ARGOS

Autonomous Rover for Ground-based Optical Surveillance

Critical Design Review

November 23, 2020

Presenters: Niko de Boucaud, Nick Kuljis, Margaux McFarland, Thomas Noll, Dan Stojsavljevic, Jarrod Teige
Customer: Barbara Streiffert and Jet Propulsion Laboratory
Advisor: Dr. Donna Gerren
Team: Niko de Boucaud, Henry Felstiner, Harrison Fitch, Victoria Gonzales, Nick Kuljis, Luca Kushner, Margaux McFarland, Thomas Noll, Trevor Slack, Dan Stojsavljevic, Jarrod Teige

University of Colorado Boulder

Jet Propulsion Laboratory
California Institute of Technology

Presentation Outline

1. **Project Overview**
2. **Design Solution**
    a. Drivetrain
    b. Mast
    c. Surveillance Camera
    d. Temperature Sensor
    e. Electronics/Communications
3. **Critical Project Elements**
4. **Design Requirements/Satisfaction**
    a. Navigation
    b. Data Acquisition
    c. Mast
    d. Communications
5. **Project Risk**
6. **Verification and Validation**
7. **Project Planning**

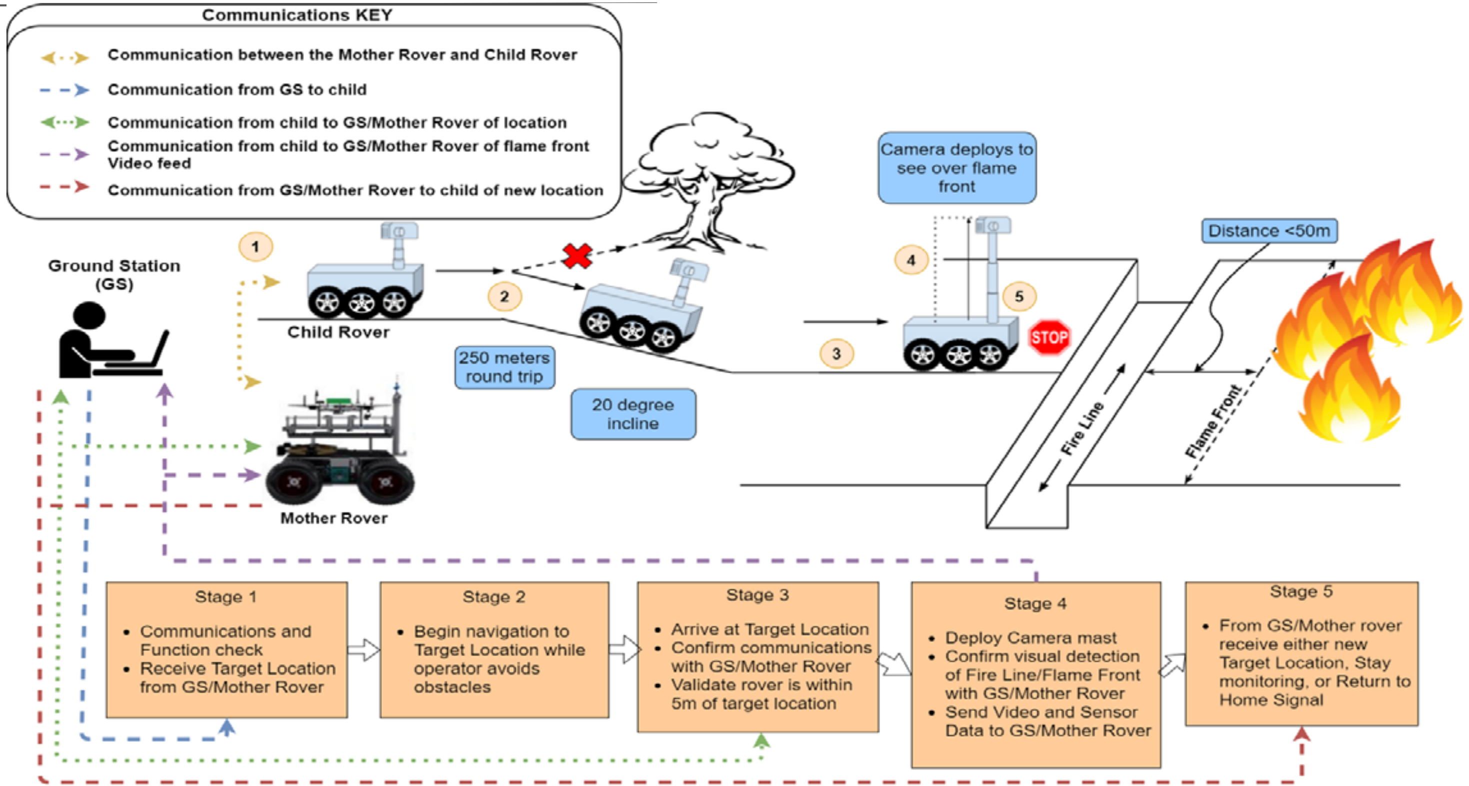
Project Overview

Mission Statement / Objectives

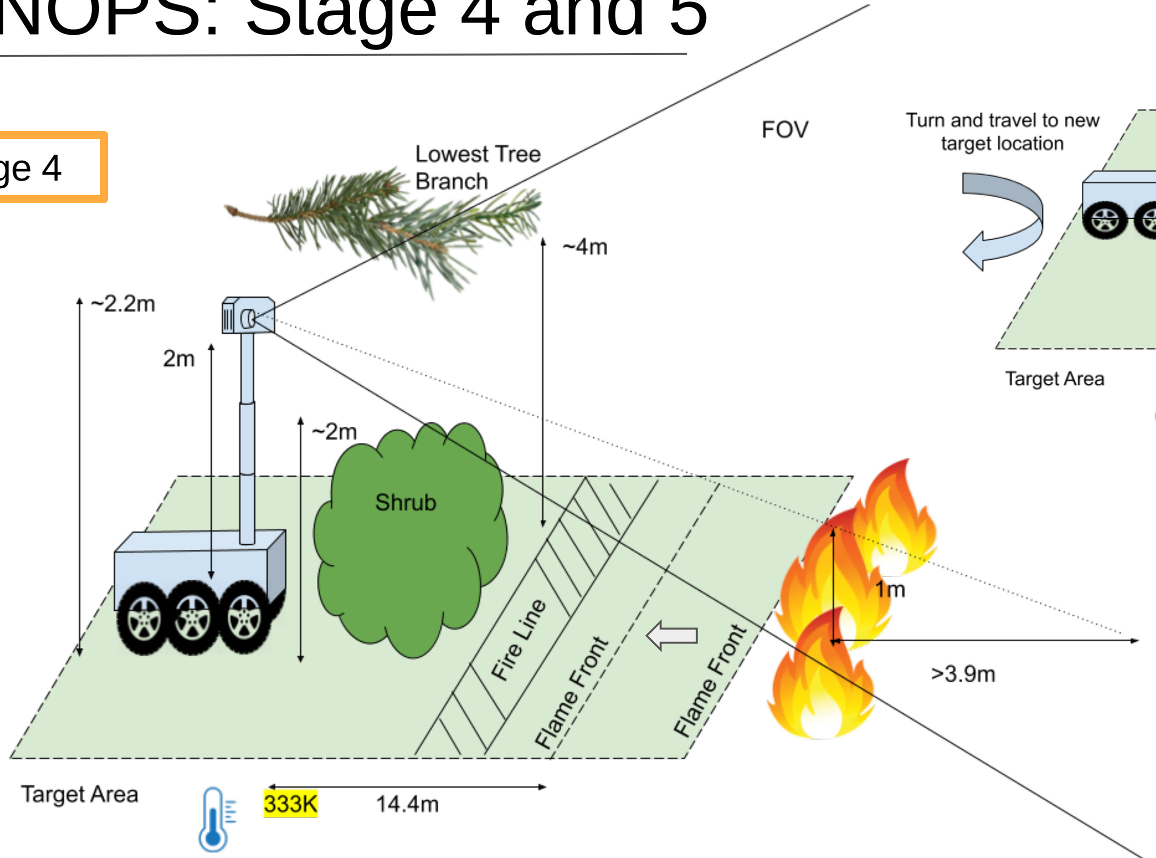
The ARGOS team shall design, build, and test a child rover that will :

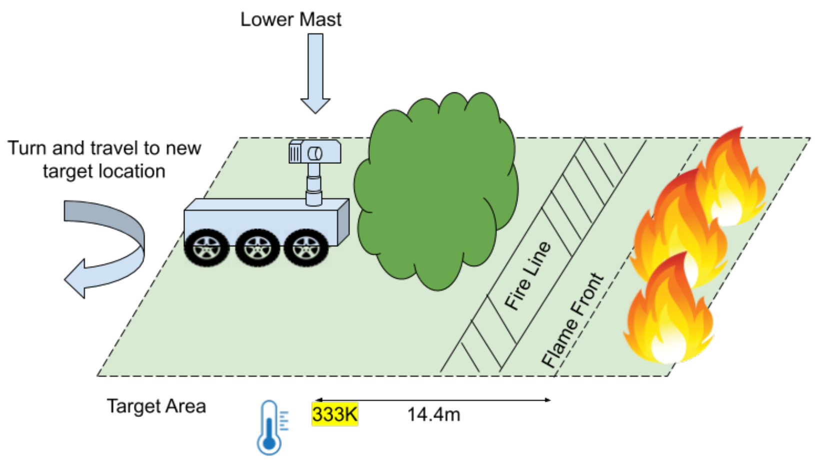
1. **Navigate** to a fireline via commands from a ground station (GS) and mother rover (MR)
2. **Collect ambient temperature data** throughout the duration of the mission
3. **Record photos/video** of a flame front from the top of an **extendable/retractable mast**
4. **Communicate** temperature data, photos, and video to the GS/MR

CONOPS


Communications KEY
Communication between the Mother Rover and Child Rover
Communication from GS to child
Communication from child to GS/Mother Rover of location
Communication from child to GS/Mother Rover of flame front Video feed
Communication from GS/Mother Rover to child of new location
Ground Station (GS)
1
Child Rover
2
250 meters round trip
20 degree incline
Mother Rover
Camera deploys to see over flame front
4
5
3
STOP
Distance <50m
Fire Line
Flame Front
Stage 1
• Communications and Function check
• Receive Target Location from GS/Mother Rover
Stage 2
• Begin navigation to Target Location while operator avoids obstacles
Stage 3
• Arrive at Target Location
• Confirm communications with GS/Mother Rover
• Validate rover is within 5m of target location
Stage 4
• Deploy Camera mast
• Confirm visual detection of Fire Line/Flame Front with GS/Mother Rover
• Send Video and Sensor Data to GS/Mother Rover
Stage 5
• From GS/Mother rover receive either new Target Location, Stay monitoring, or Return to Home Signal

CONOPS: Stage 4 and 5





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

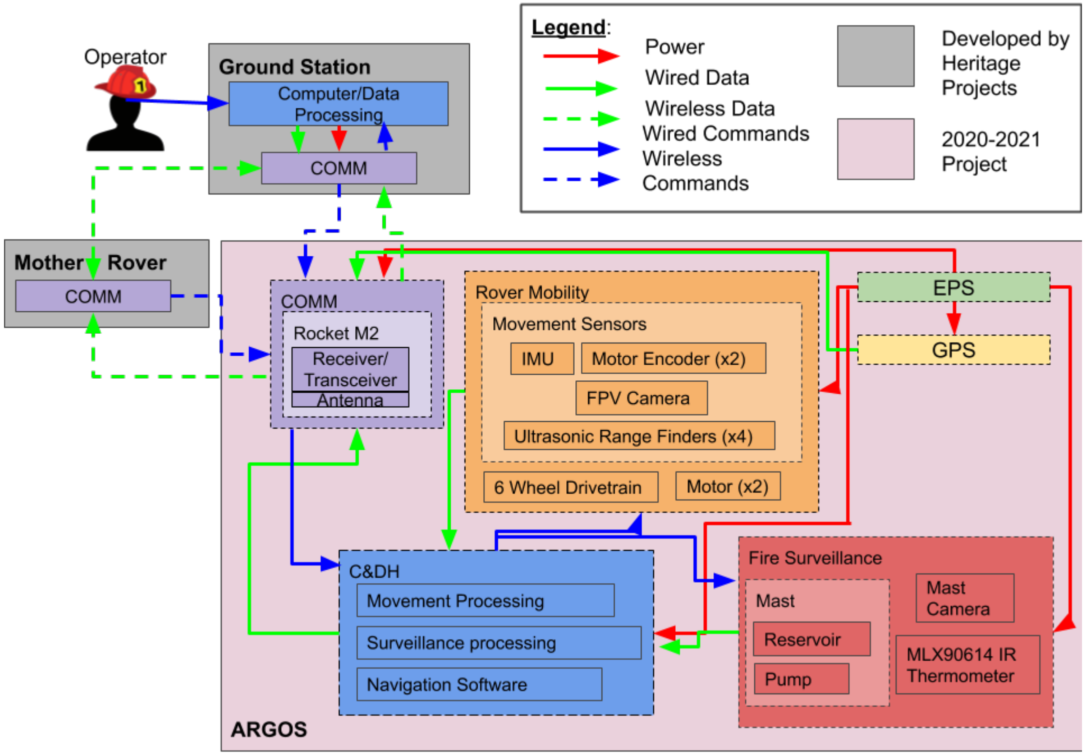
Functional Requirements

Requirement ID	Requirement Description
FR.1	The child rover shall move from a starting location to a commanded location of interest and return back to the starting location.
FR.2	The child rover shall take pictures, videos and ambient temperature data to be sent to the ground station.
FR.3	The child rover shall use a mast to take photos and video from a vantage point above the rover's body.
FR.4	The child rover shall receive commands from both the ground station and the mother rover and transmit captured data back to the ground station and the mother rover.

Design Solution

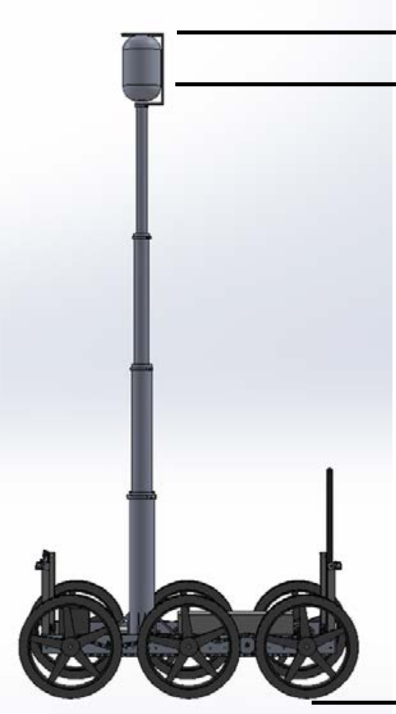
Project Purpose and Objectives | **Design Solution** | Critical Project Elements | Design Requirements & their Satisfaction | Project Risks | Verification and Validation | Project Planning | Backup Slides

Functional Block Diagram



Note:
Acknowledgements are also sent following every command.

Final Design: Overview



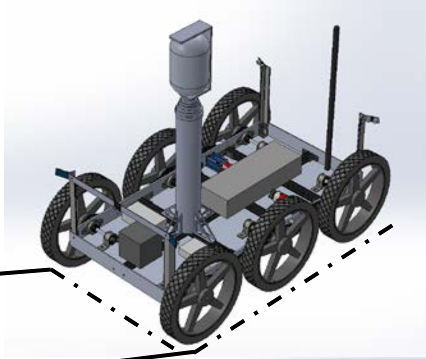
Total Extended Height: 2.28m

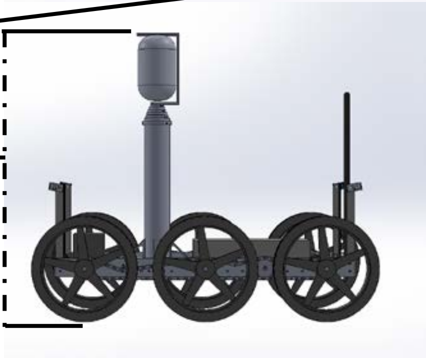
Camera Height: 2.10m

Total Width: 0.65m

Total Length: 1.15m

Total Unextended Height: 0.98m



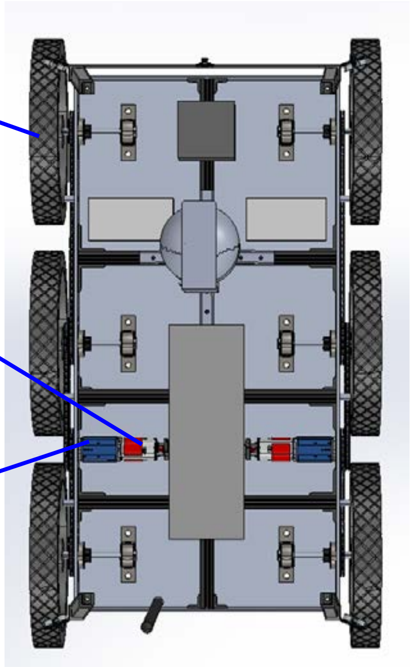


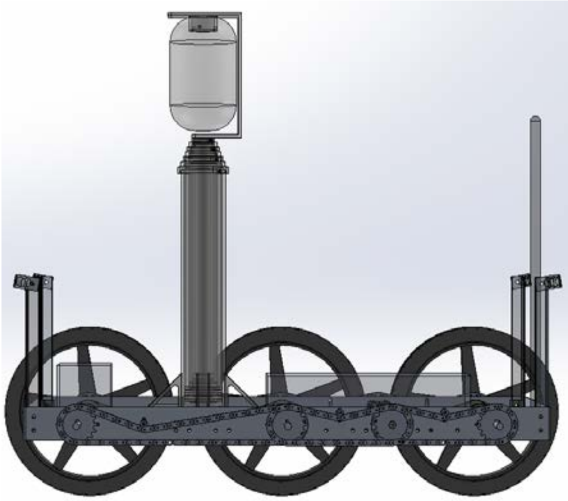
Final Design: Drivetrain

Swisher Wheels
- 34.925 cm Diameter

AndyMark 775 Redline Motor

57 Sport Gearbox
- 64:1 Gear Ratio



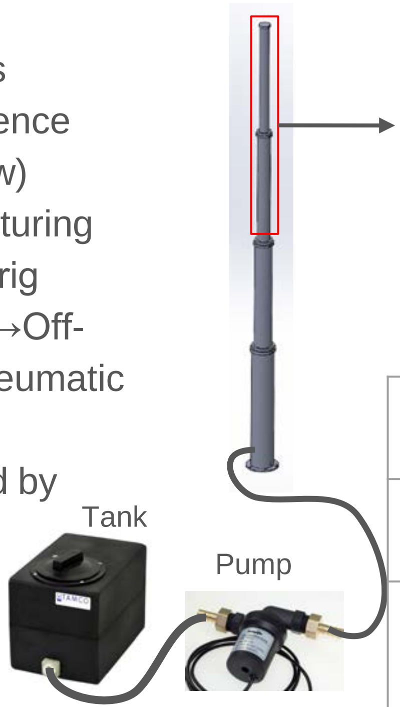


Project Purpose and Objectives | Design Solution | Critical Project Elements | Design Requirements & their Satisfaction | Project Risks | Verification and Validation | Project Planning | Backup Slides

Final Design: Mast

Hydraulic Mast

- Operator controls raise/lower sequence (GUI camera view)
- Multiple manufacturing concerns → test rig
- Test rig failure? →Off-Ramp: COTS pneumatic mast
- Decision required by 1/22/2021



Hydraulic Test Rig

- Tests for manufacturability and functioning of full mast
- More details in Verification and Validation

Hydraulic Test Rig Operation

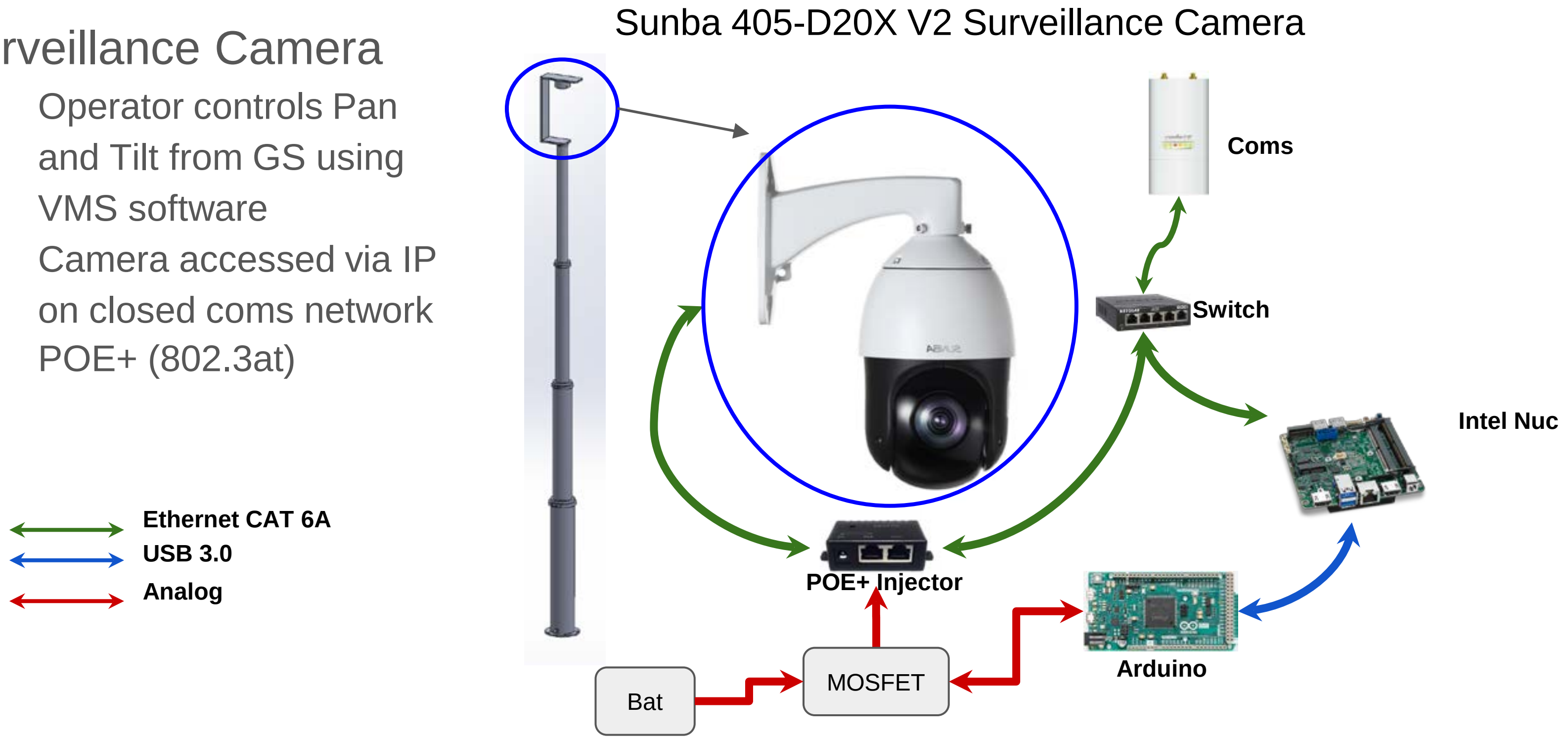
	Integration Complexity	Manufacturing Complexity	Operation Complexity	Cost	Power Consumption
Hydraulic Mast	Low (est. 5 hrs)	High (est. 50 hrs)	Low (operator)	$600	50 W
COTS Pneumatic Mast	High (est. 50 hrs)	Low (est. 10 hrs)	High (closed loop control)	$900	210 W

