Conceptual Design Review

Deployed RF Antennas for GPS-denied Optimization and Environmental Navigation

DRAGON

Dawson Beatty, Christian Carmack, Jeremy Fie, Chris Greer, Ross Kloetzel, Jack Maydan, Kyle Nieukirk, Virginia Nystrom, Amanda Siirola, Ryan Stewart, Luke Tafur, Ivan Yurkin

Aerospace Engineering

COHRINT

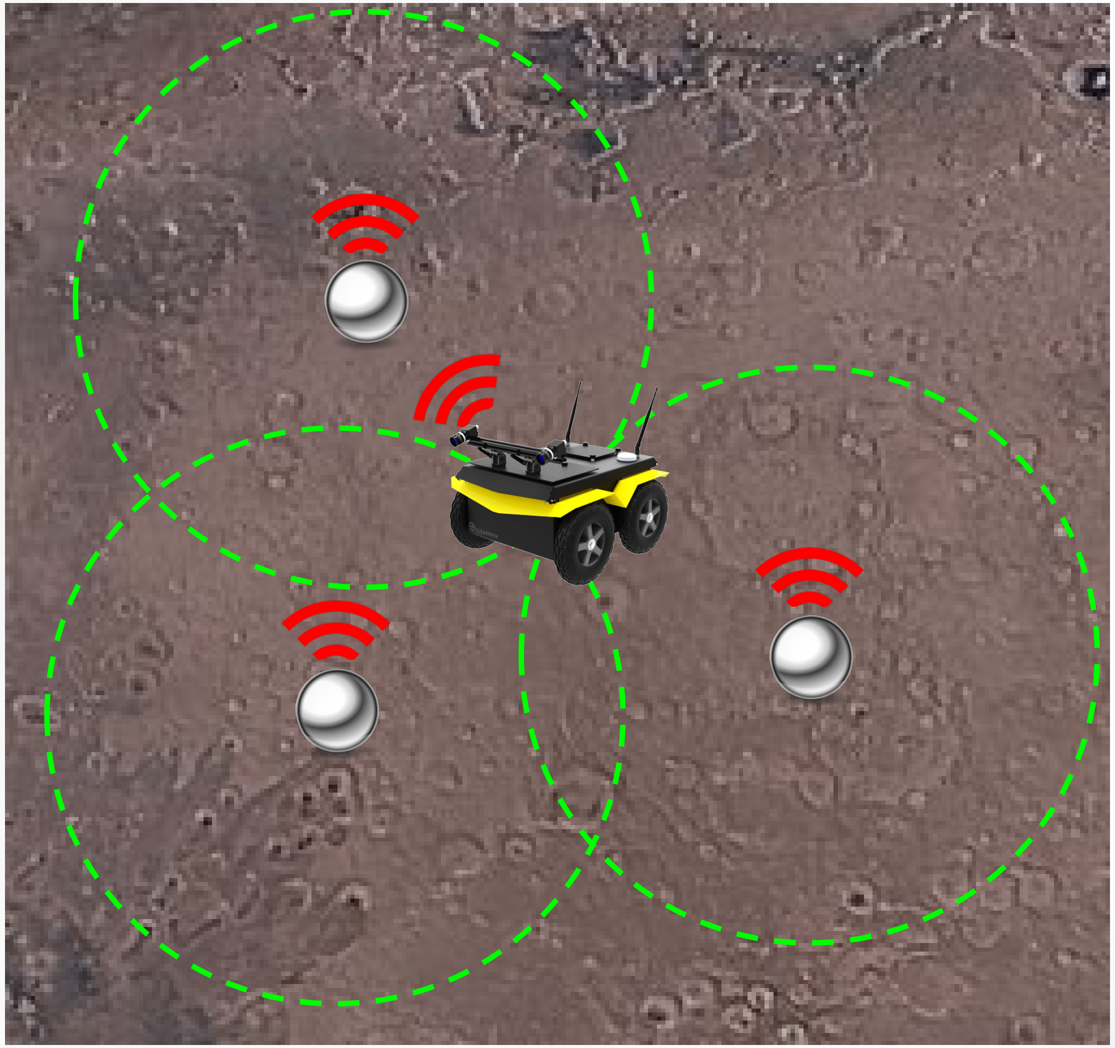
DRAGON

Project Overview

Project Overview
Design Solution
Design Requirements
Risk Mitigation
Verification & Validation
Project Plan

Project Motivation

- Imagine a rover with an objective to explore a remote location, such as Martian deserts or urban canyons
- Methods of Navigation:
  - ~~GPS~~
  - ~~Landmarks~~
  - Odometry ⟵ High Error
- The DRAGON team pursues a solution using deployed RF beacons as an in-situ GPS network to correct inertial error



Problem Statement

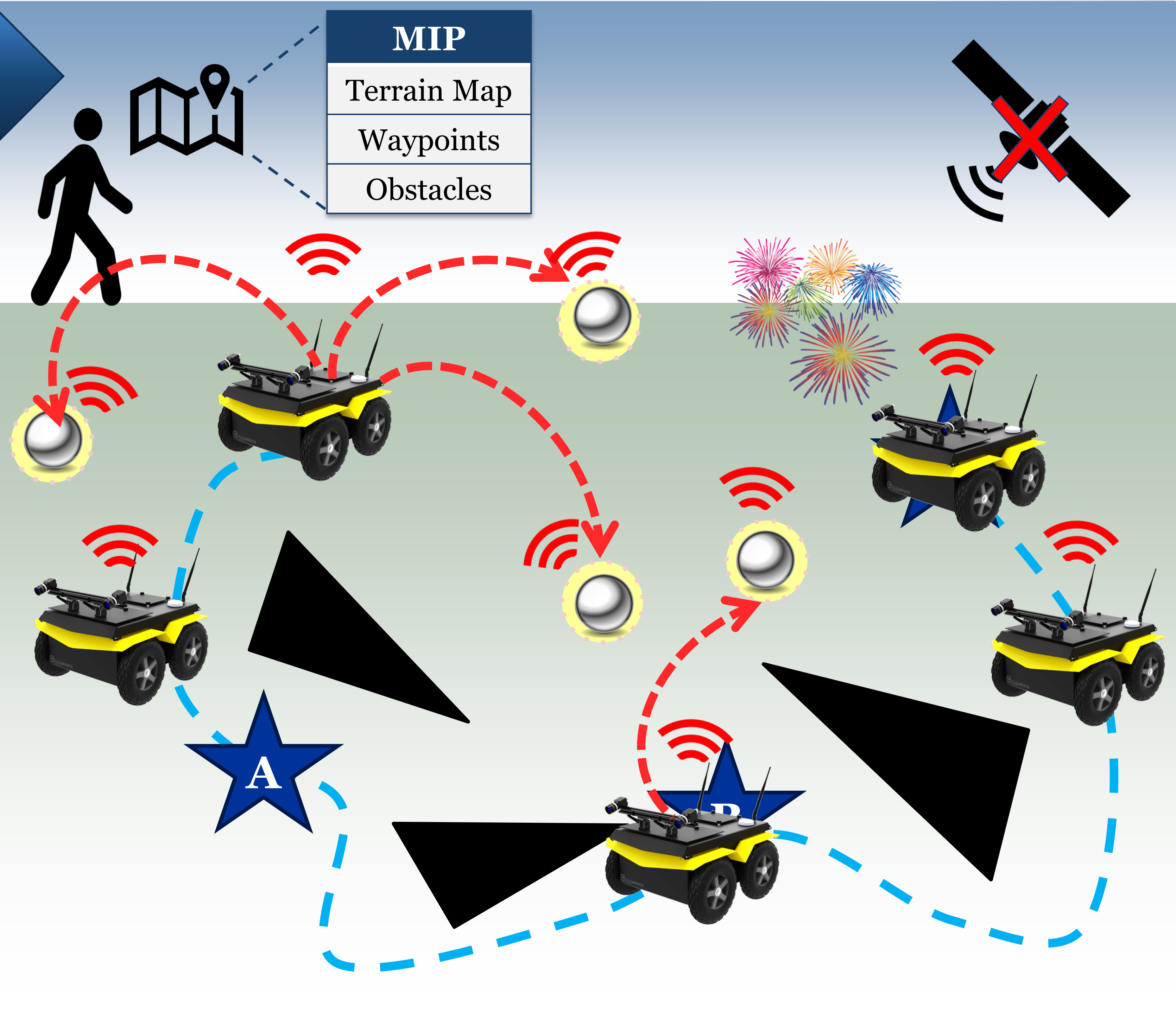
- The DRAGON team will provide a fully autonomous method to navigate an unmanned rover in GPS-denied environments with 1m accuracy

- This will be done by developing:
  - Pods which contain RF-Localization beacons.
  - Deployment mechanism to deploy pods to software-determined locations
  - Software to determine absolute position and navigate to waypoints

- As the pods will remain in the environment permanently, and can access areas the rover cannot, they will also have the *demonstrational ability* to collect and transmit environmental data.

CONOPS

Mission Planning	1	Upload Mission Information Package
	2	Collect GPS Truth Position
	3	Generate Path
	4	Generate Pod Locations
Mission Execution	5	Deploy 3 Anchor Pods
	6	Deploy & Map Pods or Move & Localize Rover
	7	Repeat 6 Until Final Waypoint



Functional Requirements

ID	Description
M1	Rover shall autonomously navigate along software generated path within 1m accuracy using RF-Localization Beacon correction to inertial navigation
M2	The rover shall estimate its absolute position
M3	The deployment mech shall have capability to deploy pods to software defined locations
M4	The rover and ground inputs shall prevent damage to all hardware systems
M5	The pods shall function as RF navigation beacons and as environmental data monitors, to the rover
M6	The pods shall be able to function as a long-term deployable environmental data monitor
M7	The team shall verify absolute navigation ability
M8	The team shall use the customer-provided hardware

Major Changes Since PDR

- Deployment Mechanism only needs to deploy pods beyond 10m and has no accuracy requirement
  - Rover is stationary while deploying pod
  - Software can determine accurate pod position post-launch

- Assume flat terrain on business field
  - Obstacles will be flat keep-out zones
  - No multipathing expected in testing environment

Design Solution

Project Overview

Design Solution

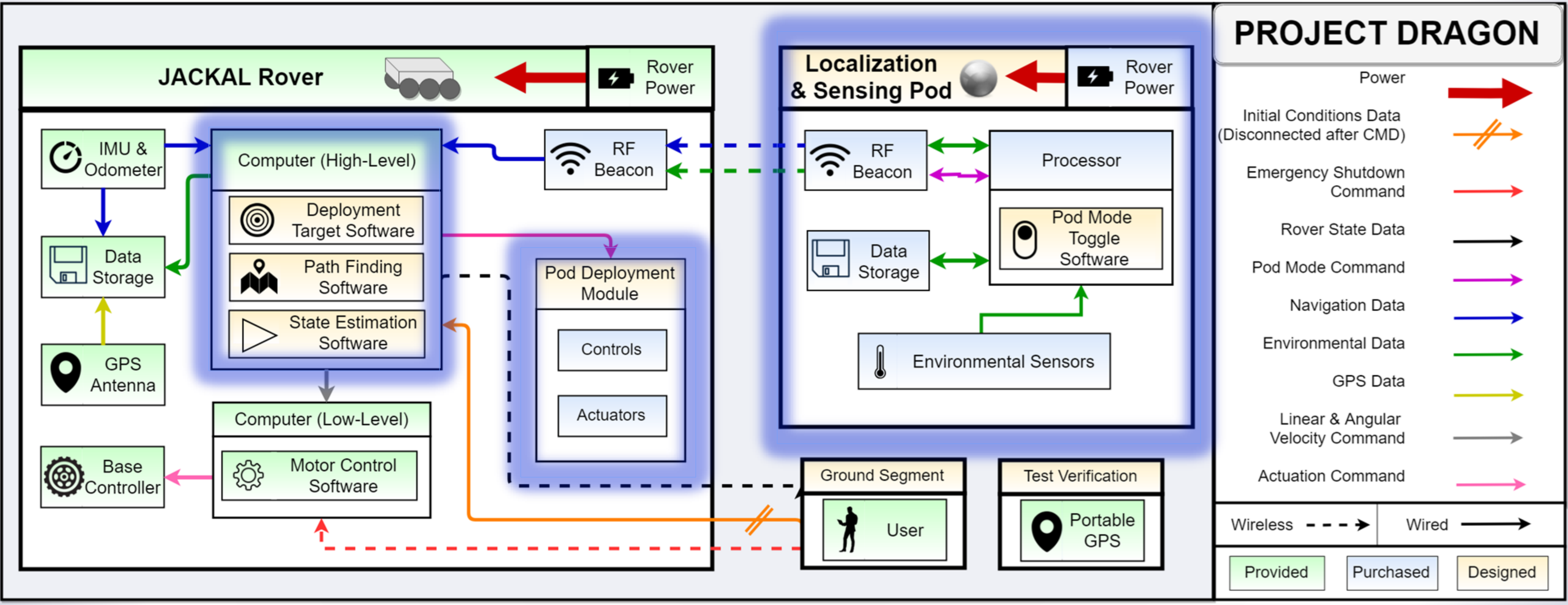
Design Requirements

Risk Mitigation

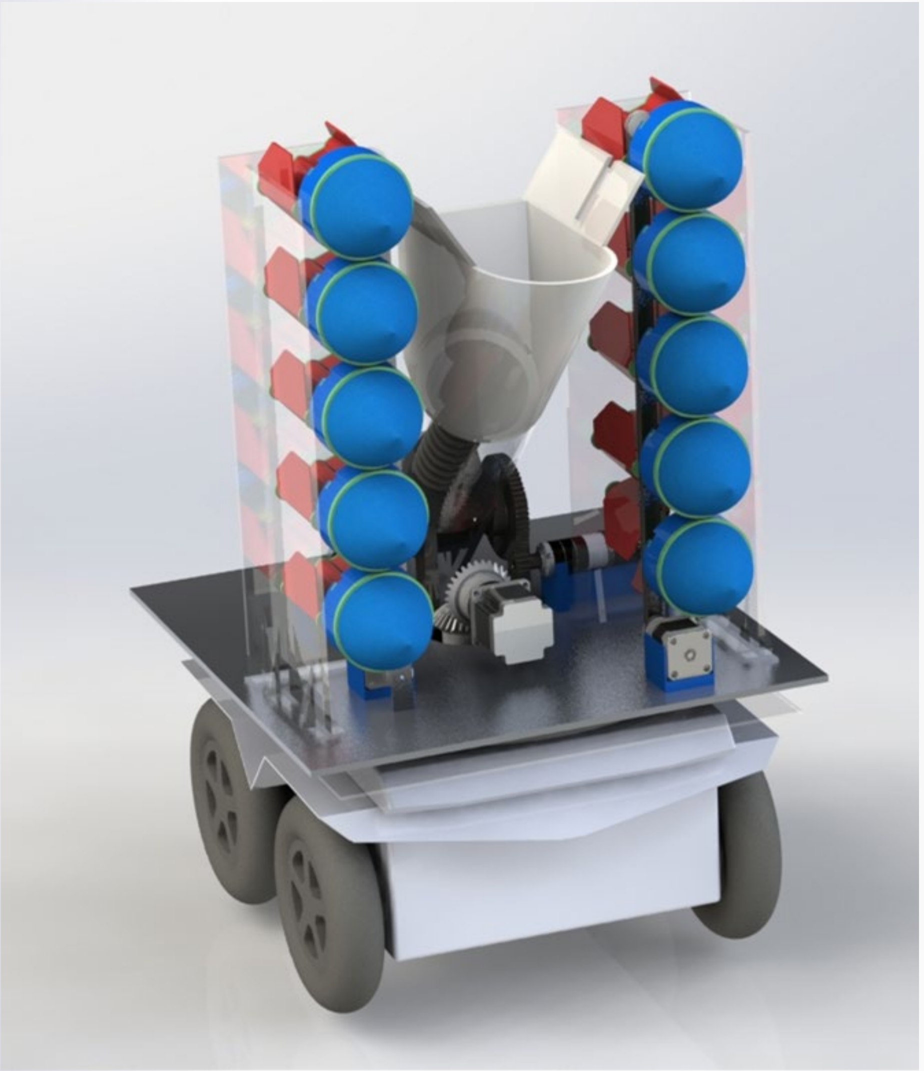
Verification & Validation

Project Plan

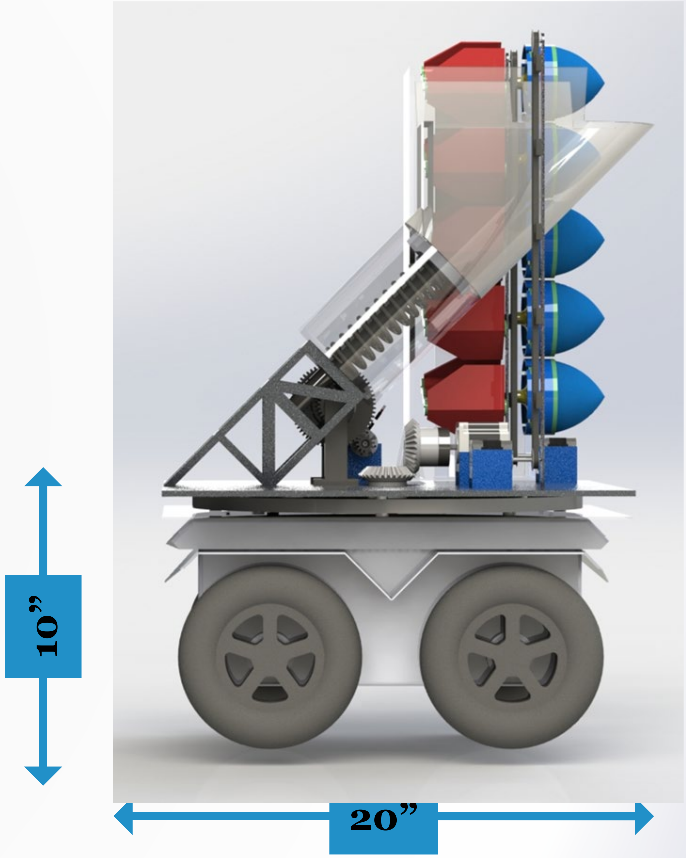
FBD


PROJECT DRAGON
JACKAL Rover
Rover Power
Localization & Sensing Pod
Rover Power
IMU & Odometer
Computer (High-Level)
Deployment Target Software
Path Finding Software
State Estimation Software
RF Beacon
Data Storage
GPS Antenna
Pod Deployment Module
Controls
Actuators
Computer (Low-Level)
Motor Control Software
Base Controller
RF Beacon
Processor
Pod Mode Toggle Software
Data Storage
Environmental Sensors
Ground Segment
User
Test Verification
Portable GPS
Power
Initial Conditions Data (Disconnected after CMD)
Emergency Shutdown Command
Rover State Data
Pod Mode Command
Navigation Data
Environmental Data
GPS Data
Linear & Angular Velocity Command
Actuation Command
Wireless
Wired
Provided
Purchased
Designed

Deployment Module Design



Front View



Side View

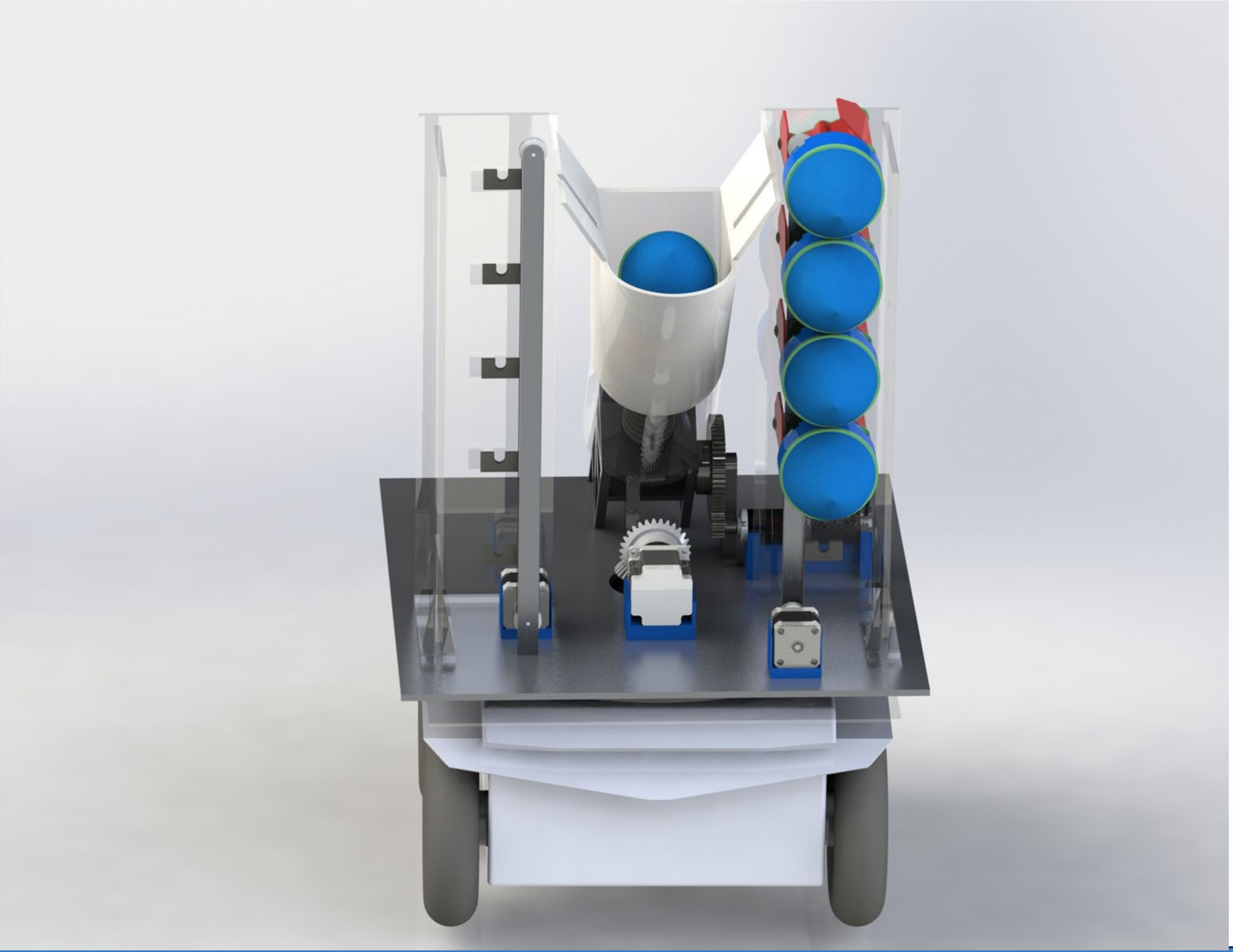
Deployment Module Design

1. Pre-deployment

Deployment Module Design

2. Reloading

- 2 NEMA 17 stepper motors
- Timing belt/conveyor system
- Alternating sides

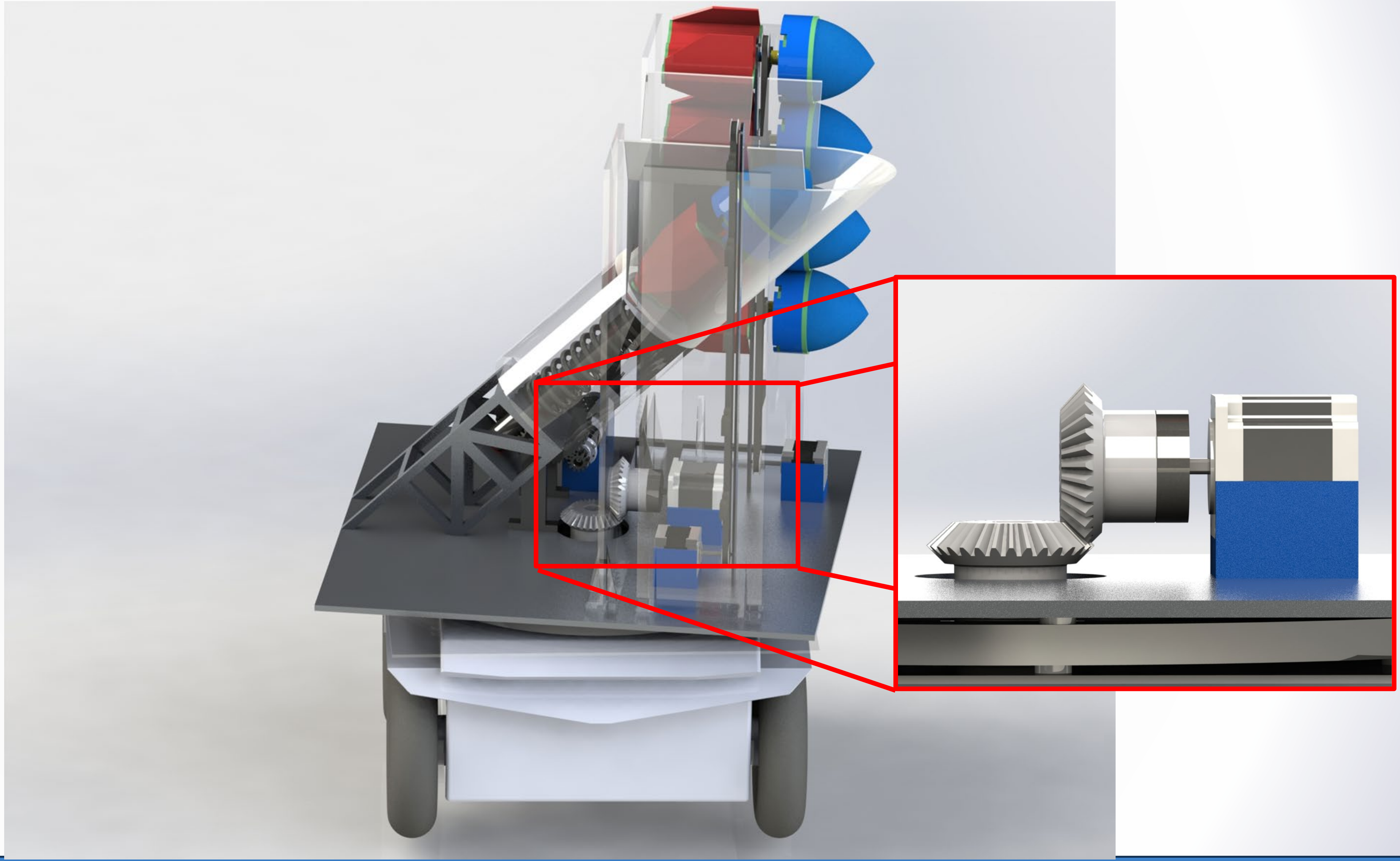


Deployment Module Design

3. Azimuth Control

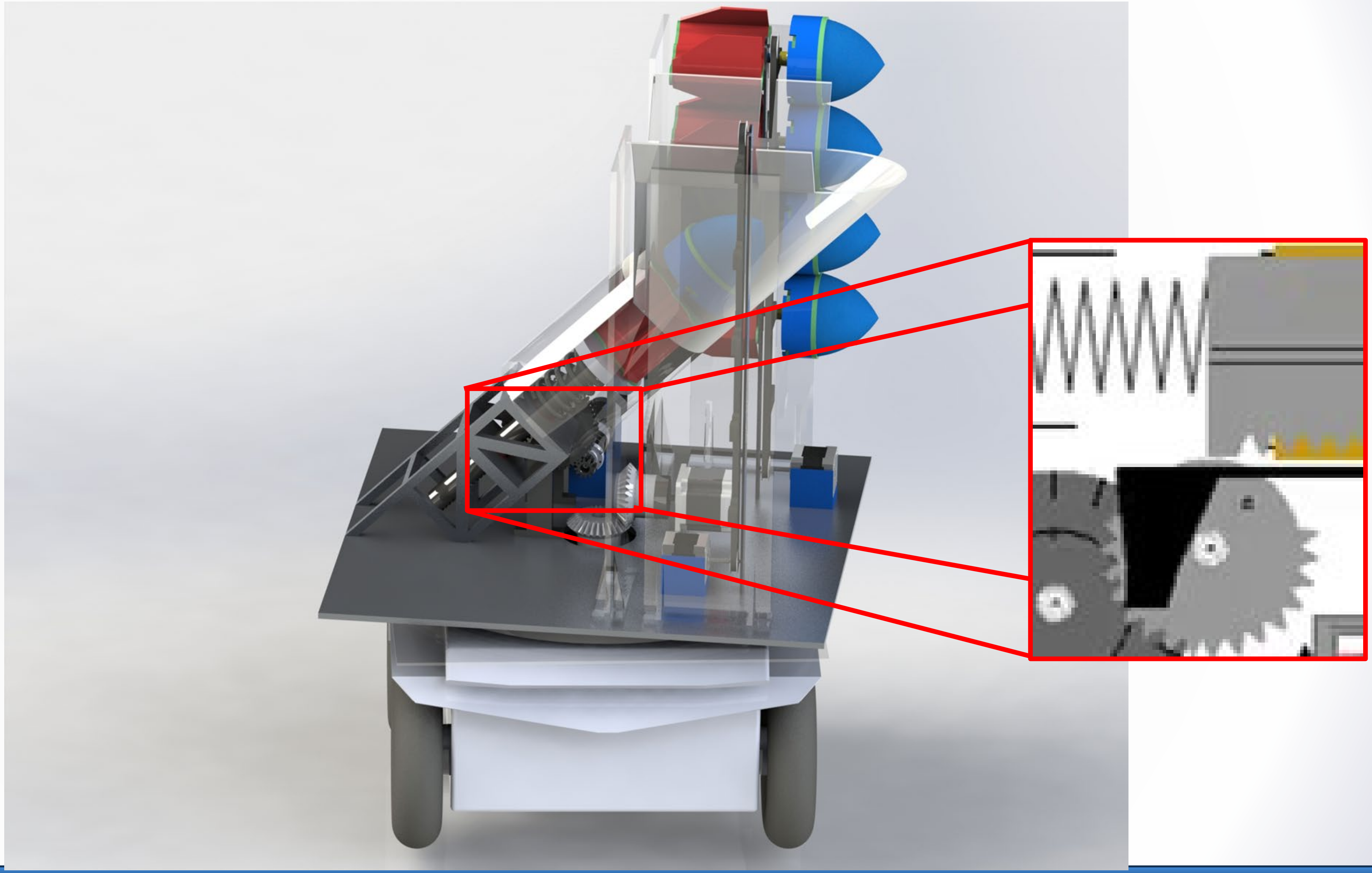
- NEMA 23 stepper motor
- Bevel Gears
- Swivel plate

