligible.



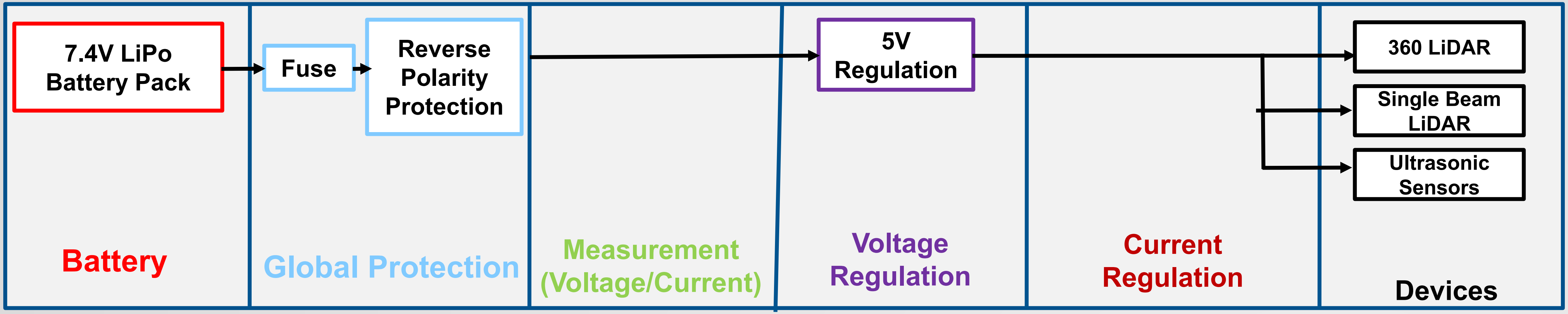
Mobility – Chassis FEA Tests :

From the FEA shown on the right, the maximum stress on the top platform of the chassis supported by 80-20 bars with a load of 500 N is around 1 e7 Pa which is within the range of the yield strength of the bottom platform.

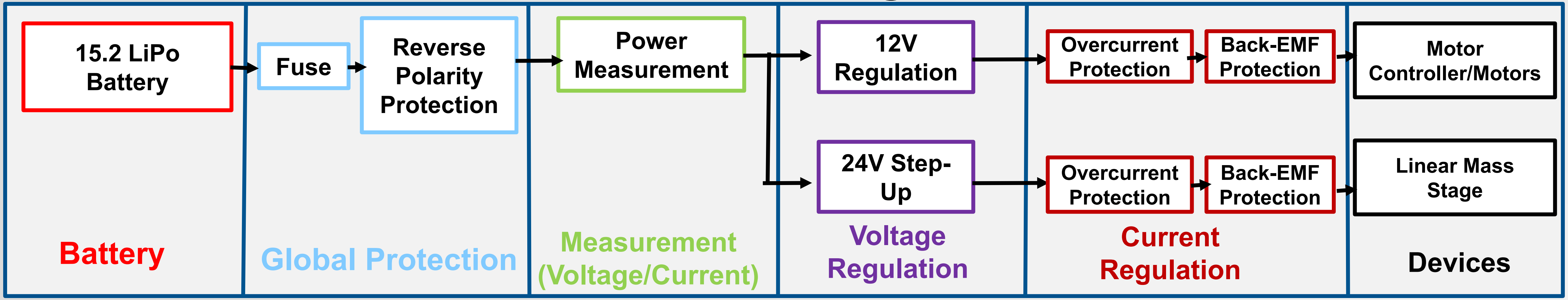


CSR Power

Power Distribution Diagrams

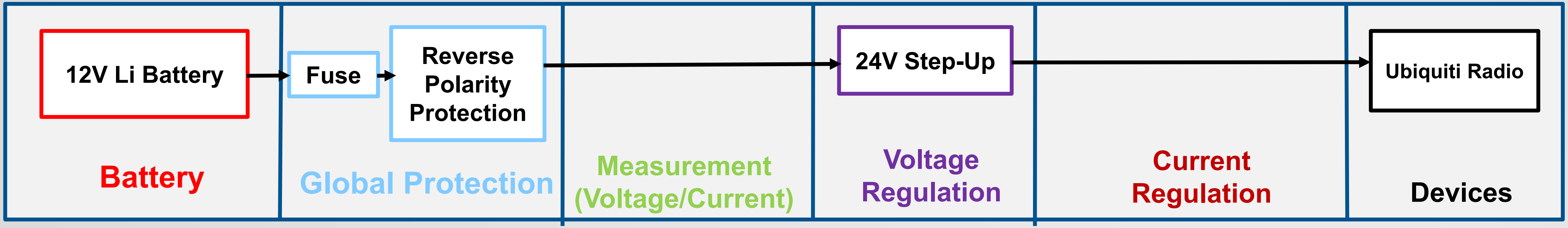


Sensing

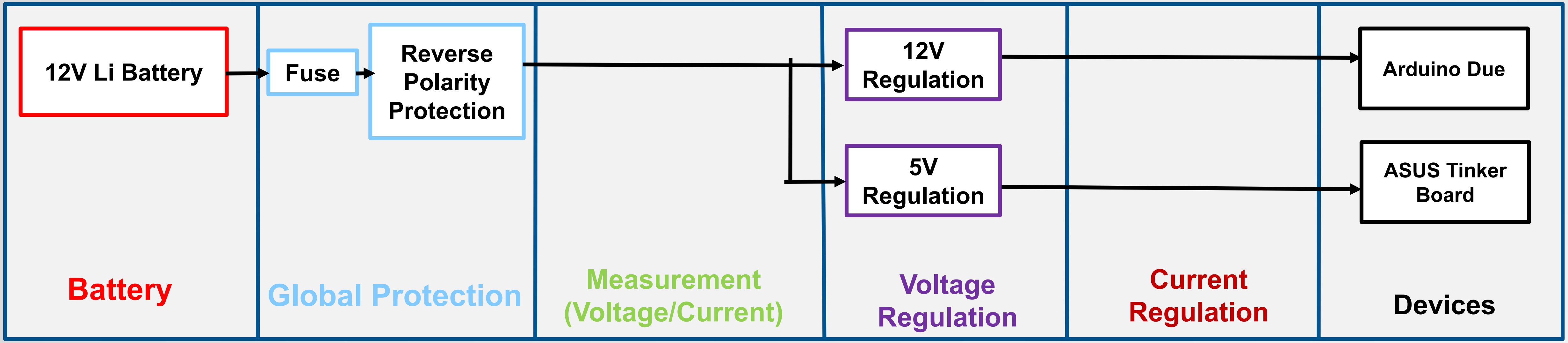


Mobility

Power Distribution Diagrams



Communications



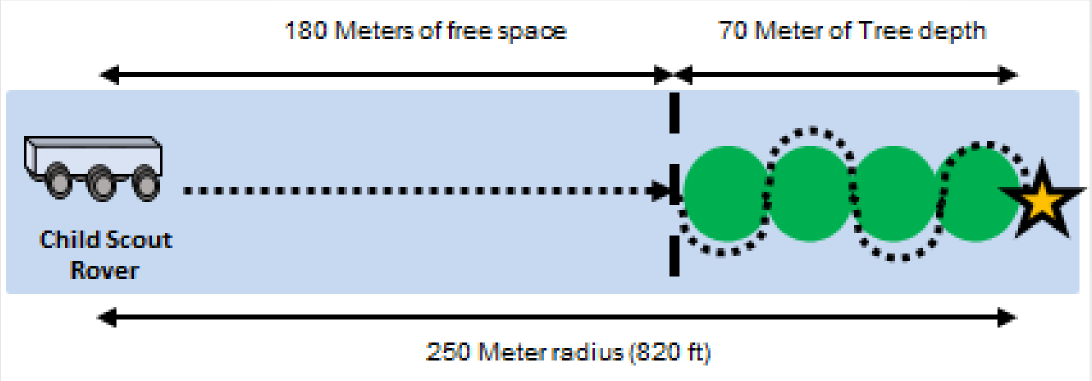
C&DH

Mobility – Power (Example Mission)

1 Hour Projected Mission

Assumptions:

- Worst case tree depth for communication (70 meters of depth)
  - 11 inches (0.2794 m) diameter trees back-to-back for the 70 meters
- Driving with average speed 0.5 [m/s]



Resulting Approximation:

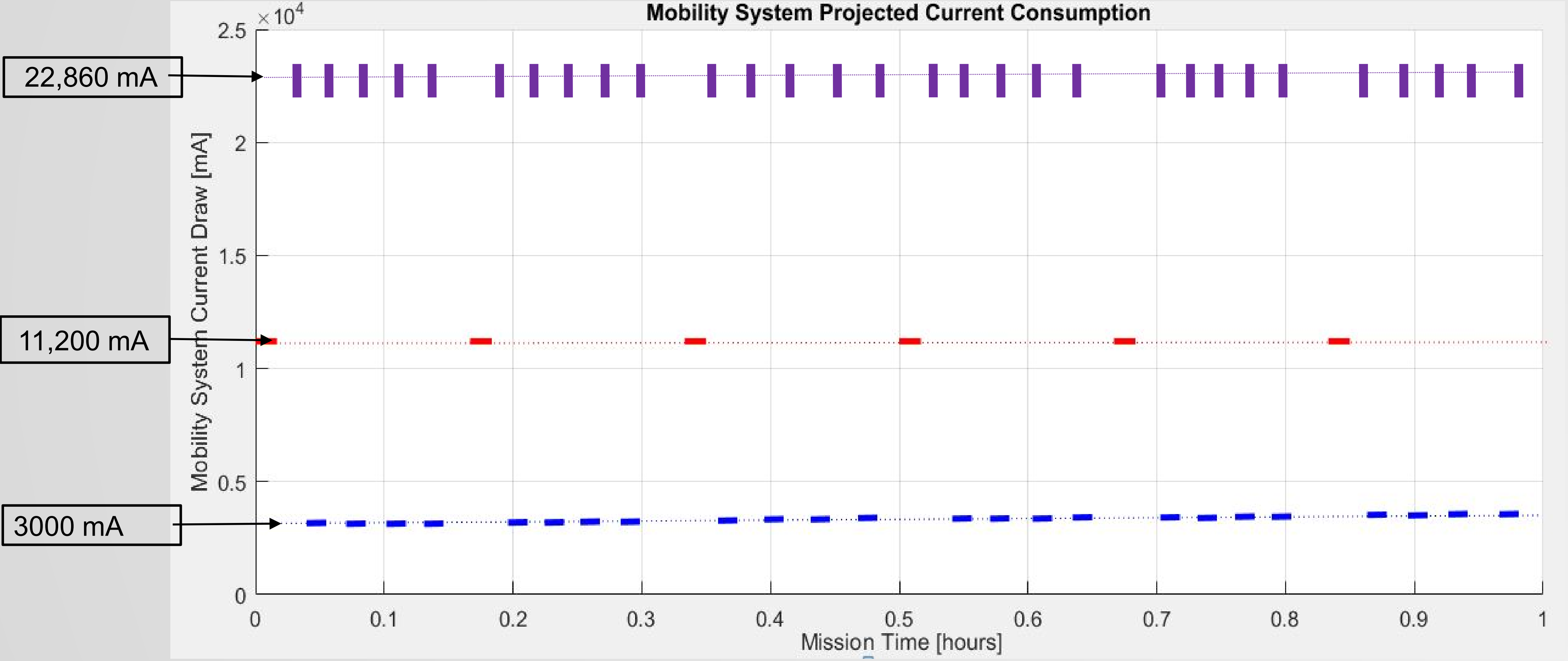
- ~0.32 hrs

Including Operations:

- Discontinuity traversal, communications delay, and obstacle traversal
- ~ 1 hr (including 20 percent margin)

Mobility – Power Analysis

Legend **Red = 1 min Incline Slope** **Blue = Flat Ground** **Purple = 4 Second Obstacle Traversal**



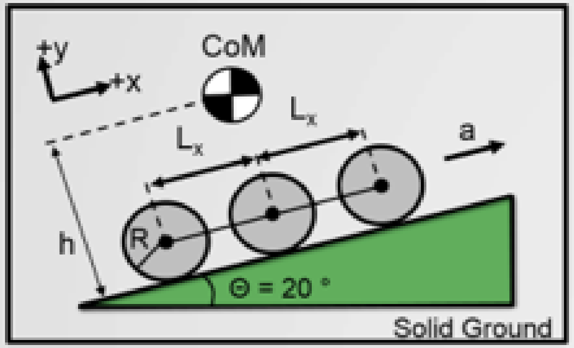
University of Colorado Boulder

Jet Propulsion Laboratory

Power Spikes - Analysis

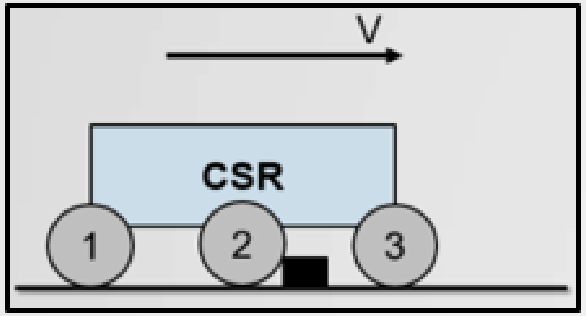
Power [W] = (Torque [N*m]*(# of motors) * Speed [RPM])/ 9.549

- Torque is the torque required for the maneuver
- RPM is a function of wheel radius and average linear speed
- Power spikes mainly occur from two scenarios:



- 1. Traveling up Inclined Slope (at 20°)
  - Total Power Required: ~**140 [W]**
  - Current Consumption per Motor: 5.6 [A]

- 2. Traversing over 2.4 [in] (0.061 [m]) obstacle
  - Total Power Required: ~**275 [W]**
  - Current Consumption per Motor: 11.4 [A]



Power Hardware

Sensing:

- x2 Adafruit 3.7 V 2 Ah LiPo Batteries in series
- Will utilize voltage regulator and current limiters

- **Mobility**:
  - x1 15.2 V 7.5Ah 100C LiPo Battery Pack
  - Will utilize a voltage regulator and current limiters
- **Comms**:
- x1 Talent Cell 12 V 3000mAh Battery Pack
- xWill utilize a voltage regulator and current limiters

C&DH:

- x1 Talent Cell 12 V 6000 mAh Battery Pack
- Will utilize voltage regulator and current limiters

Power Solution

Subsystem	Energy Capacity Required[Ah]	Power Solution Capacity [Ah]	Battery Mass [kg]	Capacity Margin [Ah]	Margin
Sensing	1.30	2.00	0.052	0.70	35%
Comms	1.65	3.00	0.18	1.35	45%
C&DH	2.31	6.00	.346	3.69	62%

*Assuming all these subsystems remain turned on for example 1 hour mission
*Inefficiencies for each subsystems are built into the capacity required

Power – Torque Equation

Power [W] = (Torque [N*m]*(# of motors) * Speed [RPM]) / 9.549

9.549 is the conversion factor between LHS and RHS (*accounts for angular velocity*)

W = (N*m) * (Revolutions / Minute)

(J / s) = (J) * (Revolutions / 60s)

Multiply through by seconds

J = J *(Revolution / 60)

1 Revolution = 2π rads

J = J * (*2π rads/60)*

J = J(.104719)*

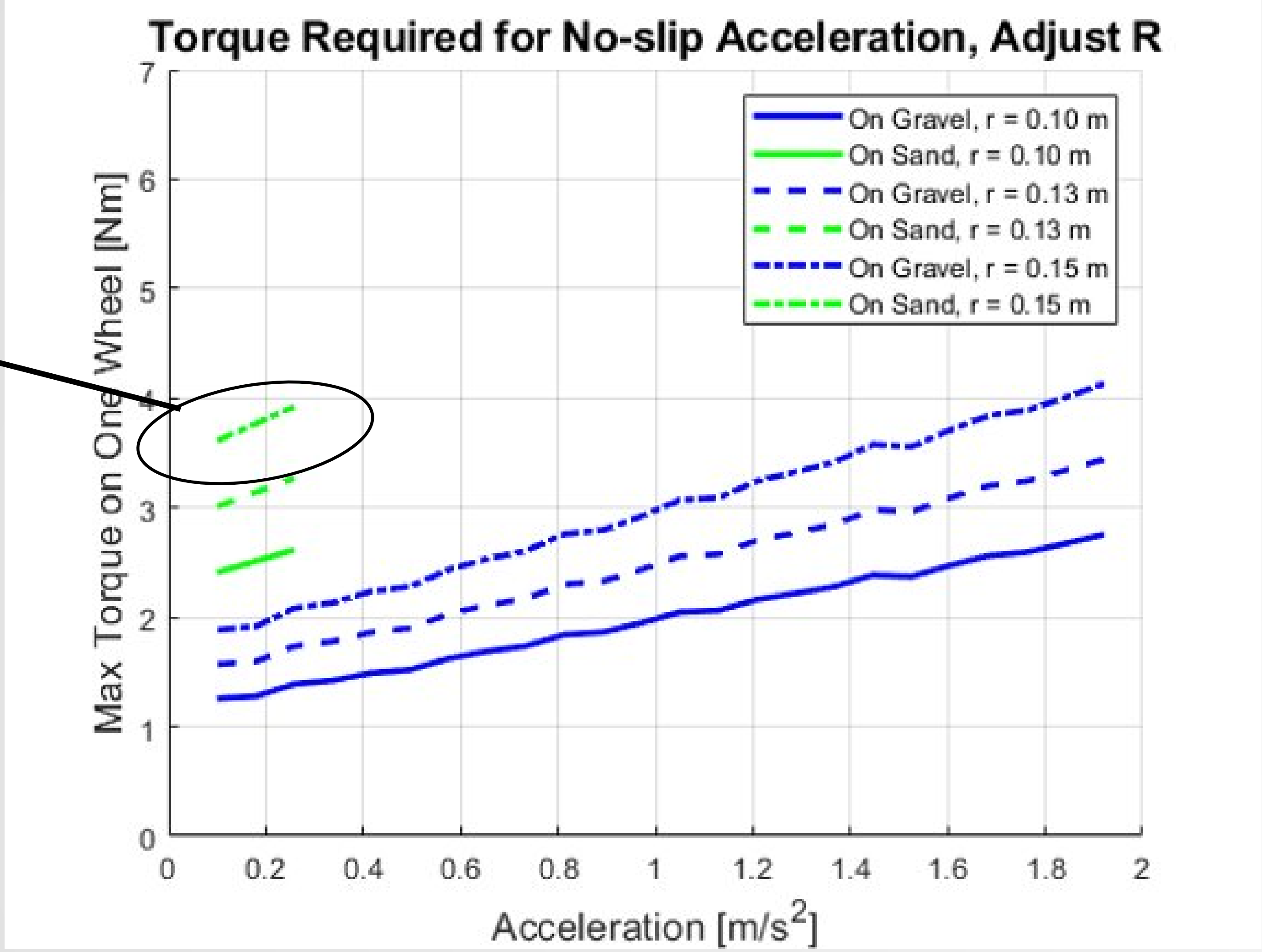
.104719 = (1 / 9.549)