Details on off-ramp pneumatic mast setup in backup slides

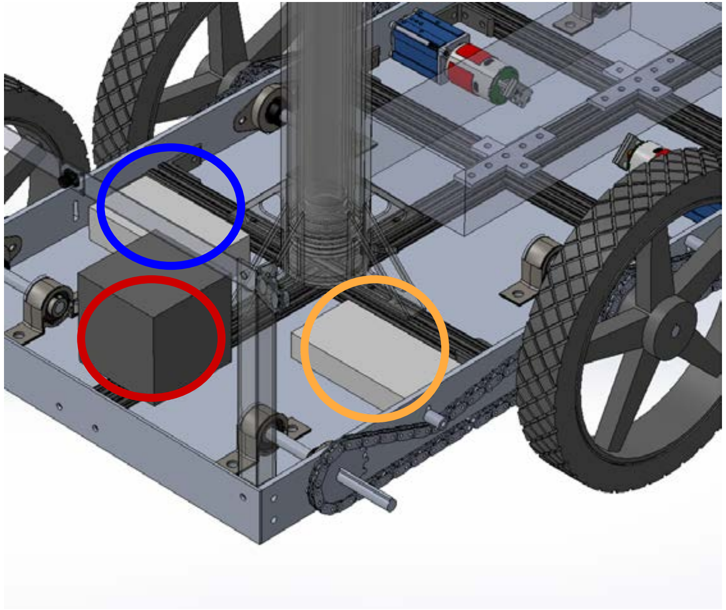
Final Design: Surveillance

Surveillance Camera

- Operator controls Pan and Tilt from GS using VMS software
- Camera accessed via IP on closed coms network
- POE+ (802.3at)



Final Design: Electronics / Communication



Intel Nuc

Sparkfun ZED-F9P

Arduino

Sparkfun BNO080

12V LiPo Battery

Rocket M2

Critical Project Elements

Critical Project Elements (CPEs)

CPE	Description	Reasoning
Maneuverability	● Traversing obstacles/inclines without tipping	● Failure results in tipping, damaged rover ● FR.1
Control	● Manual control ● Autonomous control in event of comm loss	● Failure results in possible crash, loss of rover ● FR.1
Sensors	● Video ● Temperature ● Movement sensors	● Failure results in no useful data ● FR. 2
Communications /Integration with Heritage Projects	● Source of all commands and data transfer ● MR, GS and ARGOS comm systems	● Failure results in not receiving any useful data, loss of rover ● FR.1 and FR.4

Critical Project Elements (CPEs)

CPEs

- Maneuverability
- Control
- Sensors
- Communications
- Integration with Heritage Projects

Design Requirement Focus for CDR

1. Navigation
2. Data Acquisition
3. Mast
4. Communications

Design Requirements

	Design Requirements	Focus for CDR
Navigation	• Travel over obstacles as tall as 7cm • Travel up and down slopes of 20° inclination • 250m round trip	• Mobility - drivetrain
Data Acquisition	• The surveillance camera shall have >100° FOV • Determine the ambient temperature within +/- 1°K	• Electronics + software integration • Surveillance Camera FOV
Mast	• Capable of extending to a height of 2m +/- 0.2m and retracting back down to its original height • Capable of supporting 10kg at its top	• Pressure needed
Communications	• Send time stamped video, image, and temperature data at a data rate up to 25Mbps • Upon loss of communication, the child rover shall return to its last known GPS location	• Data Rate • Loss of Comm.

1. Navigation Design Requirements and their Satisfaction

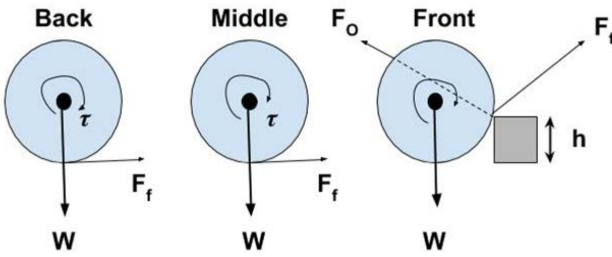
FR. 1 The child rover shall move from a starting location to a commanded location of interest and return back to the starting location.

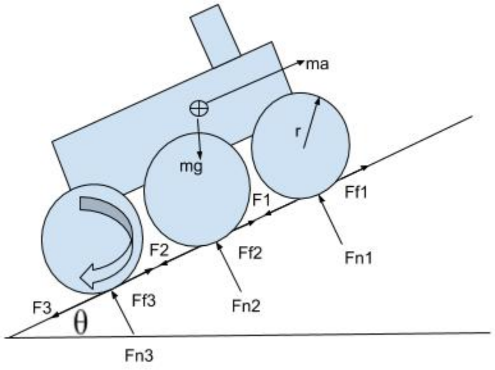
Drivetrain

- **Design Requirement**: The child rover shall travel over obstacles with heights as tall as 7cm
  - Wheel Diameter **needed** derived from obstacle maneuvering study: **33.0 cm**
  - Wheel Diameter **achieved** from Swisher Wheels: **34.93 cm**
  - Maximum torque **needed** from motor: **17.98 Nm**
  - Torque **achieved** from AndyMark 775 Redline Motor: **33.04 Nm**

- **Design Requirement:** The child rover shall be able to travel up and down slopes of 20° inclination
  - Torque from motor **needed** derived from incline study: **8.11 Nm**

- **Design Requirement:** The child rover shall be able to travel 250m round trip in any direction from it's starting location
  - Power **needed** to supply drivetrain components with average velocity of 1.02 m/s: **60.48 Wh**
  - Power **achieved** from battery selected: **150 Wh**





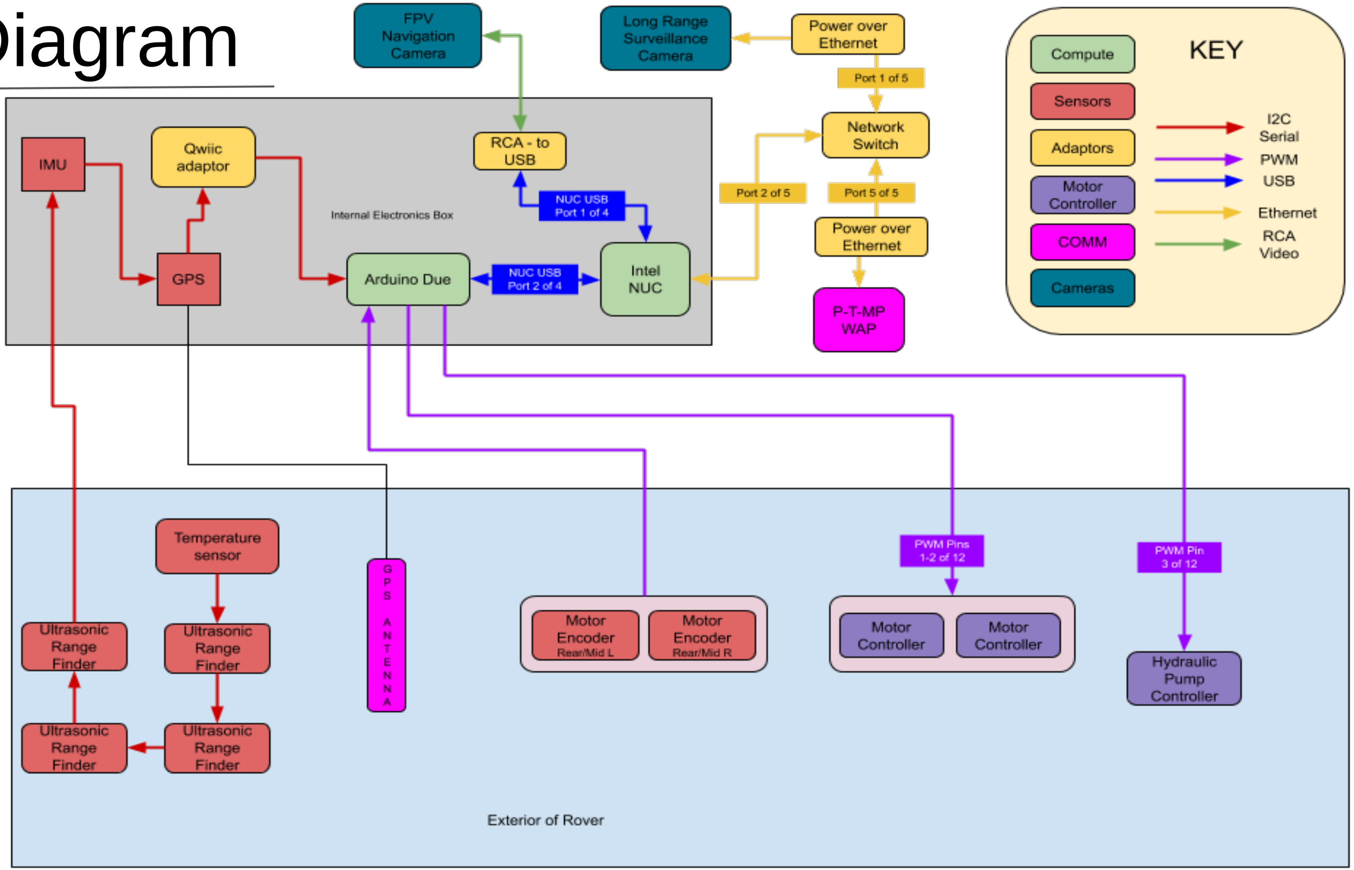
University of Colorado Boulder

Jet Propulsion Laboratory
California Institute of Technology

2. Data Acquisition Design Requirements and their Satisfaction

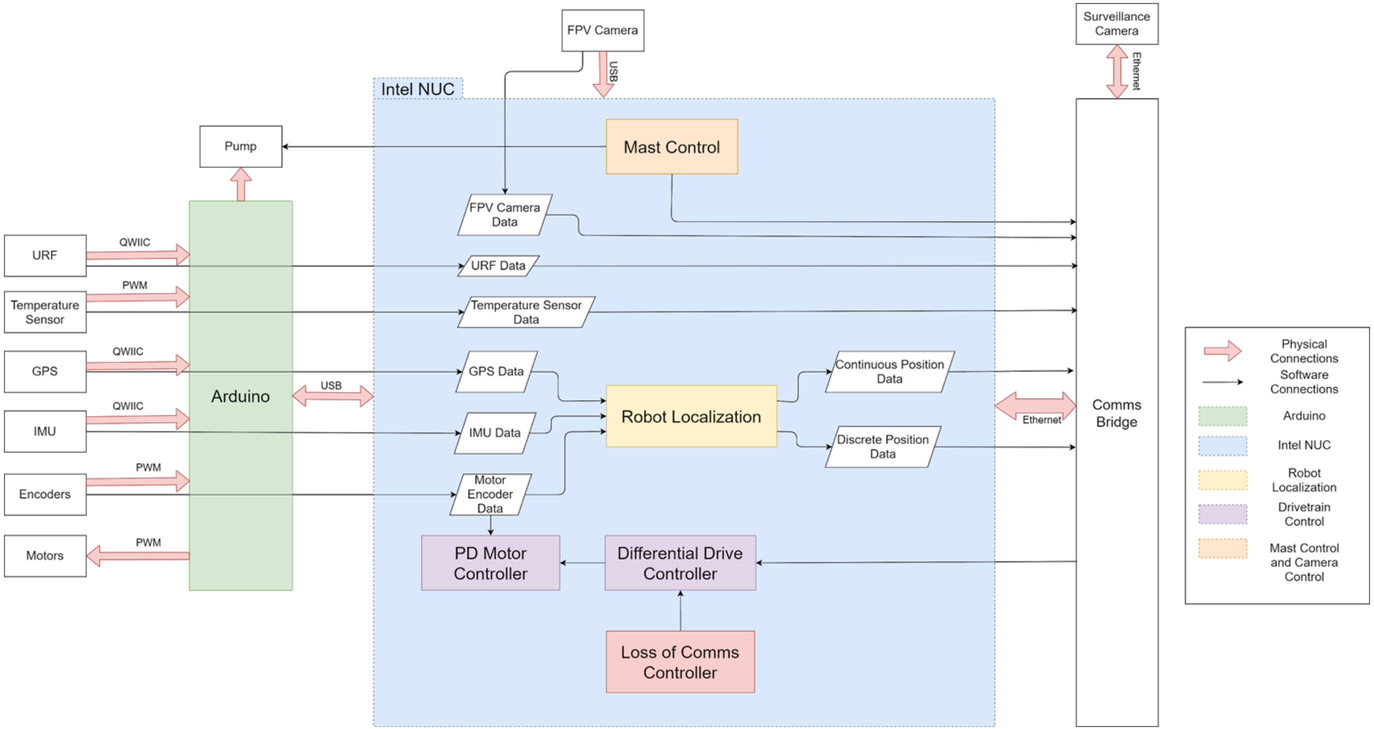
FR. 2 The child rover shall take pictures, videos and ambient temperature data to be sent to the ground station.

Electronics Diagram

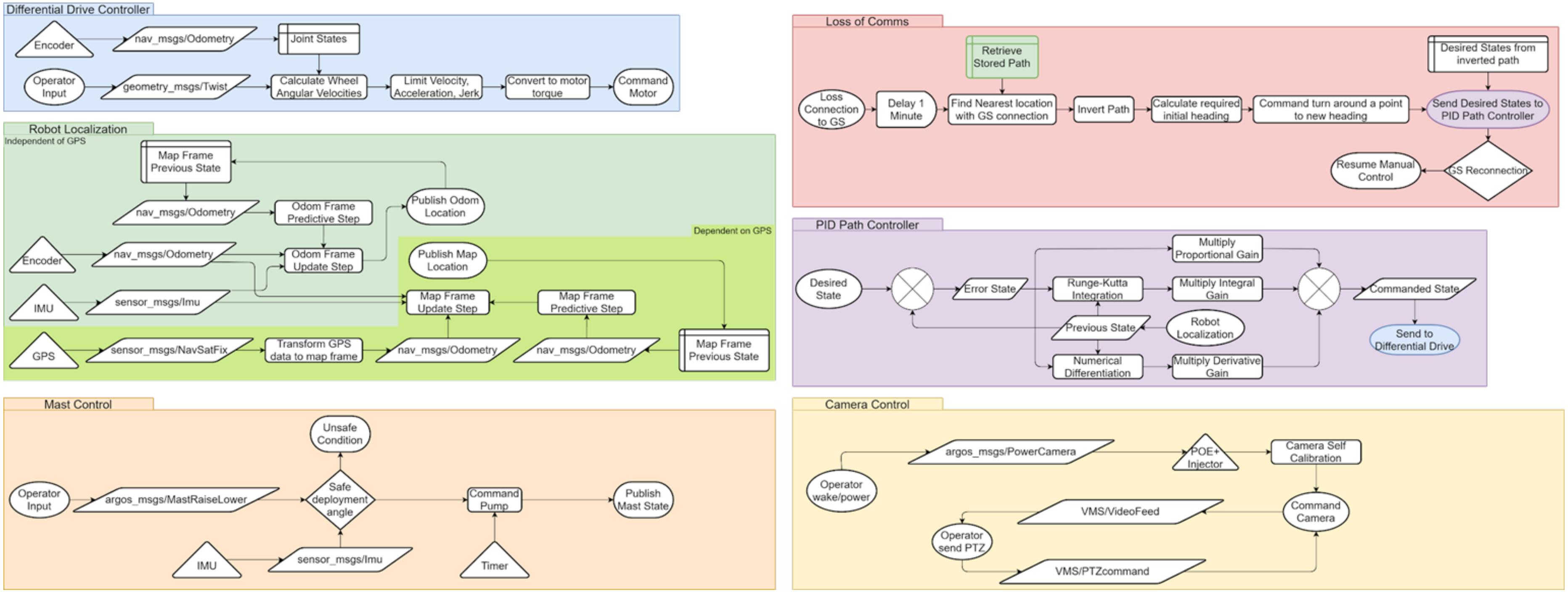


Off Ramp Electronics Diagram in Backup

Integrated Software Diagram

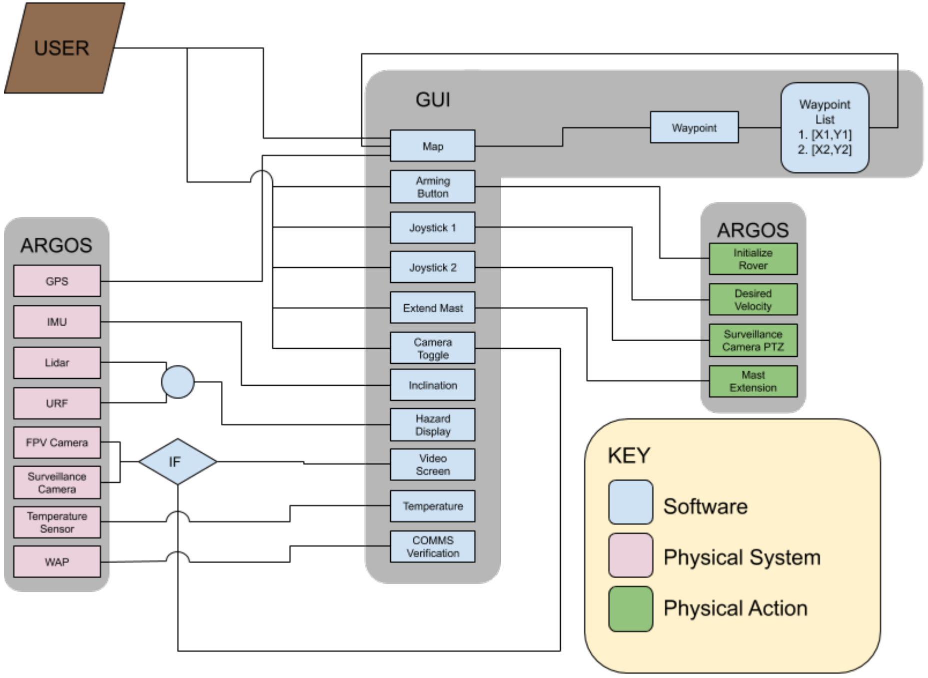


Software Diagram



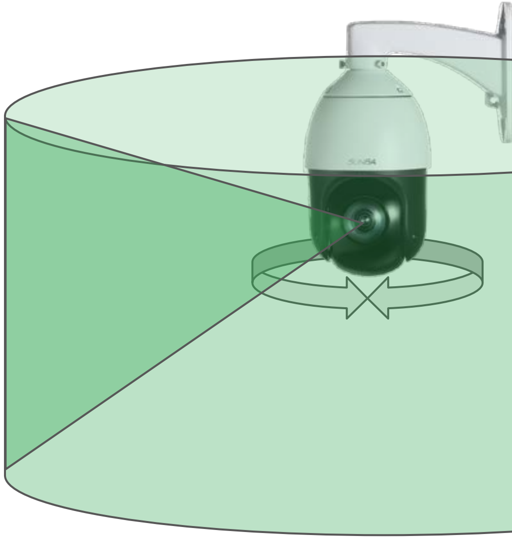
Ground Station UI

- User Functions
  - Pick Waypoints
  - Arm Rover
  - Control Rover Movement
  - Command Surveillance PTZ
  - Extend/Retract Mast
  - Select Camera
- GUI Displays
  - Map
    - Rover location
    - Waypoints
  - Video Feed
  - Hazards
  - Temperature
  - Inclination
  - Communication Verification

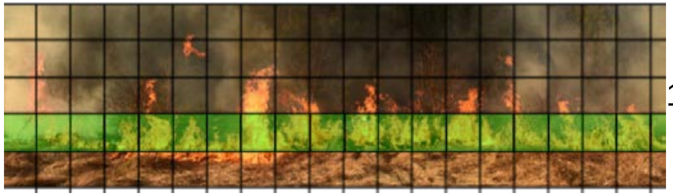


Surveillance Camera

- **Design Requirement**: The surveillance camera shall have >**100°** field of view
  - Vertical sensor size 4.826mm from camera selection
    - Focal length 4.7 to 94mm ----> 41.44° to 2.17° FOV
    - Tilt 5° to -90°
    - Total FOV **achieved**: **136.44°**
  - Horizontal sensor size 3.556mm from camera selection
    - Focal length 4.7 to 94mm ----> 54.35° to 2.94° FOV
    - Pan 360°
    - Total FOV **achieved**: **315°**



- **Design Requirement:** The camera shall provide operator with pictures and video of fire that occupy at least 20% of the vertical image.
  - Image Height **needed** for a 1m flame height is **5m**
  - Distance **achieved** from camera selection **132m**



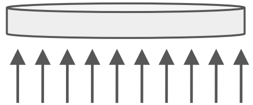
3. Mast Design Requirements and their Satisfaction

FR. 3 The child rover shall use a mast to take photos and video from a vantage point above the rover's body.

