# Preliminary Design Review

# Drone-Rover Integrated Fire Tracker

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# Mission Statement

**Drone-Rover Integrated Fire-Tracker (DRIFT)**
will develop a mother rover to secure, carry, and level an Unmanned Aerial Vehicle (UAV) for the purposes of gathering pertinent environmental data regarding locations at risk of or exposed to a wildfire.

# Project Overview: Fire Tracker System

- As a result of climate change, wildfire seasons are becoming hotter and longer
  - This allows for a wildfire to easily ignite and rapidly spread
  - United States Forest Service is consistently increasing its budget for wildfire mitigation alone
- A deployable **mother rover** and **autonomous drone** provide a low cost means of long-range reconnaissance for early detection of wildfires
- These systems can assist firefighters in investigating areas sometimes impassible by ground-based methods alone

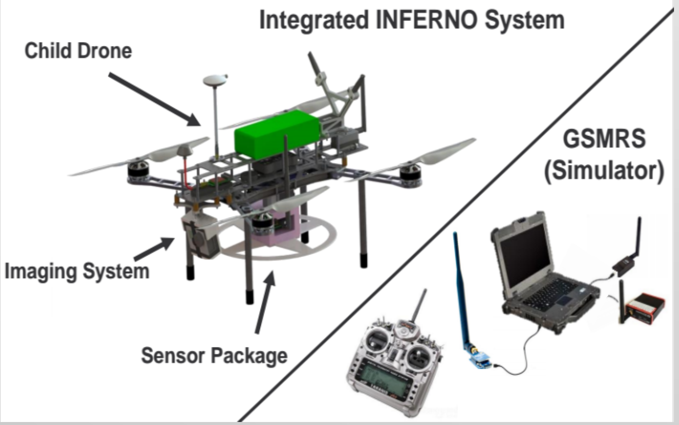
# Project Heritage

**DRIFT** will utilize both the **INFERNO** and **CHIMERA** hardware and software shown below:

**IN**tegrated **F**light **E**nabled **R**over for **N**atural disaster **O**bservation

- **INFERNO** (2015 - 2016): Semi-autonomous drone capable of transporting and deploying a temperature sensor package to a location of interest

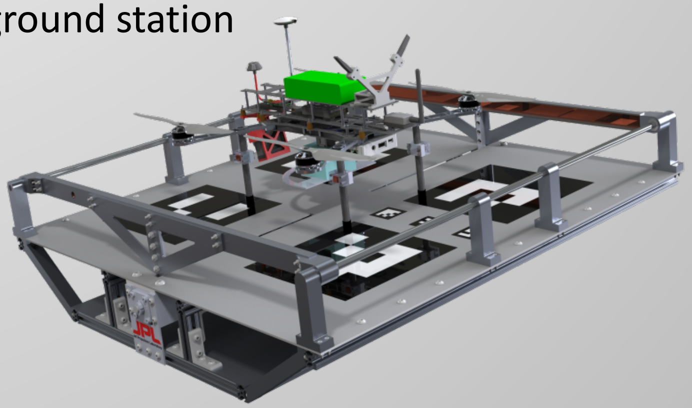
INFERNO Capabilities:
- Mission Duration: 13.5 minutes
- Fully Autonomous Takeoff
- 10 m/s Translational Flight
- Video/Imaging: 720p at 30fps
- Sensor Package: > 90% transmission of SPS data




**CHI**ld drone deployment **ME**chanism and **R**etrieval **A**pparatus

- **CHIMERA** (2016 - 2017): The landing, securing, and deployment system for the autonomous drone inherited from INFERNO

CHIMERA Capabilities:
- Capable of securing CD up to 200m from GS
- Drone recharging system can charge the CDS LiPo battery upon command
- Autonomous landing functionality utilizing image recognition upon command from ground station



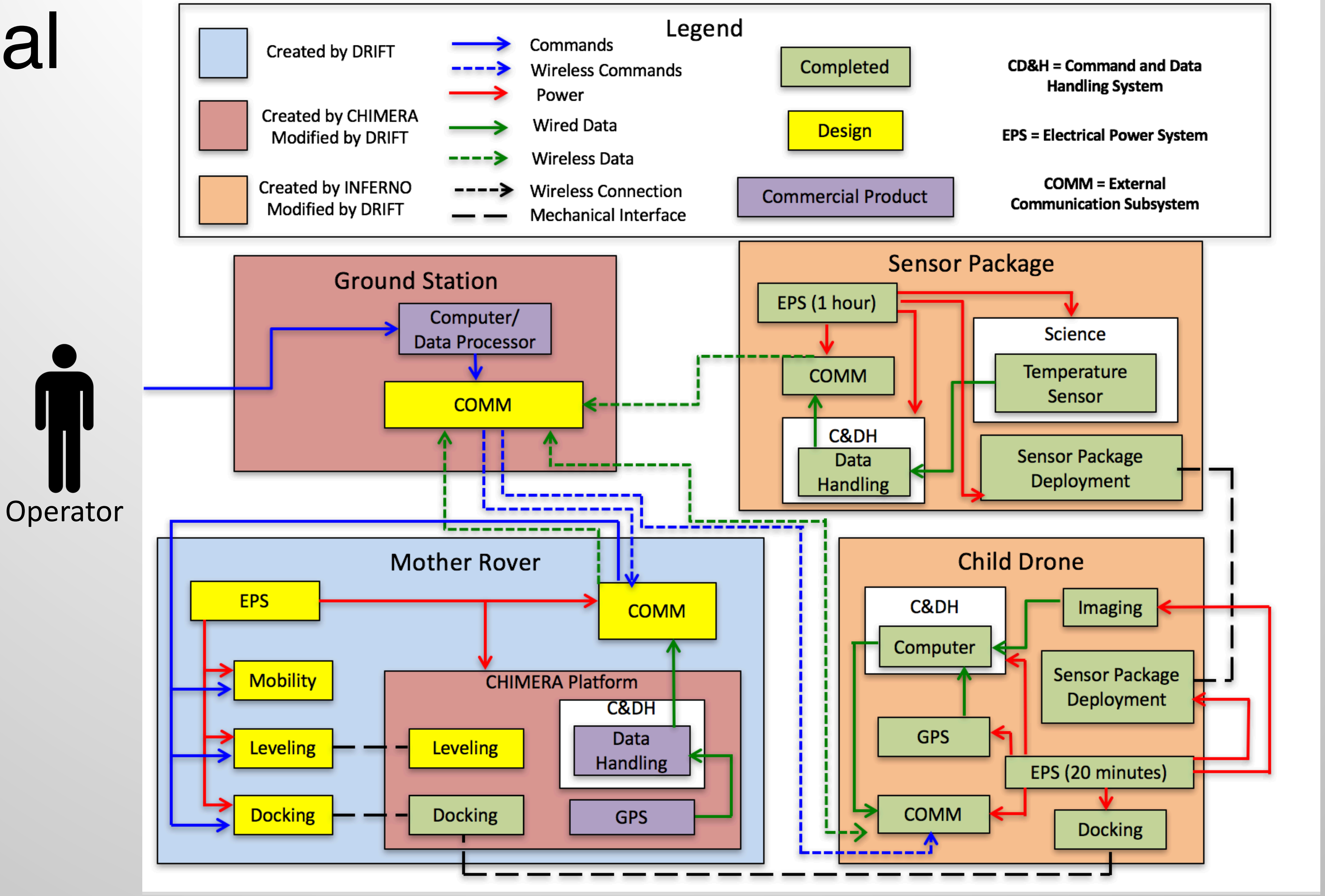
# Definitions

| Term | Definition |
|---|---|
| **Mission** | o The mother rover is deployed from a designated ground station where it traverses over defined rough terrain to a designated GPS location. At this location, the child drone is then deployed. Once the child drone drops the sensor package, it returns to the mother rover where it autonomously lands and is then secured. The mother rover returns to the ground station. |
| **Rough Terrain** | ○ Materials: lawn grass, small gravel, and fine dirt<br>○ Varying slopes from 0 to $20^0$<br>○ Traversable obstacles up to 0.127 m (5 in) tall (rocks, pinecones, etc.)<br>○ Non-traversable obstacles up to 3.05 m (10 ft) apart (trees, boulders, etc.)<br>○ Similar to California Hillside |
| **Tree Density** | ○ Trees are 3.05 m (10 ft) or more apart in woodlands area |

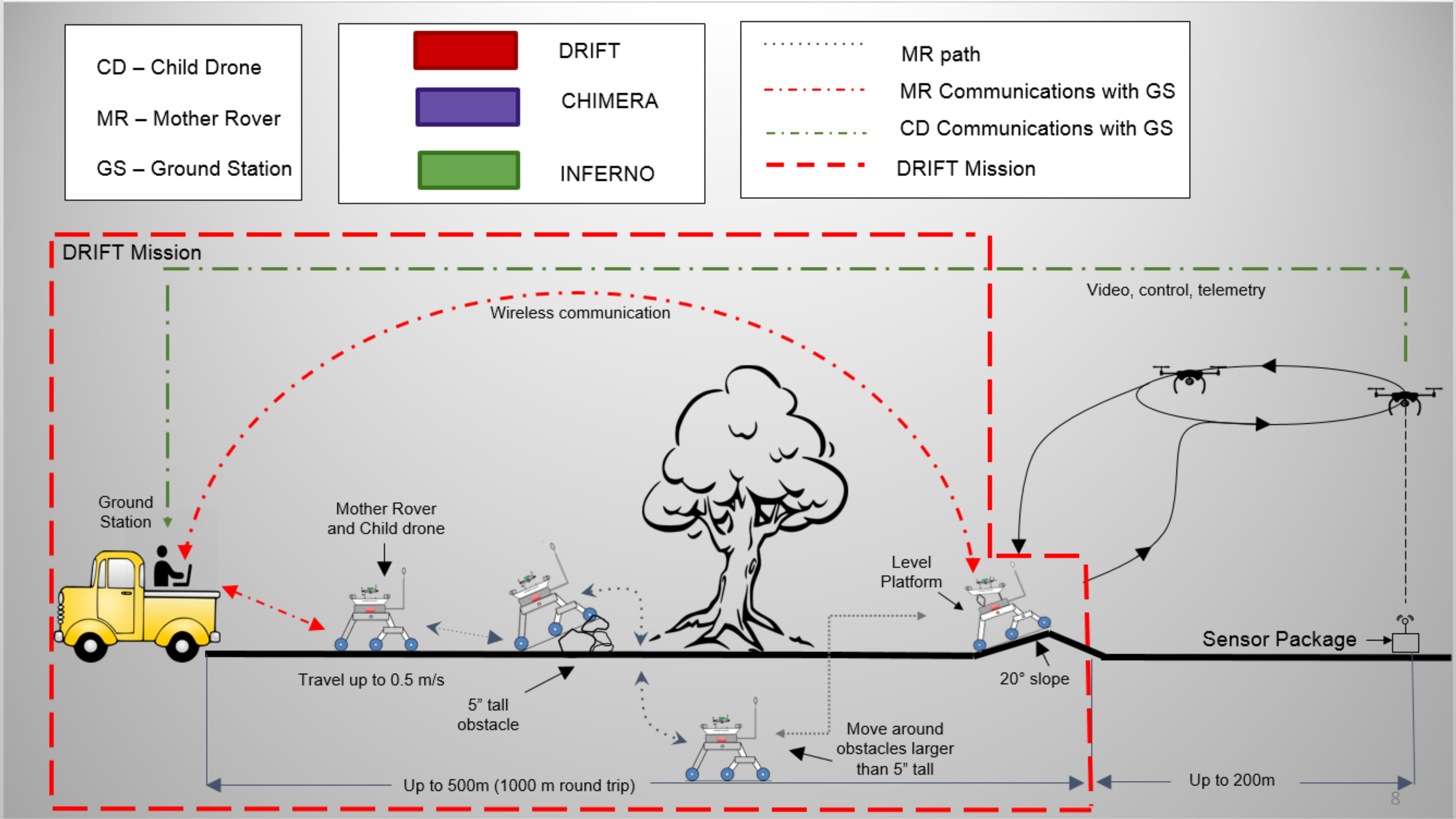
# Acronyms

| | |
|---|---|
| **DRIFT:** Drone-Rover Integrated Fire Tracker | **LP:** Landing Platform |
| **MR:** Mother Rover | **FOV:** Field of View |
| **CD:** Child Drone | **CPE:** Critical Project Element |
| **SP**: Sensor Package | **GS**: Ground System |

# Functional Block Diagram



# CONOPS



CD – Child Drone
MR – Mother Rover
GS – Ground Station
DRIFT
CHIMERA
INFERNO
MR path
MR Communications with GS
CD Communications with GS
DRIFT Mission
DRIFT Mission
Video, control, telemetry
Wireless communication
Ground Station
Mother Rover and Child drone
Level Platform
Sensor Package
Travel up to 0.5 m/s
5" tall obstacle
20° slope
Move around obstacles larger than 5" tall
Up to 500m (1000 m round trip)
Up to 200m

# Functional Requirements

| Functional Requirement | Description |
|---|---|
| FR1.0 | The MR shall integrate with the attached landing platform |
| **FR2.0** | **The MR shall receive commands from the GS at a rate of 1 Hz** |
| **FR3.0** | **The MR shall transmit data to the GS at a rate of 30 Hz** |
| **FR4.0** | **The MR shall traverse through woods and grasslands up to 500 m in any direction from the drop off point** |
| **FR5.0** | **The MR shall level to position itself for the CD to take-off and land** |

Key Project Element

# Requirements Flowdown

Communications

| **Functional Requirement** | **Description** |
|---|---|
| FR2.0 | The MR shall receive commands from the GS at 5 Hz. |
| Design Requirement | Definition |
| DR2.1 | The MR shall record a log of received commands from the GS detailed in DR2.4. |
| DR2.2 | The MR shall receive signals with a signal to noise ratio of at least 6 dB-Hz (industry standard). |
| DR2.3 | The MR shall receive commands at a distance of 500 meters. |
| DR2.4 | The MR shall receive/respond to commands from the GS for translational motion of the MR, turn video feed on/off (MR and CD), open and close the onboard CD securement mechanism, and to level the landing platform aboard the MR. |

# Requirements Flowdown

Communications

| **Functional Requirement** | **Description** |
|---|---|
| FR3.0 | The MR shall transmit specified data to the GS at 30 Hz. |
| Design Requirement | Definition |
| DR3.1 | The MR shall transmit its current GPS location to the GS with an accuracy of 5 m. |
| DR3.2 | The MR shall transmit live video feed at 1080p at 30 fps to the GS |

# Requirements Flowdown

Translational System and Motors

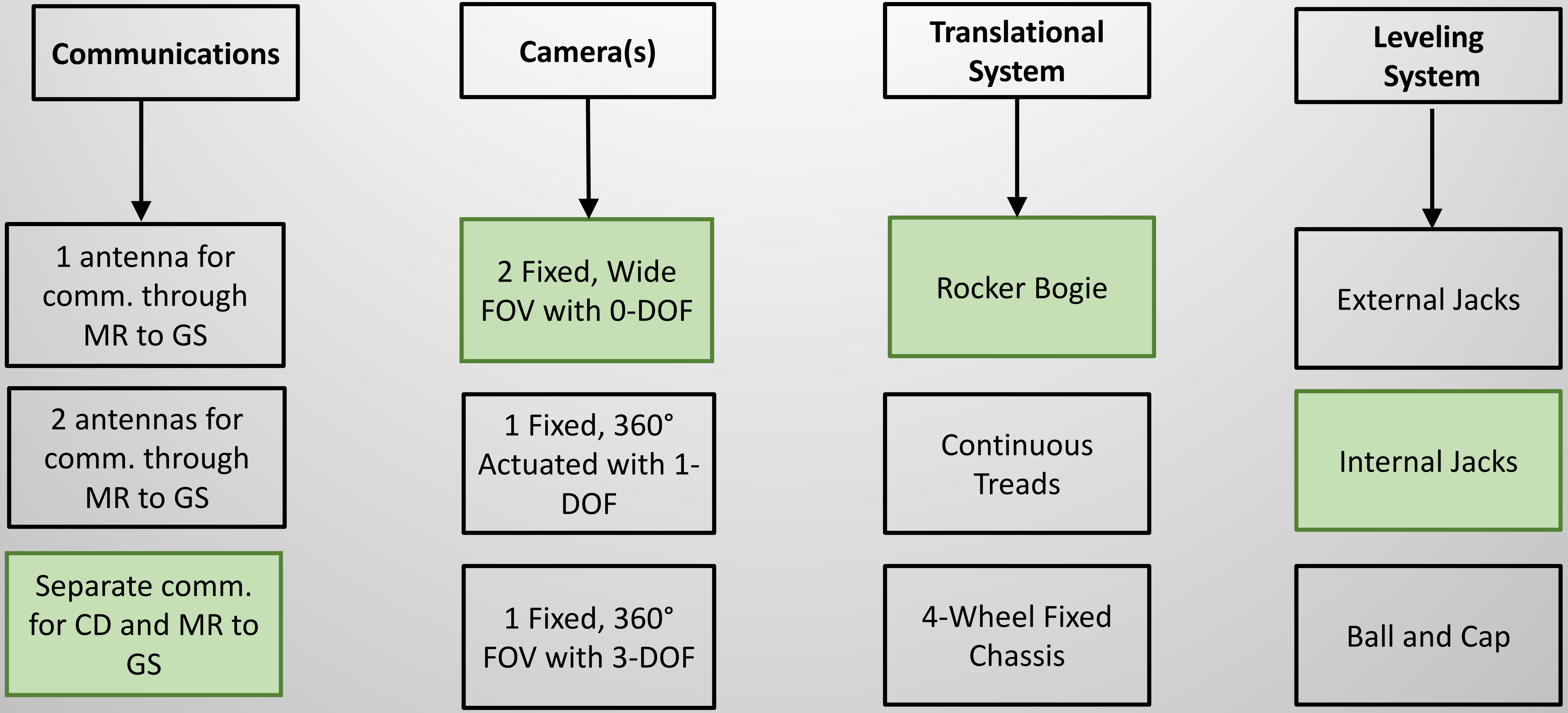
| **Functional Requirement** | **Description** |
|---|---|
| FR4.0 | The MR shall traverse through an environment with varying slope, defined obstacles that the rover shall clear, and obstacles the rover should avoid up to 500m in any direction from the drop off point. |
| Design Requirement | Definition |
| DR4.1 | The MR shall travel at a speed within the range of 0 to 0.5m/s in forward and reverse. |
| DR4.3 | The MR shall turn 90 degrees in a 10 ft. radius |
| DR4.4 | The MR shall execute received commands including moving forwards, backwards, turning, speed variation, and coming to a complete stop. |
| DR4.5 | The MR shall traverse up and down a slope of 20 degrees. |
| DR4.6 | The MR shall traverse 5 in. tall obstacles. |
| DR4.7 | The MR shall traverse lawn grass and a dirt path with loose gravel |

# Requirements Flowdown

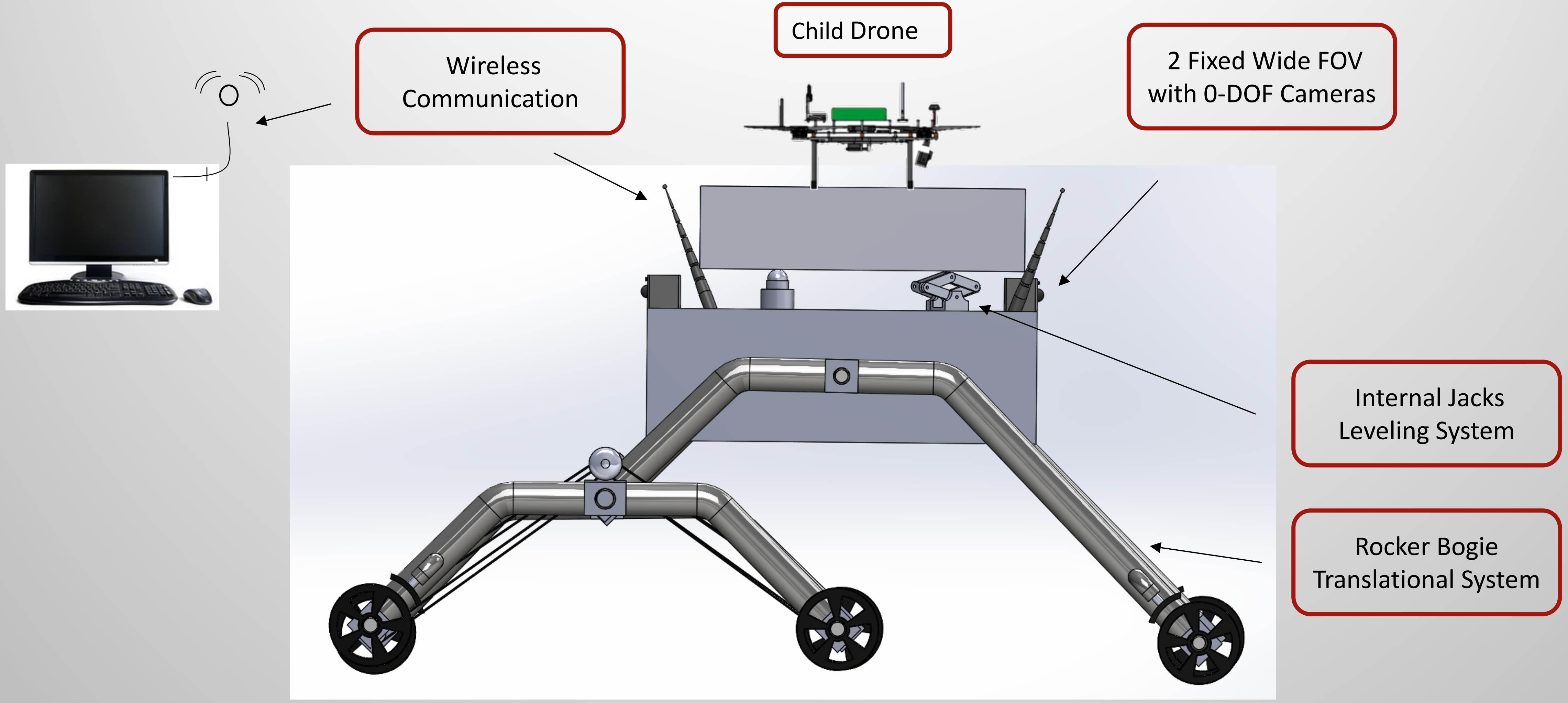
Leveling

| Functional Requirement | Description |
|---|---|
| FR5.0 | The MR shall position itself for the CD to take-off and land safely such that it is able to be secured possibly by the MR's securement mechanism |
| Design Requirement | Definition |
| DR5.1 | The MR shall level itself within 3.5 degrees after coming to a complete stop. |
| DR5.2 | The MR shall hold a completely stopped position a slope of 20 degrees by using a wheel locking mechanism. |

# Design Options Considered



# DRIFT Baseline Design

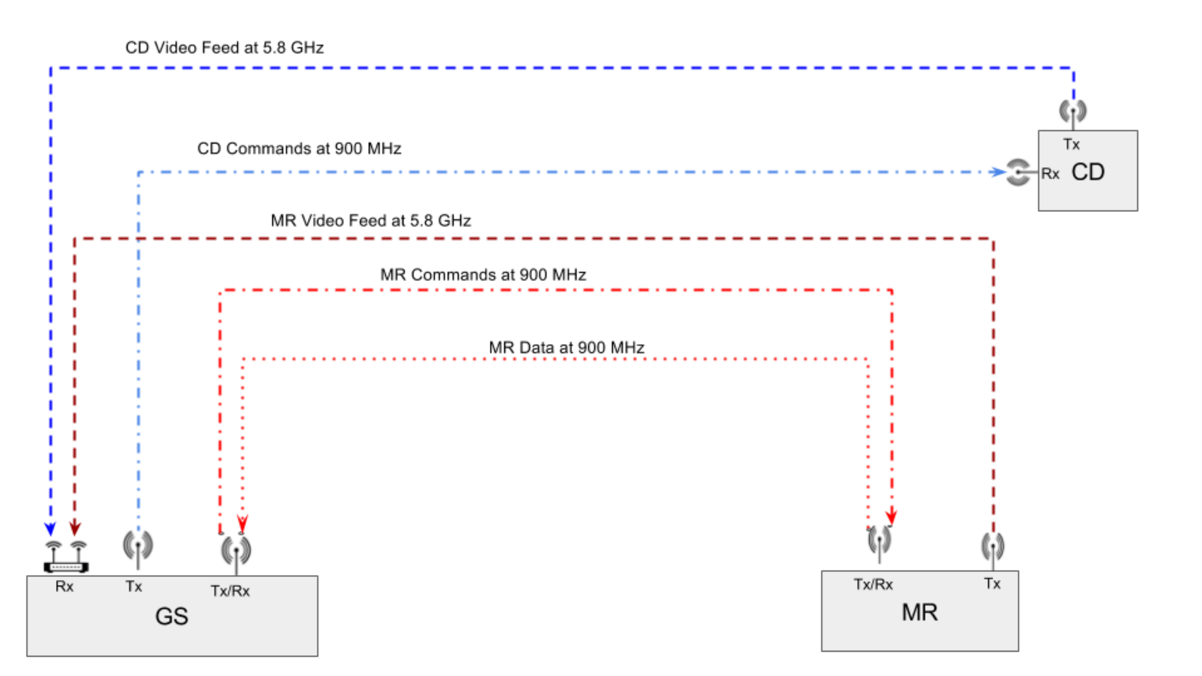


# Communications

# Communications Feasibility

## Baseline Design

- Existing Lines
  - CD Video Feed
  - CD Commands
- New Lines
  - MR Video Feed
  - MR Commands
  - MR Data




## Assumptions

- The CD is high enough so that signal loss through the trees is minimal
- The MR signal is travelling partially through open space, and partially through trees

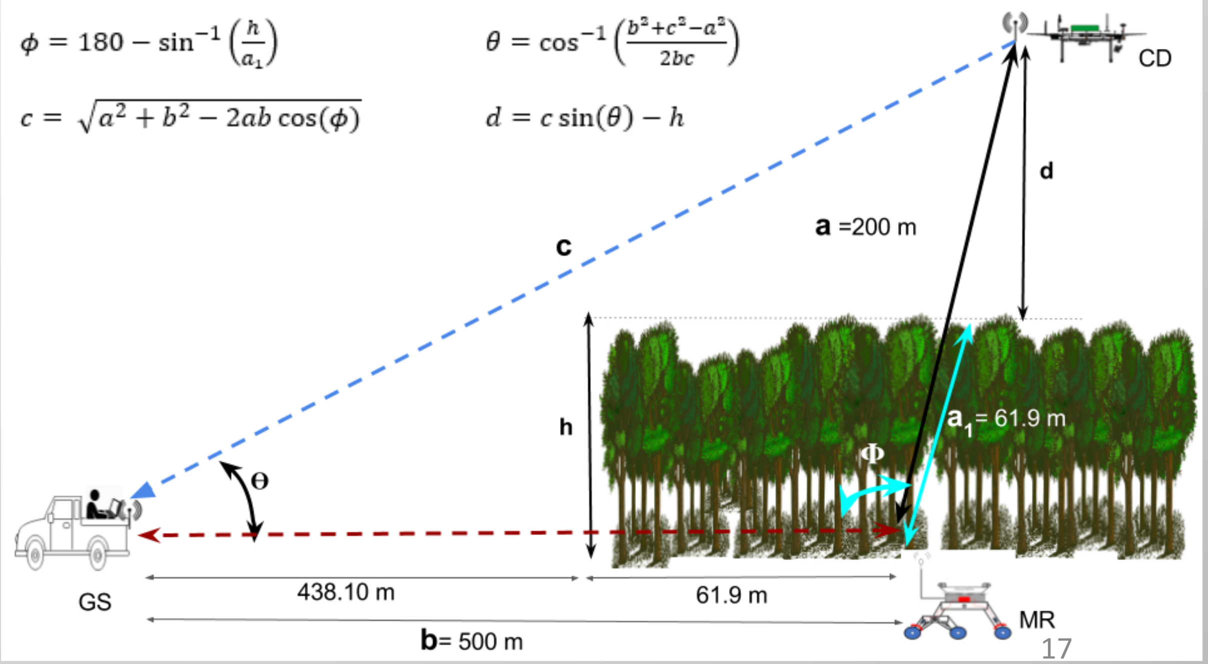
| h | ϕ | θ | d |
|---|---|---|---|
| 20 m | 161.2 deg | 5.35 deg | 44.6 m |
| 40 m | 139.7 deg | 11.2 deg | 89.1 m |

$$\phi = 180 - \sin^{-1}\left(\frac{h}{a_1}\right)$$

$$\theta = \cos^{-1}\left(\frac{b^2+c^2-a^2}{2bc}\right)$$

$$c = \sqrt{a^2 + b^2 - 2ab\cos(\phi)}$$

$$d = c\sin(\theta) - h$$



# Results from Link Budget

| | | LINK MARGIN | COST |
|---|---|---|---|
| CD Video Feed | Downlink | 35.24 dB | Antenna - $25 |
| MR Video Feed | Downlink | 38.16 dB | Antenna - $25 |
| MR Command | Uplink | 58.65 dB | XBee Pro S3B - $45<br>Antenna - $15 |
| MR Data | Downlink | 60.65 dB | XBee Pro S3B - $45<br>Antenna - $15 |

- **Signal loss due to 61.9 m of trees : 32.16 dB**
  - Using experimentally created models, loss due to foliage estimated to be –163.43 dB (averaged between models for similar frequencies) for 500m, not including path loss

Nonzero Gradient Model from *Radio Science Vol. 38 Iss. 5*

$$L_{tree} = R_{\infty} d + k\left(1 - e^{-\frac{(R_0 - R_{\infty})}{k} d}\right)$$

# Why 500 Meters of Forest is Not Feasible

**Possible Forest Distance?**

- Link budget for 5.8 GHz at 500m produces link margin of 38.16 dB
- Radio Science's model, using link margin, and constant values for 2 GHz and 11.6 GHz, shows forest range can be from **62.3 m to 86.9 m**

**5.8 GHz Band Limiting Factor**

- Trees will produce a signal loss of –163.42 dB, not including free space loss.
- Free space loss of –163.43 dB occurs at range of 610.9 km, meaning a system would have to be found with an effective range of 610.9 km

Equation for free space loss:

$$L_s = 20\log\left(\frac{\lambda}{4\pi R}\right)$$

**Improvements?**

- Antenna array to increase gain
  - surpasses the budget restrictions
  - takes far too long to construct
- Higher power version of current system
  - Increases gain by 60+ dB
  - Pricing much higher than budget

# Leveling System

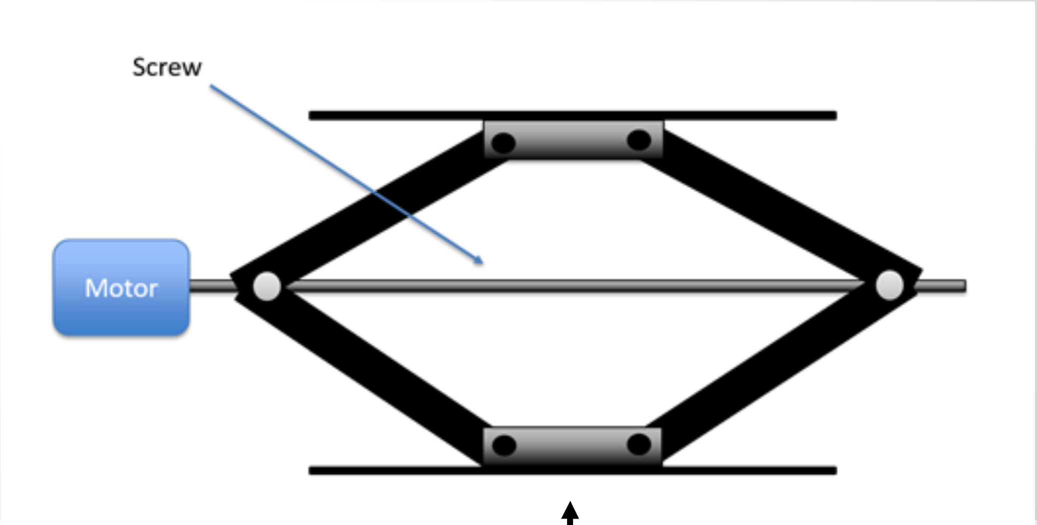
# Leveling System Feasibility

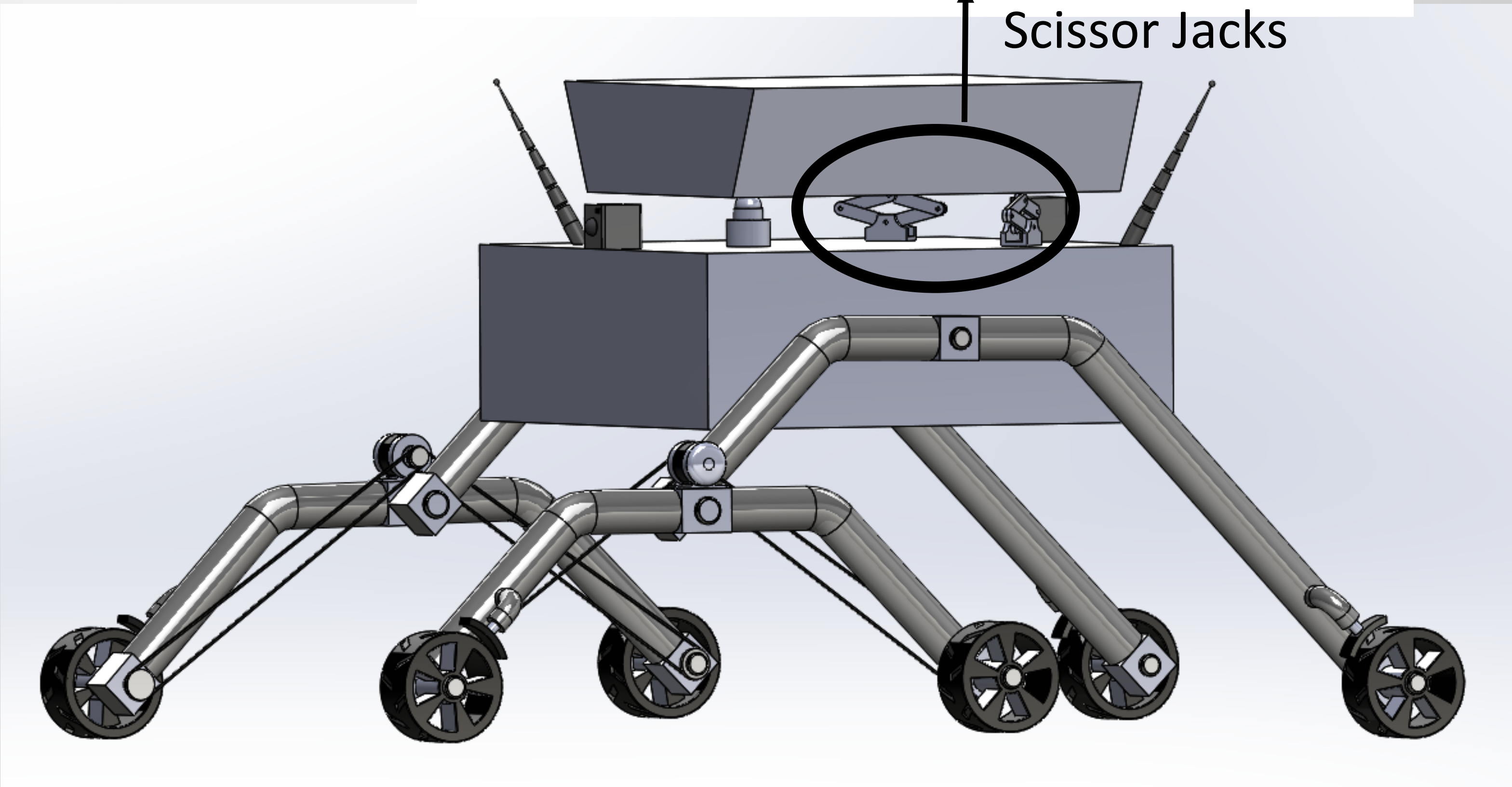
**Requirements**
- Minimum lift force= 50 lb
- Minimum lift height= 14.8 in

**Specifications**
- Lift force = 2,000 lb
- Lift height = 18.75 in
- 25 lb unit weight
- Required torque < 25 in-lb

**Results**
- Well within budget and weight constraints, scissor jacks provide necessary lifting force and height for leveling the landing platform.