J = J / 9.549 →

Power[W] = {Torque[N*m] *Speed[RPM]} / 9.549

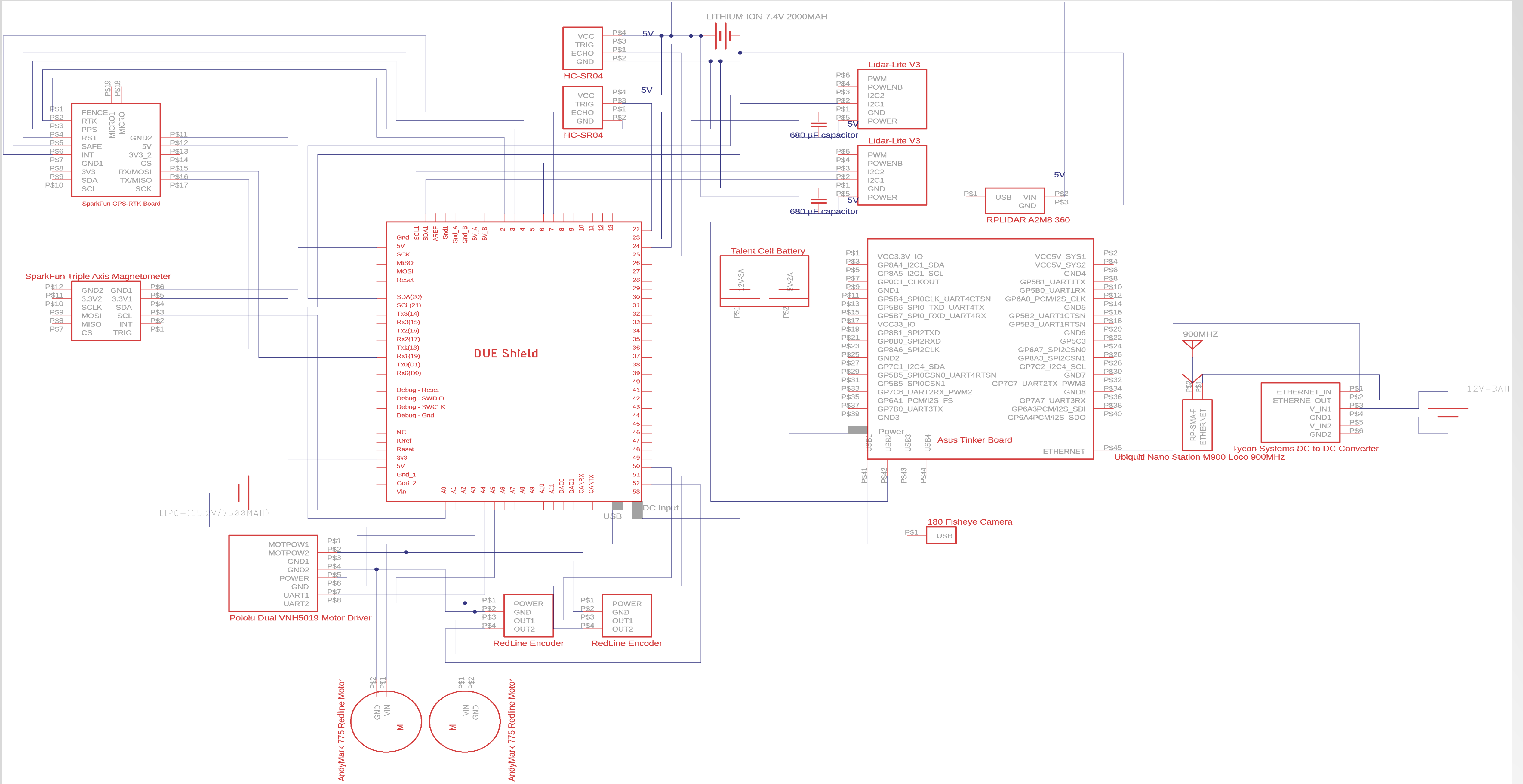
Power – Inclined Slopes of 20°

3.67 [N*m] for 2 motors equals 7.34 [N*m] of torque



Electronics

Electric Schematic of CSR



Environmental Sensing

Visualization of 360° LiDAR Mounting

Description:

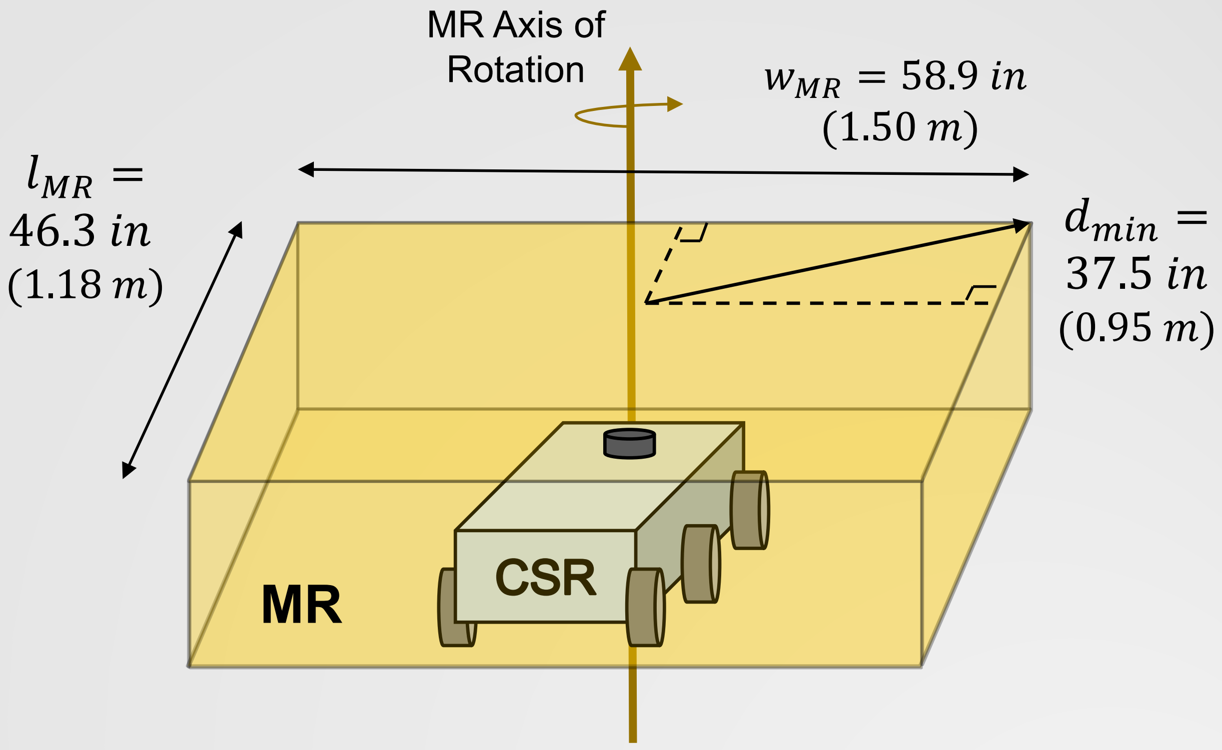
- Object detection feasibility is based on the dimensions of the MR, not the CSR
- The parameter d_{min} is the minimum distance the LiDAR sensor can be so that the MR will not collide with an obstacle (more information in backup slides)

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

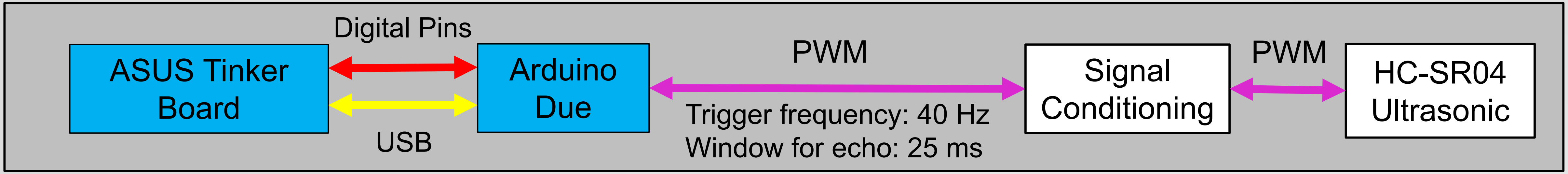
Requirement Allocation:

These MR dimensions determine the range for the SENS.1



Exact sensor mounting positions on CSR TBD

Discontinuity Depth Sensing – Integration

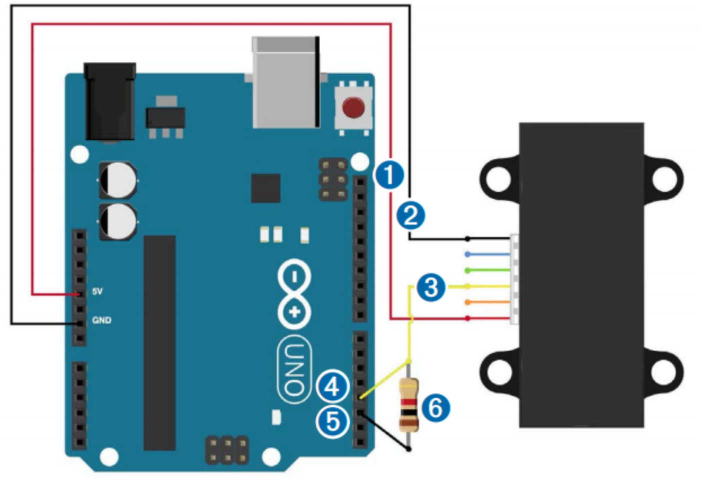


Integration Needs

- Physical hardware interface (2 PWM pins)
- Tinker Board ROS integration (software)
- Arduino sketch that controls the PWM triggers/echoes to sensor (software)
  - HC-SR04 maximum response time is 17.4 ms which is < 25 ms
  - HC-SR04 has enough to time to receive trigger and return echo before next trigger is received
- Signal conditioning
  - Digital signaling is usually resistant to system noise, so most likely, additional filtering is not required

Integration Info for LiDAR-Lite v3

PWM Arduino Wiring



Item	Description	Notes
1	5 Vdc power (+) connection	Red wire The sensor operates at 4.75 through 5.5 Vdc, with a max. of 6 Vdc.
2	Power ground (-) connection	Black Wire
3	Mode-control connection	Yellow wire
4	Monitor pin on microcontroller	Connect one side of the resistor to the mode-control connection on the device, and to a monitoring pin on your microcontroller.
5	Trigger pin on microcontroller	Connect the other side of the resistor to the trigger pin on your microcontroller.
6	1kΩ resistor	

- This is an example of a hookup to an Arduino Uno
- It utilizes two PWM pins on the Arduino
    - The Due has 12 total PWM ports
- The PWM requires two pins on the Arduino, but only communicates with one pin on the device itself

PWM Data Rate

- Arduino baud rate = 9600 bps
- PWM data storage = 2 bytes at 100 Hz
- Total data rate = 1600 bps
- Arduino can process data in time

PWM Control Specifications

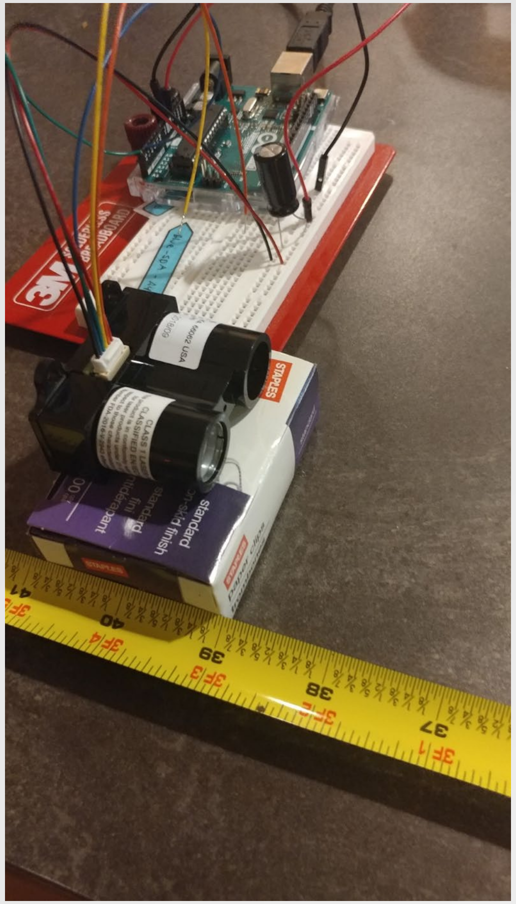
- PWM Trigger – pulling mode-control connection (pin 5 on diagram) LOW will trigger the sensor for the duration of the pull
- PWM Echo – Time of the LOW voltage echo determines the distance (10 us/cm)
    - Monitored with pin 4 in diagram

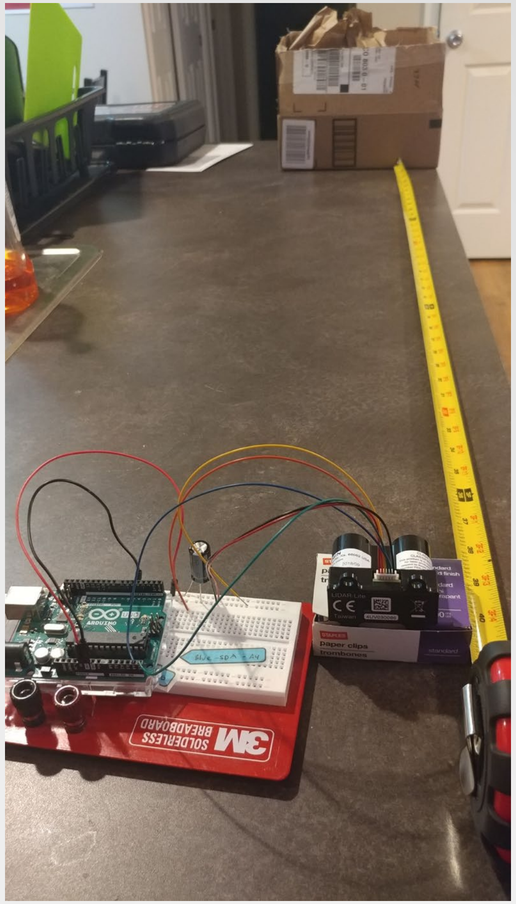
LiDAR Lite Testing

Test objective: Determine if the LiDAR has lots of error associated with it's readings

Test Setup:

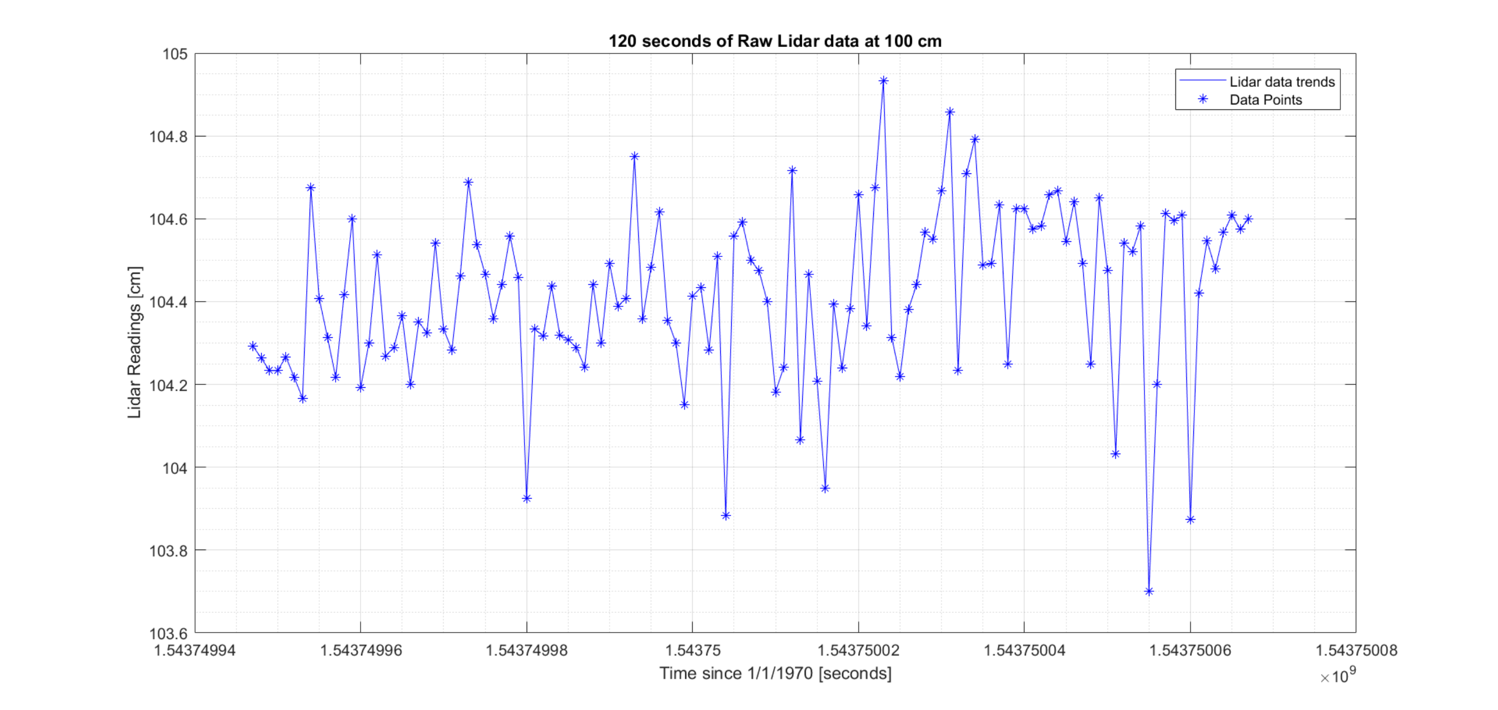
- This LiDAR was placed at 1 meter away from a carboard box, which would represent an obstacle
- The LiDAR was connected to an Arduino Uno over I2C, and the serial data output was recorded using RealTerm.
- **Equipment used:** LiDARLiteV3, 1000uF Capacitor, Solderless breadboard, Arduino Uno, Jumper Wires, Laptop, RealTerm Desktop app, cardboard boxes
- **Measurements required:** Distance measurements at 1 m





LiDAR Lite Results

- The LiDAR data varied from around 103 to 105 cm
- 120 seconds of data was captured
- Multiple tests were conducted and every time the LiDAR reported values greater than the expected value
- The required threshold for the single beam LiDAR needed is 1 m, and since the measurement errors are greater, there will not be an issue.

