ARGOS

Autonomous Rover for Ground-based Optical Surveillance

Preliminary Design Review

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Project Overview → **Baseline Design** → **Feasibility Studies** → **Summary**

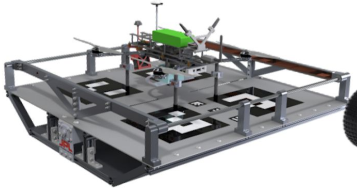
Project Overview

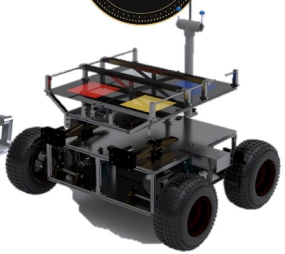
Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

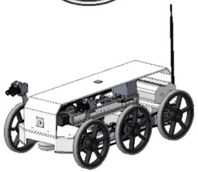
Heritage Projects

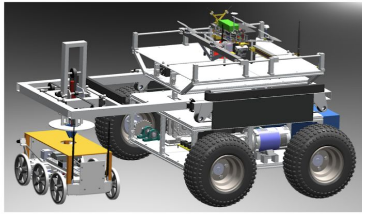
JPL's Fire Tracker System is made to be a low cost, hands off tool for fire identification.

2015-2016	2016-2017	2016-2017	2018-2019	2019-2020
INFERNO	CHIMERA	DRIFT	HERMES	ATLAS









Motivation

- The Fire Tracker System currently lacks the ability to take high quality photos/videos.
- Forest fires often are in an environment with obstacles blocking line of site, providing a camera mast will give a better perspective for operators.

Mission Statement / Objectives

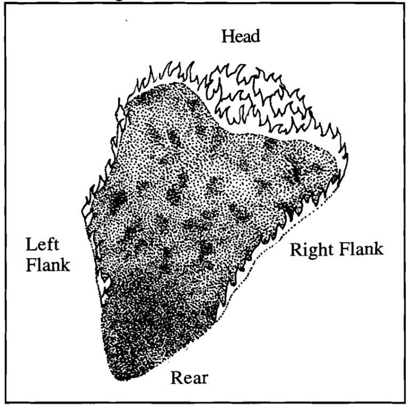
The ARGOS team shall design, build, and test a child rover that will :

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 or fireline from the top of an **extendable/retractable mast**
4. **Communicate** temperature data, photos, and video to the GS/MR

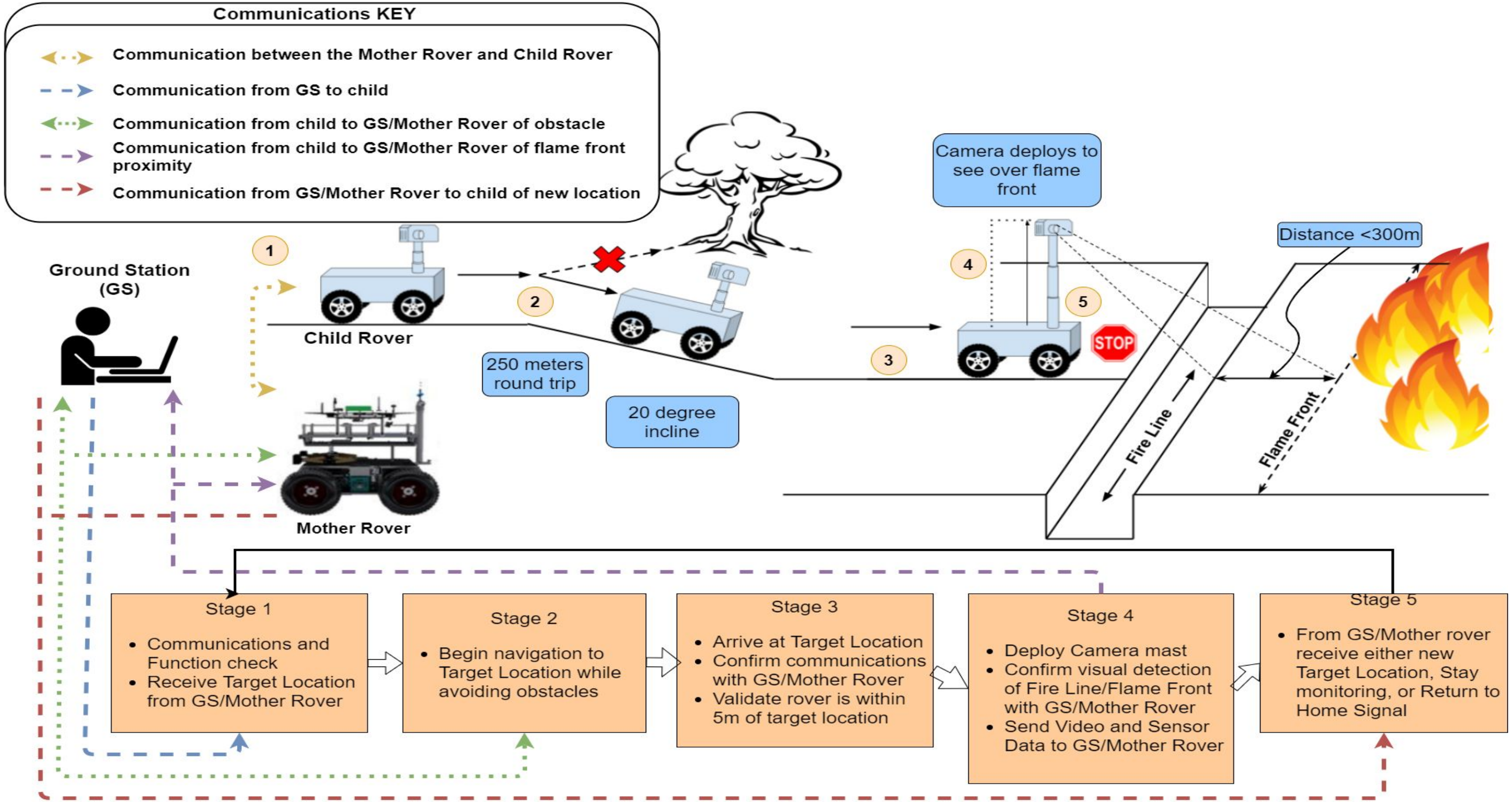
Definitions

- **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/m^2)
- **Terrain** : specification of the forest floor which ARGOS must traverse (detailed definition in backup slides)

Figure 6—Parts Of A Fire

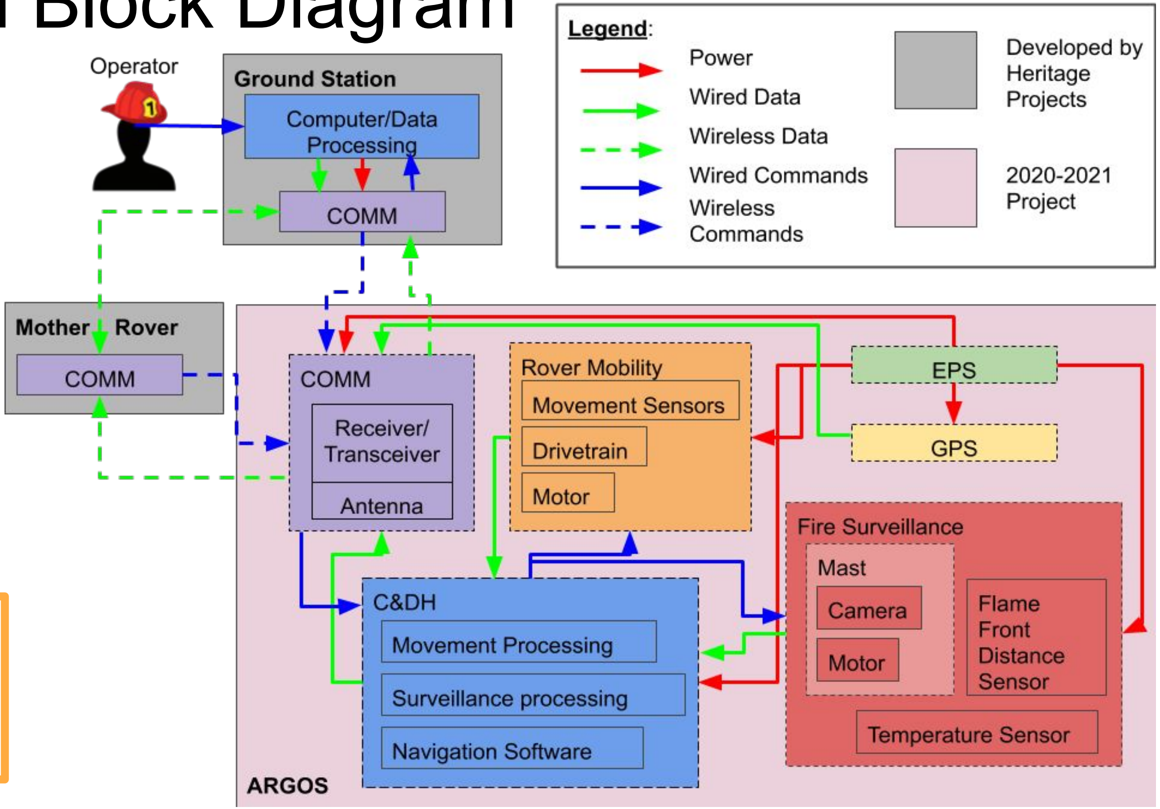


CONOPS

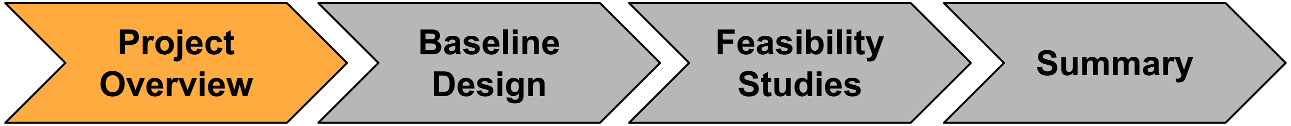


Communications KEY
Communication between the Mother Rover and Child Rover
Communication from GS to child
Communication from child to GS/Mother Rover of obstacle
Communication from child to GS/Mother Rover of flame front proximity
Communication from GS/Mother Rover to child of new location
Ground Station (GS)
1
2
3
4
5
Child Rover
Mother Rover
250 meters round trip
20 degree incline
Camera deploys to see over flame front
STOP
Distance <300m
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 avoiding 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

Functional Block Diagram



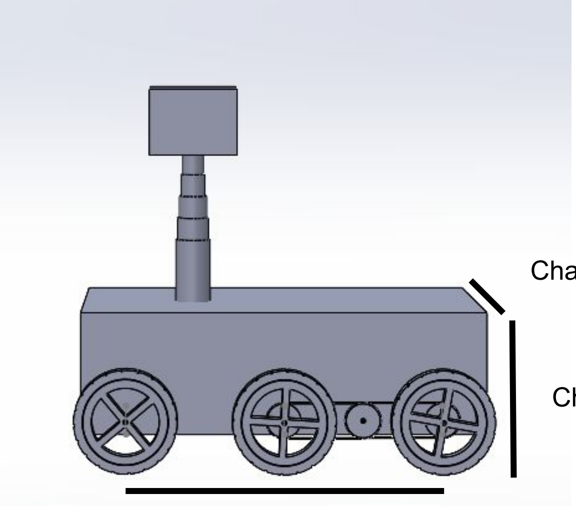
Note:
Acknowledgements are also sent following every command.