**Feasible** by Demonstration

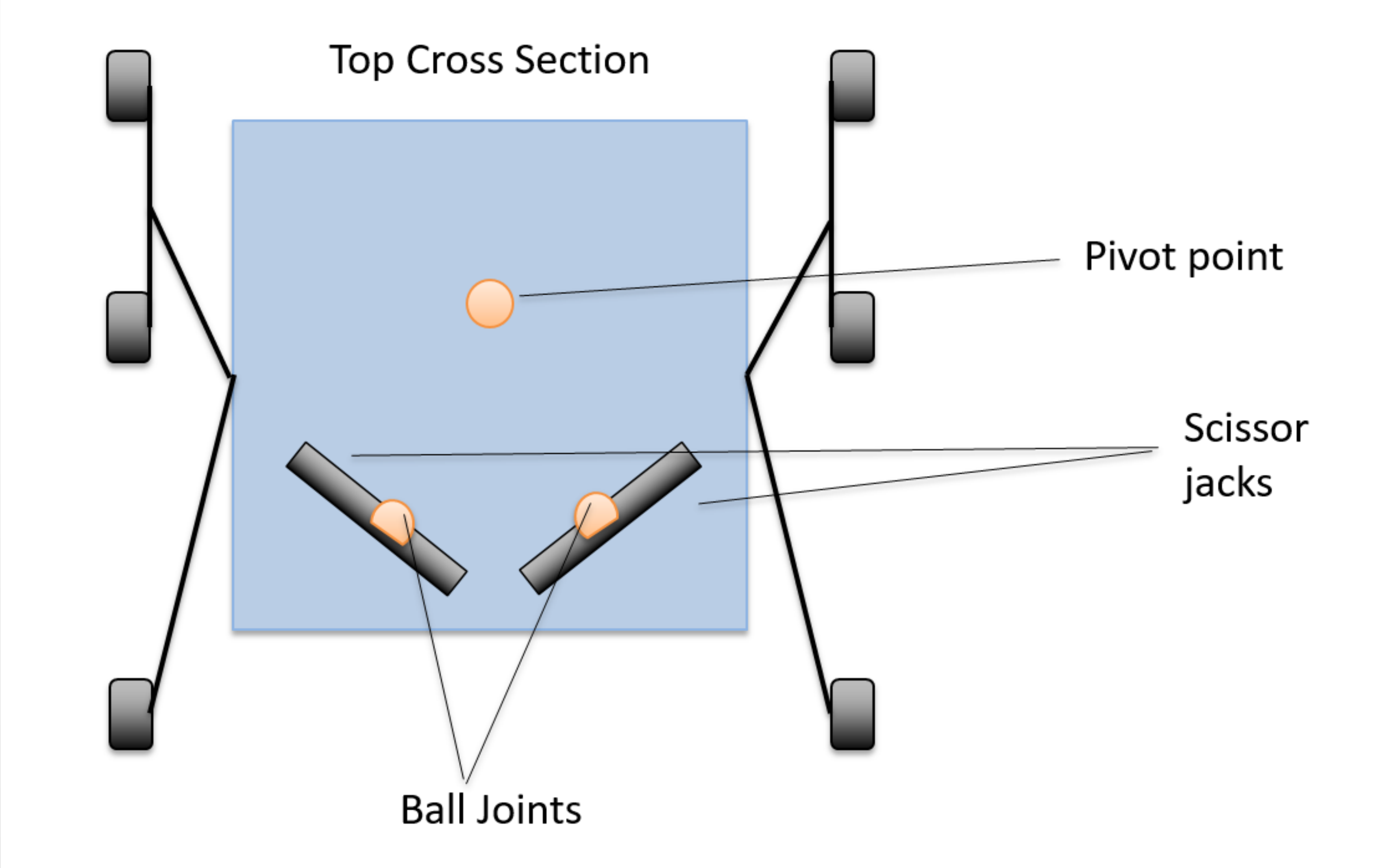


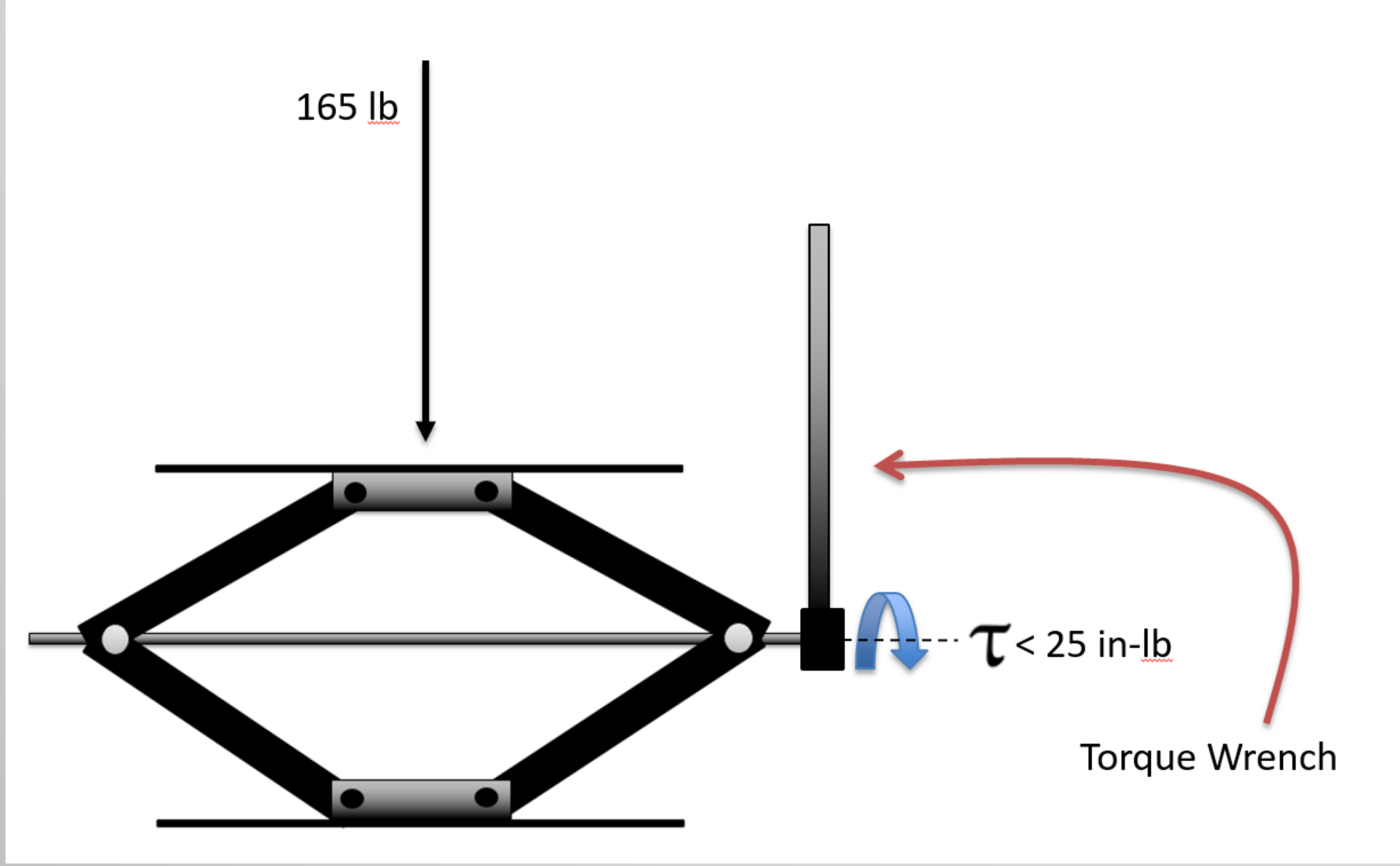
# Leveling System Jack Configuration

**Assumptions**

- Rover is facing uphill during leveling
- Rover is stationary during leveling
- Slope is less than or equal to 20 degrees



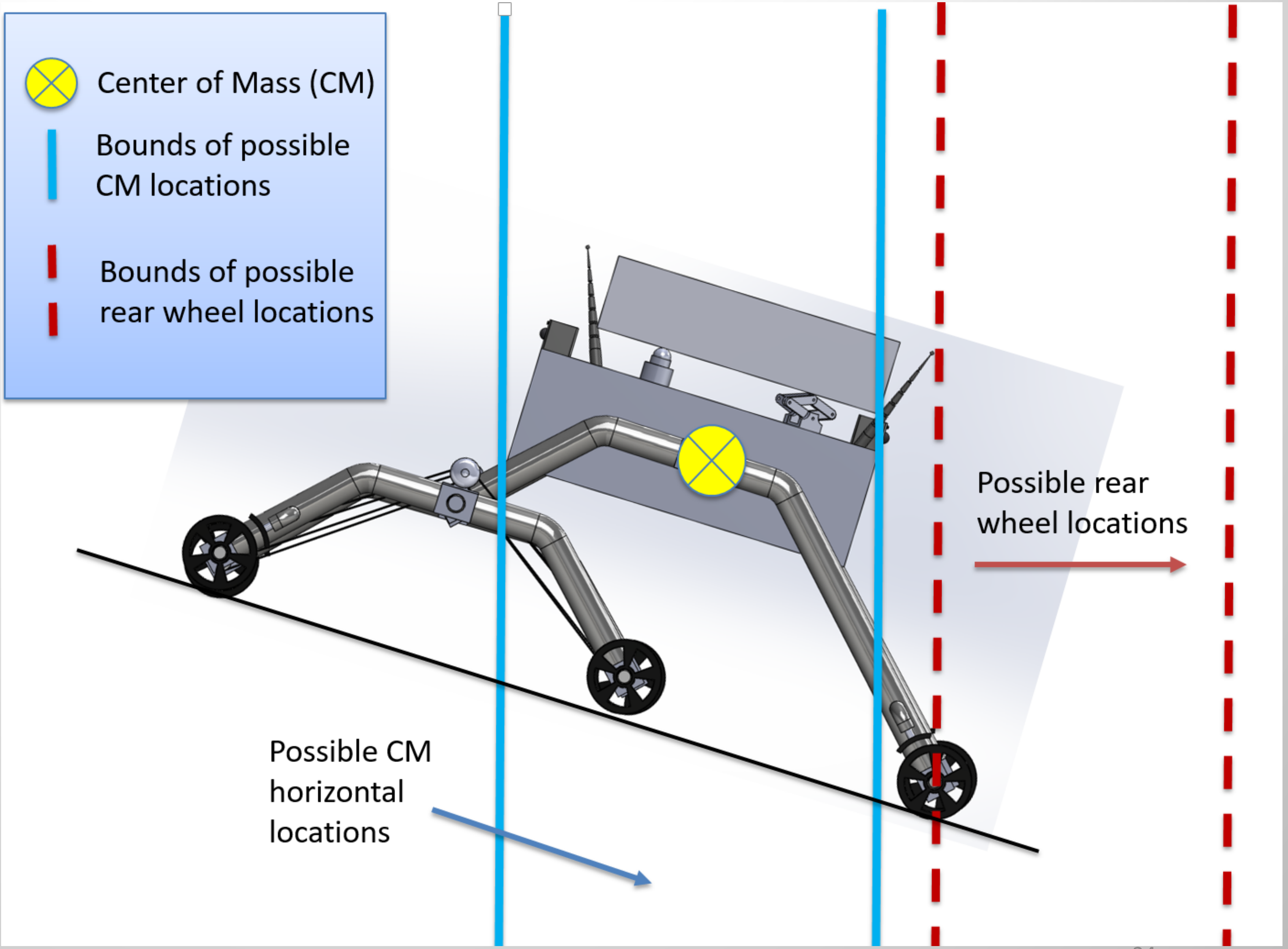
# Leveling System Torque Test




- A torque wrench was used to better understand the feasibility of the scissor jacks. Setting the torque wrench to its lowest setting (25 in-lb) and using it to lift a 165 lb human up, the torque wrench did not release.
- With an extreme situation of 165 lb and one scissor jack, the minimum torque needed is very low. With the 55 lb platform and two scissor jacks, the motors needed to lift the platform will be in the range of 25 in-lb or less.

# Leveling System Tipping Analysis

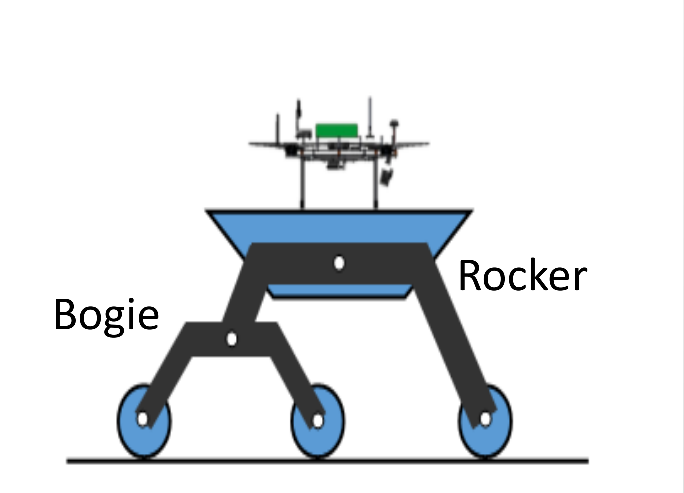
Due to the flexible size in choosing the rocker dimensions, even the most extreme possible location of the center of mass will not be downhill from the rear wheel of the rover.

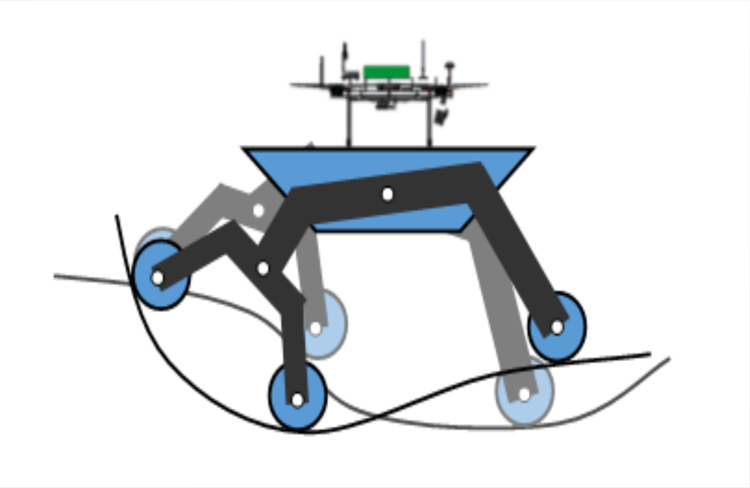


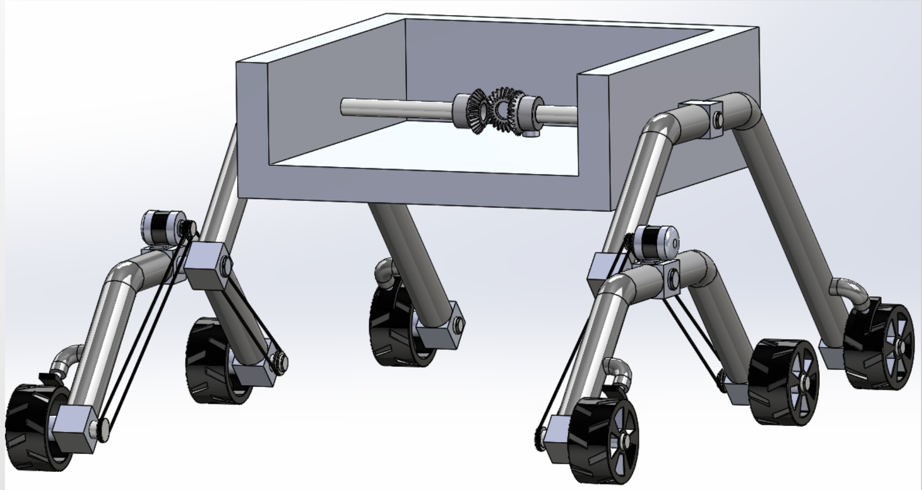
# Translational System Structure

# Translational System Structure

**Baseline Design**



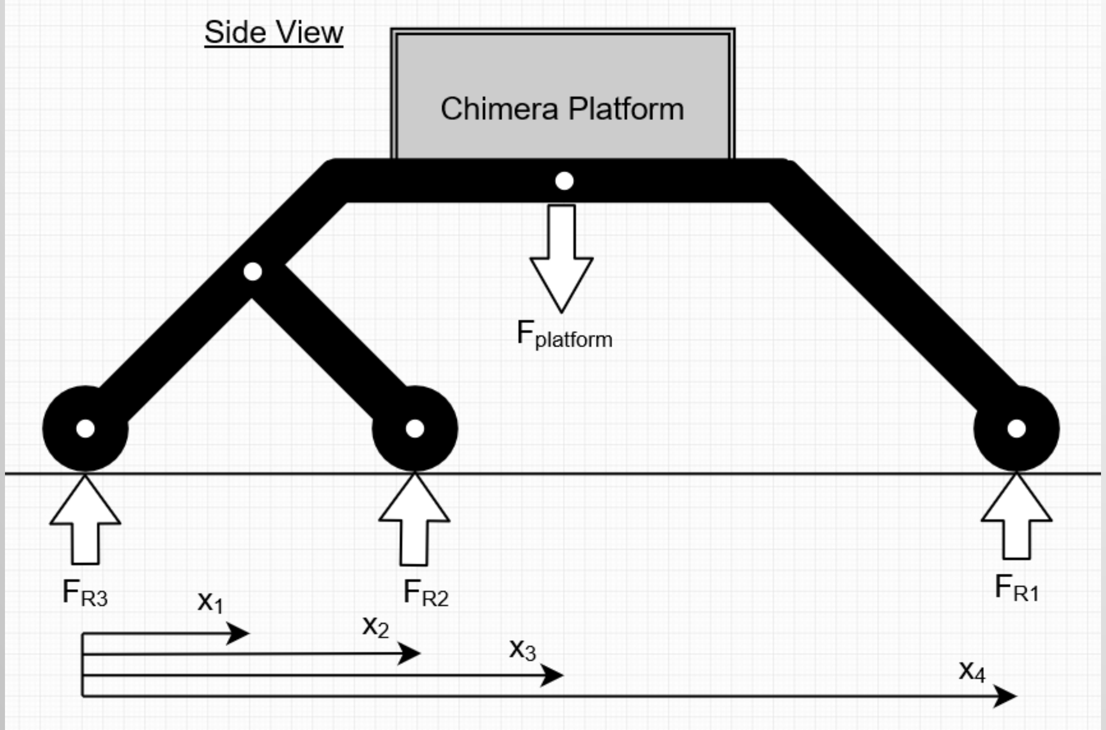


- Rocker Bogie System
  - 3 Wheels on each side -  2 connected in bogie then pinned to rocker connecting the 3rd wheel
  - Uses counter rotation differential system to keep platform at average pitch angle of two rockers
  - Can keep all 6 wheels on the ground when navigating obstacles
  - Used very successfully in all mars rover missions
    - Ability to clear obstacles greater than wheel diameter.

# Rocker Bogie Suspension System Feasibility

## Structural Sizing

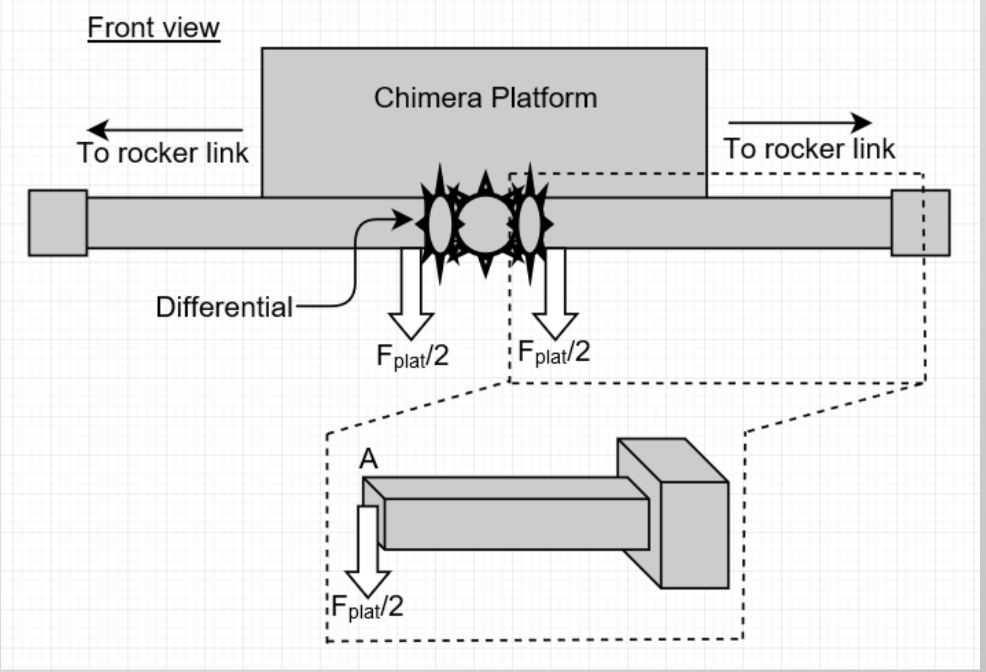
- Generally open to many design options
- Required to satisfy clearance and stability
- Many configurations can provide stability and clearance.




$\frac{x_2}{x_1} = 3 * \frac{(x_4 - x_3)}{(x_4 - x_1)}$ $where$ $\frac{x_2}{x_1} = 2$ for equal weight distribution among all wheels

## Structural Assumptions

- Classical Beam Theory
- Mass of platform distributed evenly and center of gravity positioned exactly at the center.
- Rocker chassis-differential link tip acts as main support




Beam Tip Deflection: $\nu_A = -\frac{PL^3}{3EI_{zz}}$

Maximum Shear Stress (square cross section): $\tau_{max} = 1.5\frac{V}{A}$

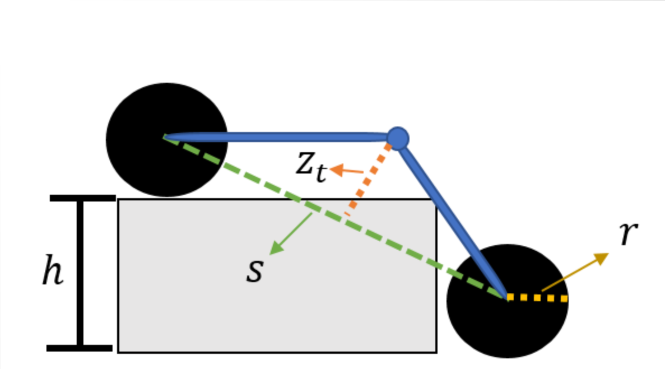
# Clearance Feasibility

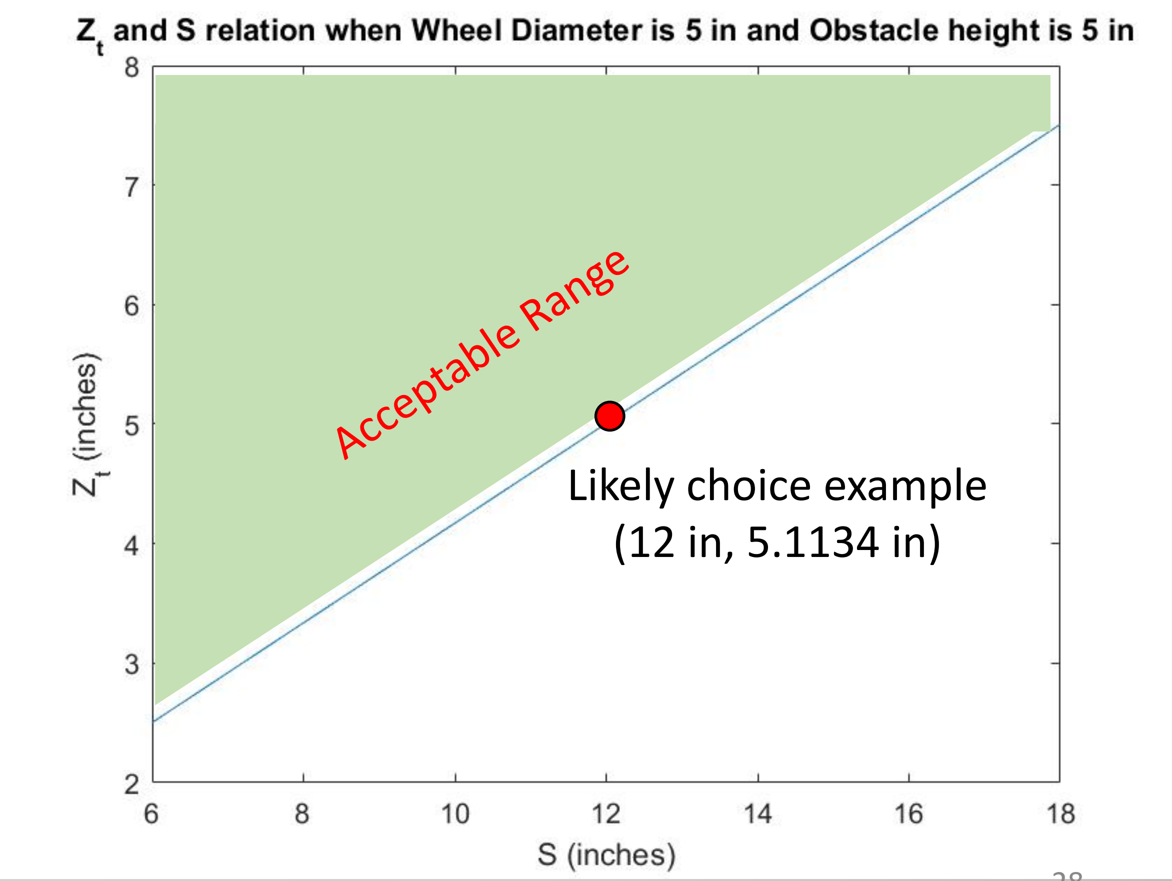
- A primary constraint for the frame design is obstacle clearance of the bogie component.
- The following relationship was found and tested for the bogie and an acceptable range of the bogie height and wheel distance was found for constant obstacle height and wheel radius.

$$z_t = \frac{s}{\sqrt{\left(\frac{r\sqrt{s^2-h^2}+(h-r)h}{(h-r)\sqrt{s^2-h^2}-hr}\right)^2+1}}$$

- Used wheel diameter as 5 inches and obstacle height as 5 inches to ensure outputs were realistic values

**Feasible:**
by Analysis



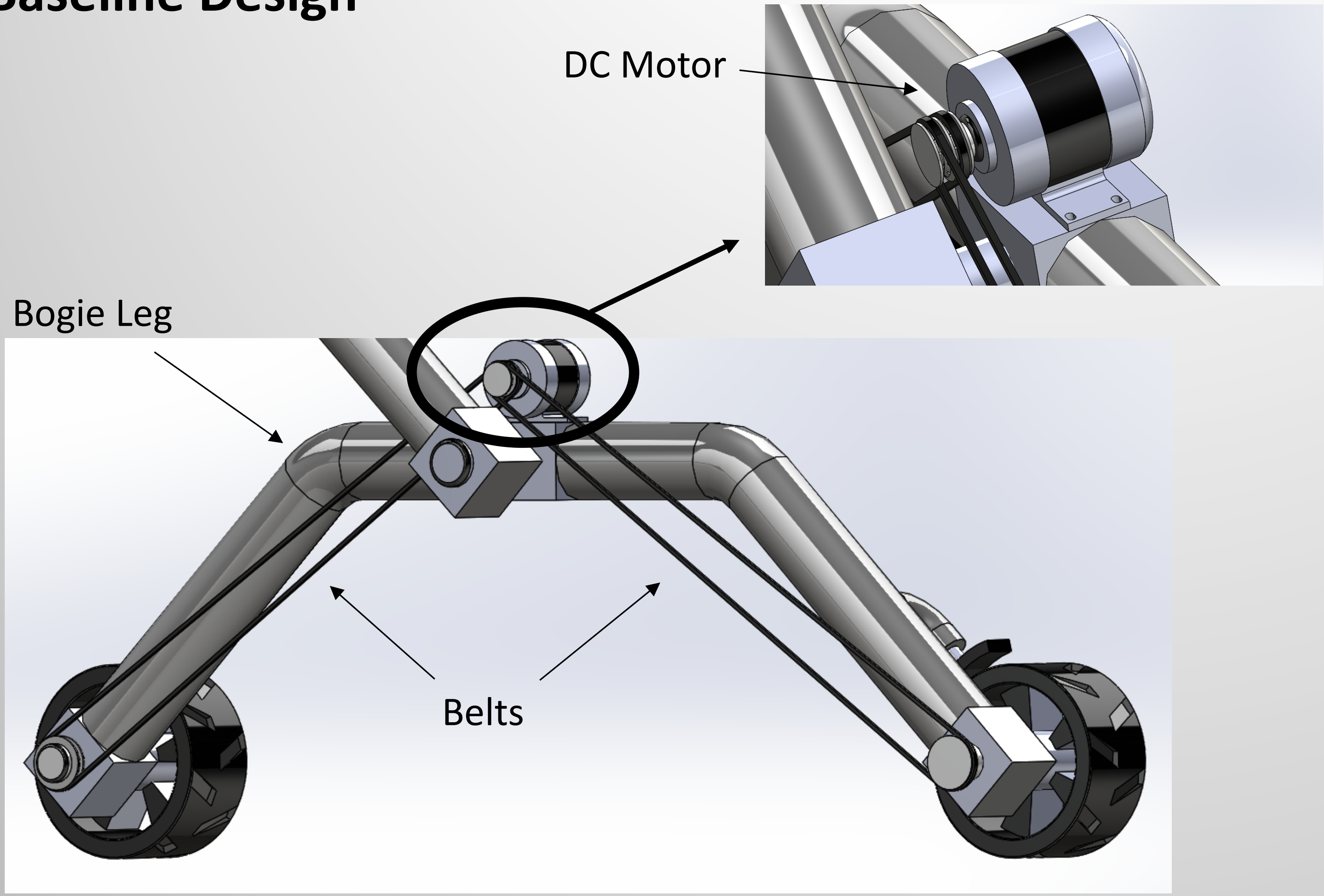
# Rocker Bogie Feasibility Summary

- Restricted primarily to bogie design, rest of design very open to modification to help mitigate tipping or other requirements for other systems. Bogie design has many design choices seem to make sense given the size of the platform.
- Historically very successful .
- Structural Analysis showed little concern for stresses and strains in using a light aluminum
- Cost and weight when predicted higher than expected still fit into project without concern.

# Motors for Translational System

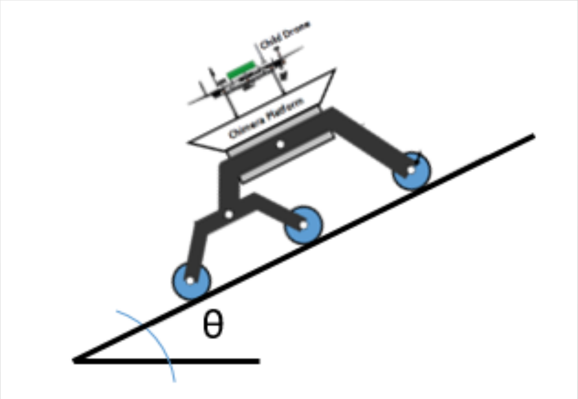
# Driving System for Bogie Feasibility Analysis

## Baseline Design




## Assumptions for Analysis

- Motor efficiency is not 100%
- Air resistance is negligible
- Inclination of the surface is greater or equal to zero
- Friction is not negligible
- MR is treated as a point mass



# Motor Torque - Model

**Treat the entire MR as a point mass:**

**Sum of the forces is equal to the acceleration of the MR up the incline:**

$$F_{torque} - F_{fric} - F_{||} = F_a$$

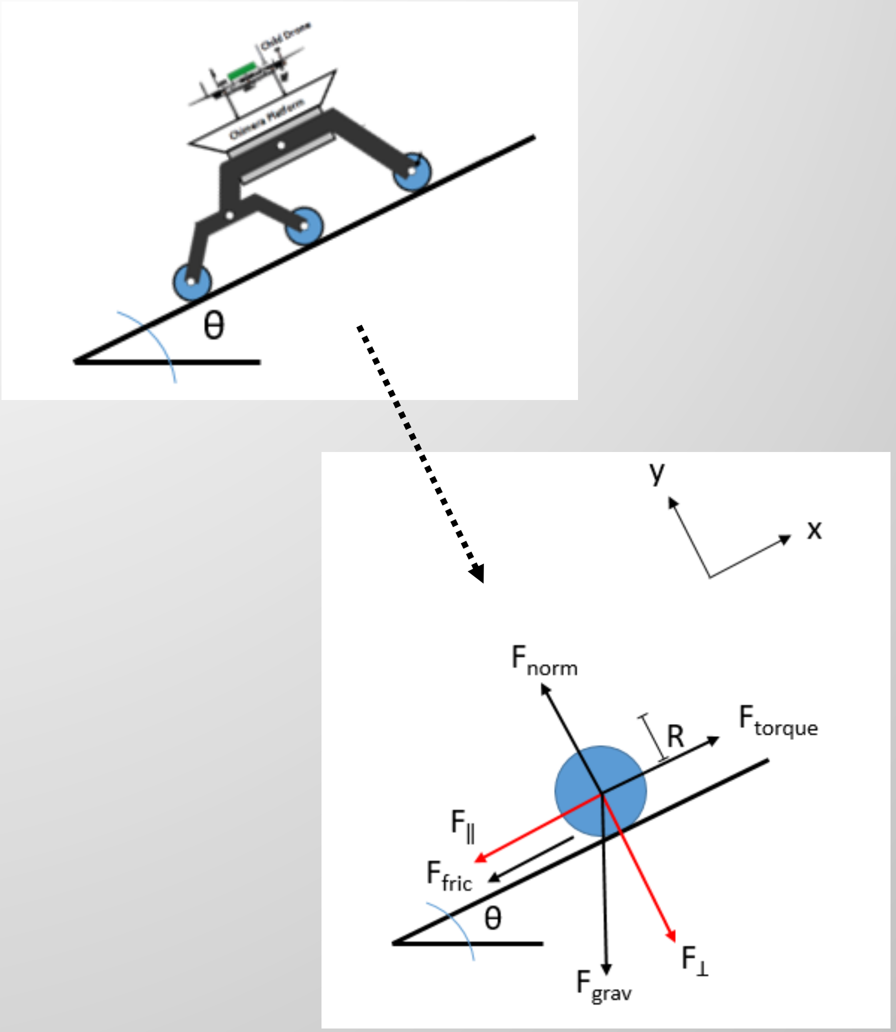
$$F_{torque} = F_{fric} + F_{||} + F_a = \left[\left(\frac{mV}{t}\right) + mg(\sin\theta + \mu\cos\theta)\right]$$

**The total supplied torque from each of the two motors:**

$$T_{req} = \left[\left(\frac{mV}{t}\right) + mg(\sin\theta + \mu\cos\theta)\right] * R * \left(\frac{1}{e}\right) * \left(\frac{1}{2}\right)$$

**The power required from each of the two motors:**

$$Power_{req} = \left(\frac{1}{2}\right) * F_{torque} * V$$



# Weight Budget Analysis

| Component | Quantity | Total Weight (lb.) | Weight (kg) | |
|---|---|---|---|---|
| Rocker Bogie Structure | 1 | 50 | 22.8 | MetalsDepot |
| Differential Gear Drive | 1 | 12 | 4.5 | Various[1][2][3] |
| LP & CD | 1 | 55 | 24.9 | CHIMERA SFR |
| Battery | 1 | 50 | 22.8 | WindyNation |
| Cables / Hardware | - | 5 | 4.5 | |
| Motors | 2 | 100 | 22.8 | Brother |
| Base Structure | 1 | 25 | 11.3 | |
| Wheels | 6 | 11 | 5.0 | Amazon |
| Wheel-Locking Mechanism | 4 | 15 | 13.6 | Amazon |
| Scissors Jacks | 2 | 65 | 29.5 | Etrailer |
| **Total** | | **388** | **176** | |