Hydraulic Telescoping Mast

- **Design Requirement:** The child rover shall have a mast capable of extending to a height of 2m +/- 0.2m and retracting back down to its original height
  - Satisfied through model geometry:
    - Extension height = 1.86m
    - Compacted height = 0.56m
- **Design Requirement:** The child rover shall have a mast capable of supporting 10kg of weight on the top
  - Satisfied through required pressure study
  - Assume:
    - Pressure force on top cap alone
    - Sliding friction force negligible
  - Result:
    - Pressure required: 265 kPa ~ 38 psi
    - Pump pressure: 145 psi
  - Mast rupture study result:
    - Pressure to rupture mast: 400 psi (FOS = 1.5)

Top Cap



$$F_{press} = P_{top} \times A_{top}$$

$$F_{press} = W_{mast} + W_{cam}$$

4. Communications Design Requirements and their Satisfaction

FR. 4 The child rover shall receive commands from both the ground station and the mother rover and transmit captured data to the ground station and the mother rover.

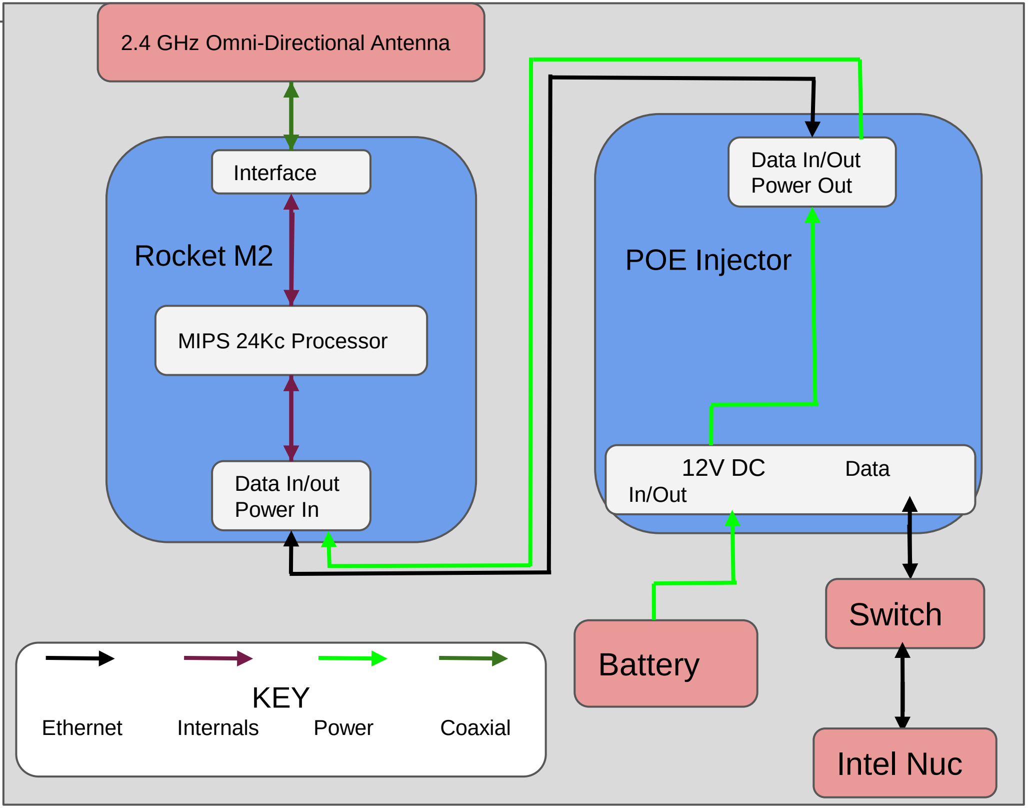
Communications Design

- **Design Requirement:** The child rover shall send time stamped video, image, and temperature data at a data rate up to 25Mbps

- **Comms (Rocket M2):**
  - PtP and PtM bridging
  - Reduces Attenuation
  - Data Rate: 6-24Mbps w/ Modulation: 802.11g
  - Power Draw: 6.5 W
  - Monitors Data Rate & Signal Strength

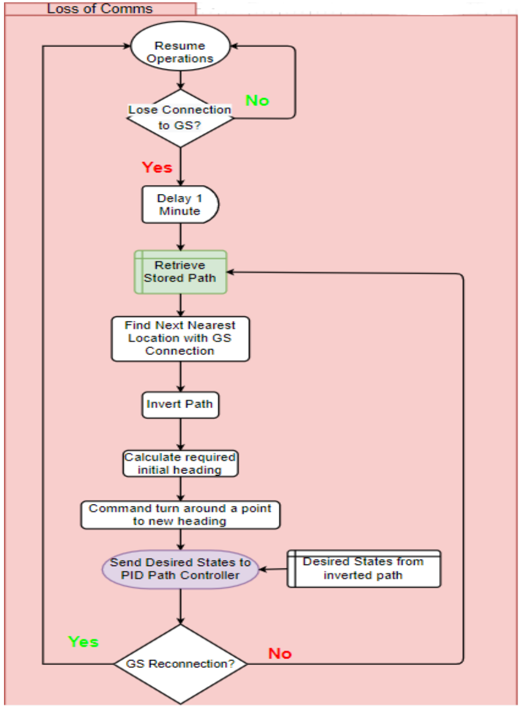
- **POE-1 Injector:**
  - 24V output
  - 12-56VDC input

- **Omni-Directional Antenna:**
  - -2.4 GHz Frequency
  - -12 dBi Gain



Communications - Loss of Connection

- **Design Requirement:** Upon loss of communications, the child rover shall return to the last known GPS coordinate.
- **Assume:**
  - The path ARGOS took to its current location is safe when reversed
  - Connectivity is location dependent
  - PID Controller
    - Built on existing ROS move_base package
  - Simulated in Gazebo
- **Result:**
  - Maximum distance from path: 0.34 m < 0.65 m, one rover width



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

Project Risks

Risk Introduction

Severity Risk Levels

Levels	Technical	Schedule
1	Minimal or no impact	Minimal or no impact
2	Slightly below expectations but still in operational requirements	More time required to complete task but still able to be completed by time deadline
3	Slightly below operational requirements, needs minimal modification to design	Minimal schedule slip and completion deadline needs to be moved back
4	Performance is at an unacceptable level, off ramp design or redesign of subsystem is necessary	Schedule is pushed back to an extent that the critical path of the project is delayed
5	Unacceptable performance that does not have a solution	Key milestones in the project are unachievable

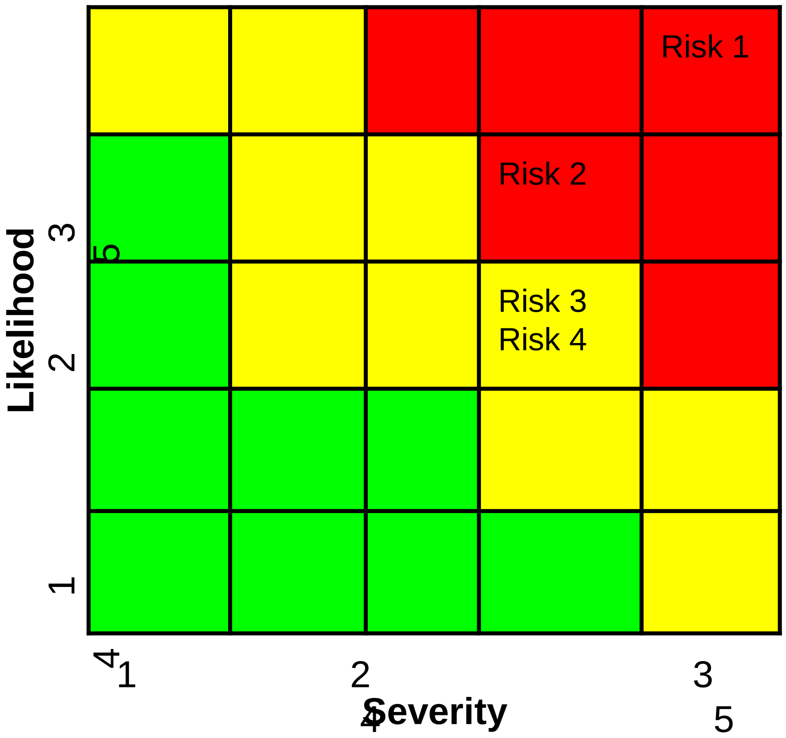
Risk Likelihood

Level	Likelihood
1	Improbable
2	Remote
3	Ocasional
4	Probable
5	Frequent

Risk Descriptions

Risk	Type	Description	Effect
1	S	Software development will be time consuming and complex	System integration of subsystems will not be possible. Functional requirements cannot be met and verified. **Key milestones will not be met.**
2	T	Design of hydraulic mast is complex and requires seals connecting each section to have tight manufacturing tolerances	If connecting points between sections have over pressurization fluid will leak and the mast will fail to stay extended. **Off ramp or redesign of subsystem required**
3	T	Attenuation of signal causing loss of communication with GS	Unable to send live photos/videos back to GS. **Redesign of subsystem required**
4	T	Motor failure due to overheating from stalling	Motors do not function properly and cannot complete mission. **Redesign of subsystem required**

Before Mitigation



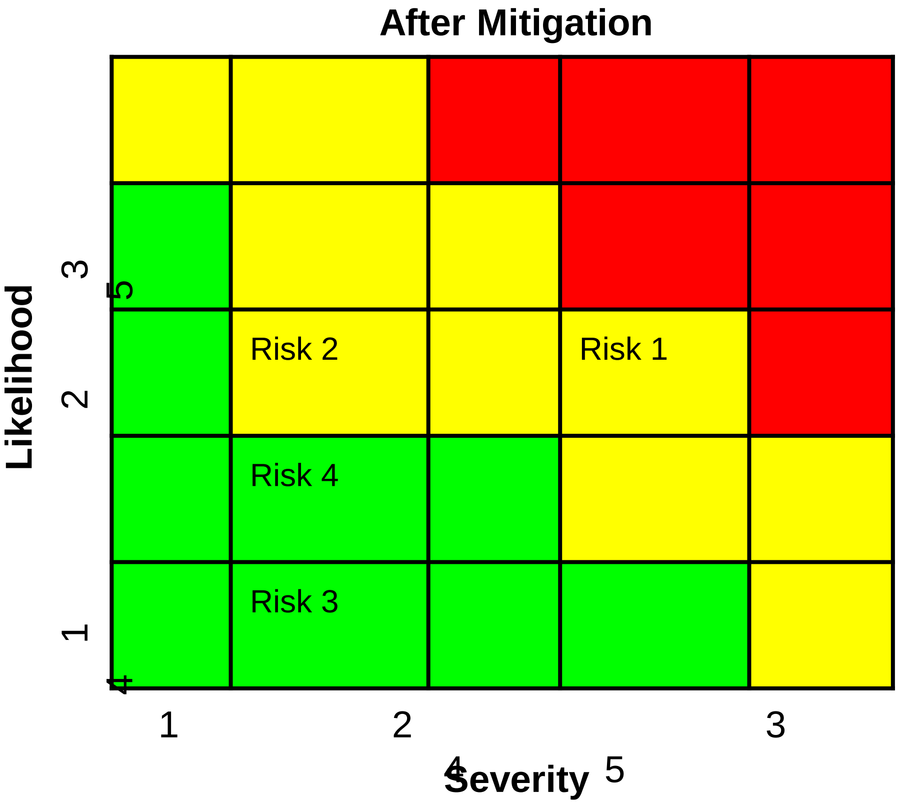
Project Purpose and Objectives | Design Solution | Critical Project Elements | Design Requirements & their Satisfaction | **Project Risks** | Verification and Validation | Project Planning | Backup Slides

University of Colorado Boulder

JPL Jet Propulsion Laboratory California Institute of Technology

Risk Mitigation

Risk	Mitigation Strategy
1	Allocate enough time for code development with a sufficient time margin. Assigned four team members to development and frequent code reviews.
2	Test rig has been designed and planned for testing next semester. If the test is not successful by 1/22/21 the off ramp design shall be used.
3	Test attenuation early, utilize high gain antennas and ensure that the rover has the ability to return to the last known GPS point.
4	Design for sufficient airflow to reach the motor and use vent plate spacers or heat sinks to achieve this.



Project Purpose and Objectives > Design Solution > Critical Project Elements > Design Requirements & their Satisfaction > **Project Risks** > Verification and Validation > Project Planning > Backup Slides

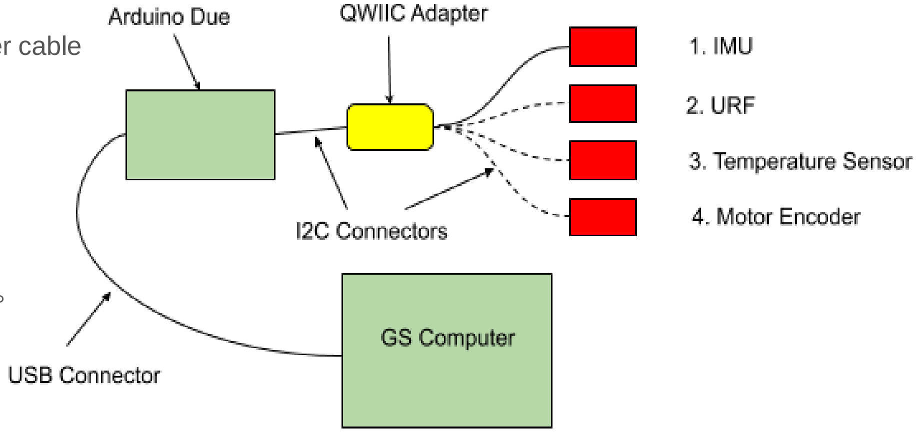
University of Colorado Boulder

Jet Propulsion Laboratory California Institute of Technology

Verification and Validation

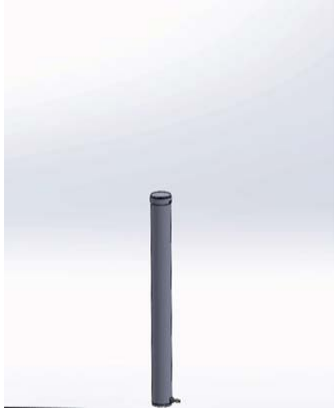
Verification and Validation: Sensors

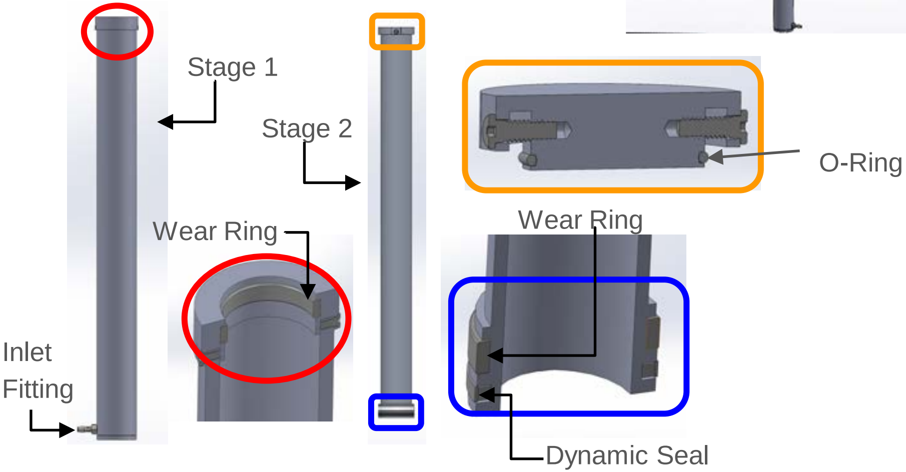
- **Objective**
  - Determine accuracy of each individual sensor and also data throughput for each sensor
- **Test Plan**
  - Using the Arduino Due connect the IMU, Ultrasonic Range Finders, temperature sensor, and the motor encoders individually. When connected check for data throughput and complete sensor specific tests to look at sensor accuracy.
- **Requirements Verified**
  - FR. 1 The child rover shall move from a starting location to a commanded location of interest and return back to the starting location.
  - The child rover shall be able to determine the ambient temperature within ± 5° C at the location of interest
- **Required Hardware**
  - Sensors: IMU, 2 URF, Temperature Sensor, Motor Encoder
  - Arduino Due, Qwiic Adapter, I2C Serial Cable, USB connecter cable
  - GS Computer
- **Required Measurements**
  - Data throughput of each sensor and total data throughput
  - Individual Sensor Measurements
    - IMU: Degree measurement is within ± ½ °
    - URF: Minimum detectable obstacle width ~0.5m
    - Temperature Sensor: Temperature is within 1K
    - Motor Encoder: Minimum detectable angle of 0.5237°
- **Test Location**
  - AERO Building
- **Test Errors**
  - Noise in the signals



Verification and Validation: Mast Test Rig

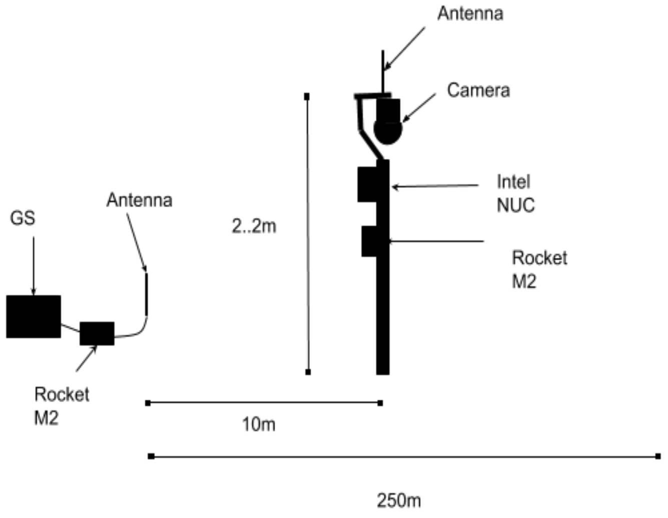
- **Objective**
  - Determine if small scale rig of the hydraulic mast can properly extend to full height.
- **Test Plan**
  - Fill unextended mast with hydraulic oil, connect the mast to a reservoir filled with more hydraulic oil and connect the reservoir to pressurized air. Pressurize the reservoir to push the mast up until it reaches full extension and check for binding during extension. Depressurize and repeat cycle 20 times. Take apart the mast and check for degradation of the seals.
- **Requirements Verified**
  - FR. 3 The child rover shall use a mast to take photos and video from a vantage point above the rover's body.
- **Required Hardware**
  - Two stage hydraulic mast
  - Air compressor
  - Oil reservoir
  - Two connector fittings
  - Hydraulic fluid
- **Required Measurements**
  - Pressure inside of the mast
- **Test location**
  - AERO Machine Shop
- **Test Errors**
  - Scaling up from small scale mast to final mast design





Verification and Validation: Live Video Feed

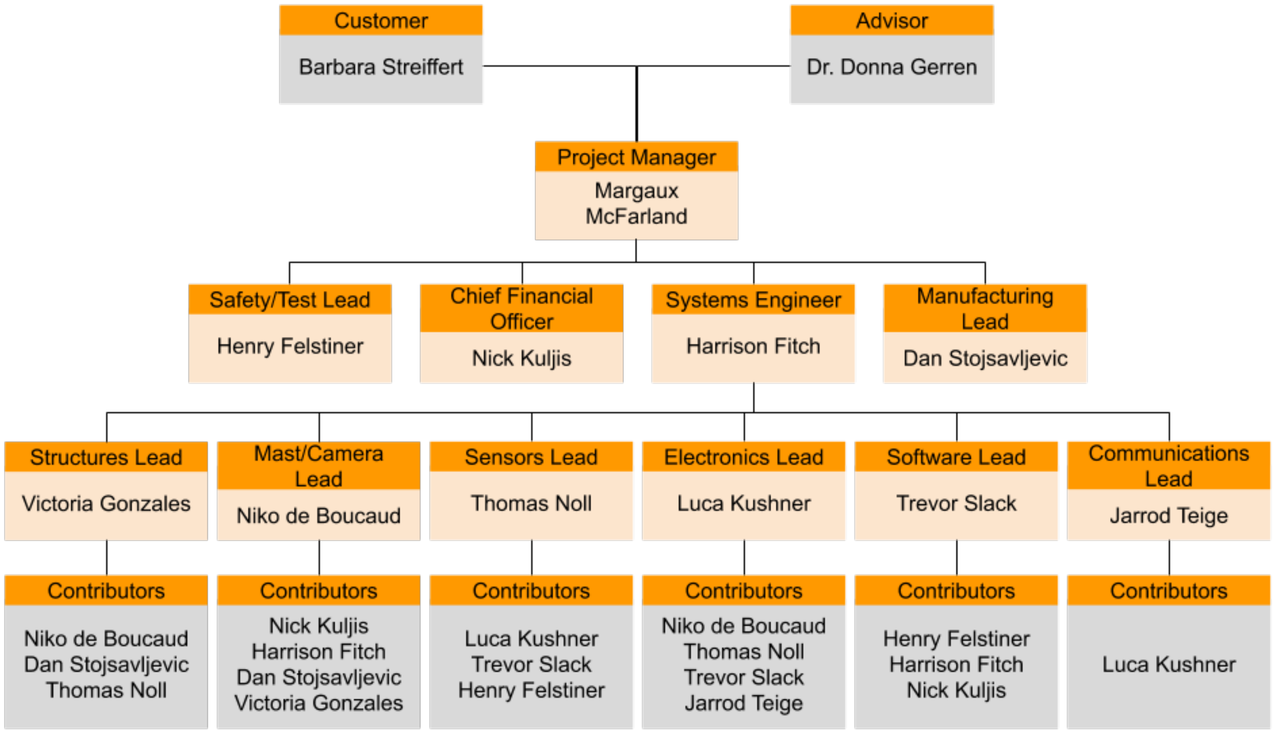
- **Objective**
  - Determine if surveillance camera/FPV camera connected to Intel NUC and Rocket M2 through the network switch can send live video feed to GS at varying distances.
- **Test Plan**
  - Connect 405-D20X PoE surveillance camera, Intel NUC, and point to multipoint transmitter through the network switch. Then move the camera from 10m to 250m by 30m increments away from the GS receiver.
  - Repeat for FPV camera
- **Requirements Verified**
  - The child rover shall send time stamped video at a data rate up to 25Mbps
- **Required Hardware**
  - 405-D20X PoE surveillance camera
  - Intel NUC
  - 2 Rocket M2
  - Ground Station computer
  - 2.2m Tripod
  - 2 Radio Antennas
- **Required Measurements**
  - Data rate of communication system and camera at varying distances
- **Test Location**
  - Outside(AERO Building Field)