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.

Baseline Designs

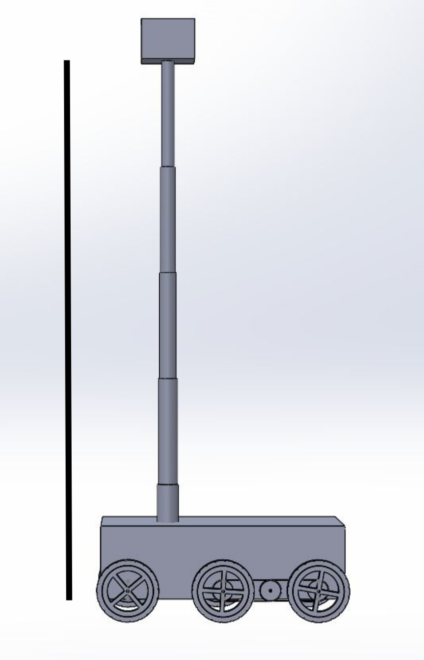


Chassis Width: 0.5m

Chassis Height: 0.35m

Wheelbase Length: 0.7m

Extended Mast Height: 2m



Critical Project Elements (CPEs)

CPEs

- Maneuverability
- Control
- Sensors
- Communications
- Integration with Heritage Projects
- COVID-19 Constraints

Focus for PDR

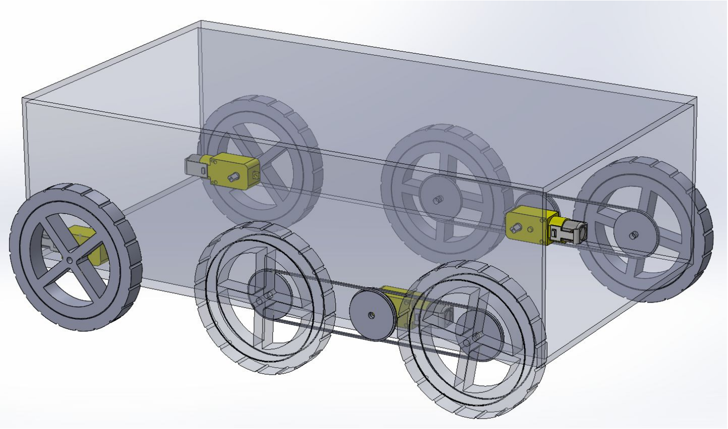
1. Navigation
   - -Drivetrain
   - -Obstacle Avoidance
2. Mast
3. Communications

Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

Baseline Design: Drivetrain

Meets Functional Requirement FR.1

- **Options Considered:** 4 wheels, 6 wheels, Tank treads, and Rocker Bogie
- **Key Criteria:**
  - Obstacle maneuvering
    - 360 degree turn
    - inclines - 20 degrees
    - Obstacles - up to 7cm
  - Power consumption

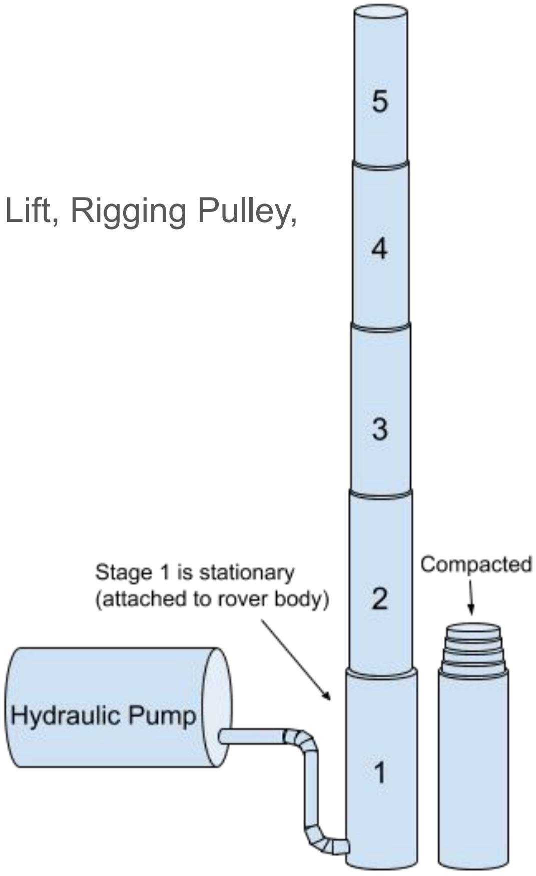


- **Design Chosen**: 6 Wheel Configuration
  - 3 wheels and 2 motors on each side, middle and rear wheels connected by gear chain
  - Useful for maneuvering over obstacles and stability during motion without excessive power consumption

Baseline Design: Mast

Meets Functional Requirement FR.3

- **Options Considered:** Telescoping, Scissor Lift, Dual Joint Fold-Over, Screw Lift, Rigging Pulley, Zippermast and Fold-Over + Telescoping
- **Key Criteria:**
  - Support Weight and Stability
    - Maximum weight capacity at full extension
    - Effect of small wind gusts and vibrations
  - Ratio of Extended to Compacted Height
  - Design/Manufacturing Complexity
- **Design Chosen**: Telescoping (hydraulic system) with 5 Stages
  - Nested hydraulic cylinders → **high support weight and stability**
  - Multiple nested stages → **maximum height >> compacted height**
  - Average complexity; est. **100-150 hours** to design and manufacture

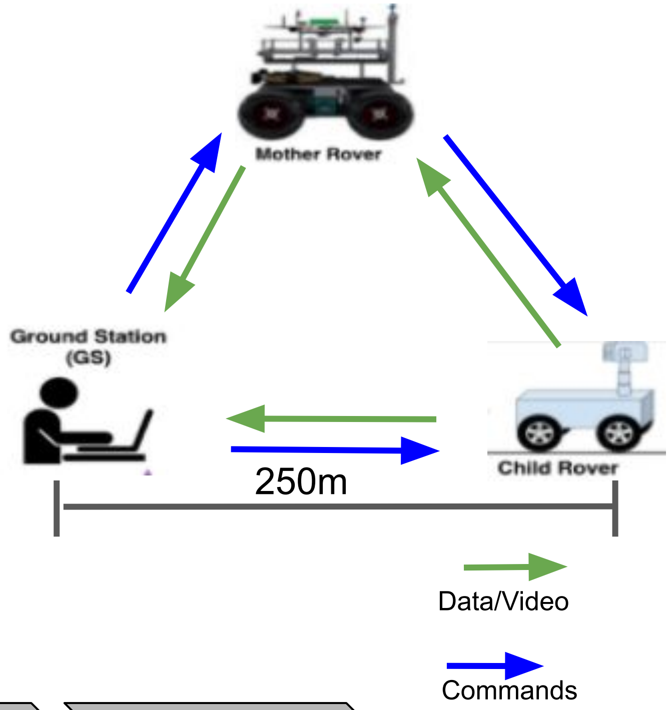


Project Overview | **Baseline Design** | Feasibility Studies | Summary

Baseline Design: Communications

Meets Functional Requirement FR.4

- **Options Considered:**
  - UHF (300MHz - 3 GHz) radio, SHF(3GHz+) radio, cell-tower, and laser communications
- **Key Criteria:**
  - Data transfer rate: 6-24 Mbps
  - Line of Sight range: 1+ KM
  - Attenuation losses: less than 60 dB
  - Commercially available?
- **Design Chosen:**
  - UHF - 2.4GHz radio with point to point/multipoint connectivity
    - Meets all key criteria



Feasibility Analysis

Critical Project Elements (CPEs)

CPEs

- Maneuverability
- Control
- Sensors
- Communications
- Integration with Heritage Projects
- COVID-19 Constraints

Focus for PDR

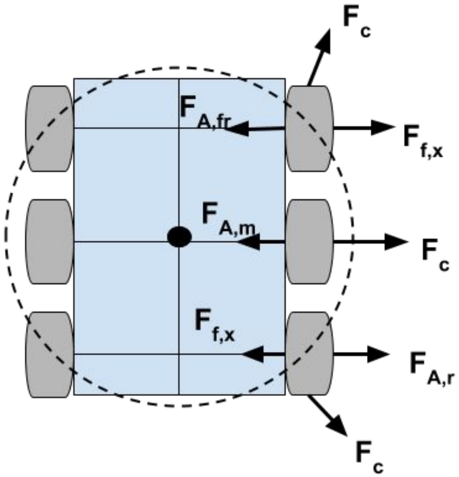
1. Navigation
   -Drivetrain
   -Obstacle Avoidance
2. Mast
3. Communications