Angle: ± 140°



Deployment Module Design

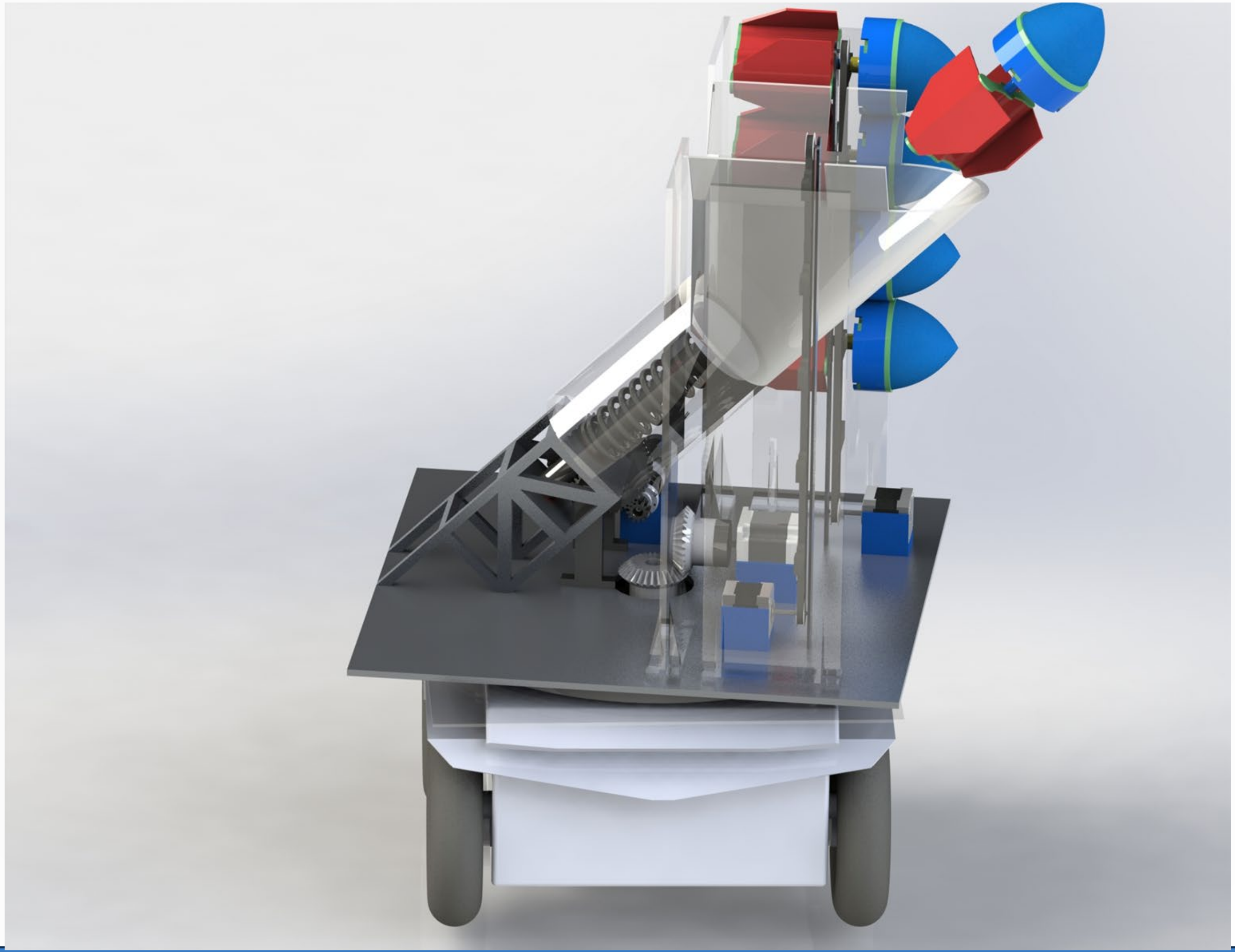
4. Spring Compression
   - 24V Brushed DC Motor
   - Rack/pinion system



Deployment Module Design

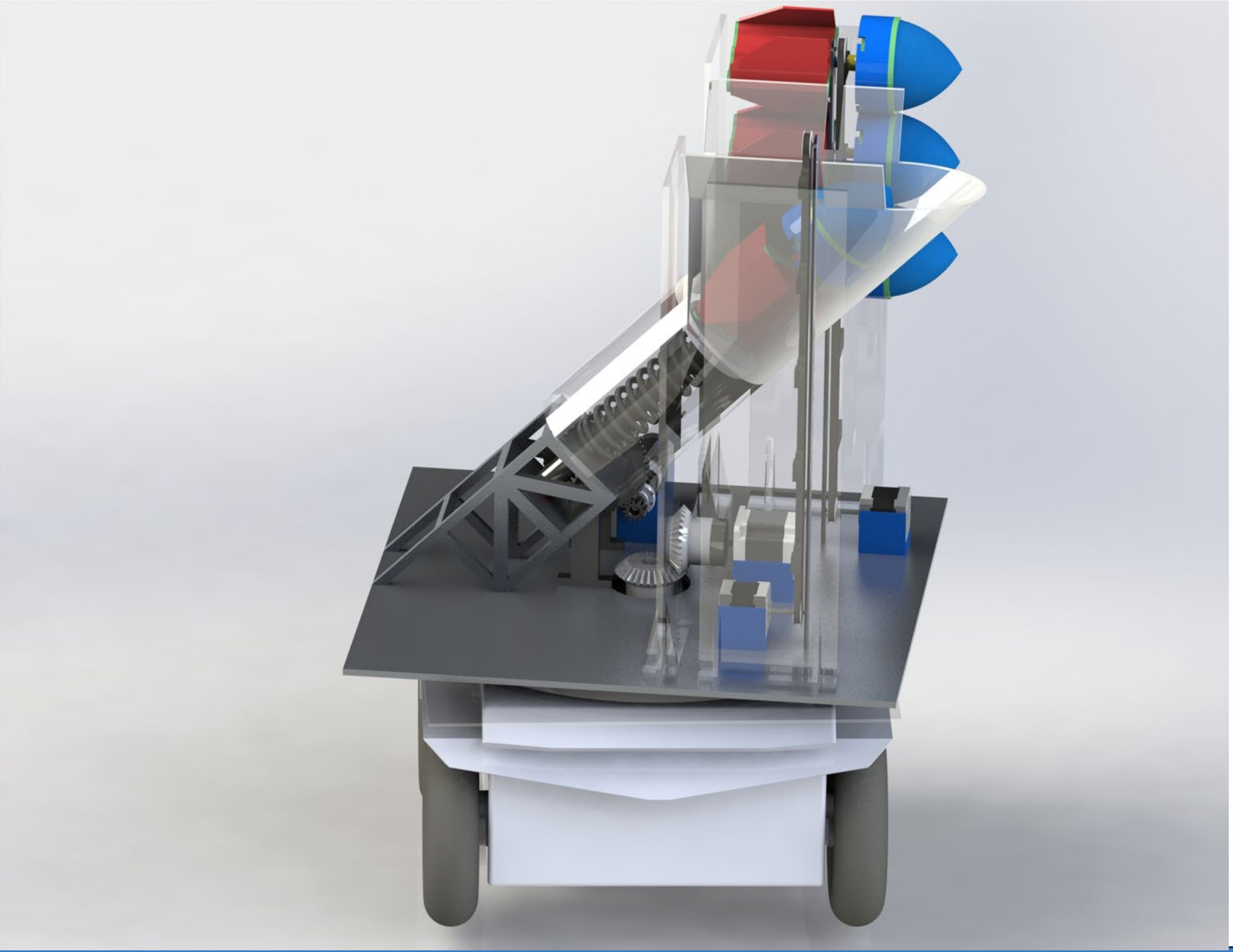
5. Deployment

Distance: 12 m

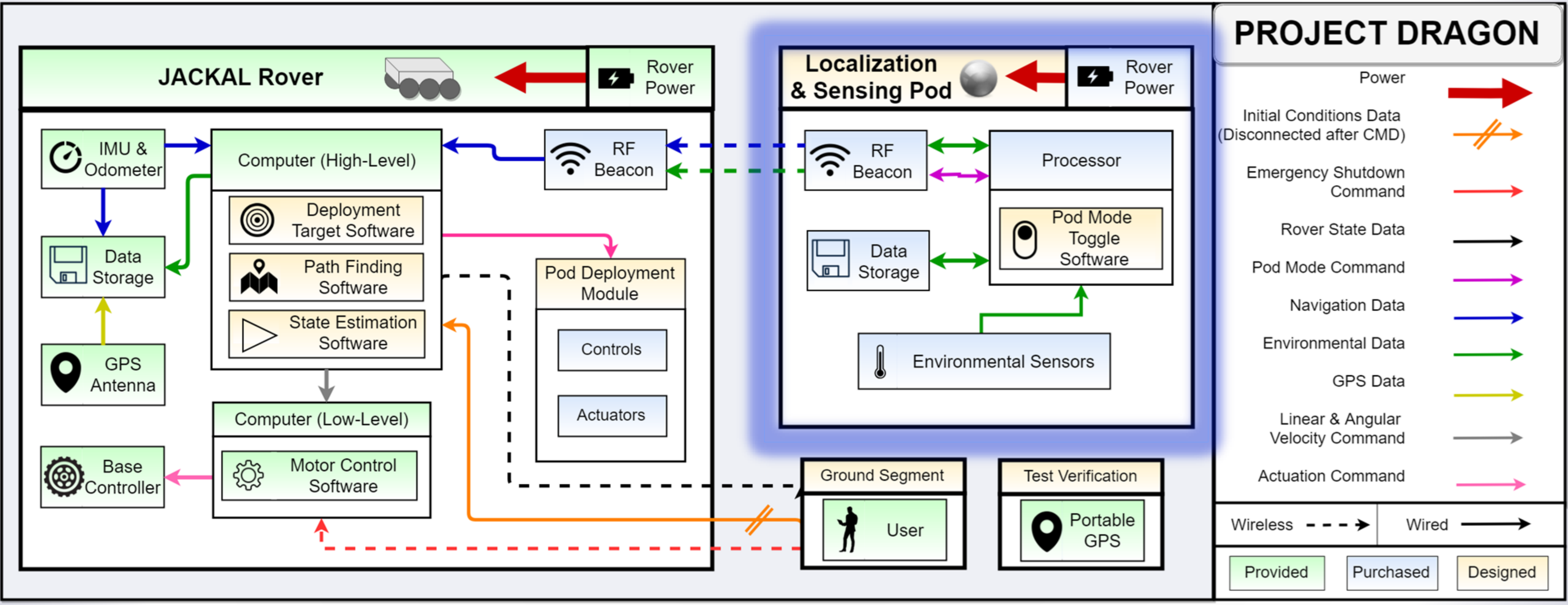


Deployment Module Design

6. Repeat



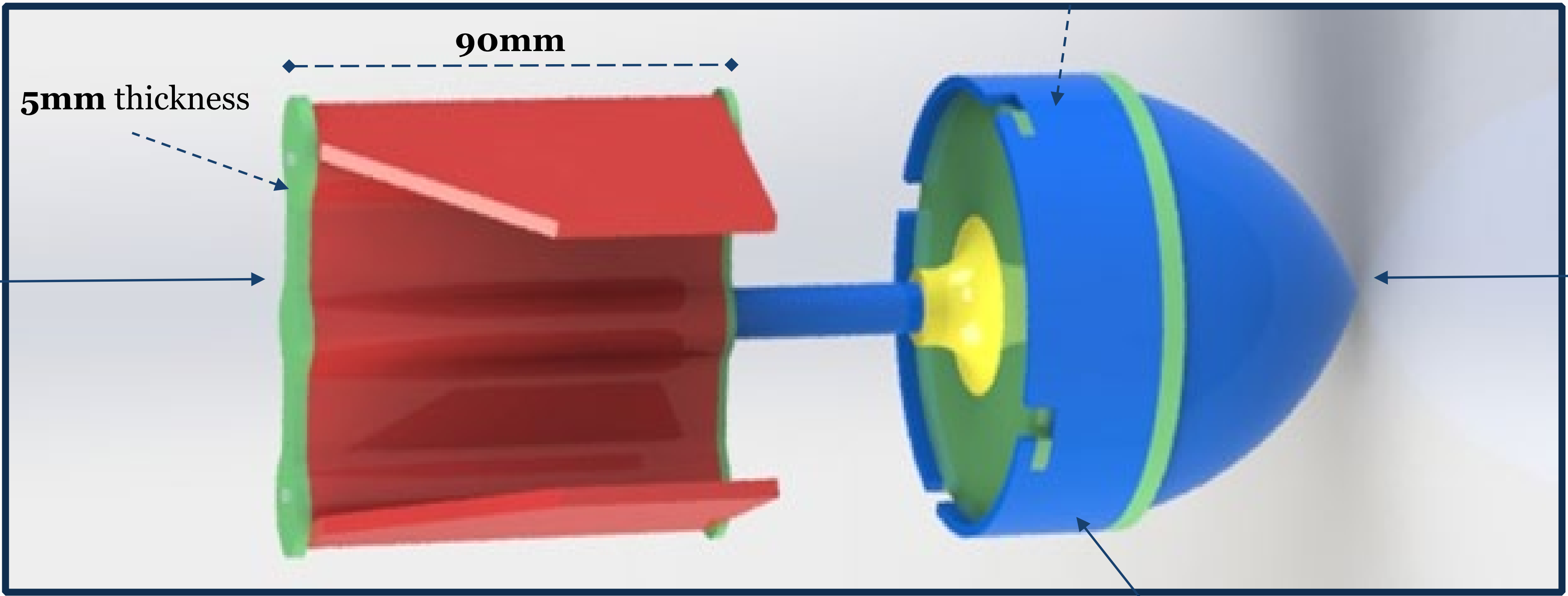
FBD



JACKAL Rover
Rover Power
IMU & Odometer
Computer (High-Level)
RF Beacon
Deployment Target Software
Path Finding Software
State Estimation Software
Data Storage
GPS Antenna
Pod Deployment Module
Controls
Actuators
Computer (Low-Level)
Motor Control Software
Base Controller
Localization & Sensing Pod
Rover Power
RF Beacon
Processor
Pod Mode Toggle Software
Data Storage
Environmental Sensors
Ground Segment
User
Test Verification
Portable GPS
PROJECT DRAGON
Power
Initial Conditions Data (Disconnected after CMD)
Emergency Shutdown Command
Rover State Data
Pod Mode Command
Navigation Data
Environmental Data
GPS Data
Linear & Angular Velocity Command
Actuation Command
Wireless
Wired
Provided
Purchased
Designed

Pod Structure Design

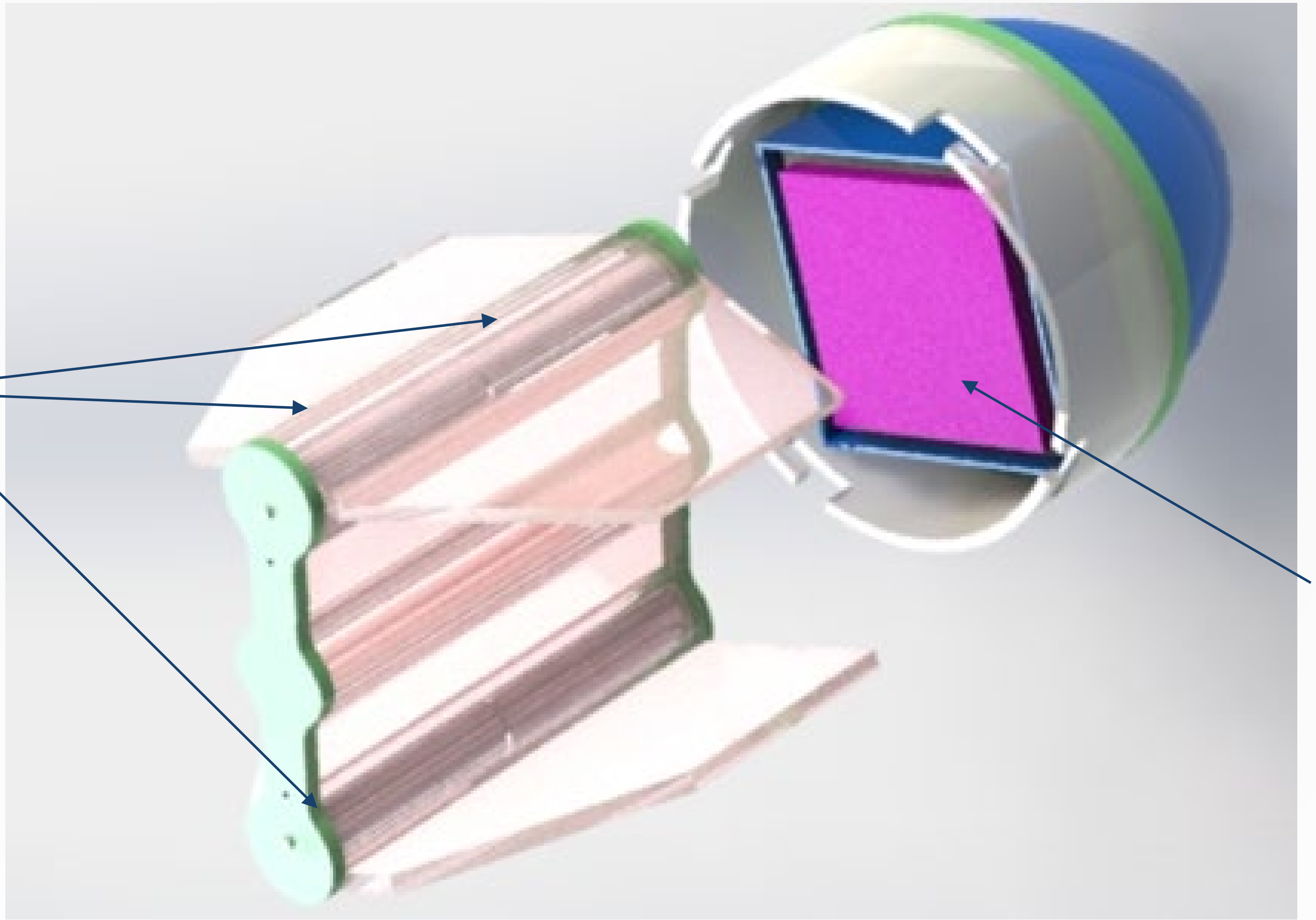
Pod structure contains the ranging electronics which are deployed from the cannon.



Pod Structure Design

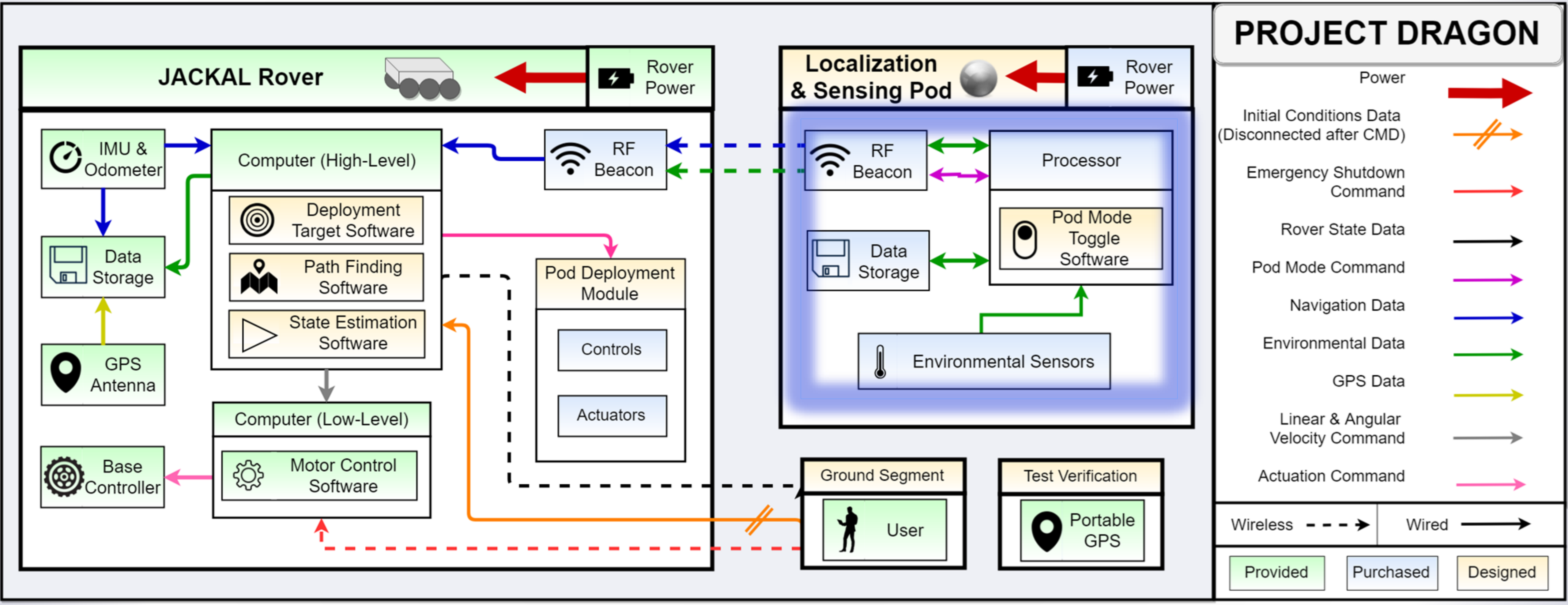
Pod structure contains batteries in tail for power, electronics are potted for resilience.

Batteries (AAA) stored in tail



Electronics (purple board) stored in blue tray, potted on all sides using polyurethane

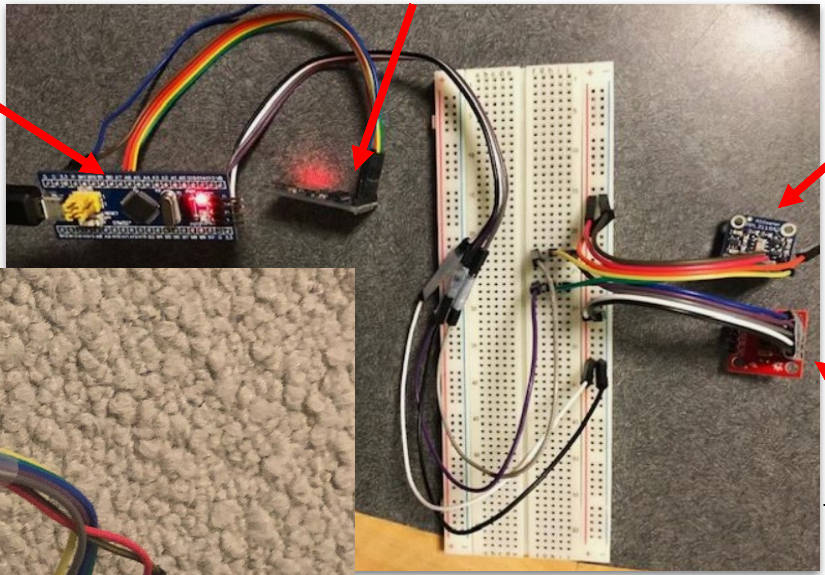
FBD



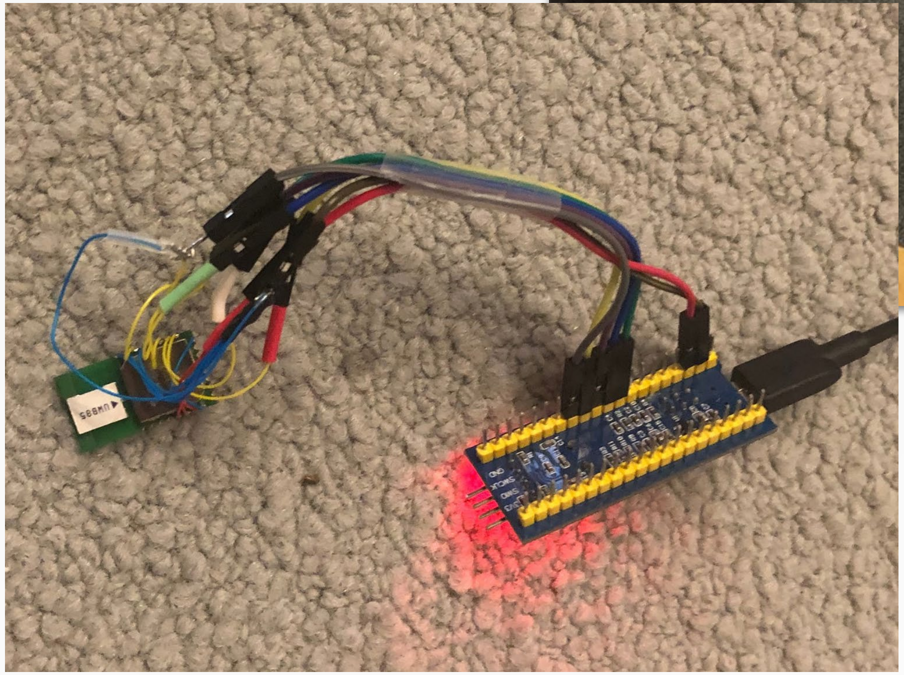
JACKAL Rover
Rover Power
IMU & Odometer
Computer (High-Level)
RF Beacon
Data Storage
Deployment Target Software
Path Finding Software
State Estimation Software
Pod Deployment Module
Controls
Actuators
GPS Antenna
Computer (Low-Level)
Motor Control Software
Base Controller
Localization & Sensing Pod
Rover Power
RF Beacon
Processor
Data Storage
Pod Mode Toggle Software
Environmental Sensors
Ground Segment
User
Test Verification
Portable GPS
PROJECT DRAGON
Power
Initial Conditions Data (Disconnected after CMD)
Emergency Shutdown Command
Rover State Data
Pod Mode Command
Navigation Data
Environmental Data
GPS Data
Linear & Angular Velocity Command
Actuation Command
Wireless
Wired
Provided
Purchased
Designed

Blue Pill Integration

- Purpose:
  - Provide ranging data and store environmental data.
- Design:
  - Used a Blue Pill with an STM32 processor to integrate ranging chip, SD card reader, and environmental sensor.
- Specs:
  - Accurate to ~22 cm, 30 measurements/second



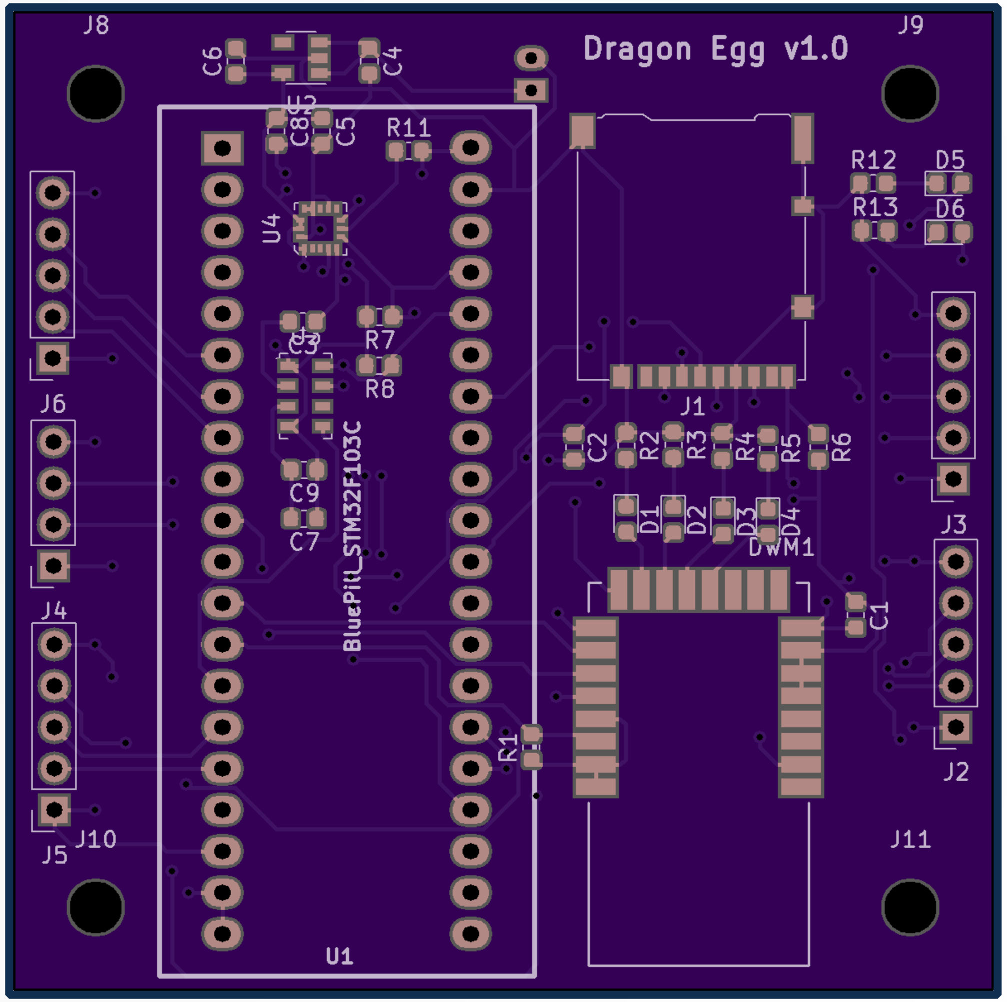
Sensors Integrated on Breadboard with Blue Pill