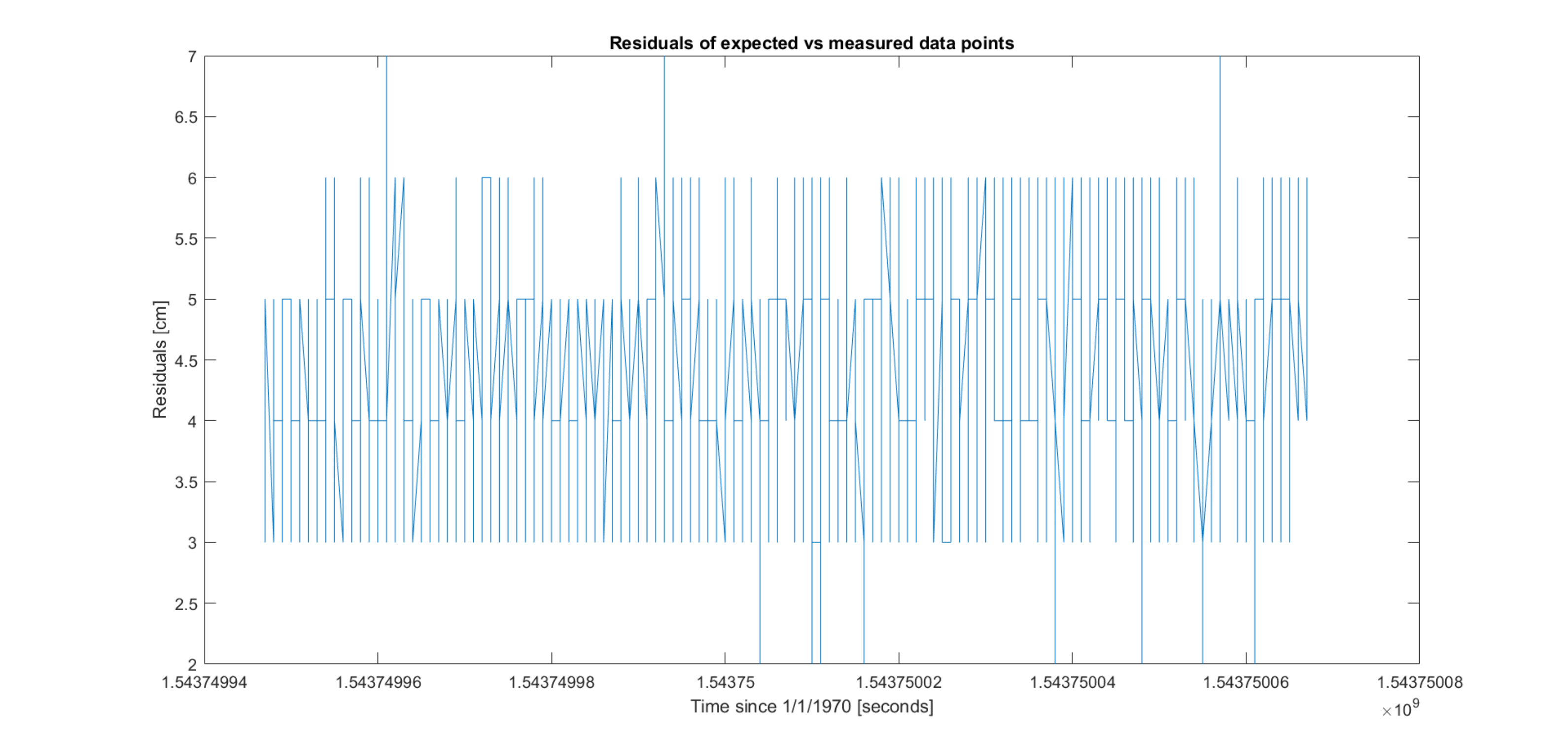


LiDAR Lite Results

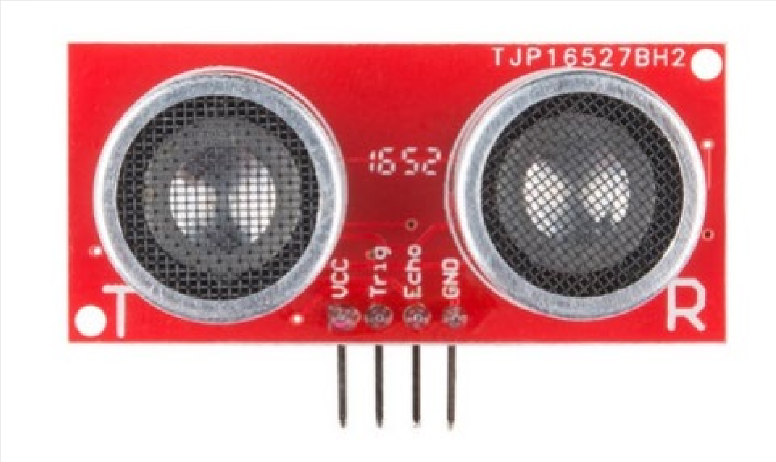
Residuals were determined by subtracting the measured outputs versus expected value of 100 cm

- The measurements resulted in an average error of 4.42 %

Sources of Error: Connection using solderless breadboard could have contributed to the error. A measuring tape was used at 39 3/8 inches which is approximately a meter, however there is inaccuracy associated with the test setup

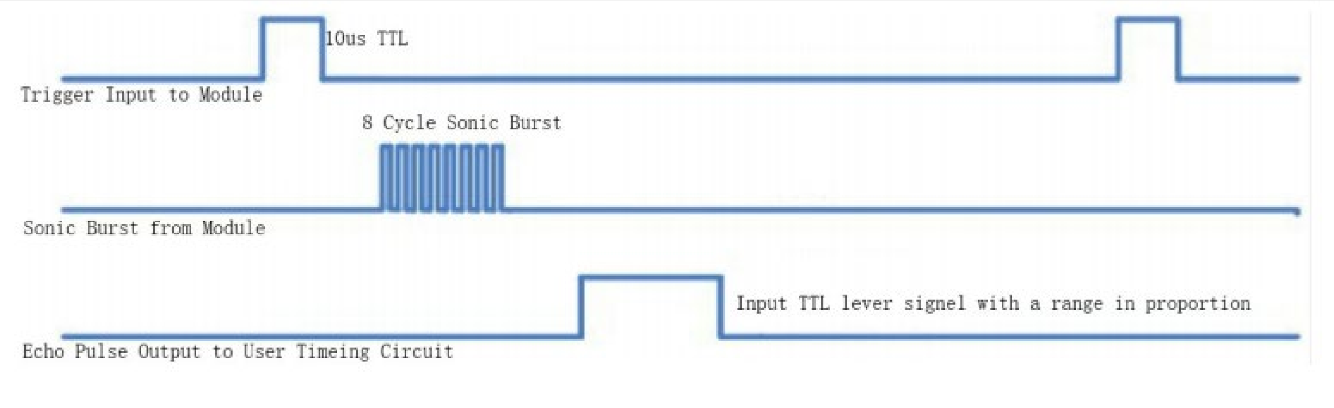


Integration Info for HC-SR04



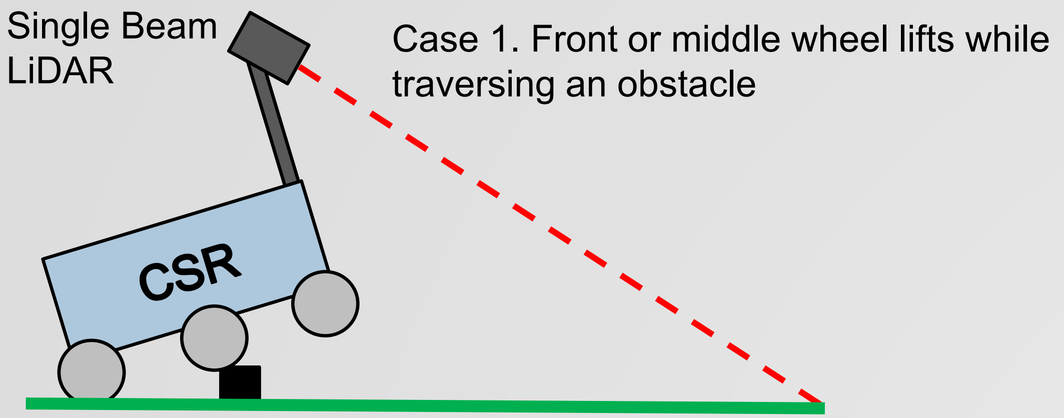
- Direct connection required between trigger and echo pins to 2 independent PWM pins on the Arduino
- Powered separately from the Arduino

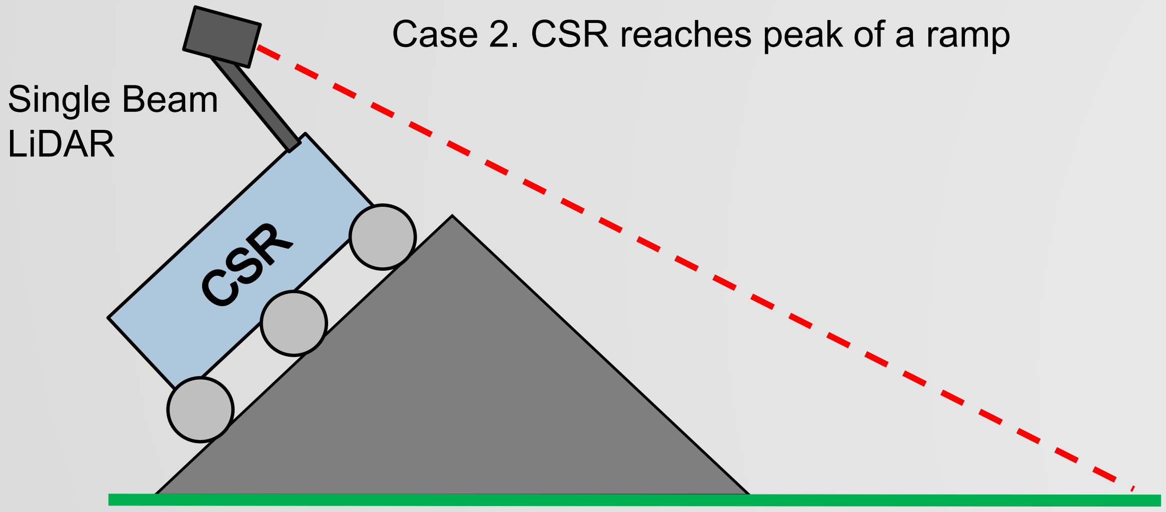
PWM Timing Diagram



- Triggered by pulling the Trig pin to HIGH voltage
- 8 cycle sonic burst is ultrasonic burst from the sensor
- Response will pull HIGH voltage on Echo pin time dependent like LiDAR-Lite 3
  - Formula: range = high level time * velocity (340M/S) / 2

Edge Cases of Detection- Single Beam LiDAR



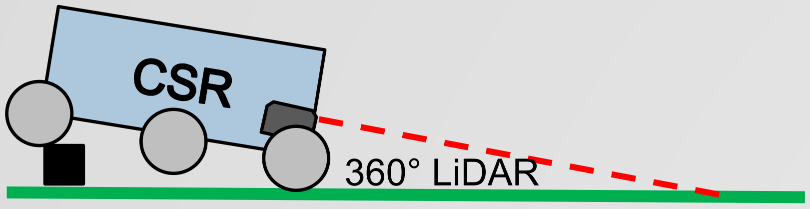


In both cases, the LiDAR detects a distance greater than threshold **falsely indicating a discontinuity.**

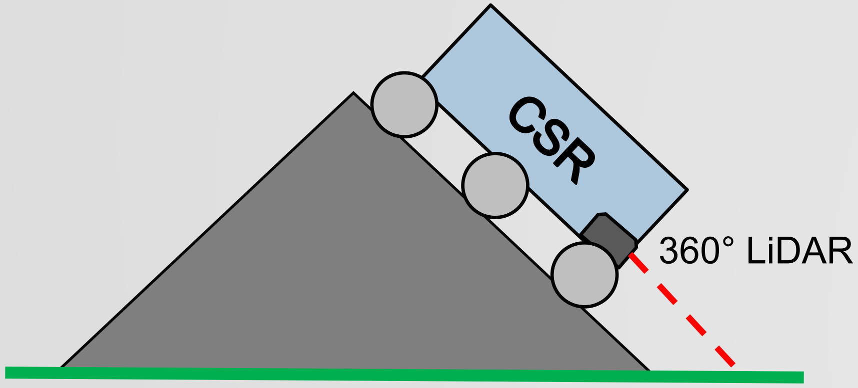
Solution: Use an onboard accelerometer to measure the orientation of the CSR. If the CSR is not level, **ignore single beam LiDAR data**.

Edge Cases of Detection- 360° LiDAR

Case 1. Back wheel lifts while traversing an obstacle



Case 2. CSR travels down a slope near level surface



In both cases, the LiDAR detects level surface and falsely identifies it as a non-traversable obstacle.

Solution: Again, use an onboard accelerometer to measure the orientation of the CSR. If the CSR is not level, **ignore single beam LiDAR data**.

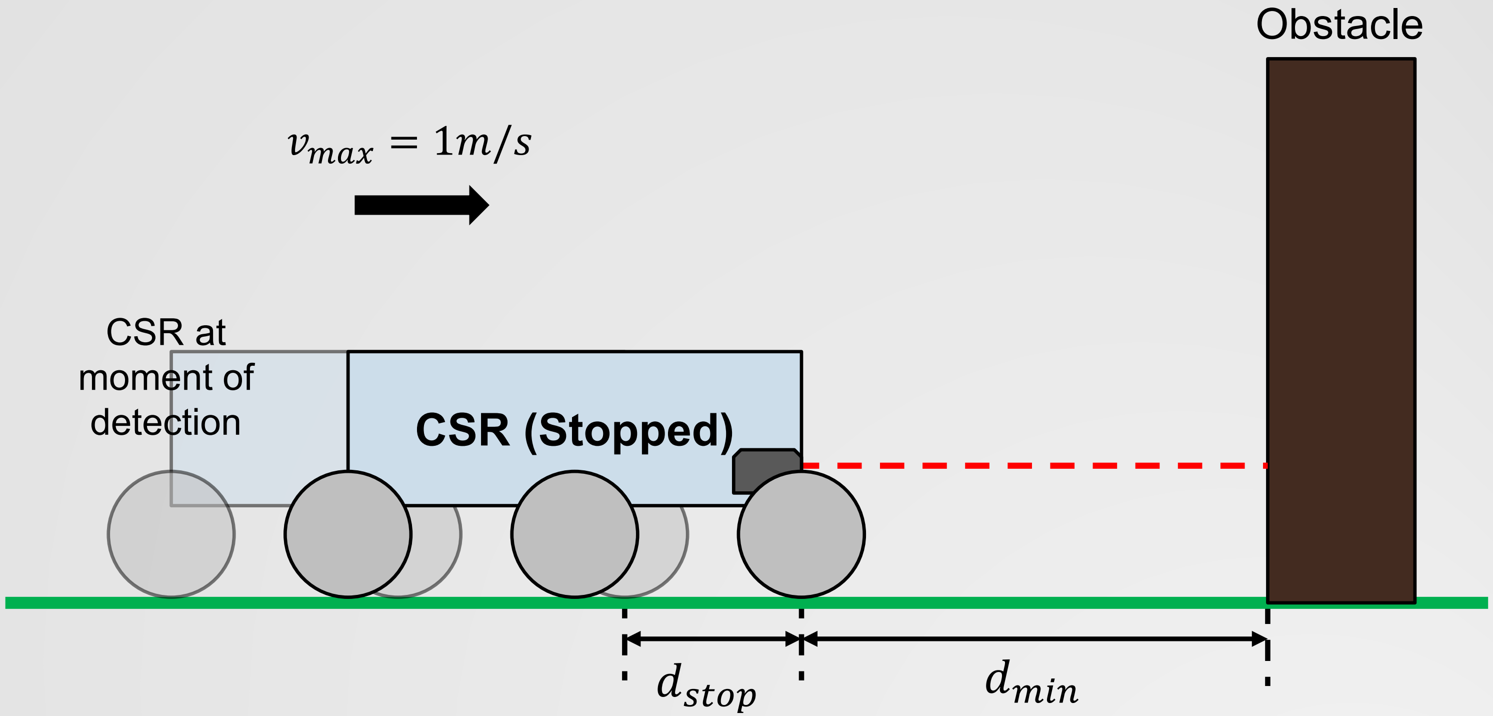
In-Plane Objects – Detection Speed

Feasibility Item:

- Will the CSR have enough time to stop once an obstacle is detected by the in-plane sensor?

Worst Case Scenario:

- If scan just misses object, it must make a full revolution before it detects the object
- Once sensing occurs, the CD&H system must determine if object is detected
- If detected, CSR must control motors to stop

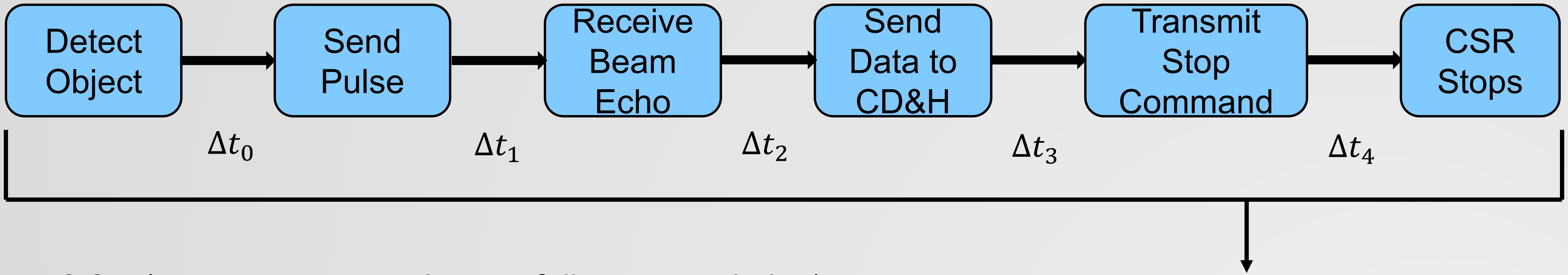


$d_{stop} + d_{min}$ must be < range of LiDAR

In-Plane Objects – Detection Speed

RPLIDAR A3 Specs:
Scan rate: 5-20 rev/s
Response time: 0.06 ms

Flow Diagram of Stopping Sequence



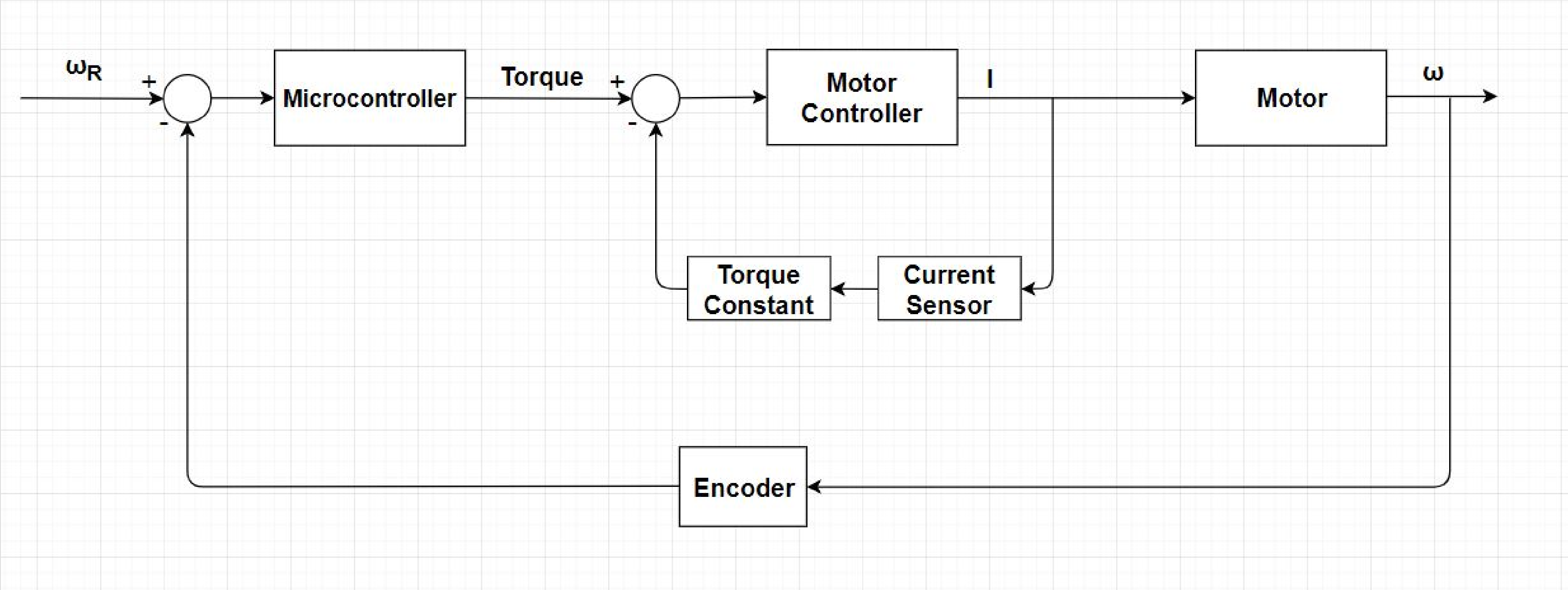
Δt_0 = 0.2 s (worst case scenario; one full scan revolution)
Δt_1 ~ 0 s (time of pulse; speed of light)
Δt_2 = 0.00025 s (sensor response time)
Δt_3 = 0.00006 s (data processing time; estimated from data processing analysis)
Δt_4 = 0.15 s (time for CSR to stop due to skidding; next slide)

$$t_{tot} = \Delta t_0 + \Delta t_1 + \Delta t_2 + \Delta t_3 + \Delta t_4$$
$$t_{tot} \approx \Delta t_0 + \Delta t_4 = 0.35\ s$$
$$d_{stop} = v_{max} t_{tot} \approx 0.35\ m$$