1. Navigation Feasibility Analysis

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

Navigation: Drivetrain Turning Study

- **Validation:**
  - Can the turn be performed?
  - What are the axial loads?
- **Assumptions**:
  - Constant angular velocity
  - In place turn
  - Weight evenly distributed on each wheel
  - Geometrically centered COM
- **Max axial load** on wheel while turning found:
  - **30 Newtons** given:
    - ω = 1 rad/s, Length = .7m, Width = .5m, μ = .7, total mass = 30 kg
    - From referencing heritage projects

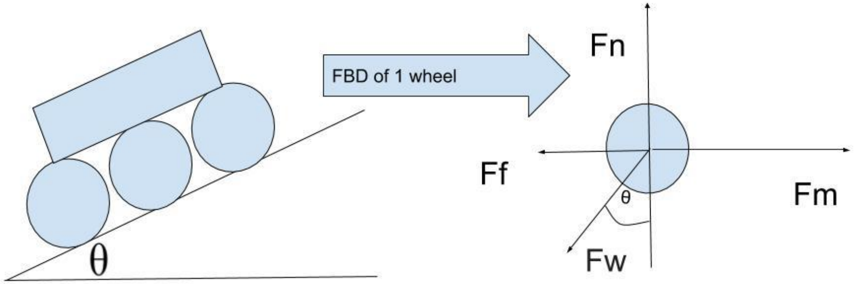


$$F_{A,fr} = \frac{m}{6}\left(\frac{\mu g L_y}{\sqrt{L_x^2+L_y^2}} + \omega L_x^2\right)$$

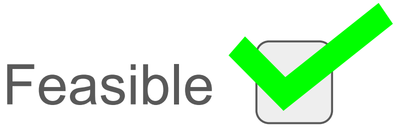
Feasible

Navigation: Drivetrain Incline Maneuvering Study

- **Validation**
  - Can it make it up an incline?
  - What is the max torque?
- **Assumptions**
  - Roll w/o slipping
  - Wheel is a Point Mass
  - Center of Mass is in the Center of the Chassis
- **$\mu \geq .7$** for no slipping up the incline
- **Max τ** experienced (on 20 degree incline) with max acceleration of 1 m/s² was **32.95 Nm**



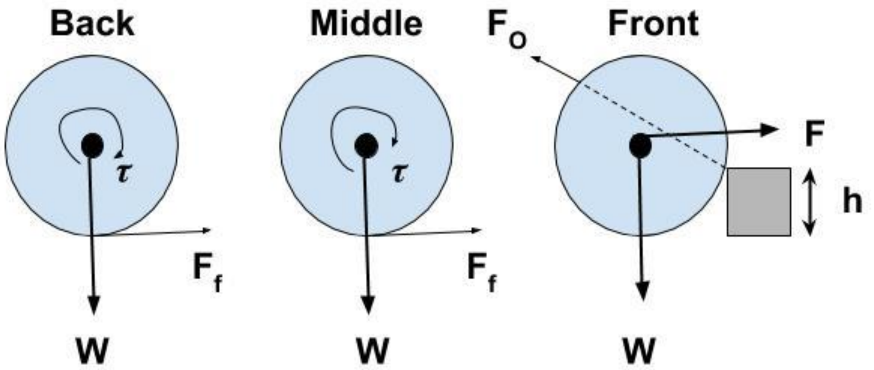
The max τ per motor (4 motors) is 8.24 Nm



Project Overview | Baseline Design | **Feasibility Studies** | Summary

Navigation: Drivetrain Obstacle Maneuvering Study

- **Validation:**
  - Can the rover maneuver a 7cm obstacle?
  - Minimum radius of the wheel?
    - Total mass of 30kg
    - μ = 0.7
    - $\tau_{motor} = F_{f,max} r$
- **Assumptions:**
  - Roll no slip
  - Negligible roll resistance
  - Mass equally distributed on each wheel



$$\tau_F > \tau_W$$

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

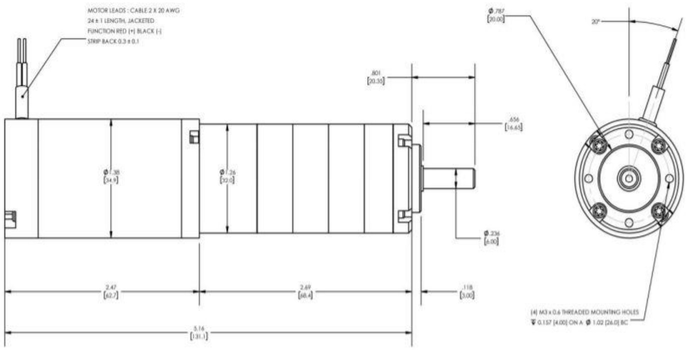
Minimum Radius required: .1 m ~ 4 in

Feasible

Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

Navigation: Drivetrain Power Study

- **Validation**
  - Is the power required acceptable for a DC motor?
- **Assumptions**
  - The efficiency (η) for a DC motor is about 70%
  - Using max torque values
  - Ranged Velocity of 0-3 m/s
- The **max power required** for each motor is **3.86 Watts**
  - Max power was determined at 3 m/s
  - **Total Power** (4 motors) is **15.44 W**
- The **max RPM** is **4.7**



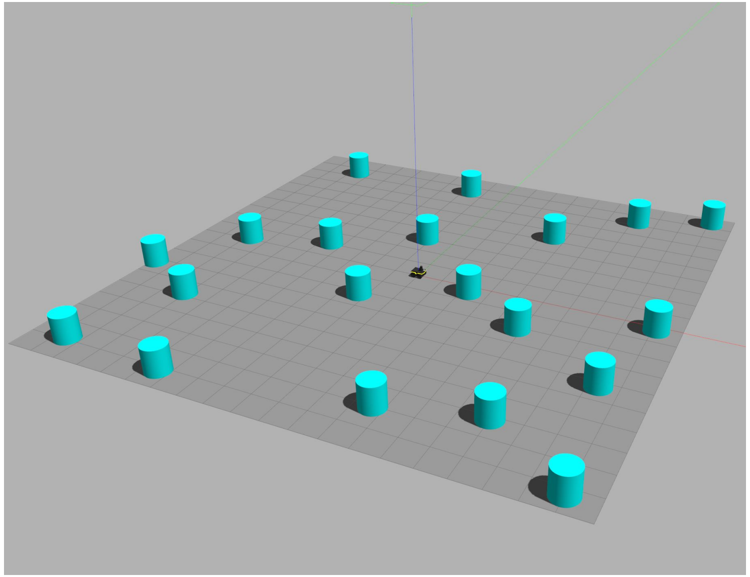
MMP S14-247C

- **Specifications**
  - **12VDC Input Voltage**
  - **1.6 A rated current**
  - **4.9 RPM output speed**
  - **8.92 Nm torque**

Feasible

Navigation: Waypoint and Obstacle Avoidance

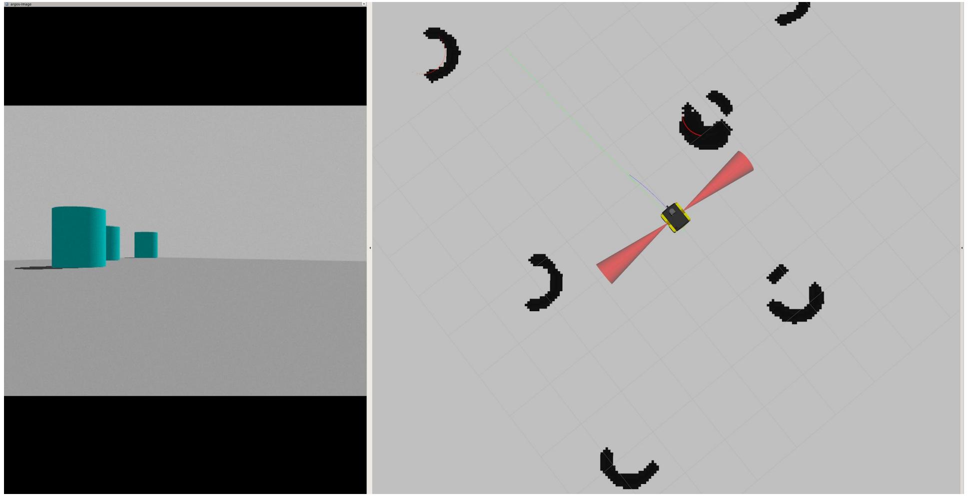
- **Validation**
  - Can ARGOS navigate to a waypoint while avoiding obstacles?
- **Assumptions**
  - Terrain simplified to trees modeled as cylinders
    - Level ground, no underbrush
  - LiDAR has 120º FOV
  - Rover can turn in place
- **Simulation**
  - Start and waypoint location randomized with constant distance
  - Gazebo using Open Dynamics Engine (ODE)
  - Clearpath Jackal used to represent ARGOS
    - Identical degrees of freedom, similar size
  - All terrain types simulated 100 times each



Gazebo sim terrain type D

Navigation: Waypoint and Obstacle Avoidance

- **Robustness**
  - Type A (0 tree/acre)
    - 100%
  - Type B (100 trees/acre)
    - 97%
  - Type C (170 trees/acre)
    - 96%
  - Type D (200 trees/acre)
    - 89%
- More complex simulations will be run before CDR
  - Realistic ARGOS model
  - Full terrain