DWM1000 Integration with Blue Pill

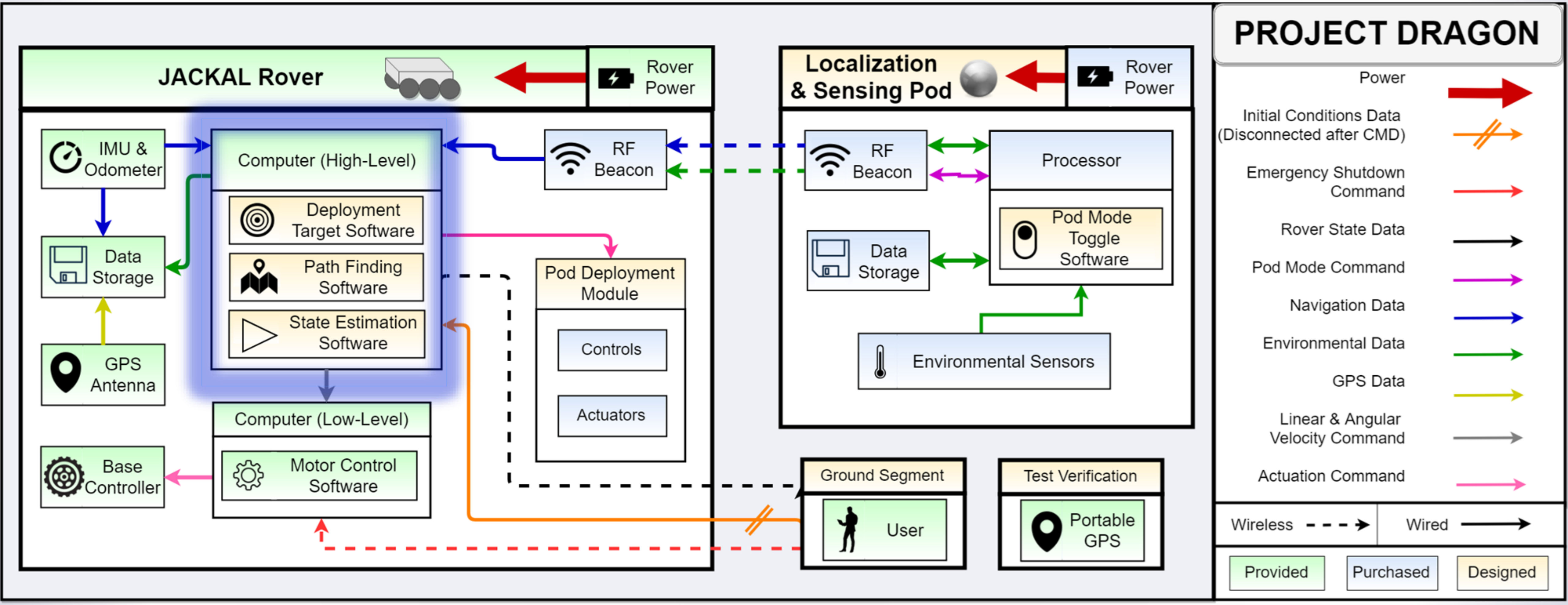
Custom PCB Design Board Layout

- Purpose:
  - Integrates DWM1000, SD card reader, environmental sensor, and accelerometer into one board to reduce size, increase reliability, and add mounting holes.
- Design:
  - Used reference schematics to help form a board design.
- Specs:
  - 6 [cm] x 6 [cm]



Dragon Egg Shield for Blue Pill [6cm x 6cm]

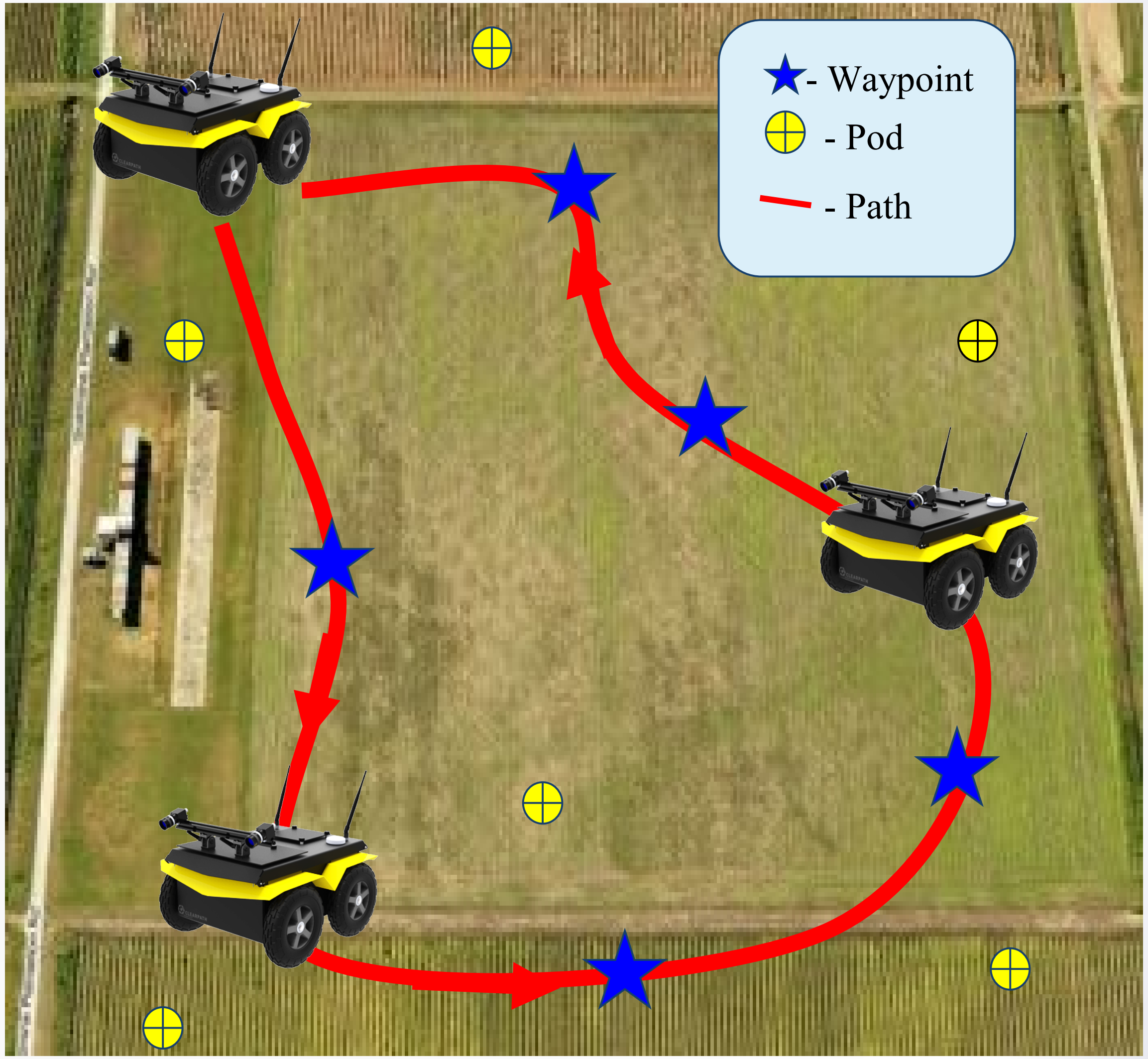
FBD



JACKAL Rover
Rover Power
IMU & Odometer
Computer (High-Level)
Deployment Target Software
Path Finding Software
State Estimation Software
Data Storage
GPS Antenna
RF Beacon
Pod Deployment Module
Controls
Actuators
Computer (Low-Level)
Motor Control Software
Base Controller
Localization & Sensing Pod
Rover Power
RF Beacon
Processor
Pod Mode Toggle Software
Data Storage
Environmental Sensors
Ground Segment
User
Test Verification
Portable GPS
PROJECT DRAGON
Power
Initial Conditions Data (Disconnected after CMD)
Emergency Shutdown Command
Rover State Data
Pod Mode Command
Navigation Data
Environmental Data
GPS Data
Linear & Angular Velocity Command
Actuation Command
Wireless
Wired
Provided
Purchased
Designed

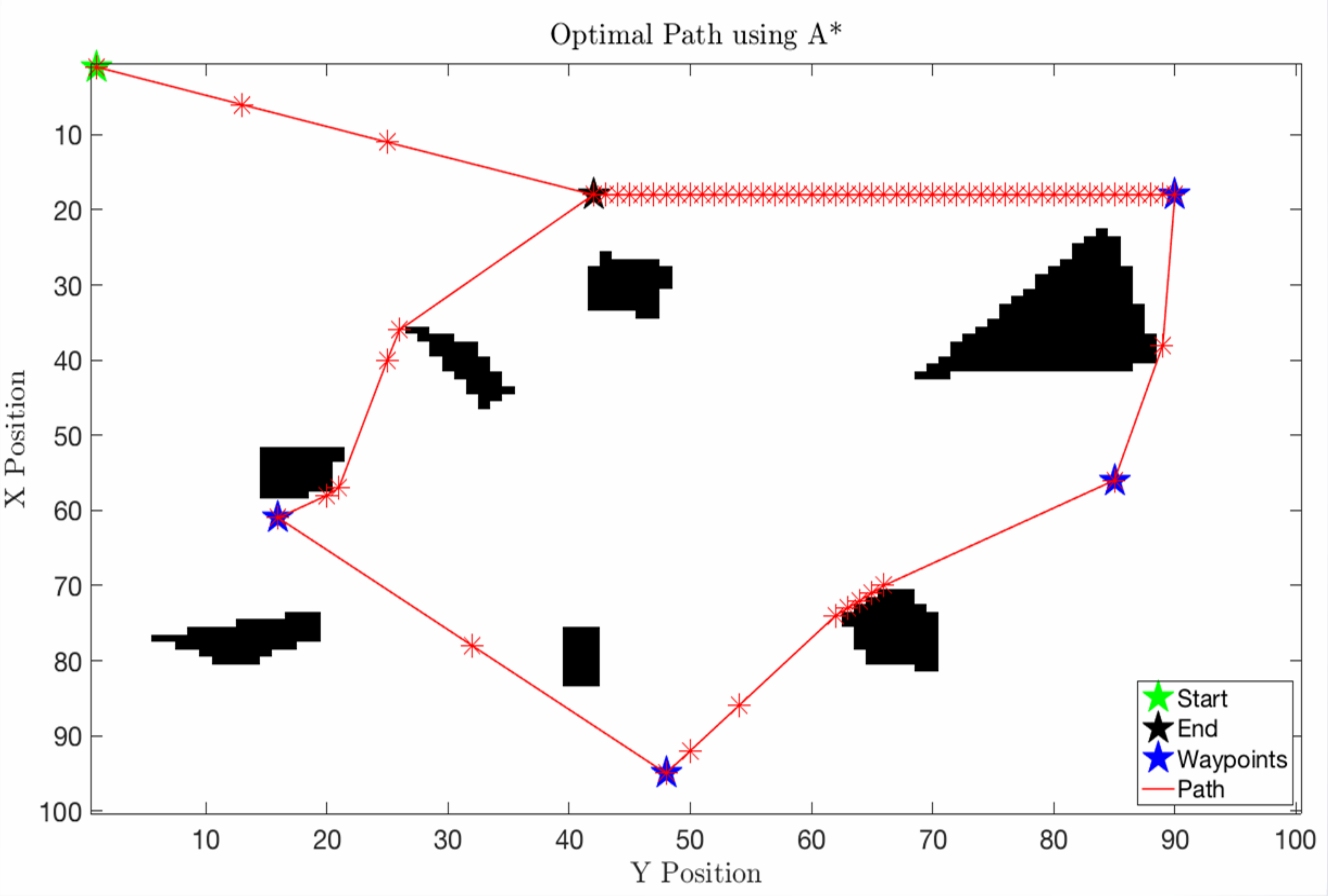
Navigation Subsystem: Design Solution

- Subsystem Purpose:
  - Design and implement software to allow rover to navigate mission path while meeting functional requirements and sending proper commands to other subsystems
- Subsystem Goals:
  - Generate safest closed loop path for rover through waypoints while avoiding obstacles
  - Communicate with pod mesh network
  - Use pod ranging data to algorithmically correct odometry error (gSLAM) and correct path deviance using onboard control



Navigation Subsystem - Pathfinding

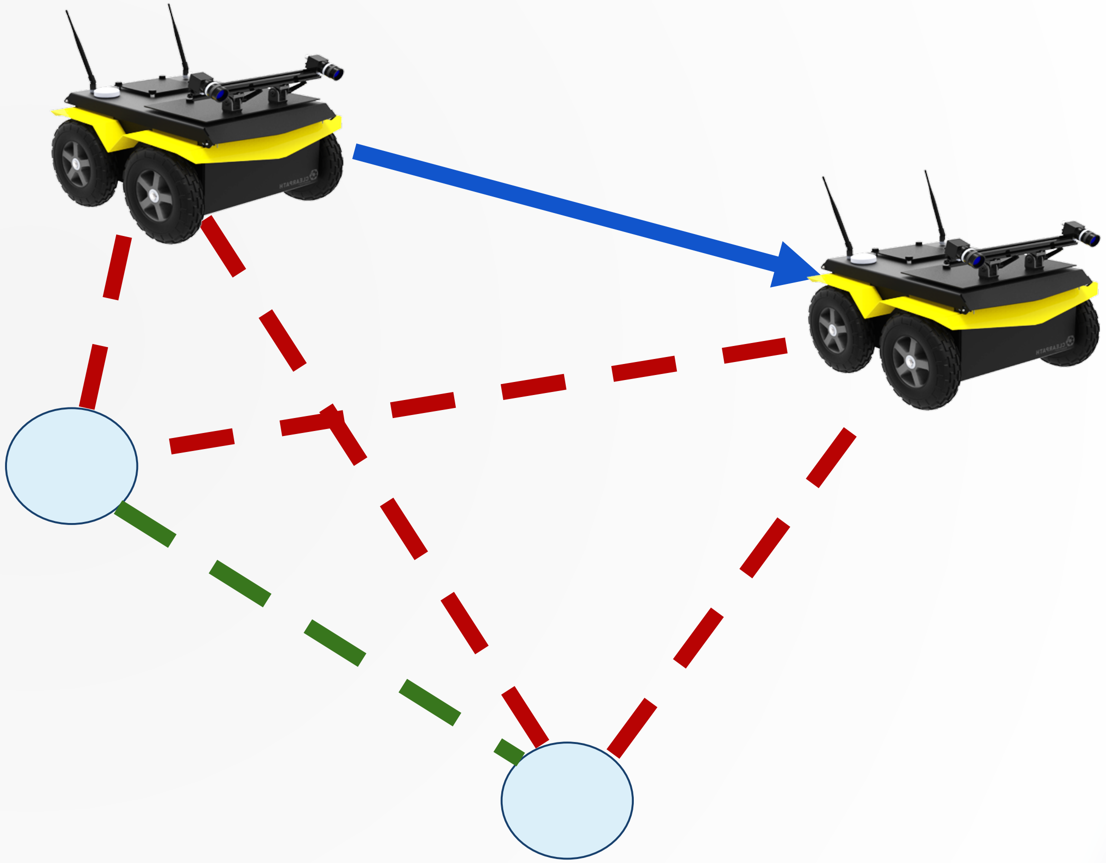
- Purpose:
  - Command rover to waypoints while avoiding obstacles using A* path algorithm
- Design:
  - A* determines shortest path between waypoints and around obstacles
  - Path points passed separately as commands for the rover to track
- Specs:
  - 1 m buffer to grazing keep-out zones
  - Variable tolerance for commands



MIP Map with Sample A* Path
(Red is path points, blue is waypoints, black obstacles)

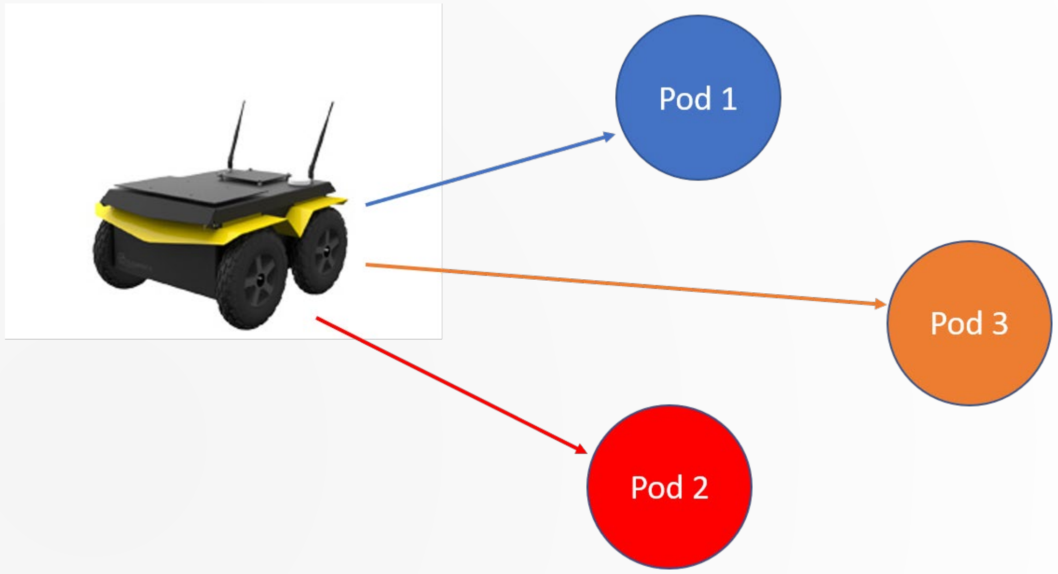
State Estimation Software Design

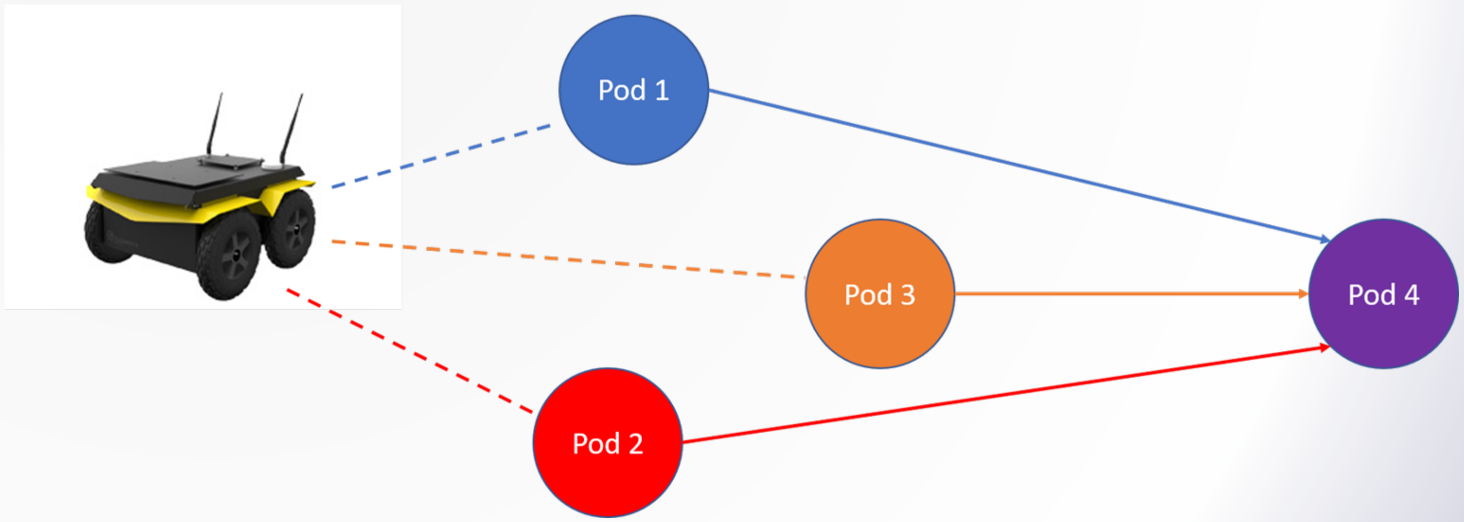
- Purpose:
  - Estimate rover and pod positions, high accuracy
- Design:
  - Graph-based SLAM (Simultaneous Localization And Mapping)
  - Builds up graph/matrix with rover and pod positions as vertices



Mesh Network Design

- Purpose:
  - Calculated distances between rover and pods as well as distances from different pods
  - Used in gSLAM calculations
- Design:
  - Use a DWM1000 RF module with unique identifiers
- Specs:
  - Tx Power: -42 dBm
  - Frequency: 3.5 GHz

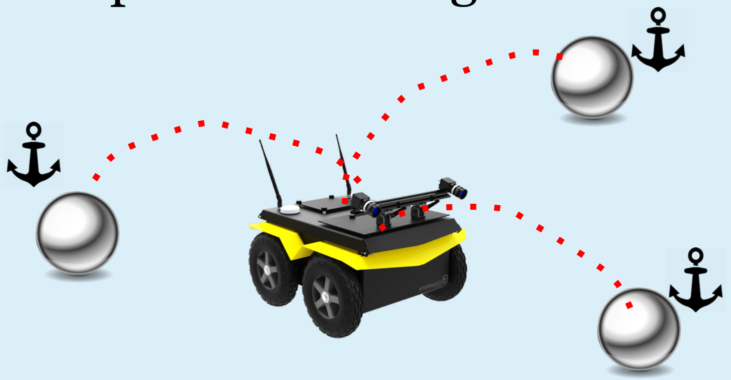




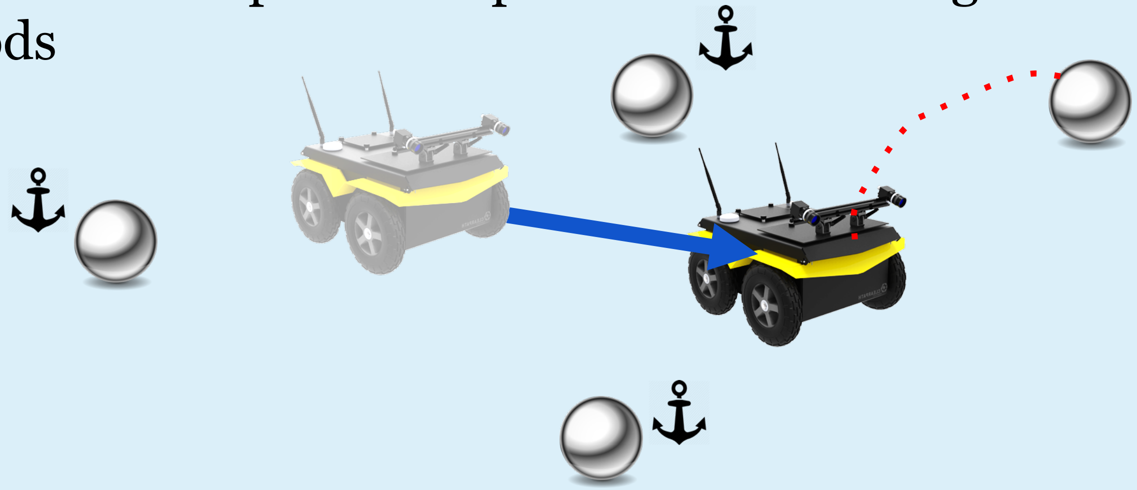
Deployment Target Software Design

- Purpose:
  - Tell rover at what position and angle 10 pods should be deployed to minimize error in rover position (< 1 m)
- Design:
  - Places pods to keep rover within a triangle of 3 pods
- Specs:
  - 10 pods keep total uncertainty in rover position < .92 m within a 100m x 100m map

1. Place 3 anchor pods in a triangle around rover



2. Place new pod to keep rover within triangle of pods

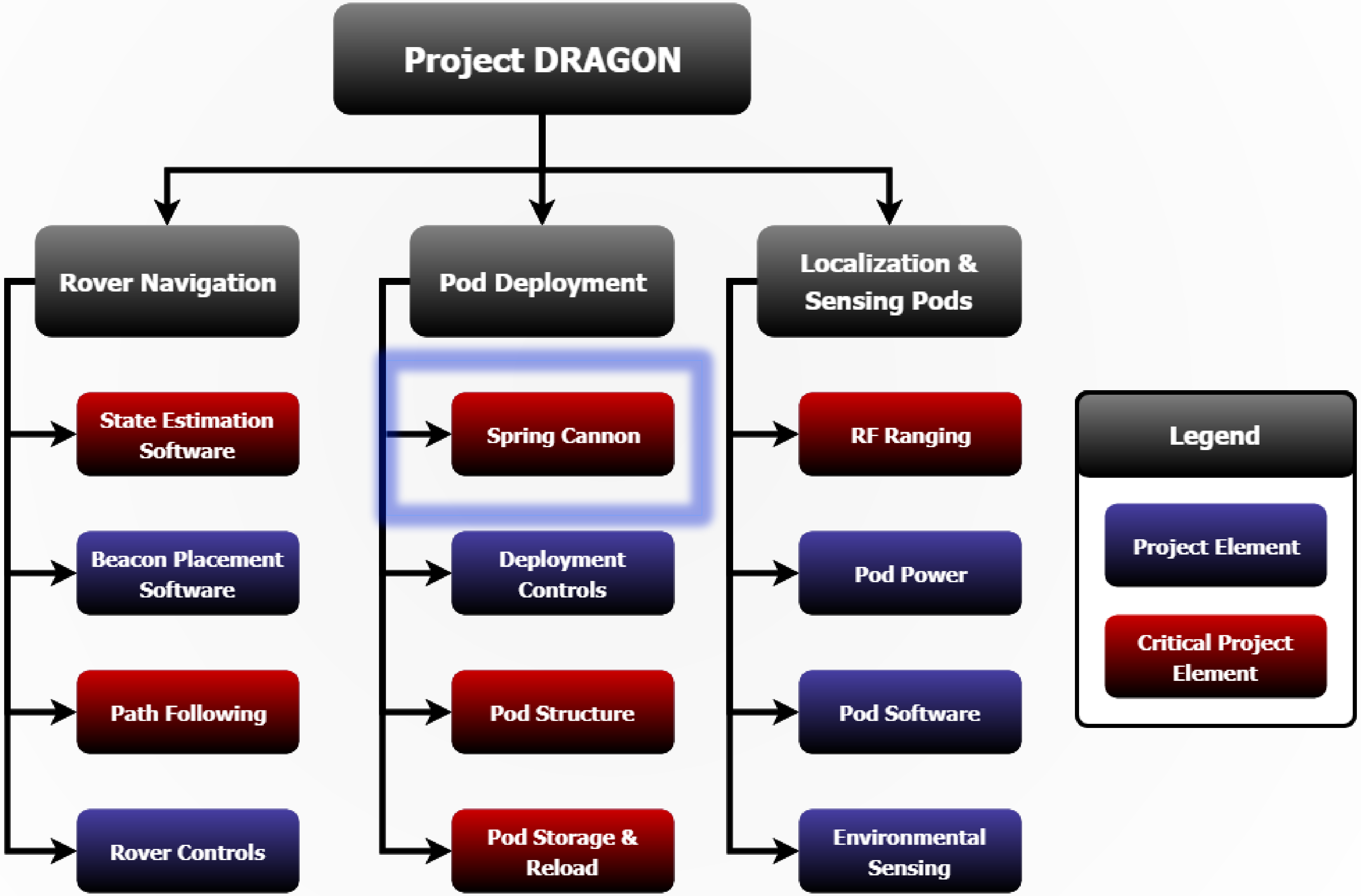


DRAGON

Design Requirements

Project Overview | Design Solution | Design Requirements | Risk Mitigation | Verification & Validation | Project Plan

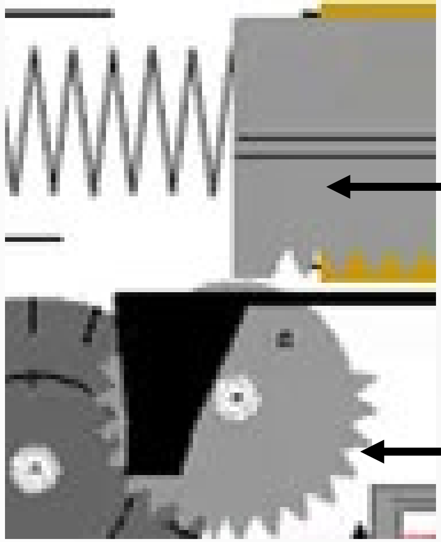
Critical Project Elements

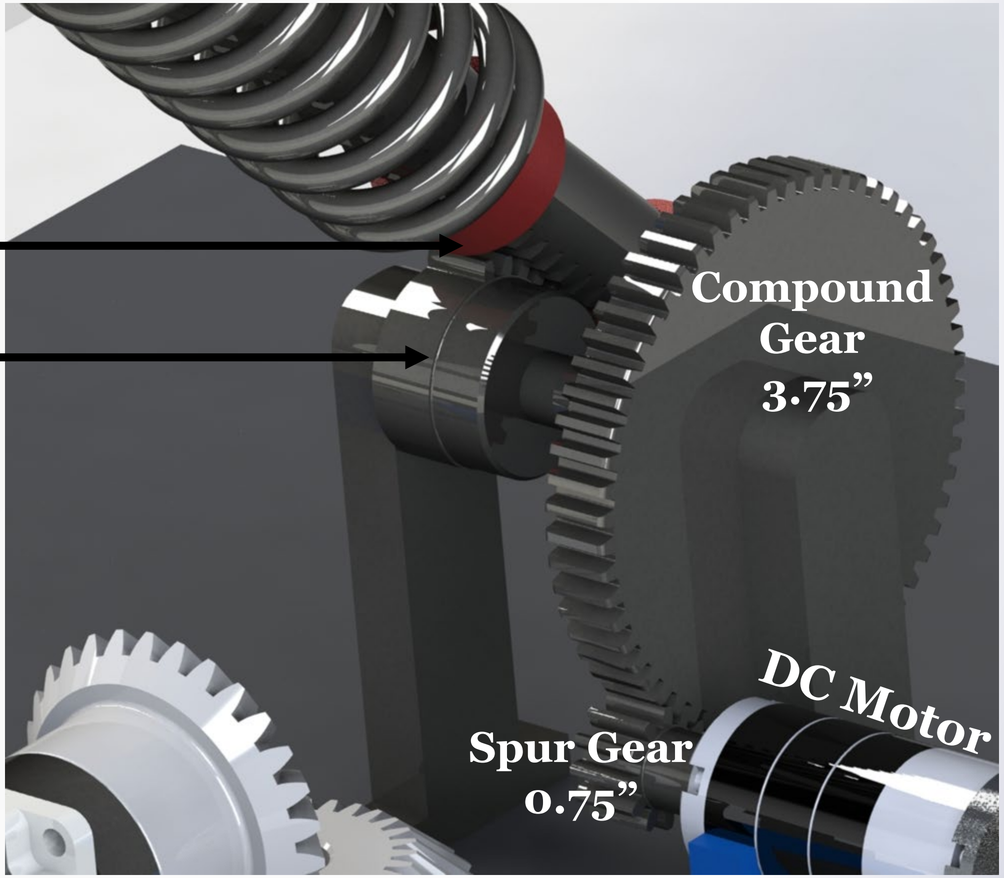


Deployment Module Design: Spring Compression

D3.8	**DM shall have the following range: No less than 10m**	

- The rack and pinion device needs to deploy to the required distance while withstanding the forces caused by spring compression