$d_{stop} + d_{min} = 1.3\ m \ll$ range of LiDAR (25 m), so CSR stops in time

FEASIBLE

In-Plane Objects – Detection Speed



To stop the CSR, a command of zero angular velocity will be inputted into the microcontroller and negative torque will be applied to the wheel. Since the settling time can be very small depending on the gains used in the loop, we can assume the wheel will stop spinning immediately. Therefore, the stopping time can be calculated using the friction coefficient:

$$a = \mu g$$

$$t = {}^{v}/_{a} = {}^{1}/_{\mu g} = 0.15\ s$$

Where μ is assumed to be 0.7

Discontinuity Detection – Detection Speed

Feasibility Item:

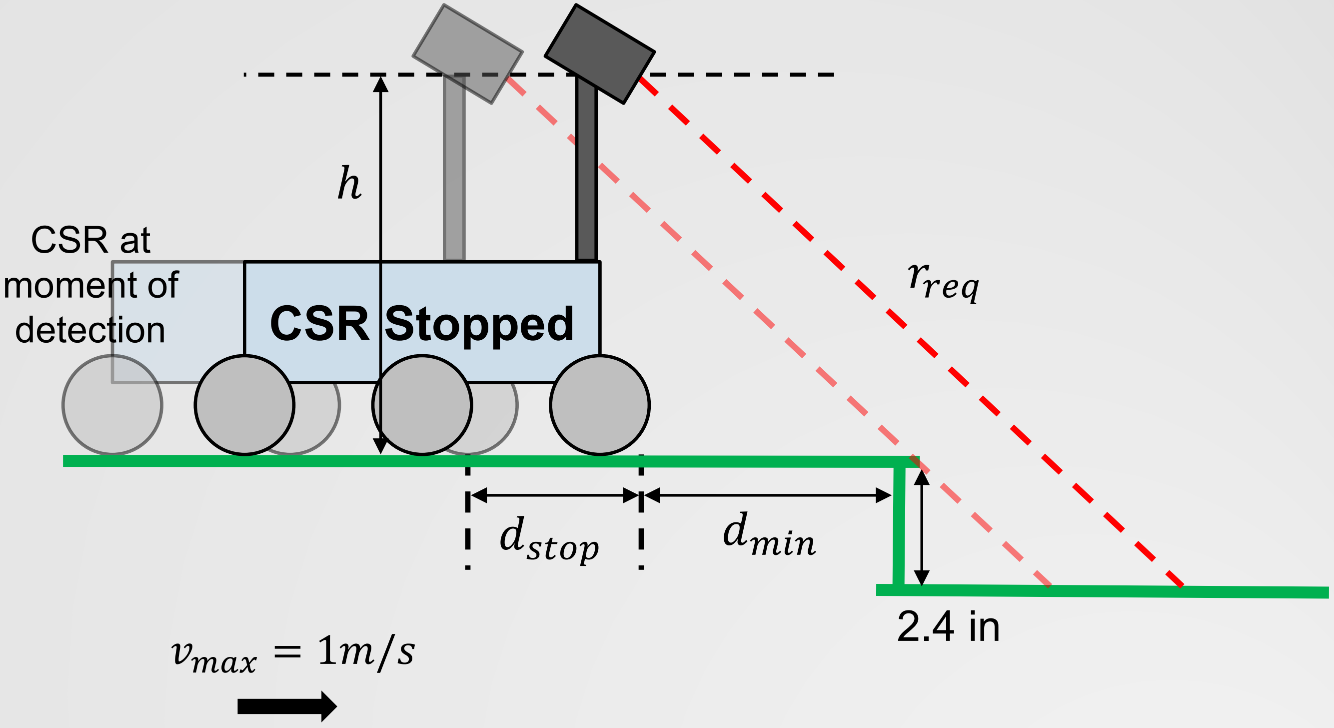
- Will the CSR have enough time to stop once a discontinuity is detected by the single beam sensors?

Worst Case Scenario:

- From discontinuity detection feasibility, worst case is when h = 0.2 ft

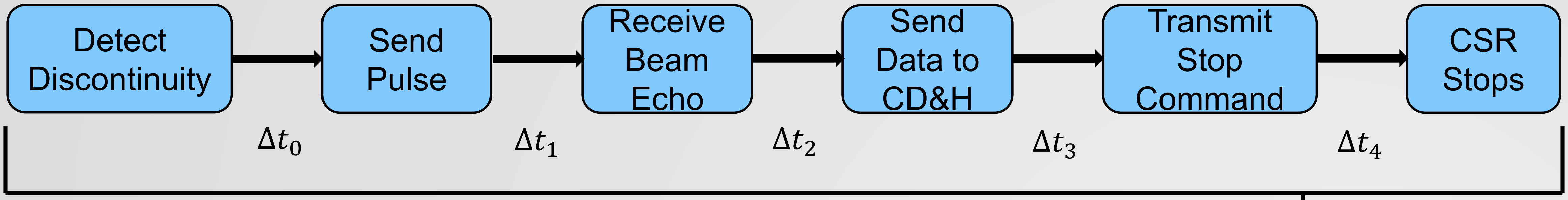
$$r_{req} = {[h + (2.4\ in)]} \Big/ {cos\left[tan^{-1}\left(\frac{d_{stop} + d_{min}}{h}\right)\right]}$$

r_{req} must be < range of LiDAR



Discontinuity Detection – Detection Speed

Flow Diagram of Stopping Sequence



Δt_0 = 0 s (no worst case scenario; detecting and sending pulse happen simultaneously)
Δt_1 ~ 0 s (time of pulse; speed of light)
Δt_2 = 0.020 s (sensor response time)
Δt_3 = 0.025 s (data processing time; estimated from PWM analysis)
Δt_4 = 0.15 s (time for CSR to stop due to skidding; previous slide)

$$t_{tot} = \Delta t_0 + \Delta t_1 + \Delta t_2 + \Delta t_3 + \Delta t_4$$
$$t_{tot} \approx \Delta t_4 = 0.15\ s$$
$$d_{stop} = v_{max} t_{tot} \approx 0.15\ m$$

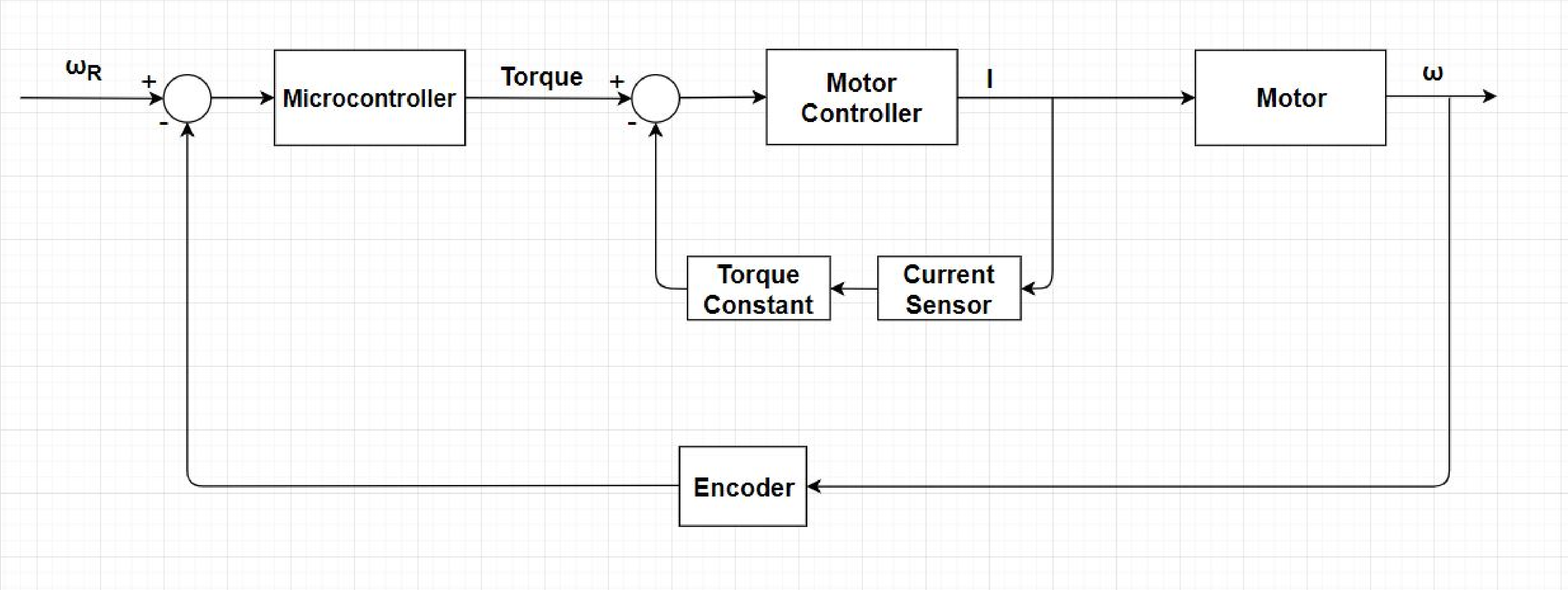
Use equation on previous slide to get r_{req}
$r_{req} = 2.2\ m \ll$ range of LiDAR (40 m), so CSR stops in time

FEASIBLE

Guidance, Navigation, and Control

Speed Control Closed Loop Algorithm

This control will be an active loop through the entire mission



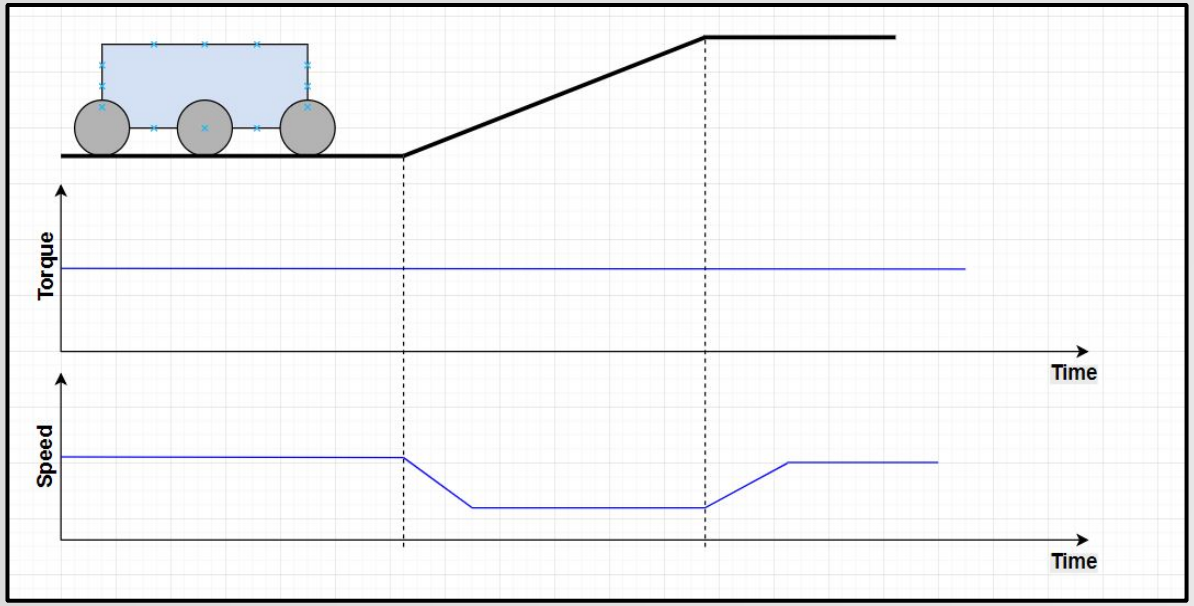
ω_R : Input command for desired angular velocity

ω : Measured angular velocity of the wheel

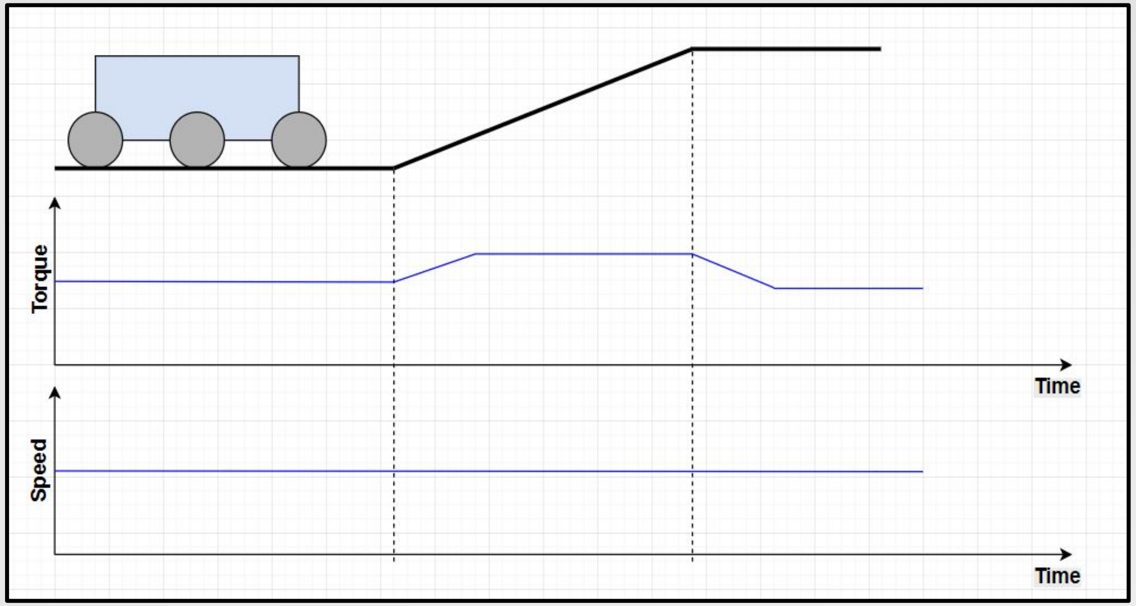
I : Current applied to the motor

Speed Control Visualization

Without control



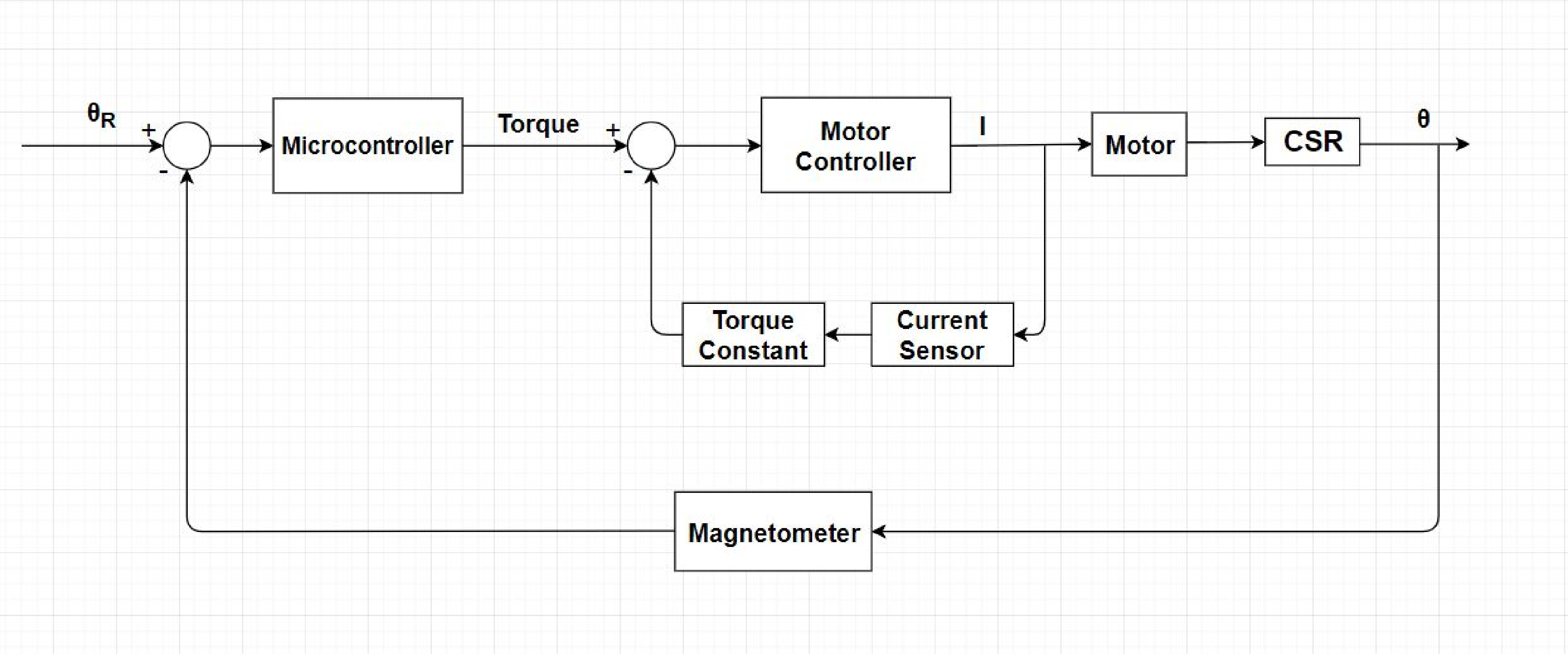
With control



The speed closed loop control system is used to maintain the speed of the CSR by outputting different torque at different situations such as going over obstacles, traversing on a slope, etc.