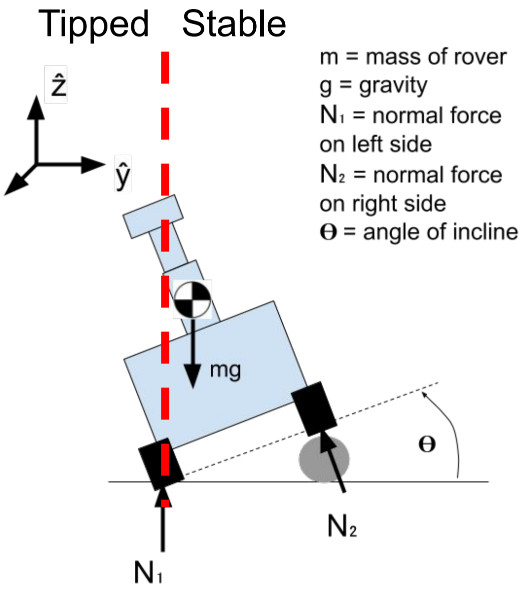
Plausible

2. Mast Feasibility Analysis

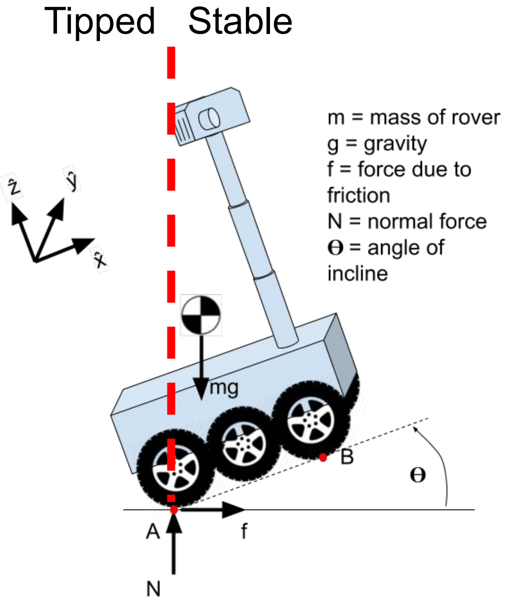
FR. 3 The child rover shall use a mast to take photos and video from a vantage point above the rover's body.

Mast Structures Study

- **Validation:**
  - Can rover traverse obstacles at various inclines and declines without tipping?
  - How does height and mass on top of the mast affect tipping?
- **Assumptions:**
  - Camera/top of mast is a point mass
  - Rover is a rigid body
- **Different Cases Considered:**
  - Side-to-side tipping about x̂
  - Front/back tipping about ŷ



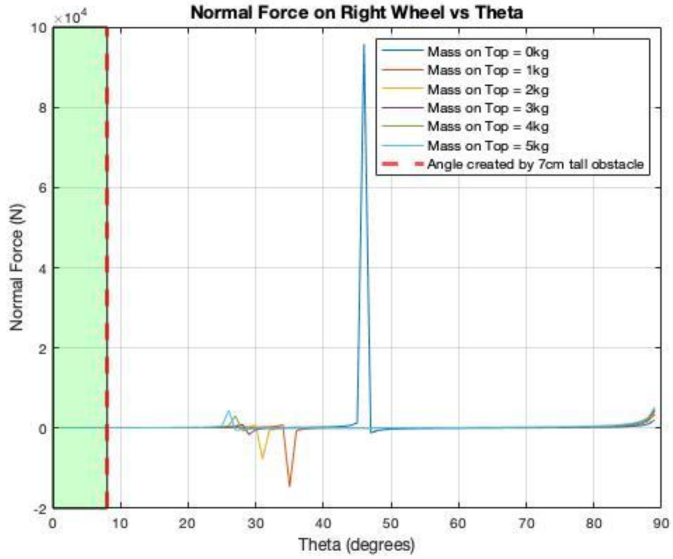
Longitudinal Tip



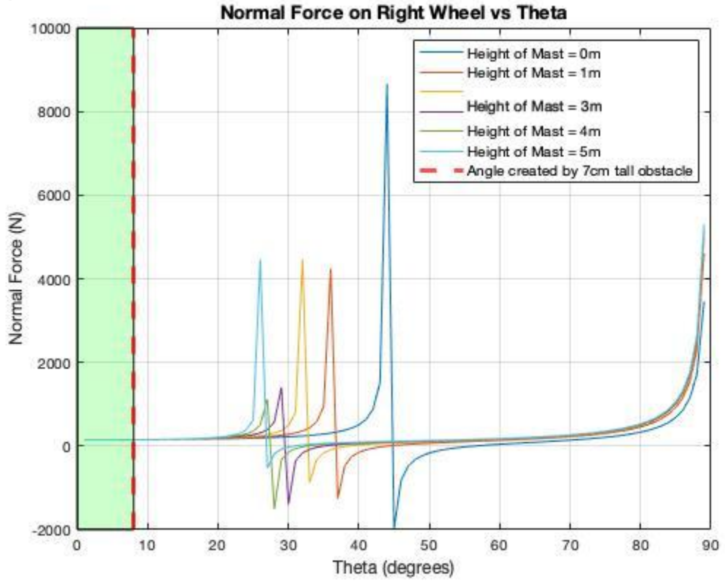
Lateral Tip

Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

Mast Structures Study: Longitudinal Results



Tipping angle ~23 degrees

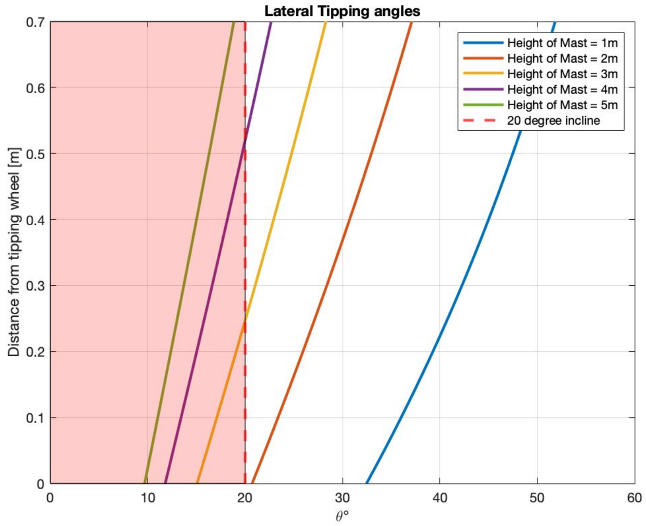


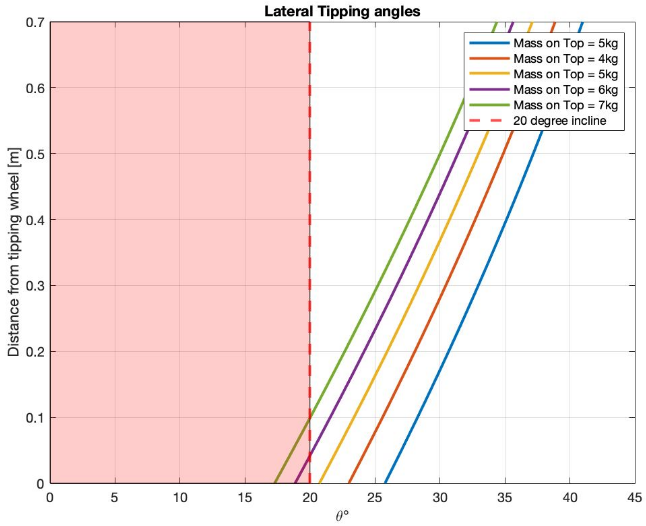
Tipping angle ~20 degrees

$$N_2 = \frac{y_{cg} * mg}{2y_{cg}cos(\theta) - z_{cg}sin(\theta)}$$

Feasible

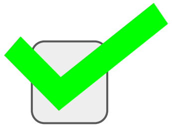
Mast Structures Study: Lateral Results





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

Feasible



Project Overview | Baseline Design | **Feasibility Studies** | Summary

Mast Power Study

- **Validation:**
  - Estimate the power required to extend the mast
  - How does the extension time affect power required?
- **Assumptions:**
  - Center of mass of camera is at mast top
  - Center of mass of each section is at its middle
  - Change in height of hydraulic fluid and camera dominate power required
  - Pump efficiency: 0.7

Results:

$t_{extend} = 60s$
$P_{required} = 2.8W$

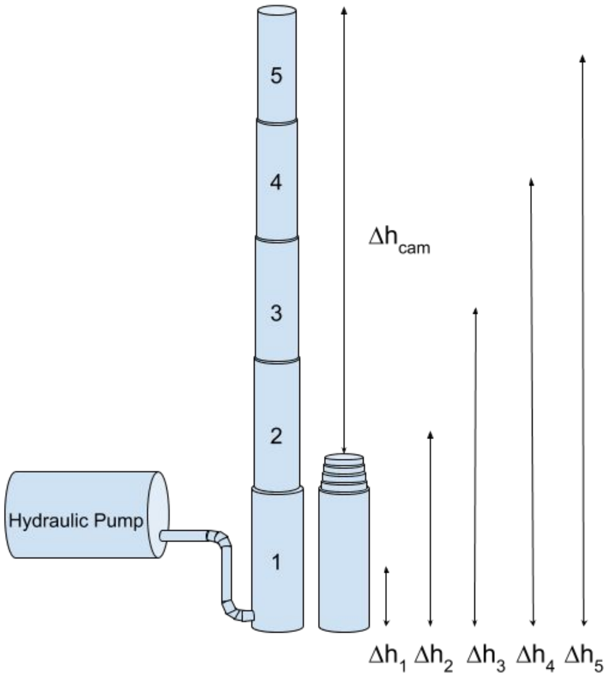
$t_{extend} = 30s$
$P_{required} = 5.7W$

$t_{extend} = 20s$
$P_{required} = 8.5W$

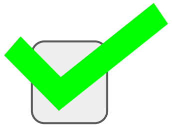
Target:

$\mathbf{t_{extend} = 10s}$
$\mathbf{P_{required} = 17W}$

$t_{extend} = 5s$
$P_{required} = 34W$



Feasible



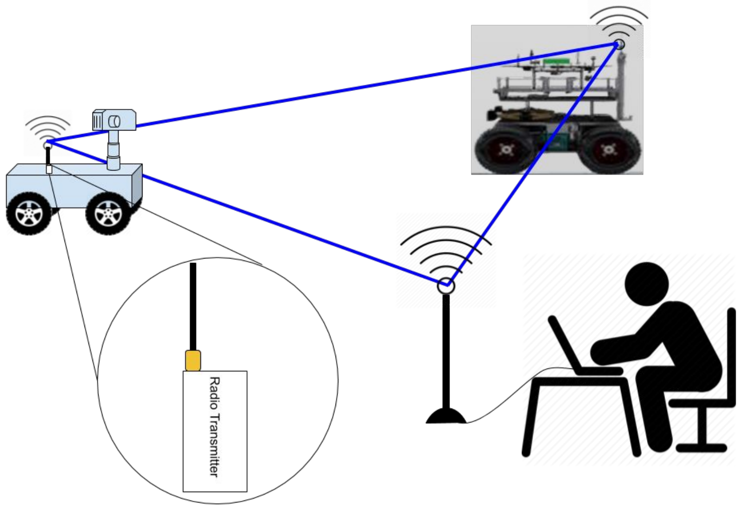
Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

3. Communications Feasibility Analysis

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.