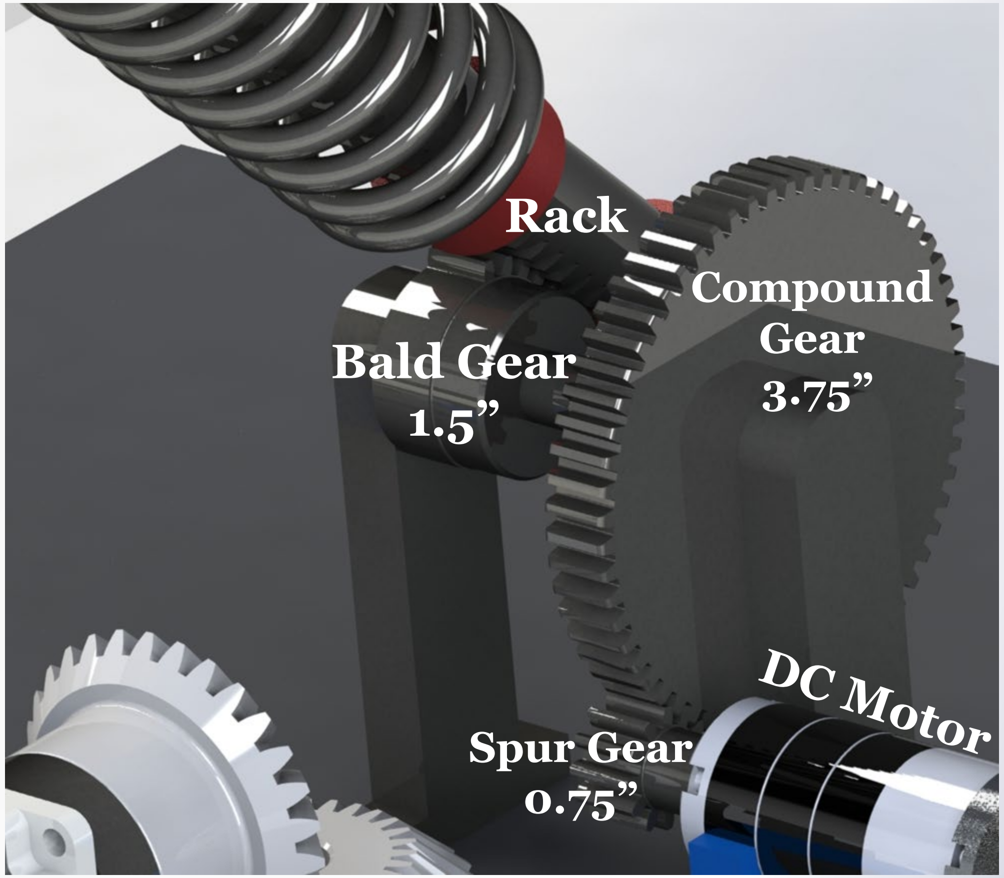




Spring Compression

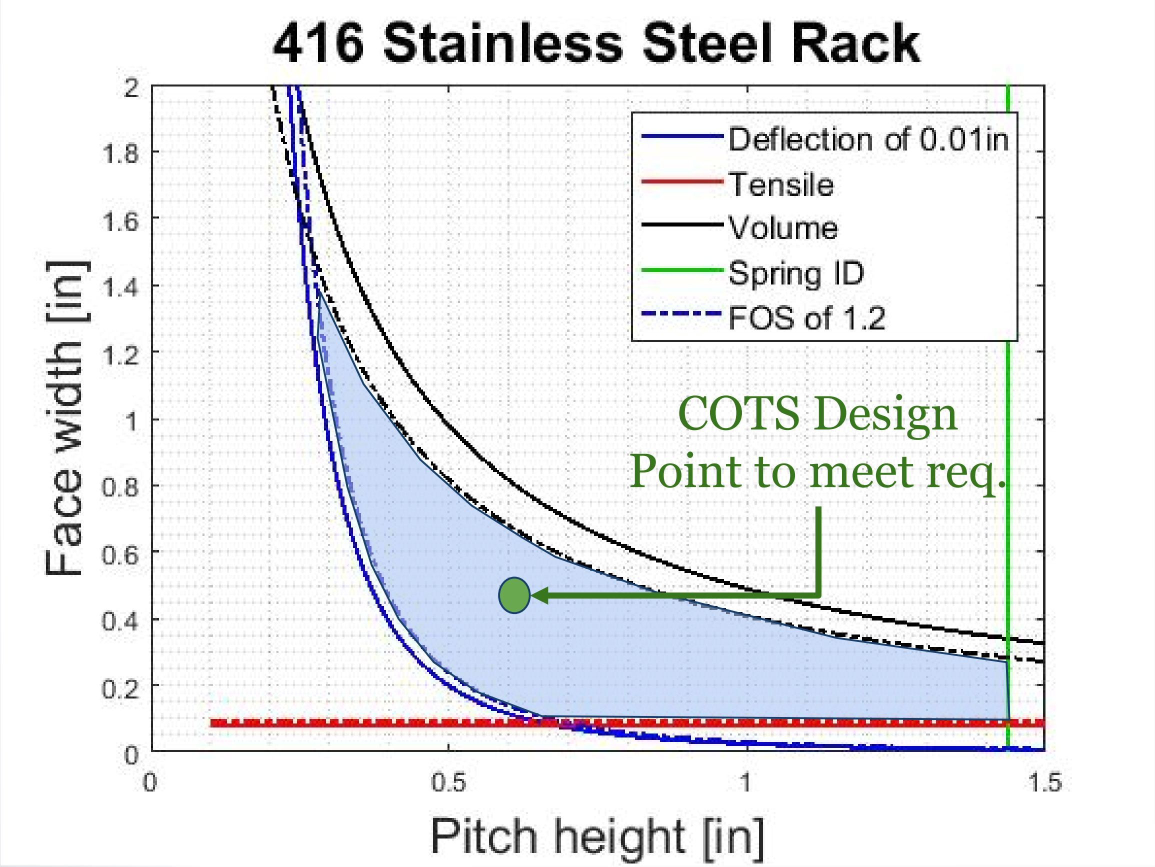
1. Spring and Motor Forces and Torques

Component	Value
Max Spring Force	300 lbs
At the rack and bald gear	225 in-lb
Compound gear	225 in-lb
Gear ratio	5:1
Motor spur gear	45 in-lb
Maximum motor torque	59 in-lb



COTS steel gears will be used for reliability and precision

Spring Compression

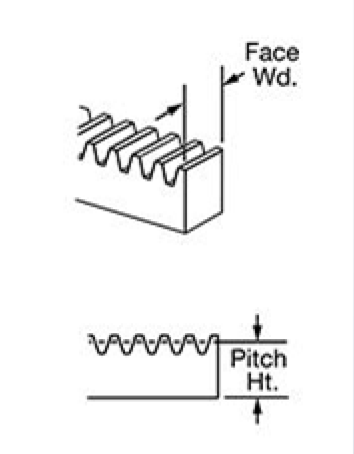


2. Design space for rack

Assumed:

- All tangential force applied to single tooth
- Beam support are 2” apart
- Mass must be less than 0.772 lbs

Design Point	Value
Pitch Height	0.625”
Face Width	0.438”
Rack Length	9.05”
Mass of plate and rack	0.705 lbs



Spring Decompression Analysis

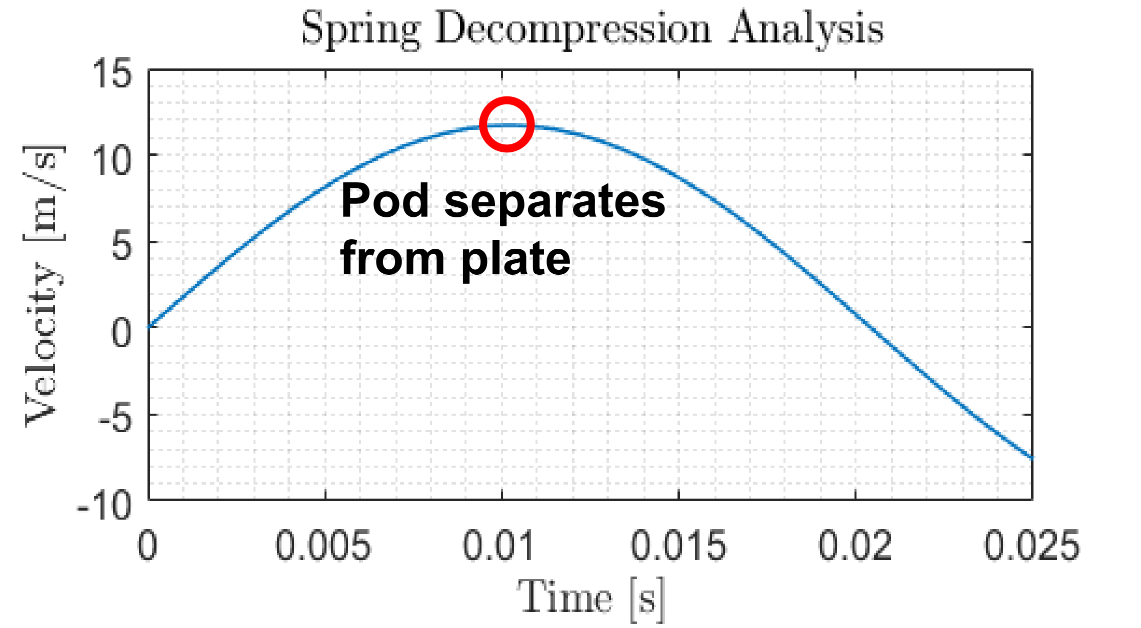
3. Verification of selected components

Plate and Rack mass = 320 [g]

Pod mass = 500 [g]

k ≅ 17,800 [N/m]

Max Compression = 0.076 [m]



Max Velocity = 11.21 [m/s]

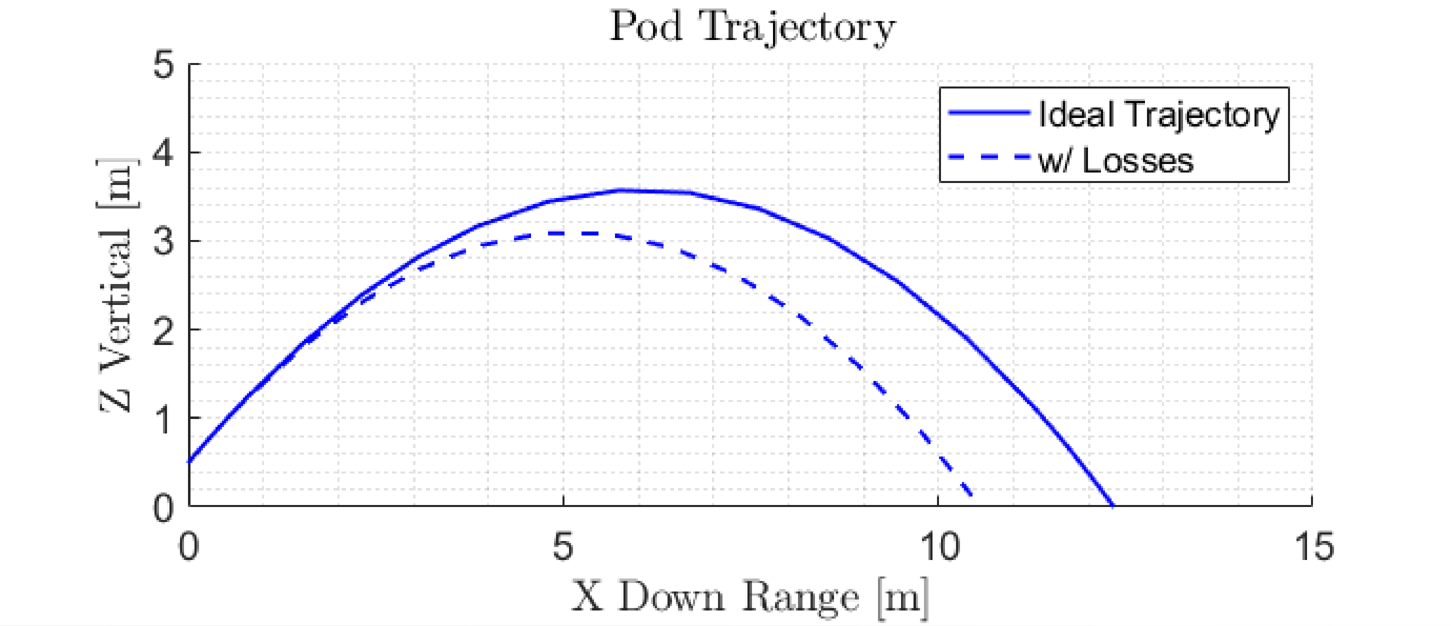
Trajectory Analysis

$V_0 = 11.21 \pm 1$ [m/s]

$A = 0.0065$ [m^2]

$C_d = 1$

$Z_0 = 0.5$ [m]



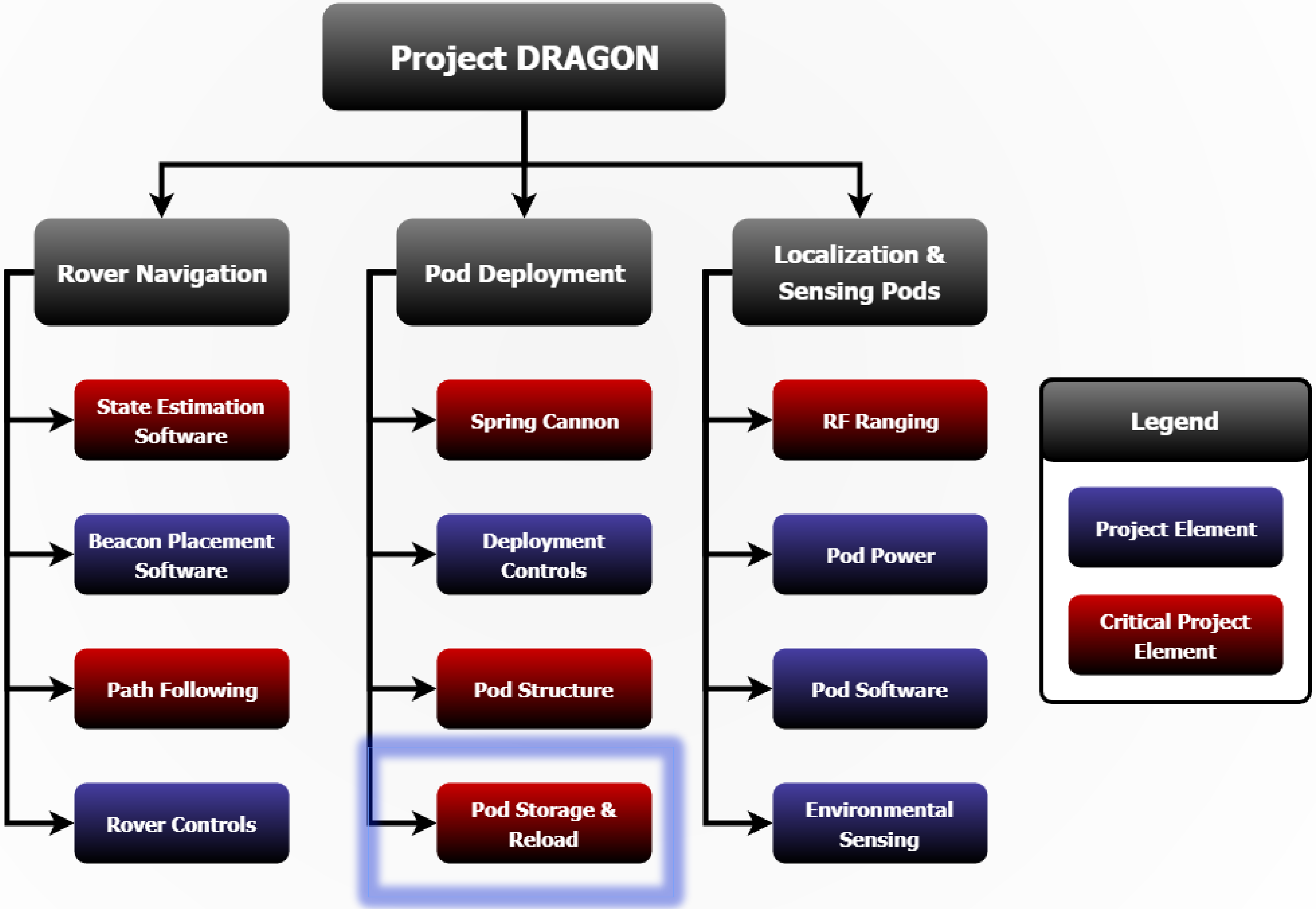
Losses due to:

- Incomplete Spring Compression
- Cannon Friction

Ideal Distance = 12.2 [m]
Min Distance = 10.5 [m]

D3.8	DM shall have the following range: No less than 10m	✓

Critical Project Elements

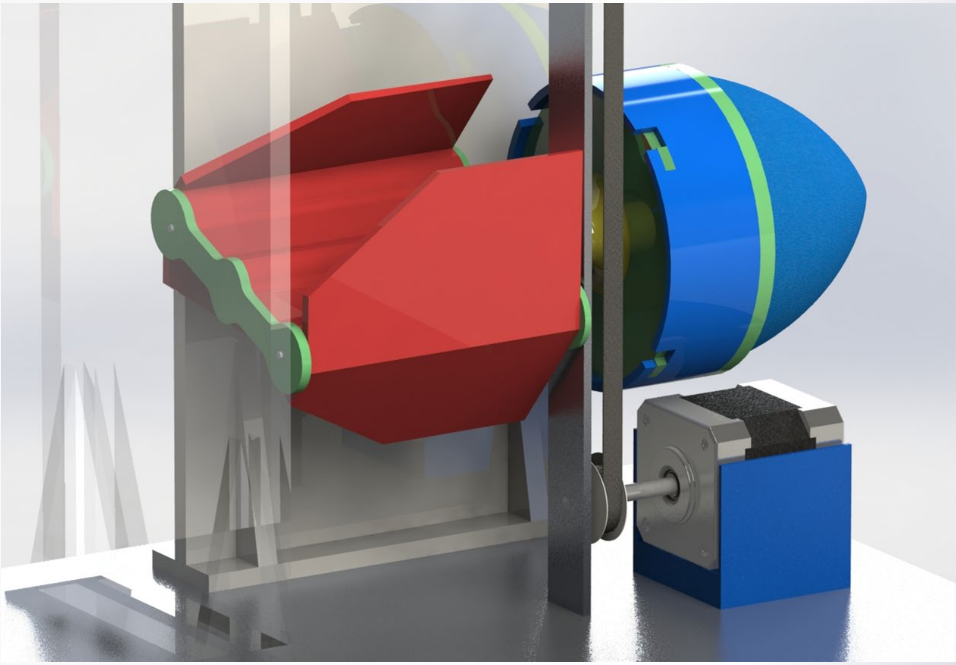


Reloading Mechanism: Gearing and Motor

D3.5.1	DM shall be capable of reloading and deploying a new pod every 2 minutes	✓

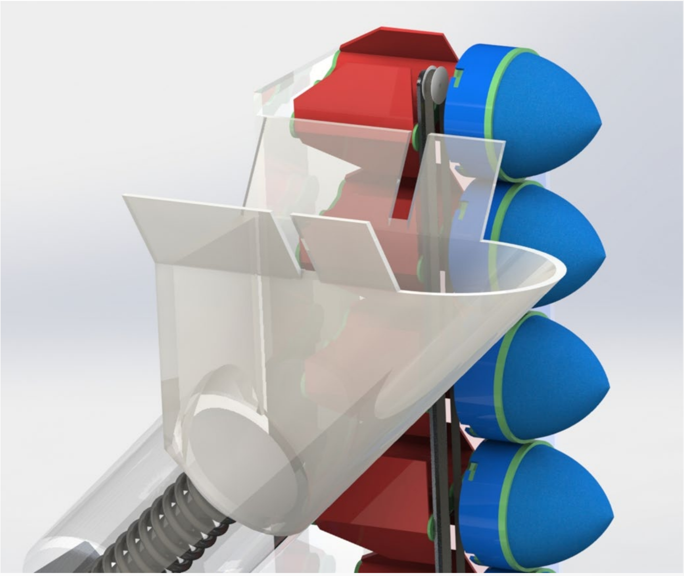
- Pods need to be loaded in a timely manner such that the mission can be completed in specified time

Design Point	Value	Requirement
Reload Time	< 5 sec	2 min
Max Motor RPM	600	0.5
Motor Holding Torque	6.12 kg-cm	3.81 kg-cm



Reloading Mechanism: Funnel

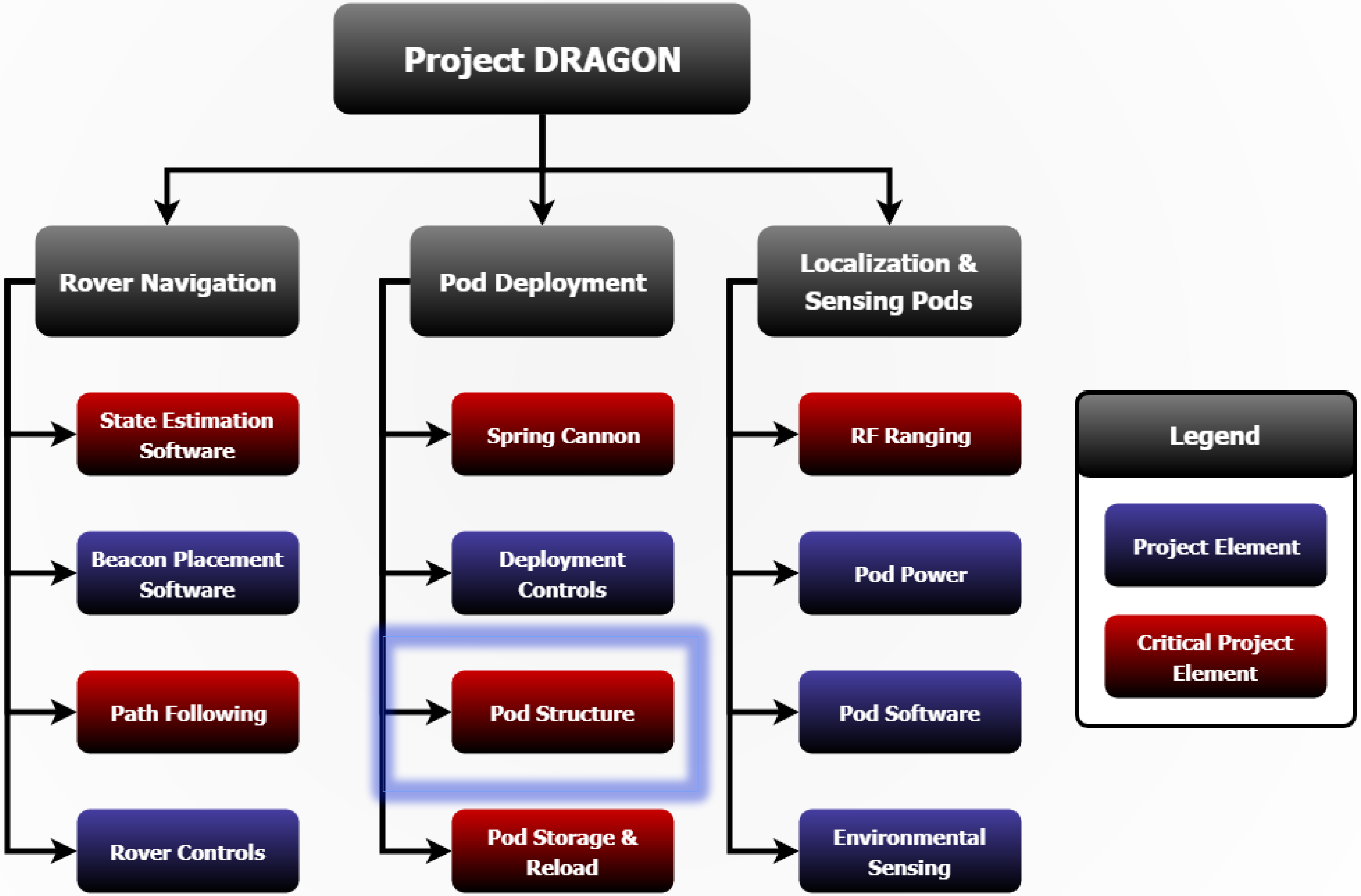
D3.5.2	Pods shall slide completely into deployment tube in a nose-forward configuration.	✓



Drop height in video: ~0.75”

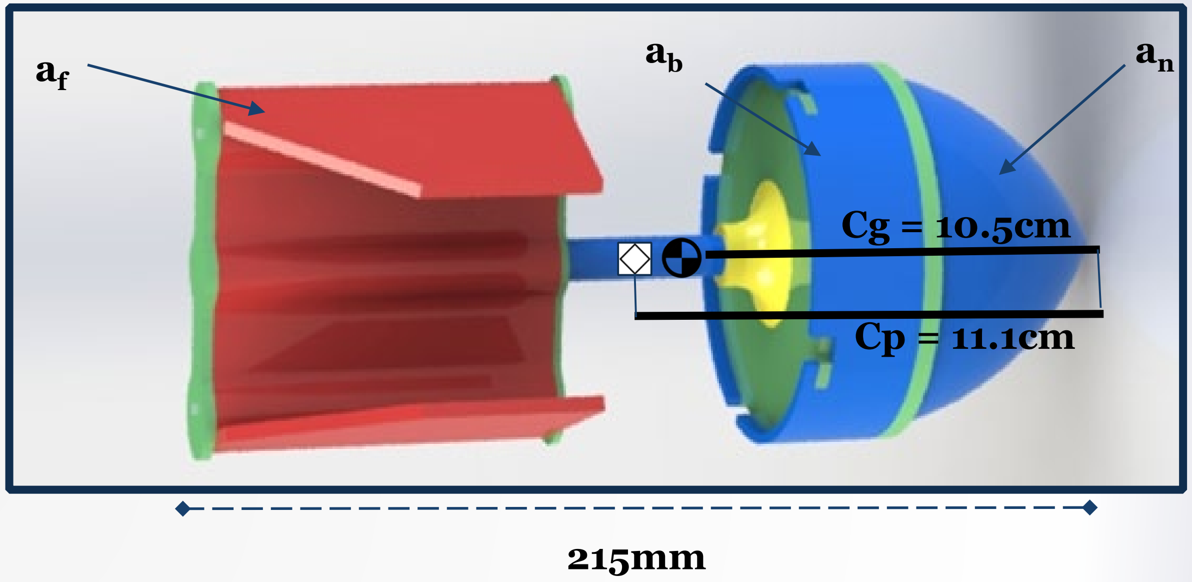
Actual designed drop height: 0.79”

Critical Project Elements



Pod Structural Design: Aerodynamics

- Purpose:
  - Minimize aerodynamic drag
  - Maximize aerodynamic stability
- Design:
  - Cp is behind the Cg, aerodynamic stability is achieved
  - Minimizing drag: area rule, sweeping fins, and minimizing area
  - Fins also provide spin stability



$$cp\,A = d_n a_n + d_b a_b + d_f a_f$$

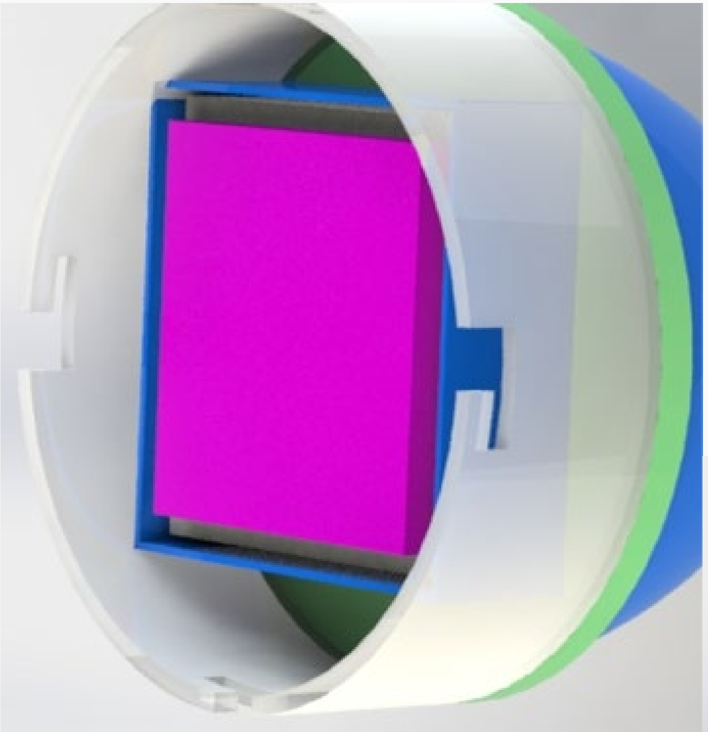
Simplified cP calculation, validated via CFD

- Specs:
  - From Nose: Cp = 11.1cm, Cg = 11.0cm, **with ballast Cg = 10.5cm = stable**
  - A cD of 0.25 was calculated via CFD

P5.4.6	**P - Pods shall be stable to promote range and impact orientation**	✓

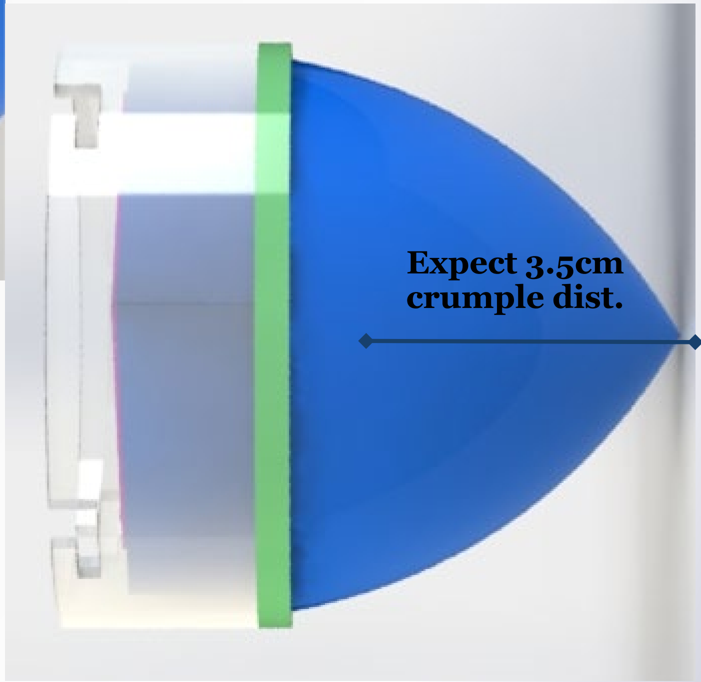
Pod Structural Design: Impact Struct.