# Motor Torque – Model Results

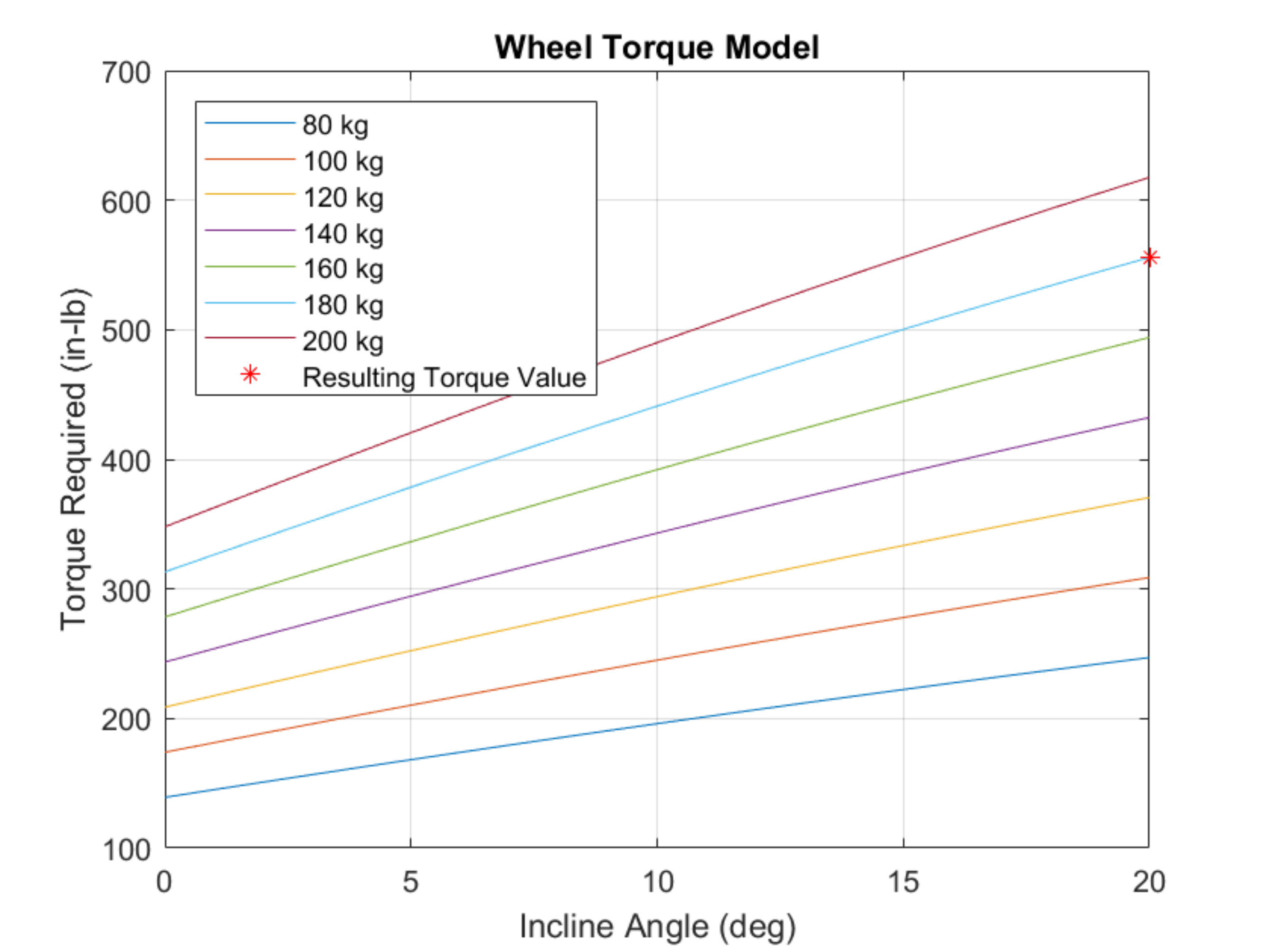
**Required torque for each of the 2 motors for various weights versus the incline angle**

- Required torque at a **20°** slope is **556 in-lb**

**Parameters:**

- Velocity = 0.5 m/s
- Efficiency = 65 %
- Wheel Diameter = 0.127 m= 5 in
- 2 motors

**Observation**: An increase in mass leads to a severe increase in required torque, leading to a greater cost for each motor

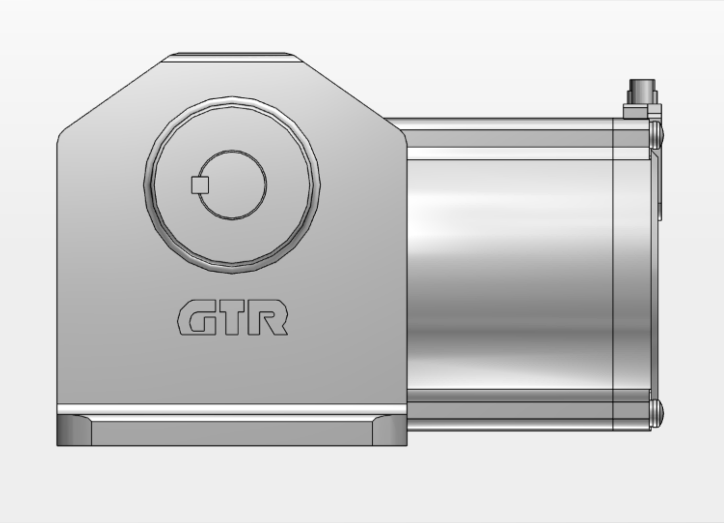


# Motor Torque and Wheel RPM - Feasibility

**Current System Parameters**
- Mass = 180 kg = 392 lbm
- Wheel Diameter = 0.127 m = 5 inches
- Assumed Motor Efficiency = 65 %
- Maximum velocity = 0.5 m/s
- Time to accelerate to maximum speed = 5 seconds
- Incline Angle = 5 degrees
- 6 wheels with 2 motors powering the front two wheels via a belt drive

**Result**
- Applied torque must be greater than **556 in-lb**
- Resulting maximum RPM: **75.19 RPM**
- Power Required: **494.5 W**

**Feasible** by Analysis:
- Found potential motors that are able to produce the desired, calculated torque values




**Possible Motor Selection**
**Brother: Brushless DC Gearmotor**
- 991 in-lb
- 62 RPM
- Between 80% and 90-% efficient
- 1000 W
- 12 V DC
- $453 each
- Inherent "braking" mechanism

# Motor Torque and Wheel RPM - Feasibility

- The required torque for the most extreme situation of a 180 kg rover on a 20 degree slope was calculated to be 556 in-lb.
- By using two, 991 in-lb brushless DC motors made by *Brother*, the torque required for the MR will be met leaving a large amount of room for frictional losses, pulley losses, additional motor inefficiency, and MR mass changes.
- By powering four wheels with two motors, not only does the cost of the translational system decrease, but the MR maneuverability and wheel traction benefit.
- Additionally, the motor chosen provides an inherent braking system

# Validation and Verification

| Functional Requirement | Testing |
| --- | --- |
| FR1.0 | Demonstration – The CD will remain secure on the Mother Rover during transport over the designated terrain such that it does not slide over the platform<br>Analysis – Structural integrity will be analyzed through CAD simulation of entire system. |
| FR2.0 | Demonstration – The MR will demonstrate receipt and execution of commands sent from the GS including translational motion, video feed control, securement mechanism control, as well as leveling control. |
| FR3.0 | Demonstration – The MR will be located 500 meters from the GS and the system will demonstrate transmission of the data including: GPS location as well as live video feed from MR and CD |
| FR4.0 | Demonstration – The MR will be driven over a flat dirt path, a $20^o$ dirt path (constructed in house), and a 5 in obstacle to a maximum distance of 500m from the drop off point |
| FR5.0 | Characterization – Use instrumentation, such as an accelerometer, to ensure the leveling system levels the platform to within 3.5 degrees on a 20 degree slope.<br>Demonstration – The MR will be placed on a $20^o$ slope where its wheels will be locked in |

# Facilities and Resources

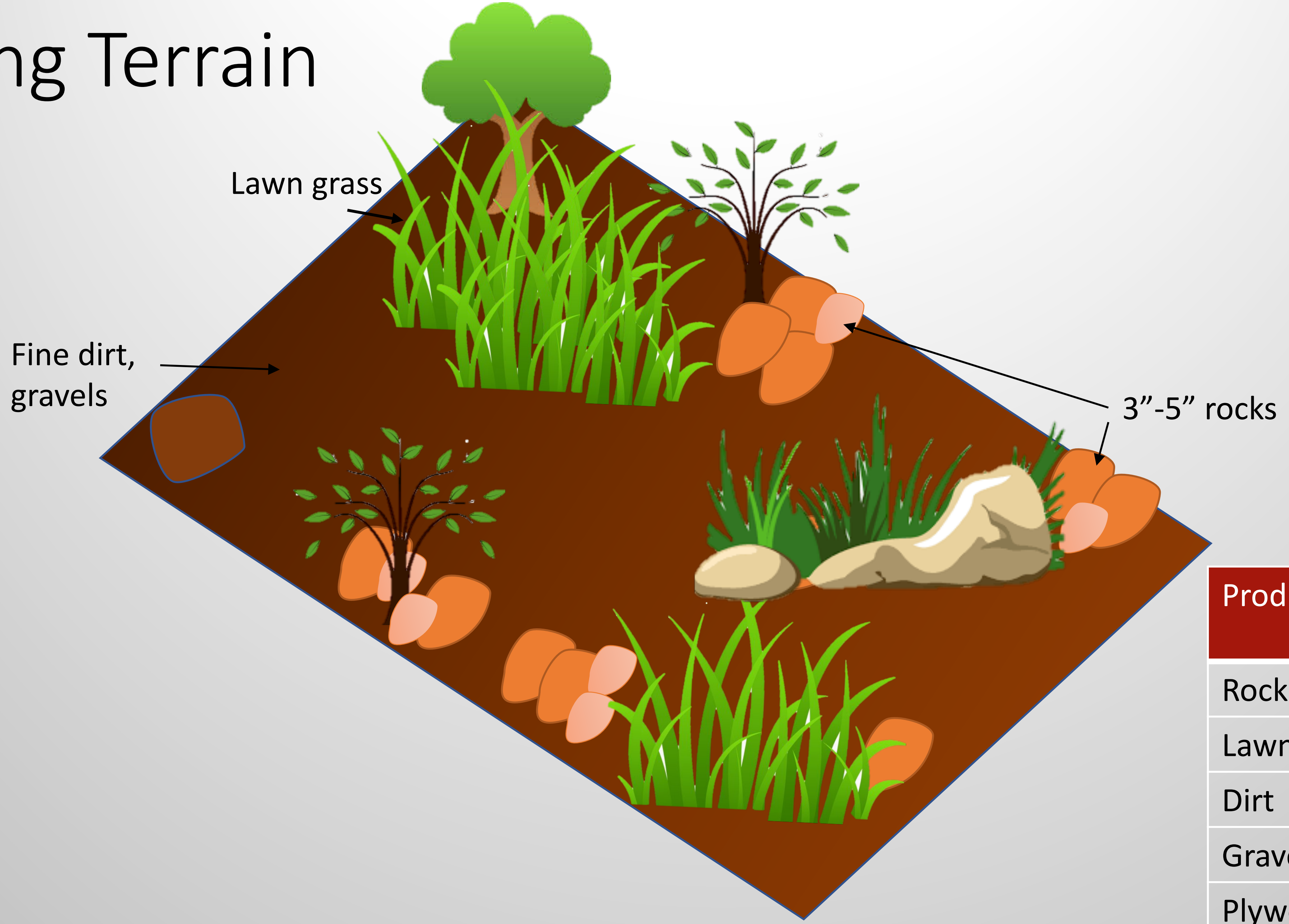
**Testing Facilities**

- Construct defined rough terrain out of plywood, filled with either loose gravel or lawn grass (test one at a time).
  - 5 inch obstacles (rocks) for the rover to traverse
  - Wide enough and long enough (4 by 10 feet) for turn radius test to be completed
  - This will be propped against a bench to create $20^o$ slope.
- Another option (weather permitting) is take mother rover to Chautauqua for rough terrain testing
  - Rocks/obstacles greater than

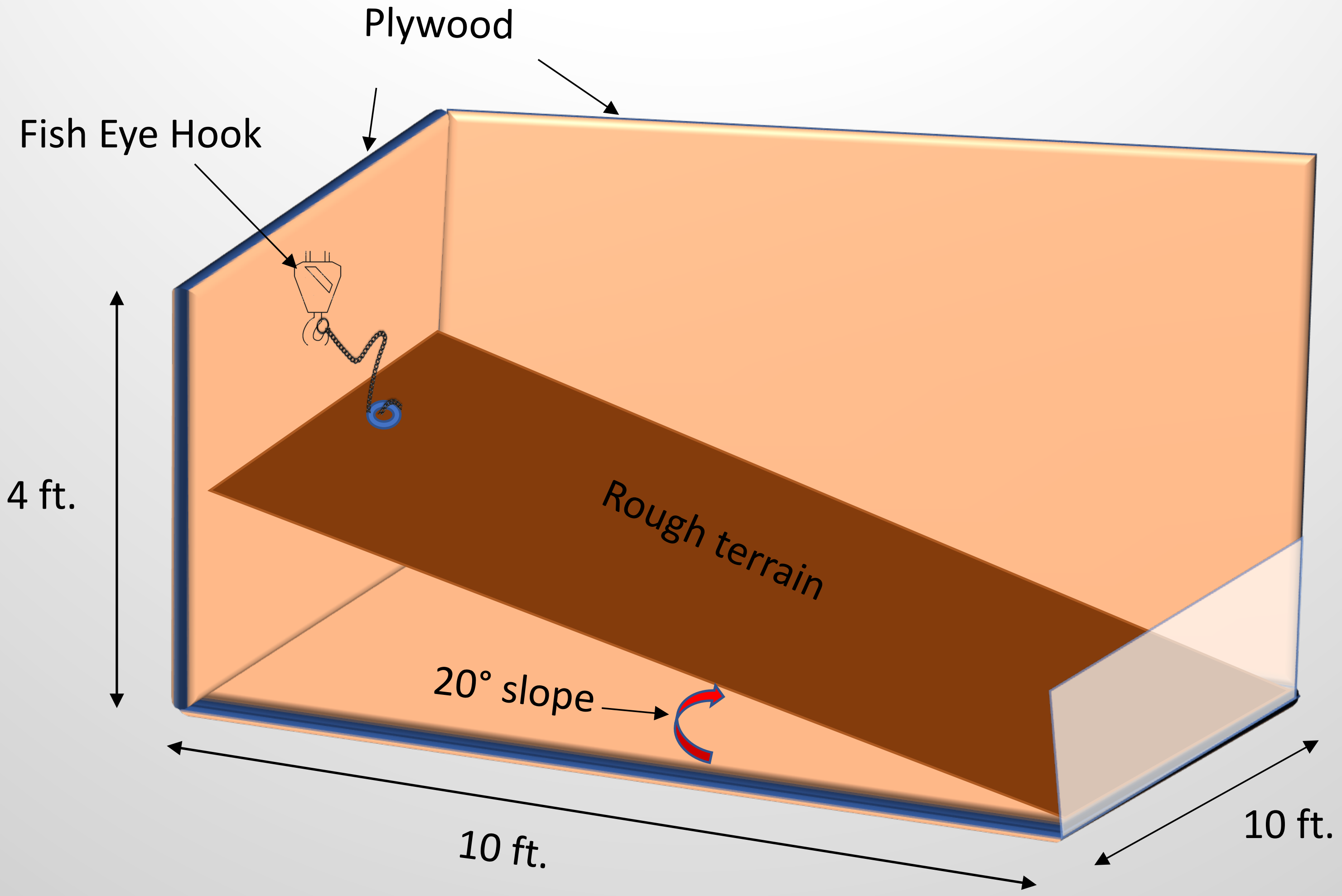
**Resources**

- Rover Operator
- Barbara Streiffert
- CU AES Senior Project 2017-2018 PAB
- Spectrum Analyzer (Comm Testing)

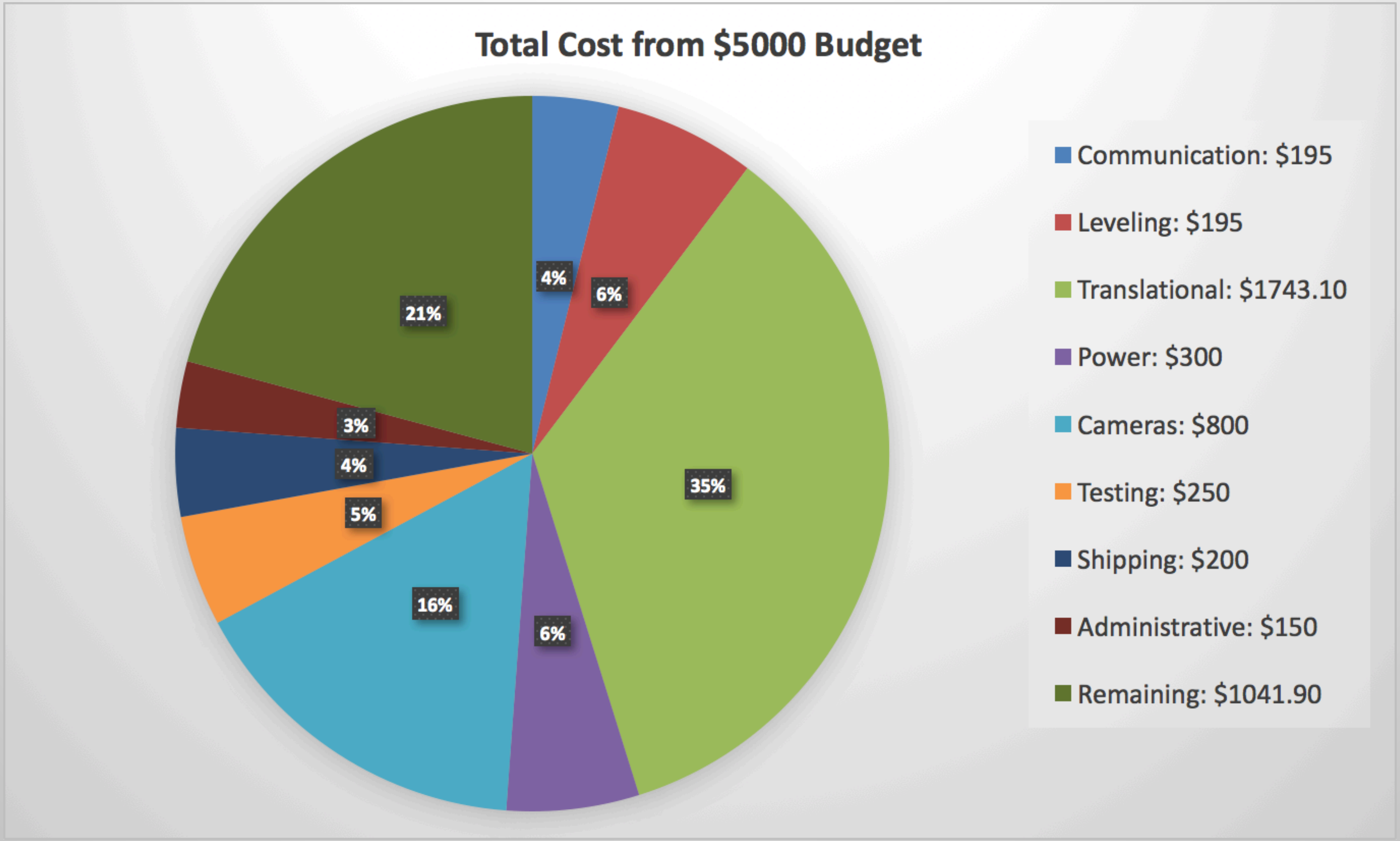
# Testing Terrain



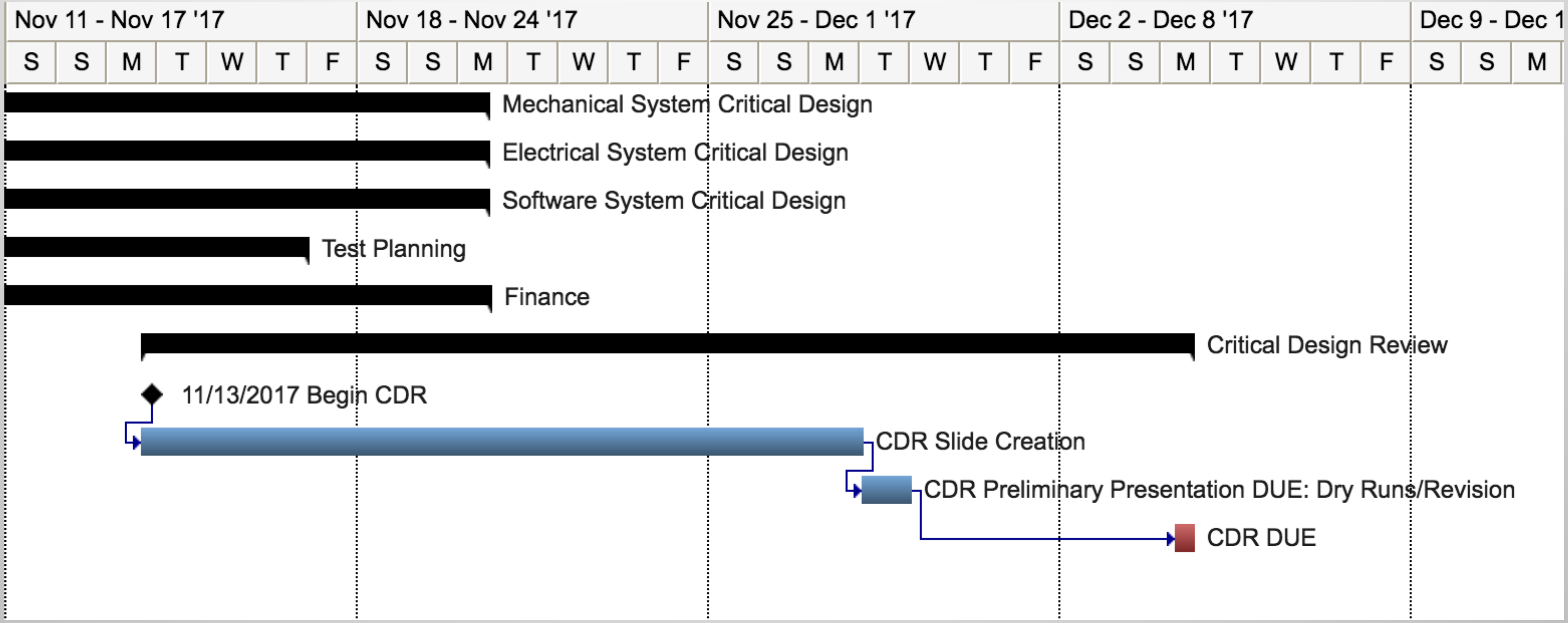

| Products | |
|---|---|
| Rocks | Home Depot |
| Lawn Grass | Home Depot |
| Dirt | Home Depot |
| Gravel | Walmart |
| Plywood | Home Depot |


Plywood
Fish Eye Hook
4 ft.
Rough terrain
20° slope
10 ft.
10 ft.

# Financial Budget Analysis



# Schedule to CDR



# Conclusion

## Preliminary Design Summary

| Critical Project Element | Feasible Design Solution |
|---|---|
| Communications | Separate Communications for CD and MR to GS |
| Translational System Structure | Rocker Bogie Suspension System |
| Motors for Translational System | Two 556 inlb Torque Motors<br>• Drives four wheels using a belt drive |
| Leveling System | Internal Scissor Jacks |

# Backup Slides

# Table of Contents

**Primary Slides**

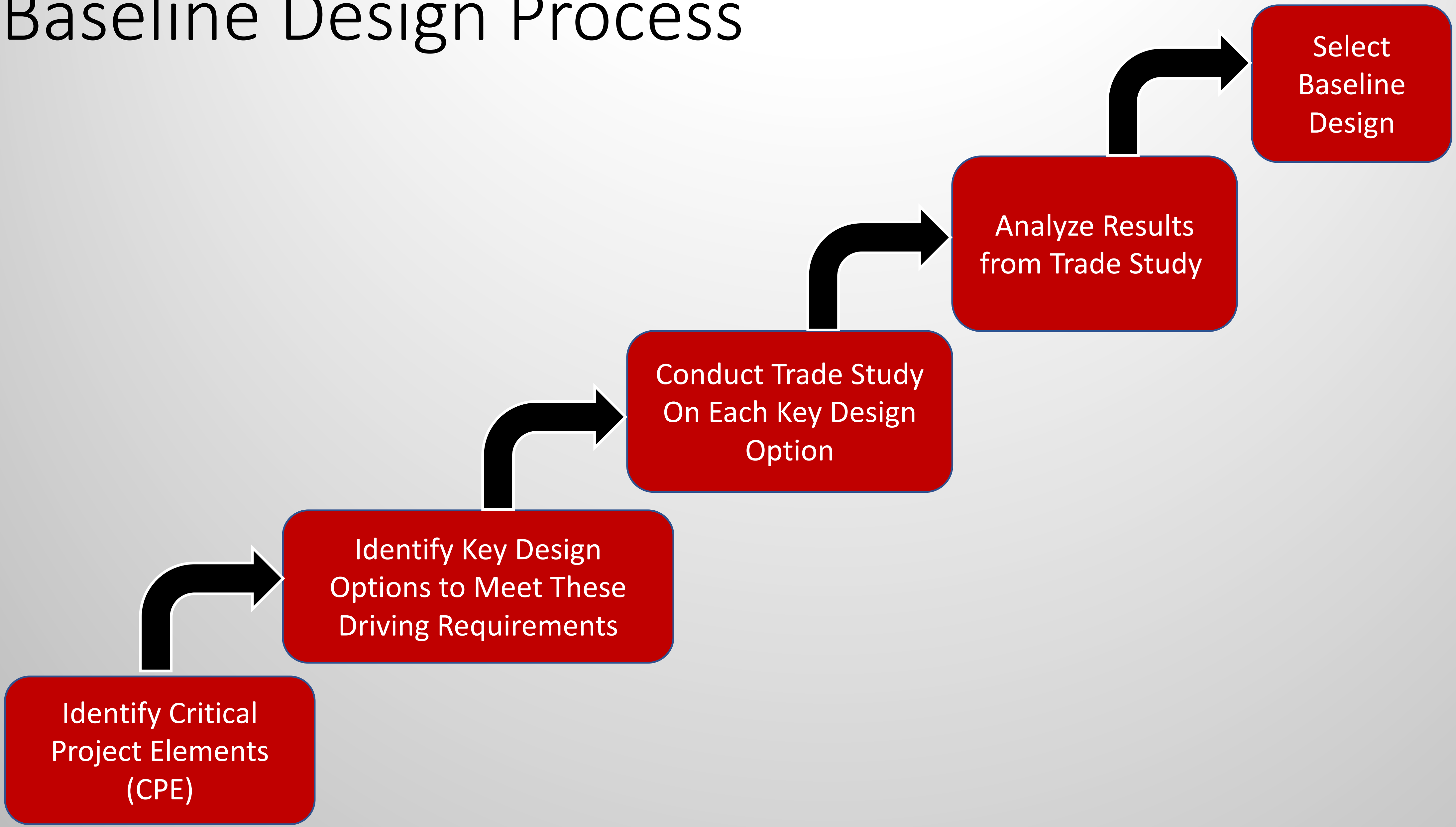


**Backup Slides**

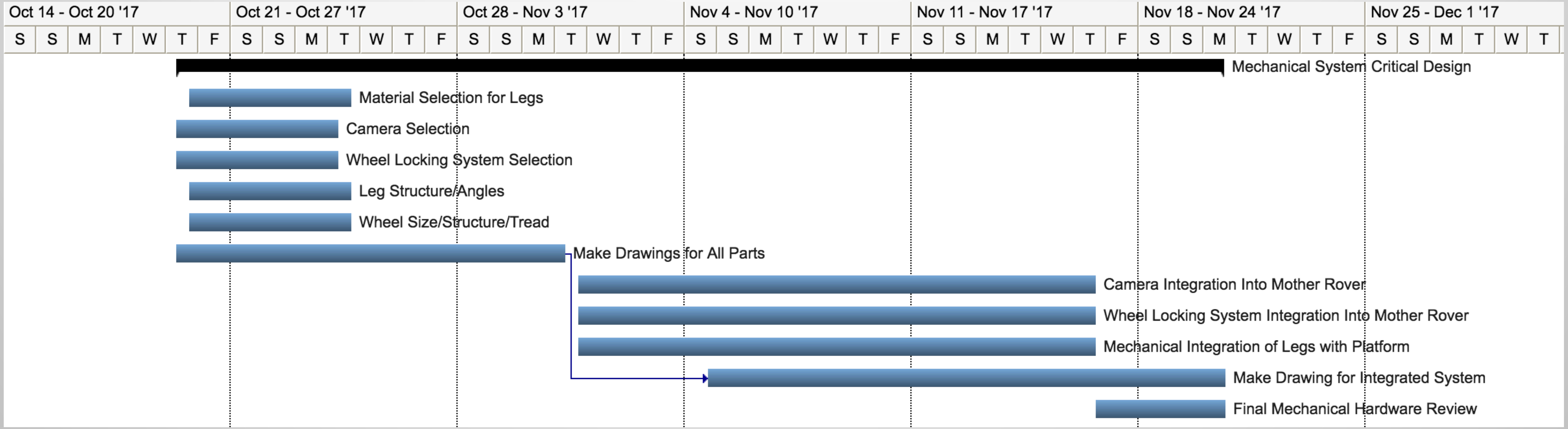
# Budget

| Subsystem | Part Name | Description | Cost | Quantity | Discount | Total Cost |
|---|---|---|---|---|---|---|
| Communication | Transmitter | Transmitting signal | $25.00 | 2 | 0.00% | $50.00 |
| Communication | Antennas | receiving signal | $25.00 | 1 | 0.00% | $25.00 |
| Communication | Xbee Tranceiver | tranceiving things | $45.00 | 2 | 0.00% | $90.00 |
| Communication | Xbbee Aentennas | antenna things | $15.00 | 2 | 0.00% | $30.00 |
| Leveling | Inclinometer/hardware | Code & Housing & Wiring | $40.00 | 1 | 0.00% | $40.00 |
| Leveling | Leveling Jack | Leveling of platform | $40.00 | 2 | 0.00% | $80.00 |
| Leveling | Motors | Motors to turn jacks | $100.00 | 2 | 0.00% | $200.00 |
| Translational | Al-0601 | 1x1in 6ft sections, 5 sections | $42.90 | 5 | 0.00% | $214.50 |
| Translational | Brake Pad | NOA Pads | $20.00 | 4 | 0.00% | $80.00 |
| Translational | Brake Linear Actuator | Brake Linear Actuator | $31.90 | 4 | 0.00% | $127.60 |
| Translational | Motor | Motors to turn rover | $453.00 | 2 | 0.00% | $906.00 |
| Translational | Motor Driver | Hardware for microcontroller for motor | $30.00 | 1 | 0.00% | $30.00 |
| Translational | Wheel | Wheels for rover | $10.00 | 6 | 0.00% | $60.00 |
| Translational | Misc. Hardware | Pins, bolts, screws, etc | $100.00 | 1 | 0.00% | $100.00 |
| Translational | Differential | Balances rover in uneven terrain | $225.00 | 1 | 0.00% | $225.00 |
| Power | 12 V Battery | Battery Power for Rover Car battery | $100.00 | 2 | 0.00% | $200.00 |
| Power | Hardware | Hardware & Wiring | $100.00 | 1 | 0.00% | $100.00 |
| Cameras | Go Pro Hero | Cameras | $400.00 | 2 | 0.00% | $800.00 |
| Testing | Misc | Testbed | $250.00 | 1 | 0.00% | $250.00 |
| Administrative | Misc | Printing | $150.00 | 1 | 0.00% | $150.00 |
| Shipping | Misc | Shipping items to CO | $200.00 | 1 | 0.00% | $200.00 |
| | | | | | **System Total** | **$3,958.10** |
| | | | | | **Remaining Cost** | **$1,041.90** |

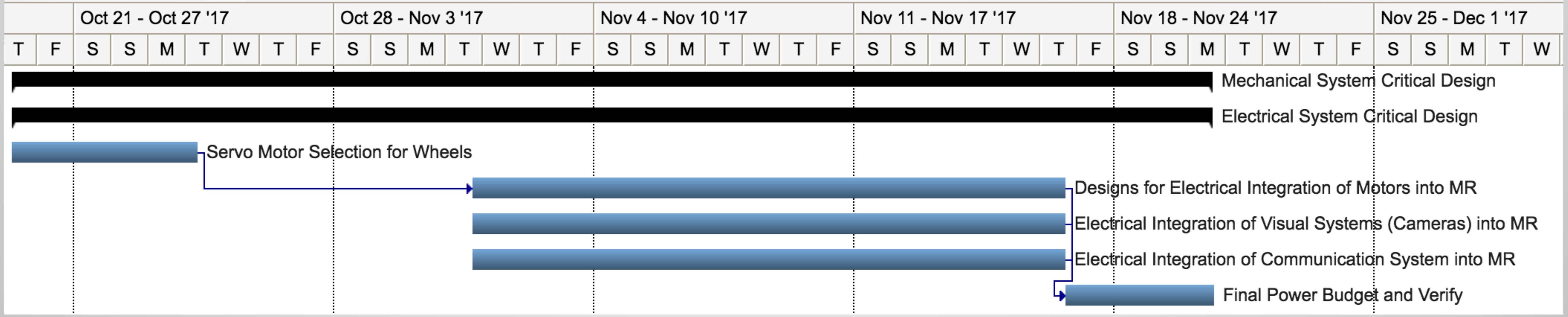
# Baseline Design Process



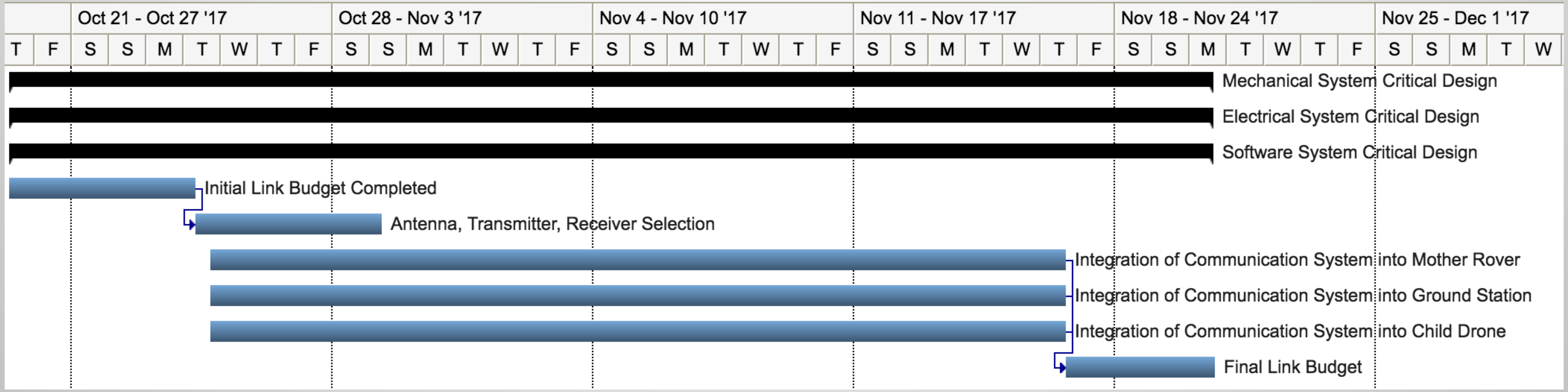
# Schedule to CDR: Mechanical System Critical Design