Communication Study

- **Validation:**
  - Can the rover communicate with the GS and MR at 250m through forest?
- **Assumptions:**
  - Trees begin at 0 meter
- **Different Cases Considered:**
  - Obstacle free link budget
  - Various models of forest attenuation



Communications: Link Budget

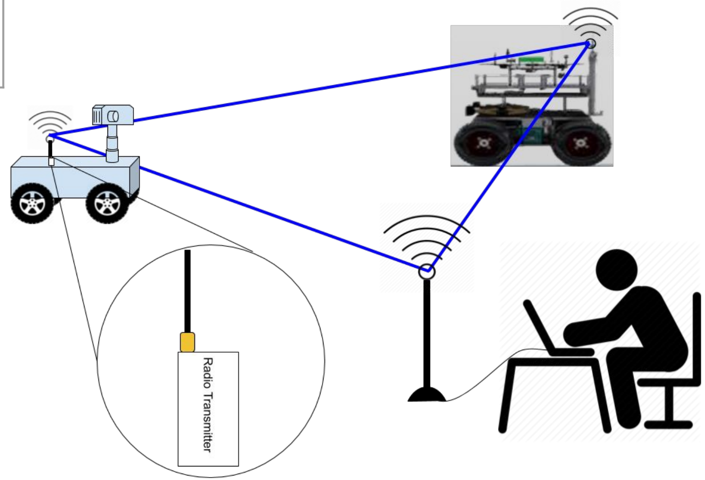
Key Parameters:

Distance (d) = 250m	Transmitter Power (Tx) = 28 dBm	Antenna Gains (Gr/x) = 13 dB
Frequency (f) = 2400 MHz	Receiver Power (Rx) = -97 dBm	Estimated Losses (L) = 4 dB

*Values taken from heritage compatible hardware and estimates are subject to change with part choice

$$FSPL = 20log(d) + 20log(f) - 27.55 = \boxed{88\ dB}$$

$$Link\ Margin = T_x - FSPL + G_x + G_r - R_x - L = \boxed{58\ dB}$$

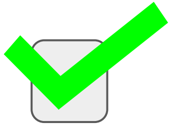


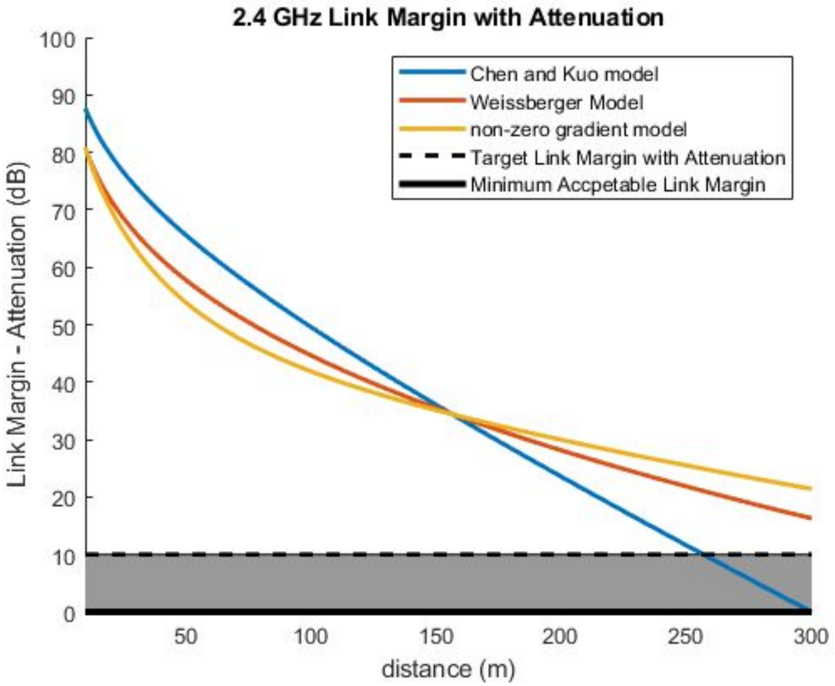
Communications: Attenuation Study

$$\textit{Link Margin with Attenuation} = \textit{Link Margin} - \textit{Attenuation} > 10\ dB$$

- Three different models for vegetal attenuation, all models show success.
- Each model assumes that vegetation begins at zero meters.

Feasible





Project Overview | **Baseline Design** | **Feasibility Studies** | **Summary**

Summary

Status Summary

Element	Feasible?	Justification	FR
Navigation	Yes/Plausible	1. Axial loads while turning reasonable to make 360 degree turn 2. Wheel radius required to go over 7cm obstacle is reasonable 3. Successfully moves to waypoint. More complexity needed	FR.1
Mast	Yes	1. Tipping condition is met at an angle greater than that created by max obstacle height 2. Tipping condition for various masses and mast heights higher angle than designed 20 degree incline	FR.3
Communications	Yes	1. Link Budget with attenuation above 10 dB	FR.4

Strategy for Future Studies

Element	Test/Model	FR
Navigation	1. GAZEBO - ARGOS model 2. Model various wheel widths 3. FEM on chassis	FR.1
Mast	1. Vibration Testing/Vibrations Mode Modeling 2. Buckling Model 3. Hydraulic Fluid Mechanics	FR.3
Thermal	1. Model convective winds caused by forest fire	FR.4
Controls	1. Select, procure, and test sensors for obstacle avoidance 2. Test pan/tilt controls of camera	FR.1
Camera/Sensors	1. Select, procure and test temperature sensors and camera accuracy/resolution	FR.2

=continuation of PDR feasibility studies

=continuation of backup slides

= not yet started

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/.

"Electric Motor Efficiency," *Engineering ToolBox* Available: https://www.engineeringtoolbox.com/electrical-motor-efficiency-d_655.html.

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.

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

Savage, N., Ndzi, D., Seville, A., Vilar, E., and Austin, J., "Radio wave propagation through vegetation: Factors influencing signal attenuation," *AGU Journals* Available: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2002RS002758.

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

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

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

References Continued

An Empirical Propagation Model for Forest Environments at Tree Trunk Level - IEEE Journals & Magazine Available: https://ieeexplore.ieee.org/abstract/document/5751639.

Available: https://midwestmotion.com/products/brgp/12v/4.0-6.9rpm/7580inlb.html.

Cama-Pinto, D., Damas, M., Holgado-Terriza, J. A., Gómez-Mula, F., and Cama-Pinto, A., “Path Loss Determination Using Linear and Cubic Regression Inside a Classic Tomato Greenhouse,” *International journal of environmental research and public health* Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6572486/.

“Darcy’s Law and Hydraulic Head”: https://hydro.geo.ua.edu/GEO406_506/Lecture6.pd

“Determining Electric Motor Load and Efficiency” : https://www.energy.gov/sites/prod/files/2014/04/f15/10097517.pdf

“Friction and Friction Coefficients,” *Engineering ToolBox* Available: https://www.engineeringtoolbox.com/friction-coefficients-d_778.html.

“Radio Wave Propagation Through Vegetation”:Radio wave propagation through vegetation: Factors influencing signal attenuation

Backup Slides

Terrain Definition

- 4 terrain types increasing in difficulty
- Tree - Blue Spruce
  - Trunk Width: 0.91m
  - Spacing: 3 m

Terrain	Forest	Ground	Underbrush	Incline
Type A	Open: 0 trees per acre	Mud: Grain size: 0.00006 - 0.0039 mm (< .0002 in)	Dirt with no vegetation: - Refer only to ground classification - Scattered leaves	Maximum 0 degree incline, level ground
Type B	Understocked: ~24700 trees per square km (100 trees per acre)	Silt: Grain Size: 0.0039 - 0.0625 mm (< .003 inch)	Grass, Fallen Leaves, and No shrubbery: - Full ground coverage by leaves - Grass between 2cm - 10cm height (.8 - 4 inches) - Small roots 1-2 cm (.4 - .8 inches) in diameter	Maximum 10 degree incline
Type C	Fully Stocked: ~42000 trees per square km (170 trees per acre)	Sand: Grain Size: 0.0625 - 2.00 mm (< .08 inch)	Grass, Fallen Leaves, and Scattered Shrubbery - Shrubbery spaced by at least 1 meter - Includes type A and B underbrush - Medium roots: 3-4 cm (1.2 - 1.6 inches) in diameter	Maximum 20 degree incline
Type D	Overstocked: ~49400 trees per square km (200 trees per acre)	Gravel: Grain Size: 2.00 - 4.096 mm (< .2 inch)	Grass, Fallen Leaves, and Dense Shrubbery - No spacing between shrubbery - Includes type A, B, and C underbrush - Large Roots: 5-7 cm (2 - 2.7 inches) in diameter	Maximum 20 degree incline

Levels of Success

	Rover Movements	Surveillance	Communications
Level 1	Rover can travel on flat ground for 100m. Rover can travel in both forward and reverse 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.	Rover records the distance of the fire line and the flame front over time and calculates the speed of travel of the flame front.	Rover can communicate with the ground station and the mother rover up to 250m.