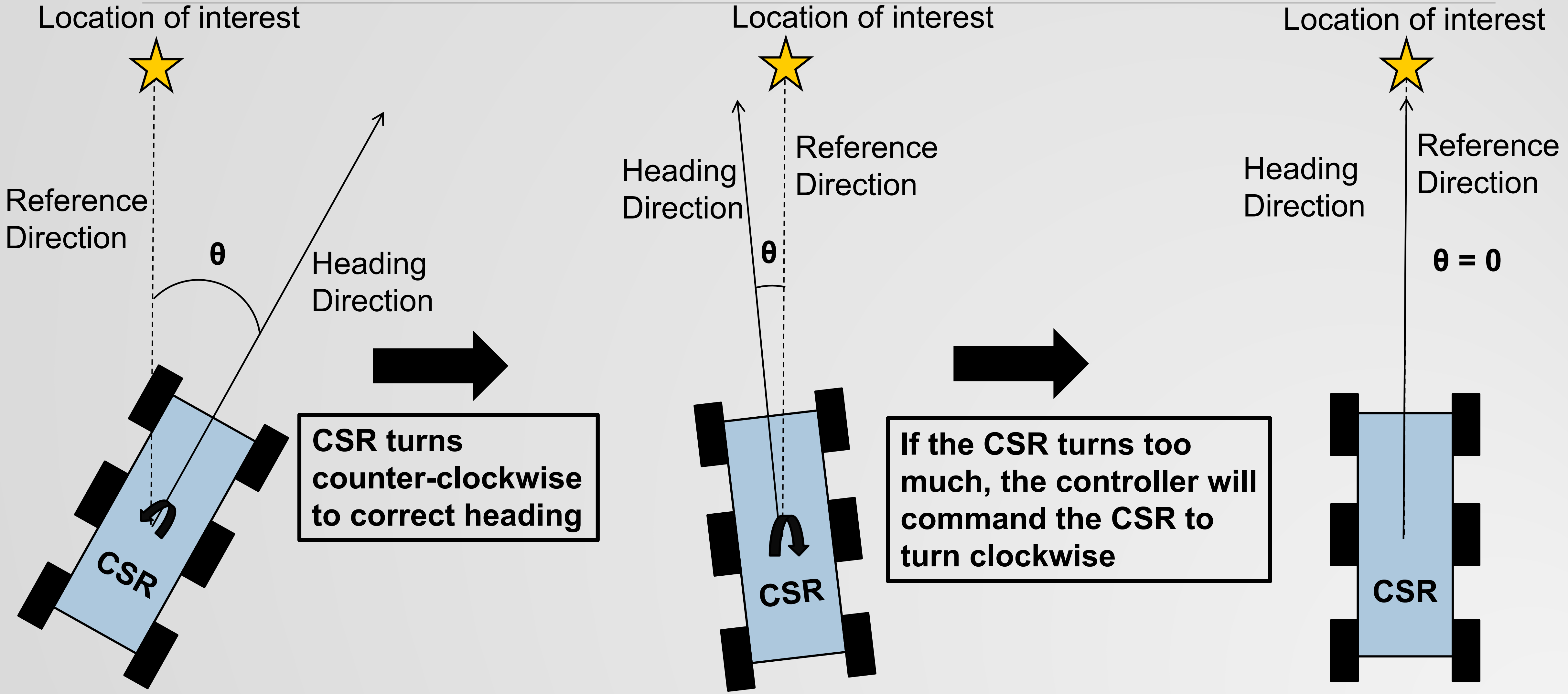
Heading Correction Closed Loop Algorithm

This control will be an active loop that only happens when the CSR receives a command from the ground station to perform a heading correction.



θ_R : Input command for desired angle
θ : Angle between heading direction and reference direction
I : Current applied to the motor

Heading Correction Visualization



Magnetometer Motor Interference Test

Purpose:
Estimate the level of magnetic interference from the motor on a magnetometer.

Materials:
- Engineering Paper
- Straight-edge Ruler
- 27.5V, 1.2A, 4500rpm, 1/50 Brushed DC Motor
- Motor Stand
- Samsung S7 Smartphone
  - SensorLab App
  - Sensor Box for Android App
  - Sensors Multitool App

Procedure:
1. Fix motor in motor stand and place on workstation.
2. Using engineering paper and a straight edge, mark phone positions every 15 cm (15 cm, 30 cm, 45 cm, 60 cm) from the motor shaft.
3. Take magnetometer measurements using the three different apps to ensure there are no issues with any one single app.
4. For each position, take the *x, y, z* magnetometer measurements for the following cases:
   a) No motor or test stand
   b) Non-powered motor and test stand
   c) Powered motor and test stand. Motor is powered for approximately 5 seconds before taking measurements to obtain a steady state measurement
5. Record the magnetometer measurement when rotating the smartphone.

Magnetometer Motor Interference Test

Results:

Motor State	Distance [cm]	Magnetic Field [uT]		
		x	y	z
No motor	15	13	-44	-1
	30	16	-33	-15
	45	5	-28	-20
	60	0	-20	-31
Motor, off	15	12	-44	-3
	30	16	-32	-16
	45	--	--	--
	60	--	--	--
Motor, on	15	14	-44	-3
	30	17	-32	-16
	45	--	--	--
	60	--	--	--

Motor State	Angle [deg]	Magnetic Field [uT]		
		x	y	z
No motor	0	-56	-15	59
	90	13	24	-6
	180	-5	-20	77
	270	16	77	-12

NOTE: Data for "Motor, off" and "Motor, on" not recorded for 45 and 60 cm, as the measurements even closer did not significantly change

Conclusion:

The difference in the magnetic field for no motor, a non-powered motor, and a powered motor is insignificant (+/- 2 uT), even at the closest location (15 cm), especially compared to the differences of angle changes (+/- 40 uT).

Moving forward with the design, the magnetometer will be placed about 15 cm (6 in) away from the motor. If this is not sufficient, design alternatives, such as mu-metal foil shielding or increased distance, can be considered.

Heading Correction – Accuracy

Critical Items:

- What is the heading accuracy of the magnetometer?

Assumptions:

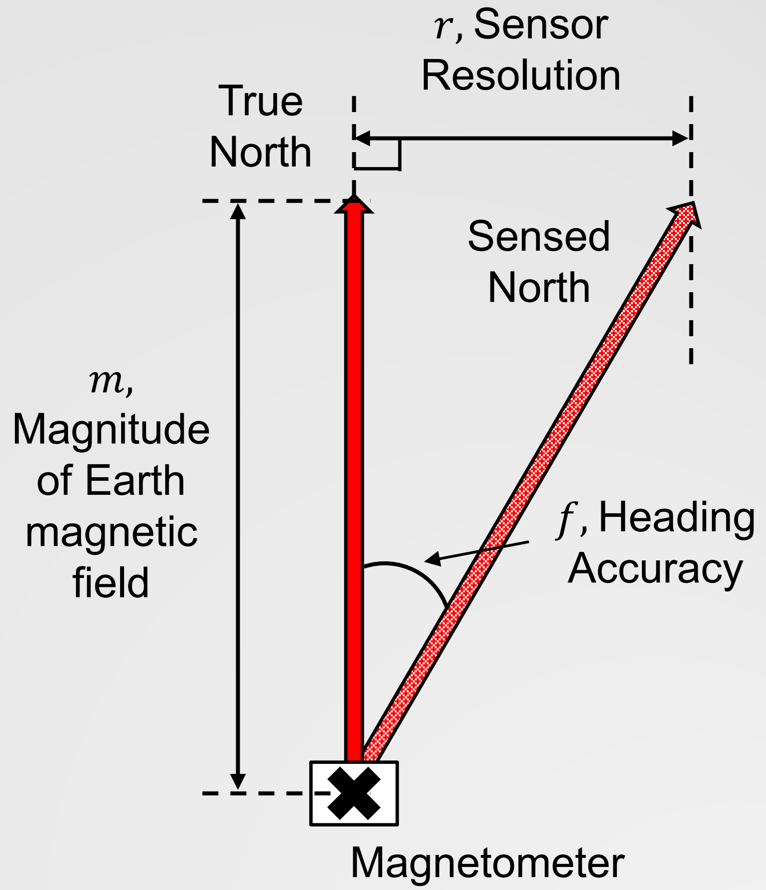
- There is no noise in the system and the magnetometer takes data continuously
- Accuracy is related to the magnitude of the magnetic field being sensed
- Earth's magnetic field's magnitude, m, ranges from 0.25 to 0.65 G (Gauss)

$$f = tan^{-1}\left(\frac{r}{m}\right)$$

Magnetometer has $r = 1\ \mu$T

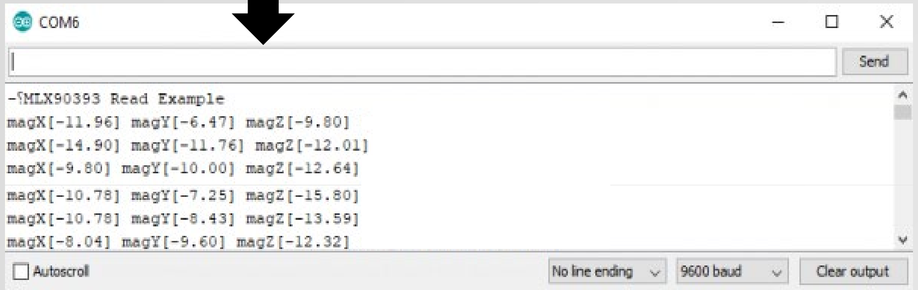
Results:

- The worst case heading accuracy f = 0.133°



Current Design Requirement Satisfaction

Using the 3 axis magnetometer raw data will be received.



Example of raw data in μT from the magnetometer's Sparkfun hookup Guide. [12]

Converting raw data -> polar coordinates

If y > 0 → $Direction = 90 - \tan^{-1}\left(\frac{x}{y}\right) * \frac{180}{\pi}$

If y < 0 → $Direction = 270 - \tan^{-1}\left(\frac{x}{y}\right) * \frac{180}{\pi}$

If y = 0 and x < 0 → $Direction = 180^0$

If y = 0 and x > 0 → $Direction = 0^0$

The direction is converted to degrees, and the CSR's heading is determined

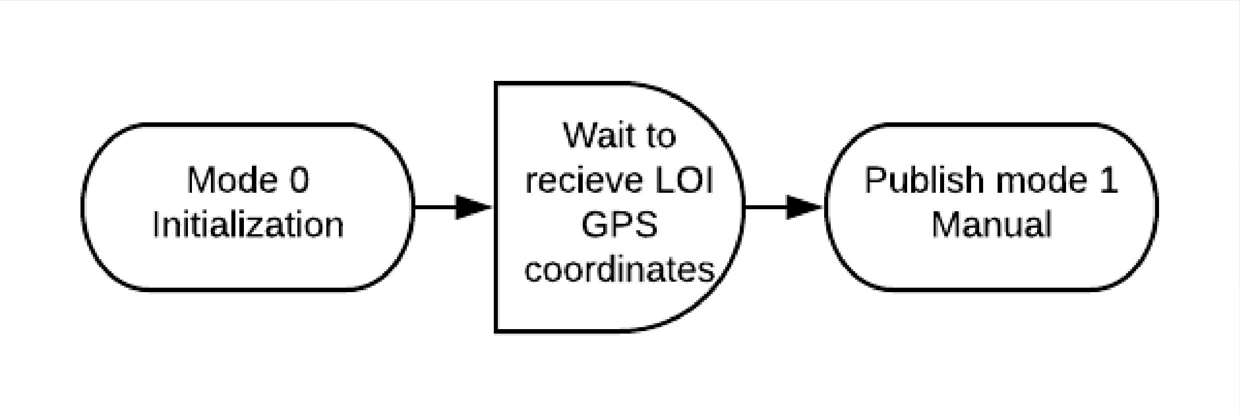
Requirement is satisfied

CDH.3.4: The CSR C&DH system shall determine the heading of the CSR

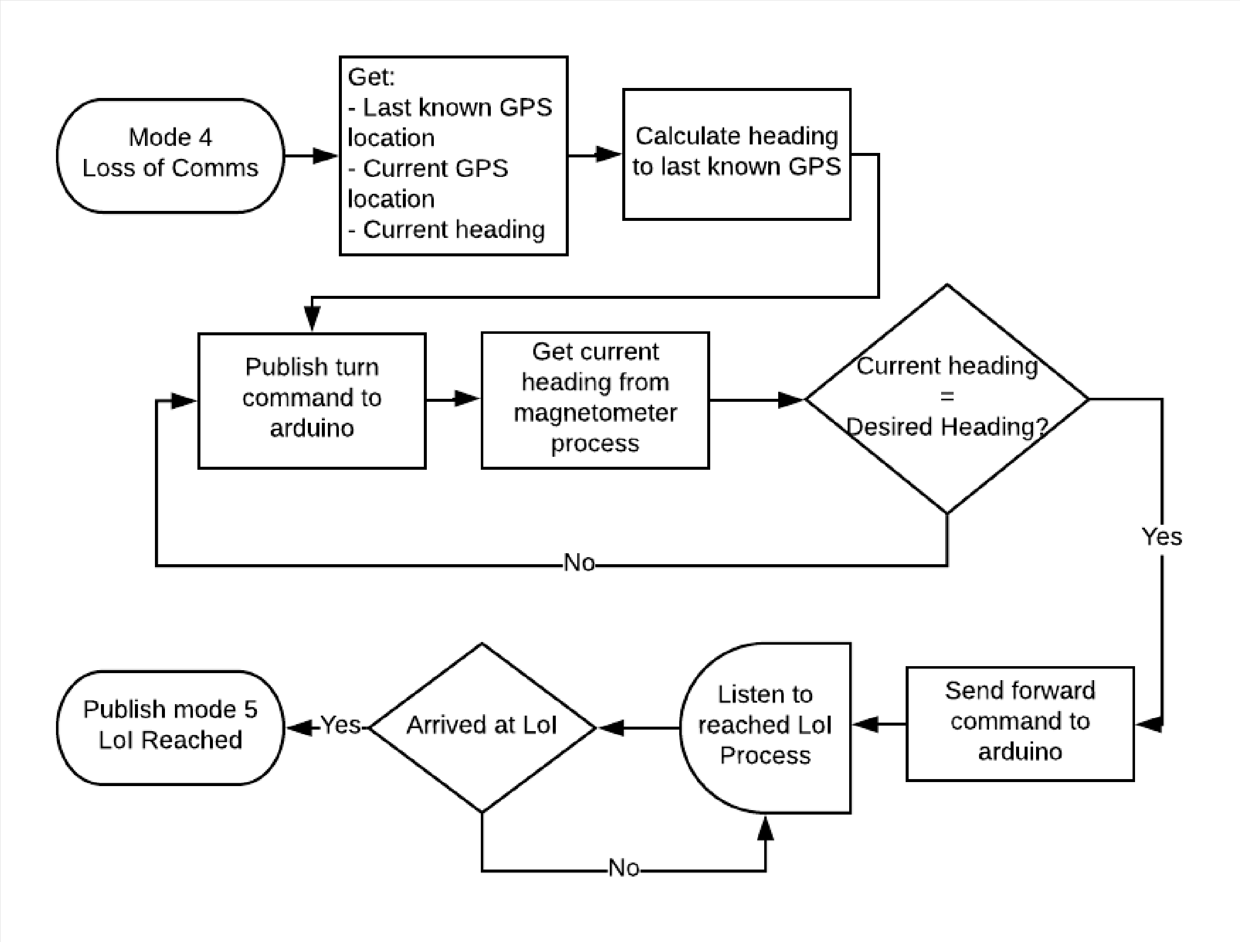
Equations are from HoneyWell's "Compass Heading using Magnetometers" Guide. [13]

Software Backup

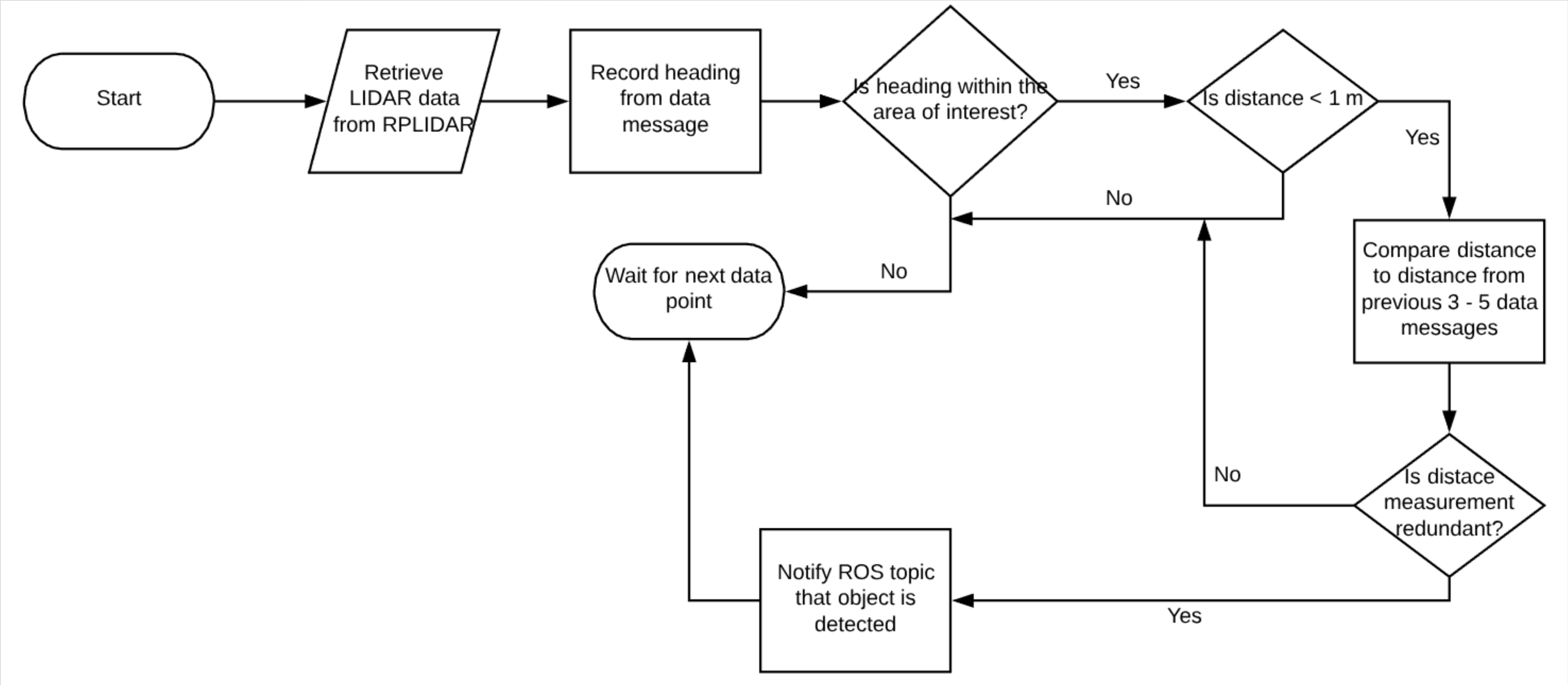
GNC CSR Initialization Mode Diagram



GNC CSR Loss of Comms Mode Diagram



Environment Sensing Object Detection Diagram



Main Loop Pseudo Code

```
While (roscore)
    getMode()
    While (mode == 0):
        Initialization mode
    End
    While (mode == 1):
        Manual mode
    End
    If (mode == 2):
        Semi-Autonomous mode
    End
    If (mode == 3):
        Discontinuity traversal mode
    End
    If (mode == 4):
        Loss of comms mode
    End
    While (mode == 5):
        LOI arrival mode
    End
End
```

- This will function as the main loop program which constantly checks what mode to be in.
- This main loop will run on the ASUS Tinker Board
- ‘mode’ variable can change outside of the loop since will be a multithreaded program.