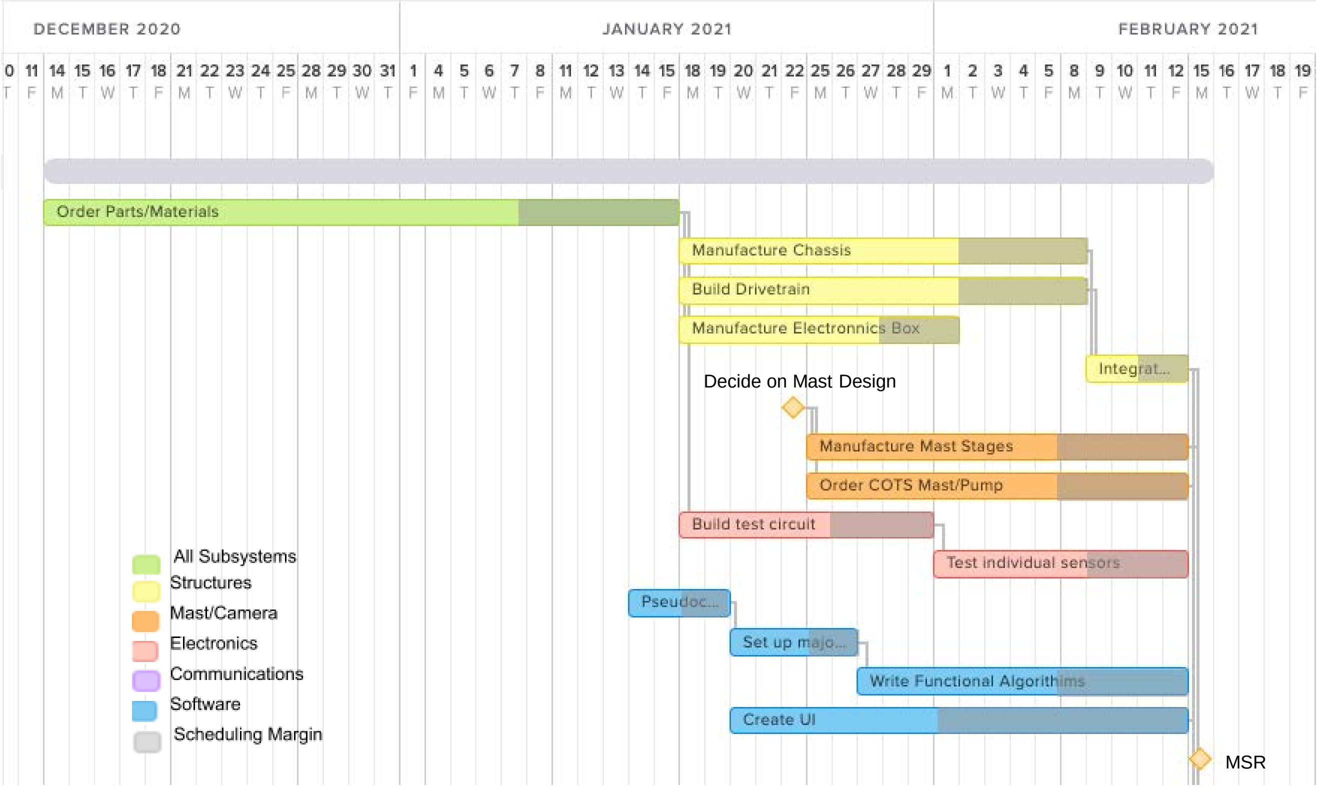
Project Purpose and Objectives | Design Solution | Critical Project Elements | Design Requirements & their Satisfaction | Project Risks | **Verification and Validation** | Project Planning | Backup Slides

Project Planning

Organizational Chart

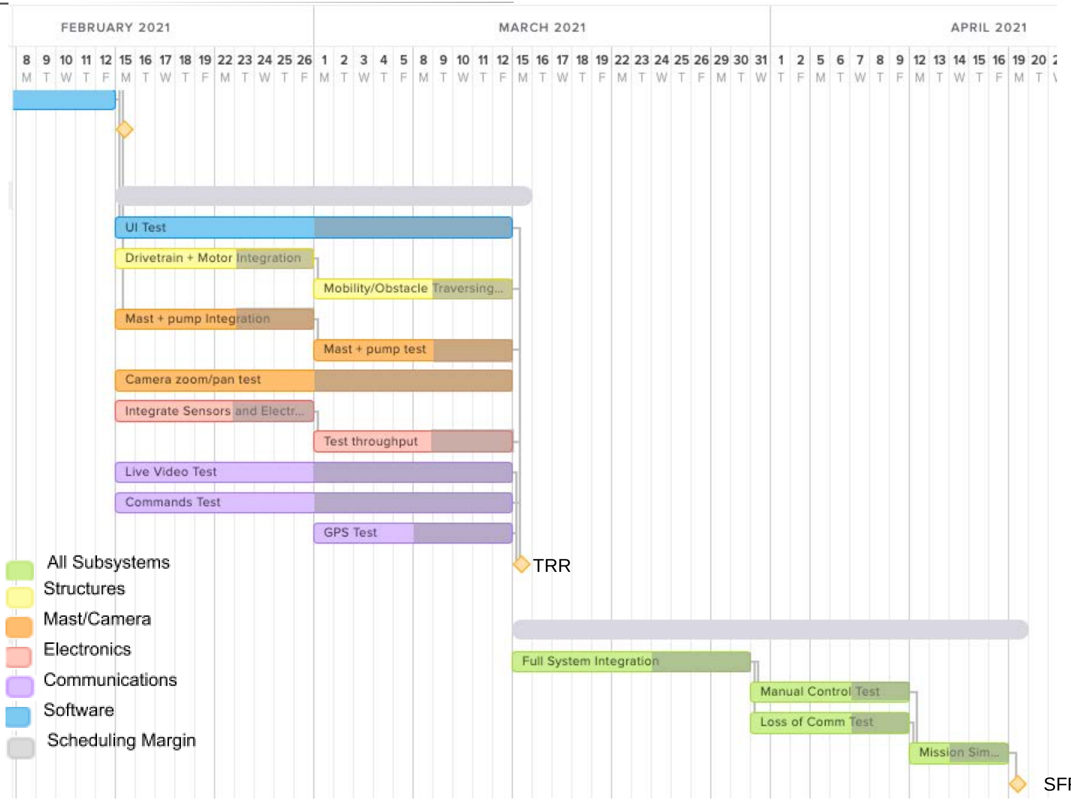


Work Plan



DECEMBER 2020
JANUARY 2021
FEBRUARY 2021
Order Parts/Materials
Manufacture Chassis
Build Drivetrain
Manufacture Electronnics Box
Integrat...
Decide on Mast Design
Manufacture Mast Stages
Order COTS Mast/Pump
Build test circuit
Test individual sensors
Pseudoc...
Set up majo...
Write Functional Algorithims
Create UI
MSR
All Subsystems
Structures
Mast/Camera
Electronics
Communications
Software
Scheduling Margin

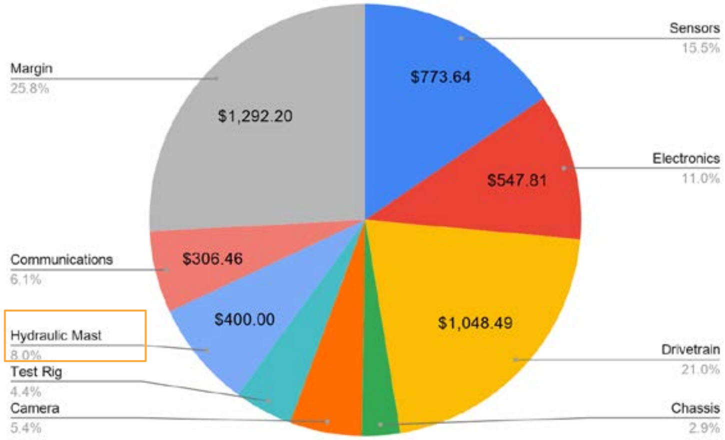
Work Plan

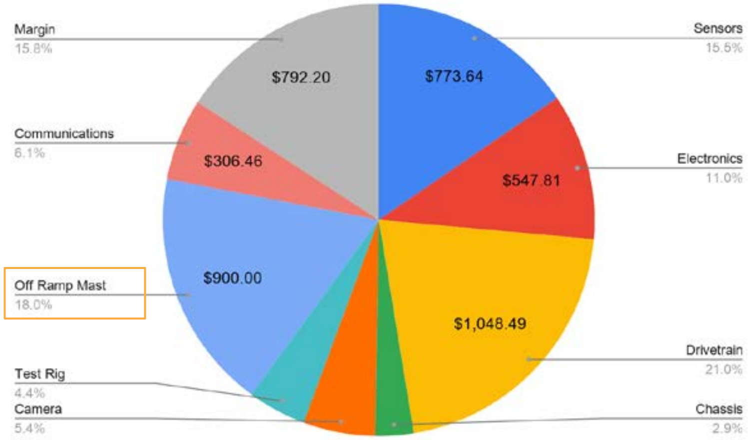

FEBRUARY 2021
MARCH 2021
APRIL 2021
UI Test
Drivetrain + Motor Integration
Mobility/Obstacle Traversing...
Mast + pump Integration
Mast + pump test
Camera zoom/pan test
Integrate Sensors and Electr...
Test throughput
Live Video Test
Commands Test
GPS Test
TRR
All Subsystems
Structures
Mast/Camera
Electronics
Communications
Software
Scheduling Margin
Full System Integration
Manual Control Test
Loss of Comm Test
Mission Sim...
SFR

Cost Plan

- **Hydraulic Mast**
  - Most expensive subsystems:
    - Drivetrain
    - Sensors
  - Estimated Total Cost = **$3,707.80**
  - Margin = **$1,292.20**

- **Off-Ramp COTS Mast**
  - Most expensive subsystems:
    - Drivetrain
    - Mast
  - Estimated Total Cost = **$4,207.80**
  - Margin = **$792.20**





University of Colorado Boulder

Jet Propulsion Laboratory
California Institute of Technology

Test Plan - Phase 1

- Phase 1: pre-integration, all tests are independent

Phase 1				
Subsystem(s)	**Test**	**Date**	**Testing Facility**	**Equipment**
Mast/Camera	• Mast test rig - fit of tubes, leaks	1/14/21	Aero Machine Shop	Hydraulic fluid supply
Sensors	• Individual sensor accuracy and throughput	2/1/21	Aero Building/at Home	Test circuit/controller
Software	• UI of ground station with sample data	2/15/21	At Home	none
COMM	• Live video • Sample commands	2/15/21	Outside	Ground station

Test Plan - Phase 2

- Phase 2: somewhat integrated, depend on phase 1 tests

Phase 2				
Subsystem(s)	**Test**	**Date**	**Testing Facility**	**Equipment**
Structures	● Drivetrain + motor ● 360° turn ● 250m round trip ● Obstacle traversing	3/1/21	Aero Building/Outside	Power Supply, sample ~7cm tall obstacle
Mast/Camera	● Pump + mast ● Camera zoom/pan	3/1/21	Aero Building/ at Home	Hydraulic fluid
Sensors/ Electronics/ Software	● Throughput of all sensors ● UI of actual sensor data	3/1/21	Aero Building/at Home	Complete circuit
COMM/ Electronics	● GPS + COMM	3/1/21	Outside	Ground station

Test Plan - Phase 3

- Phase 3: fully integrated, depend on phase 1 and 2 tests

Phase 3				
Subsystem(s)	**Test**	**Date**	**Testing Facility**	**Equipment**
all	• Manual control tests	3/31/21	Outside	N/A
all	• Loss of communication - navigation test	3/31/21	Outside	N/A
all	• Full mission simulation	4/12/21	Outside	N/A

Questions?

References

"Appendix A: Flame Radiation Review." *Wiley Online Library*, John Wiley & Sons, Ltd, 31 Jan. 2014, onlinelibrary.wiley.com/doi/pdf/10.1002/9781118903117.app1.

Belwariar, R., A* Search Algorithm Available: https://www.geeksforgeeks.org/a-search-algorithm/.

Chang, D L. *Compressive Properties and Laser Absorptivity of Unidirectional Metal Matrix Composites*. Aerospace Corporation, 30 Sept. 1986, apps.dtic.mil/dtic/tr/fulltext/u2/a176194.pdf.

Çengel Yunus A., and John M. Cimbala. *Fundamentals of Thermal-Fluid Sciences*. 4th ed., McGraw-Hill Higher Education, 2012.

"Estimating Winds for Fire Behavior." *National Wildfire Coordinating Group (NWCG)*, www.nwcg.gov/publications/pms437/weather/estimating-winds-for-fire-behavior.

Marder-Eppstein, E., "ROS Navigation," ros.org Available: http://wiki.ros.org/navigation?distro=noetic.

"Materials Engineering," *Hydraulic oil ISO 68 [SubsTech]* Available: https://www.substech.com/dokuwiki/doku.php?id=hydraulic_oil_iso_68.

N. Koenig and A. Howard, "Design and use paradigms for Gazebo, an open-source multi-robot simulator," 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566), Sendai, 2004, pp. 2149-2154 vol.3, doi: 10.1109/IROS.2004.1389727.

References (cont.)

Sandoval, Alexander, et al. “HERMES Manufacturing Status Review.” 4 Feb. 2019.

Stanford Artificial Intelligence Laboratory et al., 2018. Robotic Operating System, Available at: https://www.ros.org.

Storey, Theodore G, et al. “Crown Characteristics of Several Coniferous Tree Species.” *U. S. Department of Agriculture Forest Service Division of Fire Research* , Aug. 1955, doi:10.5962/bhl.title.122542.

“Trees and Shrubs for Mountain Areas - 7.423.” *Colorado State University Extension*, Colorado State University, 29 May 2018, extension.colostate.edu/topic-areas/yard-garden/trees-and-shrubs-for-mountain-areas-7-423/.

Wildland Fire Suppression Tactics Reference Guide. National Wildfire Coordinating Group, 1996.

“Wildfires: Interesting Facts and F.A.Q.” *Natural History Museum of Utah*.

Kim, A., 2019. *Runcam Nano2 FPV Camera Review*. [video] Available at: <https://www.youtube.com/watch?v=PvIURJ_74G0&t=203s> [Accessed 1 November 2020].

Maloney, S. (n.d.). Critical Seal Design Tolerance Charts. Retrieved from https://www.colonialseal.com/downloads/press-releases/Seal_tolerances.pdf

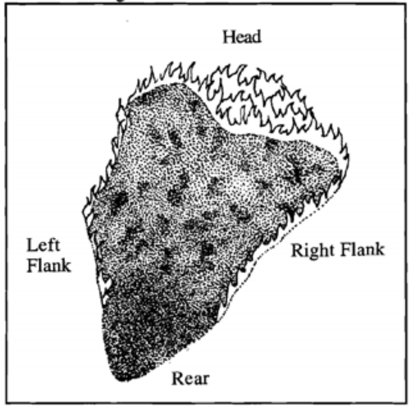
RPLIDAR A2 Introduction, Datasheet by Seeed Technology Co., Ltd. (n.d.). Retrieved November 20, 2020, from https://www.digikey.co.za/htmldatasheets/production/1984492/0/0/1/rplidar-a2-introduction-datasheet.html

Backup Slides

Definitions

- **Fireline :** a trench cleared of any flammable material, dug at the edge of a forest or brush fire to halt the spread
- **Flame Front :** the leading edge of the forest fire perimeter
- **Survey :** to record video/take photos
- **Fire Surveillance :** a subsystem of ARGOS consisting of the sensors and components needed to survey the fire line
- **Tipping Condition :** condition when rover tips too far to the side or in the front or back and falls over
- **Obstacles :** rocks, tree stumps, fallen branches, or other debris found on the forest floor which can have heights up to 7cm
- **Tree density :** measure of how many trees will be in an area (# trees/acres)
- **Terrain :** specification of the forest floor which ARGOS must traverse (detailed definition in backup slides)

Figure 6—Parts Of A Fire



Design Requirements

FR. 1 The child rover shall move from a starting location to a commanded location of interest and return back to the starting location.

Design Requirement ID	Description
MOV.1.1	The child rover shall be able to perform a 360 degree turn.
MOV.1.2	The child rover shall be able to travel in forward and reverse motion.
MOV.1.3	The child rover shall be able to travel up and down slopes of 20 degree inclination.
MOV.1.4	The child rover shall be able to travel over obstacles with heights as tall as 7cm.
MOV.1.5	The child rover shall be able to travel 250m round trip in any direction from its starting location.
CDH.1.1	The child rover shall be able to detect when a tipping condition is met(when the rover falls over) and send an alert to the ground station/mother rover.

Design Requirements

FR. 2 The child rover shall take pictures, videos and ambient temperature data to be sent to the ground station.

Design Requirement ID	Description
SURV.2.1	The camera shall have >100 degrees field of view.
SURV.2.2	The camera shall provide operator with pictures and video of fire that occupy at least 20% of the vertical image.
CDH.2.3	The child rover shall be able to determine the ambient temperature within +/- 1 °K at the location of interest.

Design Requirements

FR. 3 The child rover shall use a mast to take photos and video from a vantage point above the rover's body.

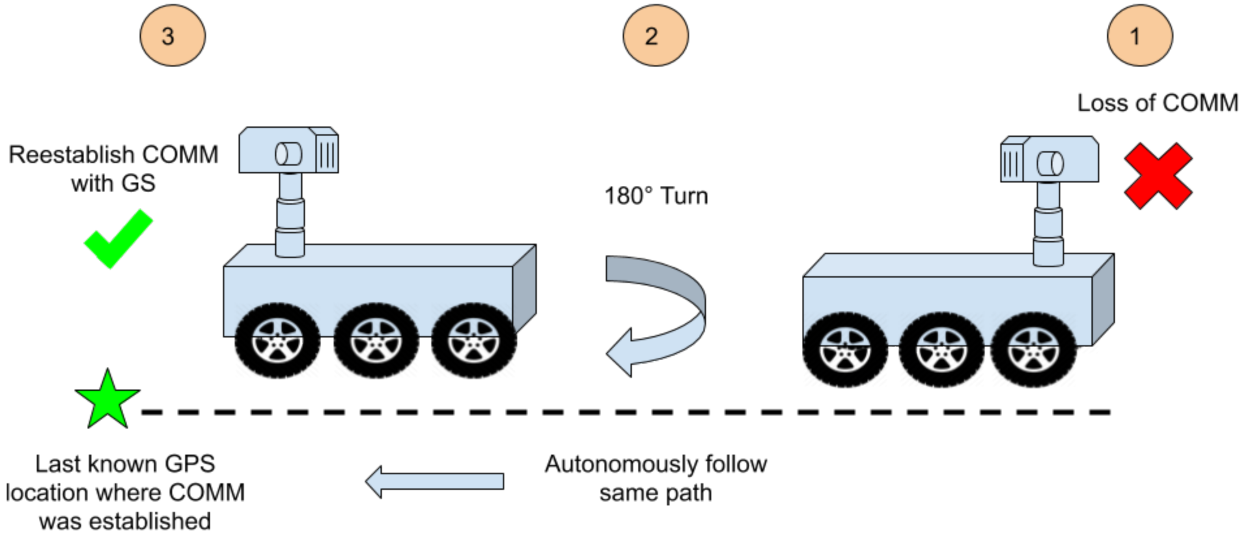
Design Requirement ID	Description
SURV.3.1	The child rover shall have a mast capable of extending to a height of 2m and retracting back down to its original height.
SURV.3.2	The child rover shall have a mast capable of supporting 10kg of weight on the top.

Design Requirements

FR. 4 The child rover shall receive commands from both the ground station and the mother rover and transmit captured data to the ground station and the mother rover.

Design Requirement ID	Description
COM.4.1	Upon loss of communication, the child rover shall return to its last known GPS location (storage of waypoints).
COM.4.2	The child rover shall send time stamped video, image, and temperature data to the ground station and mother rover at a data rate up 25Mbps.
COM.4.3	The ground station shall confirm if the child is within +/- 5m of the desired location.
COM.4.4	The child rover shall send its location every 1.5s to the ground station/mother rover.
COM.4.5	The mother rover/ground station shall be able to command the child rover to navigate to specified GPS coordinates in real time .
COM.4.6	The mother rover/ground station shall be able to command video feed on/off.
COM.4.7	The mother rover shall be able to receive commands from the ground station at a data rate up 25Mbps.
COM.4.8	The mother rover shall be able to send temperature data and video to the ground station and vice versa.