Drivetrain Backup Slides: Turning

Force Balance:

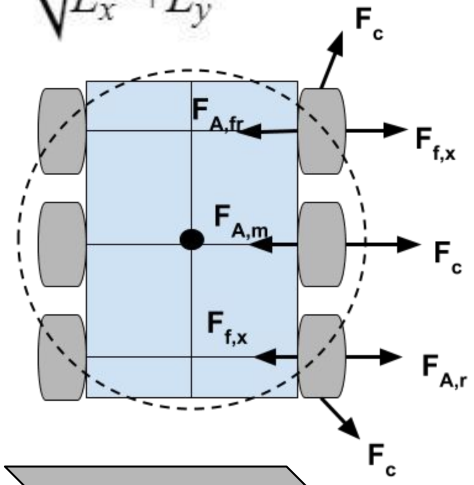
$$F_{fx} = \frac{m}{6}\left(\frac{\mu g L y}{\sqrt{{L_x}^2 + {L_y}^2}}\right)$$

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

$$F_{A,m} = \frac{m}{6}(\omega {L_x}^2)$$

$$F_c = \frac{m}{6}(\omega {L_x}^2)$$

$$F_{A,r} = \frac{m}{6}\left(\frac{\mu g L_y}{\sqrt{{L_x}^2 + {L_y}^2}} - \omega {L_x}^2\right)$$



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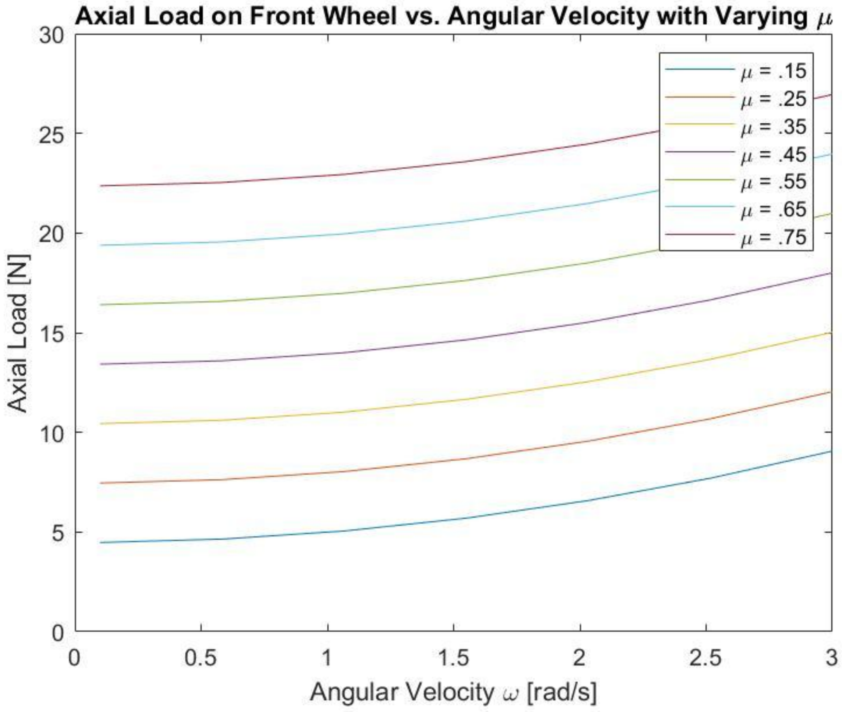
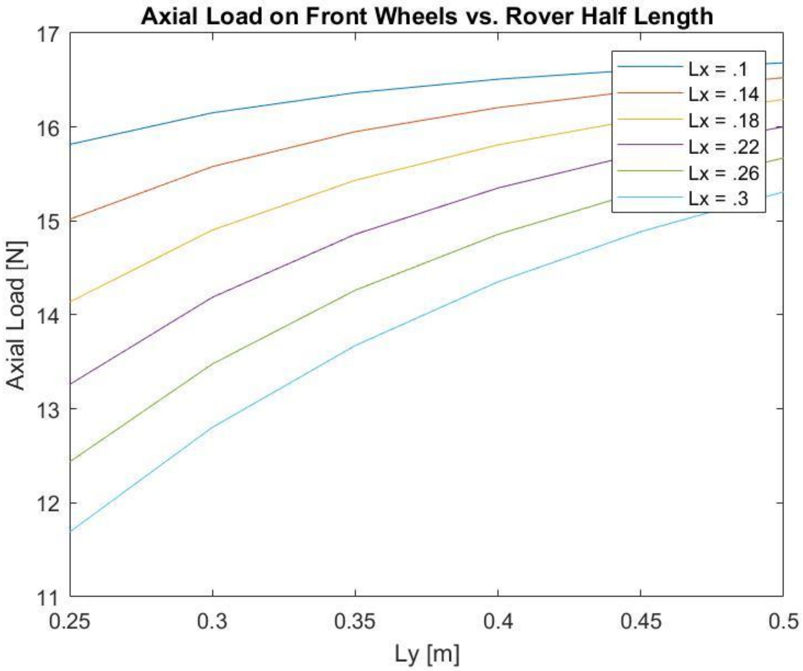
Drivetrain Backup Slides: Turning

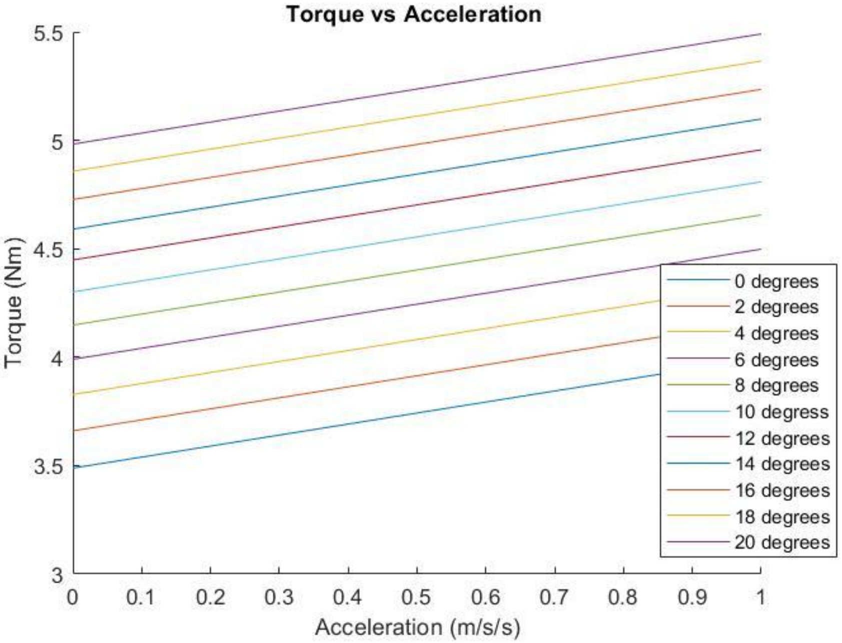
Sensitivity Analysis





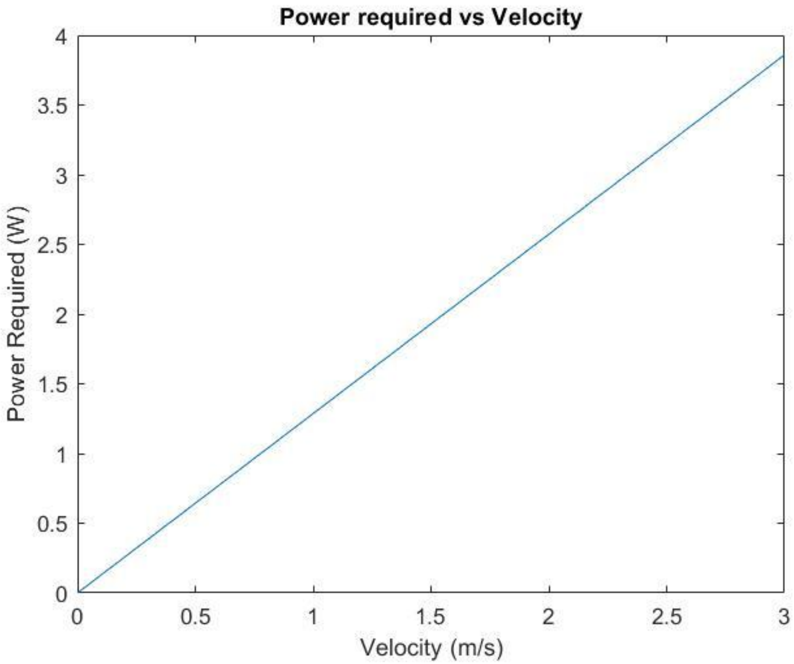
Drivetrain Backup Slides: Incline Maneuvering

- **Definitions of Forces**
  - Fn = normal Force of the Wheel
  - Ff = friction force from the Terrain
  - Fm = force of the motor
  - Fw = weight of the wheel
  - **θ** = inclination angle
- **Force Equations**
  - Fs ≤ μ*Fn for no slipping
  - Fw = m*g
  - Fm = τ/r
- **Sum of Forces**
  - ΣFy = 0 = Fn-cos(θ)mg
  - ΣFx= ma = (τ/r) - μcos(θ)mg-sin(θ)mg



Drivetrain Backup Slides: Power Study

- **Equations**
  - RPM = V / π*diameter
  - Frequency = (1/60) * RPM
  - $\omega = 2*\pi*$Frequency
  - $\tau = r*(ma+\mu\cos(\theta)+\sin(\theta)mg)$
  - Power = $Fm*V*(1/\eta) = \tau*\omega*(1/\eta)$
- **Conditions where maxP was obtained**
  - At max torque
  - At 20 degree incline
  - At 1 m/s²