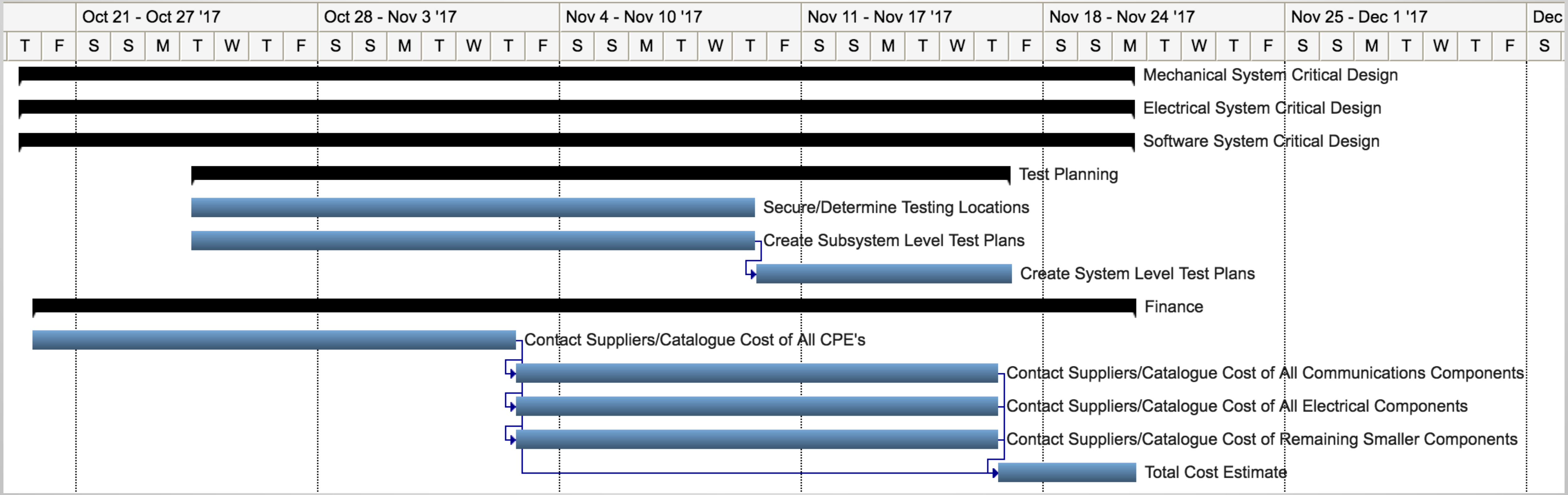
# Schedule to CDR: Electrical System Critical Design



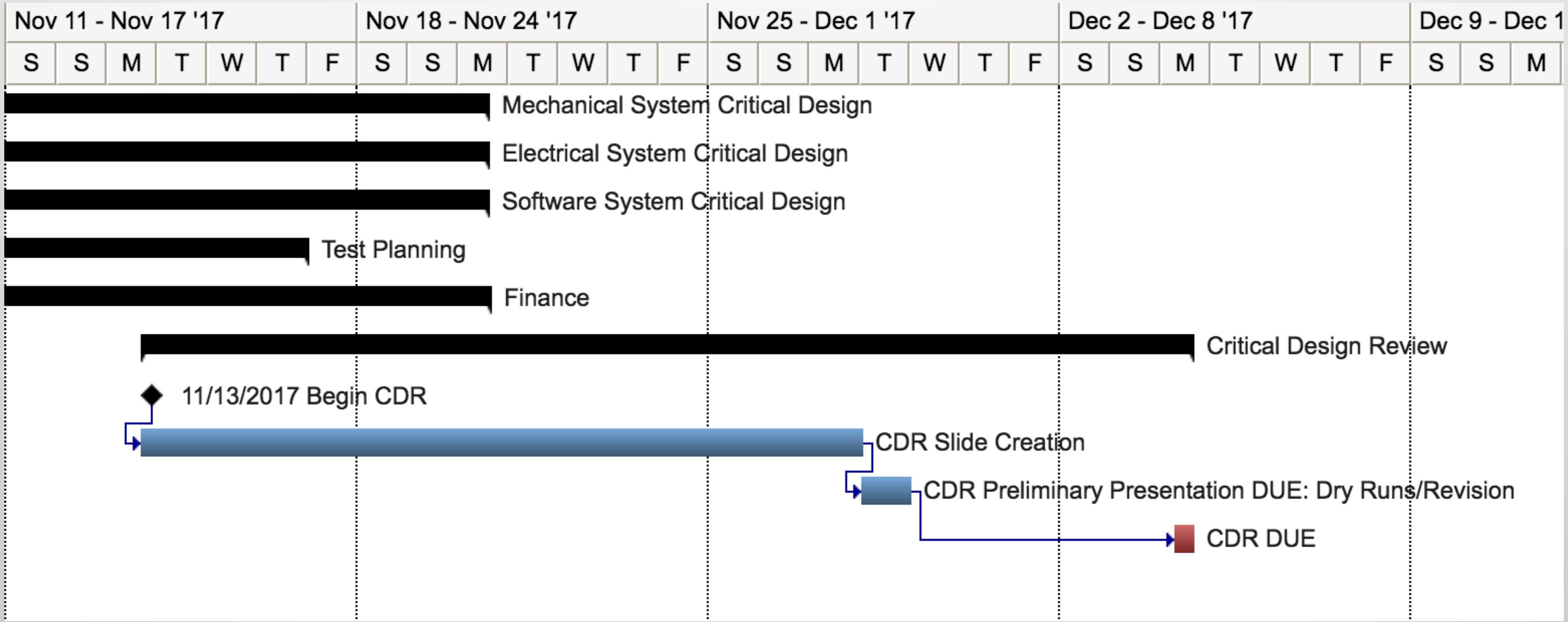
# Schedule to CDR: Software System Critical Design



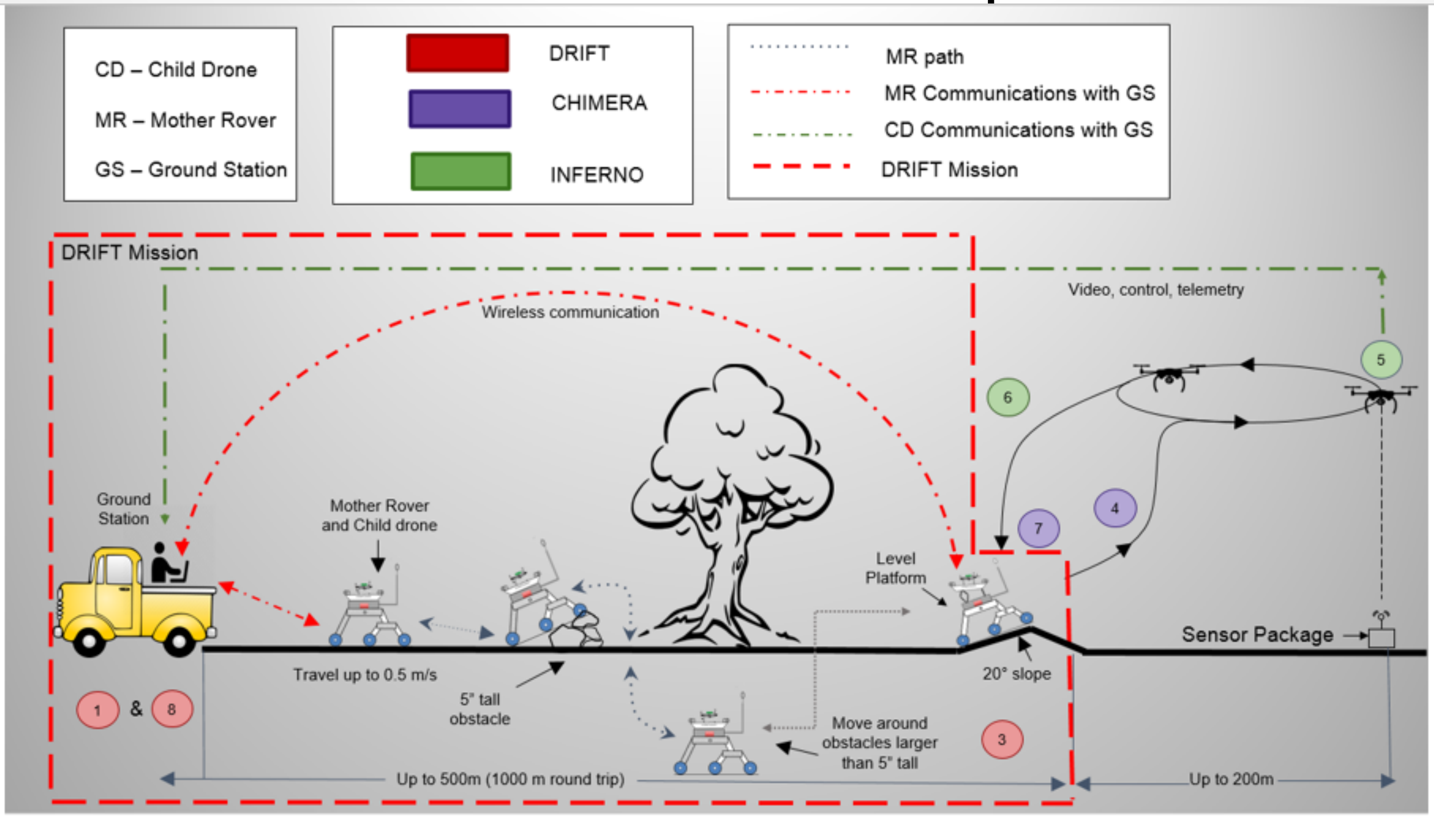
# Schedule to CDR: Testing and Finance



# Schedule to CDR: Presentation Creation



# CONOPS – Full CONOPS with Squares




**1. Transport and Setup**

- Drop off system at location
- Turn on and secure the system
- Establish communication with GS

➡

**2. Navigate to Specified Location(s)**

- Travel up to 500 m up to 0.5 m/s
- Utilize waypoints and GPS
- Maneuver over and around obstacles
- MR receives and transmits data to GS

➡

**3. Verification and Level out**

- MR verifies location with GS

➡

**4. MR Deploy Child**

- MR commands CD
- MR receives and transmits data between CD and GS

➡

**5. Child Deploy Probe**

➡

**6. Child return to MR**

➡

**7. MR Capture Child**

- CD receives commands from MR to land

➡

**8. MR returns to GS**

- Retrieve the MR at GS
- Turn off system

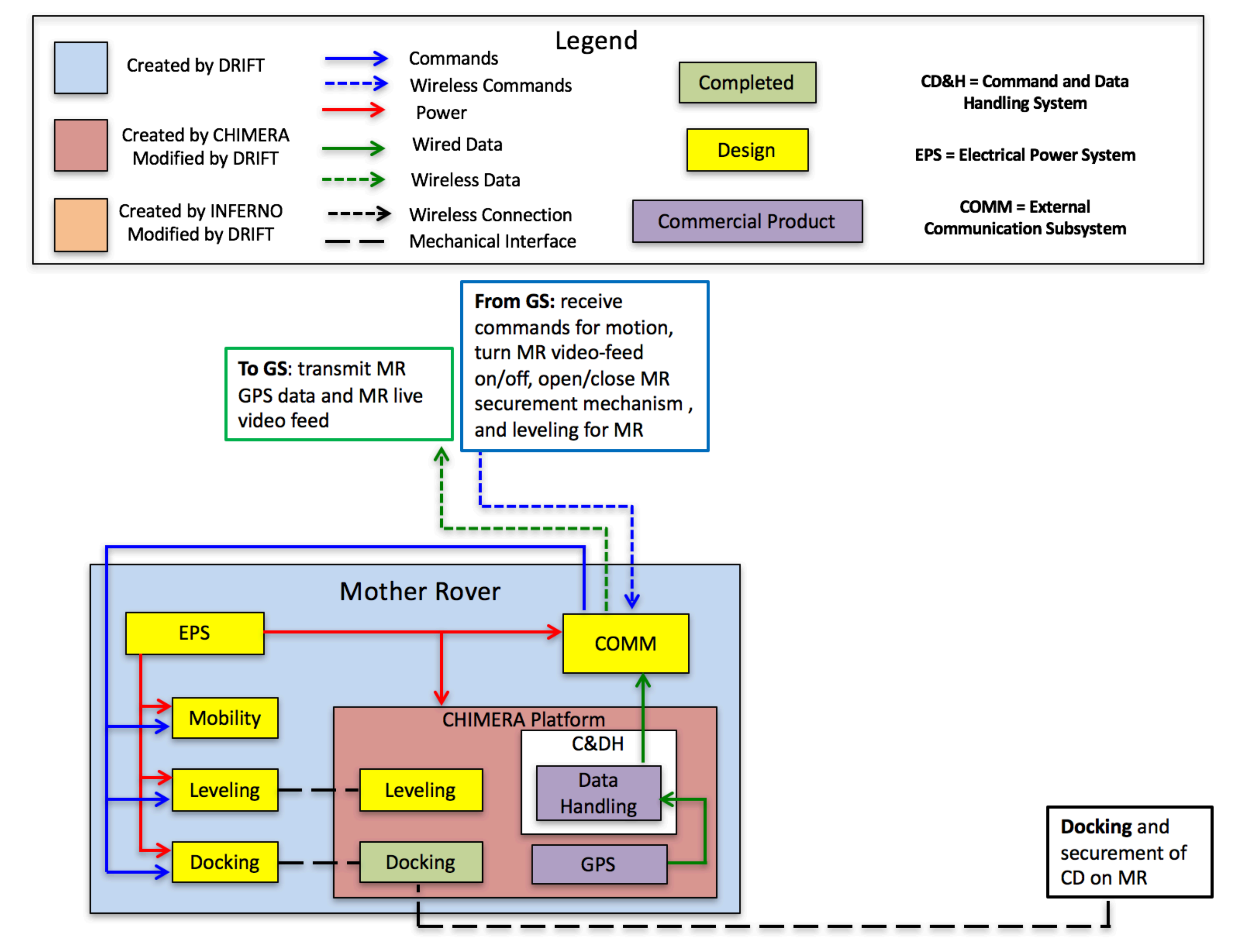
# Requirements Flowdown Continues

| Functional Requirement | Description |
|---|---|
| FR1.0 | The MR shall integrate with the attached landing platform |
| FR2.0 | The MR shall receive commands from the GS |
| FR3.0 | The MR shall transmit data to the GS |
| FR4.0 | The MR shall traverse through woods and grasslands up to 500m in any direction from the drop off point |
| FR5.0 | The MR shall level to position itself for the CD to take-off and land |

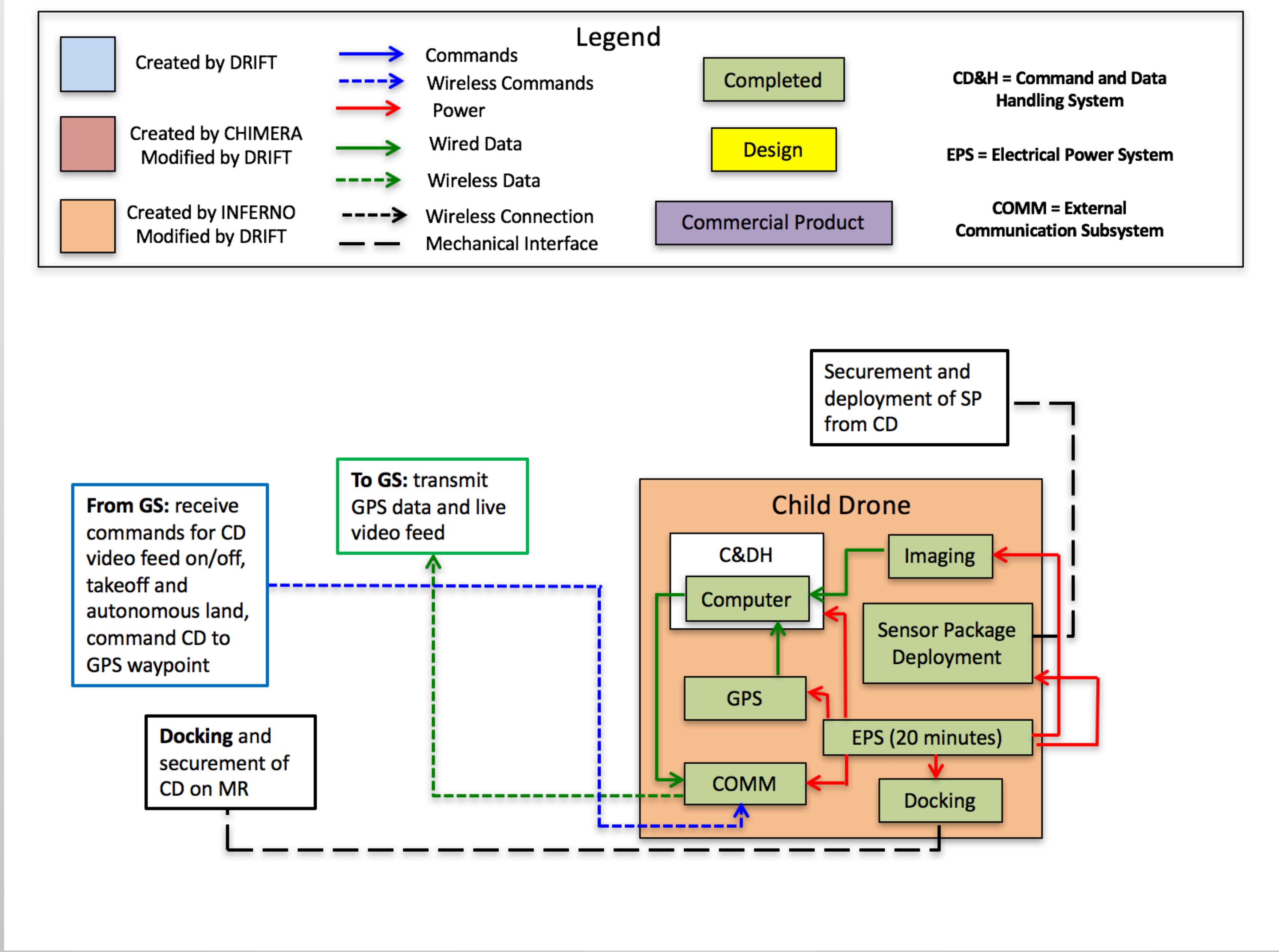
# Requirements Flowdown Continued

| **Functional Requirement** | **Description** |
|---|---|
| FR1.0 | The MR shall integrate with the attached landing platform |
| Design Requirement | Definition |
| DR1.1 | The MR shall have sufficient structural integrity capable of supporting the size (1.1m X 1.1m) and weight (55lbs) of the LP and CD without deformation to the structure. |
| DR1.2 | The MR shall incorporate the preexisting software/hardware of the LP to operate through one communication system. |
| DR1.3 | The LP shall be fixed permanently to the MR. |

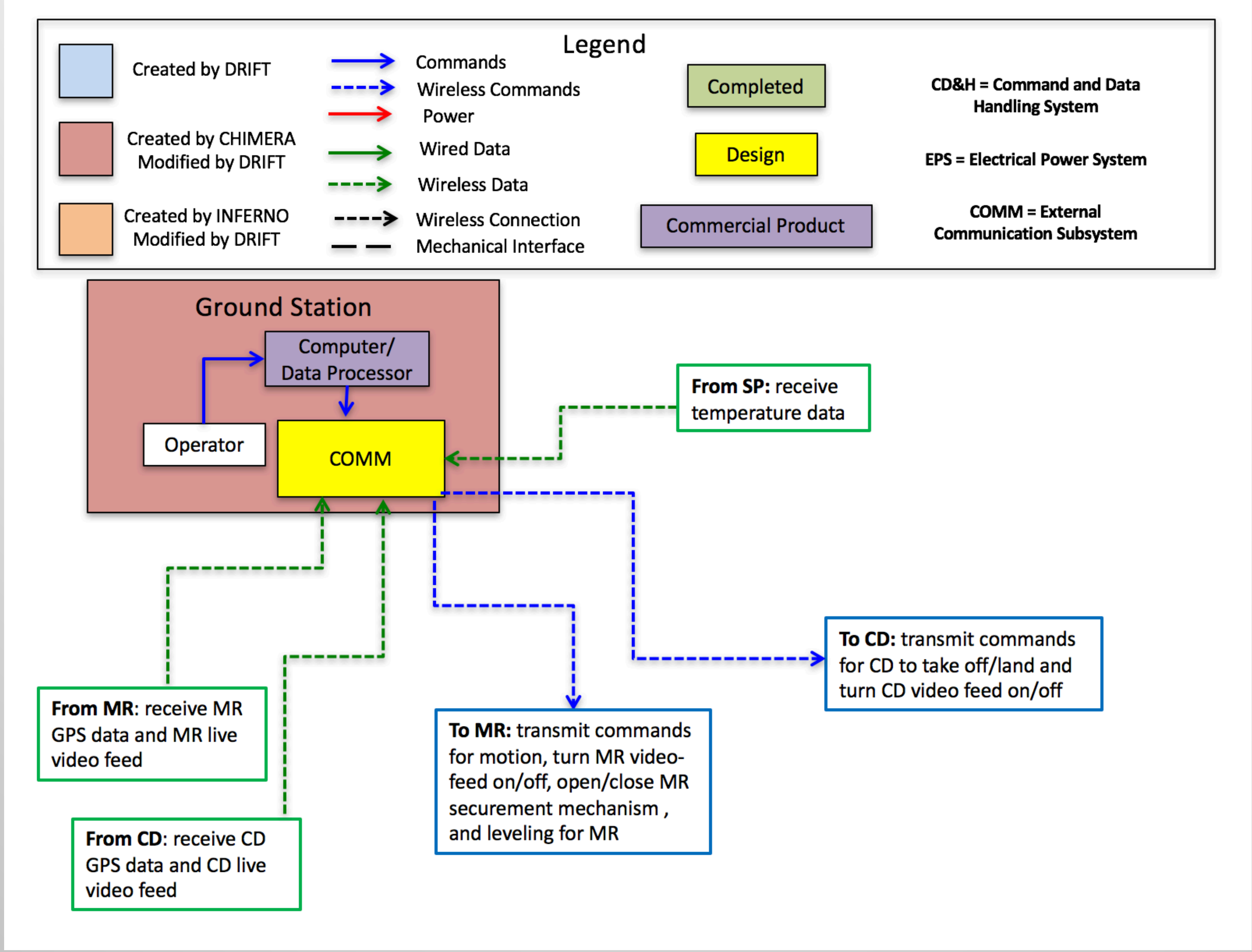
# Mother Rover Functional Block Diagram



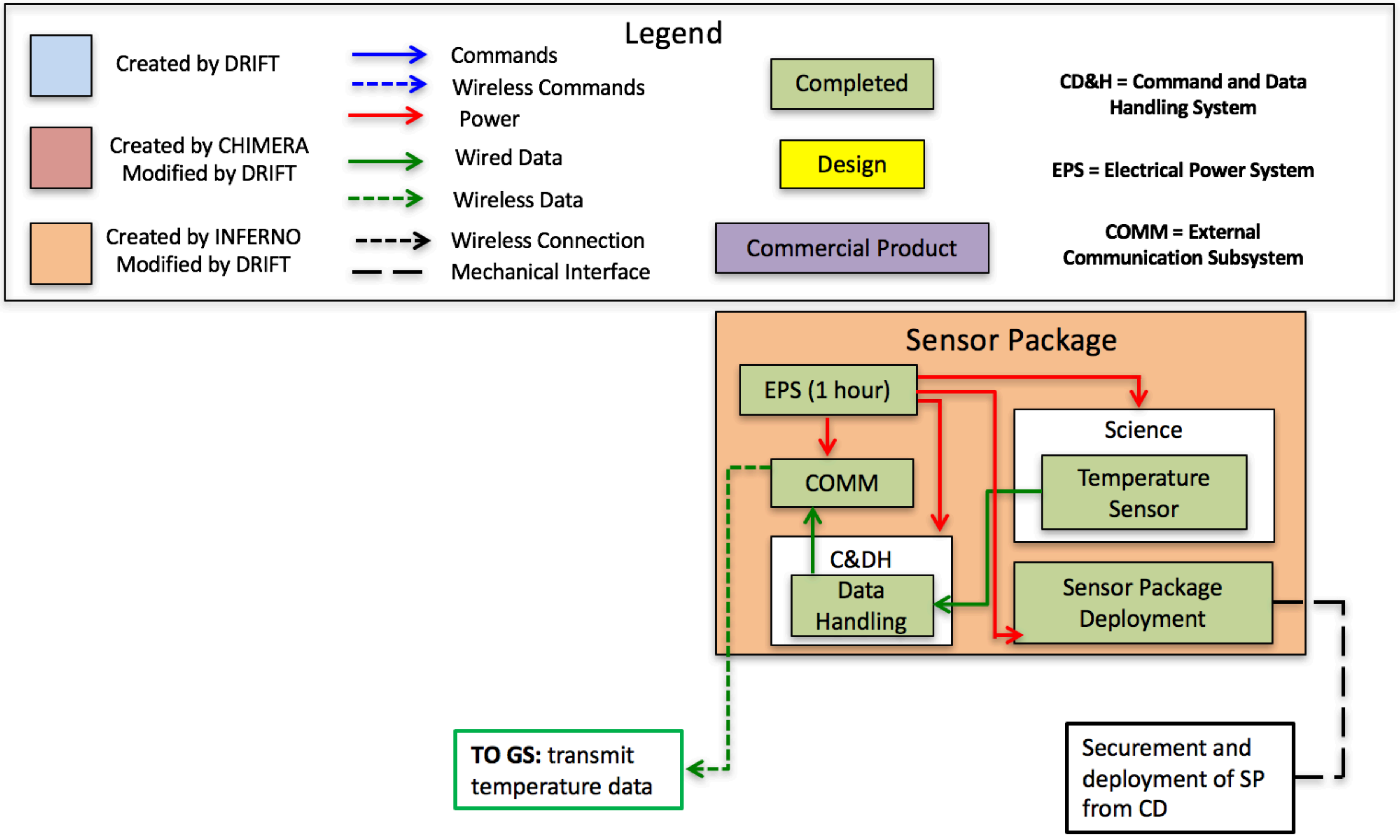
# Child Drone Functional Block Diagram



# Ground Station Functional Block Diagram



# Sensor Package Functional Block Diagram



# Trade Study

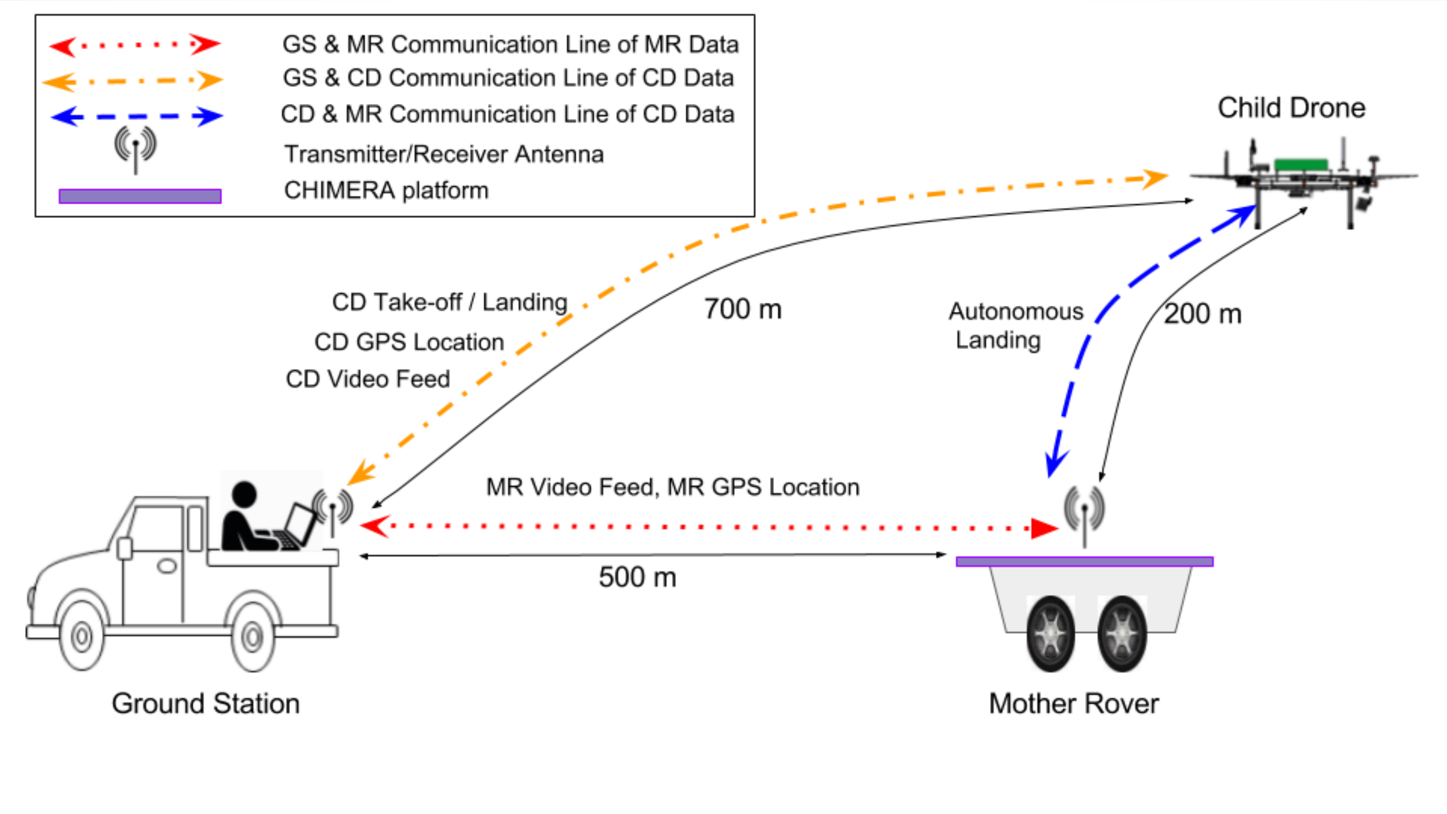
# Trade Study - Communications

**1) Original communication System**

**2) One Line of Communication Through MR**

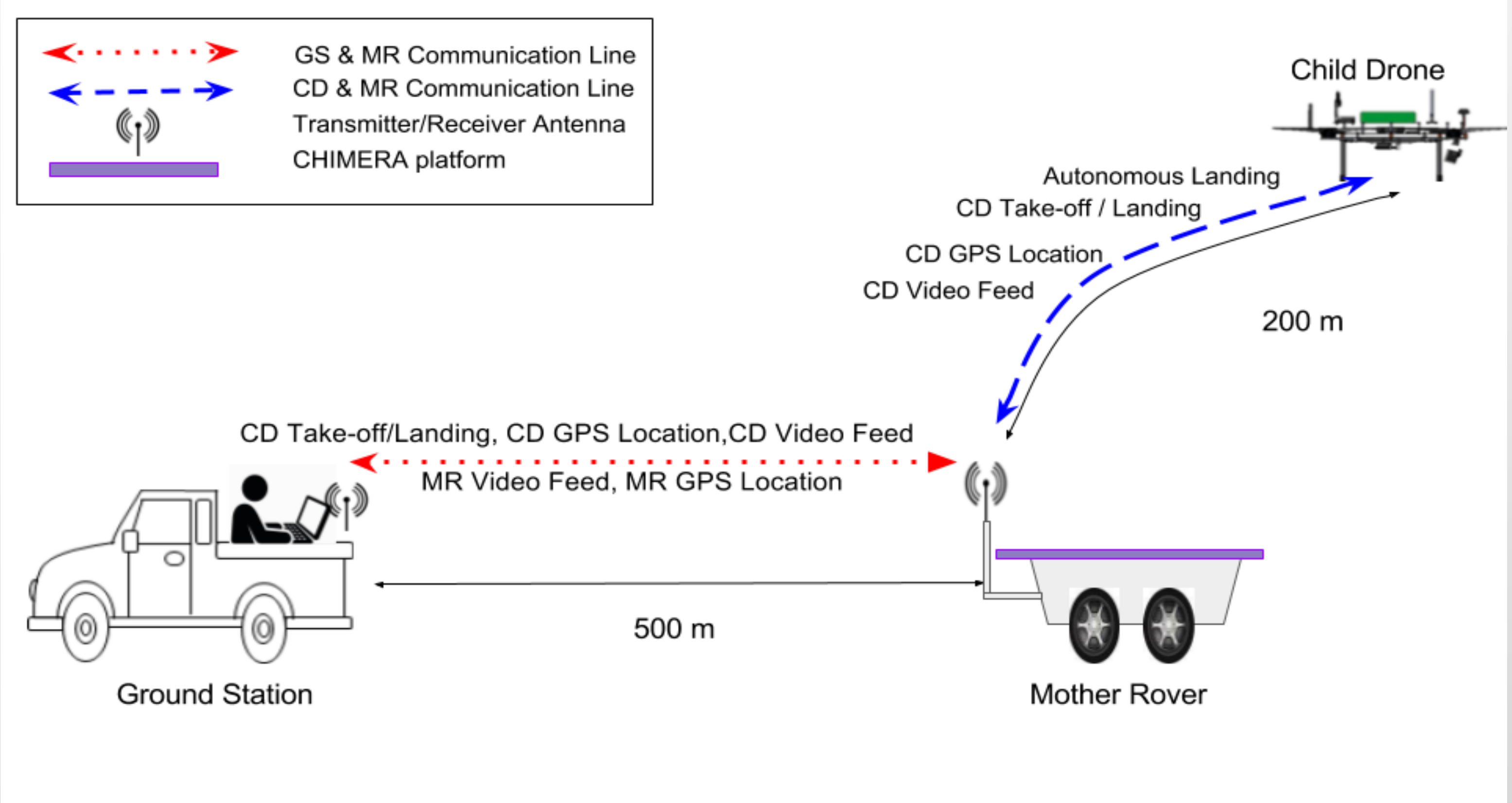
**3) Multiple Lines of Communication Through MR**

# Original Communication system



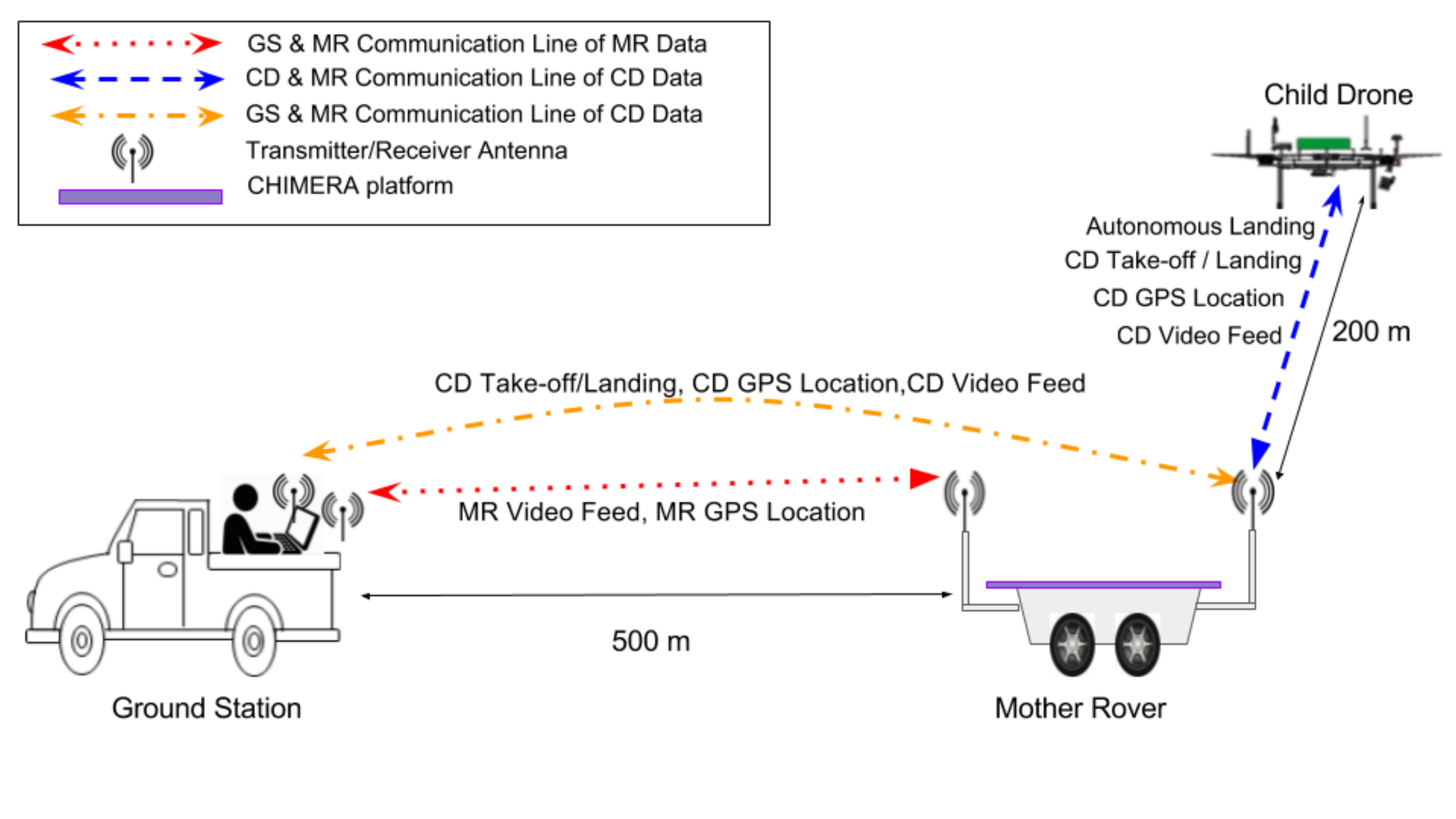

| Description | Pros | Cons |
|---|---|---|
| Software is not complex | X | |
| Inexpensive | X | |
| Messages do not need to be altered in MR | X | |
| Does not fit requirements (communications through MR) | | X |
| 700 meter connection to CD | | X |
| Both systems will need decent power | | X |