Loss of Communications CONOPS



Levels of Success

	Rover Movements	Surveillance	Communications
Level 1	Rover can travel on flat ground for 100m. Rover can travel in the forward direction and can turn 360 degrees with a turn radius less than two rover body lengths.	Ambient temperature data is recorded from a temperature sensor with an accuracy of +/-1 °C throughout the mission. Rover records timestamped photos of the flame front via a camera on a mast.	Rover can receive GPS commands from the ground station and the mother rover. Rover can transmit temperature data and video/images to the ground station and mother rover at 1 Hz 0m from ground station or in the same room via radio remote control.
Level 2	Rover can travel on various terrain, including leaves, scattered underbrush, dirt and mud, while staying upright. Rover can travel on a 20 degree incline. Rover can turn 360 degrees with a turn radius less than one rover body length.	Rover records timestamped video of the flame front via a camera on a mast.	Rover can communicate with the ground station and the mother rover up to 100m with no obstacles (0 trees/m2).
Level 3	Rover can turn 360 degrees on the spot. Rover can follow GPS waypoints and detect large obstacles, such as trees and dense bushes, in its path and avoid hitting them. Rover can detect a tipping condition by measuring its angular motion.	Rover's mast is extendable and retractable.	Rover can communicate with the ground station and the mother rover with obstacles (0.25 trees/m^2).
Level 4	Rover can detect small obstacles, such as rocks and small bushes, and navigate a path around them. Rover can navigate to a GPS waypoint within +/-5m of the coordinates.	N/A	Rover can communicate with the ground station and the mother rover up to 250m.

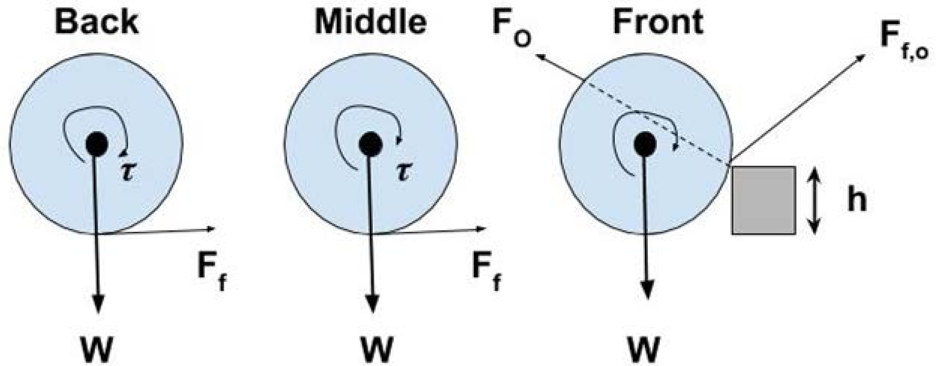
1. Navigation Design Requirements

FR. 1 The child rover shall move from a starting location to a commanded location of interest and return back to the starting location.

Obstacle Maneuvering

- Validation:
  - What wheel radius is needed to maneuver a 7cm obstacle?
  - What is the max torque from the motors?
- Given:
  - Total mass = 30 kg
  - μ = 0.7 on ground and obstacle
- Assumptions
  - Rolling without slipping
  - Negligible Roll Resistance
  - majority of mass Mass acting on fror wheel
  - 3 Cases
- Torque:
  - $\tau_{motor} = F_{f,max} r$

$$\tau_{m,max} = 12.0\ Nm$$

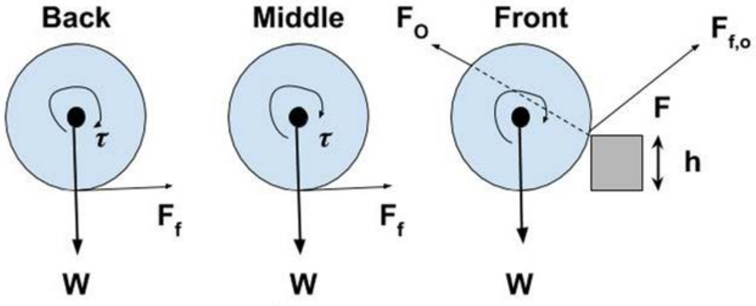


Results:
Minimum Radius Required: 16.7 cm
Minimum Diameter Required: 33.4 cm

Swisher Wheels
- 34.925 cm Diameter

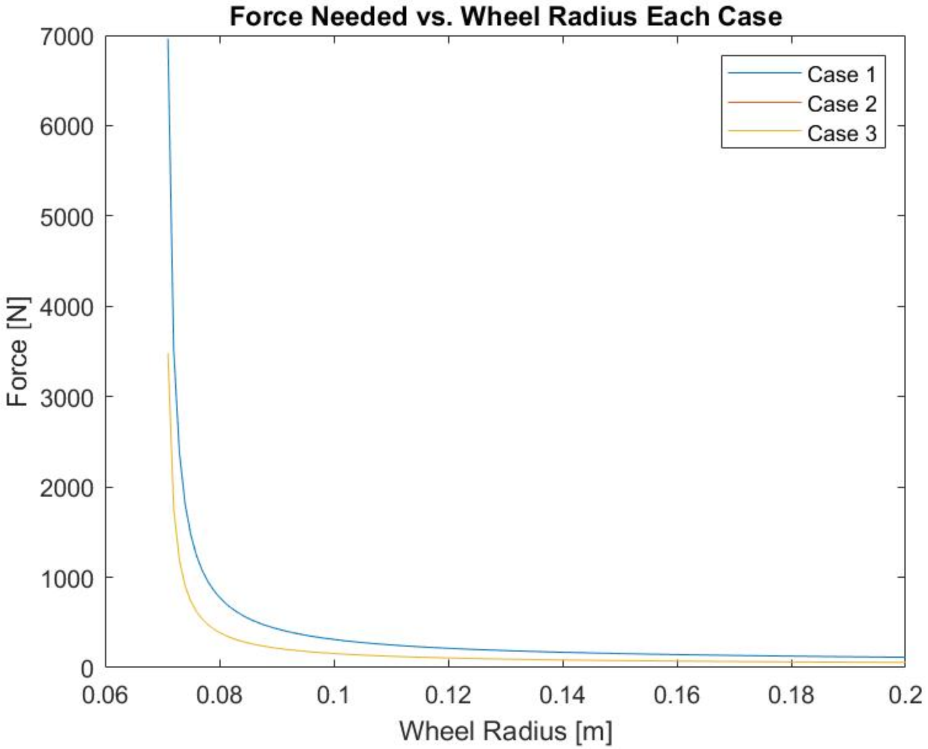
AndyMark 775 Motor and 57 Sport Gearbox
- 36:1 Gear Ratio
- 25.2 Nm Stall Torque

Drivetrain Feasibility - Obstacle Maneuvering



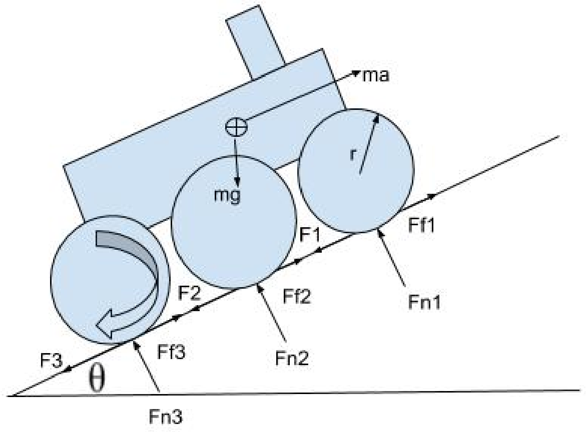
$$F > \frac{mg\sqrt{2rh - h^2}}{r - h}$$

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



Drivetrain - Incline Maneuvering

- Validation:
  - Can this Child Rover maneuver up inclines of at least 20 degrees
- Given:
  - Total mass = 30 kg
  - μ = 0.7 for kinetic friction of the ground and Child Rover
  - Angle of incline is examined from 0° to 20°
- Assumptions
  - Estimated center of mass is a fair approximation
  - 2-Dimensional Rigid Body



Torque Needed For each Wheel To move up Incline

$Ff=m*g(\mu*\cos(\theta)-\sin(\theta))$

$\tau=Ff*r$

Drivetrain - Power Study

- Validation:
  - How much Power will the motors need to use?
  - How long will the motors be able to run?
- Given:
  - **250 m** round trip
- Assumptions
  - Motor Efficiency varies on Torque from specifications sheet
  - 30 Obstacles present during trip (4 seconds tp drove over 1 obstacle)
  - 6 total inclines of 20 degrees that take about 1 minute each to drive up

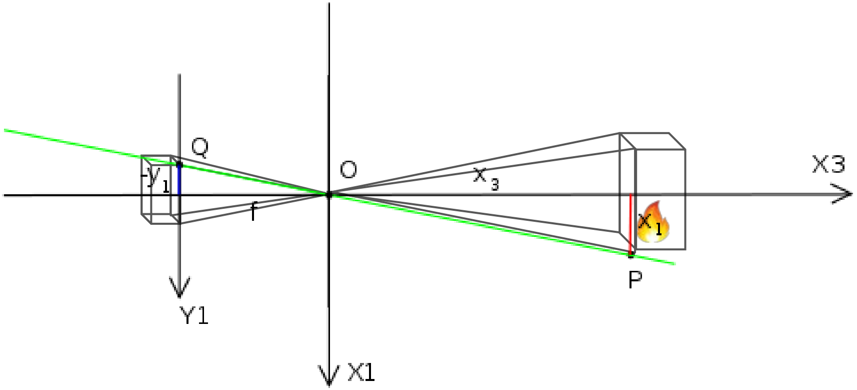
Measurement	Level Ground	Inclined Slope	Obstacles (7 cm)
Time	16.4 min	6 min	2 min
Torque	6.4 Nm	8.11 Nm	P17.98 Nm
Capacity needed	7.05 Wh	6.86 Wh	6.25 Wh

Equations: $\omega = v*r$ while varying velocity we get a power
$P = \omega*\tau$ and the capacity $C = P*time$ (in hours)

2. Data Acquisition Design Requirements

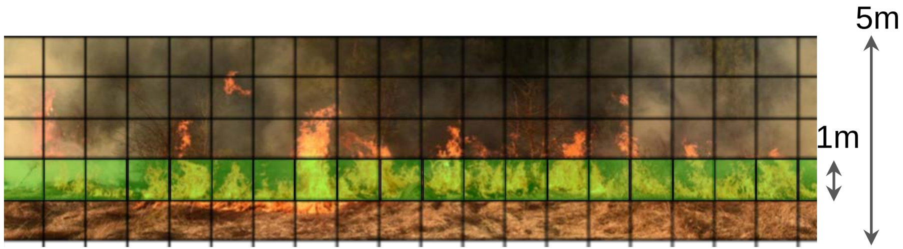
FR. 2 The child rover shall take pictures, videos and ambient temperature data to be sent to the ground station.

Camera FOV and Percentage



$$FOV = 2arctan(\frac{y_1}{f})$$

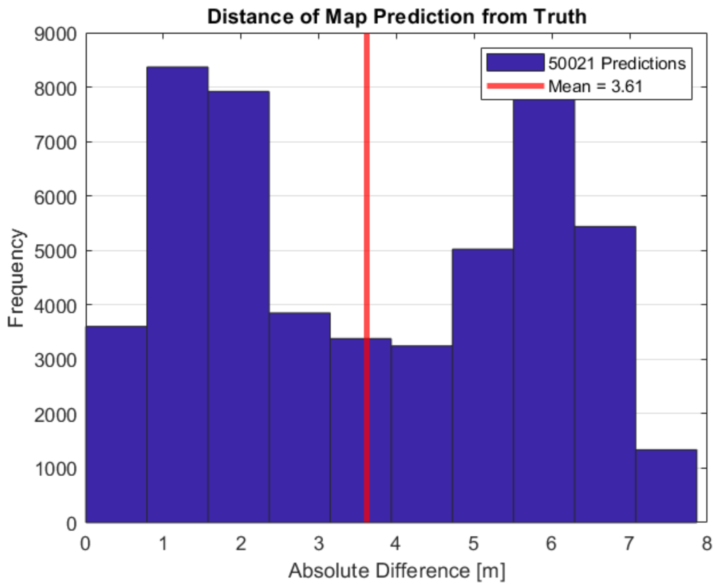
$$x_2 = \frac{x_1}{FOV}$$



Software - Localization

- Validation:
  - Can ARGOS determine its position to within +/- 5m
- Given:
  - Extended Kalman Filter (EKF)
  - Encoders, IMU, GPS
  - Linear Velocity = [-1.75,1.75] m/s
  - Angular Velocity = [-1,1] rad/s
- Assumptions:
  - Gaussian noise
  - No Slip
    - EKF filters out large deviations i.e. slip conditions

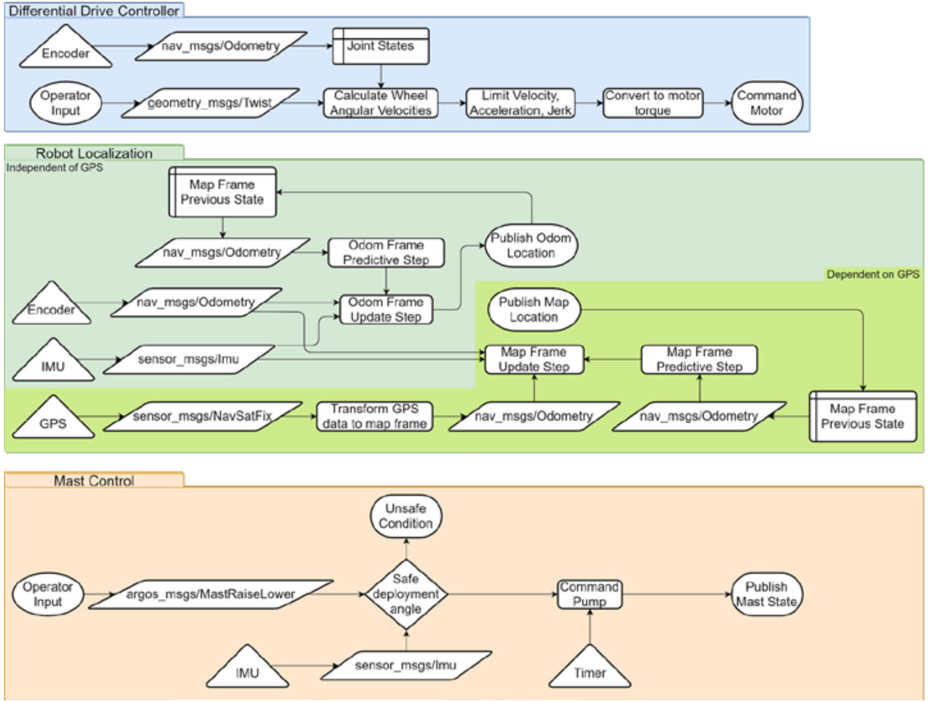
Study	Feasibility Outcome	Maximum Allowable Difference
Determine Position	± 3.61 m	± 5 m

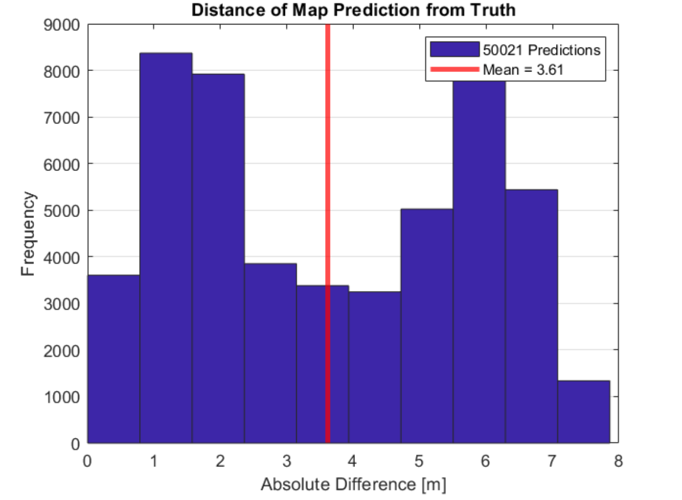


Feasible 

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

Software Diagram

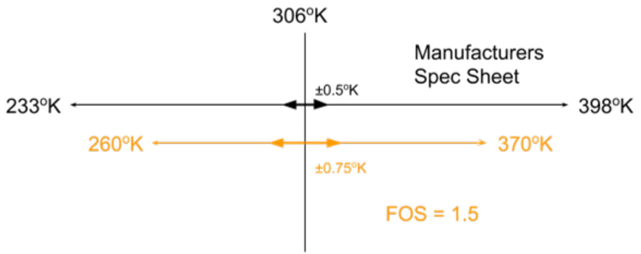




Study	Feasibility Outcome	Maximum Allowable Difference
Determine Position	± 3.61 m	± 5 m

Temperature Sensor

- **Design Requirement**: The child rover shall be able to determine the ambient temperature within ±1 °K at the location of interest.
  - Temperature accuracy **achieved ± 0.75**° K



Study	Feasibility Outcome	Required Min/Max
Maximum Temperature	370ºK	306ºK
Accuracy	± 0.75ºK	± 1ºK

SparkFun Digital Temperature Sensor - TMP117 (Qwiic)

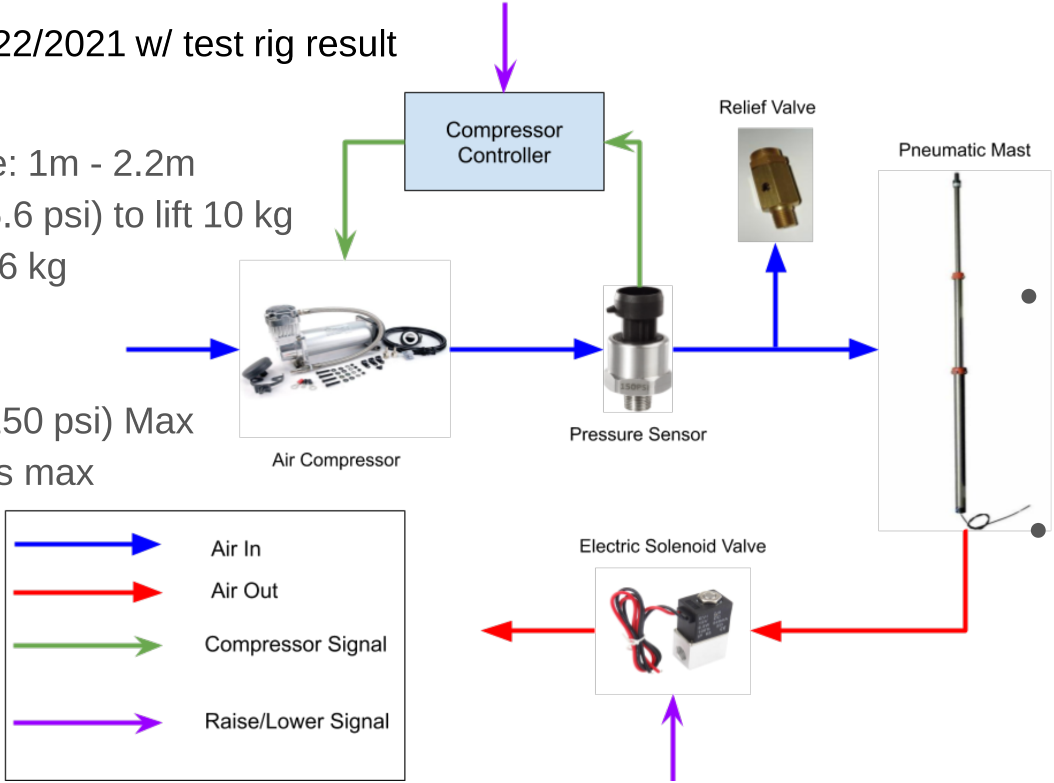
3. Mast Design Requirements

FR. 3 The child rover shall use a mast to take photos and video from a vantage point above the rover's body.