Mast Backup Slides: Case 1

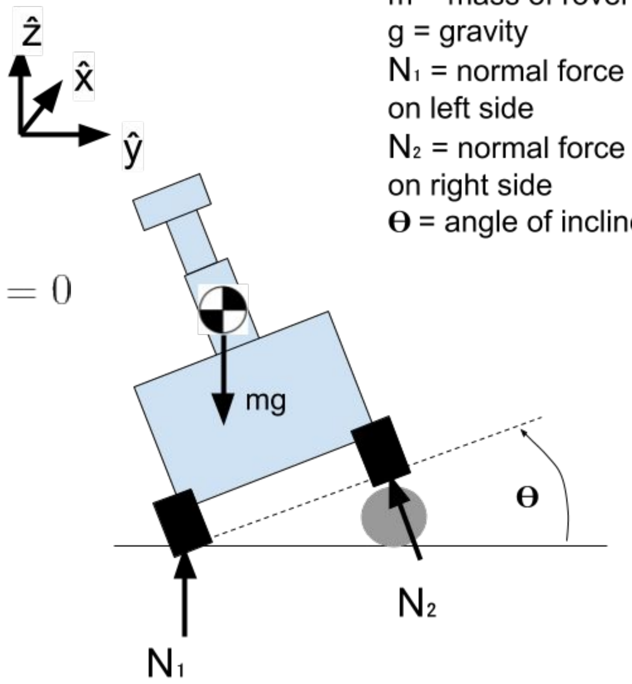
Governing Equations:

$$\Sigma F_y = N_2 * sin(\theta) = 0$$

$$\Sigma F_z = -mg + N_1 + N_2 * cos(\theta) = 0$$

$$\Sigma M_{cg} = (y_{cg} * N_2 * cos(\theta)) - (y_{cg} * N_1) - (z_{cg} * N_2 * sin(\theta)) = 0$$

$$N_2 = \frac{y_{cg} * mg}{2y_{cg}cos(\theta) - z_{cg}sin(\theta)}$$



m = mass of rover
g = gravity
N_1 = normal force on left side
N_2 = normal force on right side
θ = angle of incline

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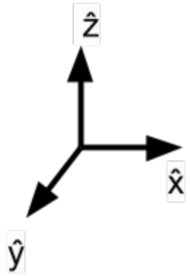
Mast Backup Slides: Case 2

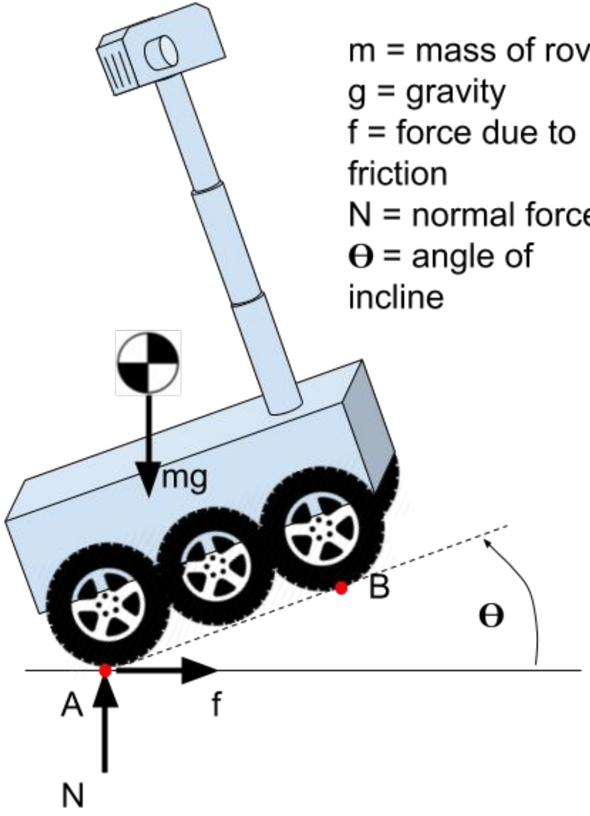
Governing Equations for Incline:

$$M_A = mg(h_{cg}sin(\theta) - l_{cg}cos(\theta)))$$

Governing Equations for Decline:

$$M_B = mg(h_{cg}sin(\theta) - (l - l_{cg})cos(\theta))$$





m = mass of rover
g = gravity
f = force due to friction
N = normal force
ϴ = angle of incline

Mast Backup Slides: Power Required

Volume of Each Section:

1: 0.002m^3 2: 0.0016m^3 3: 0.00129m^3 4: 0.00098m^3 5: 0.00073m^3

Density of Hydraulic Fluid:

880 kg/m^3

Mass of Camera and Each Section:

M_{cam}: 5kg M_1: 1.77kg M_2: 1.43kg M_3: 1.1kg M_4: 0.87kg M_5: 0.64kg

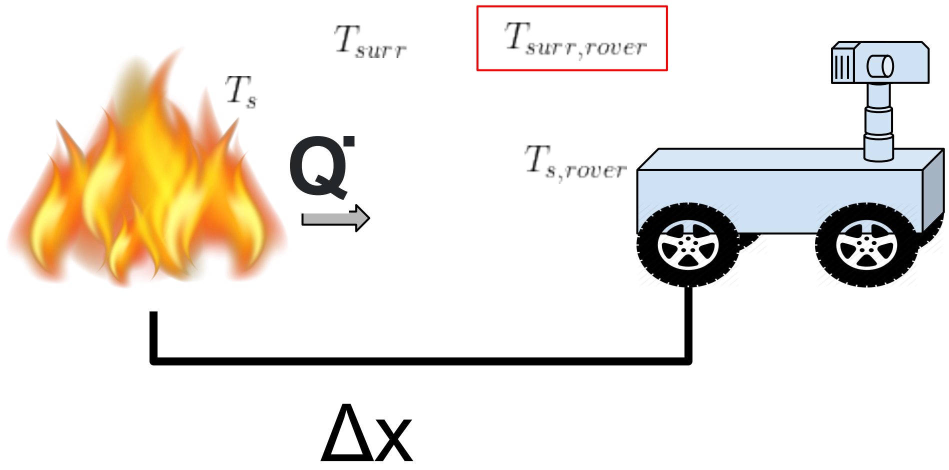
Equation:

$$P_{req} = \frac{(m_{cam}\Delta h_{cam} + m_1\Delta h_2 + m_2\Delta h_2 + m_3\Delta h_3 + m_4\Delta h_4 + m_5\Delta h_5)g}{t}\frac{1}{\eta_{motor}} \quad (1)$$

Fire Surveillance: Thermal Model

- **Validation:**
  - What temperatures might ARGOS experience at various distances from the flame front?
- **Simplifying Assumptions:**
  - No wind (no forced convection)
  - Radiation is the only form of heat transfer accounted for (all natural convection goes directly upwards, away from the rover)
  - The fire stays stationary and burns at a constant temperature

Thermal Model: Inputs



Variable	Value(s)
As	50m²
Ts	1073K
Tsurr	288.15K (std day)
Arover	(0.5x0.3) = 0.15m²
Ts,rover	288.15K (std day)
ε	0.551 (max)
α	[0.2,1]
Δx	[0,100m]

Thermal Model: Governing Equations

Rate of heat transfer emitted by fire :

$$\dot{Q}_{emit} = \epsilon * \sigma * A_s * (T_s^4 - T_{surr}^4)$$

Inverse Square Law

Rate of heat transfer absorbed by rover:

$$\dot{Q}_{rad,rover} = \boxed{\frac{\dot{Q}_{emit}}{x^2}} = \epsilon * \sigma * A_{rover} * (T_{surr,rover}^4 - T_{s,rover}^4))$$

Temperature of air immediately surrounding rover:

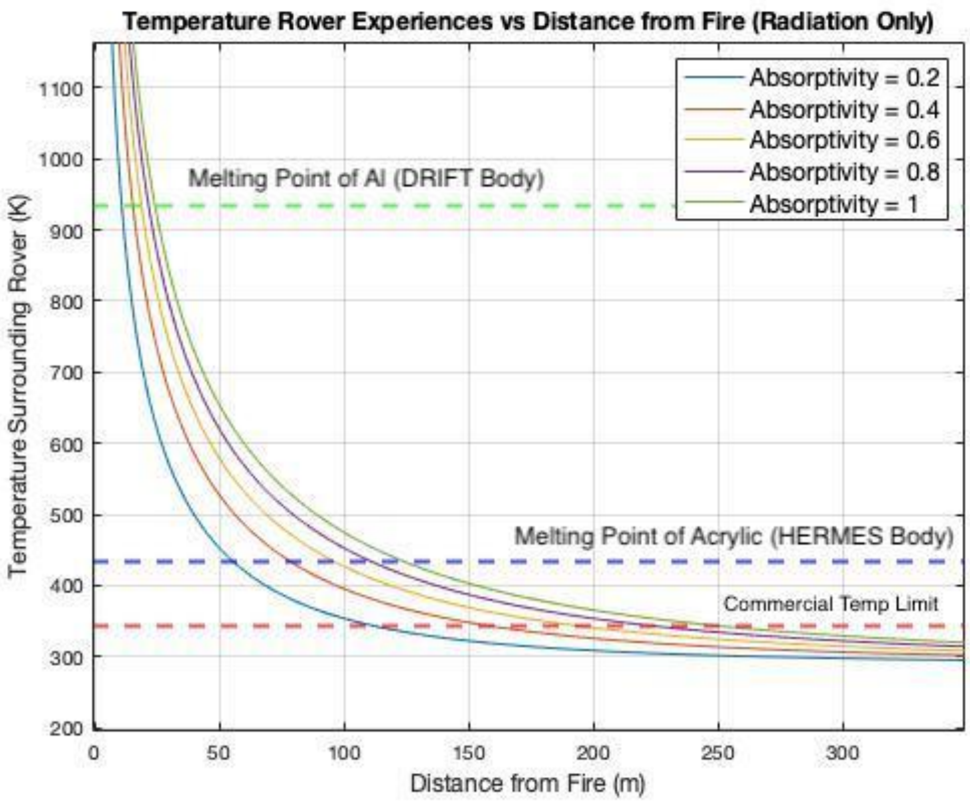
$$T_{surr,rover} = (\frac{\alpha * \dot{Q}_{rad,rover}}{\epsilon * \sigma * A_{rover}} + T_{s,rover}^4)^{\frac{1}{4}}$$

Thermal Model: Results

Takeaways:

- Max allowable distance from fire ~125 -275m depending on material (still less than 300m)
- Model is an optimistic estimate without accounting for convection