# One Line of Communication Through MR




| Description | Pros | Cons |
|---|---|---|
| Few points of failure | X | |
| Can backup and store easily on MR | X | |
| Low power required | X | |
| Shorter communication distance through each device | X | |
| Inexpensive | X | |
| Intricate Software | | X |
| Have to combine messages | | X |

# Multiple Lines of Communication Through MR




| Description | Pros | Cons |
|---|---|---|
| Software is not too complex | X | |
| No communication over distance > 500 meters | X | |
| Expensive | | X |
| Risk of the multiple sensors causing interference | | X |
| Many possible points of failure | | X |
| Higher power required | | X |

# Trade Metrics - Communication

| Metric | Weight | Description |
|---|---|---|
| Reliability | 35% | Reliability of the communication system is the measure of how well the communication system transmits and receives the required data. It weighs the highest at 35% because the communication systems between INFERNO, CHIMERA, and DRIFT need to be integrated so that the Fire Tracker System works properly. |
| Signal Attenuation | 30% | Signal attenuation is the reduction of signal strength during the signal transmission. It is the second most important metric weighted at 30% as during wireless communication, signal losses can occur easily due to the obstructions and interference from neighboring electronic devices. The MR needs to travel 500m in any direction through the rough terrain. In order for the signal to be transmitted and received efficiently, signal attenuation along the way needs to be considered. |
| Time Required | 15% | The time required is defined as the total number of labor hours needed to complete all communication line requirements. Since the two previous projects communicate independently from each other, the time needed for the software integration in communication line is the third most important metric at 10%. The time required to install and write the code for the hardwares to work properly is essential in consideration so that the project can be completed on time. |
| Software Complexity | 10% | Software complexity is the amount of new lines of codes need to be written to integrate all MR subsystems. Most of the existing codes on the original communication system does not need much changes and are inherited. These inherited codes just need to be changed or modified so that it can handle the upgraded version that DRIFT made by adding the mother rover on the communication line. |
| Cost | 10% | Cost of establishing the communication system is not a big part of the project as most of the hardware needed for the system is not as expensive as the other key design options. Majority of the hardware is inherited from previous projects and only needs minor improvements. |

# Metric Ratings - Communication

| | Ratings | | | | |
|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 |
| Reliability (percent failure) | >50% | 25%-50% | 5%-25% | 1%-5% | <1% |
| Time Required | >400 hours | 300-400 hours | 200-300 hours | 100-200 hours | <100 hours |
| Signal Attenuation | System interferes with itself, has high loss from obstruction | System interference with itself,has low loss from obstruction | System only has high loss from obstruction | System only has low loss from obstruction | Only loss is due to free space loss |
| Software Complexity | System cannot use currently implemented code and must start from scratch | System needs to edit most of the existing code and parse new messages | System needs to have existing messages combined and parsed | System needs to redirect messages to new sources | System only needs to do minor edits to the current messages |
| Cost | >$ 500 | $250 - $500 | $100 - $250 | < $100 | No additional cost |

# Trade Study- Result

| Metric | Weight | Original Communications System | One Line of Communication Through MR | Multiple Lines of Communication Through MR |
|---|---|---|---|---|
| Reliability | 35% | 4 | 4 | 4 |
| Time Required | 15% | 4 | 3 | 4 |
| Signal Attenuation | 30% | 2 | 4 | 1 |
| Software Complexity | 15% | 5 | 3 | 4 |
| Cost | 5% | 4 | 3 | 3 |
| **Total** | **100%** | **3.55** | **3.65** | **3.05** |

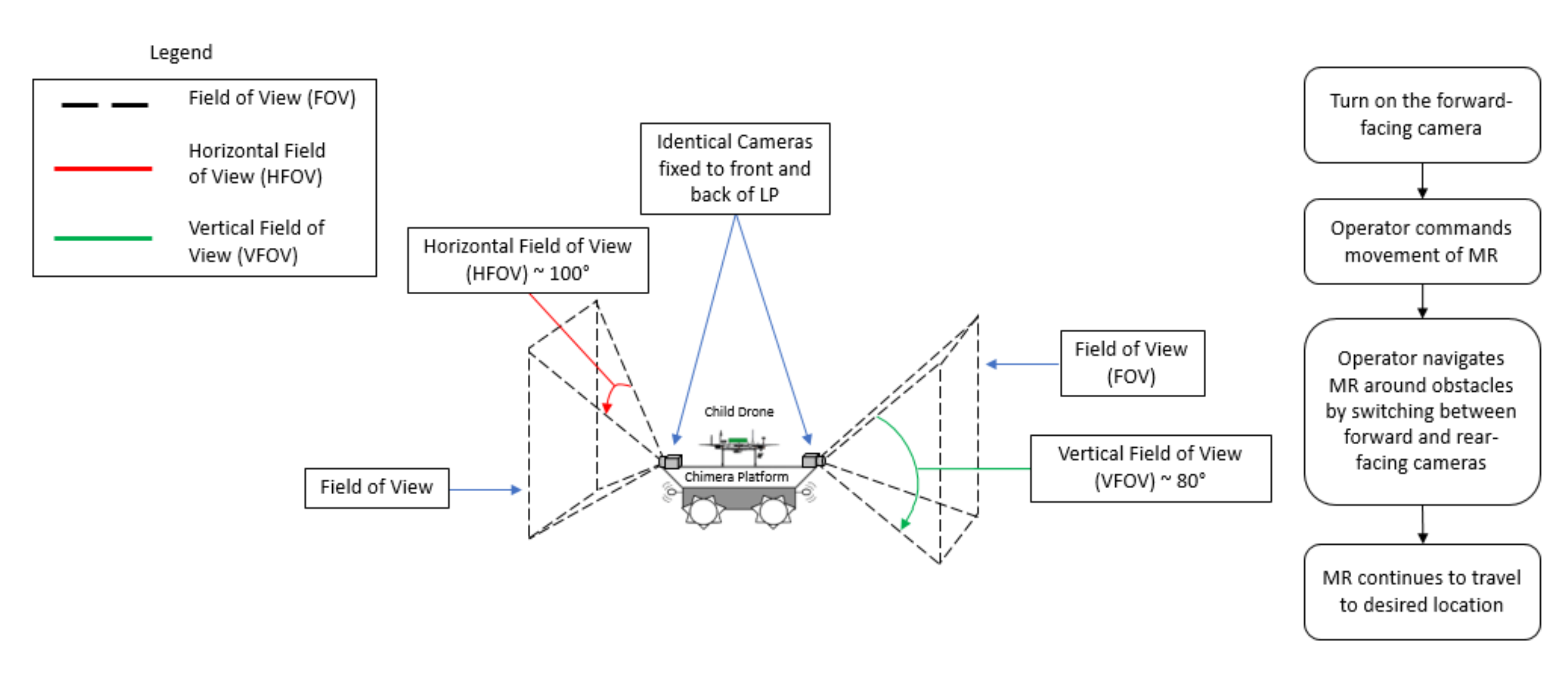
# Trade Study – Hazard Camera

1) **2 Fixed, Wide Horizontal-FOV Cameras with 0-DOF**

2) **1 Actuated, Narrow Horizontal-FOV Camera with 1-DOF**

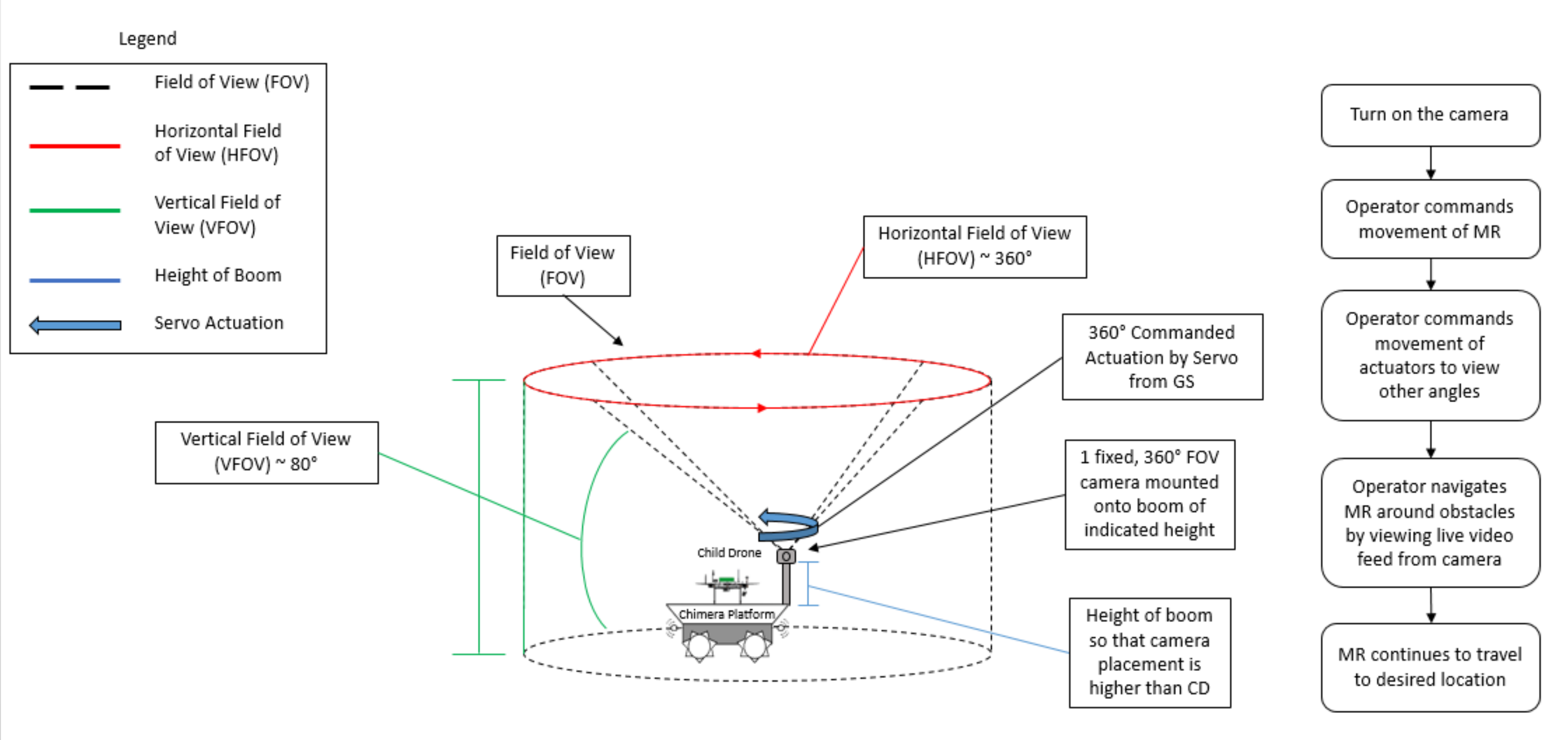
3) **1 Actuated, Narrow Horizontal-FOV Camera with 1-DOF**

# 2 Fixed, Wide Horizontal-FOV Cameras with 0-DOF



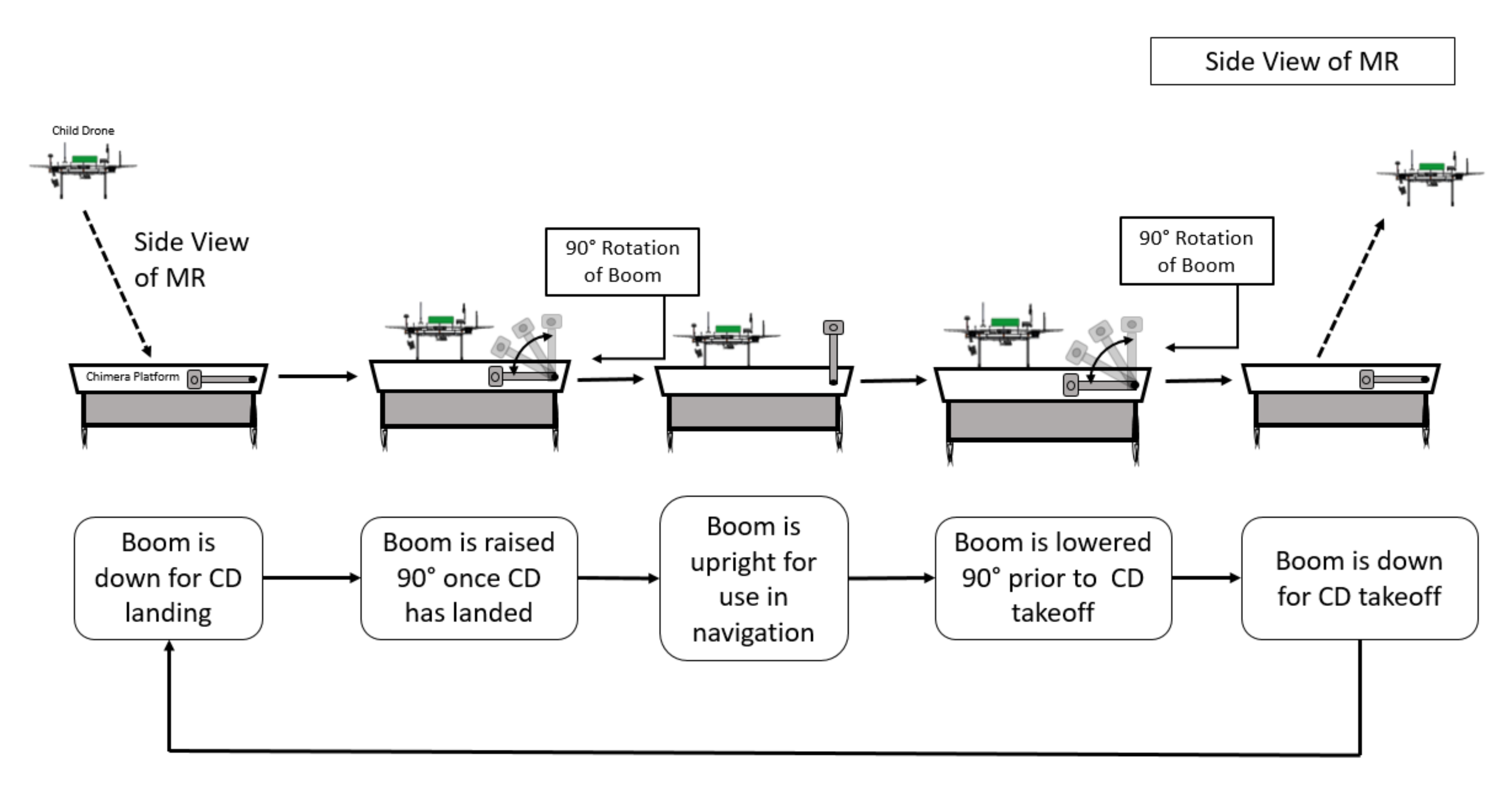

| Description | Pros | Cons |
|---|---|---|
| Simple design concept (fixed/no moving parts) | X | |
| Transmission of two imaging sources | | X |
| Cannot provide 360° HFOV without moving the MR | | X |
| Repositioning of the MR required | | X |
| Distortion of image due to wide HFOV | | X |

# 1 Actuated, Narrow Horizontal-FOV Camera with 1-DOF

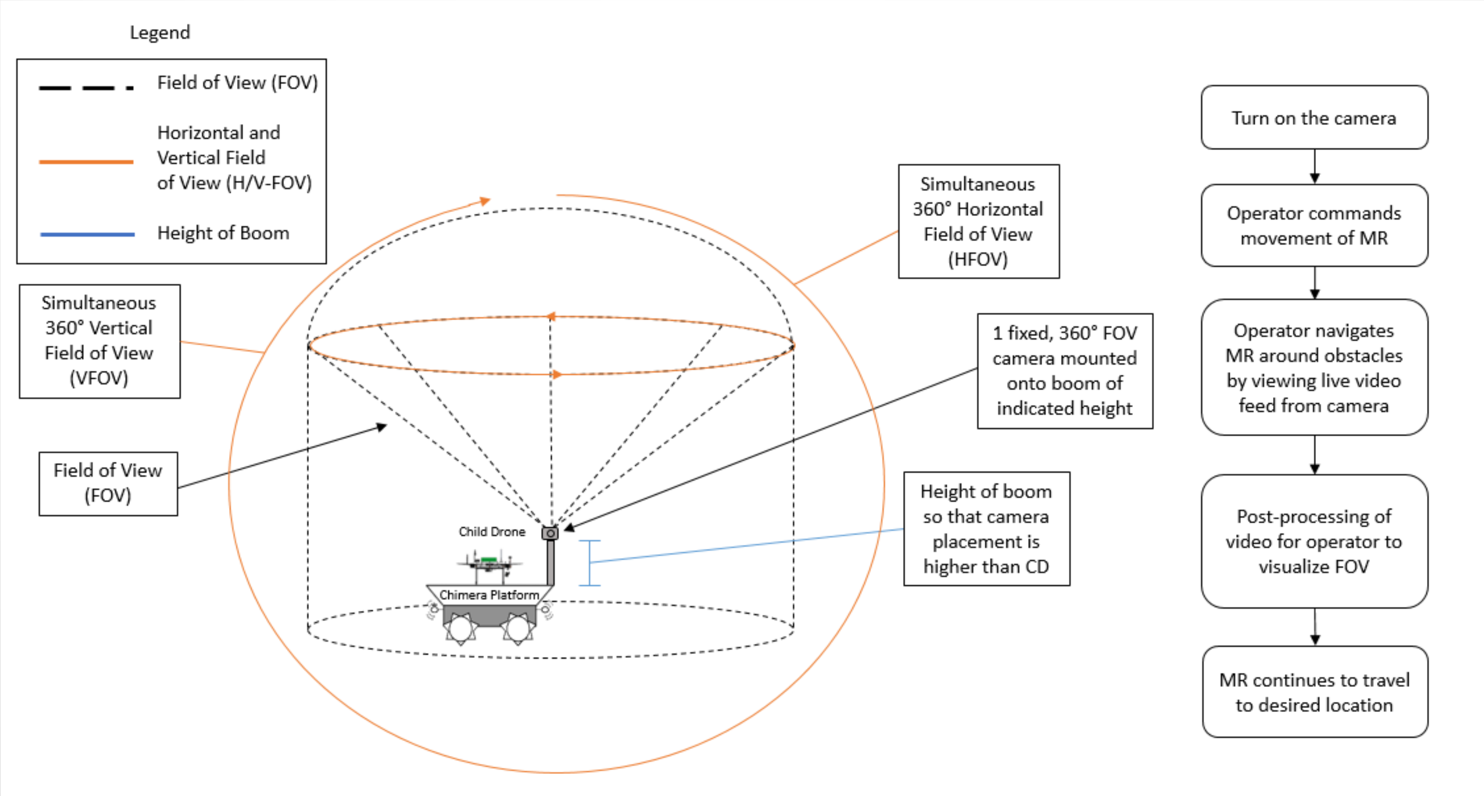



| Description | Pros | Cons |
|---|---|---|
| Can obtain 360° HFOV without moving the MR | X | |
| Transmission of single imaging source | X | |
| Limited image distortion | X | |
| Complicated mechanical design concept (actuated & raising/lowering mechanism) | | X |
| Must be placed with CD out of view (elevated) | | X |
| Additional software for camera pointing control and raising / lowering of boom | | X |

# Raising and Lowering Boom



# 1 Fixed, 360° Horizontal/Vertical -FOV Camera with 3-DOF




| Description | Pros | Cons |
|---|---|---|
| Transmission of single imaging source | X | |
| Provides simultaneous 360° HFOV and VFOV | X | |
| Must be placed on boom with CD out of view (elevated) | | X |
| Complicated mechanical design concept (raising/lowering mechanism) | | X |
| Distortion of image due to wide HFOV | | X |
| Obtaining the video camera / cost | | X |
| Large Bandwidth | | X |
| Additional software for raising / lowering of boom | | X |

# Trade Metrics– Hazard Camera

| Metric | Weight | Description |
|---|---|---|
| Reliability | 30% | The reliability is defined as how well the system can do its job consistently and its probability of success. In terms of the camera system, the reliability is categorized as the ability of the transmission to reach the GS from the MR, and vice versa. When multiple cameras are utilized, the reliability of the transmission of both sources decreases as the interference of the two sources becomes more probable. This category is ranked highest because it is one of the most critical elements of the camera system. If there is limited transmission between the GS and MR, operation of the MR cannot happen and the MR will not move. |
| Performance/ Effectiveness | 20% | The performance / effectiveness of the camera system is defined as the capability of the operator to gain a 360° horizontal field of view of the location of the MR using the camera system in the least amount of time. If a low resolution image with a narrow HFOV is transmitted to the GS (operator), the ability of operating the MR becomes difficult and it will take more time to obtain the 360° HFOV. Increasing the field of view and resolution would increase the performance / effectiveness value. |
| Software Complexity | 15% | The software complexity is closely tied with the time required to enable the system to communicate with the GS. With an increased number of cameras utilized and commands necessary to control the camera (including actuation), the software complexity increases. |
| Mechanical Complexity | 15% | The mechanical complexity is defined as the total number of parts necessary to fix the camera to the LP. Moving parts would increase the mechanical complexity of the system because there is more potential for failure. |
| Time Required | 10% | The time required is the total number of hours required to implement the camera system to the MR and meet all of the defined requirements associated with the system. If the camera system is not completed by the time for final testing, the control of the MR cannot be conducted when the MR is out of sight of the operator. |
| Cost | 10% | The cost of the camera system is defined as the total number of dollars to be spent on the cameras, mechanical integration, and communication systems. The cost will increase with more complex mounting systems and actuation of the camera, as well as the capabilities of the video camera itself. |

# Metric Ratings– Hazard Camera

| | Ratings | | | | |
|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 |
| Reliability (percent failure of camera system) | <50% | 50% - 70% | 70% - 80% | 80% - 90% | >90% |
| Performance /Effectiveness | 360° HFOV can never be obtained | 360° HFOV obtained after viewing the video feed in a post-processor, taking more than 2 minutes | 360° HFOV can be obtained in less than 2 minutes but greater than 1 minute of receiving the video feed | 360° HFOV can be obtained in less than one minute of receiving the video feed | 360° HFOV is obtained instantaneously |
| Software Complexity | Commands necessary to control multiple cameras with multiple moving mechanisms | Commands necessary to turn video feed on and off for more than one camera and control actuation for both | Commands necessary to turn video feed on and off for one camera and control actuation | Commands necessary to only turn video feed on and off for two cameras | Commands necessary to only turn video feed on and off for one camera |
| Mechanical Complexity | Actuation of camera is required and attachment system is unable to be built in house | Actuation of camera is required and attachment system is designed and built in house | Actuation of camera is required and attachment system is bought, assembled, and attached to the MR | No moving parts and attachment system is designed and built in house | No moving parts and attachment system is bought, assembled, and attached to the MR |
| Time Required | >200 hours | 200 - 150 hours | 150 - 100 hours | 100 - 50 hours | <50 hours |
| Cost | >$500 | >$500 - $400 | >$400 - $300 | >$300 - $200 | <$200 |

# Trade Study – Results

| Metric | Weight | 2 Fixed, Wide HFOV Cameras | 1 Actuated Camera with 360° Rotation | 1 Fixed Camera that Records 360° HFOV and VFOV |
|---|---|---|---|---|
| Reliability | 30% | 5 | 4 | 3 |
| Performance / Effectiveness | 20% | 3 | 3 | 5 |
| Software Complexity | 15% | 4 | 3 | 5 |
| Mechanical Complexity | 15% | 4 | 2 | 4 |
| Time Required | 10% | 4 | 3 | 4 |
| Cost | 10% | 3 | 3 | 2 |
| **Total** | **100%** | **3.9** | **2.37** | **3.85** |

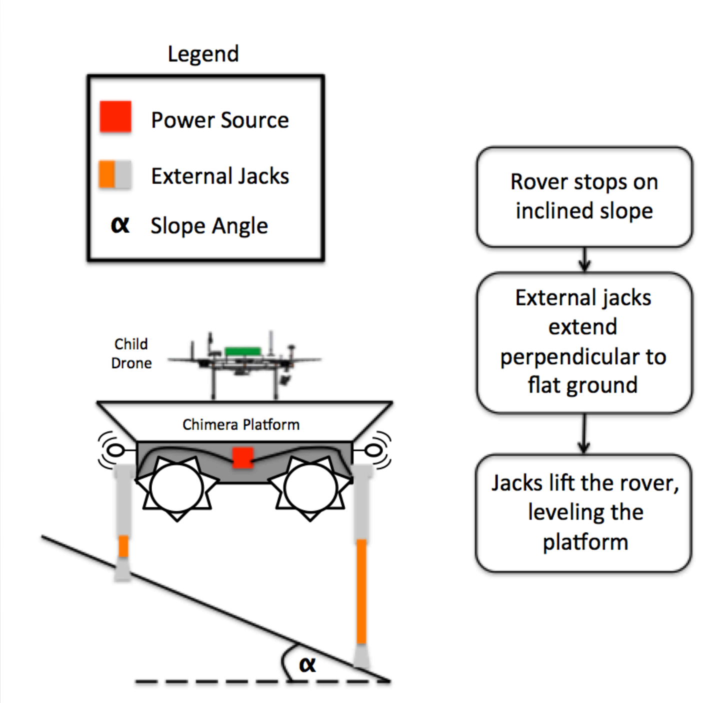
# Trade Study – Leveling System

**1) External Jacks**

**2) Ball and Cap**

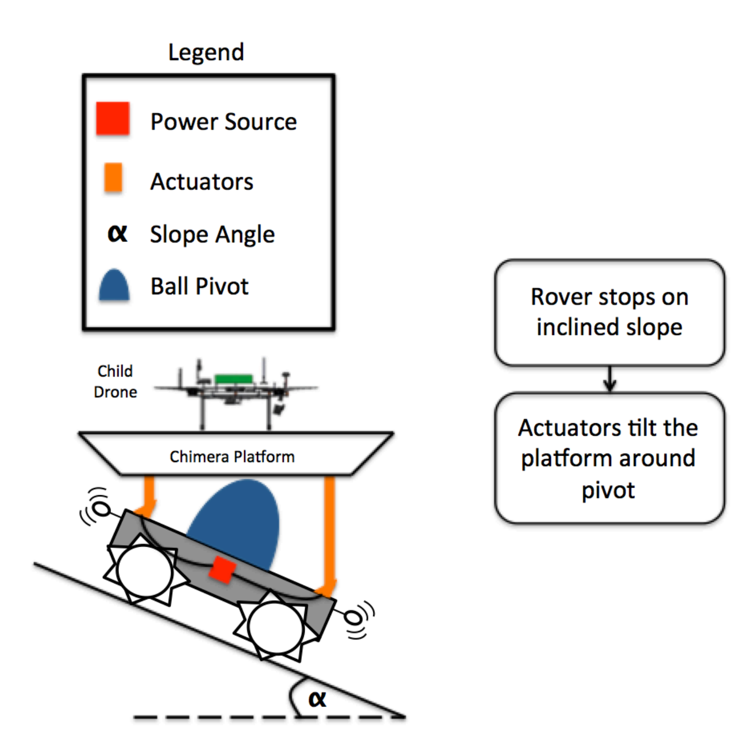
**3) Internal Jacks**

# External Jacks



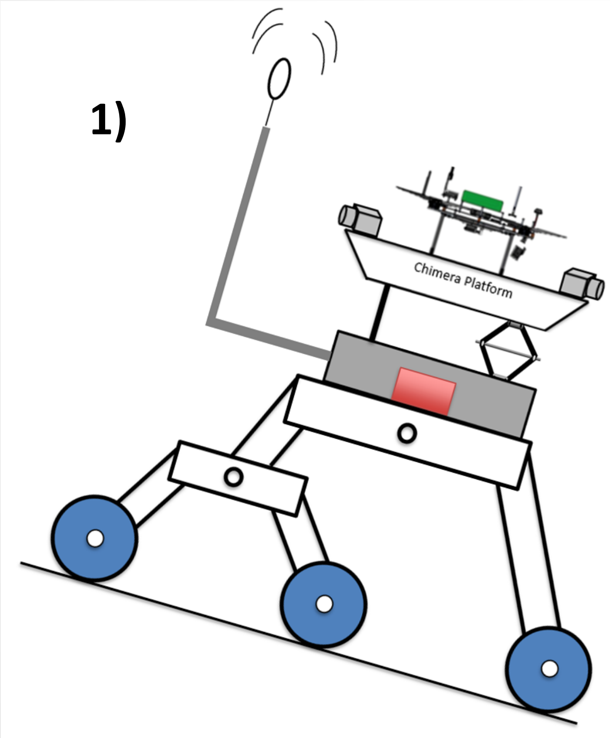

| Description | Pros | Cons |
|---|---|---|
| No custom components | X | |
| Reliable | X | |
| Simple integration | X | |
| Can be used as an alternative to wheel-locking | X | |
| Heavy | | X |
| Restricts rover dimensions | | X |
| Requires firm terrain | | X |

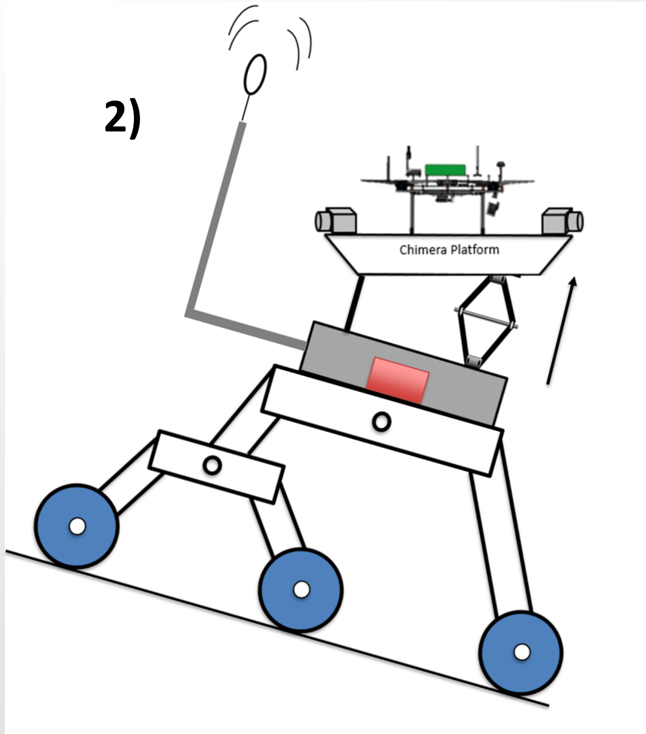
# Ball and Cap




| Description | Pros | Cons |
|---|---|---|
| Lightweight | X | |
| Terrain-independent | X | |
| Majority of LP weight at center of gravity | X | |
| Doubles as mechanical integration method | X | |
| Lighter load on actuators | X | |
| Expensive | | X |
| Complicated custom fabrication | | X |

# Internal Jacks




| Description | Pros | Cons |
|---|---|---|
| Little or no custom components | X | |
| Terrain Independent | X | |
| Doubles as mechanical integration method | X | |
| Large space requirements | | X |
| Heavy | | X |

# Trade Metric– Leveling System

| Metric | Weight | Description |
|---|---|---|
| Time Required | 15% | Time required is given a 15% weight because the integration of the leveling system and the integration of the platform to the rover fall under similar categories so the amount of time spent on the leveling system will overlap to the integration of the platform to the rover |
| Accuracy | 15% | Accuracy is given a weight of 15% because if the platform is not leveled within 3.5 °, the CD can not take off or land. If the CD is unable to deploy, the mission has failed. |
| Cost | 25% | Cost has a weight of 25% because the leveling system has the potential to be very expensive. With a budget of only five thousand dollars, the leveling system has potential to take up a quarter of it. |
| Mechanical Complexity | 25% | Mechanical complexity has a weight of 25% because leveling a rover of this size and weight has not been done in a number of different configurations. The system used will have custom parts no matter which design chosen. |
| Manufacturability | 20% | Manufacturability is given a weight of 20% because the manufacturing for the leveling system could be very complex since this system is not commonly used in rovers. With the potential of having all custom parts, manufacturability has to be a heavy consideration. |

# Metric Ratings– Leveling System

| | Ratings | | | | |
|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 |
| Time Required | >200 hours | 140-200 hours | 80-140 hours | 40-80 hours | < 40 hours |
| Accuracy (% off 3.5°) | > 50% | 25%-50% | 15%-25% | 5%-15% | < 5% |
| Cost | \$1000 - \$1500 | \$700 - \$1000 | \$500 - \$700 | \$300 - \$500 | \$100 - \$300 |
| Mechanical Complexity | Unique custom components with little to no existing existing documentation | Many moving parts with some custom components | Some moving parts with proven components | Proven components with minimal moving parts | All pieces prefabricated with established integration methods |
| Manufacturability | In house manufacturing/assembly - with custom design | In house manufacturing/assembly | In house assembly with purchased and manufactured parts | In house assembly with all purchased parts | Purchased prebuilt |

# Trade Study- Result

| Metric | Weight | External Jacks | Ball and Cap | Internal Jacks |
|---|---|---|---|---|
| Time Required | 15% | 2 | 2 | 4 |
| Accuracy | 15% | 4 | 5 | 4 |
| Cost | 25% | 4 | 3 | 4 |
| Mechanical Complexity | 25% | 3 | 4 | 4 |
| Manufacturability | 20% | 3 | 2 | 4 |
| **Total** | **100%** | **3.25** | **3.2** | **4** |

# Leveling System Hydraulic vs Scissor Jack

Hydraulic Jack

| | Pro | Con |
|---|---|---|
| 25 lb per unit | | X |
| $100 per unit | | X |
| Cannot be made in house | | X |
| Built-in actuation | X | |
| 28 inch retracted length | | X |

Scissor Jack

| | Pro | Con |
|---|---|---|
| 20 lb per unit | | X |
| $30 per unit | X | |
| Must add motor | | X |
| 5 inch retracted height | X | |
| No pre-existing electronics | X | |