Off-Ramp: COTS Pneumatic Mast

Take off-ramp by 1/22/2021 w/ test rig result

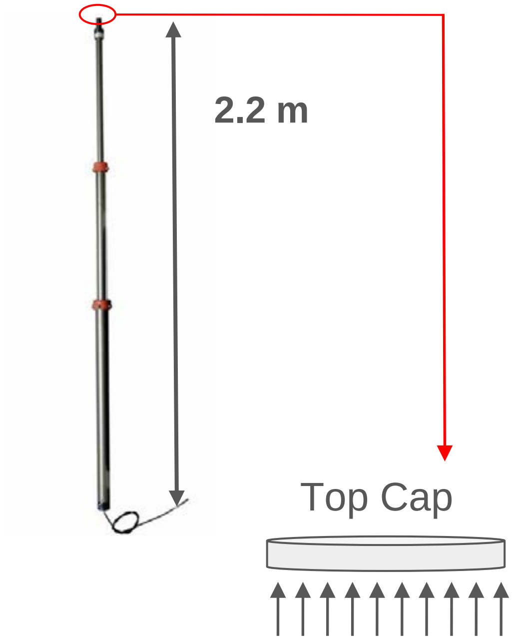
- **Pneumatic Mast**
  - Height Range: 1m - 2.2m
  - ~321 kPa (46.6 psi) to lift 10 kg
  - Capacity: 13.6 kg
  - Cost: $640
- **Air Compressor**
  - ~1034 kPa (150 psi) Max
  - 12V, 23 Amps max
  - Cost: $202



- **Pressure Sensor**
  - Sensing Range: 0-1034 kPa (0-150 psi)
  - Outputs: 0.5-4.5V linear voltage
  - Cost: $25
- **Solenoid Valve**
  - 12 V, 0.54 Amps
  - 689 kPa (100 psi)
  - Cost: $10
- **Relief Valve**
  - 345 kPa (50 psi) blow off pressure
  - Cost: $8

Pneumatic Telescoping Mast

- **Design Requirement:** The child rover shall have a mast capable of extending to a height of 2m +/- 0.2m and retracting back down to its original height
  - Satisfied through model geometry:
    - Extension height = 2.2m
    - Compacted height = 1m
- **Design Requirement:** The child rover shall have a mast capable of supporting 10kg of weight on the top
  - Satisfied through manufacturer specifications
  - Result:
    - Pressure required: 324 kPa ~ 47 psi
    - Air compressor pressure: 150 psi
  - Maximum mast load capacity: 13.6 kg



$$F_{press} = P_{top} x A_{top}$$

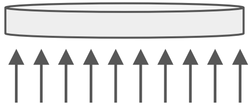
$$F_{press} = W_{mast} + W_{cam}$$

Hydraulic Mast Pressure Study

Design Requirement:

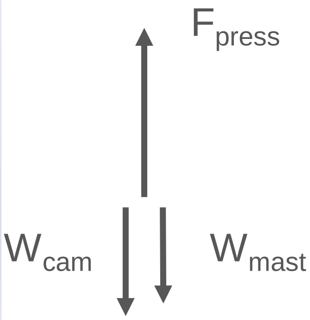
- Validation:
  - Determine pump pressure required to fully extend mast
- Given:
  - Maximum mass of camera: 10kg
  - Maximum mass of mast: 10kg
- Assumptions:
  - Upward pressure force acts on top cap only
  - Sliding friction forces negligible

Top Cap



$F_{press} = P_{top} x\ A_{top}$

$F_{press} = W_{mast} + W_{cam}$



Result:

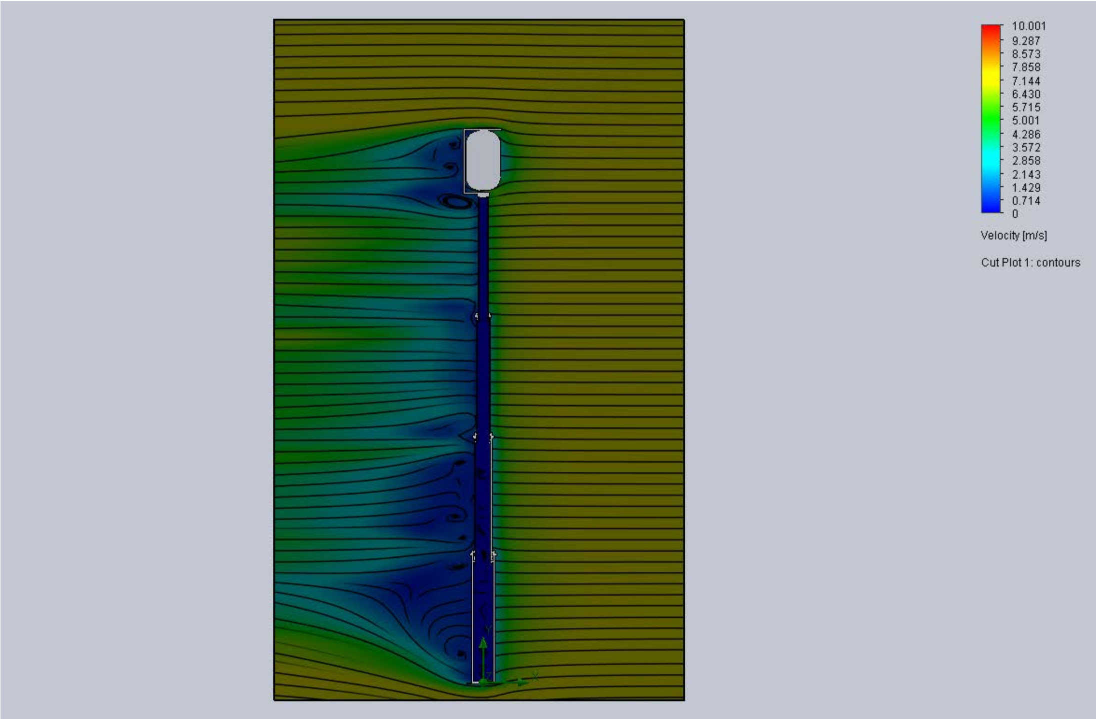
P_{req} = 264,810 Pa ~ 40 psi

P_{pump}= 725 psi → Bursting and shearing between sections analyzed in backup slides

Mast Aerodynamic force

- **Validation**
  - Can the mast sustain winds without tipping
- **Assumptions**
  - Wind speeds at 7m/s

Drag ≈ 2.9N



4. Communications Design Requirements

FR. 4 The child rover shall receive commands from both the ground station and the mother rover and transmit captured data to the ground station and the mother rover.

Communications-Bandwidth

2.4 Ghz Radio Frequency
Data Rate: 6-24 Mbps

- Validation
  - Has bandwidth to send/receive all data

- Assumption
  - Data Rate will be on the lower end

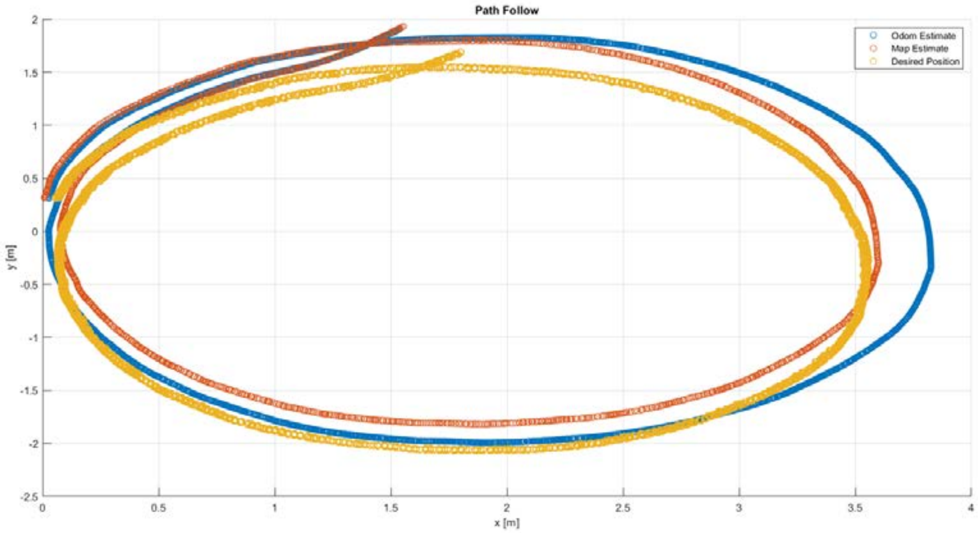
- Bandwidth
  - Video feed to GS(Mast Camera): 5.7 Mbps
  - Operator Commands from GS to ARGOS: ~16 bits
  - Sensor data from ARGOS to GS: ~115,320 bits

Insert GS,ARGOS,MR

Maximum Bandwidth: 5.7115 Mbps

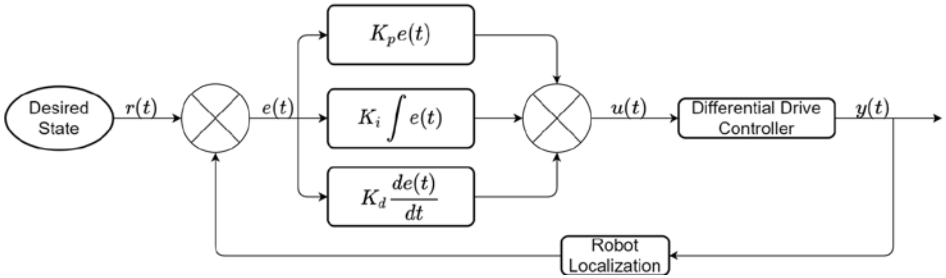
Communications- Loss of Comms

- Simulated in Gazebo
  - Distance travelled: 25 m
  - Linear Velocity: 0.5 m/s
- Move_base package
  - Input: waypoints
  - Algorithm: PID control loop
  - Output: Geometry_msgs/Twist to the differential drive controller



Communications- Loss of Comms

- Simulated in Gazebo
  - Distance travelled: 25 m
  - Linear Velocity: 0.5 m/s
- Move_base package
  - Input: waypoints
  - Algorithm: PID control loop
  - Output: Geometry_msgs/Twist to the differential drive controller

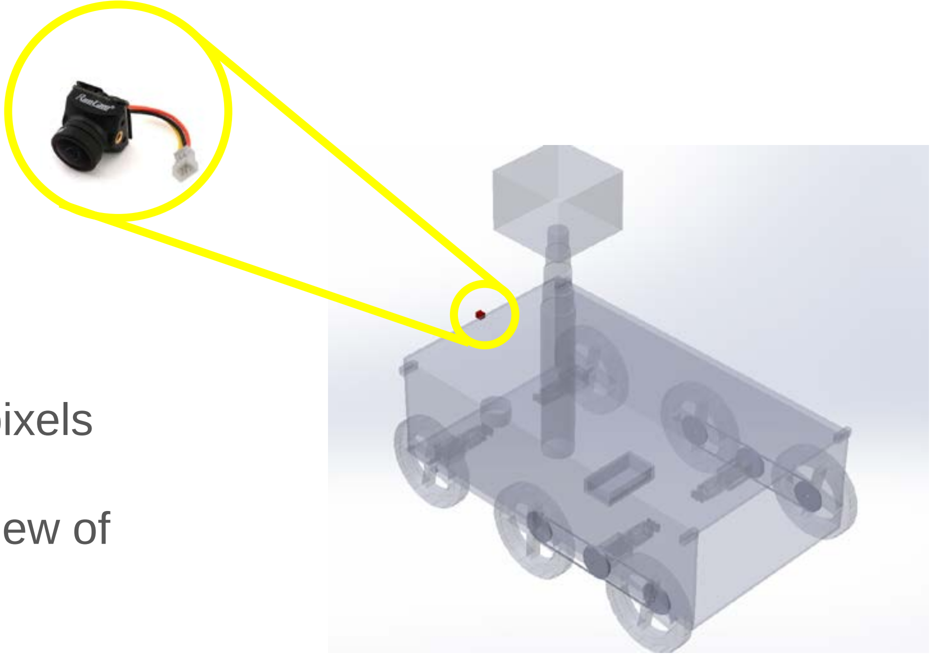


Baseline Design: Sensors - FPV Camera

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Meets Level of Autonomy 1

- Runcam Nano 2 FPV Camera
  - Input 3V to 5V
  - 1.8mm or 2.1mm lens
    - 155 to 170 Degrees FOV
  - 700 TVL Resolution or 976*494 pixels
  - Cost : $20
- Allows Operator to have first person view of rover to allow for operator control

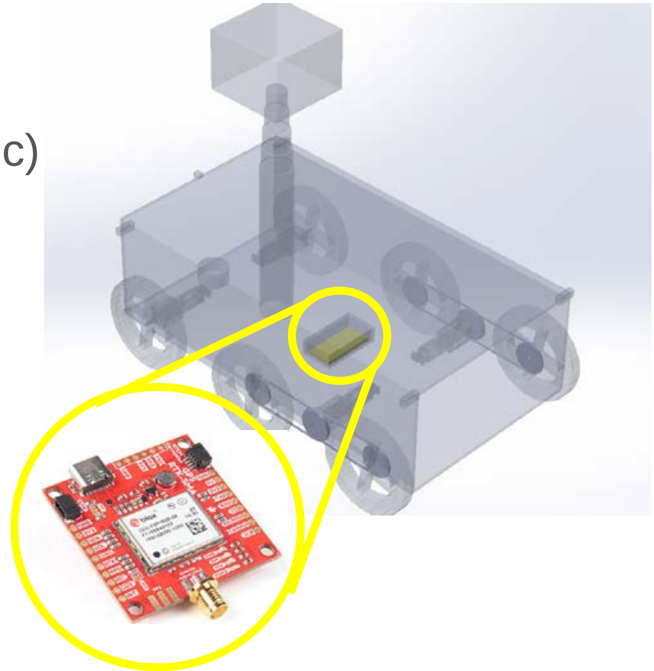


Baseline Design: Sensors - GPS

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Meets Level of Autonomy 1

- SparkFun GPS-RTK-SMA Breakout - ZED-F9P (Qwiic)
  - Input: 5V/3.3V @ 68mA to 130mA
  - Output: I2C
  - Receives both L1C/A and L2C bands
  - Horizontal Accuracy:
    - 2.5m without RTK(Real Time Kinematic)
    - 0.010m with RTK(Real Time Kinematic)
  - Cost: $219.95
- **Purpose**
  - Detect rovers position for waypoint navigation



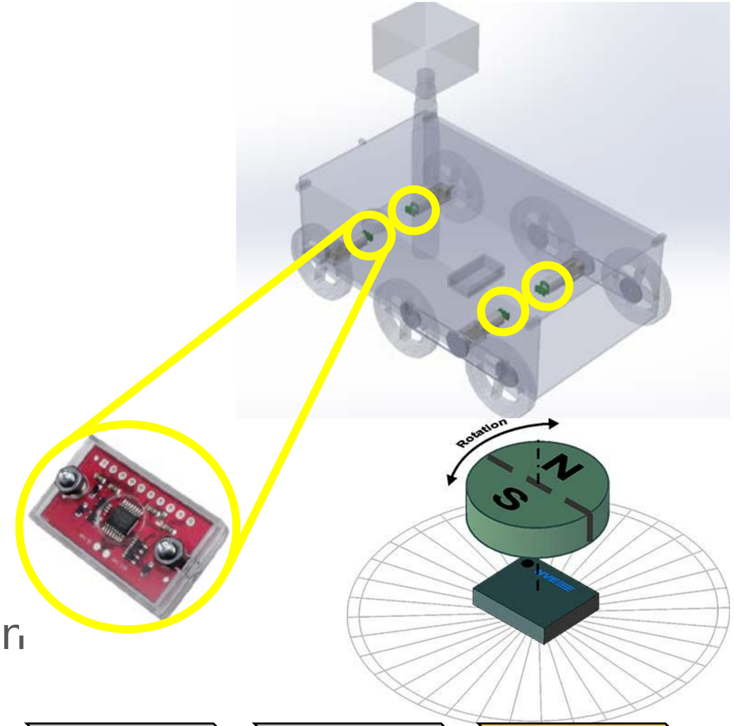
Sparkfun ZED-F9P

Baseline Design: Sensors - Motor Encoder

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Meets Level of Autonomy 2

- AndyMark 3749 Mag Encoder
  - Input: 5V @ 40mA
  - Output: 1024 bin PWM
  - Rating: 30,000 RPM
  - Cost: $47
- Purpose
  - Determine angular velocity and position of each motor shaft to determine rover position and velocity.

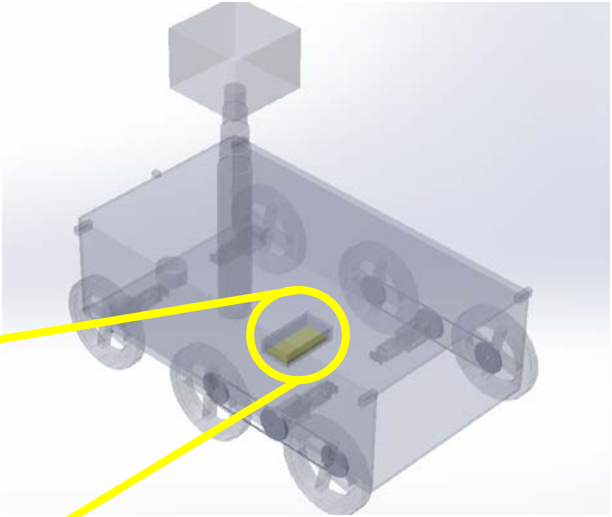


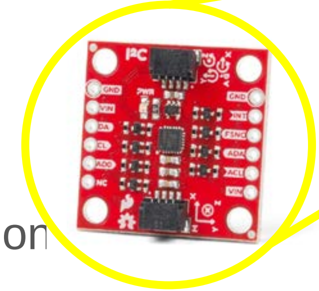
Baseline Design: Sensors - IMU

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

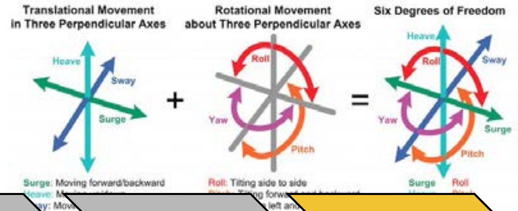
Meets Level of Autonomy 1

- SparkFun VR IMU Breakout - BNO080 (Qwiic)
  - Input: 1.65V-3.6V
  - Output: I2C
  - Rotation Vector
    - Dynamic Error: 2.5°
    - Static Error: 1.5°
  - Cost: $34.95
- **Purpose**
  - Detect rovers inclination for possible tipping condition





Sparkfun BNO080

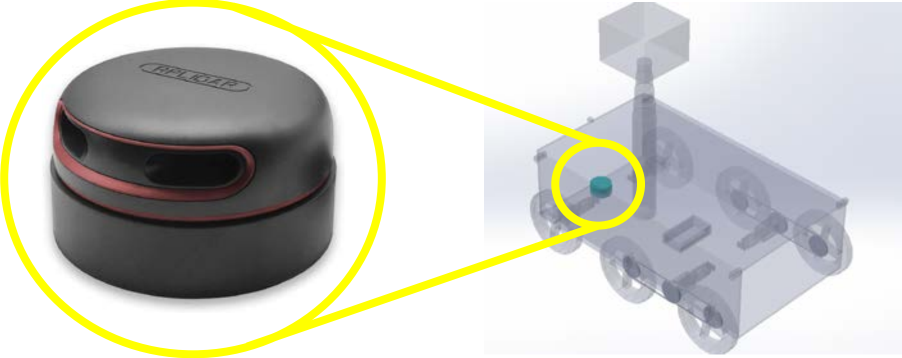


Baseline Design: Sensors - LiDAR

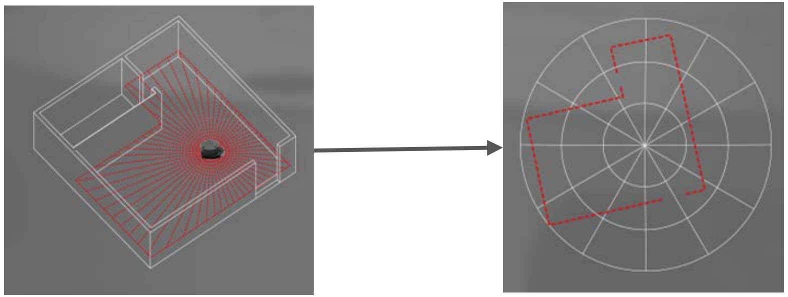
Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Meets Level of Autonomy 3

- SLAMTEC RPLIDAR A2
  - Range: 0.2m to 8m ± 0.005m
  - FOV: 360º ± 0.25
    - Limited to <180º
  - Cost: $320
- **Purpose**
  - Detect obstacles during autonomous navigation



SLAMTEC A2M8



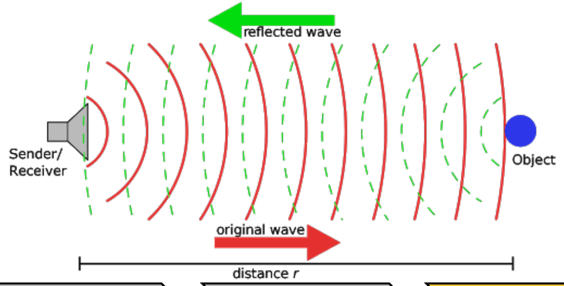
Baseline Design: Sensors - Ultrasonic Range Finder

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Meets Level of Autonomy 3

- Zio Ultrasonic Distance Sensor HC-SR04 from Sparkfun
  - Range: 0.02m to 4m
  - FOV: 15º
  - Output: I2C
  - Cost: $14
- **Purpose**
  - Detect obstacles in LiDAR blind spots during autonomous navigation

Sparkfun HC-SR04



Navigation Sensors: FPV Camera

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

- **Validation**
  - Can an operator detect an obstacle and send a stop command before colliding with it?
- **Assumptions**
  - Velocity = 3m/s
  - Kinetic Friction coefficient 0.35
  - Full skid stop and turning not allowed
  - FOS = 1.5

Source	Latency	Reference
Camera to GS	50 ms	Similar components test
Operator reaction	250 ms	Human Average
GS to Rover	50 ms	Similar components test
Arduino To Motor	100 ms	5000 clock cycles
Total	450 ms	

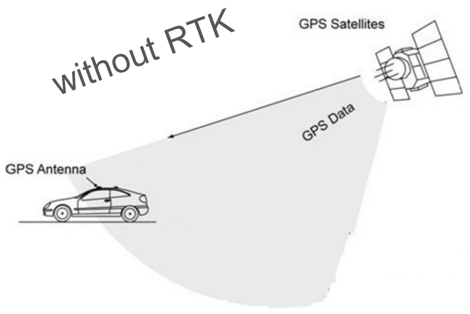
Stopping distance from kinematics	2m
Distance traveled during latency	450ms x 3 m/s = 1.35m
Min distance from object with FOS	5.03m

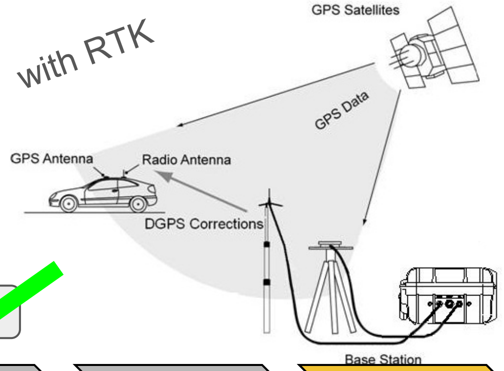
Feasible ✓

Navigation Sensors: GPS

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

- **Validation**
  - Can the GPS sensor confirm the rover is within 5m of some target location
- **Assumptions**
  - FOS 1.5
  - RTK base station will exist
- **Horizontal Accuracy:**
  - 2.5m without RTK(Real Time Kinematic)
  - 0.010m with RTK(Real Time Kinematic)