Mode 0 (Wait for GPS) Pseudo Code

```
While (mode == 0):
        If (received_GPS):

                mode == 1

        End
End
```

- This mode is started at the beginning before anything is started.
- Waits in a loop after initialization of everything until a GPS coordinate is received from the GS.
- Once it is received then it will save the LOI GPS coordinate as variable.
- Once there is a LOI GPS coordinate than will switch to Mode 1.
- Just a waiting loop to proceed once everything is initialized and the GPS LOI has been determined.

Mode 1 (Manual) Pseudo Code

```
While (mode == 1):
    If(button_pressed):
        If (button_type == forward):
            controlMotors(forward)
        End

        If (button_type == backward):
            controlMotors(backward)
        End

        If (button_type == left):
            saveAndSendGPS()
            controlMotors(left)
        End

        If (button_type == right):
            saveAndSendGPS()
            controlMotors(right)
        End

        While (button_pressed And (not loss_comms)
            And (not reached_loi) And (not discontinuity)
            And (not mode_switch)):

            checkCommands()
        End

        stopMotors()
    End
End
```

- **Mode Helper Functionality:**
    - saveAndSendGPS() – Save the current GPS coordinate and send it to GS to save a list of waypoints
    - controlMotors() – This gets the user input direction from the GS to publish to the motors
    - stopMotors() – This stops all motor functionality
    - checkCommands() – This checks all ros nodes signals to break the loop
    - getUserInput() – This function sends the button_pressed and button_type signal

- **Background ROS Nodes Functionality:**
    - checkDiscontinuity Node – Constantly checks for discontinuity and signals to switch to mode 3
    - reachedLOI Node – Constantly compares the current heading to loi heading to switch to mode 5
    - commLoss Node – Constantly checks for loss of comms to switch to mode 4
    - modeSwitch Node – Constantly checks for user input to switch to a mode manually

Mode 2 (Semi Autonomous) Pseudo Code

```
If (mode == 2):

        fixOrientation()

        goForward()

        While ((not object_detected) And (not loss_comms)
                And (not reached_loi) And (not discontinuity)
                And (not mode_switch)):

                checkCommands()
        End

        stopMotors()
End
```

Mode 3 (Discontinuity) Pseudo Code

```
If (mode == 3):
        #This while loop is manual control until user allows to proceed
        While (not (user_proceed)):
                #Similar code as Mode 1 goes here

        #Once it hits here then will function autonomously
        slowerSpeed()
        goForward()

        Discontinuity_not_crossed = true

        While (discontinuity_not_crossed):
                If(checkFrontGap() And (mass_spot == mass_center)):
                        stopMotors()
                        moveMassBackward()
                        goForward()
                End

                If(checkFrontAndBack() And (mass_spot == mass_back)):
                        stopMotors()
                        moveMassForward()
                        goForward()

                        While (backWheelOnFirstLedge()):
                                Wait()
                        End
                End

                If(checkBackNoGap() And (mass_spot == mass_front)):
                        stopMotors()
                        moveMassCenter()
                        saveAndSendGPS()
                        signalComplete()

                        discontinuity_not_crossed = false
                End
        End
End
```

Mode 4 (Loss Comms) Pseudo Code

```
If (mode == 4):
        If(compareGPS()):
                fixOrientation()

                goForward()

                While (not (reached_last_gps))
                        checkCommands()
                End

                stopMotors()

                mode = 5

        End

        Else
                mode = 5
        End
End
```

Mode 5 (LOI Reached) Pseudo Code

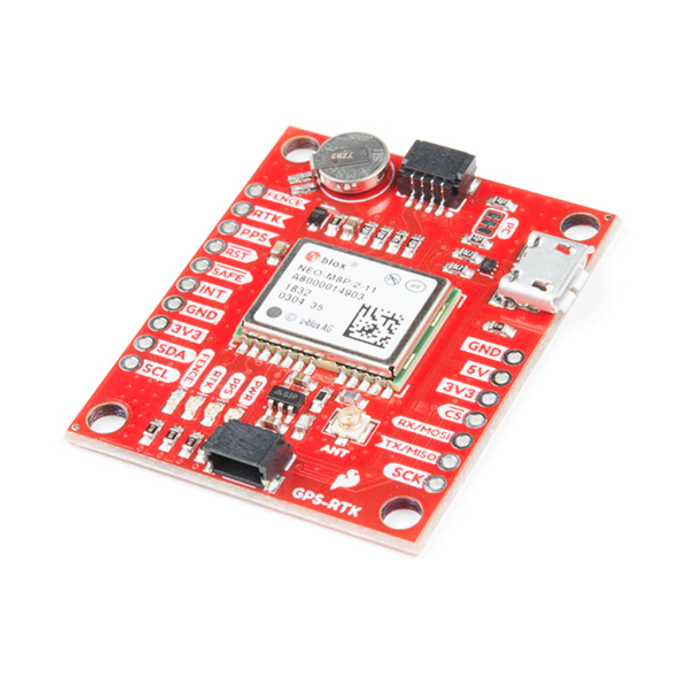
```
While (mode == 5):
        #This is when the CSR reaches the last known GPS coordinate
        If (lost_comms):
                checkComms()

                If (comms == open):
                        mode = 1
                End
        End

        #This is when the CSR reaches the LOI w/out problems
        If (reached_loi):
                        mode = 1
        End
End
```

GPS

To ensure that the CSR has accurate GPS data for loss of communication situations, and for final path verification an accurate GPS must be used.

SparkFun GPS-RTK Board – NEO – M8P-2 (Qwiic)

- $199.95
- Four communication ports: USB, UART , I^2C, SPI
- Voltage: 3.3 V
- **Horizontal Position Accuracy: .025 m with RTK (Real Time Kinematics)**
- Max Navigation Rate: 4 Hz



GPS

How does it work?

- A GPS receiver capable of RTK takes in normal signals from the Global navigation Satellite Systems (GNSS) along with a Correction Stream
  - Raw streams from the GPS satellites are captured, and the logs are post processed by an open source program called RTKLIB

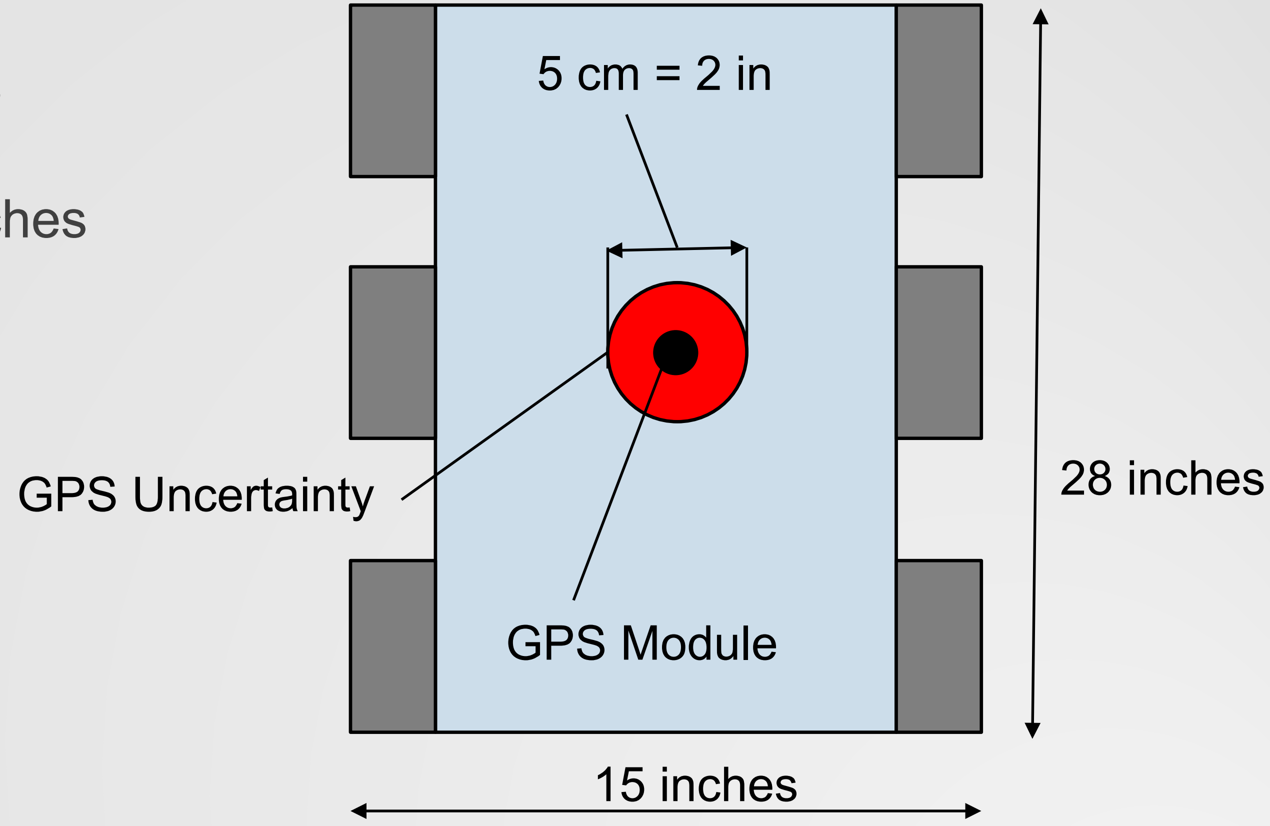
This module is capable of mobile and base station operations

- One board serves as a base station and produces RTCM correction data.
  - RTCM = Radio Technical Commission for Maritime. RTCM is related to the bytes of correction data
  - Each RTCM message contains details about the GPS/GNSS network
- Another board will serve as the mobile GPS RTK receiver
  - The GPS receiver parses the correction data
  - The GPS module will output NMEA sentences with latitude and longitude information
    - NMEA = National marine electronics association, a standard data format for GPS

In summary, 2 of these boards and a GPS antenna will be required.

GPS Error

- The GPS error is contained within the confines of the CSR
- Due to this, the uncertainty of the GPS should be negligible
- Diameter of uncertainty is 5 cm = 2 inches
- Width of CSR is 15 inches > 2 inches
- Length of CSR is 28 inches > 2 inches

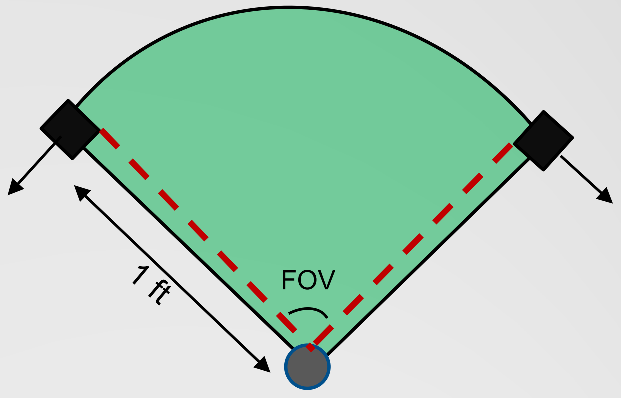


Verification and Validation

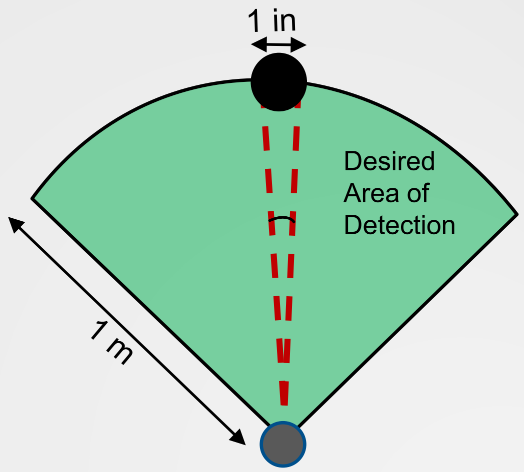
Phase 1 –Obstacle Detection Testing

Objective	• Determine 360° LiDAR FOV and range • Determine 360° LiDAR angular resolution
Test Plan	**FOV and Range:** • Place 2 boxes 1 ft from the LiDAR such that the "box-LiDAR-box" angle is 103.5 degrees • Verify the LiDAR can detect the boxes in the edges of its FOV and increase the angle between the boxes until at the edge of the LiDAR FOV, Measure and record final FOV **Angular Resolution:** • Place 1 in .diameter pole at 1 m from the LiDAR • Verify the sensor returns at least 2 data points measuring distance to pole • Move pole further away from LiDAR and repeat until 2 data points are no longer returned
Requirements Verified	**SENS 3.1**: The CSR Sensing system shall detect objects at least 37.5 inches (3.125 ft, 0.9525 m) from the Sensing system **SENS 3.1.1:** The CSR Sensing system shall detect objects within a field of view of at least 103.5 degrees from the Sensing system **SENS 3.1.2**: The CSR Sensing system shall detect objects at least 1 inch in width
Required Equipment & Software	360° LiDAR sensor, Arduino
Required Measurements	Angular resolution calculation and FOV measurement
Test Errors	Human error, sensor measurement error
Test Location	CU Boulder Business Field

FOV and Range Test



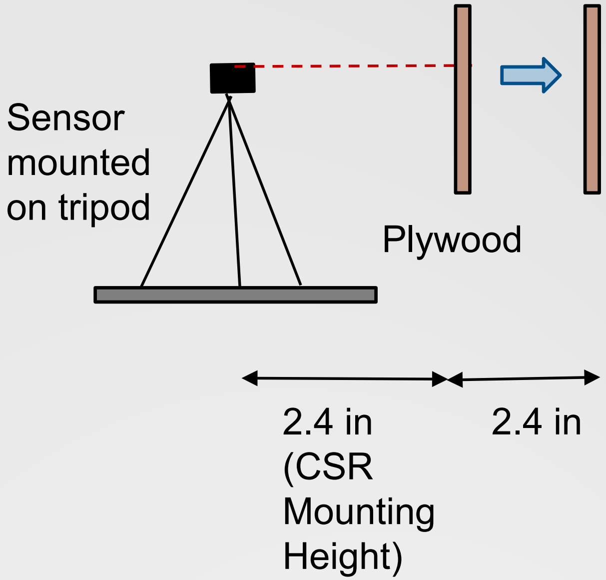
Angular Resolution Test



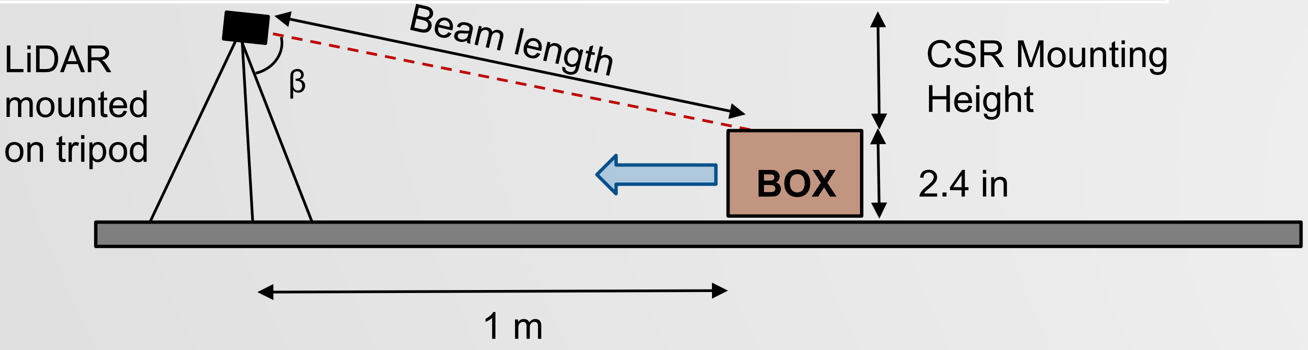
Phase 1 –Discontinuity Detection Testing

Objective	•Detect a discontinuity with single beam LiDAR •Detect a discontinuity with ultrasonic sensor
Test Plan	**Single Beam LiDAR:** • Place LiDAR on tripod at mounting angle and place box 1 m from LiDAR • Move box toward LiDAR, when LiDAR beam hits ground Arduino should send a "STOP" signal **Ultrasonic Sensor:** • Place ultrasonic sensor on tripod and place plywood CSR Mounting Height from sensor • Move plywood 2.4 in. away from sensor, at 2.4 in. Arduino should send a "MOVE" signal
Requirements Verified	**SENS 3.3:** The CSR Sensing system shall detect discontinuities at least 2.4 inches deep
Required Equipment & Software	Single Beam LiDAR, Ultrasonic Sensor, Arduino, Arduino code
Required Measurements	• Successful test once "STOP" signal is received from Arduino to simulate when to stop the CSR at 1 m from discontinuity (LiDAR reading > Beam Length +/- threshold) • Successful test once "MOVE" signal is received from Arduino to simulate when to move the moving mass (ultrasonic reading = 4.8 in. +/- threshold)
Test Errors	Human error, sensor measurement error