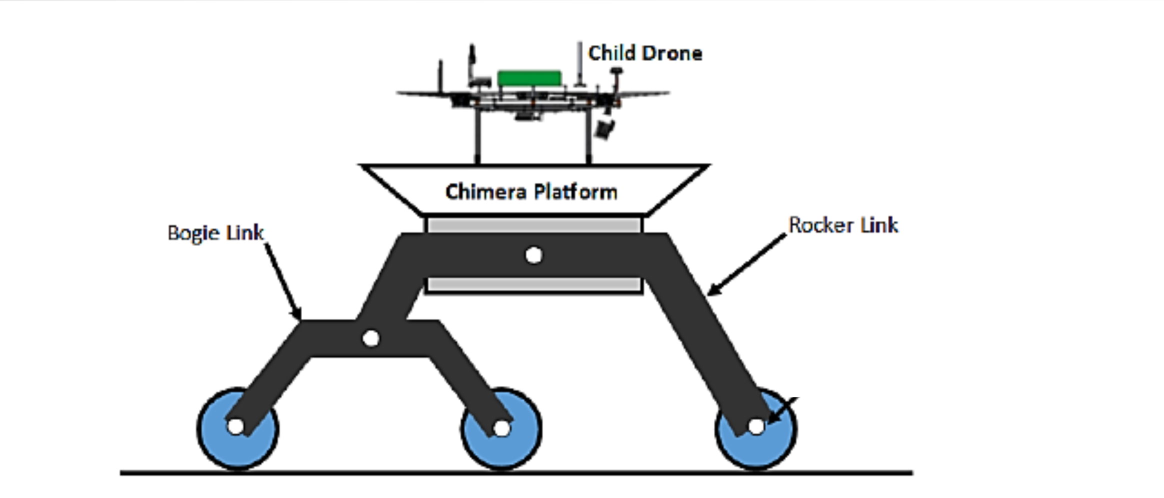
# Trade Study Translational System

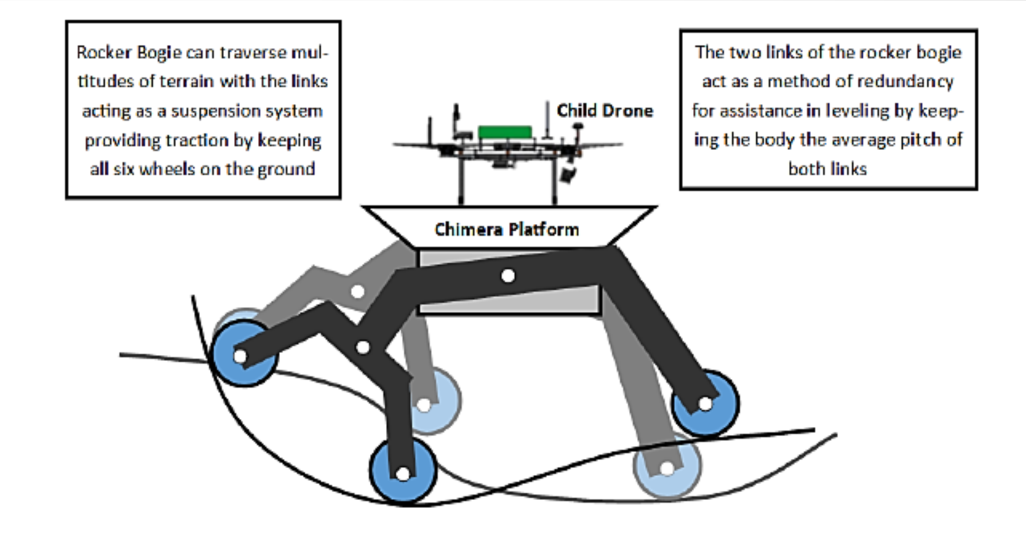
1. **Rocker Bogie**

2. **Continuous Tread**

3. **Fixed Chassis**

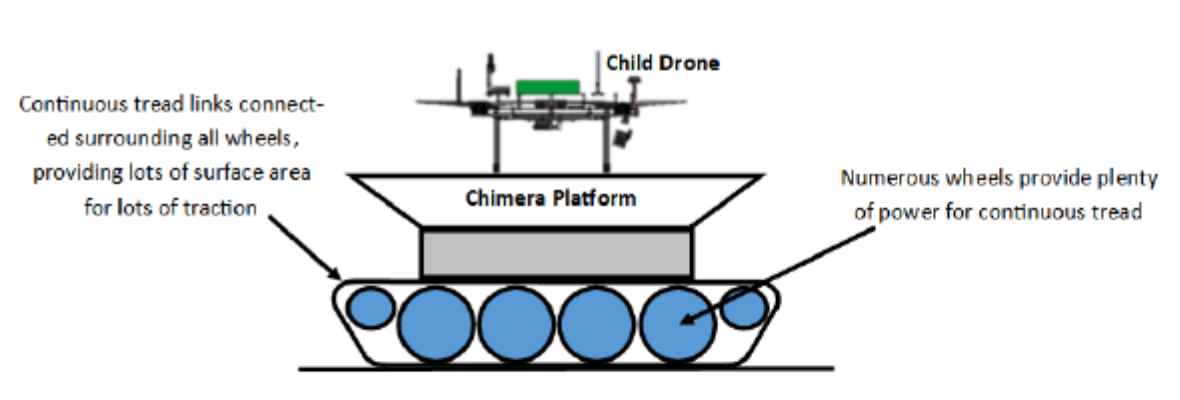
# Rocker Bogie

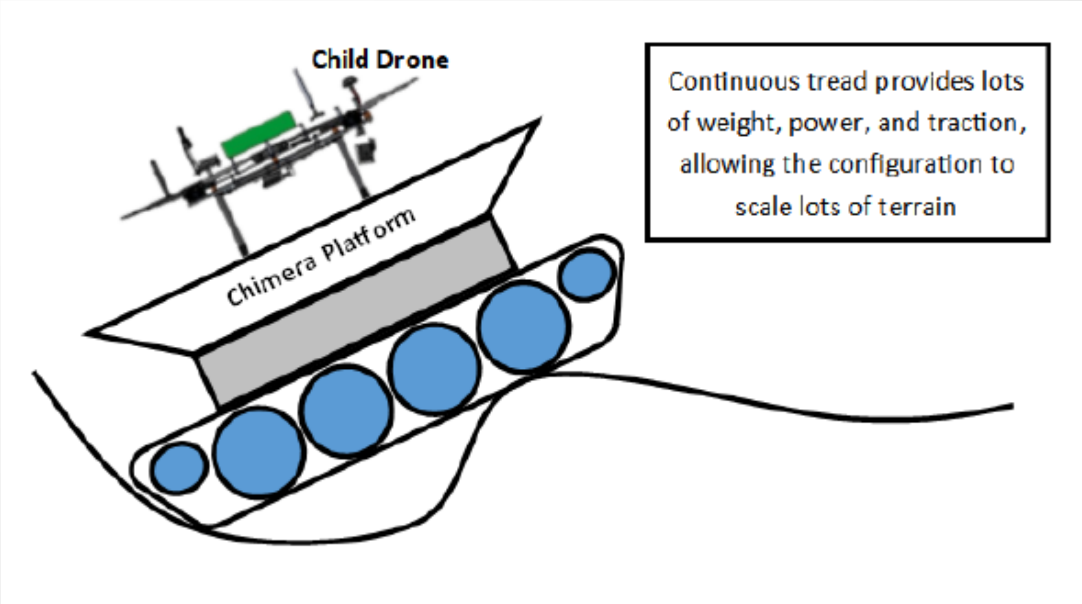



| Description | Pros | Cons |
|---|---|---|
| Can climb over obstacles up to twice the wheel diameter | X | |
| Wheel construction minimizes chance of losing contact with ground | X | |
| Low tipping potential | X | |
| Optimum speed of system under 0.6 m/s | X | |
| Configurations possible with capability of in place turning | X | |
| High design complexity | | X |
| Requires very durable material selection for legs | | X |

# Continuous Tread




| Description | Pros | Cons |
|---|---|---|
| Hard wearing and damage resistant | X | |
| Can turn in place | X | |
| Terrain Capable due to weight distribution | X | |
| Heavy construction lowers center of mass reducing tipping potential | X | |
| High design complexity | | X |
| Will lose contact with ground while navigating over obstacles | | X |
| Heavy | | X |

# Fixed Chassis

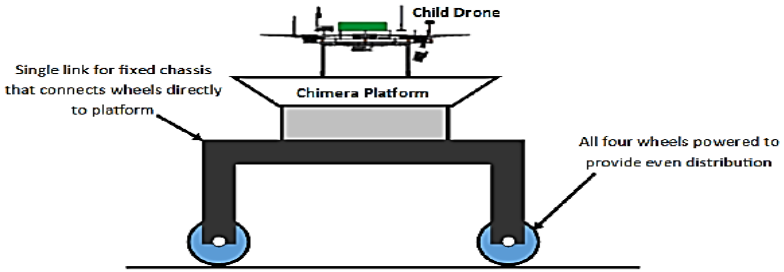
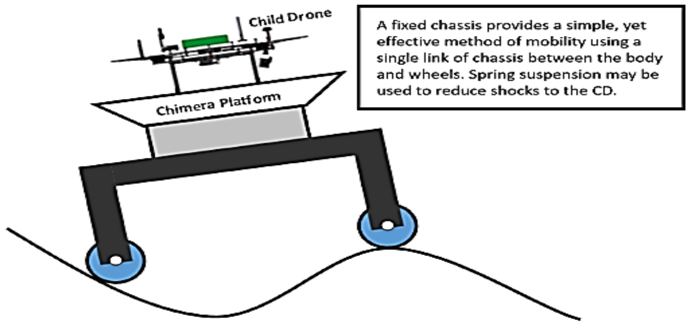
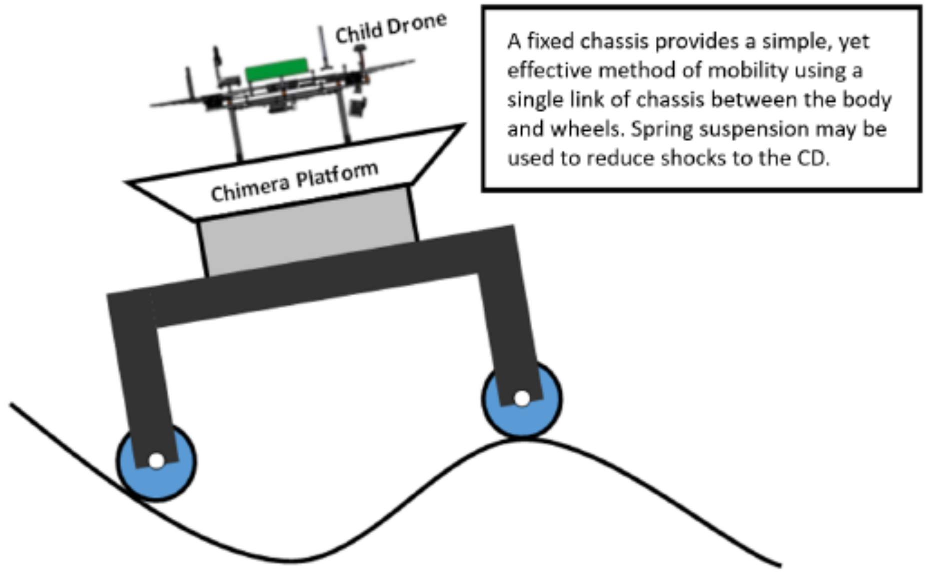



**Figure 25. A four wheel fixed chassis provides a simple, yet effective method of mobility**




| Description | Pros | Cons |
|---|---|---|
| Simple Construction | X | |
| Has configurations with turning in place capabilities | X | |
| Minimizes total moving parts | X | |
| Less terrain capability | | X |
| Comparatively higher tipping potential | | X |
| Can lose contact with ground when navigating over obstacles | | X |

# Trade Metrics - Translational

| Metric | Weight | Description |
|---|---|---|
| Time Required | 10% | In order for the mission to be successful the design and construction must be completed in a timely manner, however this will be one of the more complex portions of design and should be assigned a significant amount of time. So while it is still a factor, this metric is assigned a smaller percentage because some of the other metrics may directly cause the success or failure of other requirements. |
| Mechanical Complexity | 10% | Mechanical complexity is defined by the amount of moving parts necessary and the amount of custom designed parts that must be integrated together. The time required to design the translational mechanism will depend primarily on the mechanical complexity of the system. This section receives 20% because the project is conducted tightly constrained schedule and therefore also needs to be completed on time while still ensuring all mechanical parts will function correctly. |
| Cost | 10% | Cost is another major constraint with a limited budget, and the range of prices between each design may vary greatly. Since the translational mechanisms will be relatively large and will involve possibly complex structures and parts, cost is one of the major factors associated with the design decision. |
| Power Consumption | 15% | Power consumption will be a key design factor for translational mechanisms because the motors are the main element that will require the most power in order to keep moving. The heavier the rover, the more power consumption will be required. |
| Terrain Capability | 30% | Terrain capability is defined as the ability for the considered mechanism to traverse the earlier defined "rough" terrain requirement. The rover is required to travel through off road conditions, and therefore if the rover can traverse over objects the same size or larger as defined in the requirements, and the rover can quickly traverse the conditions without slipping, the more useful the system will be for this application. |
| Platform Safety | 25% | Platform safety is defined as the rovers capability to transport the platform and child drone without functionally damaging either component such that it will endanger the success of the mission. Factors that can mitigate this risk would be a system that does not apply large impulsive forces while moving onto the drone, one that would have minimal risk of tipping, etc. |

# Metric Ratings - Translational

| | Ratings | | | | |
|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 |
| Time Required (hours) | >150 | 150 - 125 | 125-100 | 100-50 | <50 |
| Mechanical Complexity | Most Parts are moving. Many parts require custom design and fabrication. | Approximately half the parts have movement. Many parts require custom design and fabrication | Some moving parts, with some requiring custom design and fabrication. | Minimal moving parts less than 4 parts requiring custom design and fabrication. | Minimal moving parts, parts can all be bought off the shelf. |
| Cost | >$1500 | $1000 - $1500 | $500 - $1000 | $250 - $500 | <$250 |
| Power Consumption | Requiring more than 6 motors. Significant weight will require very powerful batteries. | Requiring more than 6 motors, moderate to high weight. | Requiring 6 or less motors. Moderate required weight. | Require 4 or less motors. Weight is moderate. | Require 2 or less motors. Weight is low, so motor power minimal. |
| Terrain Capability | Concerns present for terrain capability meeting requirements | Can achieve terrain requirements but with added design complexity. | Can clear the obstacle height in requirements with added design complexity from a basic configuration. | Can clear obstacles well over the requirements, but would require adding some complexity. | Can clear obstacles well over the requirements, without adding complexity from simple configuration. |
| Platform Safety | Tipping and potential shock are both likely and concerning | Tipping and potential shocks are both likely, but low damage potential | Tipping or shocks possible, but minimal impact on safety. | Only tipping or shocks possible, but within platforms durability restrictions. | Specifically designed to minimize tipping and shocks, so platform should see negligible forces. |

# Trade Study - Results

| Metric | Weight | Rocker Bogie | Continuous Tread | 4 Wheel Fixed Chassis |
|---|---|---|---|---|
| Time Required | 10% | 2 | 1 | 3 |
| Mechanical Complexity | 10% | 3 | 2 | 5 |
| Cost | 10% | 3 | 2 | 4 |
| Power Consumption | 15% | 3 | 1 | 4 |
| Terrain Capability | 30% | 5 | 4 | 3 |
| Platform Safety | 25% | 5 | 4 | 2 |
| **Total** | **100%** | **4.00** | **2.85** | **3.2** |

# Cost Approximation – Rocker Bogie

| Component | Total Cost |
|---|---|
| Structure | $ 200 |
| Differential | $ 225 |
| Wheels | $ 60 |
| Miscellaneous Parts + Extra if needed | $ 100 |
| **Total:** | $585 |

# Cost Approximation - Differential

| Component | Number Needed | Price Per Unit | Total |
|---|---|---|---|
| Bevel Gears | 3 | $50 | $150 |
| Steel Rods | 3 | $5 | $15 |
| Rod Brackets | 6 | $10 | $60 |
| **Total:** | - | - | $225 |

Bevel Gears Info
Steel Rods Info
Rod Brackets Info

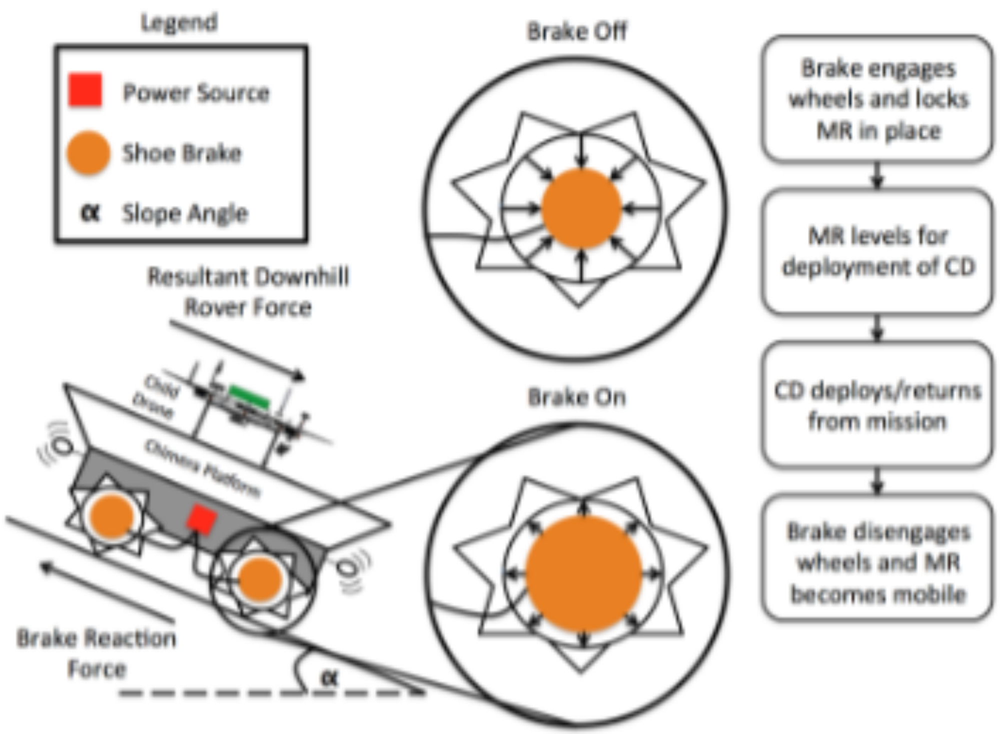
# Trade Study – Wheel-Locking Mechanism

**1) Drum Brake**

**2) Disc Brake**

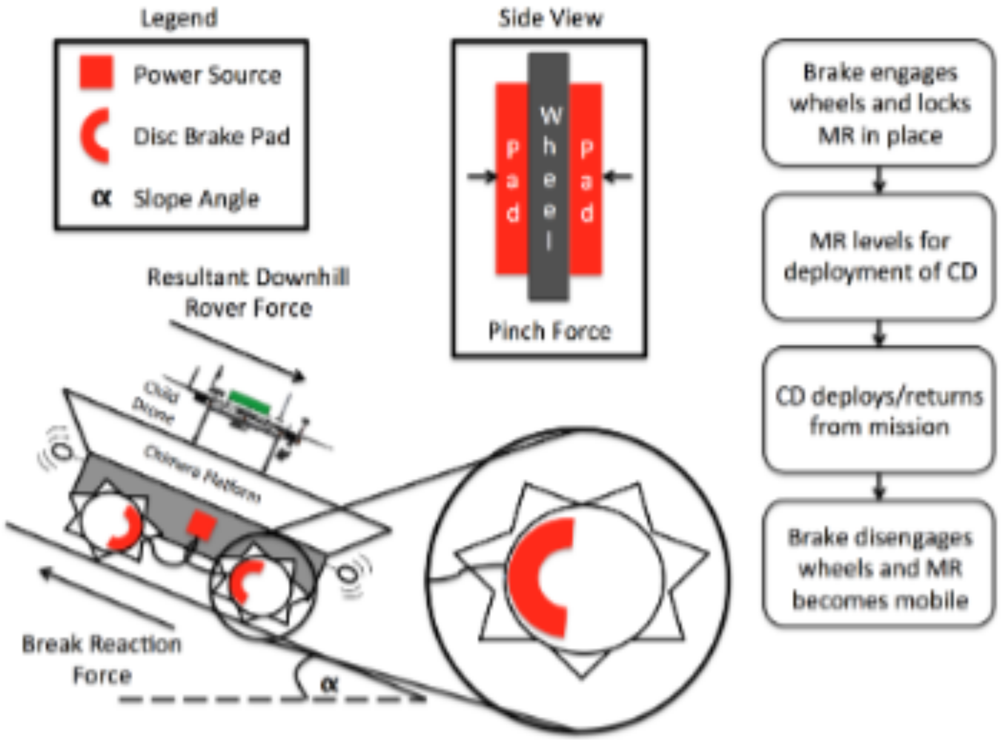
**3) Counter-torque Brake**

# Drum Brake



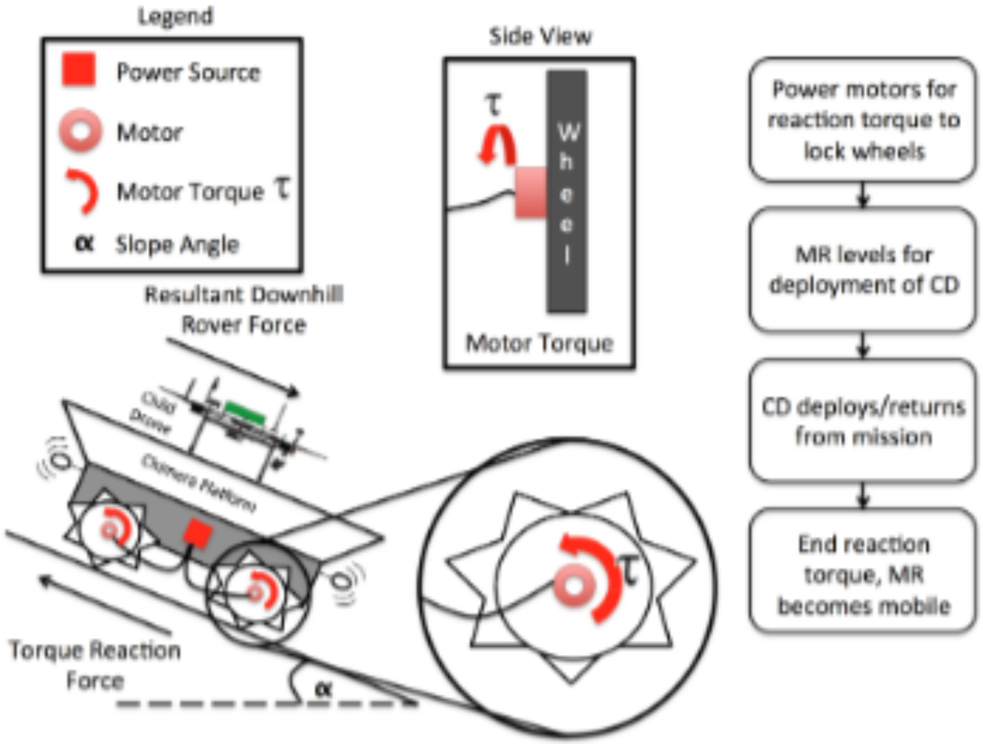

| Description | Pros | Cons |
|---|---|---|
| Simple incorporation and maintenance | X | |
| Less input force due to built-in adjustment mechanism | X | |
| Cheap production and purchase cost | X | |
| Collects water in between the brake lining and drum | | X |
| Brake heats up and wears due to friction | | X |

# Disc Brake




| Description | Pros | Cons |
|---|---|---|
| Dissipates heat well | X | |
| Easy to service due to the open air design | X | |
| Low production and maintenance cost | X | |
| Disc deformation due to vibration | | X |
| Requires assisted braking system such as power booster | | X |

# Counter- Torque brake




| Description | Pros | Cons |
|---|---|---|
| Cheap maintenance cost | X | |
| Increased capacity of the system | X | |
| Negligible amount of heat produced | X | |
| Reduces the stoppage time | X | |
| Needs to be powered throughout the operation | | X |
| Motors require high level of torque | | X |

# Trade Metrics – Wheel-Locking

| Metric | Weight | Description |
|---|---|---|
| Complexity | 30% | The complexity of the locking mechanism is ranked the highest due to the risk that comes when the child drone is docking/taking off. It is important to have the MR to be stable when the docking occurs. The ranking of each option is dependent on its capability to be implemented with the other subsystems of the MR. Additionally, an increasing number of parts associated with an option would increase its complexity. This metric needs to be satisfied in order to achieve functional and design requirements FR2.0, DR2.1 and FR5.0, DR5.2 |
| Power Consumption | 20% | Since most of the subsystems will have communication with GS, available power supply will be limited. Thus, any components that consumes power needs to be examined so that the MR is within the power budget. Failure to do so can short circuit the MR, which can break the locking system and other subsystems that are associated with the translation of the MR. |
| Manufacturability | 20% | Manufacturability is weighted 20% as it is important to be able to have the product ready for testing the MR system. It is heavily weighted because it will be time consuming depending on the resources available to successfully build and integrate the mechanism. This metric will focus on the affordability to produce or purchase the system and the possibility of the mechanism needing to be fabricated more than once. |
| Cost | 15% | The cost required to apply this mechanism is weighed at 15%, which is mainly due to the manufacturability of the system. The range of the cost can vary depending on the design and complexity of the locking mechanism. Secondly, the capability of producing the system in-house could significantly decrease the cost. |
| Time Required | 15% | The time required is defined as the time needed to implement the locking mechanism onto the MR. This time span includes designing, manufacturing, testing, and integrating the system within the MR. |

# Metric Ratings – Wheel-Locking

| | Ratings | | | | |
|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 |
| Complexity | Unique custom components with little to no existing documentation | Moving parts with low tolerance | Moving parts with high tolerance needed for operation | Minimal complexity added by the components | The system can integrate with the MR without any failure |
| Power Consumption | >40% mission power draw | >30% mission power drawn | >20% mission power draw | >10% mission power draw | No additional power drawn |
| Manufacturability | In house manufacturing/assembly with custom design | In house manufacturing/assembly | In house assembly with purchased and manufactured parts | Can be manufactured by a professional less than 3 weeks | Can be bought from an acknowledged seller in less than a week |
| Cost | >$ 500 | $400 - $500 | $250 - $400 | $100 - $250 | < $100 |
| Time Required | >175 hours | 150-175 hours | 100 - 150 hours | 50- 100 hours | <50 hours |

# Trade Study - Result

| Metric | Weight | Drum Brake | Disc Brake | Counter-Torque Brake |
|---|---|---|---|---|
| Complexity | 30% | 3 | 4 | 3 |
| Power Consumption | 20% | 4 | 4 | 2 |
| Manufacturability | 20% | 5 | 5 | 5 |
| Cost | 15% | 2 | 3 | 5 |
| Time Required | 15% | 3 | 4 | 3 |
| **Total** | **100%** | **3.45** | **4.05** | **3.5** |

# Feasibility

# Power System

# Power Budget

| Components | Average Current (A) | Maximum Current (A) | Quantity | Voltage (V) |
|---|---|---|---|---|
| DC Motor | 40 | 50 | 6 | 12 |
| Leveling Jack | 0.6 | 0.6 | 2 | 12 |
| Linear Actuator | 0.4 | 1 | 4 | 12 |
| Microcontroller | 0.5 | 1 | 1 | 3.3 |
| Tranceiver - Receiving | 0.026 | 0.026 | 1 | 0.026 |
| Tranceiver-Transmitting | 0.215 | 0.215 | 1 | 0.215 |
| Video Transmitter | 0.3 | 0.3 | 1 | 0.3 |
| **Total** | **42.04** | **53.14** | - | - |
| **Amp-Hour Required for 1.5hr Use** | | **79.71 Ah** | | |

# Power Budget - Feasibility

**Power Supply:**

- Windy Nation AGW Deep Cycle Battery
- Chemistry: Lead Acid
- Nominal Voltage: **12 V**
- Capacity: at least **100 Ah**
- Maximum Constant Discharge Current: 106 A
- Maximum Peak Discharge Current: 1200 A
- Weight: **67 lb**

**Power Regulation Circuits:**

- Voltage Regulator
- Voltage Divider
- Op-Amp

# In-Depth Feasibility - Communications

# Link Budget

## Link Budget for DRIFT

| | CD | MR | MR Commands/GPS | | | |
|---|---|---|---|---|---|---|
| **Physical Constants** | **Downlink (video)** | | **Uplink** | **Downlink** | **Units** | **Reference** |
| Speed of Light, c | 3.00E+08 | 3.00E+08 | 3.00E+08 | 3.00E+08 | m/s | Constant |
| Frequency, f | 5.80E+09 | 5.80E+09 | 9.00E+08 | 9.00E+08 | Hz | Input: From ImmersionRC |
| Wavelength, l | 5.17E-02 | 5.17E-02 | 3.33E-01 | 3.33E-01 | m | lambda = c/f |
| Range, R | 700 | 500 | 500 | 500 | m | Input: R_MR + R_CD |
| Boltzman's Constant, k | 1.38E-23 | 1.38E-23 | 1.38E-23 | 1.38E-23 | W/(Hz-k) | Constant |
| | | | | | | |
| **Data Parameters** | **Downlink (video)** | | | | **Units** | **Reference** |
| Bit Error Rate / Probablility of Bit Error , BER | 1.00E-05 | 1.00E-05 | 1.00E-05 | 1.00E-05 | [-] | Input:  From INFERNO |
| Data Coding Scheme | Unknown | Unknown | Unknown | Unknown | [-] | Input: From INFERNO |
| Required Bit Energy to Noise Ratio, Eb/No | 13 | 13 | 13 | 13 | dB | Input: From INFERNO |
| Data Rate, R | 57600 | 57600 | 57600 | 57600 | bps(Hz) | Input: Based on camera on board(CD: from INFERNO) |
| Req'd Carrier to Noise Ratio Density, C/No | 60.60 | 60.60 | 60.60 | 60.60 | dB-Hz | C/No [dB-Hz]=(Eb/No)[dB] + 10*log10(R[Hz]) |
| Required Design Margin | 6 | 6 | 8 | 6 | dB | Input: From ImmersionRC - Standard |
| **Minimum C/No Required** | 66.60 | 66.60 | 68.60 | 66.60 | dB-Hz | Req C/No |
| | | | | | | |
| **Transmitter Parameters** | **Downlink (video)** | | | | Units | Reference |
| Transmit Antenna Diameter, D | 0.034 | 0.034 | [-] | [-] | m | From INFERNO- spec sheet |
| Transmit Antenna Area, A | 9.08E-04 | 9.08E-04 | [-] | [-] | m^2 | A = pi*D^2/4 |
| Transmit Antenna Efficiency, | 2.92E-01 | 2.92E-01 | [-] | [-] | [-] | h = Ae/A |
| Transmit Antenna Effective Area, Ae | 2.65E-04 | 2.65E-04 | [-] | [-] | m^2 | Ae=l^2/(4pi)*Gt |
| Transmit Antenna Gain, Gt | 0.95 | 0.95 | 6 | 6 | dBic/dB | Input: From INFERNO current antenna spec, |
| Transmit Antenna Beamwidth | [-] | [-] | [-] | [-] | | |
| Transmit Antenna Pointing Accuracy | [-] | [-] | [-] | [-] | | |
| Transmit Antenna Pointing Loss, Lpt | [-] | [-] | [-] | [-] | | |
| Transmit Line Loss, Lt | 0 | 0 | 0 | 0 | dB | No cable for |
| Transmit Power, Pt | -2.22 | -2.22 | -2.22 | -2.22 | dBW | 10*log10(Pt_lin) |
| Transmit Power Linear, Pt_lin | 0.60 | 0.60 | 0.60 | 0.60 | W | Input: From ImmersionRC |
| Effective Isotropic Radiated Power, EIRP | -1.27 | -1.27 | 3.78 | 3.78 | dBW | EIRP = Pt[dB]+Gt[dB] |
| | | | | | | |
| **Propagation Parameters** | | | | | Units | Reference |
| Space Loss, Ls | -104.61 | -101.69 | -85.51 | -85.51 | dB | Ls [dB] = 10 * Log10((l/4pR)2) |
| Atmospheric Attenuation (clean air) , La | -0.05 | -0.05 | -0.05 | -0.05 | dB | |
| Polarization Loss, Lp | -0.2 | -0.2 | -0.2 | -0.2 | dB | Input:  Typical value |

# Link Budget

| | | | | | | |
|---|---|---|---|---|---|---|
| **Propagation Parameters** | | | | | Units | Reference |
| Space Loss, Ls | -104.61 | -101.69 | -85.51 | -85.51 | dB | Ls [dB] = 10 * Log10((l/4pR)2) |
| Atmospheric Attenuation (clean air) , La | -0.05 | -0.05 | -0.05 | -0.05 | dB | |
| Polarization Loss, Lp | -0.2 | -0.2 | -0.2 | -0.2 | dB | Input: Typical value |
| | | | | | | |
| **Receiver Parameters** | | | | | | Reference |
| Receive Antenna Diameter, D | 0.07874 | 0.07874 | [-] | [-] | m | Input: From product specs sheet |
| Receive Antenna Area, A | 6.20E-03 | 6.20E-03 | [-] | [-] | m^2 | A = p*D2/ 4 |
| Receiving Antenna Efficiency, | 2.17E-01 | 2.17E-01 | [-] | [-] | [-] | h=Ae/A |
| Receive Antenna Effective Area, Ae | 1.34E-03 | 1.34E-03 | [-] | [-] | m^2 | |
| Receive Antenna Gain, Gr | 8 | 8 | 6 | 6 | dBi | Gr = 4*p*Ae/l2 LectureNote_Lab11 slide 17 |
| Receive Antenna Beamwidth, q | 90.00 | 90.00 | [-] | [-] | degrees | Product specs |
| Receive Antenna Pointing Accuracy, q_t | 45 | 45 | [-] | [-] | degrees | Worst possible value |
| Receive Antenna Pointing Loss, Lpt | -3.00 | -3.00 | [-] | [-] | dB | Lpr[ dB] = -12*(q_t/q)2 |
| Receiver Cable Loss (see noise), Lc | -0.5 | -0.5 | -0.5 | -0.5 | dB | Input: typical value |
| Receiver Figure of Merit, FOM | 2.19E-02 | 2.19E-02 | 1.64E-02 | 1.64E-02 | dB/K | Gr[dB]/Ts |
| | | | | | | |
| **Receiver Noise** | | | | | Units | Reference |
| Receiving Antenna Noise Temperature, K | 290 | 290 | 290 | 290 | K | Standard room temperature: 290K |
| Receiver Cable Loss, Lc | -0.5 | -0.5 | -0.5 | -0.5 | dB | SMAD Table 13-10 |
| Receiver Noise Figure, NF | 1 | 1 | 1 | 1 | dB | Input: based on chosen receiver or SMAD Table 13-10 |
| Receiver Noise Factor, F | 1.26 | 1.26 | 1.26 | 1.26 | [-] | F = 10^(NF/10); Hoffman_Ch9 Eq (9.4.4) |
| Receiver Noise Temperature, Tr | 75.09 | 75.09 | 75.09 | 75.09 | K | T [K] = 290*(F-1) Hoffman_Ch9 Eq (9.4.4) |
| Reference Temperature, To | 290.00 | 290.00 | 290.00 | 290.00 | K | SMAD Eqn 13-24 = 1 + Tr/To |
| Receiver System Noise Temperature, Ts | 365.09 | 365.09 | 365.09 | 365.09 | K | Ts = Ta + Tr |
| Receiver System Noise Power, No | -202.98 | -202.98 | -202.98 | -202.98 | dBW-Hz | No = 10*log10 (k*Ts) |
| | | | | | | |
| **Link Budget** | | | | | Units | |
| Effective Isotropic Radiated Power, EIRP | -1.27 | -1.27 | 3.78 | 3.78 | dBW | EIRP[dB] = Pt + Lt + Gt |
| Propagation Losses, L | -107.86 | -104.94 | -85.76 | -85.76 | dB | L[dB] = Ls + La + Lp + Lpt + Lpr |
| Receive System Gain, Gr | 8 | 8 | 6 | 6 | dB | From Previous Section |
| Received Power, Pr | -101.13 | -98.21 | -75.72 | -75.72 | dBW | Pr [dB ] = Pt + Gt + Gr + Ls LectureNOte_Lab11 slide 18 |
| System Noise Power, No | -202.98 | -202.98 | -202.98 | -202.98 | dBW-Hz | No[dBW] = 10 * log10(k *Ts) |
| Actual Carrier to Noise Ratio Density, Pr/No | 101.85 | 104.77 | 127.25 | 127.25 | dB-Hz | C/N = Pr[dB] - No [dB] |
| Required C/No | 66.60 | 66.60 | 68.60 | 66.60 | dB-Hz | |
| Link Margin: | 35.24 | 38.16 | 58.65 | 60.65 | dB | |
| Possible Obstruction Loss: | 70 dB to 116 dB | | Obstruction loss if trees 10 ft apart (500 ı | | | somewhere around 129.3 dB |