Feasible, but requires further investigation



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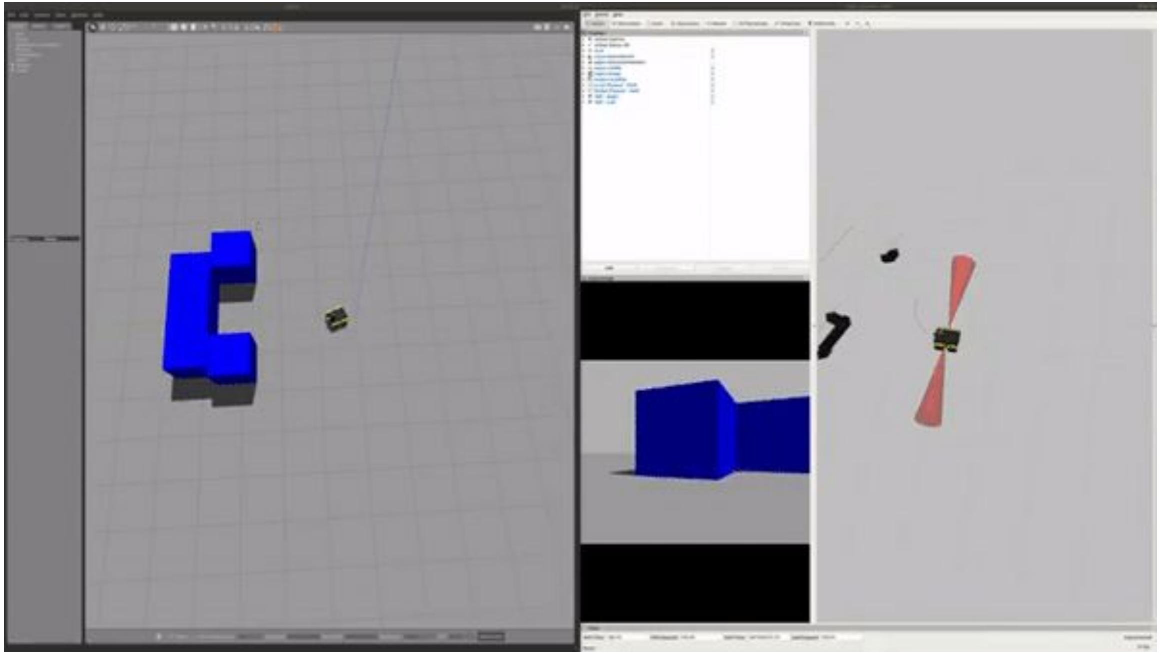
Navigation: Motion Plan Edge Case: Local Minimum



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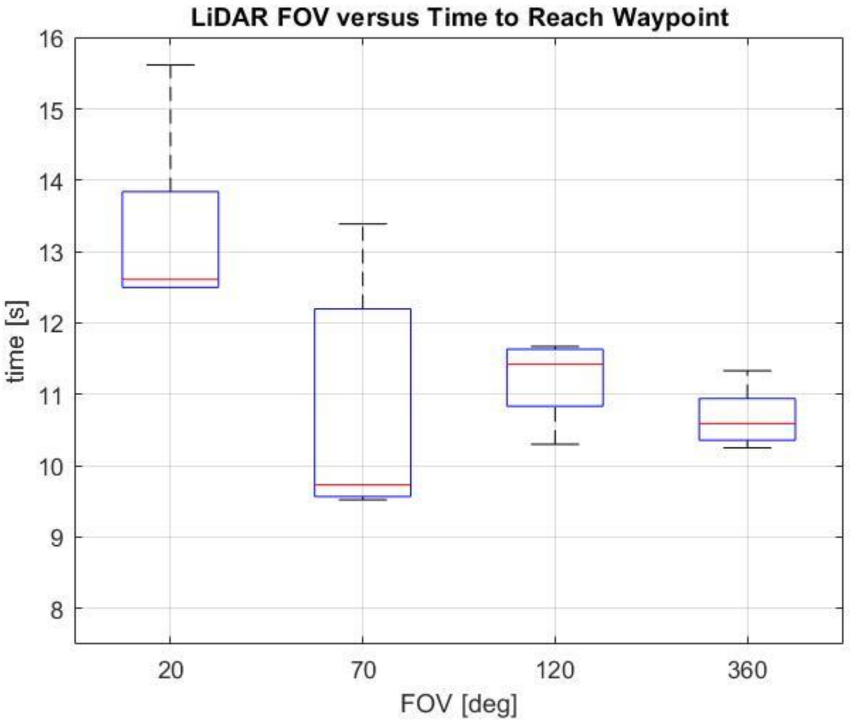
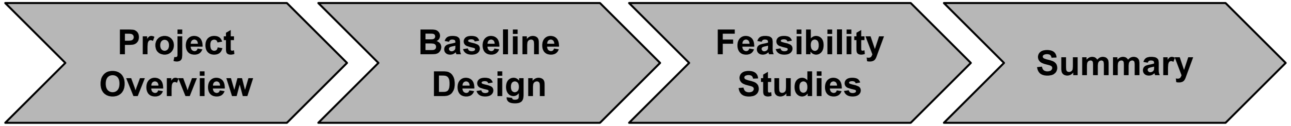
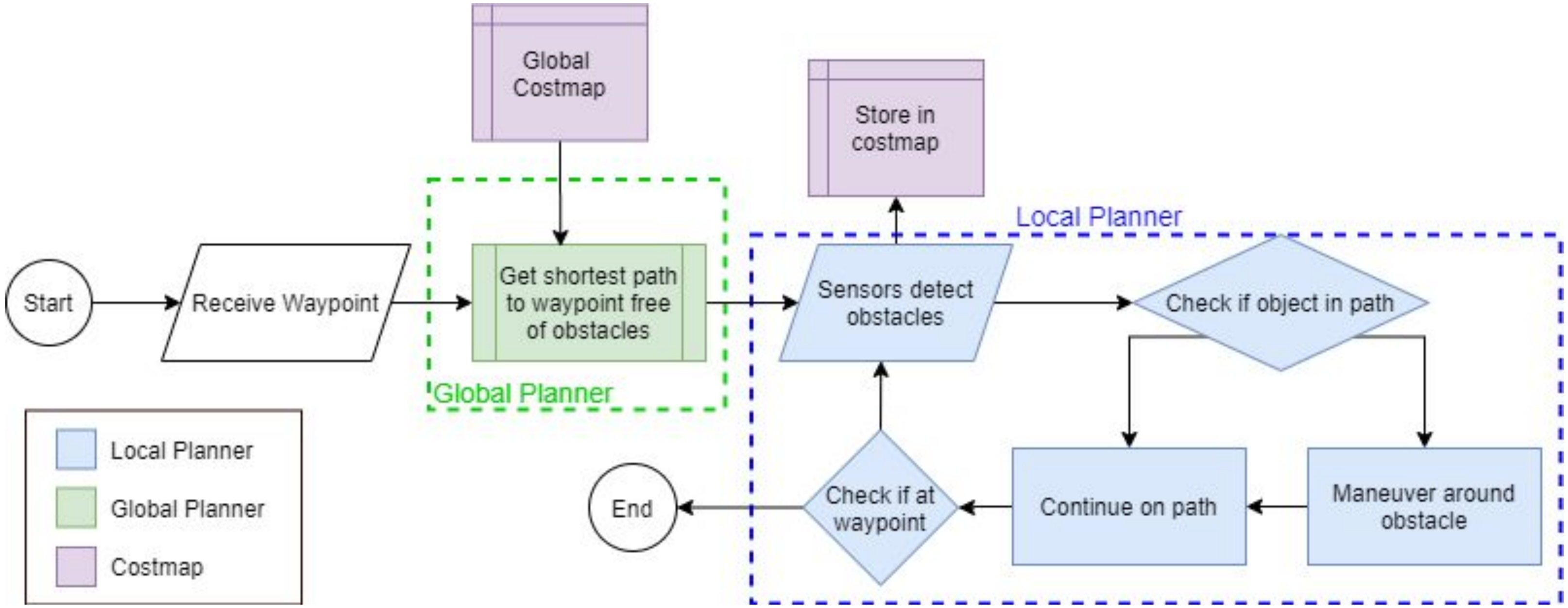
Navigation: LiDAR FOV Sensitivity



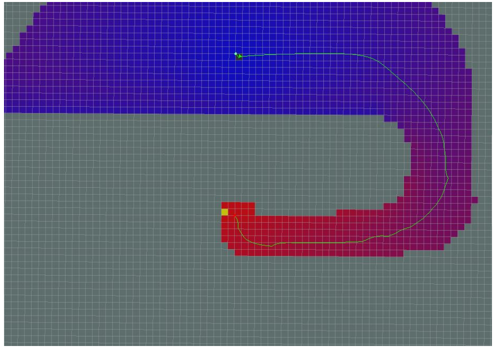


Navigation: Motion Planning Flow Chart

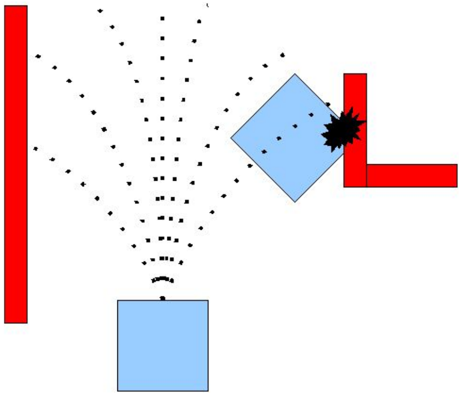


Navigation: Motion Planning

- Built on ROS Navigation package
- Costmap = discretized grid of the space
  - If node in grid contains an obstacle the cost is 1
  - If node is empty the cost is zero
- Global planner (run once)
  - Global = entire space (250 m^2)
  - A^* search on global costmap
    - Find shortest path to goal
    - A* = best-first search on a weighted graph
  - Shortest path becomes path to goal
- Local planner (run continuously)
  - Local = 10 m^2
  - Trajectory Rollout
    - Sample local space, perform forward simulation
    - Score = relation to goal, path, obstacles
    - Highest score becomes the local path



Global Planner Example



Local Planner Example