Ultrasonic Sensor Test

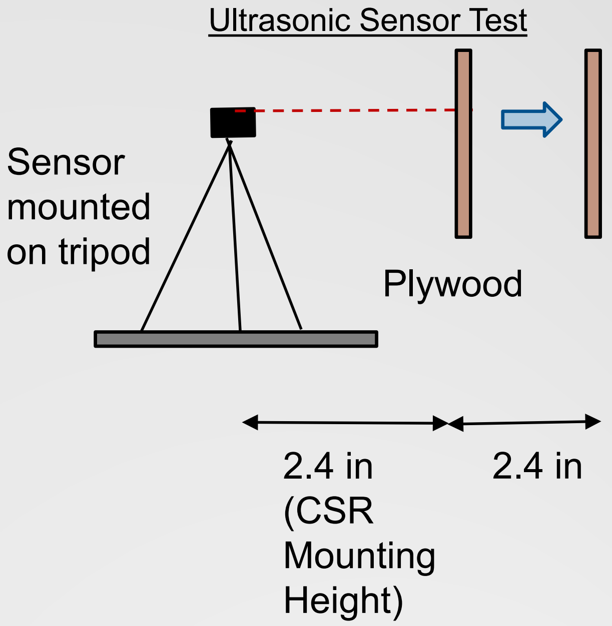


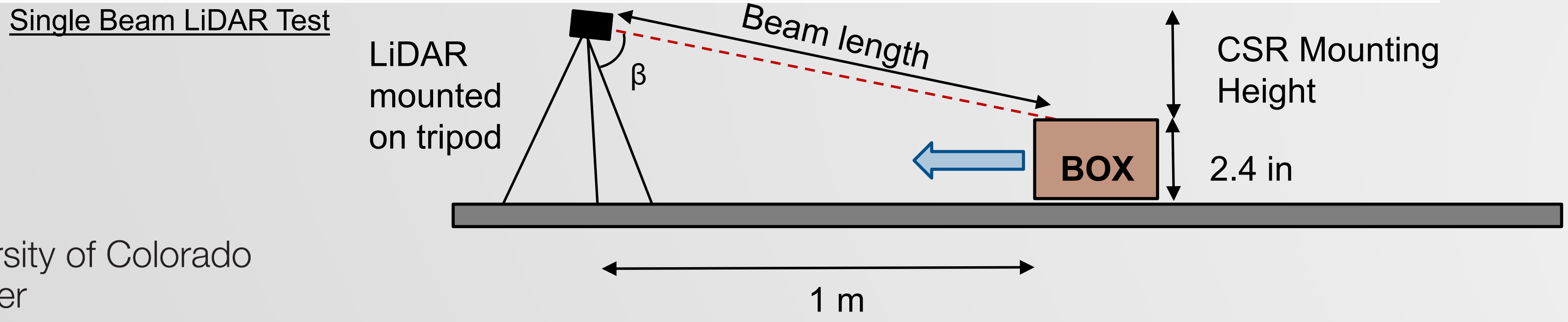
Single Beam LiDAR Test



Phase 1 –Discontinuity Detection Testing

Objective	•Detect a discontinuity with single beam LiDAR •Detect a discontinuity with ultrasonic sensor
Test Plan	**<u>Single Beam LiDAR:</u>** • Place LiDAR on tripod at mounting angle and place box 1 m from LiDAR • Move box toward LiDAR, when LiDAR beam hits ground Arduino should send a "STOP" signal **<u>Ultrasonic Sensor:</u>** • Place ultrasonic sensor on tripod and place plywood CSR Mounting Height from sensor • Move plywood 2.4 in. away from sensor, at 2.4 in. Arduino should send a "MOVE" signal
Requirements Verified	**<u>SENS 3.3:</u>** The CSR Sensing system shall detect discontinuities at least 2.4 inches deep
Required Equipment & Software	Single Beam LiDAR, Ultrasonic Sensor, Arduino, Arduino code
Required Measurements	• Successful test once "STOP" signal is received from Arduino to simulate when to stop the CSR at 1 m from discontinuity (LiDAR reading > Beam Length +/- threshold) • Successful test once "MOVE" signal is received from Arduino to simulate when to move the moving mass (ultrasonic reading = 4.8 in. +/- threshold)
Test Errors	Human error, sensor measurement error





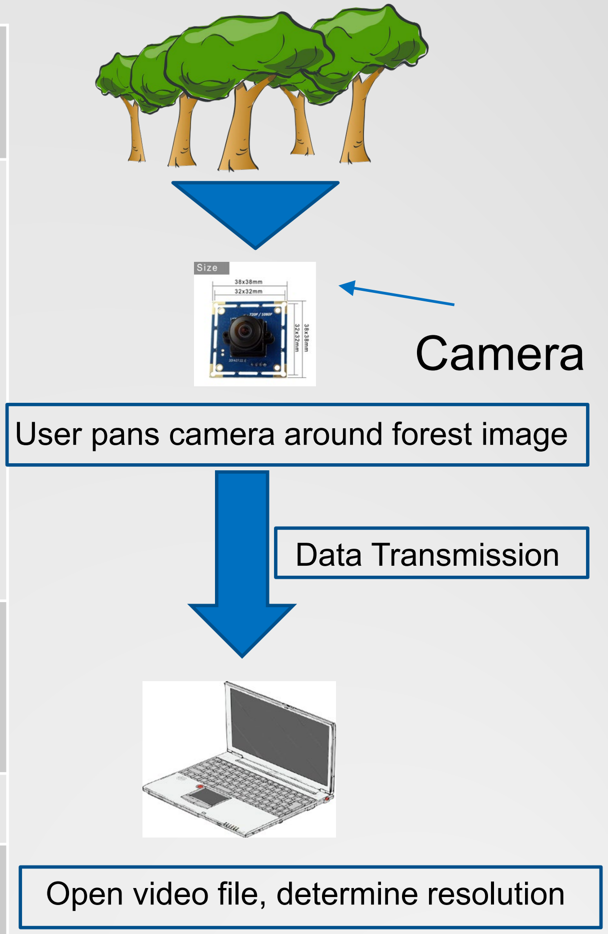
Phase 1 –Bearing Load Capacity Testing

Objective	• Determine if non-thrust rated bearings can handle the expected axial loads from skid steering.
Test Plan	• Firmly mount the bearing. • Place a plate that circular plate that is larger than the inner race, and smaller than the outer race, over the bearing's inner race. • Attach a force gauge to the plate. • Pull the forge gauge down until a force of 60N (Expected 20N, FOS=3) is reached.
Requirements Verified	**MOB.3.1:** The CSR Mobility system shall be able to perform a 0 meter radius turn up to 360°
Required Equipment & Software	Wheel bearing (0.5" ID, 1.125" OD), Force gauge mounting plate, Force gauge
Required Measurements	• Successful test once the bearing is shown to be capable of undergoing an axial load of 60N, or shown to be incapable of undergoing a load of 60N.
Test Errors	Human error, sensor measurement error

Source: PCE Instruments website

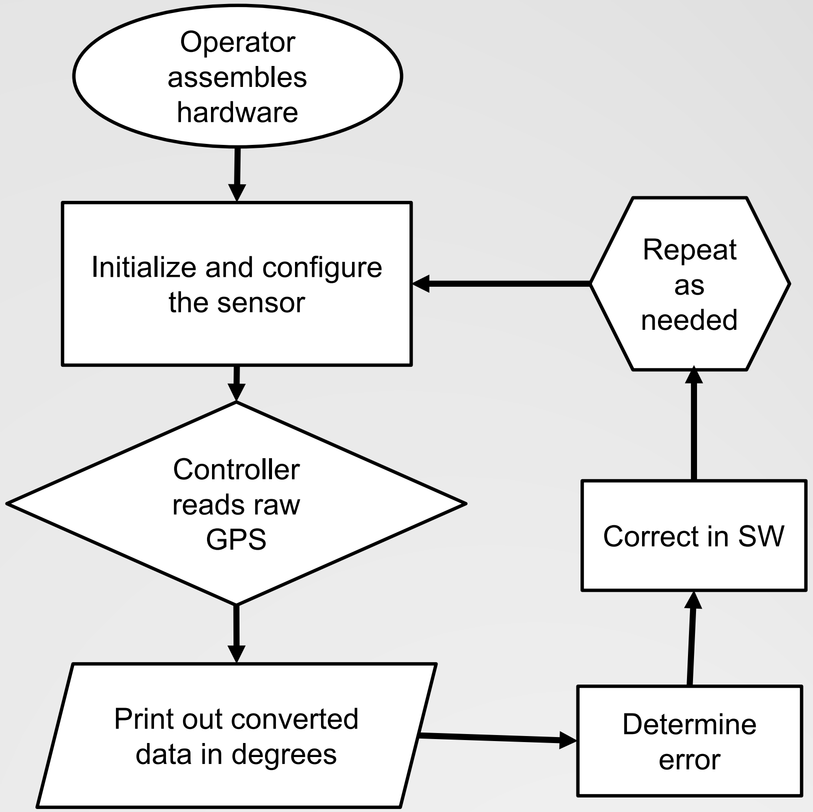
Phase 1 –Camera Operations Testing

Objective	•Verify camera system's Field of View •Quantify length of time for video/image transmission •Verify Standard Definition Resolution
Test Plan	**Field of View** • Turn camera on and take image, then video in forest location. Locate outermost objects on image, then compare to actual degree measurement/arc length of distance between trees on location. **Image/Video Transmission** • Turn camera on and take 10 second video, panning around forest testing location; send data to ground station at a distance of 250 meters and measure time of transmission • Once transmission is received by ground station, check resolution of video to verify standard definition quality
Requirements Verified	**SENS 5.1**: The CSR Sensing system shall capture video **SENS 5.1.1**: The CSR Sensing system shall capture video at Standard Definition **SENS 5.1.3:** The CSR Sensing system shall capture video with a field of view of at least 100 degrees
Required Equipment & Software	180° Fisheye Lens Camera, Ground Station Computer
Required Measurements	Distance/Degree between objects, time of transmission, video time, distance from GS to camera, video resolution
Test Errors	Estimate of Resolution, Actual Field of View



Phase 1 –GPS Accuracy Test

Objective	• Ensure the C&DH system can store and compare positioning coordinates
Test Plan	**Location of Interest Storage** • Send a location of interest GPS location to the ASUS board and verify that the ASUS receives and stores the coordinate as a variable **Tolerance Validation** • Input a GPS coordinate and have the controller determine if the input GPS location is within 5 meters of the current GPS module's output. The software will compare both GPS locations (the CSR GPS coordinates, and the inputted LOI GPS coordinates)
Requirements Verified	**CDH 3.2:** The CSR C&DH system software shall store the Location of Interest's GPS coordinates in memory. **CDH 3.2:** The CSR C&DH system shall determine if the CSR is within +/- 5 meters of the location of interest
Required Equipment & Software	• Ground Station (Laptop with Linux) • ASUS Tinker board • Arduino Due • GPS RTK Modules and antennas
Required Measurements	• GPS coordinate location
Test Errors	• GPS error and inaccuracy

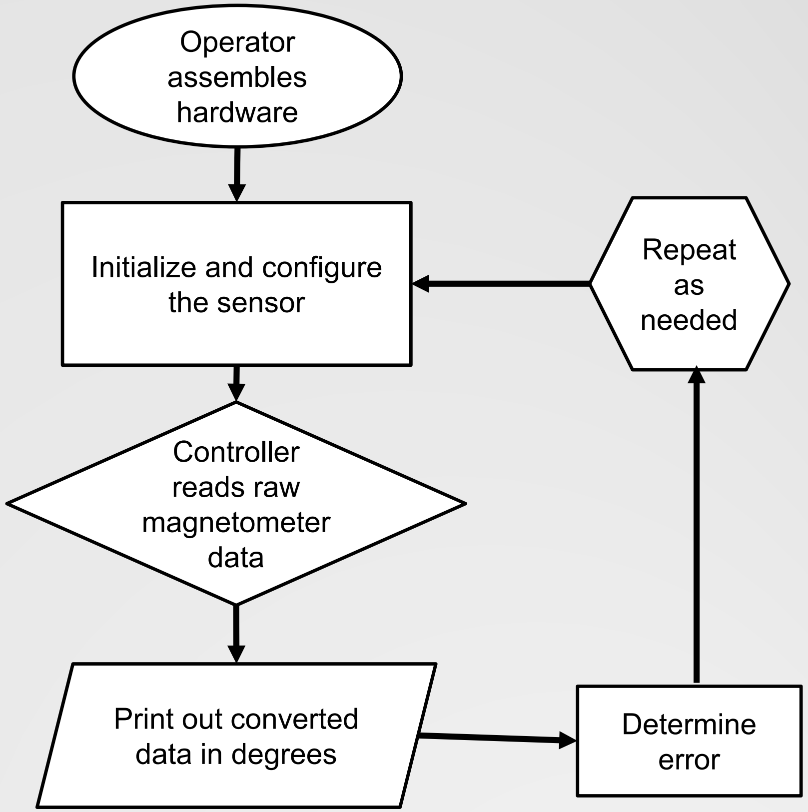


Phase 1 – Motor Magnetometer Interferance Testing

Objective	• Ensure the magnetic interference from the motors is insignificant and still allows for accurate heading measurements.

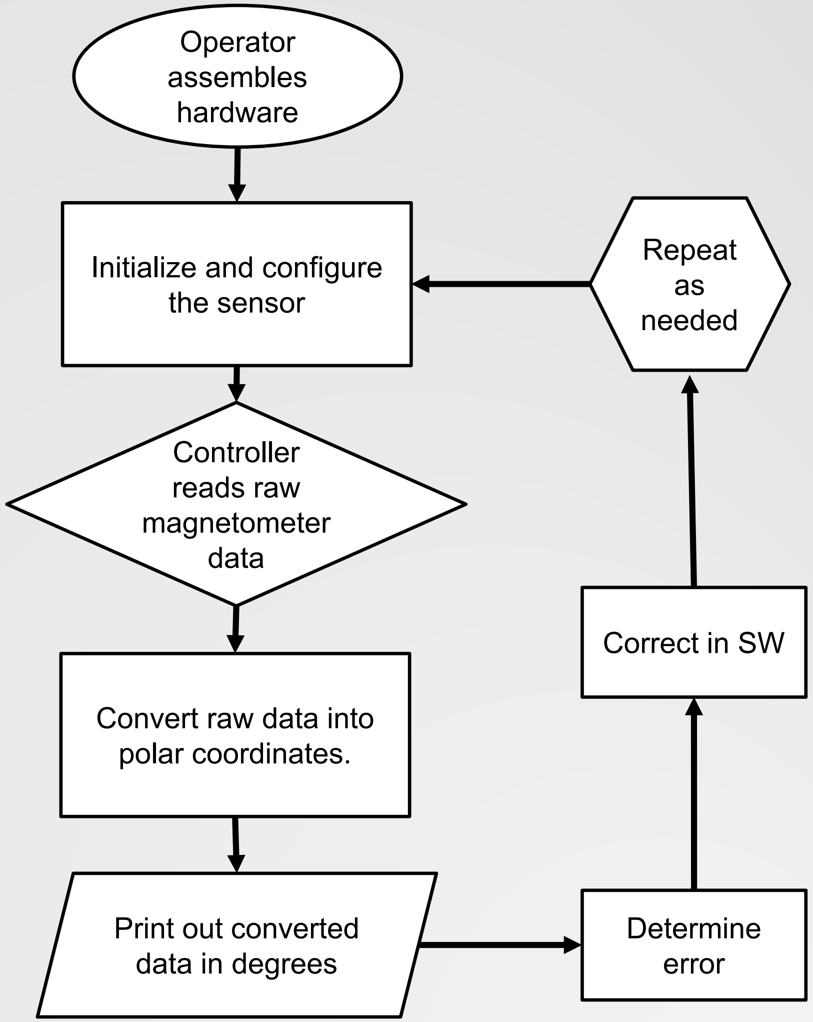
Test Plan	• Place magnetometer the expected mounting location on the CSR.
	• Capture and save magnetometer data for the following three configurations:
	    • Without the motors mounted.
	    • With the motors mounted, not powered.
	    • With the motors mounted, powered and driven.

Requirements Verified	**MOB.3.1:** The CSR Mobility system shall be able to perform a 0 meter radius turn up to 360°
Required Equipment & Software	Magnetometer, ASUS Tinkerboard, AndyMark 775 Redline Motor, Power Supply
Required Measurements	• Magnetometer readings



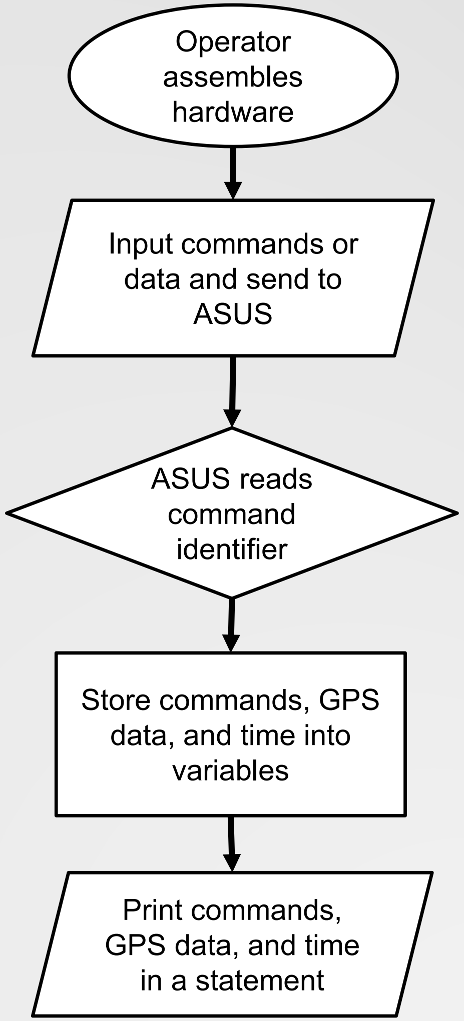
Phase 2 – C&DH Testing Heading

Objective	• Ensure the C&DH system can process magnetometer raw magnetometer data and convert this to useful heading data (heading in degrees)
Test Plan	**Determining Heading of CSR** • Assemble hardware • Initialize the sensor • Read sensor data in units of uT (MicroTesla) • Convert data to polar coordinates • Repeat multiple times, determine error • Use SW to correct error
Requirements Verified	**CDH 3.4:** The CSR C&DH system shall determine the heading of the CSR
Required Equipment & Software	• Ground Station (Laptop with Linux) • ASUS Tinker board • Arduino Due • Magnetometer
Required Measurements	• Heading data in degrees
Test Errors	• Error or inaccuracy in the sensor readings



Phase 2 – C&DH Testing

Objective	• Ensure the C&DH system can process commands by identifying, distributing, and timestamping commands and data • Ensure the C&DH system handles mode changes as intended
Test Plan	**Mode 1 Test (Manual Mode):** • Verify magnetometer correction algorithm returns correct angle between current heading and LOI location • Verify GPS coordinates are reported when a user command is given • saveAndSendGPS() command should be called • Verify time stamped data is received with returned data • Verify Mobility commands are published when forward, backward, or turn commands are sent by the user **Mode 2 Test (Semi-Autonomous Mode)** • Verify stop command is sent to Mobility when a "object detected" signal is received from Sensing **Mode 3 Test (Discontinuity Traversal Mode):** • Verify linear mass stage movement command is sent to Mobility when a pseudo-signal is sent from the Ultrasonic sensors in Sensing
Requirements Verified	CDH 1.1, CDH 1.2, CDH.2.1
Required Equipment & Software	• Ground Station (Laptop with Linux) • ASUS Tinker board • Arduino Due
Required Measurements	• Time to send and receive commands



Phase 3 –Full System LabVIEW Interface

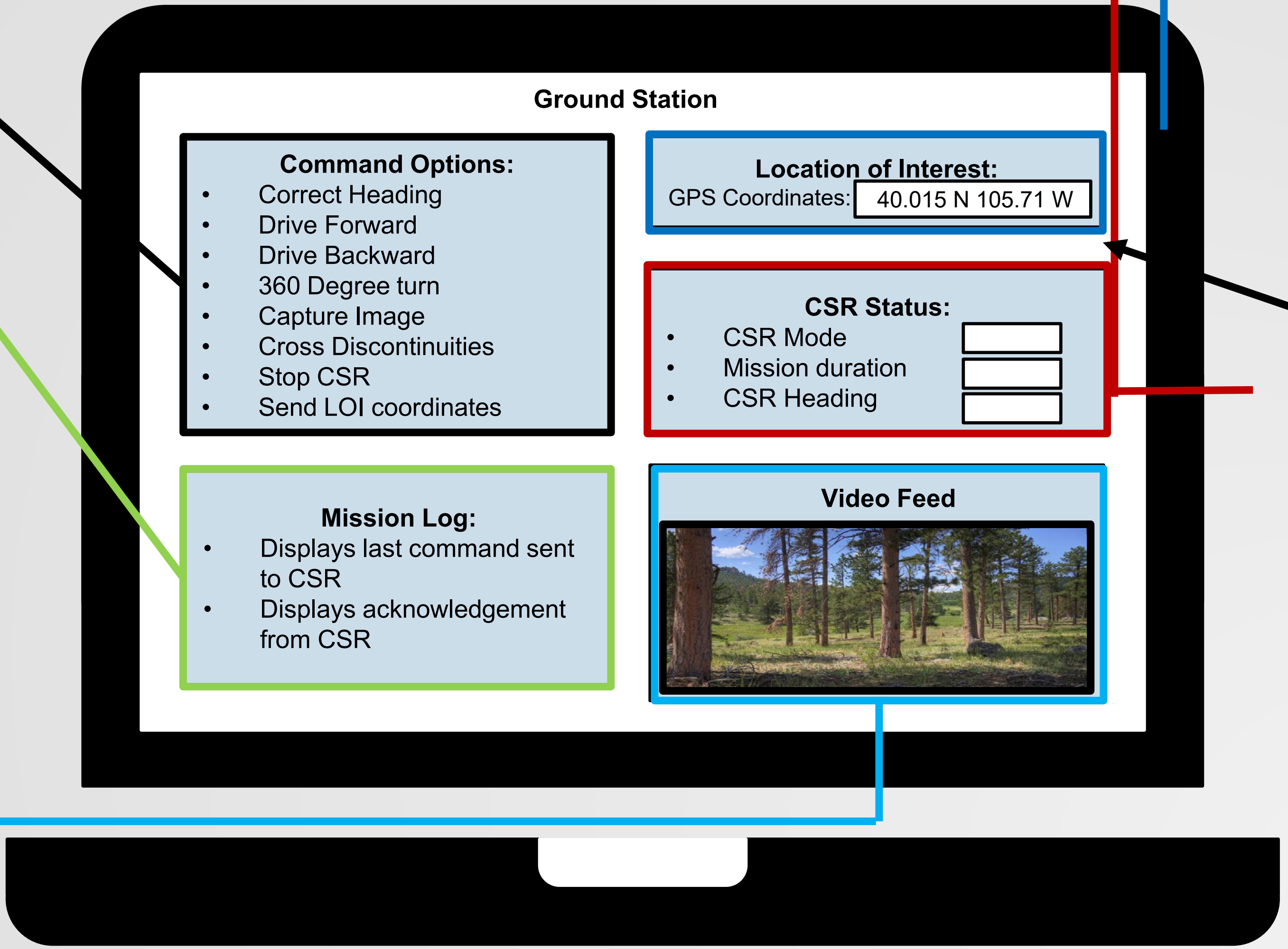
An operator will select which command the CSR should execute.