# Calculation of feasible distance:

- Link margin determined using free space loss.
- Using entirety of link margin, can find possible forest depth using

$$L_{tree} = R_{\infty}d + k\left(1 - e^{-\frac{(R_0 - R_{\infty})}{k}d}\right)$$

- Use estimates for the R and k constants found experimentally in a research document for 11.6 GHz and 2 GHz, so 5.8 GHz would be between these values

11.6 GHz Model:

$$0.55d + 5\left(1 - e^{-0.0167d}\right) = 38.16\ dB$$

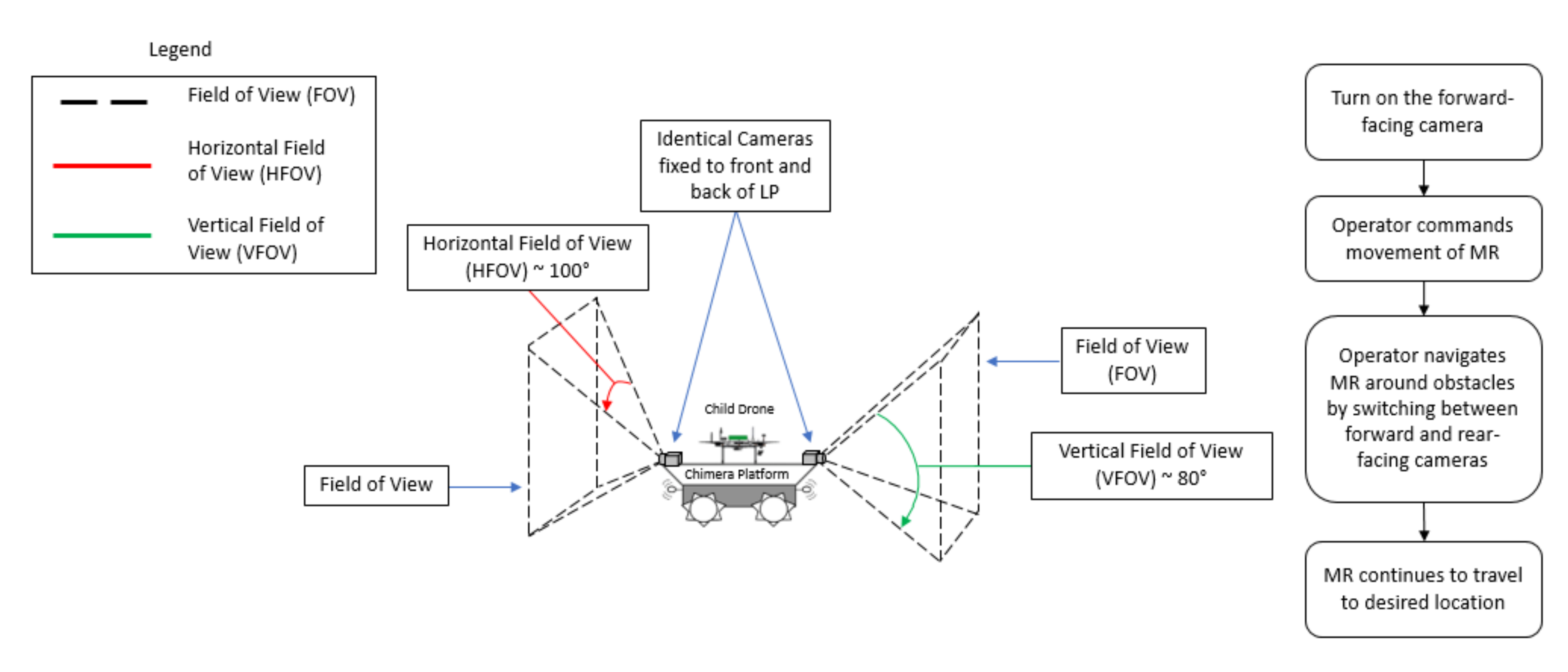
2 GHz Model:

$$0.25d + 37\left(1 - e^{-0.00714d}\right) = 38.16\ dB$$

Using these two equations, the feasible distance was found to be in the range of 62.33 m to 86.91 m

# In-Depth Feasibility – Hazard Camera

# In-Depth Feasibility – Hazard Camera



# In-Depth Feasibility – Hazard Camera

## GoPro Hero 3 Black Edition

- Previously used on the CD live video feedback system
- 2 Watt Hours – Capable of applying additional source of power
- 122.6° Horizontal FOV
- 94.4° Vertical FOV
- $379.99

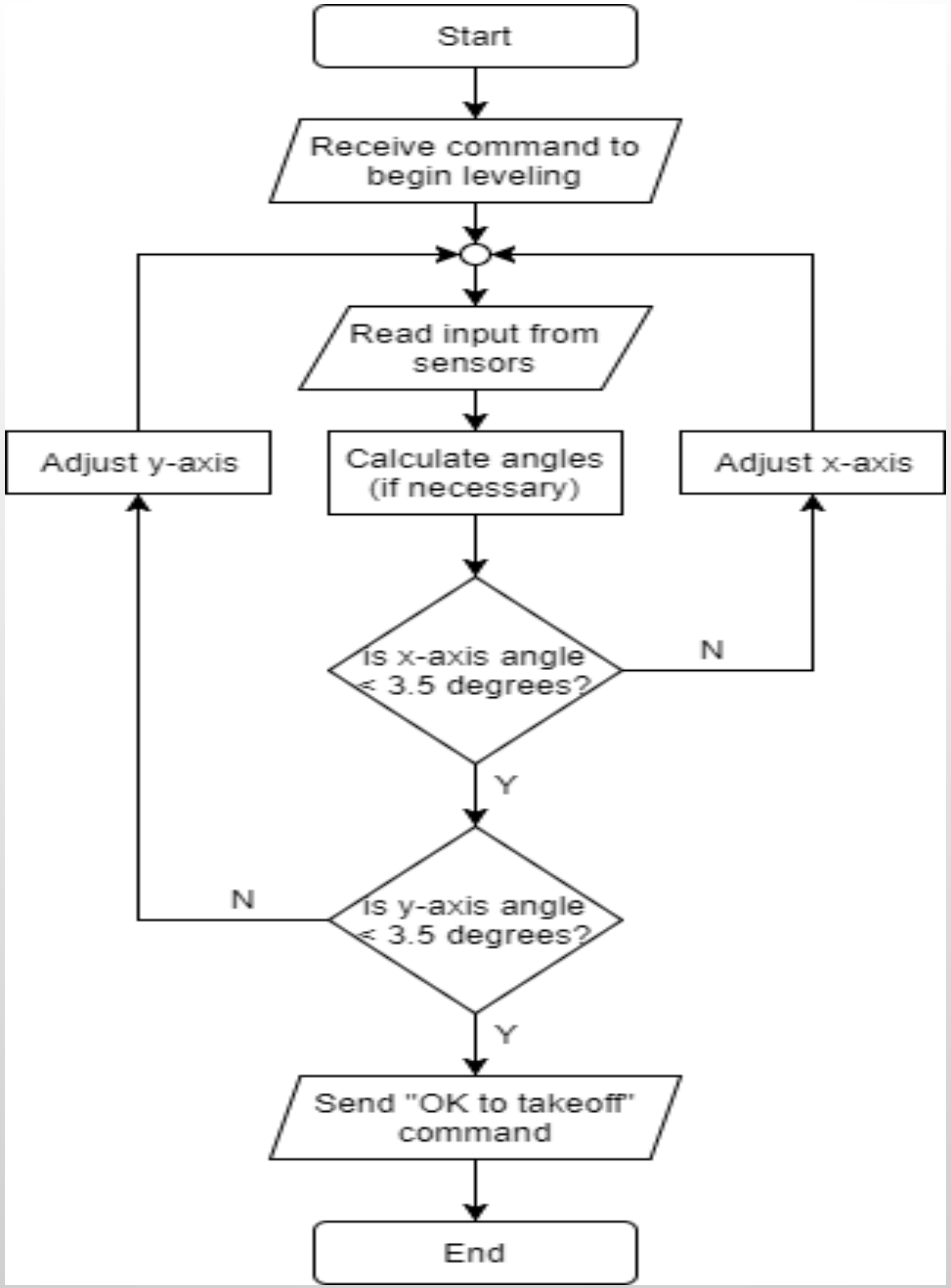

General Specifications

FOV Specifications

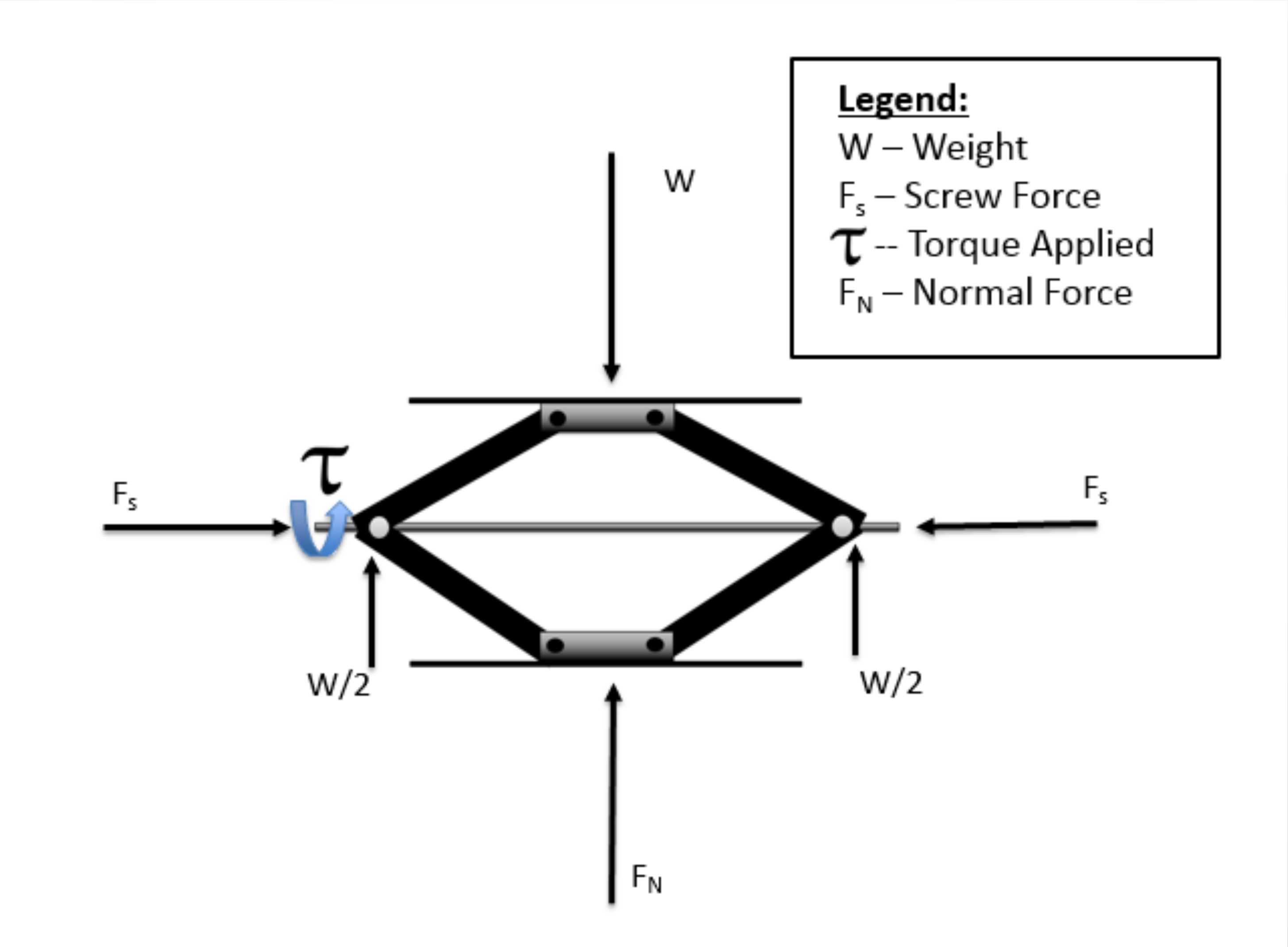
Battery Life

# In-Depth Feasibility – Leveling Mechanism

# Leveling System Flow Chart



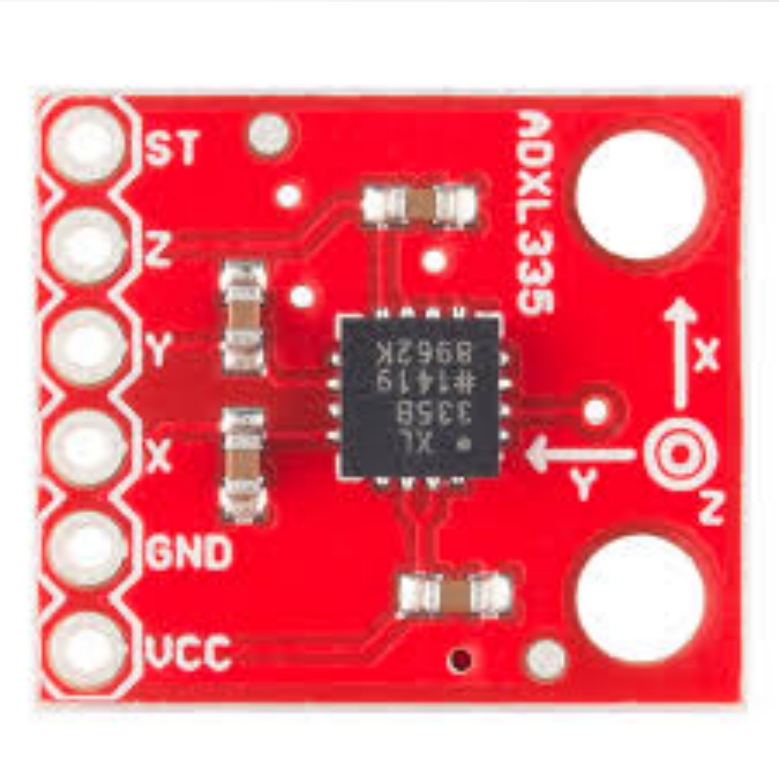
# Levelling System Free Body Diagram



# Leveling System Measurement Feasibility

**ADXL335 Accelerometer**

- Three axis measurement
- 0-3.3V output
- 350 µA draw
- 0.1° accuracy
- $7 unit cost
- Requires custom housing



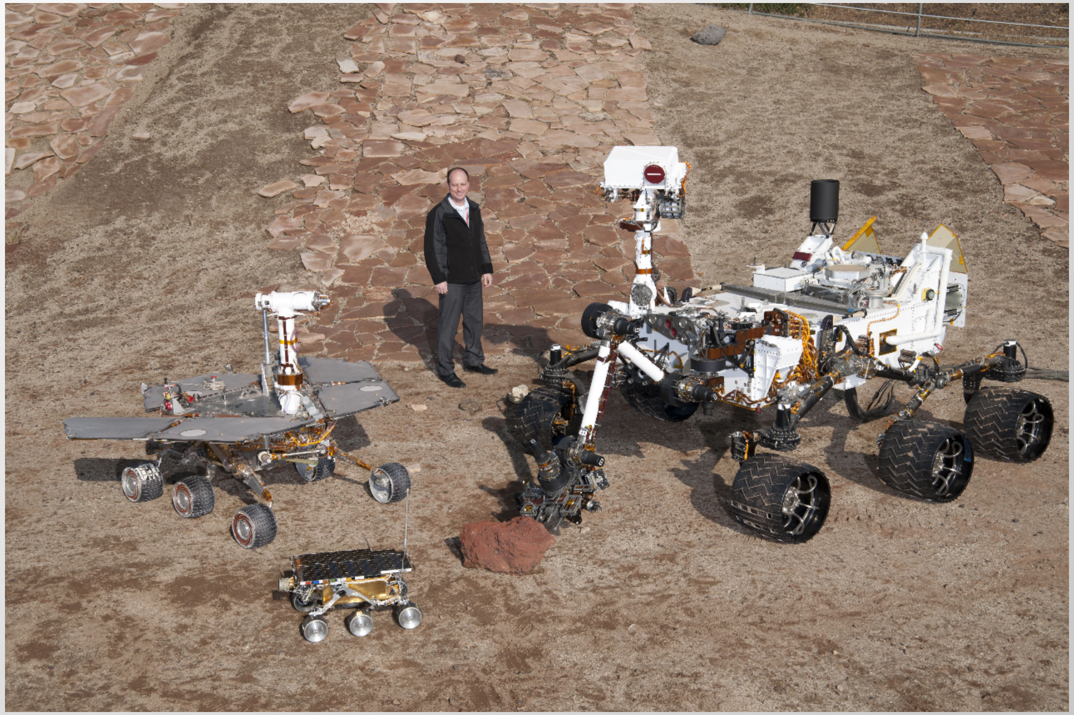

Analog Devices ADXL-335
Accelerometer

# In-Depth Feasibility – Translational System

# Translational System Historical Feasibility

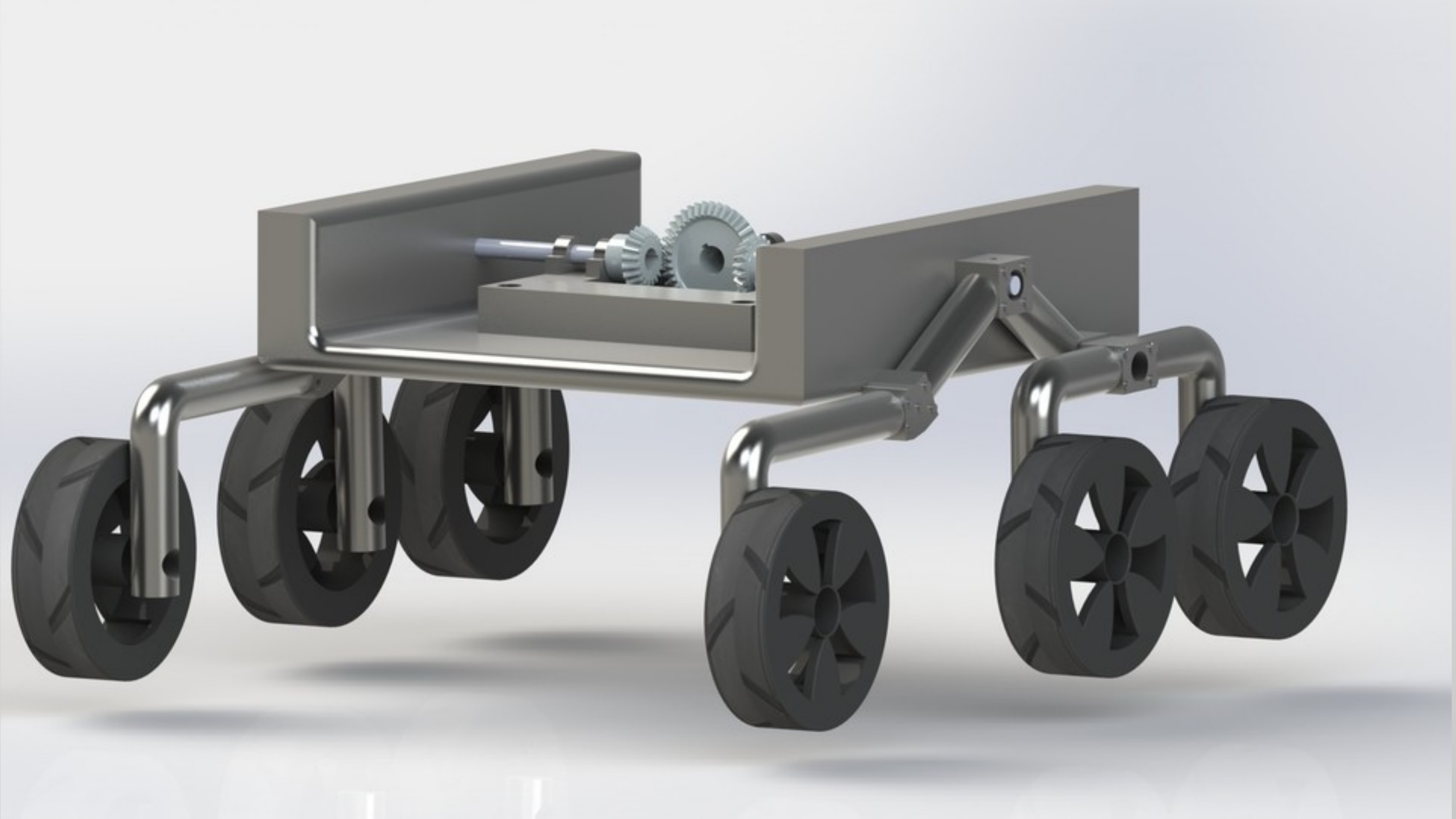
- All current US Mars Rovers utilize a rocker bogie system ( Spirit, Opportunity, Sojourner, Curiosity)

| Rover | Wheel Diameter | Weight | Obstacle Clearance Height |
|---|---|---|---|
| Spirit and Opportunity | 10 in | 400 lb | > 10 in |
| Curiosity | 20 in | 2000 lb | 25 in |
| Sojourner | 5 in | 25 lb | 7.9 in |

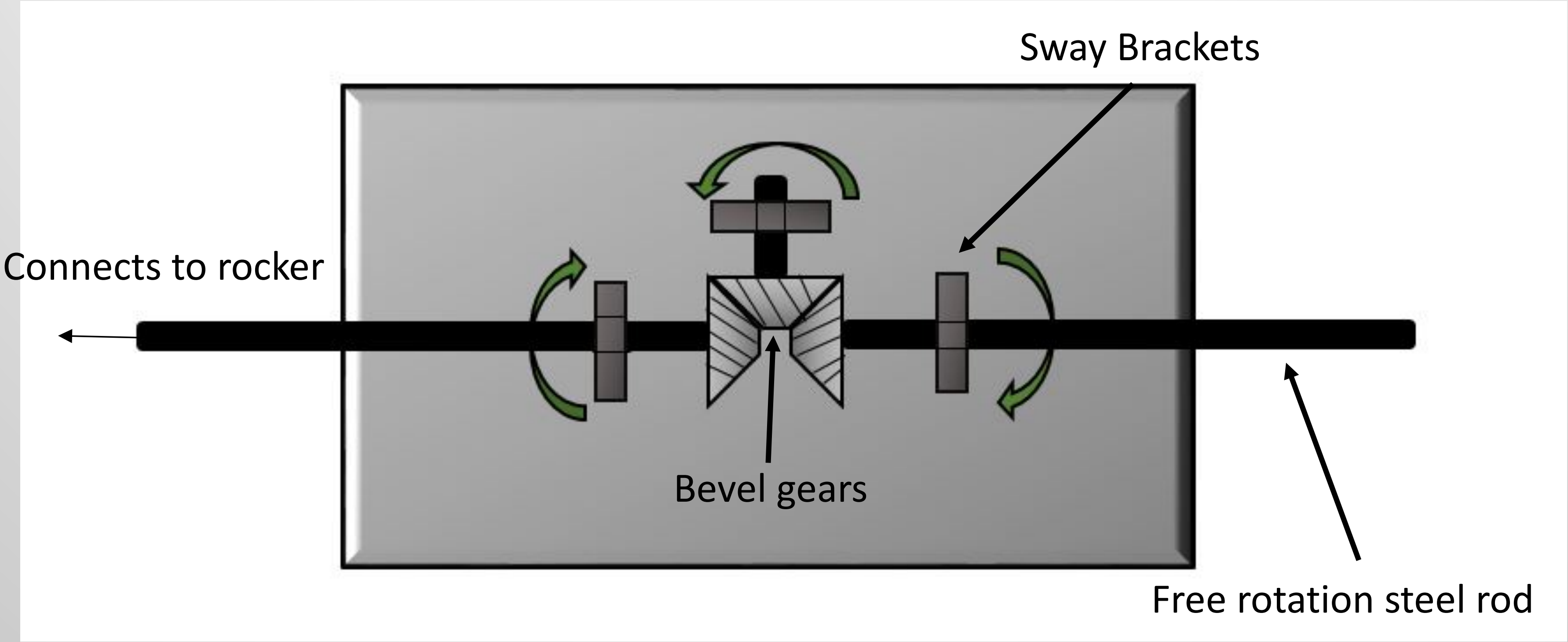


Credit: NASA

# Counter-Rotation Differential System



# Counter-rotation Differential System



# Materials for rocker bogie legs

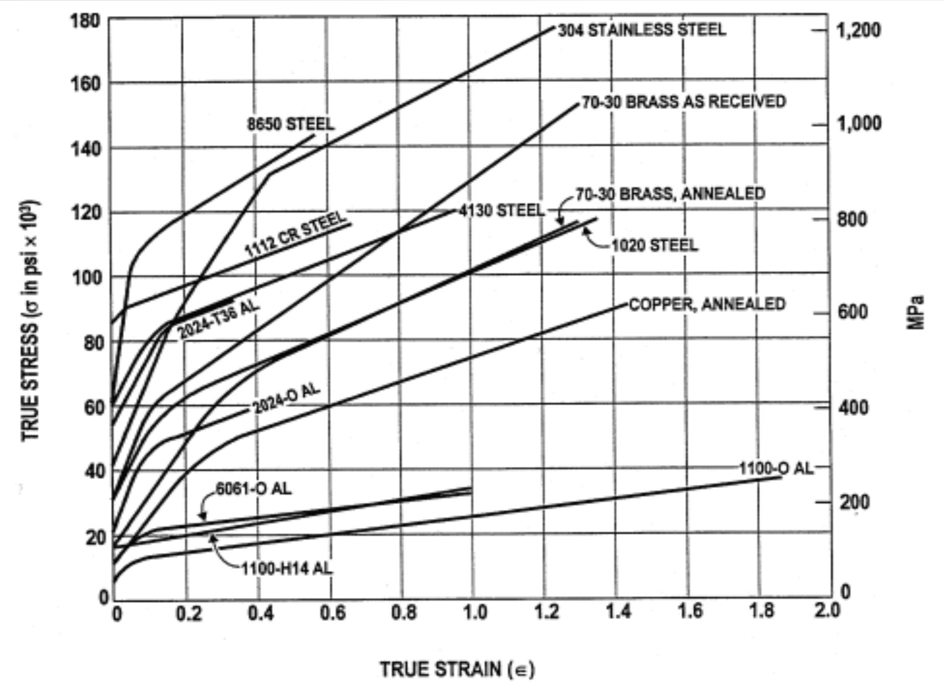
| Aluminum (6061) | Carbon Steel | Titanium |
|---|---|---|
| • Lightweight<br>• Non magnetic<br>• Ease of fabrication<br>• Applications in industry : Aerospace components and transports. Brake components and bicycle frames | • Stronger than aluminum<br>• Easy to weld and highly durable<br>• Heavier than aluminum<br>• Brittle and high corrosion<br>• Applications in industry : Infrastructure, automotive and power plants | • High Strength to weight ratio<br>• Naturally resistant to rust<br>• Able to withstand high temperature<br>• High cost compared to steel and aluminum<br>• Applications in industry : Aircraft parts and medical application |

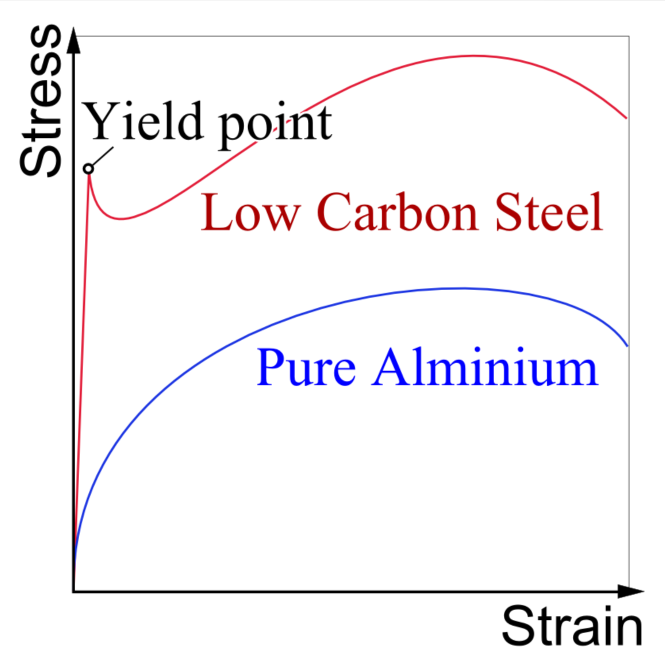
# Frame Materials

- **Aluminum** will be used as the main frame structure for the rocker bogie system
- Lightweight and easy to weld (high flexibility) into parts
- Higher load bearing capacity than steel which results in higher performance for strength.

- **Stainless Steel** will be used as the main components for the connections between the legs and frame
- Durable and can sustain increasing loads and strain over time.

| Properties/Type | Aluminum | Steel | Titanium |
|---|---|---|---|
| **Density** (kg/$m$3) | 2700 | 7570 | 4500 |
| **Tensile strength** (MPa) | 310 | 766 | 950 |
| **Shear strength** (MPa) | 207 | - | 550 |
| **Shear Modulus** (GPa) | 26 | 80 | 44 |
| **Hardness Brinell** (HB) | 95 | 247 | 330 |
| **Fatigue Limit** ( MPa) | 95.6 | 765 | 240 |



# Sizing Derivation

Assume mass distributed evenly on the platform and center of mass acts exactly on the rocker link.

$$Rocker: \sum M_1 = F_{react}(x_4 - x_3) - F_{R4}(x_4 - x_1) = 0 \qquad \sum F = F_{R4} + F_{R1} - F_{react} = 0$$

$$F_{R4} = F_{react} * \frac{x_4 - x_3}{x_4 - x_1} \qquad F_{react} = F_{R4} + F_{R1}$$

$$Bogie: \sum M_3 = -F_{R4}x_1 + F_{R2}x_2 = 0 \qquad \sum F = -F_{R4} + F_{R3} + F_{R2} = 0$$

$$F_{R2}x_2 = F_{R4}x_1 \qquad F_{R3} + F_{R2} = F_{R4}$$

Desire $F_{R1} = F_{R2} = F_{R3} \Rightarrow Let\ them\ all\ be = F_W$

1) $F_{R4} = F_{react} * \frac{x_4 - x_3}{x_4 - x_1}$

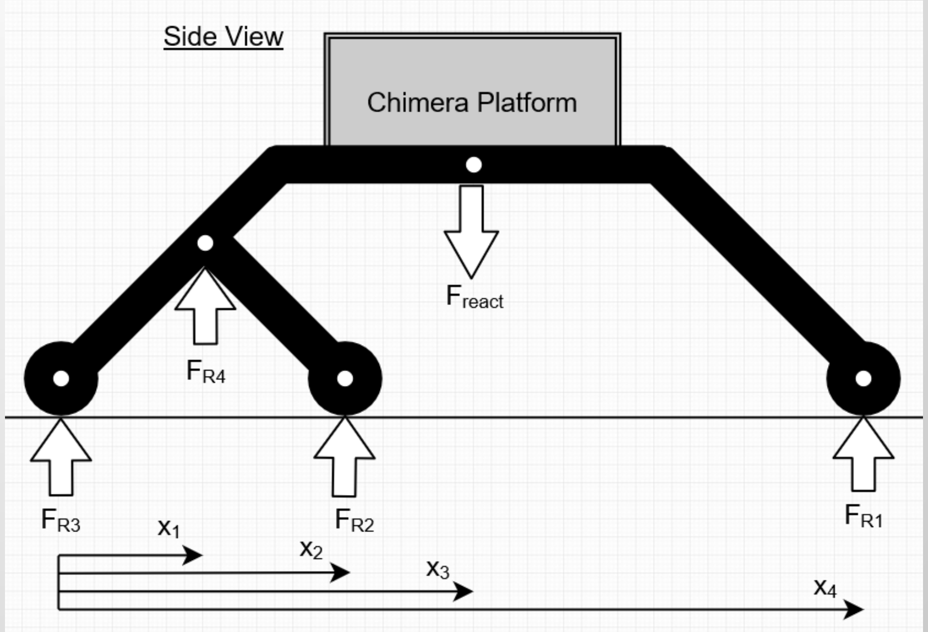
2) $F_{react} = F_{R4} + F_W$

3) $F_{R4} = 2F_W$

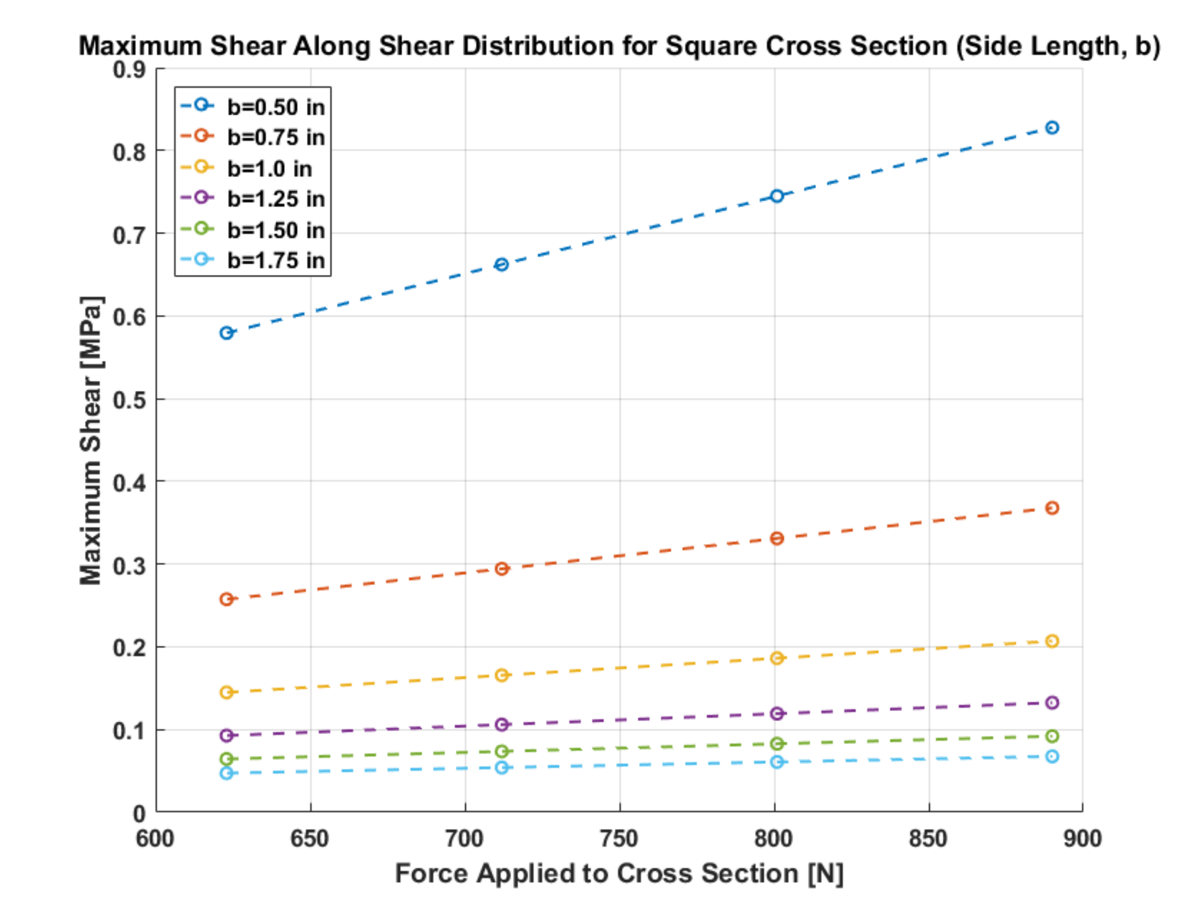
4) $F_W = F_{R4} * \frac{x_1}{x_2}$

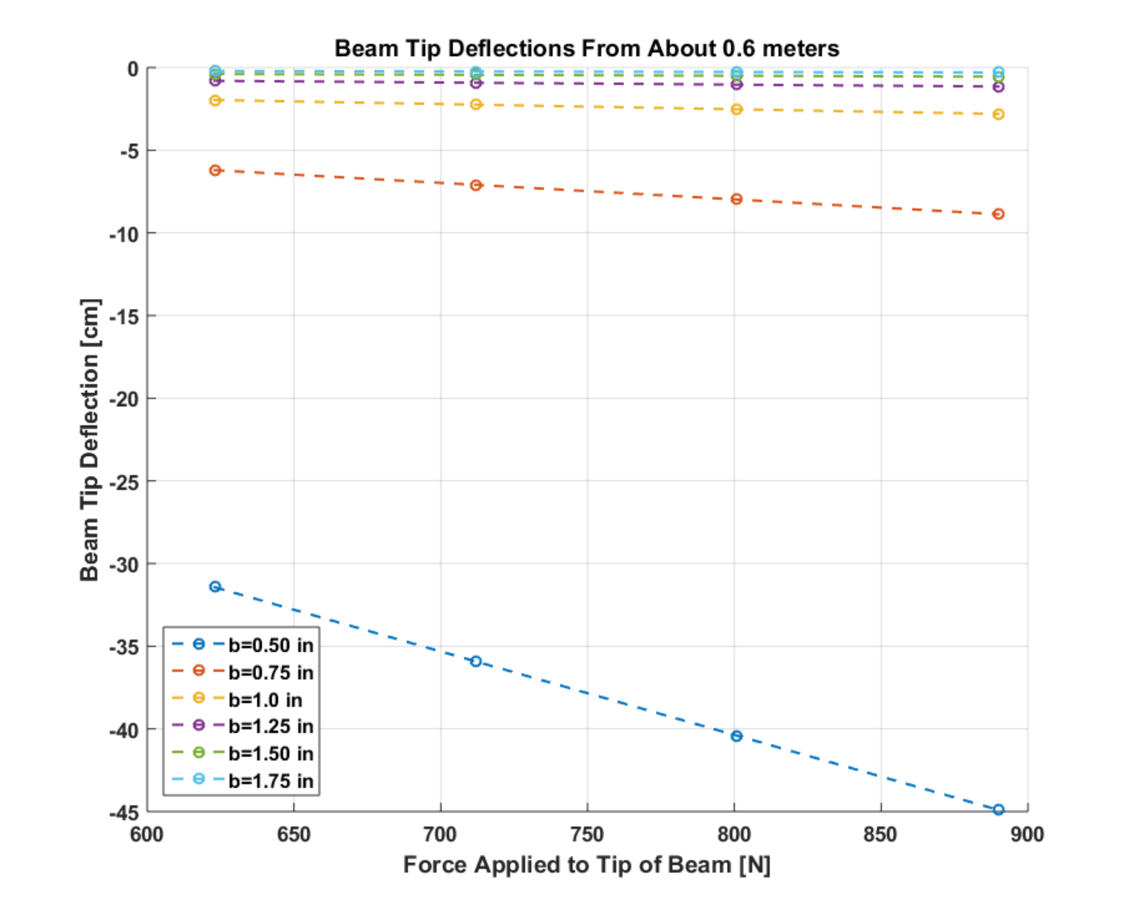
After substitutions to eliminate forces and find a function only in terms of distances:

$$\frac{x_2}{x_1} = 3 * \frac{x_4 - x_3}{x_4 - x_1}$$



# Structural Model – Al-6061, Square Bar




Shear Strength Al-6061: 207 Mpa
(Ref. Matweb)
Shear Model Ref.