- Purpose:
  - Prevent launch & impact damage
- Design:
  - Potting - bidirectional
  - Foam ‘crumple zone’ - impact only
  - Elastic Suspension - tested, unused
- Specs:
  - Potting - minimize board bending, primary failure
  - Crumple zone - increase acceleration distance
    - Add non-elastic damping to the system



Left: Electronics set in potting tray

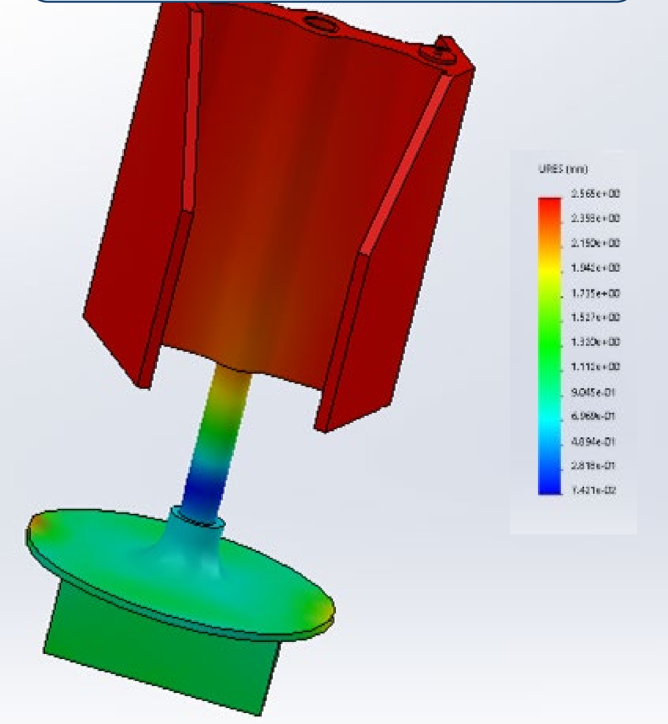
Below: Foam nose crumple zone

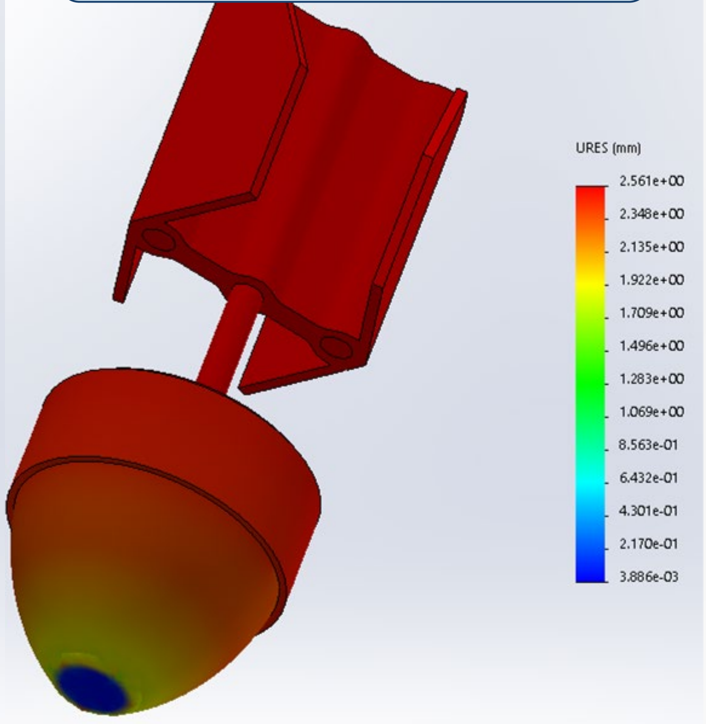


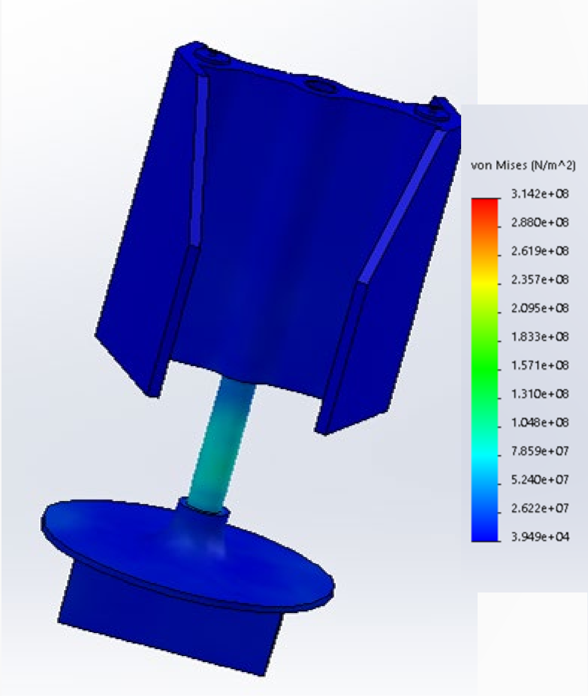
Pod Structural Design: Crumple Zone

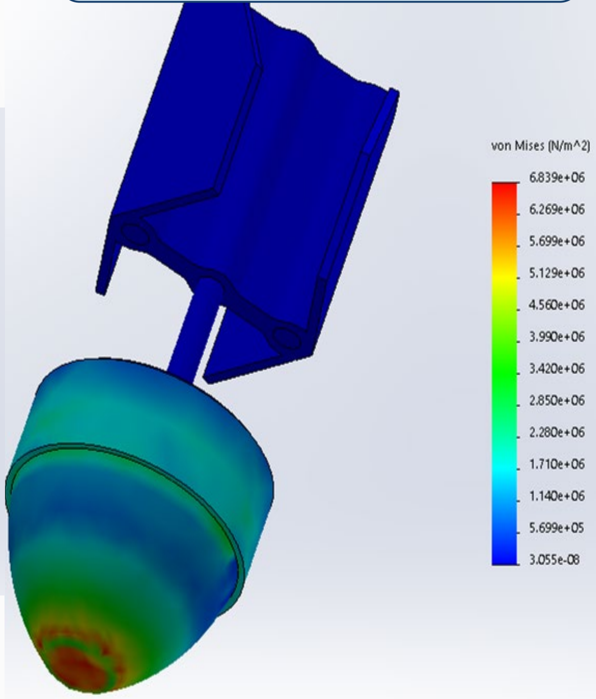
- **Computer Sim:** Drop Test 14m/s

No padding: Displacement	Crumple Zone: Displacement	No padding: Stress	Crumple Zone: Stress









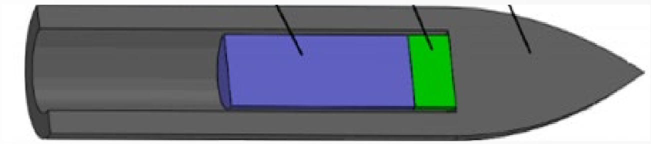
Increases displacement by factor of 7

Decreases stress by factor of 26

Pod Structural Design: Potting

Sandia National Laboratories

- Electronics surviving in kinetic impactors
  - Tank rounds: 25,000 g's accel



$$\sigma = \frac{(mass)\ (G's)(Amplification\ Factor)}{Loaded\ Area}$$

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

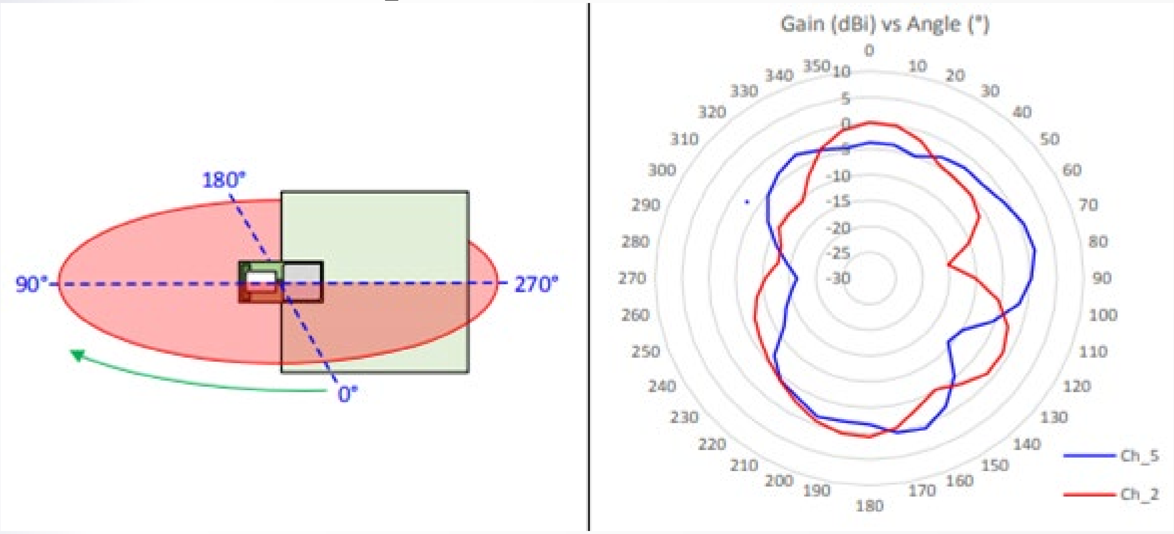
- Electronics to survive spacecraft rocket launch environment
- LASP: NASA STD 8739 1b will survive impact

Potting Material	Strain Energy Transmitted (J)	Safety Factor
Conathane EN 4/9	.0436 or 4.36%	3.0

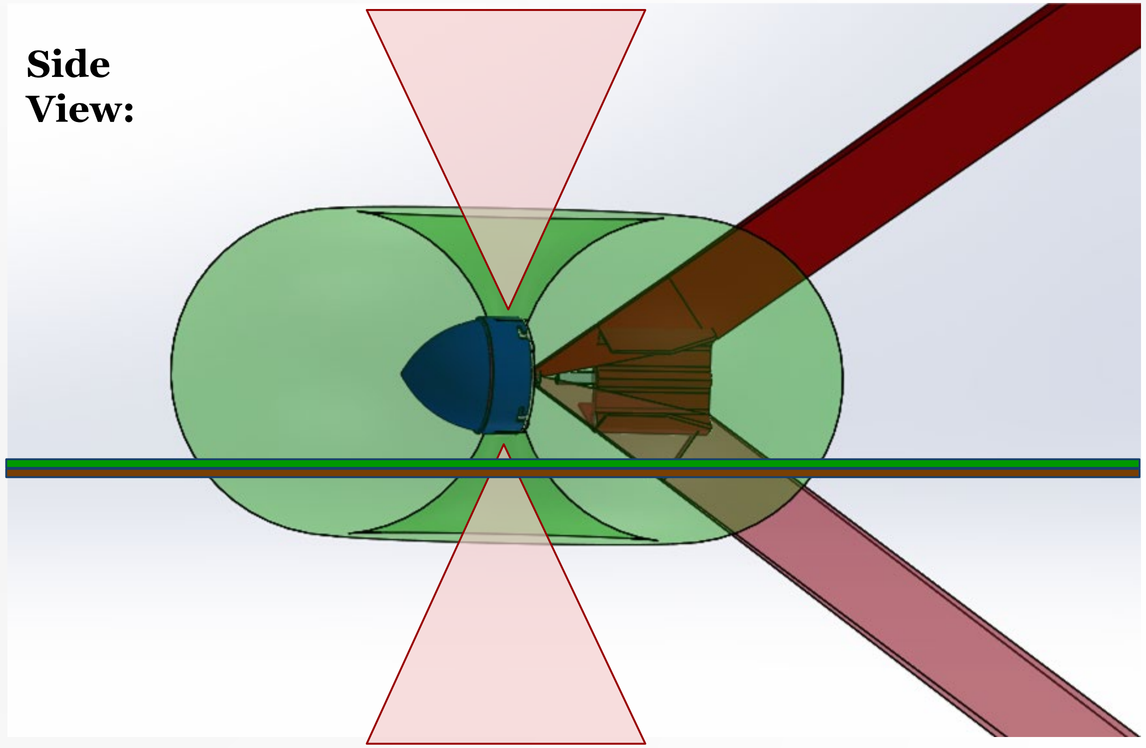
P5.4.3	P - Pod's electronics shall survive 14 m/s impact	✓

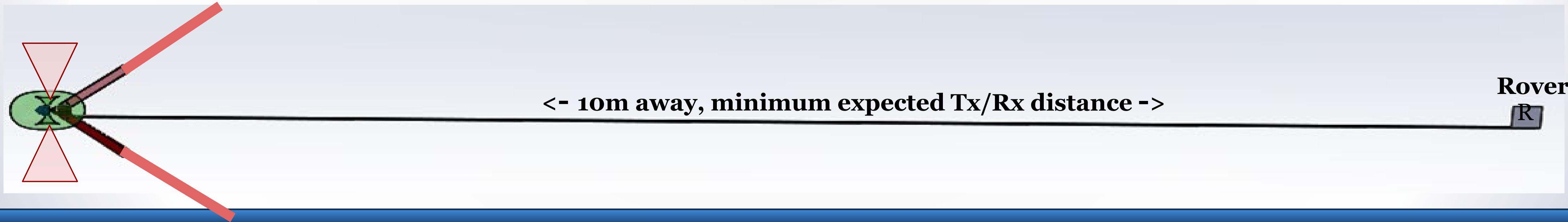
Pod Structural Design: Antenna Pattern

Datasheet antenna pattern:



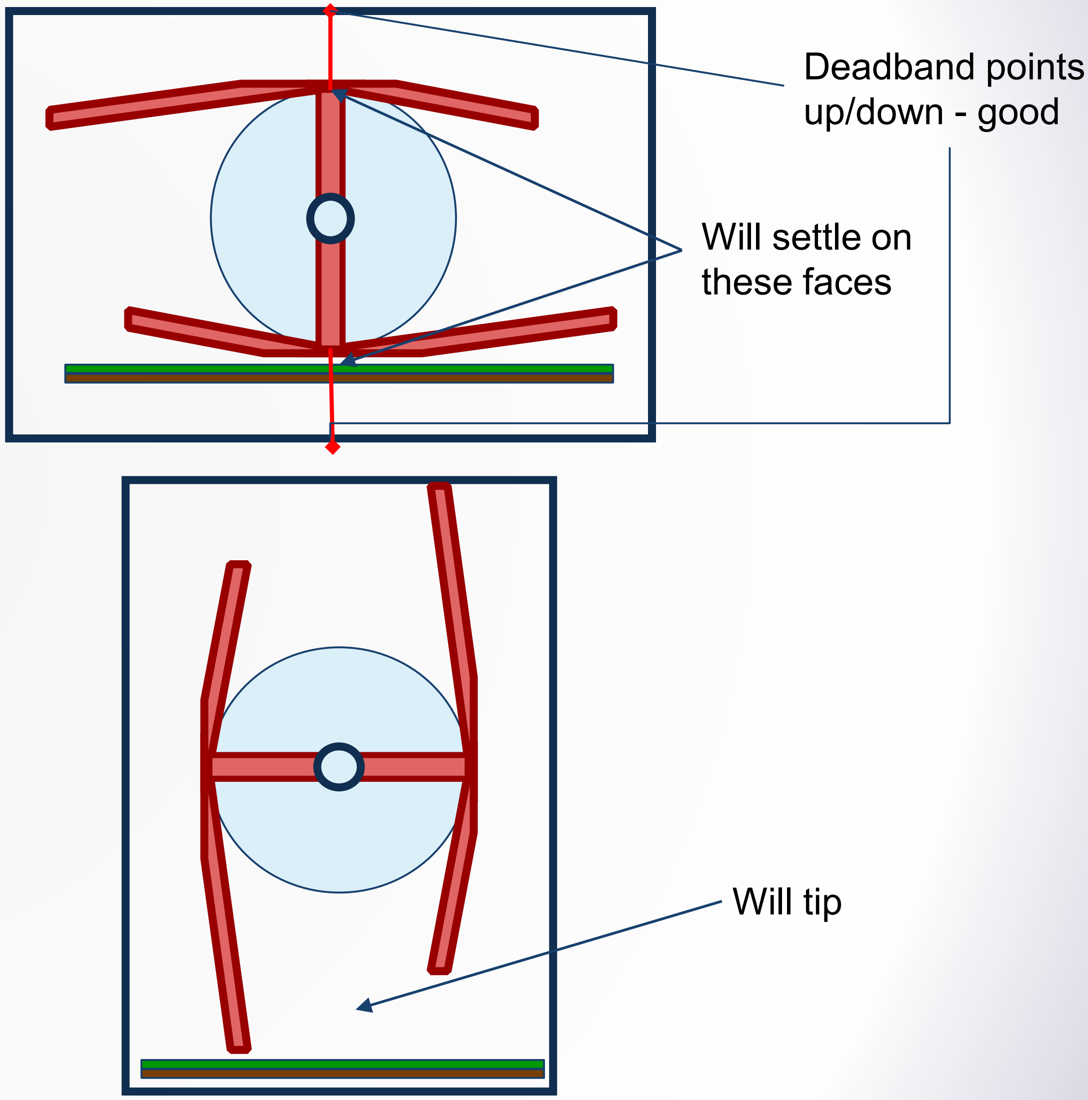
Side View:





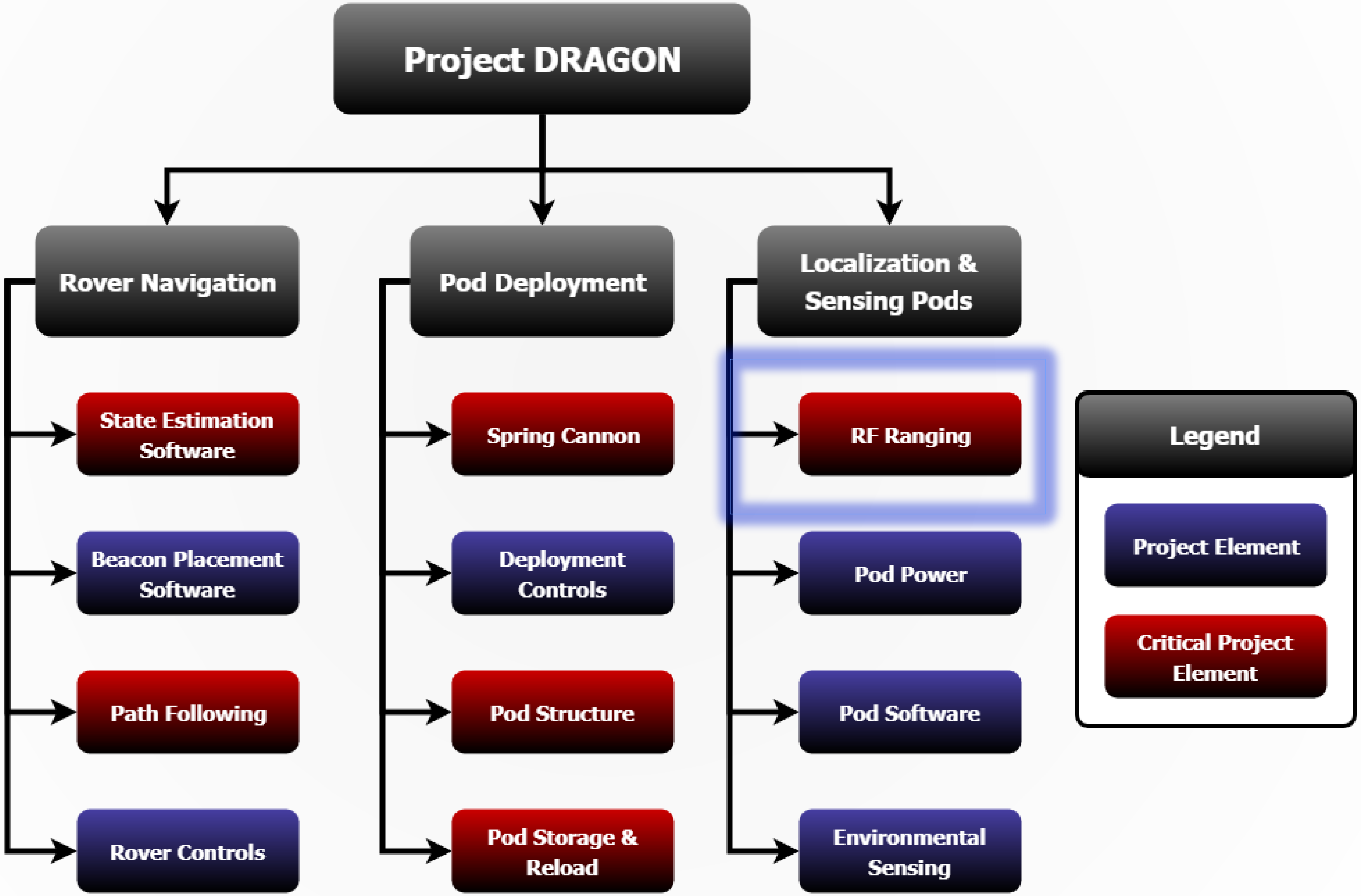
Pod Structural Design: Landing Orientation

- Purpose:
  - Minimize antenna deadband interference
- Design:
  - The geometry of the tail only allows settling in two positions, both positions are ideal for antenna Tx/Rx pattern
- Specs:
  - Deadband cone limited to:
    - 20 degrees from zenith (antenna limit)
    - 70 degrees tilt due to anhedral angle of tail



P5.4.4	P - Pods shall be designed to encourage ideal antenna orientation	✓

Critical Project Elements

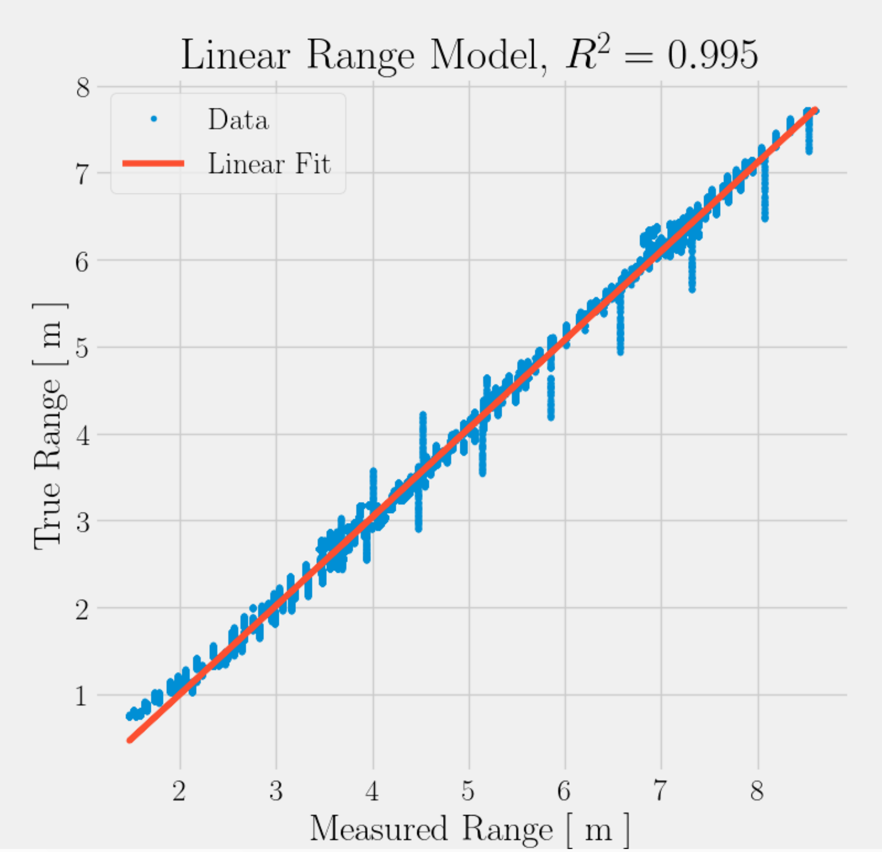


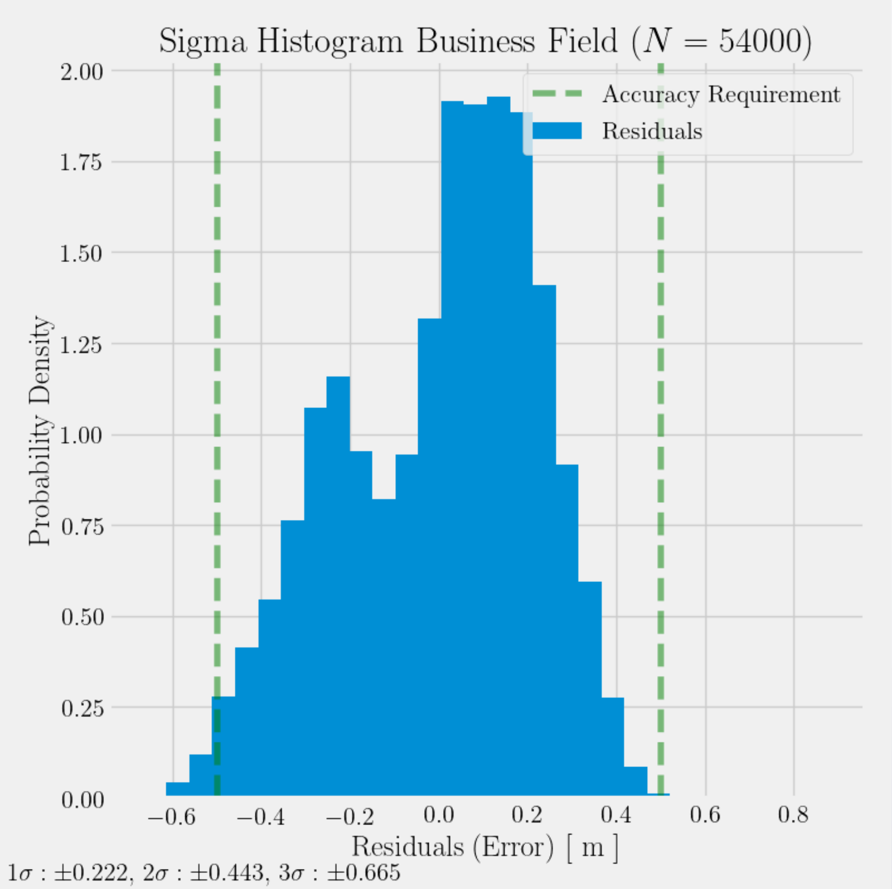
Ranging Feasibility

6.5	P - Pod shall have operational 'ranging' capability at distances no less than 60m.	✓
6.5.1	P - Pods shall have range measurement errors no greater than 0.5m averaged over 30 samples.	✓

1 σ error	0.222 m
2 σ error	0.443 m
3 σ error	0.665 m
Max Range	110 m

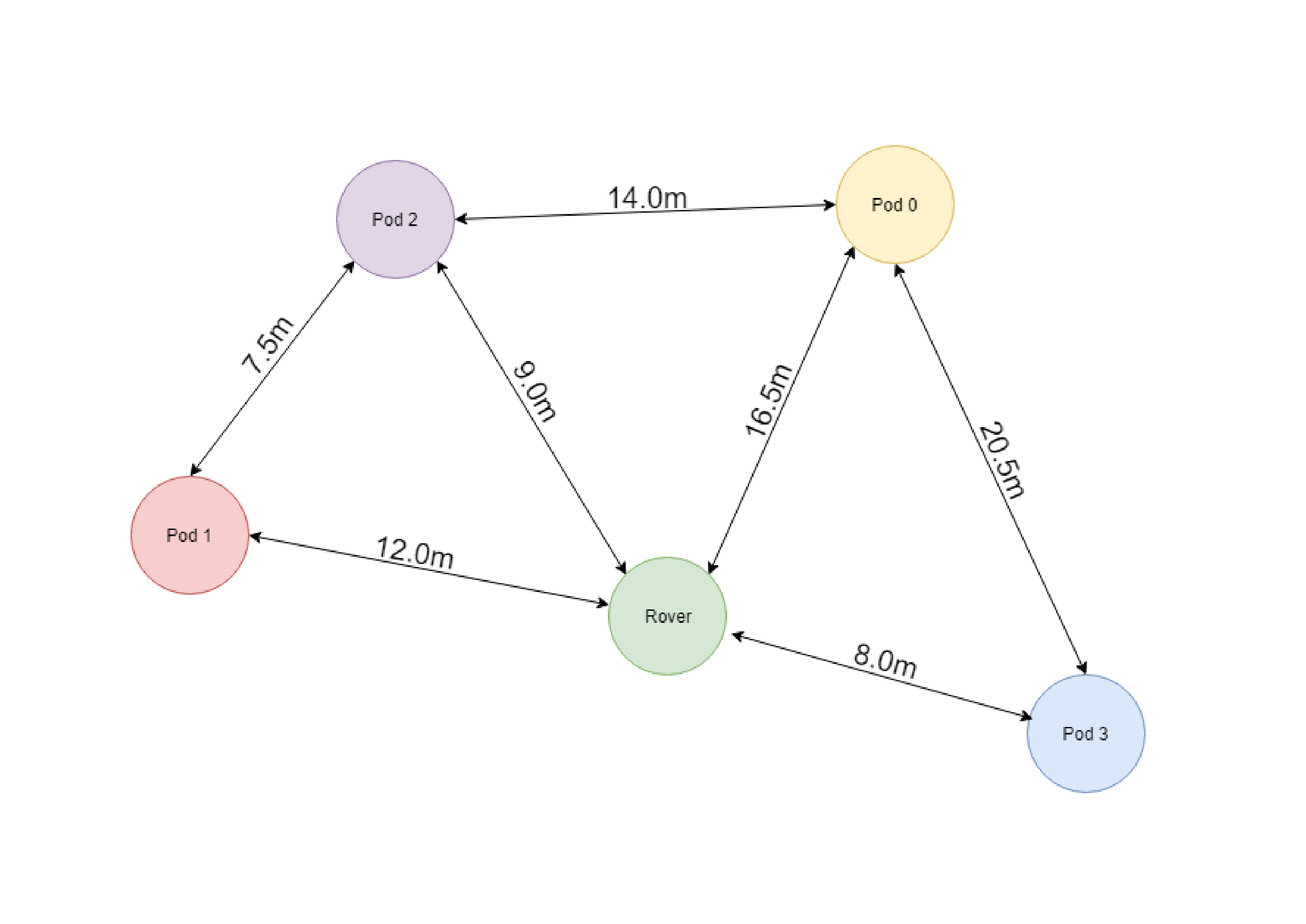
$$R_{corrected} = 1.019 * R_{measured} - 1.036\ [m]$$