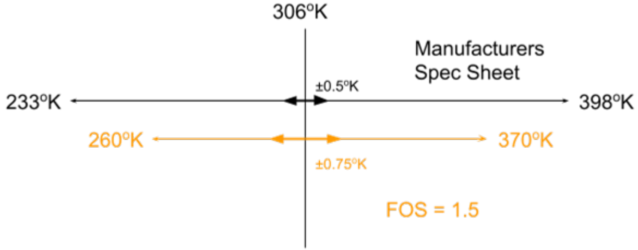


Study	Feasibility Outcome	Required Min/Max
Without RTK	3.75m	5m
With RTK	0.015m	5m

Feasible ✓

Surveillance Sensors: Temperature Sensor

- **Validation**
  - Can ARGOS take ambient temperature data with an accuracy of +/-1K?
- **Assumptions**
  - Sensor Range: 233ºK to 398ºK
  - Accuracy: ±0.5ºK
  - Ambient temperature Max: 306ºK
  - Factor of Safety = 1.5



Study	Feasibility Outcome	Required Min/Max
Maximum Temperature	370ºK	306ºK
Accuracy	± 0.75ºK	± 1ºK

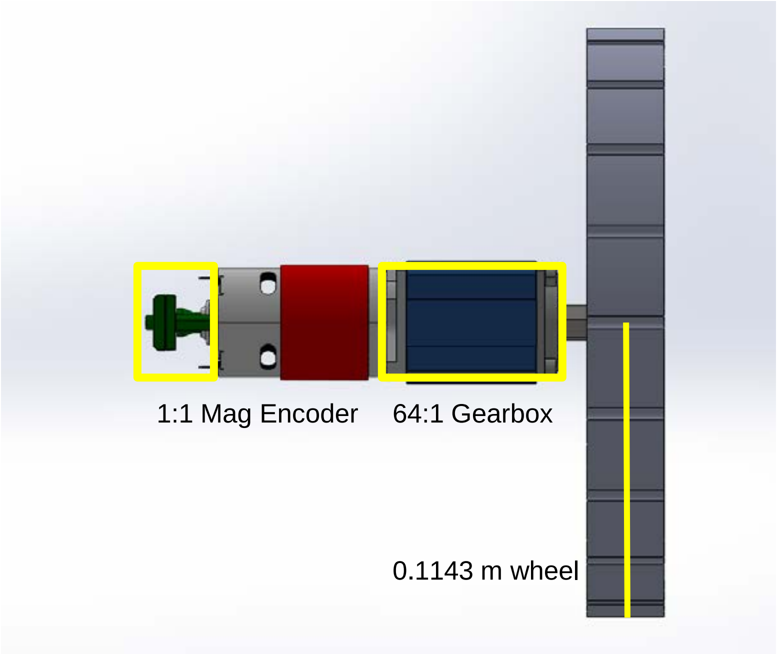
SparkFun Digital Temperature Sensor - TMP117 (Qwiic)

Feasible

Navigation Sensors: Motor Encoder

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

- **Validation**
  - Can the motor encoder accurately determine the angular velocity and position of the motor shaft
- **Assumptions**
  - 1.5 FOS on 30,000 RPM rating
  - 1.5 FOS on 1024 bin accuracy
  - 64:1 gearbox between motor and wheel
- **Maximum Rover Linear Speed**
  - 3.740 m/s > 3 m/s upper bound
- **Minimum Detectable Angle // Linear Distance**
  - 0.5273 deg // 0.9417 mm

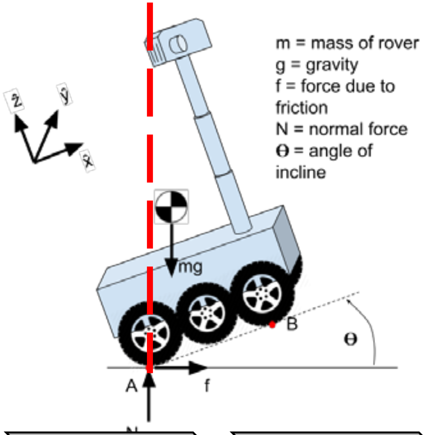


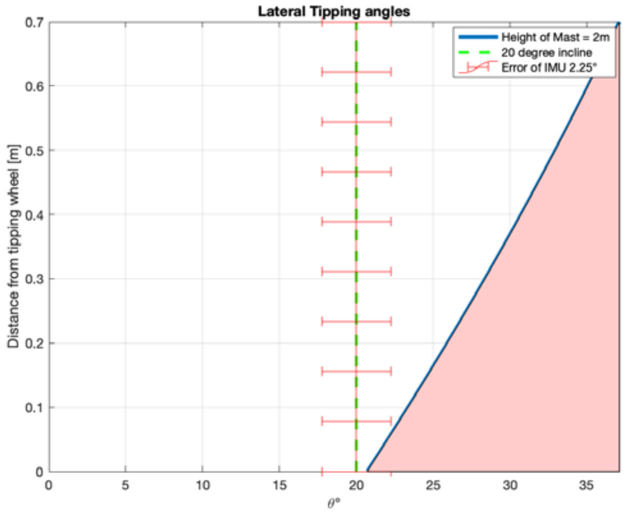
Feasible ✓

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

Navigation Sensors: IMU

- **Validation**
  - Can the IMU detect angle of inclines for possible tipping conditions
- **Assumptions**
  - Rover will not deploy the mast while moving
  - 1.5 FOS on 1.5° static error
  - Mast is 2m with a 5kg mass on top





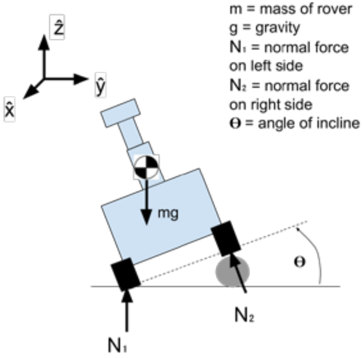
$$\theta_c = \tan^{-1}\left(\frac{x_{cg}}{z_{cg}}\right)$$

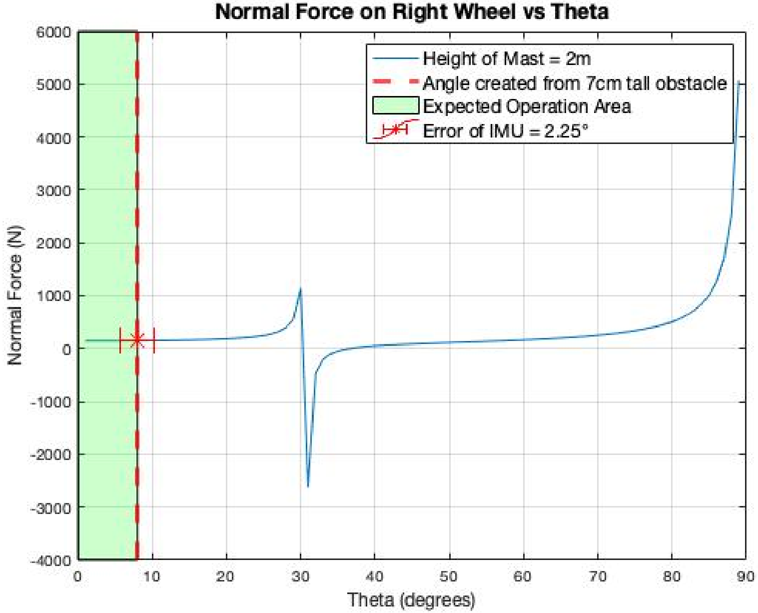
Feasible

Navigation Sensors: IMU

Sensors					
Navigation					Surveillance
Position	Translational	Rotational	Object Detection		
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature	

- **Validation**
  - Can the IMU detect angle of inclines for possible tipping conditions
- **Assumptions**
  - Rover will not deploy the mast while moving
  - 1.5 FOS on 1.5° static error
  - Mast is 2m with a 5kg mass on top



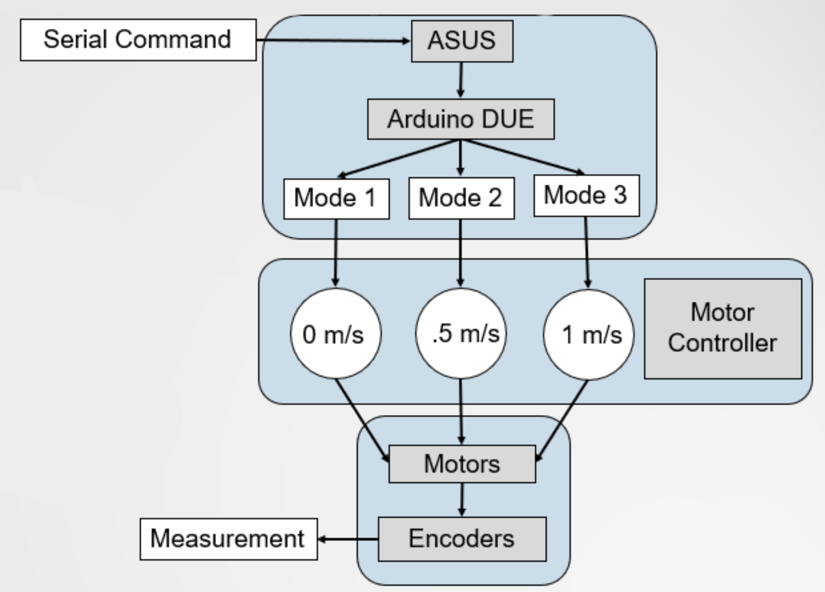


Feasible

Navigation Sensors: Microcontroller and Computer

- **Validation**
  - Can Arduino Due interface with the chosen sensors
  - Can the Arduino Due pass the measured data to the Computer at a high enough rate for navigation
- **Assumptions**
  - Accurate datasheets
  - HERMES had success with electronics system

Required	Available
3 QWIIC I2C Connectors	4 QWIIC I2C w/ Shield
10 PWM I/O	12 PWM I/O Pins

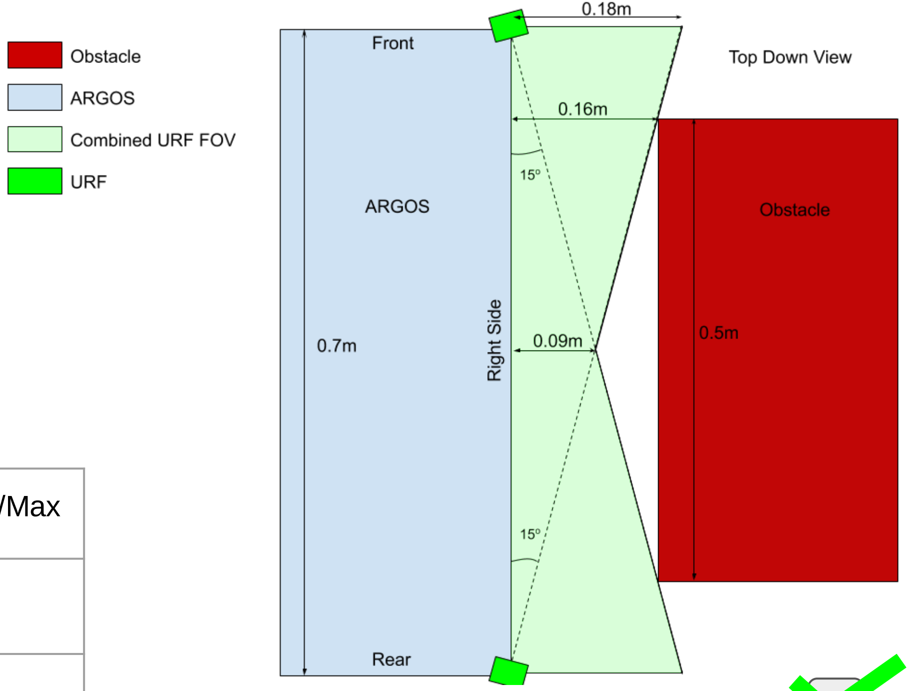


Plausible

Navigation Sensors: Ultrasonic Range Finder

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

- **Validation**
  - Can the URF detect obstacles in the LiDAR blind spots
- **Assumptions**
  - Update Period = 0.06s
  - FOV = 15º
  - Turn 360º around midpoint
  - Factor of Safety = 1.5
  - Minimum detectable obstacle width = 0.33 m



Study	Feasibility Outcome	Required Min/Max
Maximum Angular Velocity	2.9 rad/s	1 rad/s
Minimum Object Width	0.50 m	0.61 m

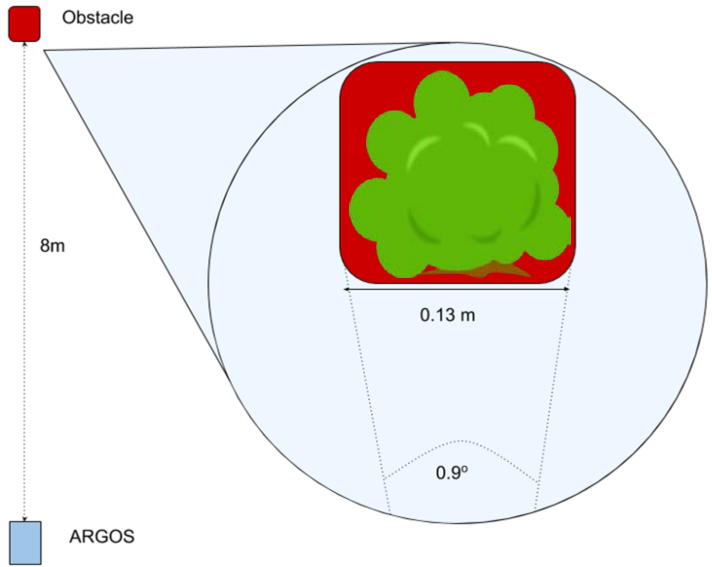
Feasible

Navigation Sensors: LiDAR

Sensors				
Navigation				Surveillance
Position	Translational	Rotational	Object Detection	
•FPV Camera •GPS	•Motor Encoder	•IMU	•FPV Camera •LiDAR •Ultrasonic Range Finders	•Camera •Temperature

- **Validation**
  - Can ARGOS detect an obstacle before colliding with it?
- **Assumptions**
  - Maximum range = 8m
  - Angular resolution 0.9º
  - Update Period = 0.1s
  - μ = 0.07
    - Rolling Friction of rubber on dirt
  - Factor of Safety = 1.5

Top Down View

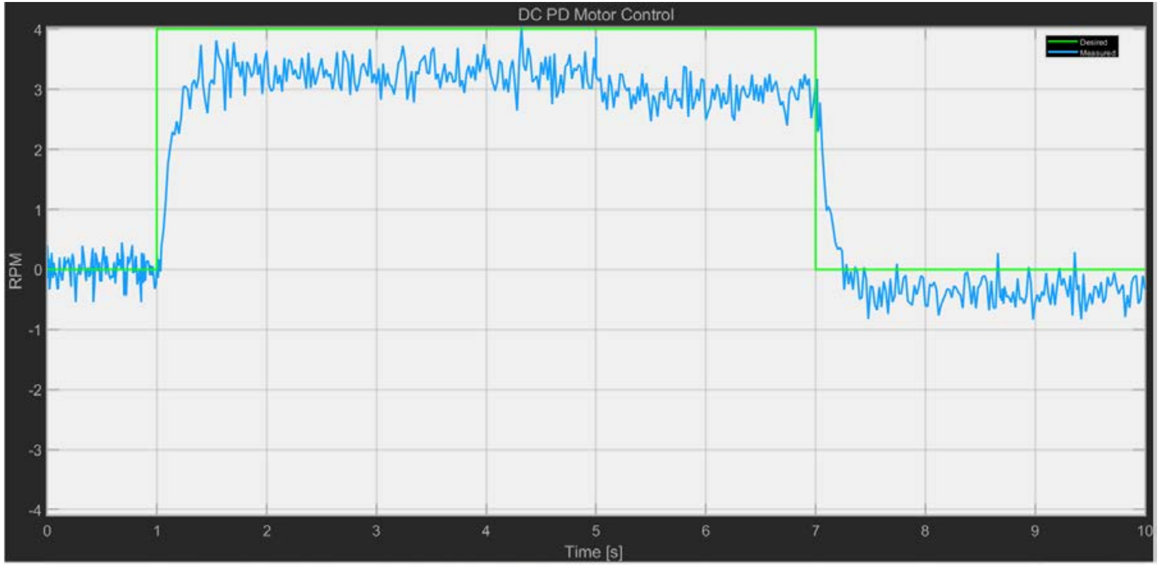


Study	Feasibility Outcome	Required Min/Max
Maximum Linear Velocity	3.43 m/s	3 m/s
Minimum Object Width	0.20 m	0.61 m

Feasible

Navigation: Motor Controller

- **Validation**
  - Can the PD motor controller command the motor to a desired rpm?
- **Assumptions**
  - Disturbance Torque happens instantaneously
  - No slip
  - 3 m/s linear velocity
  - 64:1 gear ratio
  - Andymark 775 Redline Motor
- Commands to within +/- 1.2 RPM in <1 second

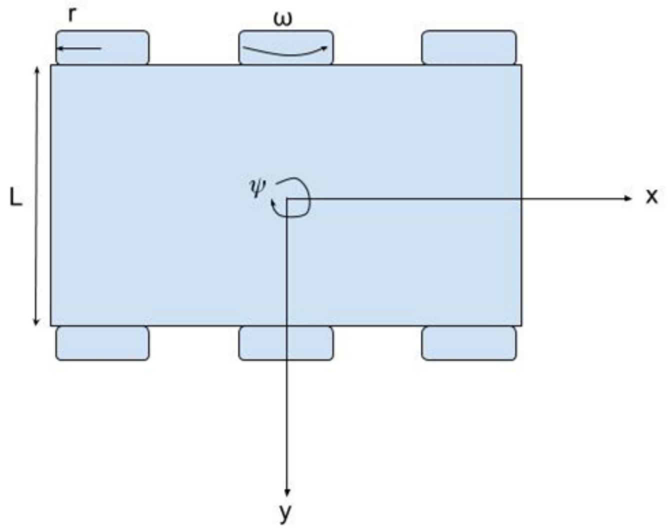


Feasible

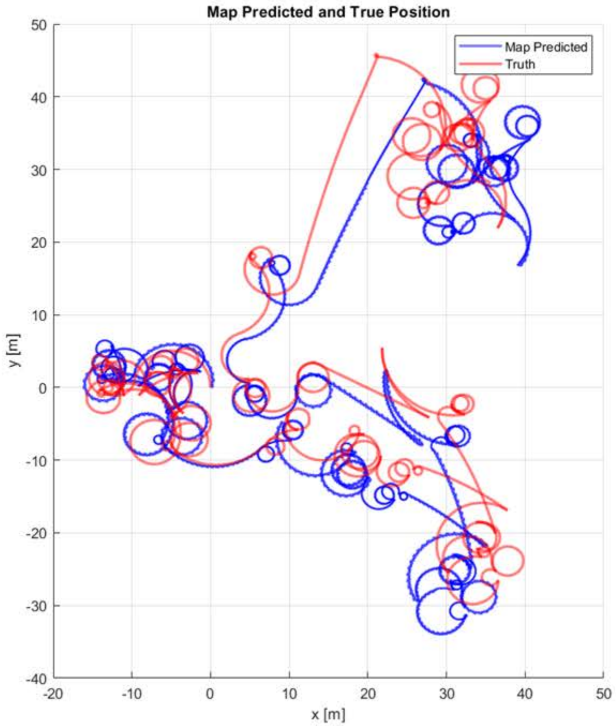
Navigation: Skid Steer EOM

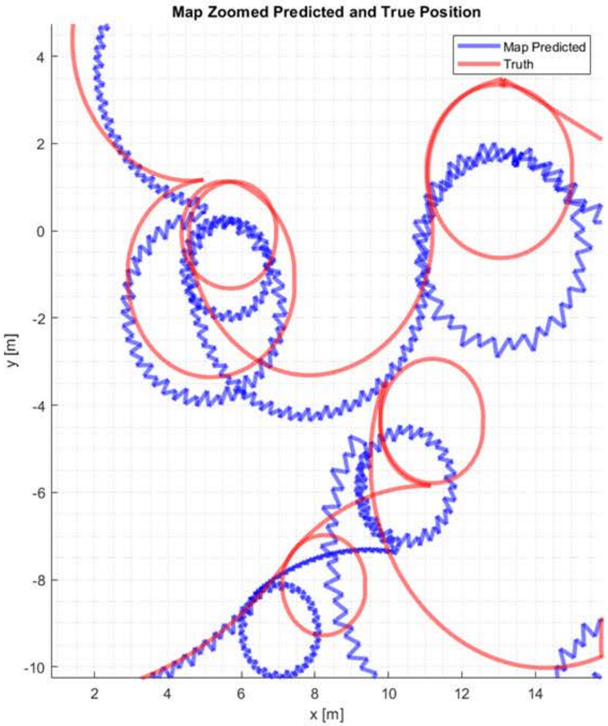
$$\dot{x} = \frac{r}{2}(\omega_r + \omega_l)\cos\psi$$
$$\dot{y} = \frac{r}{2}(\omega_r + \omega_l)\sin\psi$$
$$\dot{\psi} = \frac{r}{L}(\omega_r - \omega_l)$$

$r =$ wheel radius
$\omega_r =$ right wheel angular velocity
$\omega_l =$ left wheel angular velocity
$L =$ wheel side separation