Each command sent to and acknowledged by the CSR will be displayed in the mission log.

The operator will input the desired location of interest and send it to the CSR

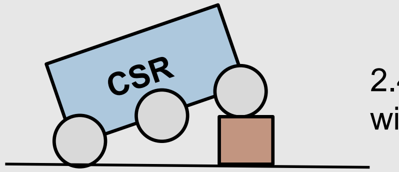
The status of the CSR is updated and displayed continuously.

Live video feed will display the environmental terrain



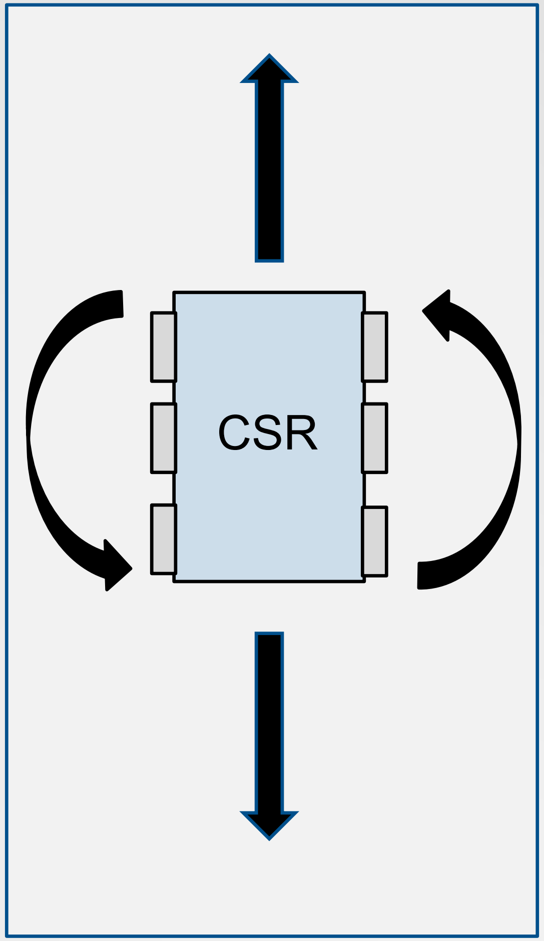
Example value for LOI is being used

Phase 3 –Environmental Maneuverability Testing

Objective	• Drive through underbrush (See Terrain Definition) • Drive over a 2.4 inch step
Test Plan	**<u>2.4 inch step test</u>** • Attach an L bracket to both 2.4 x 2.4 in. sides of a wood block with width of CSR and secure to ground with stakes • Manually drive CSR over the wood block, successful test if CSR is able to traverse  2.4 x 2.4 in wood block with width of CSR  **<u>Terrain test</u>** • Verify if CSR is able to drive on desired terrain and through underbrush
Requirements Verified	MOB 3.4, MOB 3.4.1
Required Equipment & Software	• Functional CSR with mobility system • 2.4 in. x 2.4 in. x CSR width block • Two L brackets • Two stakes • LabVIEW interface
Test Location	• CU Boulder South Campus – rocky trail terrain, small slopes, light grass

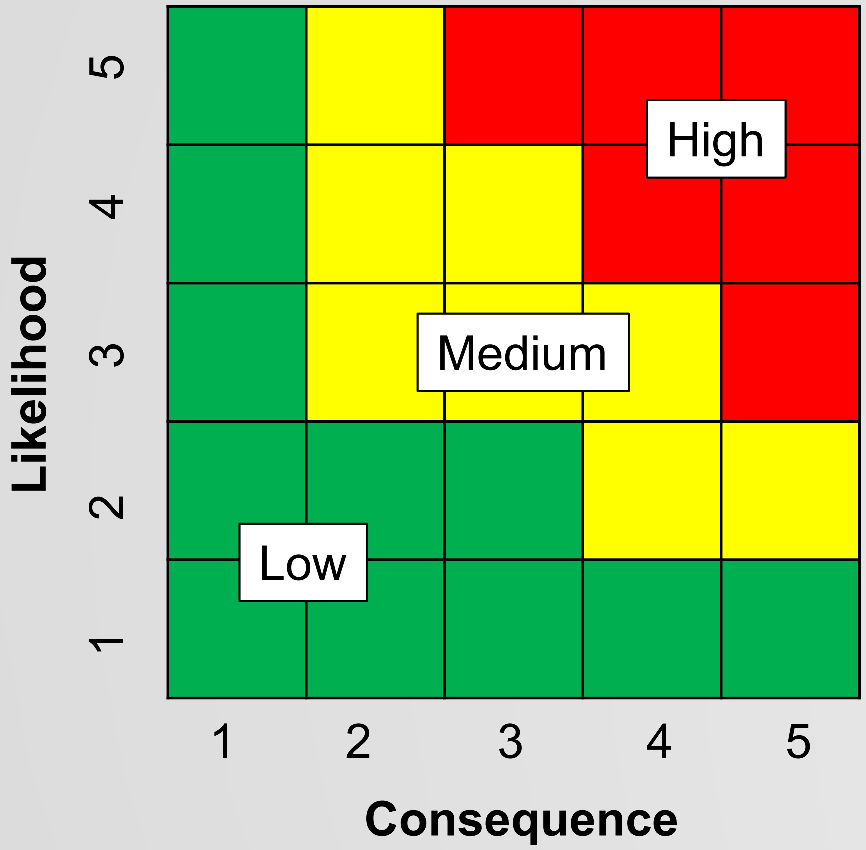
Phase 3 –CSR Functional Testing

Objective	• Verify that the mobility system can translate • Drive forward and reverse • Perform a 360° turn
Test Plan	• Conduct mobility testing for forward and reverse motion • Conduct mobility testing for 360° turn
Requirements Verified	**MOB 3.1:** The CSR Mobility system shall perform a 0 meter radius turn up to 360 degrees
Required Equipment & Software	• CSR Chassis • Motor mounts • Motors • Mobility power source
Required Measurements	• Torque • Voltage and Current (I.e. power)
Test Location	• Parking lot - flat ground



Risk

Risk Introduction



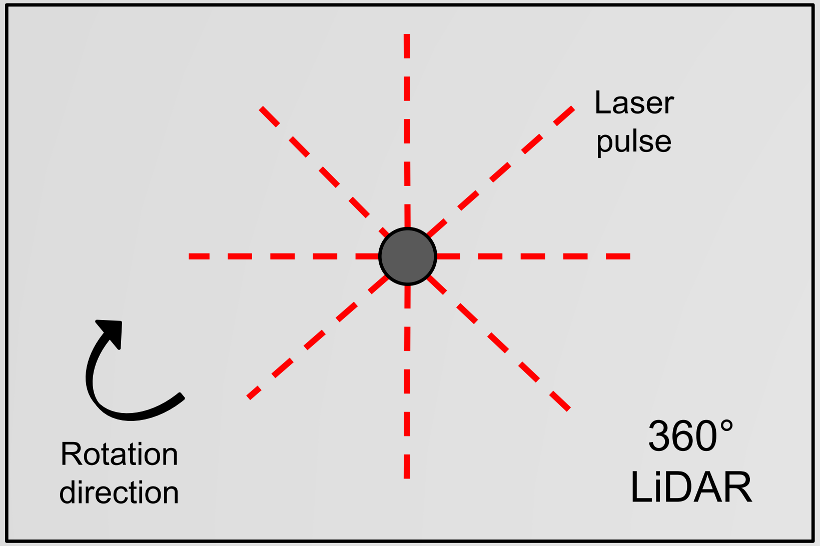
Low (Green): Minimum impact. Minimum oversight needed to ensure risk remains low.

Medium (Yellow): Some disruption. Different approach may be required. Additional management attention may be required.

High (Red): Unacceptable. Major disruption likely. Different approach required. Priority management attention required.

SENS.1.T Mitigation Off-Ramp

Planned Design Solution

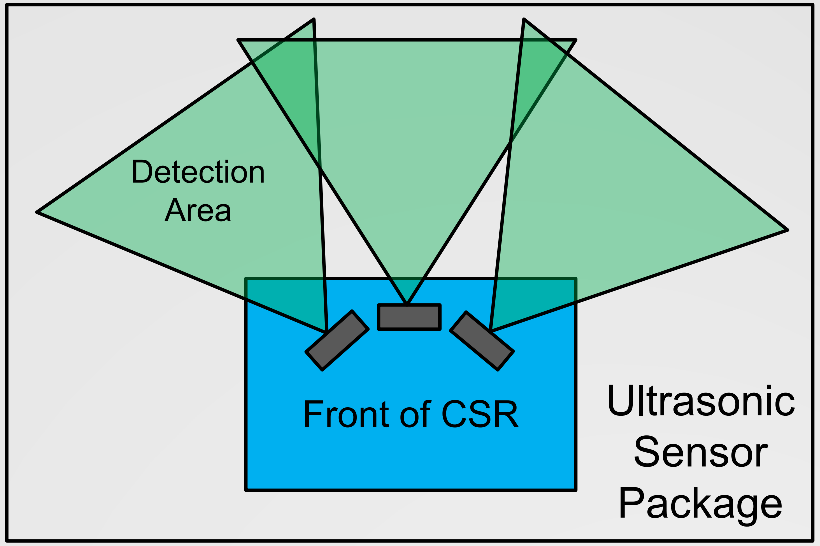


Integration Specifications:
- RPLiDAR A2M8 Laser Scanner
- USB Protocol with ASUS Tinker Board (handled with ROS package)
- Data Processing through ROS on Tinker Board

Off-Ramp Conditions:
- USB Protocol is not set up properly in the ROS package
- Processing time is > sensor response time
- Data processing takes up too much processing bandwidth (ROS cannot keep up with updating topics)

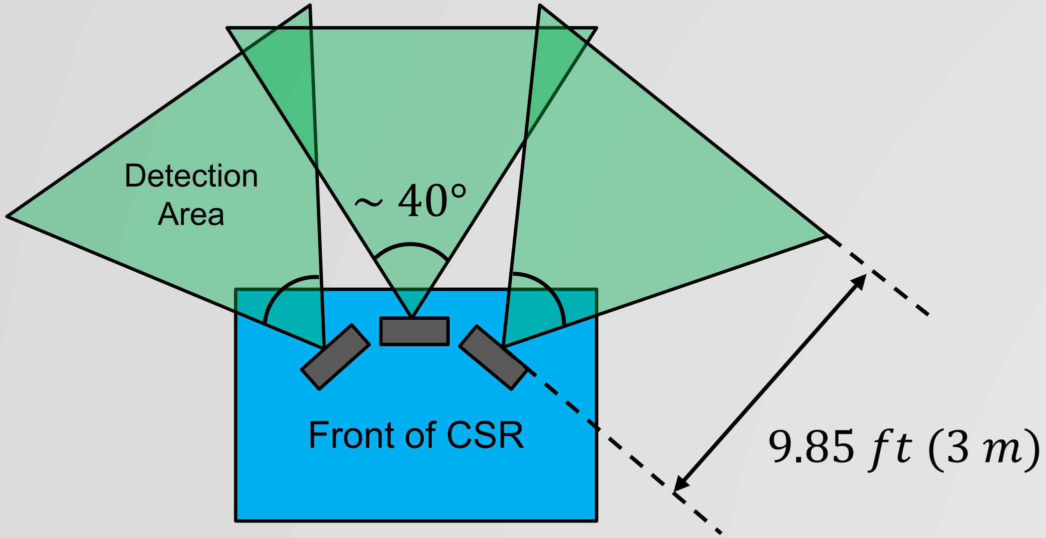
Deadline 02/04/2018

Off-Ramp Design Solution



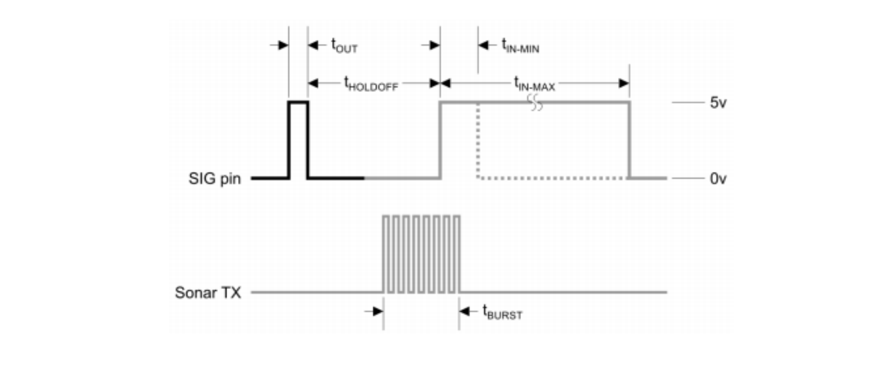
Integration Specifications:
- 3 Parallax Inc PING))) Ultrasonic Distance Sensors
- 1 Digital I/O PWM pin required per sensor
- Data Processing in Arduino Sketch on Arduino Due

SENS.1.T Off-Ramp Requirement Satisfaction



PWM Integration:

- Utilizes 1 I/O pin per device for PWM control
- Does not require specific digital PWM pins on the Arduino
    - Digital PWM is controlled with one trigger and sensor has its own procedure (diagram to the right)



(black line)	Host Device	Input Trigger Pulse	t_{OUT}	2 µs (min), 5 µs typical
(grey line)	PING))) Sensor	Echo Holdoff	$t_{HOLDOFF}$	750 µs
		Burst Frequency	t_{BURST}	200 µs @ 40 kHz
		Echo Return Pulse Minimum	t_{IN-MIN}	115 µs
		Echo Return Pulse Maximum	t_{IN-MAX}	18.5 ms
		Delay before next measurement		200 µs

	Required Specifications	Achieved Specifications	Requirements Satisfied
In-Plane Object Detection • Parallax PING))) Ultrasonic Distance Sensor	• Range – 3.125 ft (0.9525 m) • Field of View – 103.5° • Smallest Detectable Object – 1 in	• Range – 9.85 ft (3 m) • Field of View – 40*3 = 120° • Smallest Detectable Object – 0.25 – 0.75 in (determined from tests from manufacturer)	• SENS.3.1 • SENS.3.1.1 • SENS.3.1.2

Lower level risks

Risk	Description	Effect	Type	Likelihood	Severity	Total
SENS.2.T	Noise interference on magnetometer from motors	Data from the magnetometer is incorrect and therefore cannot accurately correct heading	T	5	3	15
SENS.3.T	Single Beam LiDAR's falsely detect a discontinuity when traversing an obstacle or slope	The CSR autonomously stops, this can cause the CSR to roll down the obstacle/slope and cause fatigue on the motors	T	5	2	10
MOB.3.T	Chain slippage	Tension is not sufficient to drive CSR	T	3	3	9
CDH.2.T	Insufficient thermal management of electrical components	Component failure and data not received	T	3	3	9
MOB.4.T	Wheel slippage	May not be able to overcome obstacles	T	4	2	8
MOB.5.T	Back EMF from motors	Current is sent backwards into system	T	2	3	6
MOB.6.T	Structural deformation	Chassis deforms which can cause a decrease in mobility performance	T	1	4	4
SENS.4.T	System calibration offsets	Heading correction is not accurate with LOI	T	4	1	4

Risk Mitigation

Risk	Mitigation Strategy	Likelihood	Severity	Total
SENS.2.T	Place the magnetometer a safe distance away from the motors. Test results show that 15cm should suffice, however if not can utilize mu-metal foil shielding	3	2	6
SENS.3.T	Add an accelerometer on board and use this data when the CSR is at a slope to ignore single beam LiDAR	5	1	5
MOB.3.T	Utilize chain tensioners	1	3	3
CDH.2.T	Gain familiarity of data sheets of components to understand the max power ratings of each, monitor current	1	3	3
MOB.4.T	Design for non-slip conditions, if slipping does occur can try another path, also consider wheels with deep treads	2	2	4
MOB.5.T	Chosen motor uses resistors and FET's (Field Effect Transistors) to regulate back EMF	1	3	3
MOB.6.T	Choose a strong alloy with relatively high temperature rating (Aluminum Alloy 6061)	1	3	3
SENS.4.T	Frequently check and recalibrate magnetometer when needed	2	1	2

Risk Matrices

Before Mitigation

Likelihood \ Consequence	1	2	3	4	5
5		SENS.3.T			
4	SENS.4.T	MOB.4.T			
3			MOB.3.T CDH.2.T		SENS.2.T
2			MOB.5.T		
1				MOB.6.T	

Mitigation →

After Mitigation

Likelihood \ Consequence	1	2	3	4	5
5	SENS.3.T				
4					
3		SENS.2.T			
2	SENS.4.T	MOB.4.T			
1			MOB.3.T MOB.5.T MOB.6.T CDH.2.T		