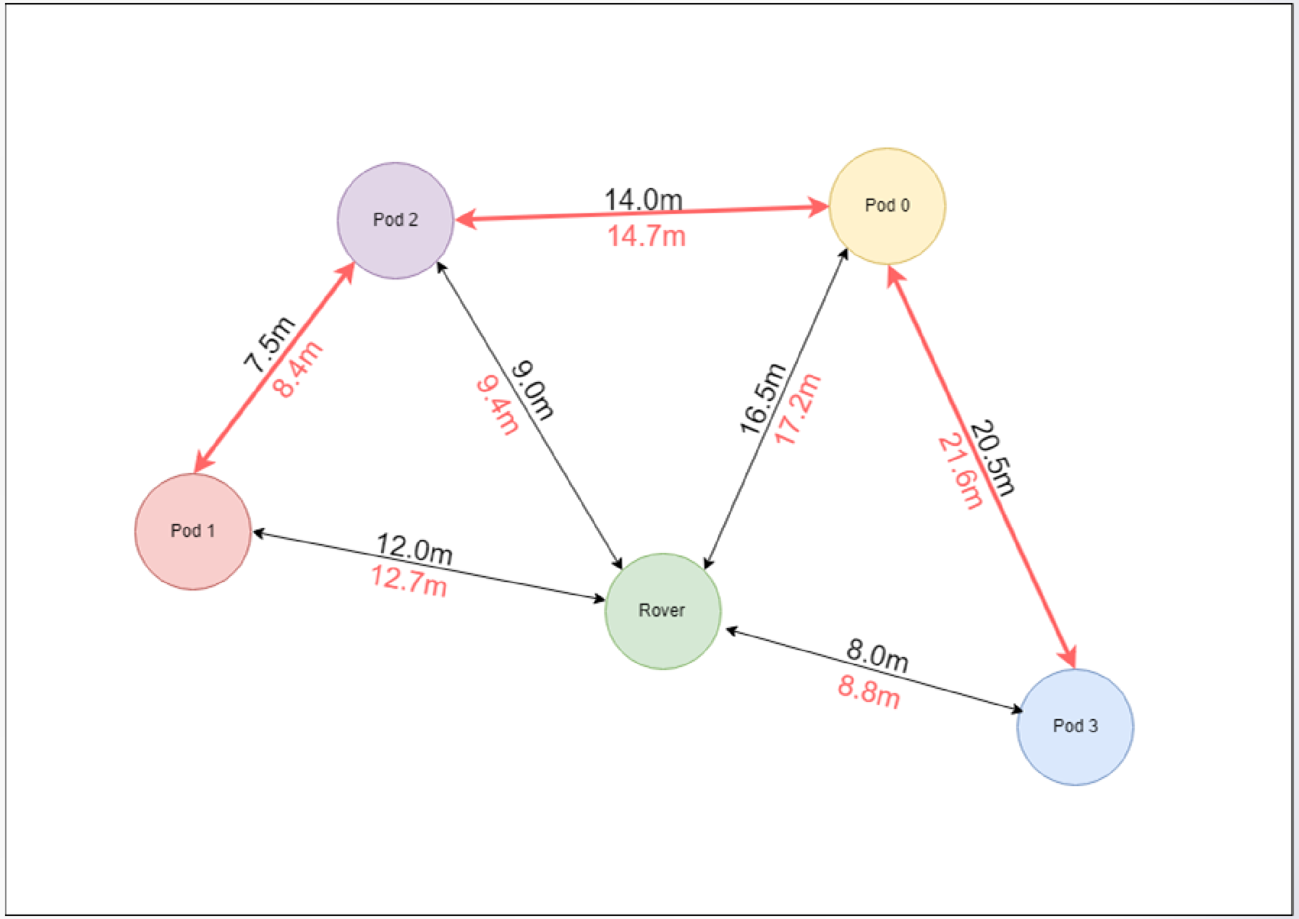
Mesh Network Test Setup

P 5.2	The pods shall communicate data to the rover and amongst themselves	



Mesh Network Test

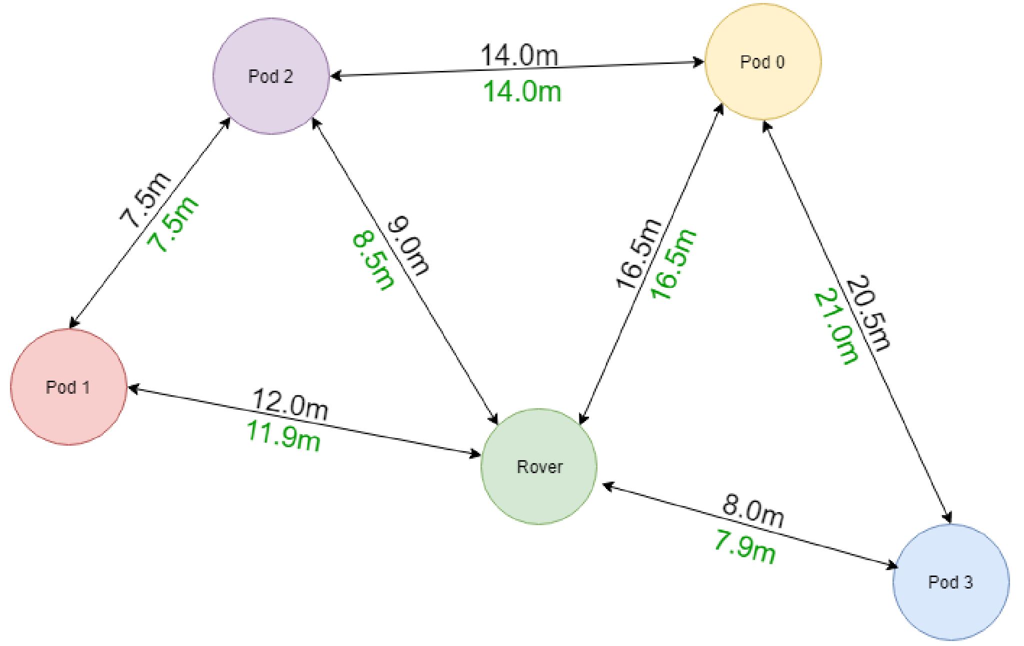
Sequence Number	Actual Distance [m]	Average Calculated Distance [m]
0	16.5	17.2
1	12.0	12.7
2	9.0	9.4
3	8.0	8.8
02	14.0	14.7
03	20.5	21.6
12	7.5	8.4



Mesh Network Test

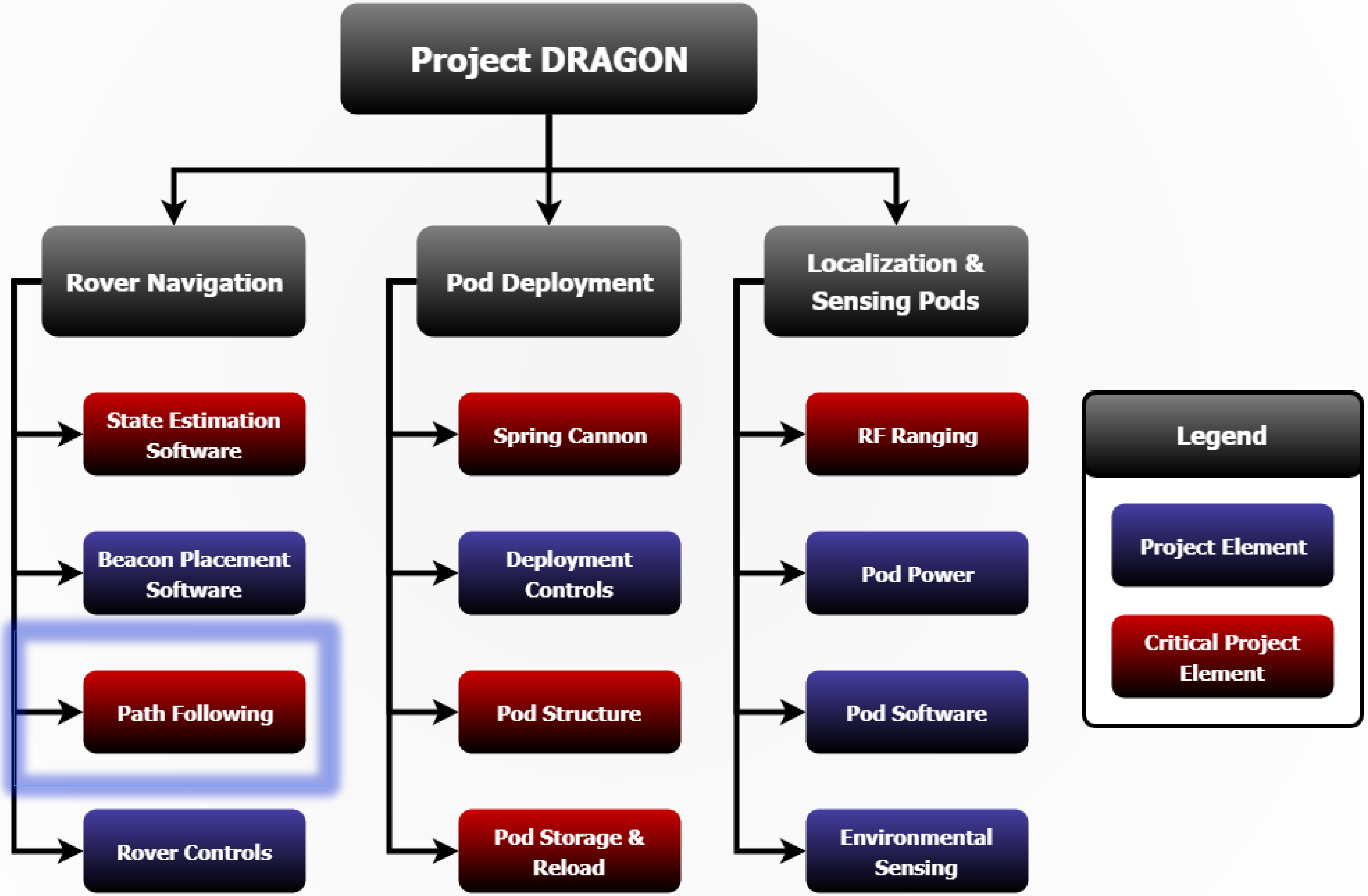
P 5.2	The pods shall communicate data to the rover and amongst themselves	✓

Sequence Number	Actual Distance [m]	Corrected Distance [m]	Error [m]
0	16.5	16.5	0.001
1	12.0	11.9	0.115
2	9.0	8.5	0.483
3	8.0	7.9	0.061
02	14.0	14.0	0.038
03	20.5	21.0	0.467
12	7.5	7.5	0.018



$$R_{corrected} = 1.019 * R_{measured} - 1.036\ [m]$$

Critical Project Elements



Navigation Feasibility - Path Requirements

S 1.2	**Rover shall use feedback control to autonomously navigate path waypoints**	

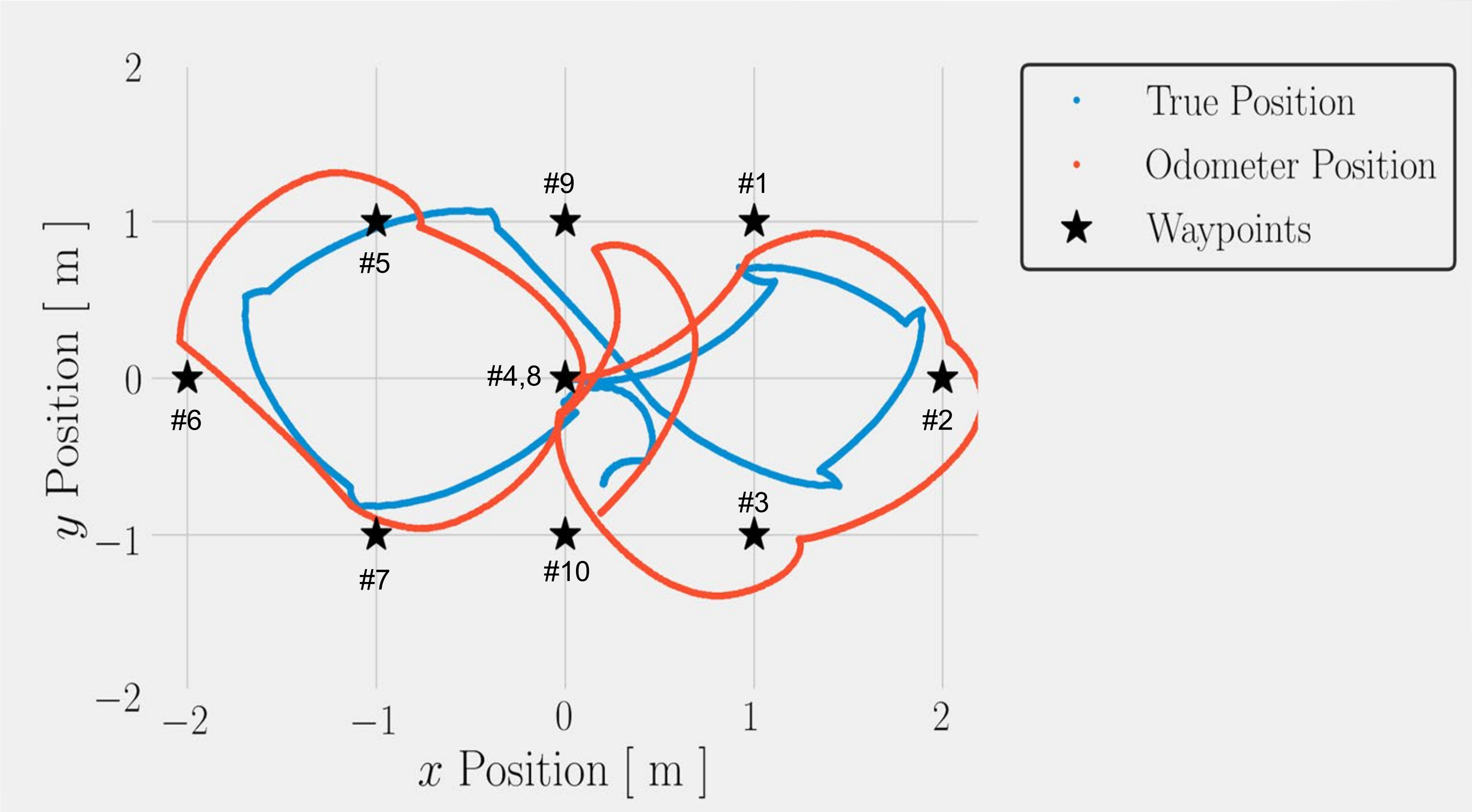
- Why?
  - Software must command the rover to navigate to waypoints determined by the A* algorithm or user input
- Designs Driven:
  - Automatic control must keep rover within 1 m of desired path at all times
  - Rover must be able to reach 10 user defined waypoints using automatic control
- Demonstration Method:
  - Use physics simulation from rover manufacturer to show command feasibility
  - Implement working simulation code on the rover (ports directly without edits)

COHRINT Test Format

- Uses 0.2 m XY tolerance and 0.1 rad yaw tolerance

Implementation

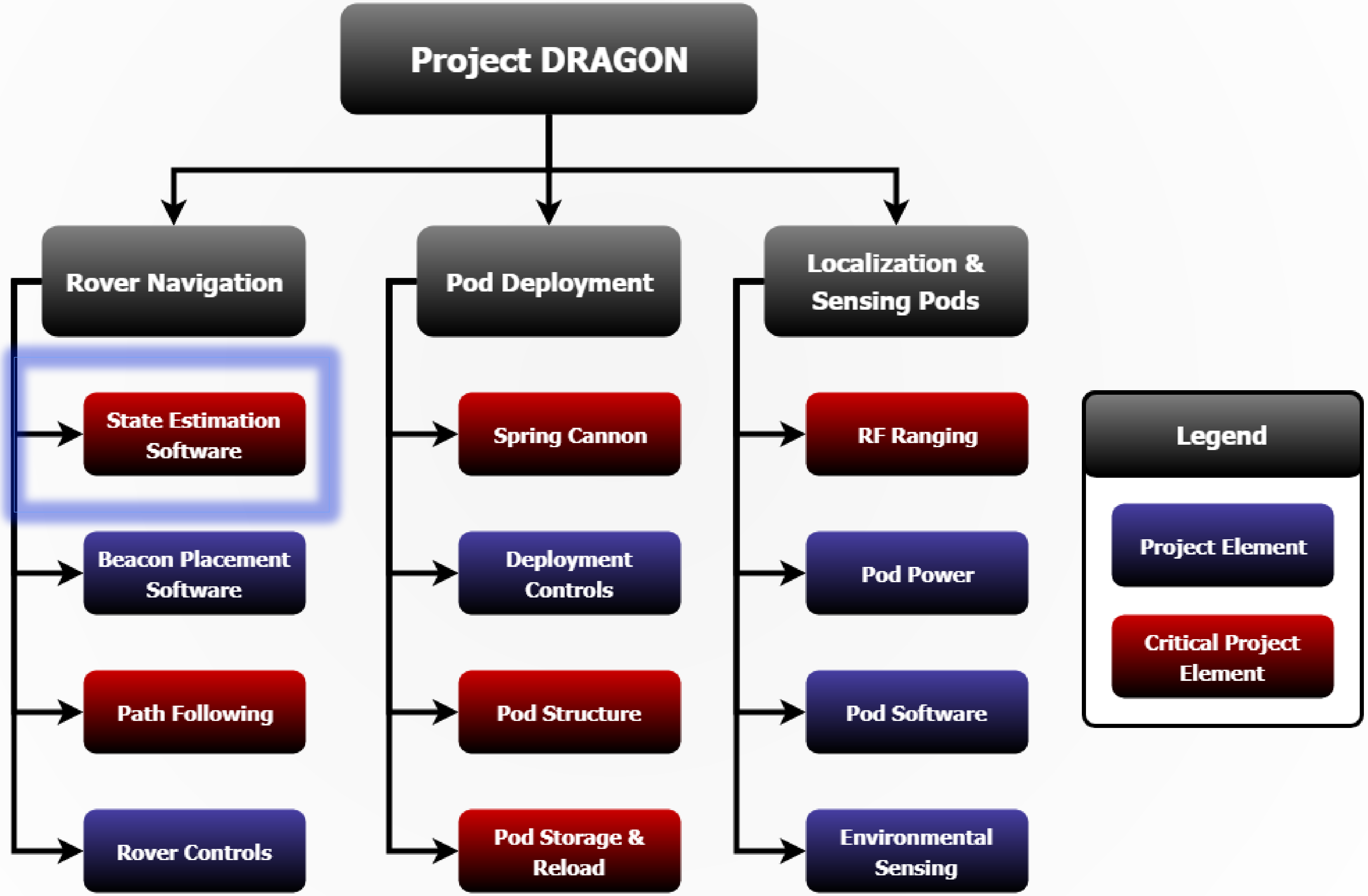
- Rover follows general path and meets waypoint tolerances based on rover estimate
- Drift in magnetometer and IMU cause the largely inaccurate path following
- Vicon (MoCap) used for truth data only



10 Waypoint Figure 8 Path

S 1.2	Rover shall use feedback control to autonomously navigate path waypoints	✓

Critical Project Elements



Navigation Feasibility - State Estimation

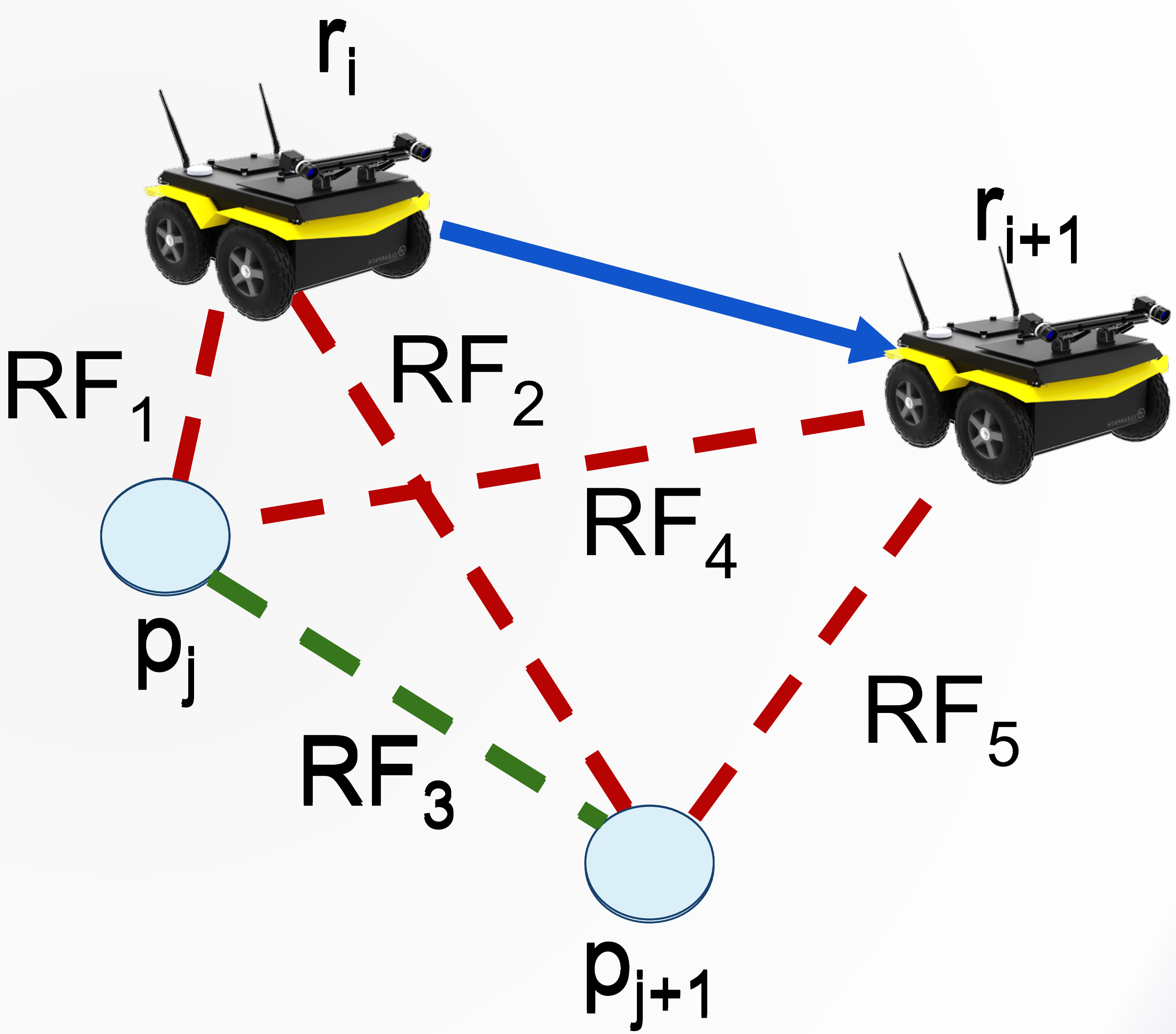
S2.1	**The software shall combine RF-Localization and inertial/odometry position estimates in order to enhance position estimation accuracy**	

- Why?
  - Inclusion of external measurements will reduce the error inherent in odometer/IMU position estimation
- Designs Driven:
  - Must be able to localize rover to within 1 meter at all points
- Demonstration Method:
  - Demonstrate the ability to include position from simulated pods to correct navigation in COHRINT space where truth is known
  - Show that graphSLAM is able to integrate actual odometer data and simulated range data to accurately estimate position

State Estimation Software Design Diagram

$$\begin{bmatrix} -1 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 0 & 0 & 1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} r_i \\ p_j \\ p_{j+1} \\ r_{i+1} \end{bmatrix} = \begin{bmatrix} \mathrm{RF}_1 \\ \mathrm{RF}_2 \\ \mathrm{RF}_3 \\ \mathrm{odom} \\ \mathrm{RF}_4 \\ \mathrm{RF}_5 \end{bmatrix}$$

$$r_{i+1} + \mathrm{RF}_5 = p_{j+1}$$



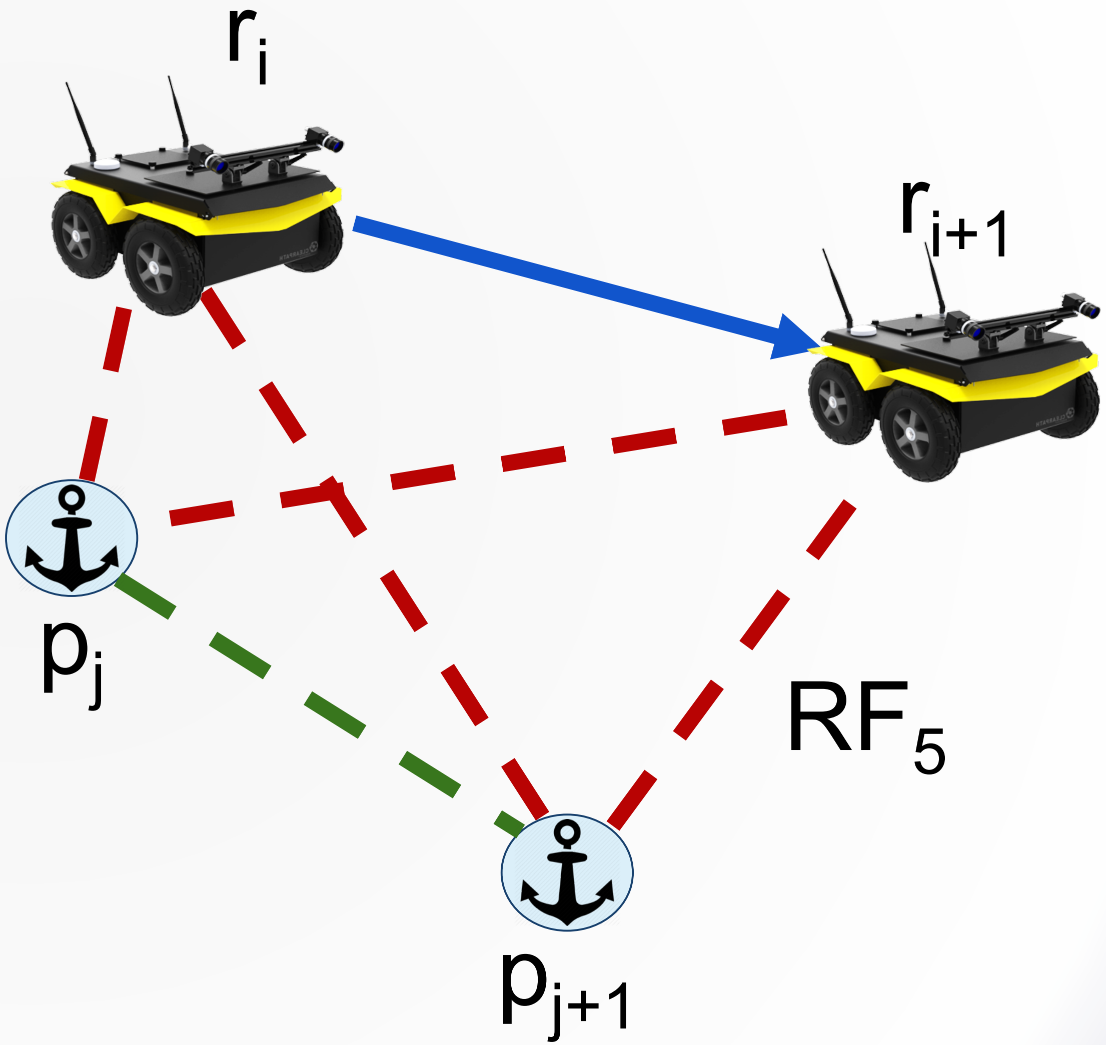
State Estimation Software Design Diagram

By solving the matrix rover position and pod position can be determined with high accuracy:

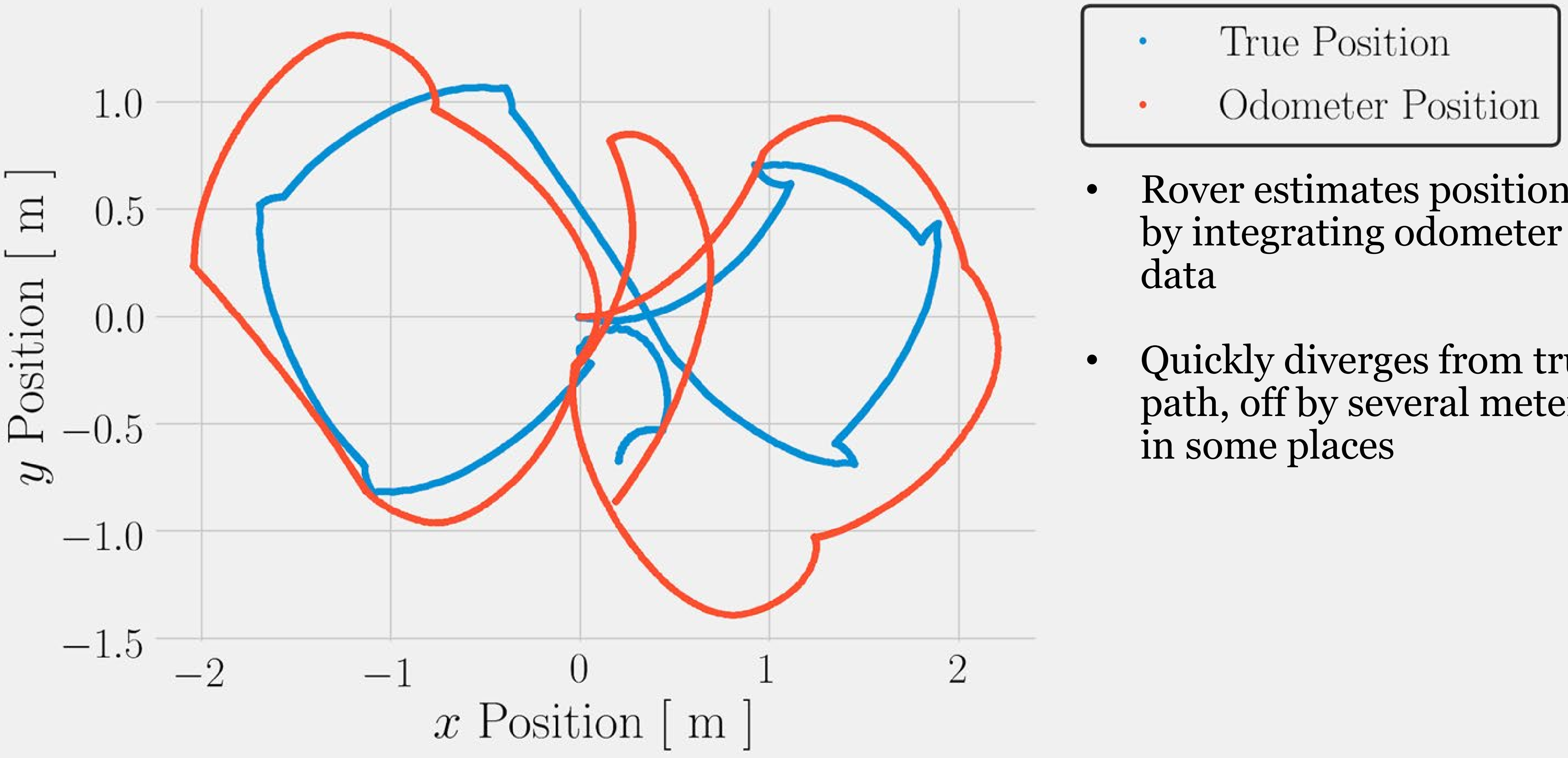
Modeled (0.1m) BOM

Modeled (0.88m) EOM

While error grows over time, the pods are non-moving and act as high accuracy references.