Software - Localization





Sensors: Encoder

$$V_{max} = \frac{30,000(RPM)}{1.5(FOS)} * 2\pi \frac{rad}{Rotation} * \frac{1(min)}{60(s)} * \frac{1}{64} * 0.1143(m)$$

$$V_{max} = 3.740\frac{m}{s}$$

$$\theta_{min} = \frac{360(deg)}{\frac{1024(bin)}{1.5(FOS)}}$$

$$\theta_{min} = 0.5273\frac{deg}{bin}$$

$$D_{min} = 0.5273\frac{deg}{bin} * \frac{1}{64} * 0.1143(m)$$

$$D_{min} = 0.9417mm$$

Sensors: URF Time Resolution

- $\Delta\psi$ = maximum angle to object
- Δt = maximum update rate of sensor
- FOS = factor of safety
- $\dot{\psi}$ = angular velocity

$$\dot{\psi} = \frac{\Delta\psi}{\Delta t}$$

$$\dot{\psi}_{working} = \frac{\dot{\psi}}{FOS}$$

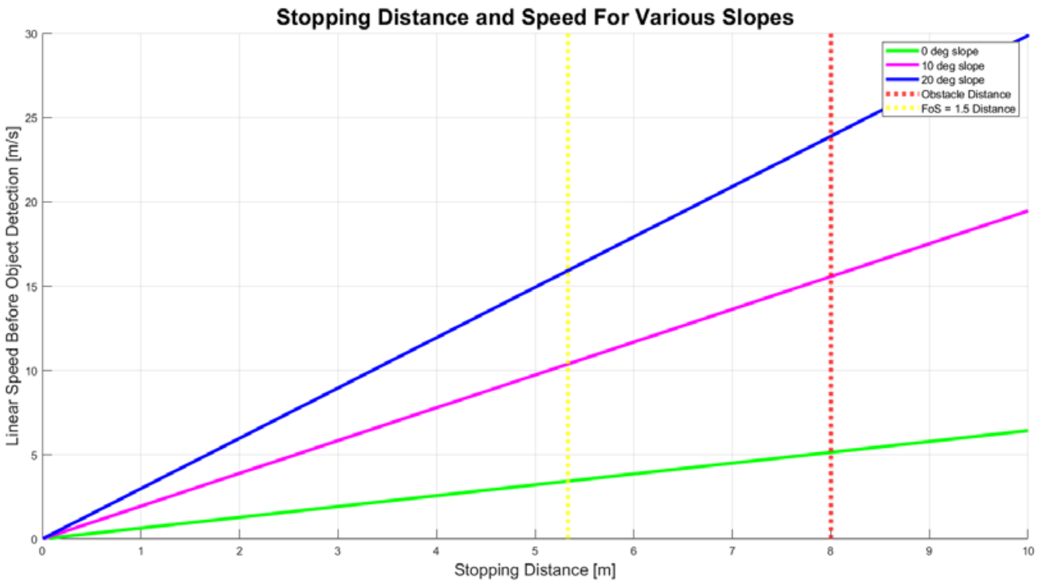
Sensors: LiDAR Time Resolution

- D = Stopping distance [m]
- $\dot{x}_i$ = Initial linear speed [m/s]
- g = 9.81, gravitational acceleration [m/s^2]
- μ = 0.07, coefficient of friction
- G = [0,0.1763,0.364], grade (0^o,10^o,20^o)
- Δt = 0.1, update period of the LiDAR

$$D = \frac{\dot{x}_i}{g(\mu + G)} + \dot{x}_i \Delta t$$

Distance after detection

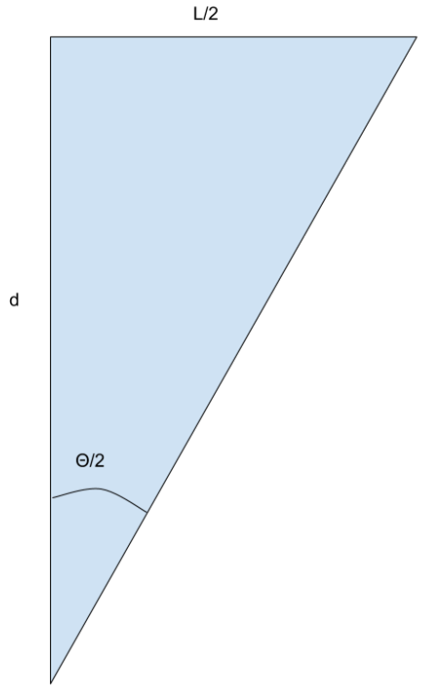
Distance before detection



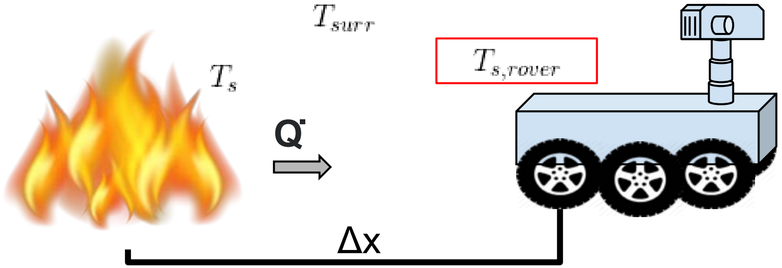
Sensors: LiDAR Cross-Section Resolution

- L_{min} = minimum detectable obstacle cross-section
- d = 8m, distance to obstacle
- Θ = 0.9º, angular resolution
- FOS = 2, factor of safety

$$l_{min} = 2d \tan \frac{\theta}{2}$$
$$l_{min,working} = l_{min} FOS$$



Thermal Model



- **Validation**
  - What temperatures will the rover experience at various distances from the flame front?
- **Assumptions**
  - Safety Factor (SF) : 2
  - Temp of Fire (Ts) : 1073K * SF
  - Fire Size : 1m x 100m
  - Wind Speed : 7m/s
  - All natural and forced convection is transferred to rover
  - View Factor : 0.003

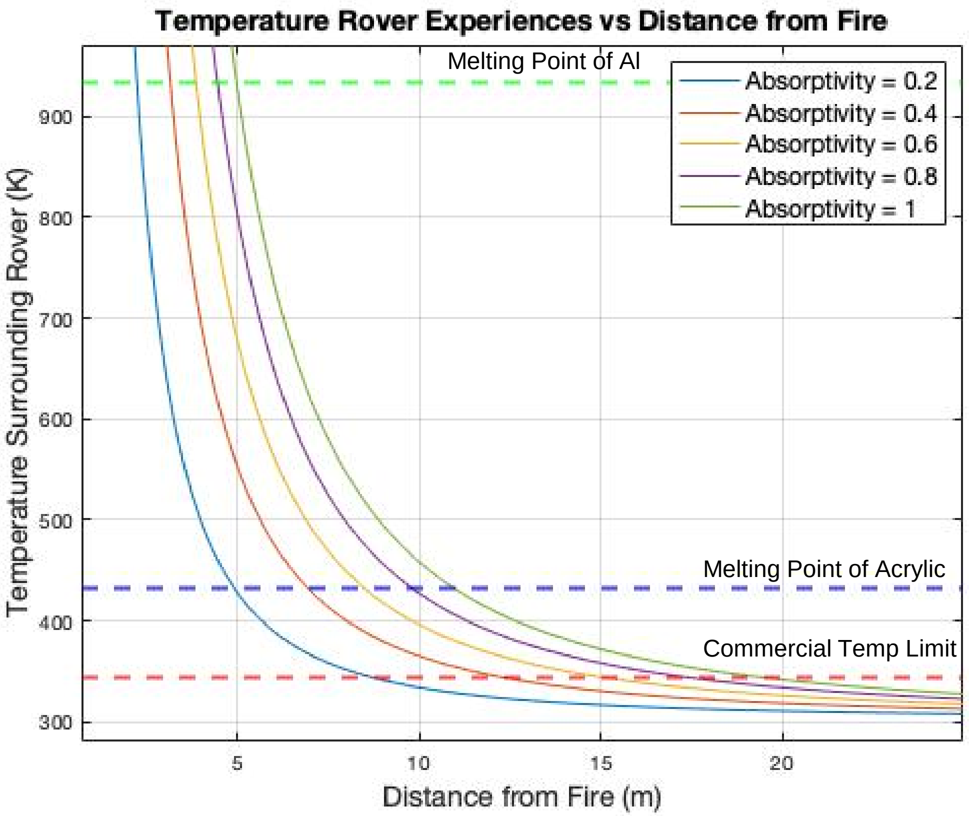
$$Q_{conv,free} = h_{conv,free} * A_s * (T_s - T_{surr})$$
$$Q_{conv,forced} = h_{conv,forced} * A_s * (T_s - T_{surr})$$
$$Q_{rad} = \epsilon * \sigma * A_s * (T_s^4 - T_{surr}^4)$$

$$Q_{inc,fire} = \frac{(Q_{rad} * F_{12}) + Q_{conv,free} + Q_{conv,forced}}{x^2}$$

$$T_{s,rover} = T_{surr} + \alpha * \frac{Q_{inc,fire}}{h_{combined} * A_{rover}}$$

Thermal Model

- Min allowable distance: **9m to 22m**
  - Black body: 22m
  - Polished Al Body: <9m
    - Absorptivity of 6061-T6 Al < 0.1



Camera wiring

NYCOIL® Cable Conduit

coiled hose used to house electrical wiring or antenna RF and positioner cable.

Subsystem Breakdown

Hydraulic Mast

Subsystem	Total
Sensors	$773.64
Electronics	$547.81
Drivetrain	$1,048.49
Chassis	$142.79
Camera	$269.99
Test Rig	$218.62
Hydraulic Mast	$400.00
Communications	$306.46
Total	**$3,707.80**
Remaining	**$1,292.20**

Off-Ramp Mast

Subsystem	Total
Sensors	$773.64
Electronics	$547.81
Drivetrain	$1,048.49
Chassis	$142.79
Camera	$269.99
Test Rig	$218.62
Off Ramp Mast	$900.00
Communications	$306.46
Total	**$4,207.80**
Remaining	**$792.20**

Bill Of Materials

Component	Distributer	Quantity	Unit Price	Shipping	Total Price	Subsystem
GPS-RTK-SMA Breakout - ZED-F9P	Sparkfun	1	219.95	0	219.95	Sensors
RedLine Encoder Kit	AndyMark	2	47	0	94	Sensors
Zio Ultrasonic Distance Sensor - HC-SR04 (Qwiic)	Sparkfun	4	13.95	0	55.8	Sensors
SLAMTEC A2M8	SAMTEC	1	319		319	Sensors
Runcam Nano 2 FPV Camera	Flight Test	1	19.99		19.99	Sensors
Infrared Thermometer - MLX90614	Sparkfun	1	29.95	0	29.95	Sensors
SparkFun VR IMU Breakout - BNO080 (Qwiic)	Sparkfun	1	34.95	0	34.95	Sensors
Arduino Due	amazon	1	39.9	0	39.9	electronics
Intel NUc	Intel	1	247	10	257	electronics
Kingston A400 120G Internal SSD M.2	amazon	1	19.99	0	19.99	electronics
GPS/GNSS Magnetic Mount Antenna	Sparkfun	1	12.95	0	12.95	electronics
SPARK Brushed DC Motor Controller	AndyMark	2	50	10	110	electronics
NETGEAR 5-Port Gigabit Ethernet Unmanaged Switch (GS305)	amazon	1	15	0	15	electronics
REDGO Video Audio VHS VCR USB Video Capture Card to DVD Converter Capture Card Adapter	amazon	1	10.99	0	10.99	electronics
SMAKN Waterproof DC/DC Converter 12V (10-30V) Step UP to 48V/4A 192W Power Supply Module	Amazon	1	29.99		29.99	electronics
12V 16Ah Deep Cycle LiFePO4 Battery	Amazon	1	49.99		49.99	electronics

Qwiic JST Connector - SMD 4-pin (Horizontal)	spark fun	4	0.5	0	2	electronics
2-Bolt Flange Bearing	Grainger	6	19.35	12.83	128.93	Drivetrain
Metal Gear	McMaster	0	60.4		0	Drivetrain
Standard Sprocket	Misuni	10	8.19	13.4	95.3	Drivetrain
Pillow Block Bearing	Grainger	6	21	0	126	Drivetrain
Talon SRX Speed Controller	AndyMark	2	99	0	198	Drivetrain
Ventilation Spacer	AndyMark	2	5	0	10	Drivetrain
1/2" Shaft	McMaster	6	8.71		52.26	Drivetrain
Chain	McMaster	10	5.49		54.9	Drivetrain
775 Redline Motor	AndyMark	2	19	8.5	46.5	Drivetrain
Swisher 13.75 in Rear Wheel	Lowe's	6	24.1	0	144.6	Drivetrain
57 Sport Gearbox	AndyMark	2	96	0	192	Drivetrain
6061 Aluminum Sheet 20x36.5	MidWest Steel & Aluminum	1	52.33	10.48	62.81	Drivetrain - Chassis
Plexiglass Black Acrylic Plate 24inx36inx1/8in	Home Depot	2	39.99	0	79.98	Drivetrain - Chassis
1-3/4" Bore Wear Ring	McMaster	2	4.73		9.46	Mast

1/4 Machine Screws	McMaster	2	2.83		5.66	Mast
3/8 Machine Screws	McMaster	2	2.74		5.48	Mast
2" OD 1.25" ID Aluminum Tube	McMaster	1	95.58		95.58	Mast
2.25" OD 1.75" ID Aluminum Tube	McMaster	1	78.26		78.26	Mast
1-3/4" Bore Dynamic Seal	McMaster	1	5.93		5.93	Mast
O-ring 1.25" bore x100 for whatever reason	McMaster	1	6.95		6.95	Mast
Quick Disconnect Fitting	McMaster	1	11.3		11.3	Mast
SUNBA 601-D25X	Amazon	1	269.99		269.99	Camera
Rocket M2	Ubiquiti	2	80		160	Communication
POE TP-DCDC-1224 Adapter	PoETexas	2	5.49		10.98	Communication
TRENDnet Reverse SMA Female to N-Type Male Weatherproof Connector Cable (6.5ft, 2M), TEW-L202	Trendnet	1	19		19	Communication
Antenna 2.4GHz 12dBi Omni-Directional WiFi w/ RP-TNC	Data Alliance	1	8.99		8.99	Communication
1ft Cat6 550 MHz UTP Snagless Ethernet Network Patch Cable, Blue	Cable Leader	2	0.77		1.54	Communication
1 Foot Male to Male 2.1mm x 5.5mm Plug DC Power Adapter Cable 18GA	Valley Enterprises	1	3.99		3.99	Communication
Tupavco tp511 Panel Antenna 2.4 GHz 20 dBi directional antenna	Tupavco	1	54.98		54.98	Communication
TP-Link 5 Port Fast Ethernet 10/100Mbps PoE Switch	Amazon	1	34.99		34.99	Communication
USB 2.0 Audio/Video Converter	Amazon	1	11.99		11.99	Communication
Total					3307.8	

Forest Research : Trees

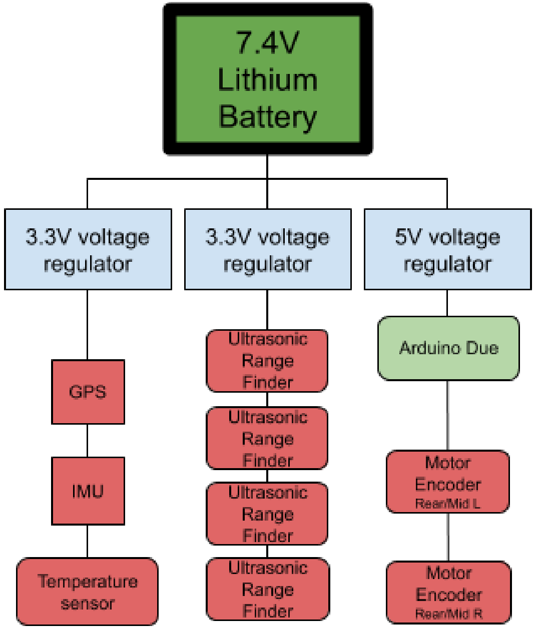
Source : https://www.fs.fed.us/psw/publications/documents/cfres_series/cfres_itr_afswp416.pdf

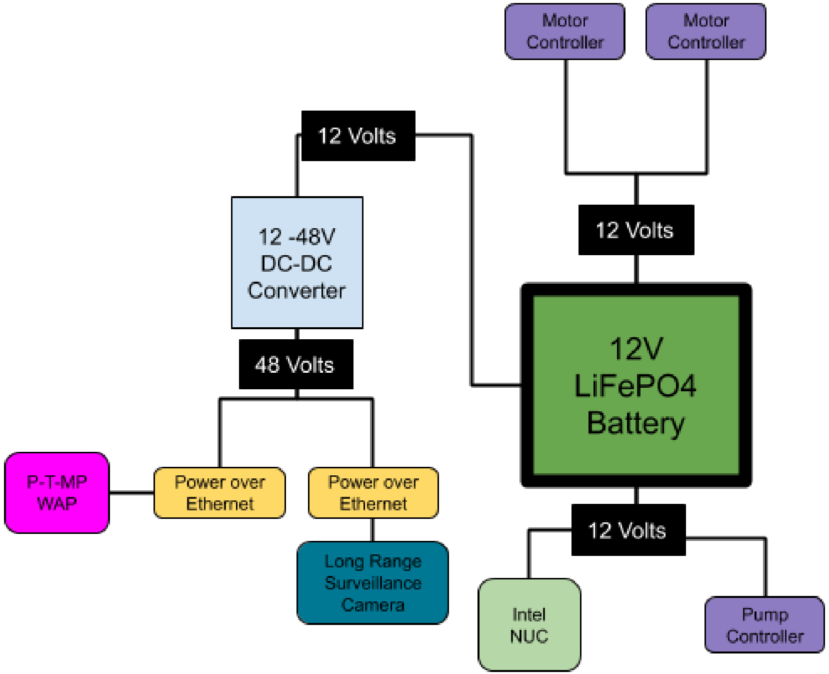
Tree Species	Average Height (ft)	Max Crown Length (ft)	Difference (ft)	Difference (m)
Ponderosa Pine	80	48.4	31.6	9.63168
Sugar Pine	175	19.6	155.4	47.36592
Western White Pine	175	48.95	126.05	38.42004
Lodgepole Pine	75	45.6	29.4	8.96112
Loblolly Pine	100	21.3	78.7	23.98776
White fir	50	49.4	0.6	0.18288
Grand fir	150	61.95	88.05	26.83764
Douglas fir	55	42.5	12.5	3.81
Engelmann Spruce	87.5	47.7	39.8	12.13104
Western Hemlock	125	39.45	85.55	26.07564
Incense Cedar	126.5	27.6	98.9	30.14472
Western Redcedar	200	31.9	168.1	51.23688
Western Larch	140	38.7	101.3	30.87624
			Average	23.82012

Forest Research : Shrubs/Bushes

Source: https://extension.colostate.edu/topic-areas/yard-garden/trees-and-shrubs-for-mountain-areas-7-423/							
	Native Colorado Shrubs						
	Shrub Speciies	Max Height (when mature, ft)	Max Height (meters)	Max Width (ft)	Max Width (m)	Min Width (ft)	Min Width (f
	Red chokeberry	6	1.8288	4	1.2192	2	0.6096
	Black chokeberry	5	1.524	5	1.524	2	0.6096
	Japanese barberry	5	1.524	5	1.524	2	0.6096
	Siberian peashrub	10	3.048	6	1.8288	4	1.2192
	Peking or Hedge cotor	8	2.4384	6	1.8288	4	1.2192
	Burning bush	6	1.8288	6	1.8288	4	1.2192
	Forsythia	6	1.8288	8	2.4384	6	1.8288
	Creeping juniper	2	0.6096	6	1.8288	4	1.2192
	Savin juniper	4	1.2192	6	1.8288	4	1.2192
	'Cheyenne' Cheyenne	6	1.8288	6	1.8288	4	1.2192
	'Cheyenne' Cheyenne	6	1.8288	5	1.524	4	1.2192
	Common ninebark	6	1.8288	6	1.8288	4	1.2192
	Nanking cherry	8	2.4384	8	2.4384	6	1.8288
	Purpleleaf sand cherr	6	1.8288	6	1.8288	4	1.2192
	Staghorn sumac	12	3.6576	8	2.4384	6	1.8288
	Alpine currant	4	1.2192	4	1.2192	3	0.9144
	Elderberry	8	2.4384	8	2.4384	6	1.8288
	Ash-leaf spirea or Ura	6	1.8288	6	1.8288	4	1.2192
	Vanhoutte spirea	6	1.8288	6	1.8288	4	1.2192
	Coralberry, buckbrush	5	1.524	5	1.524	3	0.9144
	Common lilac	8	2.4384	6	1.8288	4	1.2192
	Preston or Canadian li	8	2.4384	6	1.8288	4	1.2192
	Wayfaringtree viburn	8	2.4384	8	2.4384	6	1.8288
	Nannyberry viburnum	10	3.048	8	2.4384	6	1.8288
	European cranberrybu	10	3.048	10	3.048	8	2.4384
	American cranberrybu	8	2.4384	6	1.8288	4	1.2192
		Average	2.074984615		1.922584615		1.31298462

Power Diagram





Arduino Pinout and Serial Ability

Pin Number	Device	I/O	Additional	Sensor	Speed(KHZ)	number of sensors	total
3	MC 1	O	PWM	GPS	25	1	25
4	MC 2	O	PWM	IMU	3.00E+06	1	3.00E+06
5	PC	O	PWM	Encoder	512	4	2048
7	MOSFET	O		URF	0.00017	4	0.00068
20	Serial Chain	I	SCL	Motor Controller	100	4	400
21	Serial Chain	O	SDA	Pump controller	100	1	100
23	MC 1	O	DIR			Total: [MHz]	3.002573001
24	MC 2	O	DIR			Available	10 MHz
25	PC	O	DIR				
30	ME 1	I	PWM				
31	ME 2	I	PWM				