Worst case scenario for a full point load acting at the tip. Actual design may not be the case. Ref: Prof. Carlos Felippa

# Tread analysis

- The treads on the wheels is studied to ensure that the MR can move given enough power/torque.
- The coefficient of friction of the tread material needs to be more than 0.7[1] which is the coefficient of friction of dirt ground. Rubber and Steel wheel material both have $\mu_s = 1.02$ and $\mu_s = 0.8$ respectively on dry roads.
- Since both tread passes the limit, the analysis will be now more focused on the need of the translational system specifically the torque needed and how the tread will help in traversing the MR when in operation.

# Tread Analysis

Rubber

- Can navigate through rough terrain easily due to high friction
- Offers more grip on traversing the terrain due to large contact area
- Can decrease the braking distance due to high coefficient of friction

Steel

- Less coefficient of friction between the road and steel tires so less torque needed start traversing the MR
- But needs more torque to stop the MR
- Higher production cost than rubber tire

# Wheel Tread - Rubber

- Has greater surface contact with the ground -increases stability
- Shorter braking distance due to high coefficient of friction
- Shock absorption
    - No need to use additional spring suspension

# In-Depth Feasibility-Motors

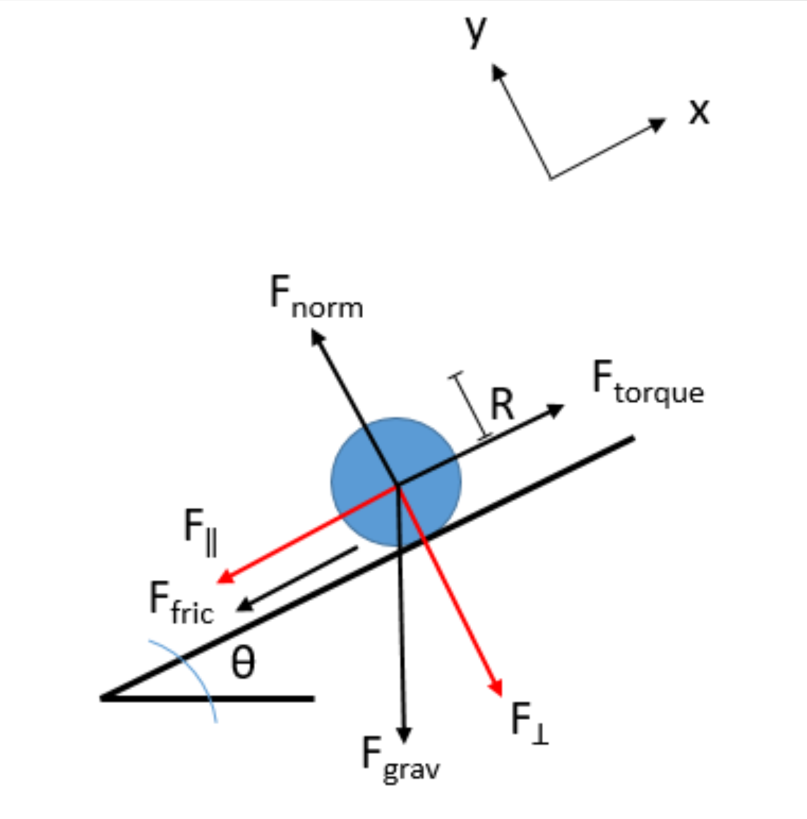
# Motor Feasibility Analysis Definitions

- $\theta$ =incline angle
- $F_{grav}$ = force of gravity on the point mass
- $F_{||}$ = force of gravity parallel to the inclined plane
- $F_{\perp}$ = force of gravity perpendicular to the inclined plane
- $F_{norm}$ = normal force
- $F_{fric}$ = frictional force
- $F_{torque}$ = force due to torque
- R = radius of the wheel
- $T_{req}$ = Required torque

# Motor Torque - Model

**Assumptions:**

- Entire MR is treated as a point mass
- Coefficient of friction is based on loose dirt
- The frictional force direction shown is based when the ball is moving upward with acceleration equal to the motor's force
- The inclined angle is not negative
- Air resistance is negligible
- Motor efficiency is not 100 %



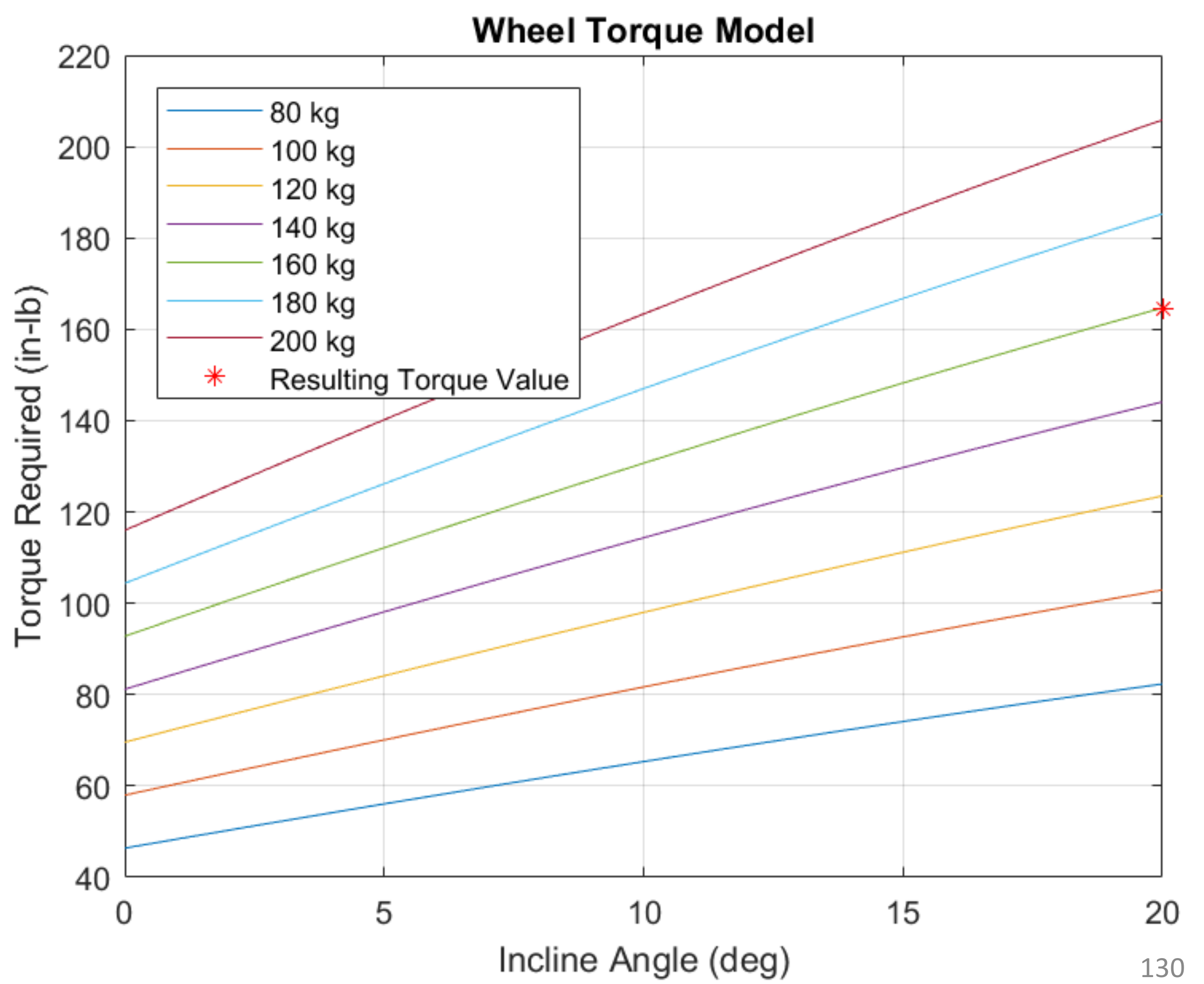
# Initial Motor Torque – Model Results

**Required torque for each of the 6 wheel motors for various weights versus the incline angle**

- This point is at 164.5 in-lb corresponding to at 20 ° slope

**Parameters:**

- Velocity = 0.5 m/s
- Efficiency = 65 %
- Wheel Diameter = 0.127 m
- 6 wheels



# Initial Motor Torque and Wheel RPM - Feasibility

**Current System Parameters:**

- Mass = 160 kg = 352.74 lbm
- Wheel Diameter = 0.127 m = 5 inches
- Assumed Motor Efficiency = 65 %
- Maximum velocity = 0.5 m/s
- Time to accelerate to maximum speed = 5 seconds
- Incline Angle = 20 degrees
- 6 wheels each with one motor

**Result:**

- Applied torque must be greater than 164.5 in-lb
- Resulting maximum RPM: 75.19 RPM

**Observation**: An increase in mass leads to a severe increase in required torque, leading to a greater cost for each motor. Additionally, it leads to a decrease in RPM, increasing required amp-hours, increasing power requirements.

Bison Gear & Engineering Corp.

- 720 Series PowerSTAR Brushless DC Right-Angle Gearmotor
- 222.4 kg-cm torque = 193 in-lb
- 25 RPM at 12 V
- $699 each

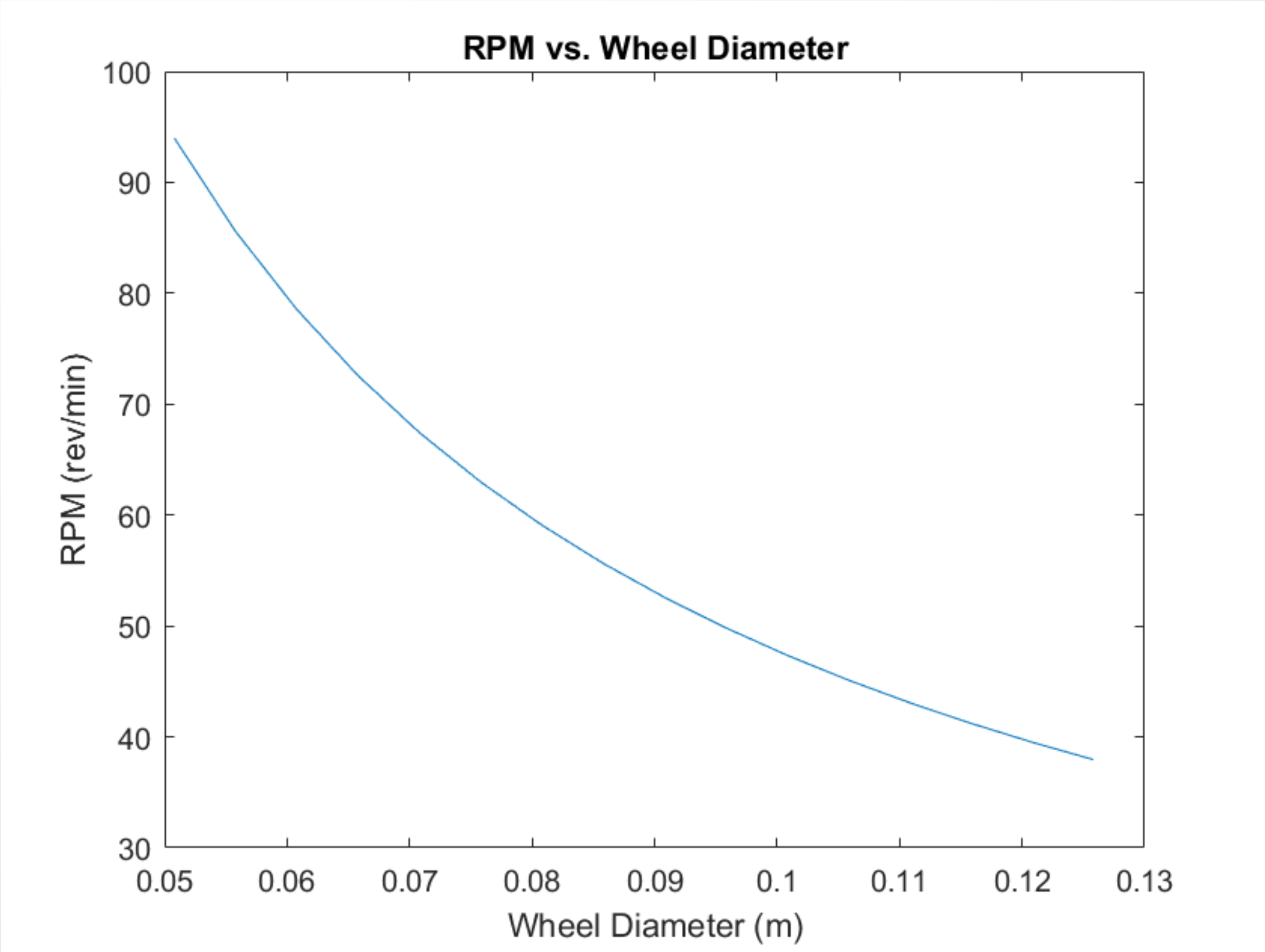
**Not feasible due to cost related to weight and required torque**

# Wheel RPM – Model Results

RPM = Velocity / (Radius*0.10472)

**Parameters:**

- Velocity = 0.5 m/s
- Efficiency = 65 %
- Wheel Diameter = 0.127 m
- 2 wheels

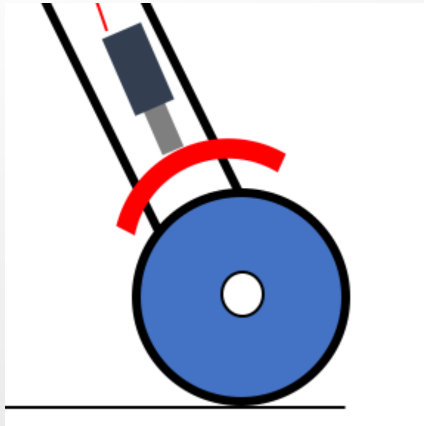


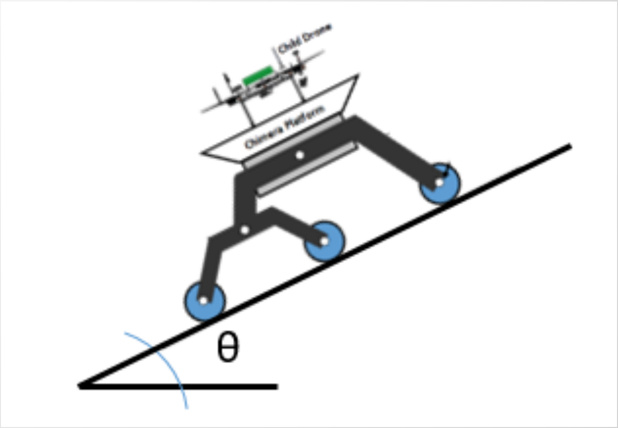
# In-Depth Feasibility – Wheel-Locking Mechanism

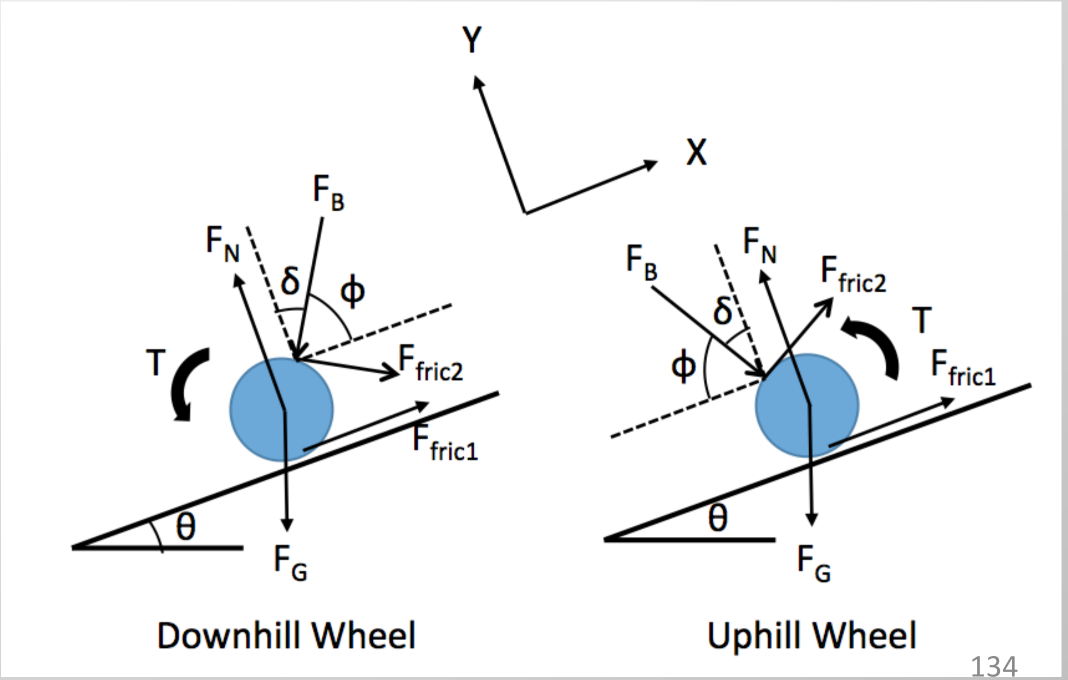
# Baseline Design - Wheel Locking Model

**Assumptions:**

- Weight is evenly distributed over 6 wheels
- Rubber-Dirt contact between wheel and ground
- Rubber-rubber contact between wheel and brake





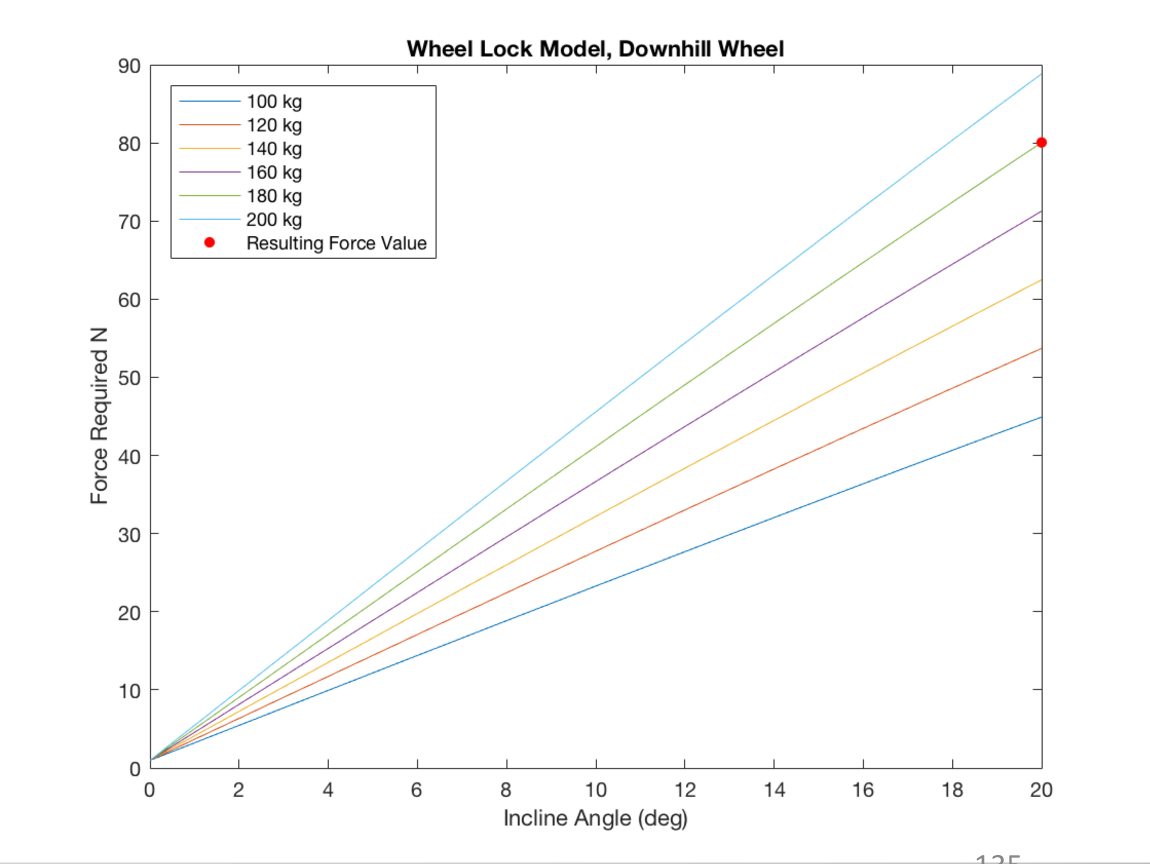
# Model Results– Downhill Wheel

**Required applied force for each of the 4 wheel brakes for various weights versus the incline angle**

Parameters:

- Velocity: 0.5 m/s
- Wheel Diameter: 0.127 m
- Wheel Mass: 5 kg
- $\mu_2$: 1.16 (rubber on rubber contact)
- $\varphi$: 45 degrees
- Stoppage Time: 1 sec

For the Uphill Wheel, the needed Brake Force at 20$^o$ with a Rover Mass of 180 kg is **80.04 N**



# Wheel Locking Feasibility

- Mass of MR with CD: 180 kg
- Max Speed of MR: 0.5 m/s

- Solution:
  - Linear Actuator Stroke 3" DC 12Volt Heavy Duty 220LB/100kg Max Lift for Automation Equipment
  - Produces up to 980 N of Force
  - Cost: $31.90

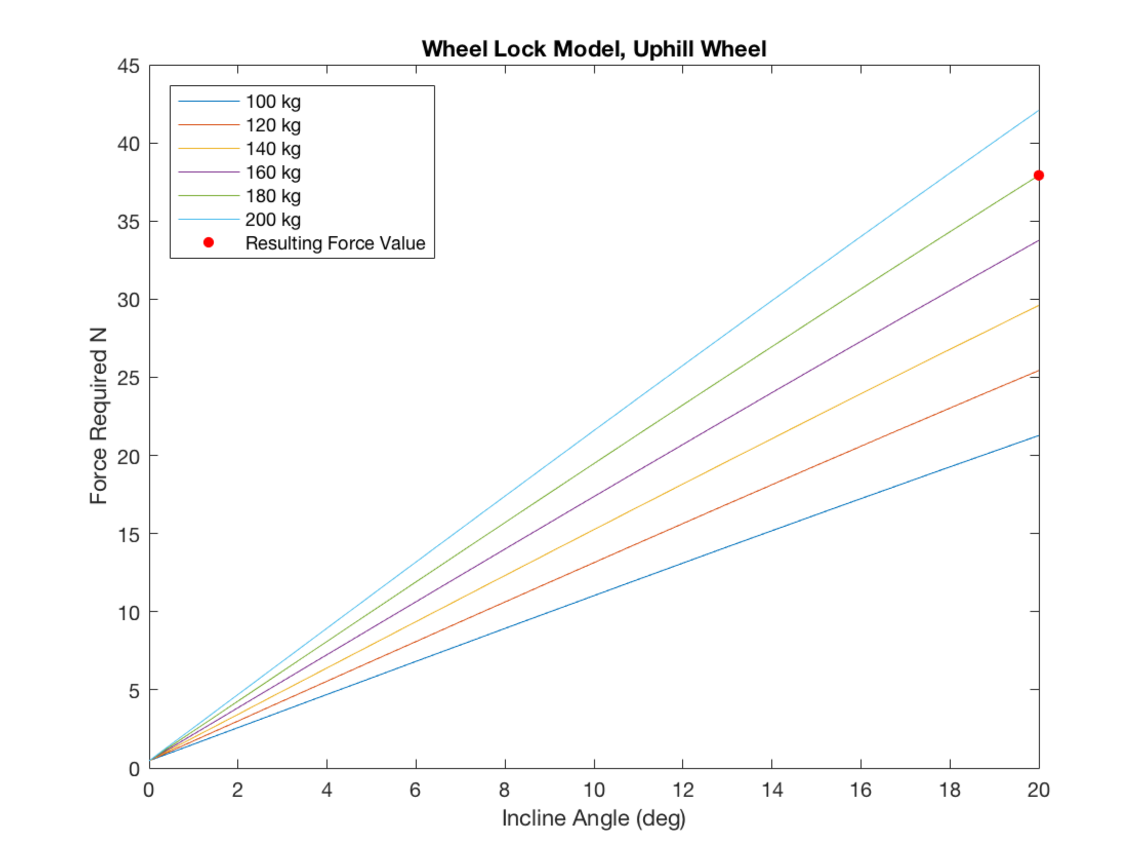
# Model Results– Uphill Wheel

**Required applied force for each of the 4 wheel brakes for various weights versus the incline angle**

Parameters:

- Velocity: 0.5 m/s
- Wheel Diameter: 0.127 m
- Wheel Mass: 5 kg
- $\mu_2$: 1.16 (rubber on rubber contact)
- $\varphi$: 45 degrees
- Stoppage Time: 1 sec

For the Uphill Wheel, the needed Brake Force at 20$^o$ with a Rover Mass of 180 kg is **37.92 N**



# Wheel Locking – Downhill Wheel Model

$\sum F_X = F_{fric1} + F_{fric2} \cos\delta - \frac{F_G}{6}\sin\theta - F_B\cos\varphi = 0$ $F_{fric1} = \mu_1 F_N$ $F_{fric2} = \mu_1 F_B$

$\sum M_O = T + F_{fric1}R - F_{fric2}R = 0$ $T = I\alpha$ $I = \frac{1}{2}MR^2$

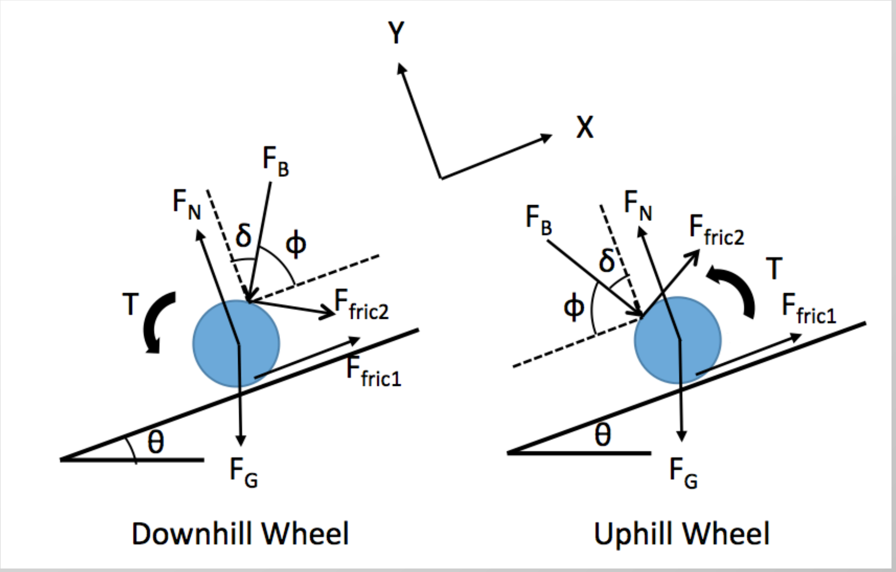
$$\sum M_O: \frac{1}{2}MR^2\alpha + \mu_1 F_N R - \mu_2 F_B R = 0 \rightarrow F_N = \frac{\mu_2 F_B - \frac{1}{2}MR\alpha}{\mu_1}$$

$$\sum F_x: \mu_1 F_N + \mu_2 F_B\cos\delta - \frac{F_G}{6}\sin\theta - F_B\cos\varphi = 0 \rightarrow \mu_2 F_B - \frac{1}{2}MR\alpha + \mu_2 F_B\cos\delta - \frac{F_G}{6}\sin\theta - F_B\cos\varphi = 0$$

$$F_B = \frac{\frac{1}{2}MR\alpha + \frac{F_G}{6}\sin\theta}{\mu_2(1+\cos\delta) - \cos\varphi}$$

$F_N$ : Normal Force
$F_B$ : Brake Force
$F_G$ : Gravity Force
$F_{Fric1}$ : Frictional Force btwn Ground & Wheel
$F_{Fric2}$ : Frictional Force btwn Brake Pad & Wheel
$\mu_1$: Coefficient of friction btwn Ground & Wheel
$\mu_2$: Coefficient of friction btwn Pad & Wheel

$T$: Wheel Torque
$\theta$: Angle of Slope
$\varphi$: Angle from Horizontal
$\delta$: Angle from Vertical
$\alpha$: Angular Acceleration
M: Mass of wheel
R: Radius of wheel
$I$: Moment of Inertia



# Wheel Locking – Uphill Wheel Model

$\sum F_X = F_{fric1} + F_{fric2}\sin\varphi - \frac{F_G}{6}\sin\theta + F_B\sin\delta = 0$ $\quad F_{fric1} = \mu_1 F_N \quad F_{fric2} = \mu_1 F_B$

$\sum M_O = T + F_{fric1}R - F_{fric2}R = 0$ $\quad T = I\alpha \quad I = \frac{1}{2}MR^2$

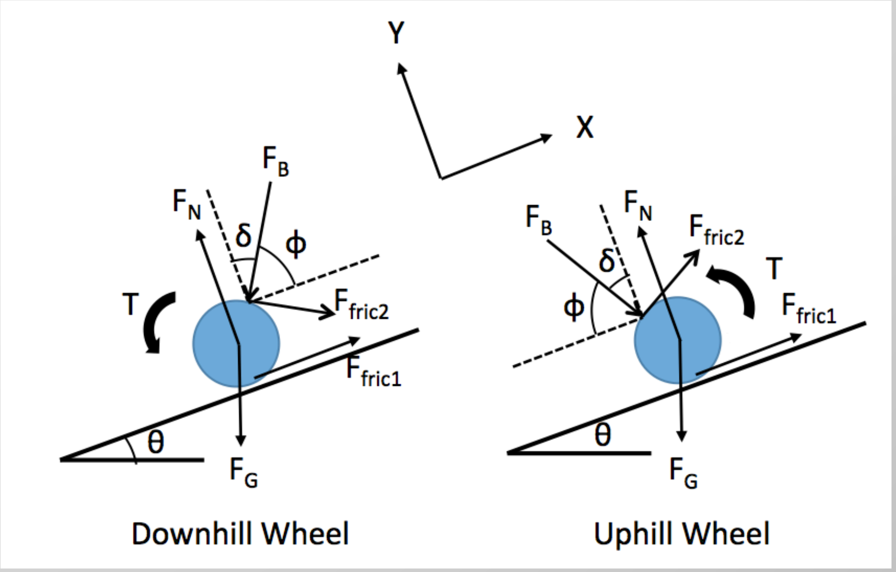
$\sum M_O\!: \frac{1}{2}MR^2\alpha + \mu_1 F_N R - \mu_2 F_B R = 0 \rightarrow F_N = \frac{\mu_2 F_B - \frac{1}{2}MR\alpha}{\mu_1}$ $\quad \gamma + \varphi = 90°$

$\sum F_x\!: \mu_1 F_N + \mu_2 F_B\sin\varphi - \frac{F_G}{6}\sin\theta + F_B\sin\delta = 0 \rightarrow \mu_2 F_B - \frac{1}{2}MR\alpha + \mu_2 F_B\sin\varphi - \frac{F_G}{6}\sin\theta + F_B\sin\delta = 0$

$$F_B = \frac{\frac{1}{2}MR\alpha + \frac{F_G}{6}\sin\theta}{\mu_2(1+\sin\varphi)+\sin\delta}$$

$F_N$ : Normal Force
$F_B$ : Brake Force
$F_G$ : Gravity Force
$F_{Fric1}$ : Frictional Force btwn Ground & Wheel
$F_{Fric2}$ : Frictional Force btwn Brake Pad & Wheel
$\mu_1$: Coefficient of friction btwn Ground & Wheel
$\mu_2$: Coefficient of friction btwn Pad & Wheel

$T$: Wheel Torque
$\theta$: Angle of Slope
$\varphi$: Angle from Horizontal
$\delta$: Angle from Vertical
$\alpha$: Angular Acceleration
M: Mass of wheel
R: Radius of wheel
$I$: Moment of Inertia



# Wheel Locking Feasibility

**Material for Brake Pads**

- Non-Abestos Organic (NAO)
  - NAO pads are made from natural materials such as glass and rubber with binding resins to hold them together.
- These brake pads does not require much heat to generate good friction.
- Coefficient of friction that about 1.0.
- Easy on brake rotor and have high resistance on vibration.

**Coefficient of Friction and Braking Distance**

- To lock the wheel and bring the MR to stop, the coefficient of friction of the translational system must be higher than the coefficient of friction of the ground.

$$\mu_s = \frac{4\times \tau_{motor}}{W_{MR}\times r_{wheel}}$$

$$d = \frac{v^2}{2\mu_s g}$$

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- "Motor Efficiency." *Portescap*, Portescap Motor Solutions, www.portescap.com/motor-solutions/motor-efficiency.

# Financial Budget Estimation Resources

- Scissor Jacks - Etrailer
- Linear Actuator - Brake
- Hazard Cameras - Amazon
- Antennas – VFM Store
- Patch Antenna – RFLinks
- XBee Pro S3B – Semiconductor Store
- Transmitter – Hobby King
- Rocker Bogie Structure - Metals Depot
- Differential System - Bevel Gears Info  Steel Rods Info  Rod Brackets Info