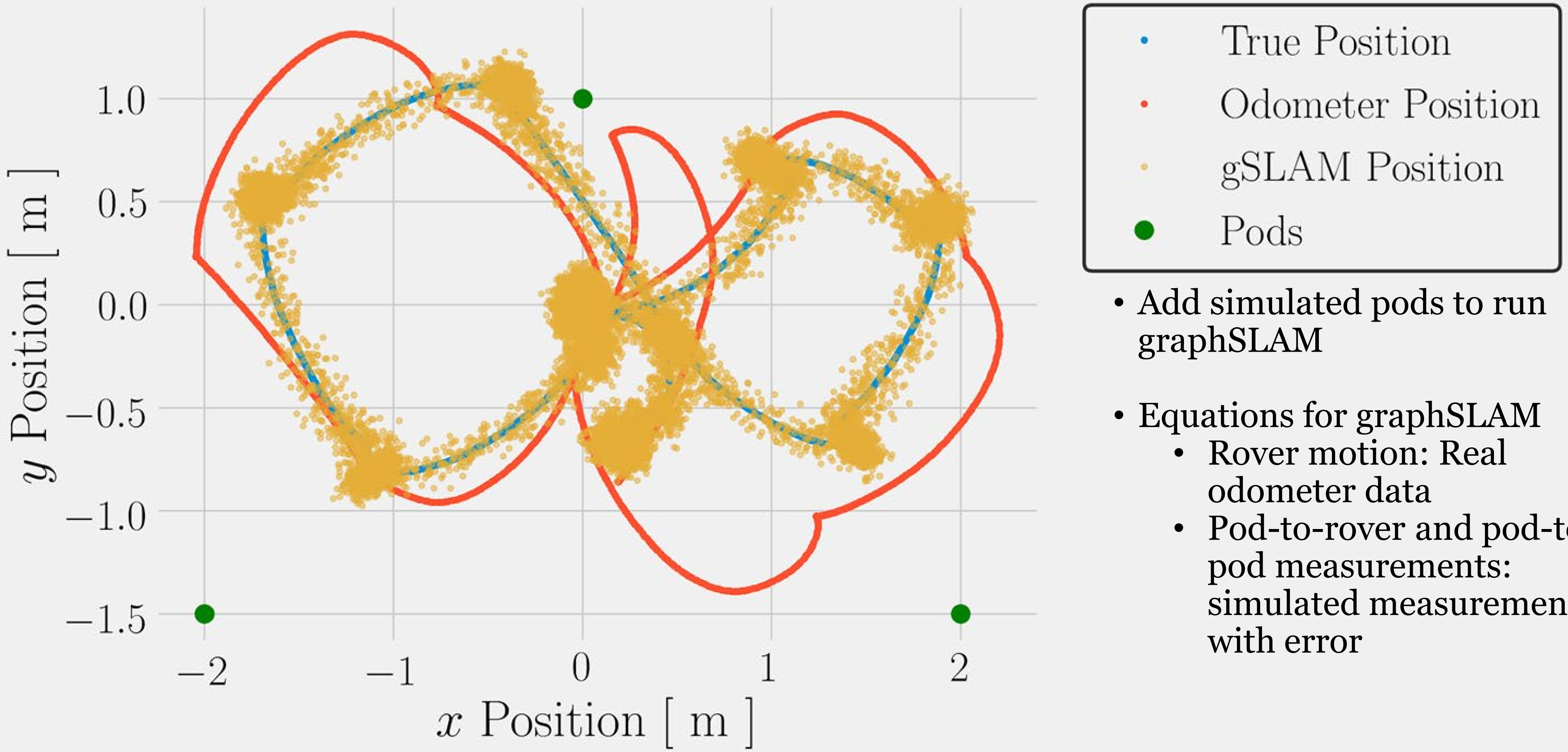
COHRINT State Estimation, Odometry Only



- Rover estimates position by integrating odometer data

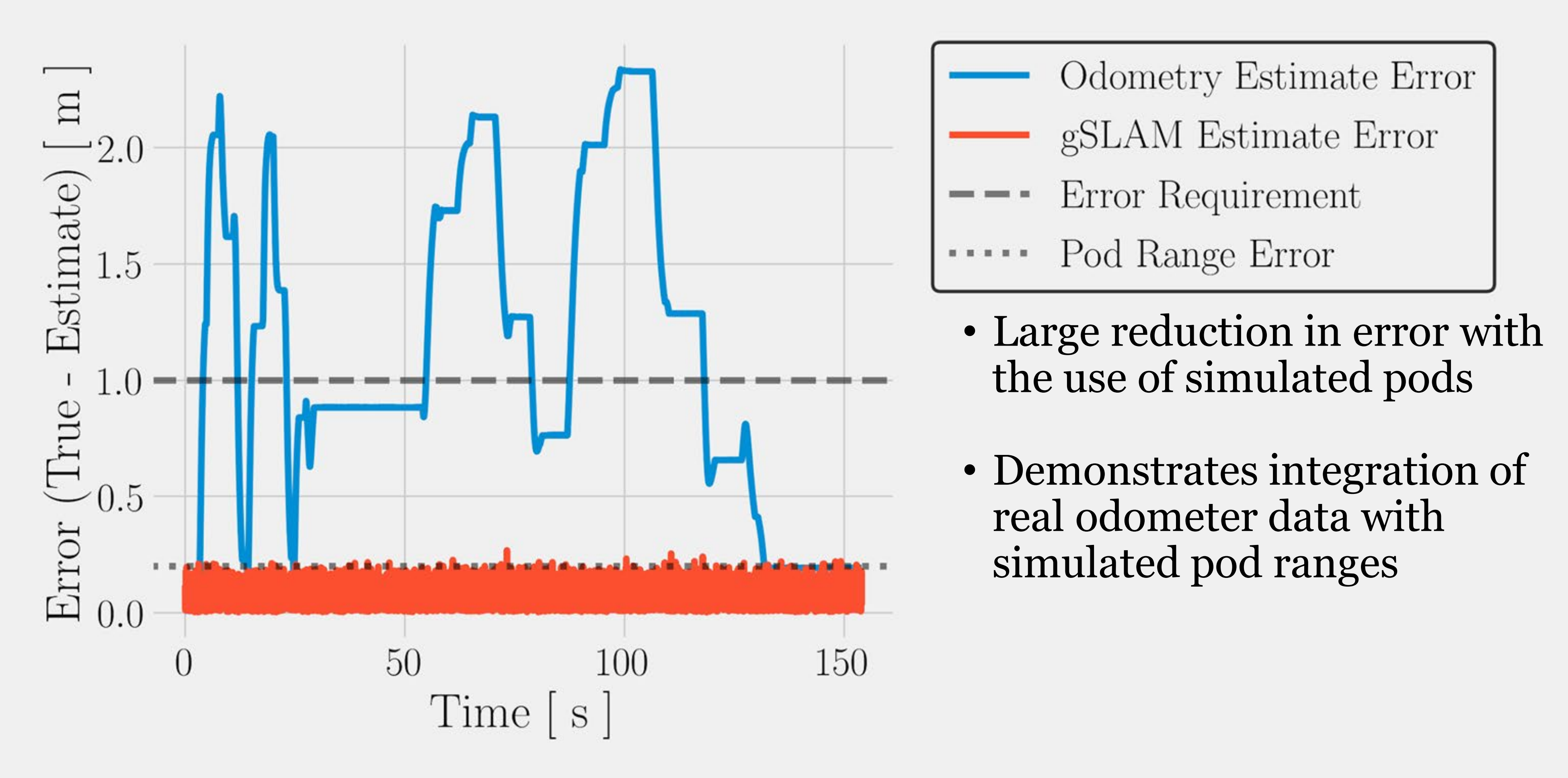
- Quickly diverges from true path, off by several meters in some places

COHRINT State Estimation with Simulated Pods



- Add simulated pods to run graphSLAM
- Equations for graphSLAM
  - Rover motion: Real odometer data
  - Pod-to-rover and pod-to-pod measurements: simulated measurements with error

COHRINT State Estimation Error



- Large reduction in error with the use of simulated pods
- Demonstrates integration of real odometer data with simulated pod ranges

S2.1	**The software shall combine RF-Localization and inertial/odometry position estimates in order to enhance position estimation accuracy**	✓

Pod Placement for Error Reduction

S 3.1.1	Software can determine pod location for placement for most effective ranging	

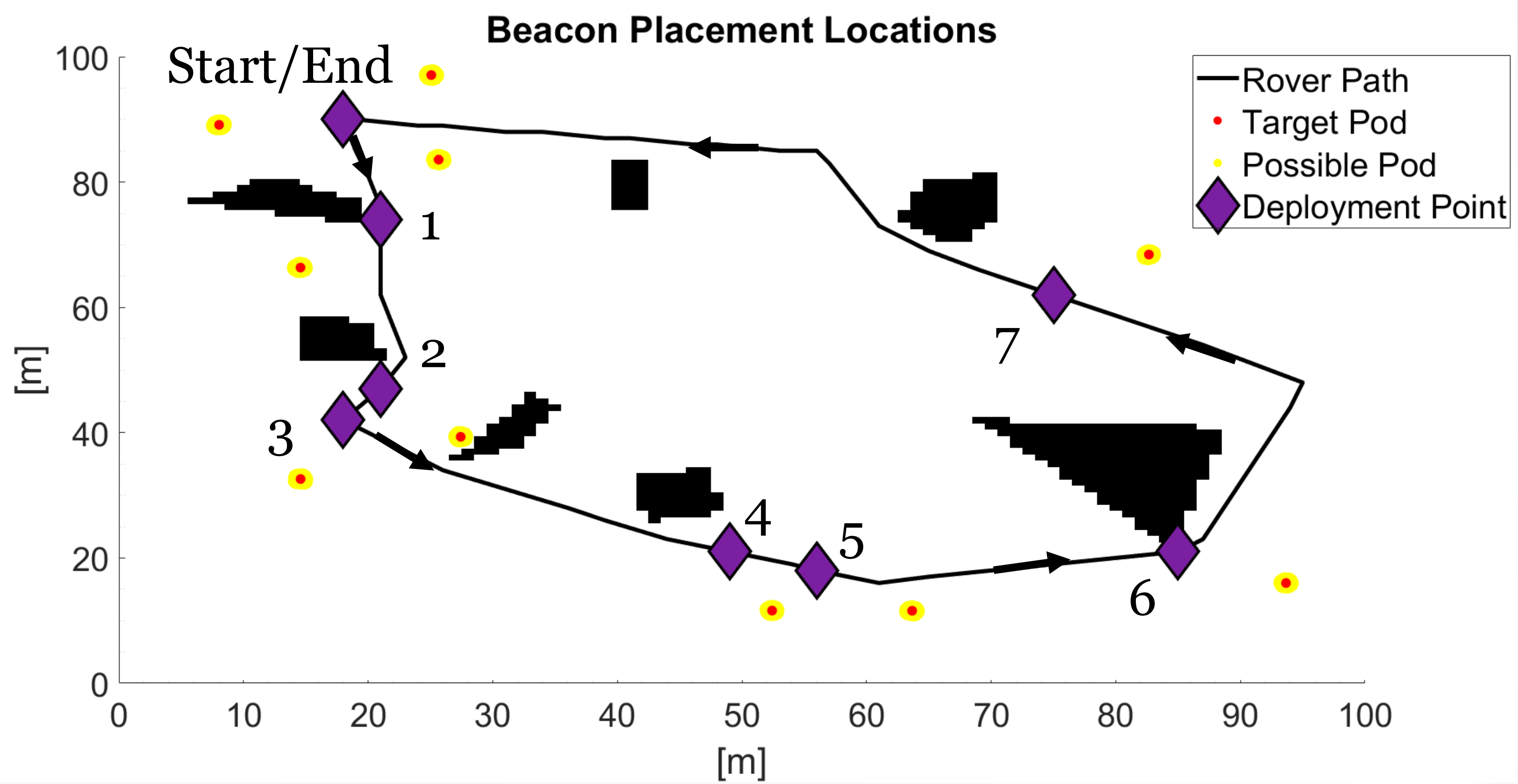
- Why?
  - Software must understand the environment and determine where to place pods for most effective localization and ranging data while avoiding obstacles
- Designs Driven:
  - Deployment Target Software must **reduce uncertainty in rover position to under 1m**
- Demonstration Method:
  - Simulate pod placement method along sample paths
  - Use Monte Carlo simulation on sources of error to show that pods can be placed such that uncertainty in rover position remains under 1m at all points along paths

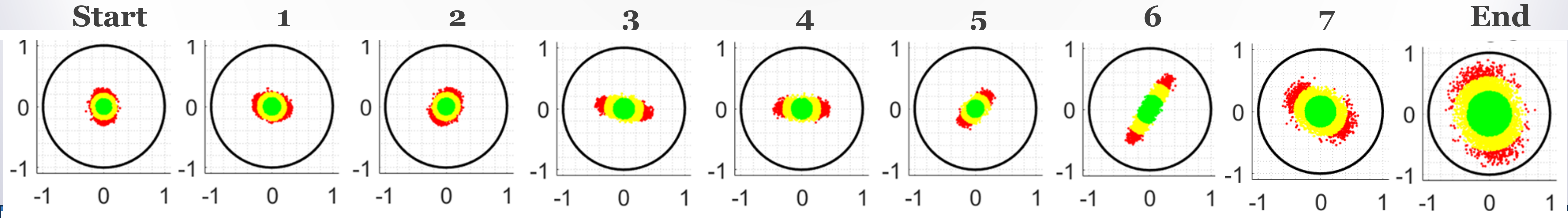
Error in Rover Position Along Path

Monte Carlo
10,000 Sims
+/- .6m error in RF ranging
Worst-case error is carried over at each step

Uncertainty in Position	
Start	.38 m
End	.92 m

S 3.1.1	Error < 1 m	✓





Risk Mitigation

Risk Descriptions

ID	Description
2	Mass too high
3	Antenna interference
6	Recoil forces
8	Potting material interference
9	Software development integration
10	Networking/Comm development
4	Reloading jam or electrical complications

		Consequence				
		1	2	3	4	5
Likelihood	5				5	7
	4				1,9	4
	3			6	3,8	
	2					10
	1					2

Mitigation:

ID	Description	Mitigation
1	Electronics damage from deployment	- Compounding multiple methods for impact dampening - Drop tests have been performed to demonstrate survivability with some of the selected electronics.
5	Deployment unable to reach max range	- Significant range margin included in design which should surmount unanticipated parasitic forces. - Modelling efforts do have high fidelity and scaled testing.
7	PCB rev delays in schedule	- PCB boards have been designed and first rev printed pre-cdr - Testing commencing and expect to send 2nd rev before Dec 20 2018

Risk Matrix: Mitigation Results:

Pre-Mitigation

		Consequence				
		1	2	3	4	5
Likelihood	5				5	7
	4				1,9	4
	3			6	3,8	
	2					10
	1					2

Post-Mitigation

		Consequence				
		1	2	3	4	5
Likelihood	5			5		
	4					
	3				1	
	2			3,7	9	4
	1		6	2,10	8	

See Appendix D for mitigation plan of all risks

Verification

Project Overview | Design Solution | Design Requirements | Risk Mitigation | **Verification & Validation** | Project Plan

Testing and Requirement Flow

Piecewise Testing	Subsystem Testing	Integration Testing	Full System Testing

9/2/18 - 12/20/18
- Small component
  - Feasibility
  - Preliminary demonstration
- Prototype Testing
	1/11/18-1/28/18
	- Subsystem build
	  - Verify compatibility
	  - Commence functionality demos
	  - Low level reqs
		1/28/18-2/25/18
		- Combining subsystems onto rover
		  - Cannon-Rover
		  - Rover Sw-Pods
		  - Cannon-Pods
			2/25/18-3/20/18

Testing and Requirement Flow

Piecewise Testing → Subsystem Testing → Integration Testing → Full System Testing

Test Type	Test ID	Requirements								
Mission Tests	FST1	M1								
	FST2	M4								
	FST3	M5	P5.2	P5.2.1	P5.2.2	P5.2.3				
	FST4									
Pod Team Tests	PT2	P5.4	P5.4.2	P5.4.3	P5.4.3.1	P5.4.3.2	P5.4.3.3	P5.4.4	P5.4.4.1	P5.4.6
	PT4	M6								
	PT5	P5.3.2	P5.3.3	P6.2	P6.3	P6.4	P6.4.1	P6.3.1.1	P6.3.1.2	
	PT6	P6.4.2	S9.2.3							
Deployment Team Tests	DT1	M3								
	DT2`	D3.8	D4.4	P5.1	D8.3.1					
	DT3	D3.5	D3.5.1							
	DT4	D3.4								
	DT5	D3.6								
	DT6	D3.7	D4.1	D4.1.1						

Test Type	Test ID	Requirements							
Navigation Team Tests	NT0	S1.3							
	NT1	S1.2	S1.2.1	S1.2.2	G4.2	G4.2.1	G4.2.2		
	NT2	S1.3.3							
	NT3	S1.3.3.1							
	NT4	S2.1.2							
	NT5	S2.1.1							
	NT6	S2.1.3							
	NT7	S3.1	S3.1.1	S3.1.2	S3.1.3	S3.1.4			
	NT8	S3.1.3.1							
	NT9	S9.2.1	S9.2.2						
	NT10	S1.3.2	S1.3.2.1	G9.4	G9.4.1	G9.4.2			
	NT11	M2	S2.1						
Inspection	Inspection	D4.1.2	D4.3	D4.5	P5.1.1	P5.1.2	P5.3	P5.3.1	...
Ground Support Tests	GT1	G1.1	G1.1.1	P3.8.1	P3.81.1	P6.1.5			
	GT2	S1.3.1	M7	S7.1	S9.2.6				
	GT3	G7.3	G7.3.1						

Verification Plan

Piecewise Testing → **Subsystem Testing** → **Integration Testing** → **Full System Testing**

Full System Testing:

- Team is ready to demonstrate full system functionality
- Verify a majority of our mission requirements at high levels

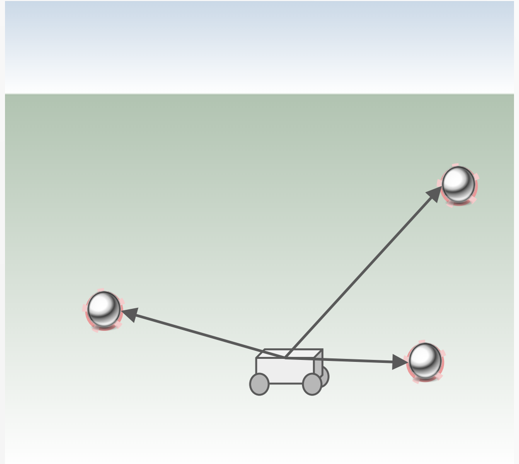
We plan <u>four</u> Full System Tests:

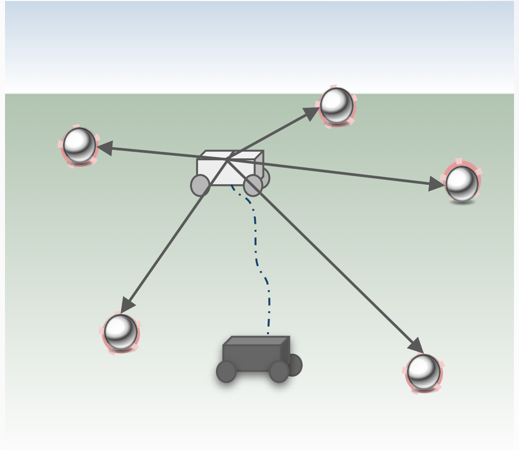
<u>Full Mission Demonstration Test</u>
<u>RF State Estimate Test</u>
FST3 and FST4

<u>See Appendix E for info on first three testing phases</u>

Testing Plan: RF State Estimate Test

Testing Location: Open flat grass field (business field or kittredge)





Materials and Special Reqts:

- Jackal rover and ranging boards
- Obtain permission for field operations
- GPS system pre-calibrated (COTS)
- Weather cooperation

Testing Procedure:

1. Begin GPS recording on rover (1e-2m accuracy)
2. 'Hand Place' pods at desired locations
3. Upload mission sequence
4. Collect first pod readings
5. Build pose estimate with rover
6. Tele-op rover to second known position
7. 'Hand Place' additional pods
8. Build second pose estimate with rover

.tar file upload, rover data ingest and process < 30 seconds

2e-2 m accuracy, 30Hz sample rate, several readings

Pose estimate, 0.3Hz generation rate, 3e-1 m accuracy

Success:

- Rover can range to pods
- Calculate pose
- Add new pods to network

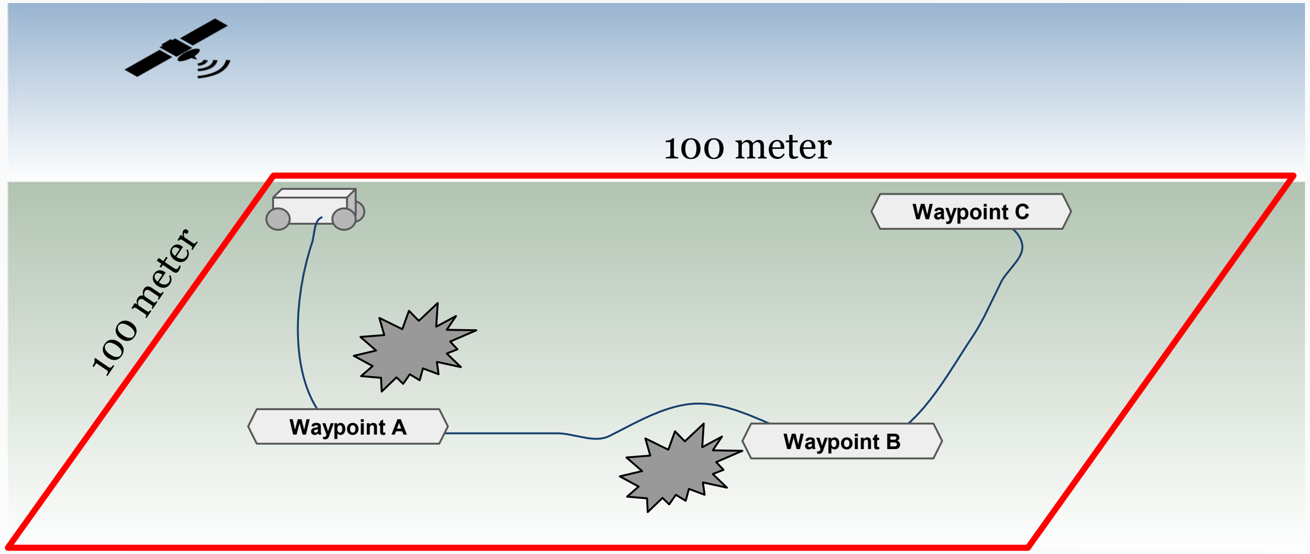
Testing Plan: Full Mission Demo Test

Objective: Full mission completion and demonstration

Testing Location: Open flat grass field (business field or kittredge)

Necessary Materials:

- Jackal rover modified with DM and 10 pods
- GPS system pre-calibrated
- MIP



Testing Plan: Full Mission Demo Test

Testing Procedure:

1. Mark waypoints and rover obstacles
2. Place team members surrounding area for range safety
3. Begin GPS recording on rover, pre-verified
4. Perform all safety checks, check: remote kill, takeover
5. Load pods and zero cannon azimuth
6. Upload mission sequence
7. Perform initial deployment, collect pod readings
8. Rover builds pose estimate, proceeds with mission
9. Collect post data mission and verify mission success

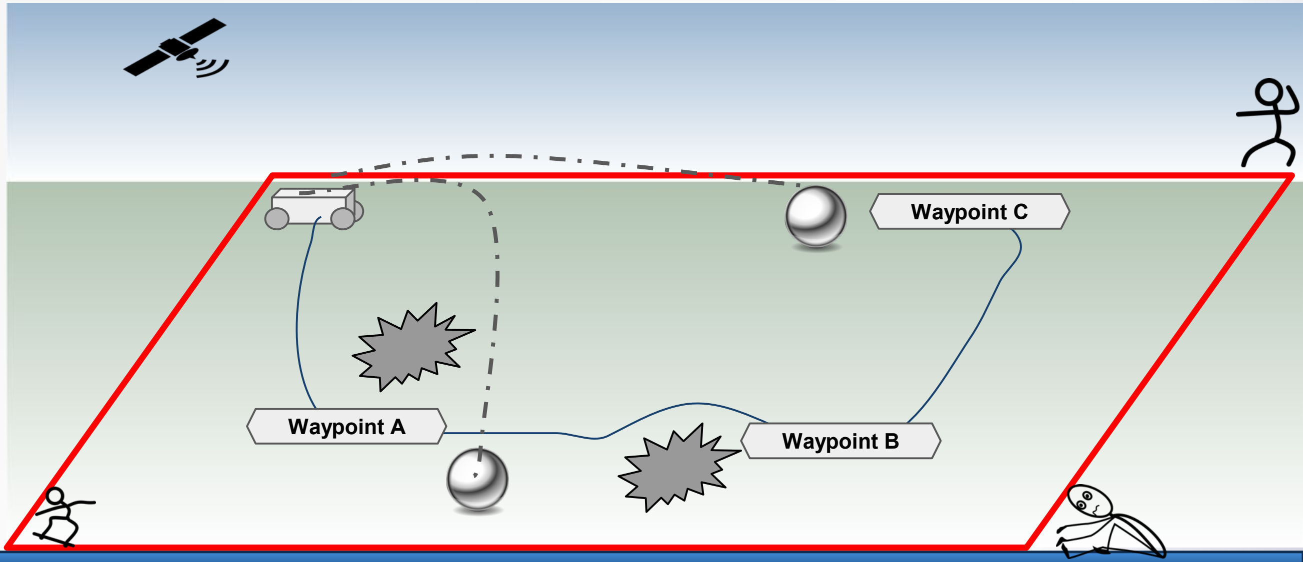
1e-2 m accuracy, 10Hz sample rate, record to ground station computer

5e-1 m accuracy, 30Hz sample rate per pod, closed loop control on rover

Success: GPS readings and rover internal estimates match within 1m at EOM

Special Requirements:

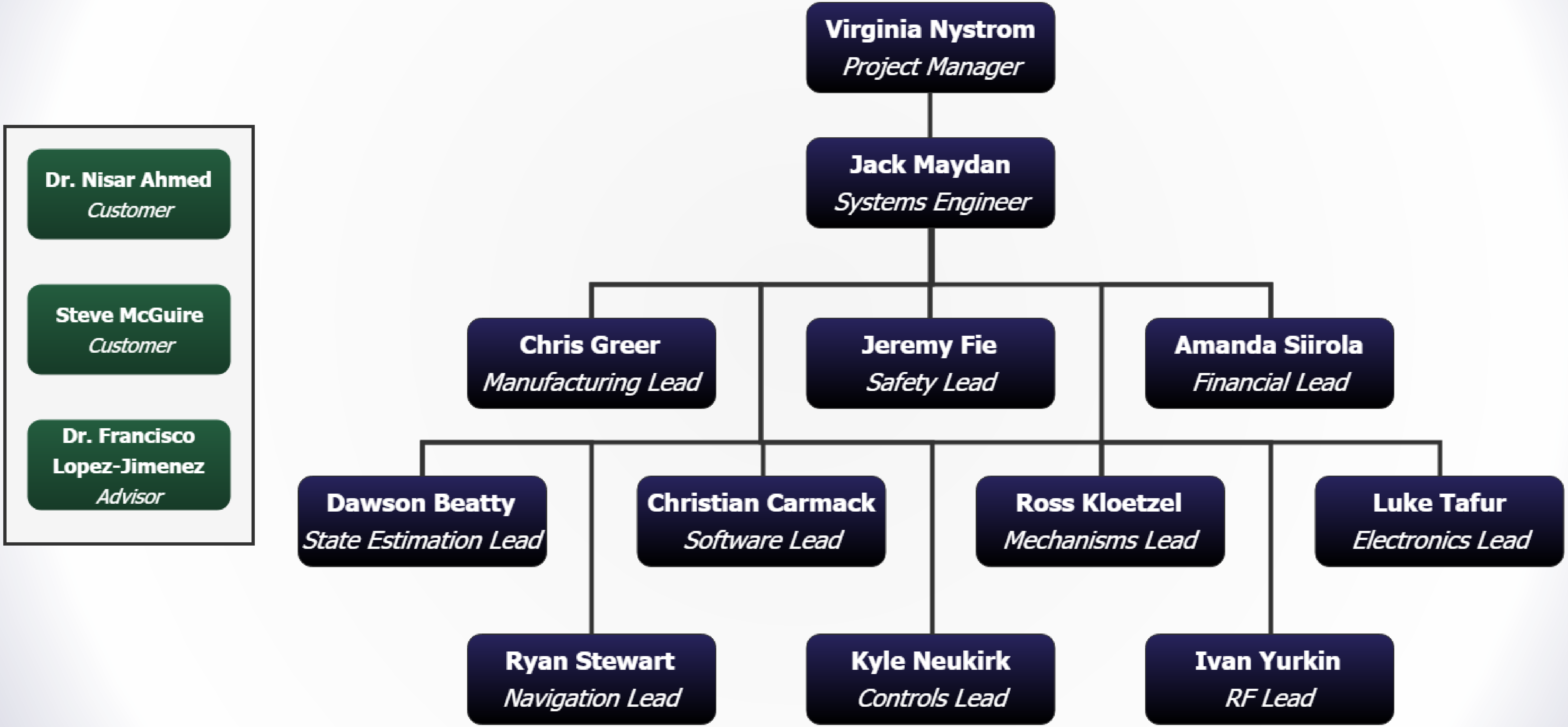
- Obtain permission for field operations
- Mark out hazard zone for range safety
- Weather cooperation



Project Plan

Project Overview | Design Solution | Design Requirements | Risk Mitigation | Verification & Validation | Project Plan

Organizational Chart

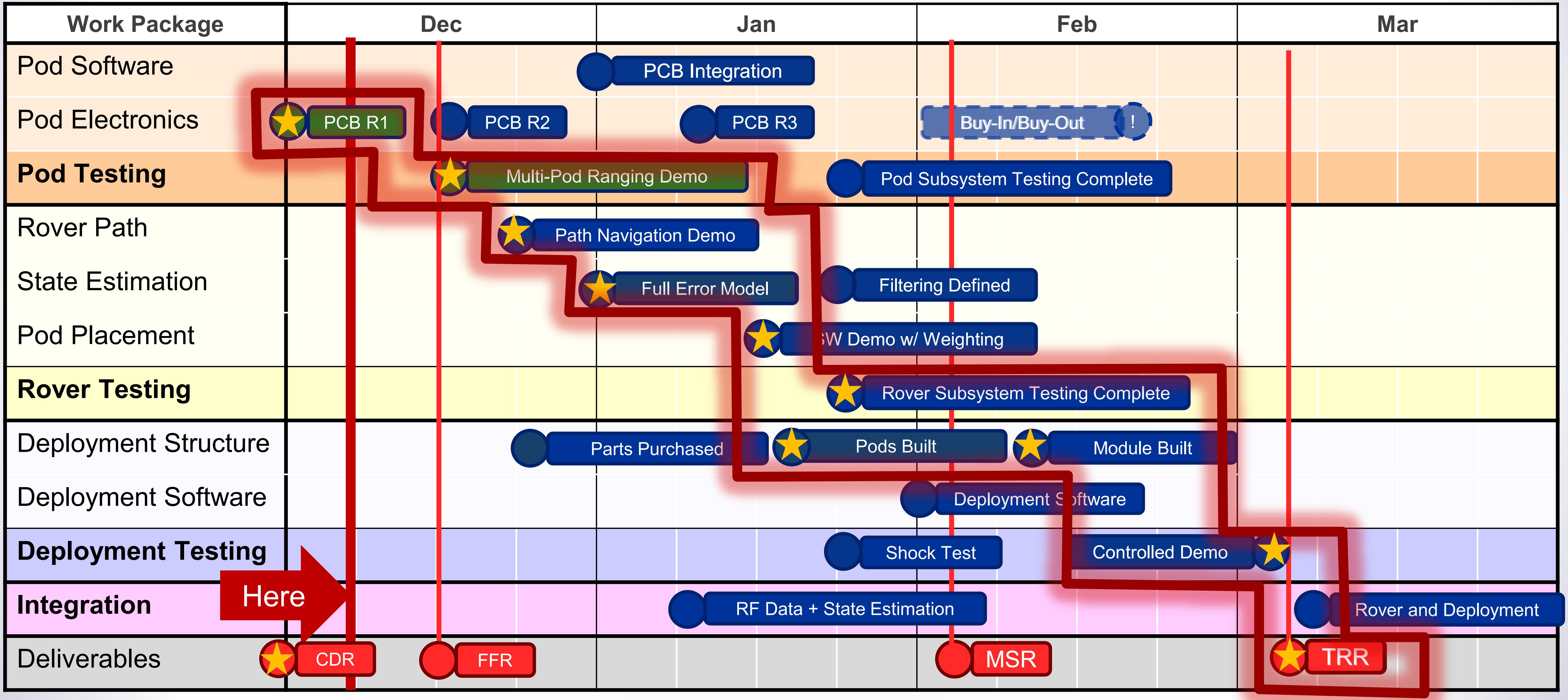


Work Breakdown Structure

Deliverables	Management	Rover	Deployment	Pod Electronics	Safety/Test
PDD	Org Chart	Research	Research	Research	Research
CDD	WBS	Software Flow	CAD Model	RF Testing	Requirements
PDR	Gantt Chart	Path Generation	Part Selection	Sensor Prototyping	Facilities Permission
CDR	Budget	State Estimation	Mass Budget	Power Budget	Procedures
FFR	Cost Plan	Deployment Algorithm	Prototyping	Schematics	Equipment
MSR	Test Plan	Executive Node	Manufacturing	Bill of Materials	
TFR	Risk Matrix	Rover Controls	Power & Controls	PCB	
AIAA		Navigation Test	Pod Shell	Sensor Calibration	
SPR		GPS Integration	Electronics Mounting	Mesh Network Software	
SPP		Verification/Validation	Deployment Test	Mode Toggle Software	
PFR		User Manual	Verification/Validation	Verification/Validation	
			Rover Integration	Shell Integration	

Complete	In Progress	Future Work

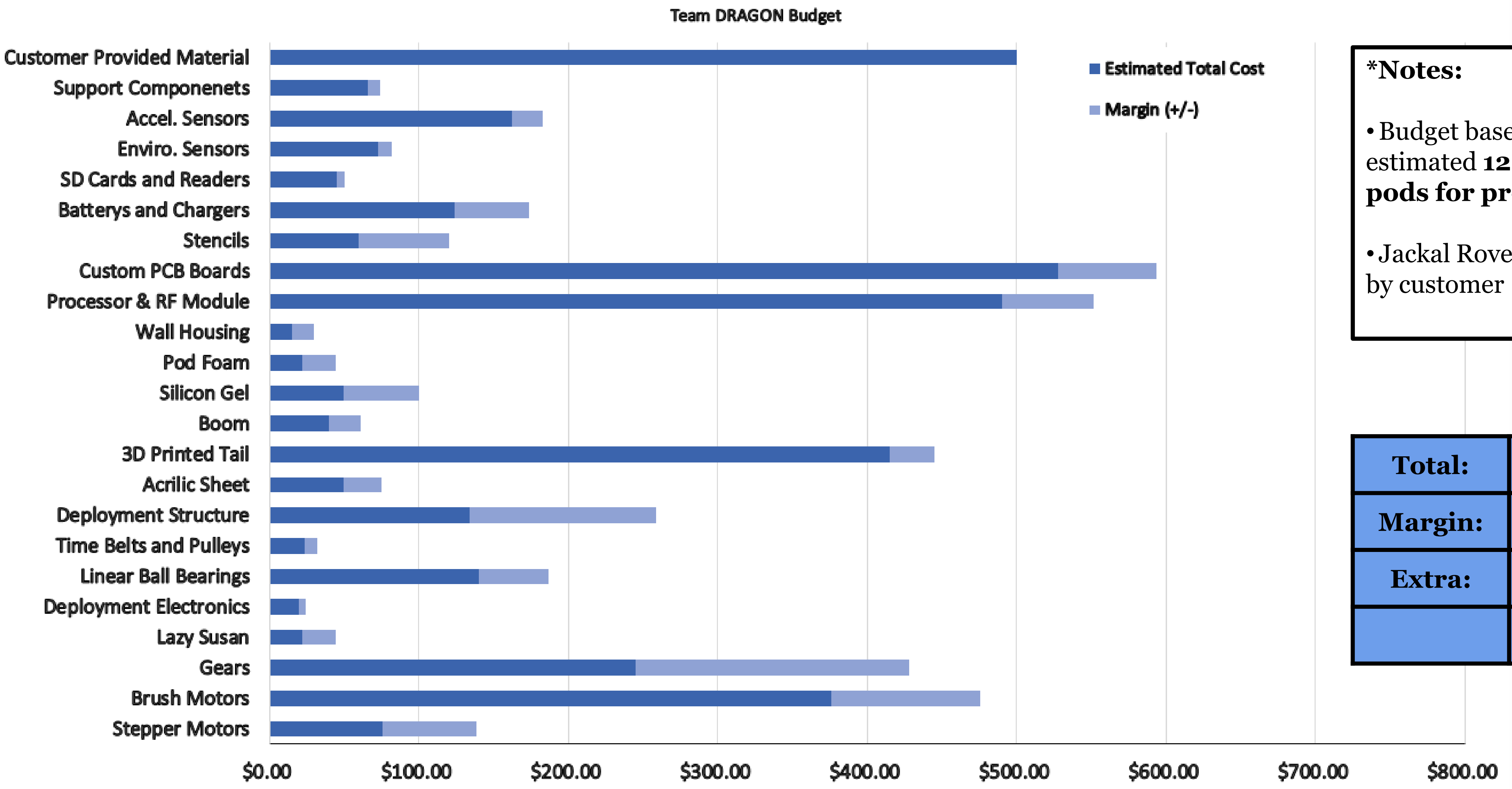
Gantt Chart


Work Package
Dec
Jan
Feb
Mar
Pod Software
Pod Electronics
Pod Testing
Rover Path
State Estimation
Pod Placement
Rover Testing
Deployment Structure
Deployment Software
Deployment Testing
Integration
Deliverables
PCB Integration
PCB R1
PCB R2
PCB R3
Buy-In/Buy-Out
!
Multi-Pod Ranging Demo
Pod Subsystem Testing Complete
Path Navigation Demo
Full Error Model
Filtering Defined
SW Demo w/ Weighting
Rover Subsystem Testing Complete
Parts Purchased
Pods Built
Module Built
Deployment Software
Shock Test
Controlled Demo
Here
RF Data + State Estimation
Rover and Deployment
CDR
FFR
MSR
TRR

Test Plan

- Rover Testing (Now-Mar):
  - Requires use of VICON Space and Rover
    - 3 team members have 24-hour access and can reserve testing space and rover
    - Team members have been trained on camera calibration
- Ranging Testing (Now-Mar):
  - Requires 2-5 antennas and boards
    - Have 3 of our own (2 additional can be requested 24 hours in advance from COHRINT)
- Deployment Testing (Feb-Mar):
  - Requires use of business field & safety cones to mark keepout zones
    - Safety materials from ITLL and Matt/Bobby will help supervise.
- Final Demonstration (April):
  - Requires use of business field & safety cones to mark keepout zones
    - Safety materials from ITLL and Matt/Bobby will help supervise.

Budget



***Notes:**

- Budget based on estimated **12 pods + 4 pods for prototyping**
- Jackal Rover provided by customer

Total:	**$3676.77**
Margin:	**$995.70**
Extra:	**$327.53**
	$5000.00

Deployed RF Antennas for GPS-denied Optimization and Environmental Navigation

Thank you for your time --
Come check out our progress in the spring!

Appendix

A: Rover Navigation

DRAGON

Navigation Subsystem - A* Optimality

- Algorithm has been used since 1950s and the optimality has been proven before
- This assumes an admissible heuristic (never overestimates cost)
- A* designed as start to end, needs to be extended to include more than one end point

Lemma 3

Let $(n_1, n_2, \cdots, n_t)$ be the sequence of nodes closed by A^*. Then, if the consistency assumption is satisfied, $p \leq q$ implies $\hat{f}(n_p) \leq \hat{f}(n_q)$.

Proof: Let n be the next node closed by A^* after closing m. Suppose first that the optimum path to n does not go through m. Then n was available at the time m was selected, and the lemma is trivially true. Then suppose that the optimum path to n does, in fact, go through m. Then $g(n) = g(m) + h(m, n)$. Since, by Lemma 2, we have $\hat{g}(n) = g(n)$ and $\hat{g}(m) = g(m)$,

$$\begin{aligned} \hat{f}(n) &= \hat{g}(n) + \hat{h}(n) \\ &= g(n) + \hat{h}(n) \\ &= g(m) + h(m, n) + \hat{h}(n) \\ &\geq g(m) + \hat{h}(m) \\ &= \hat{g}(m) + \hat{h}(m) \end{aligned}$$

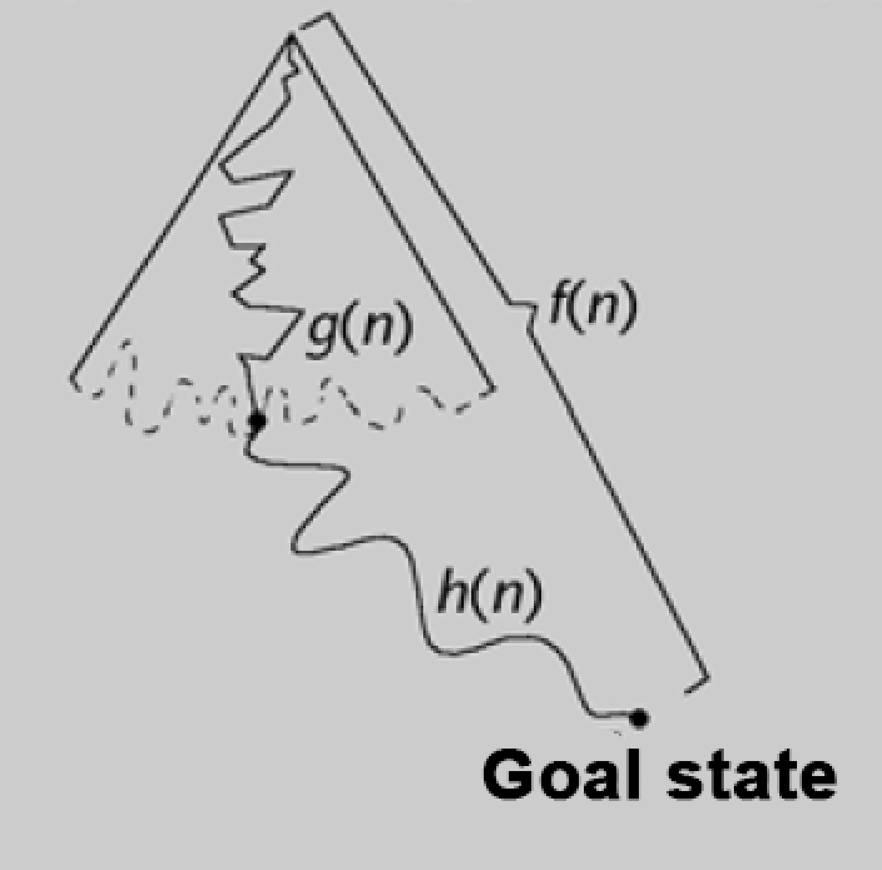
where the inequality follows by application of (5). Thus we have

$$\hat{f}(n) \geq \hat{f}(m).$$

Since this fact is true for any pair of nodes n_k and n_{k+1} in the sequence, the proof is complete.

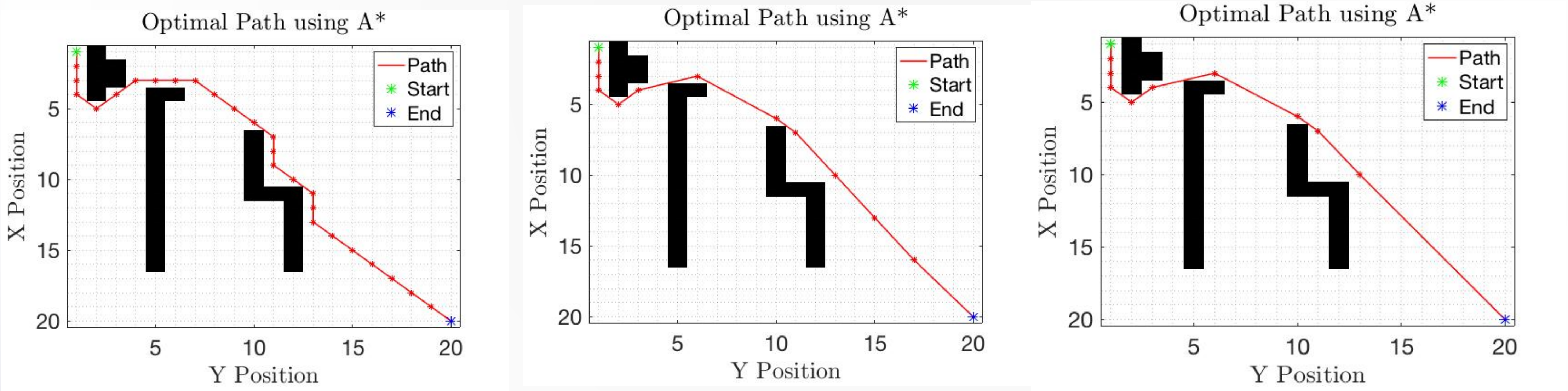
Navigation Subsystem - Heuristic

- Heuristic functions are "means to an end" approaches to problems that revolve around practicality
- For search algorithms, this means estimating the lowest cost from point A -> B
- Includes **Euclidean distance**, Manhattan distance (absolute difference between X and Y coordinates), etc.
- Must be admissible (underestimate of actual distance)



Navigation Subsystem - A* N-Search

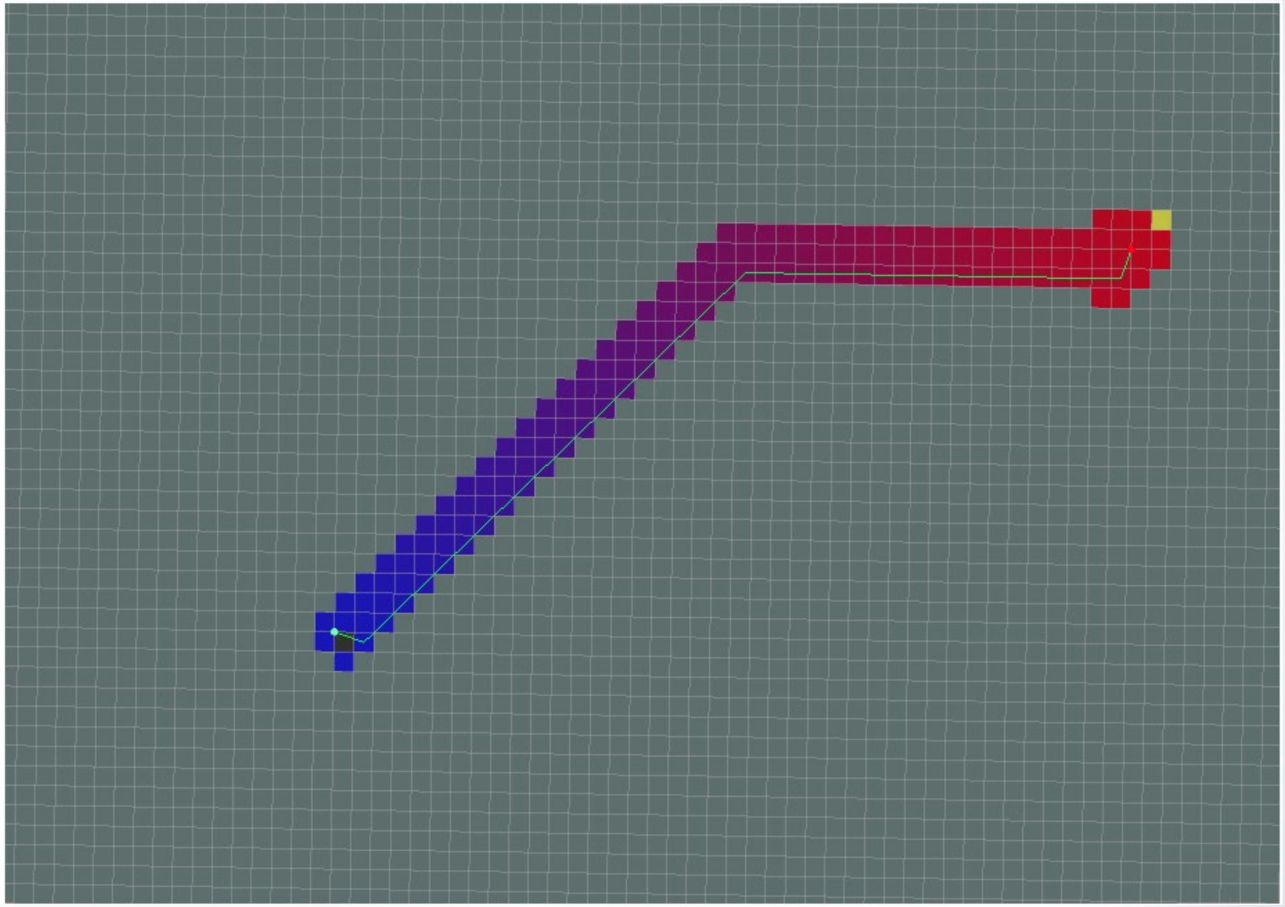
- Vanilla A* will search 8 nearest neighbors for least cost path
- Valid solution but provides grid-dependent paths that are not continuous
- Increasing number of searched neighbors “extends” A*’s range and allows for shorter, continuous paths to be developed that do not “hug” the grid (at cost of computation time)



20 x 20 Grids with 8, 128, and 4096 neighbors

Navigation Subsystem - Rover Porting

- A* and other path planning nodes exist within ROS library `global_planner`
- Vanilla 8 neighbor search but still useful for porting from MATLAB to ROS compatible language
- Ported to Python code and tested using Python IDE



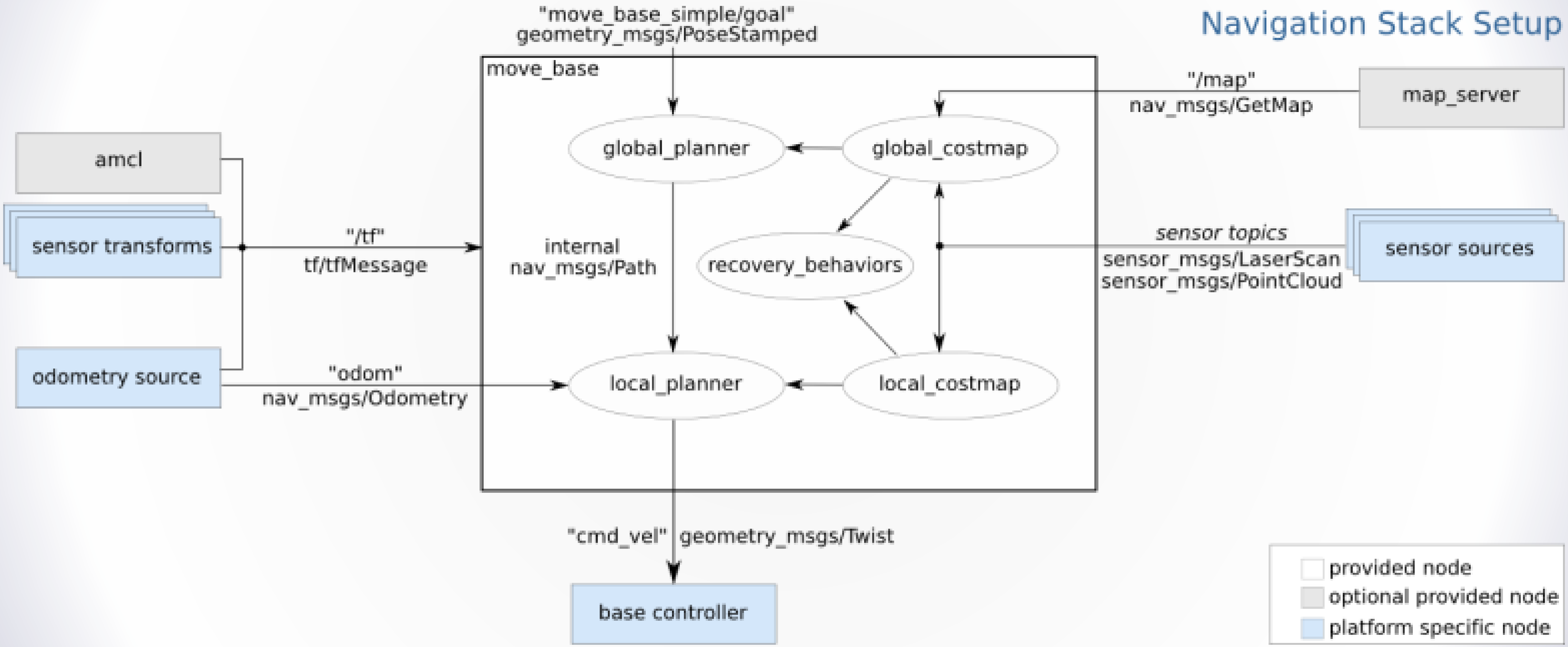
Navigation Subsystem - Computer

- Using MATLAB, maximum memory used at one time was never greater than 1.06 MB, well within available memory on rover
- MATLAB is much more costly in terms of RAM due to UI, low level ROS compatible languages will not be nearly as expensive
- Plenty of heritage and help offered from COHRINT team in porting and implementing autonomously on Jackal

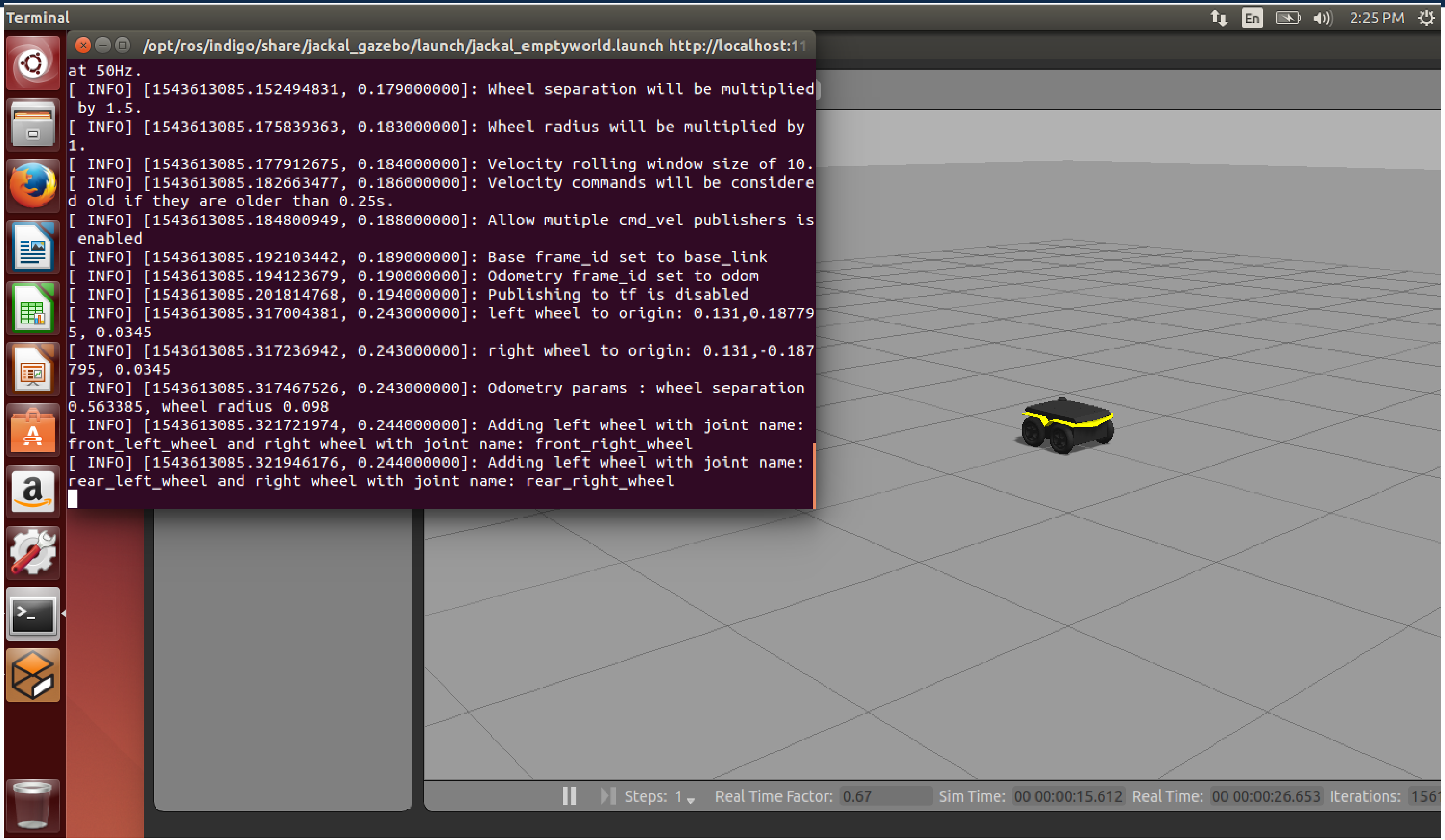
COMPUTER	Standard		Performance	
	Celeron J1800 Dual core, 2.4GHz 2 GB RAM	WIFI Adapter 32 GB Hard Drive	Intel Core i5 4570T Dual core, 2.9GHz 4 GB RAM	WIFI Adapter 128GB Hard Drive

Jackal Datasheet Specs

Navigation Subsystem - Nav Stack



Navigation Subsystem - Gazebo



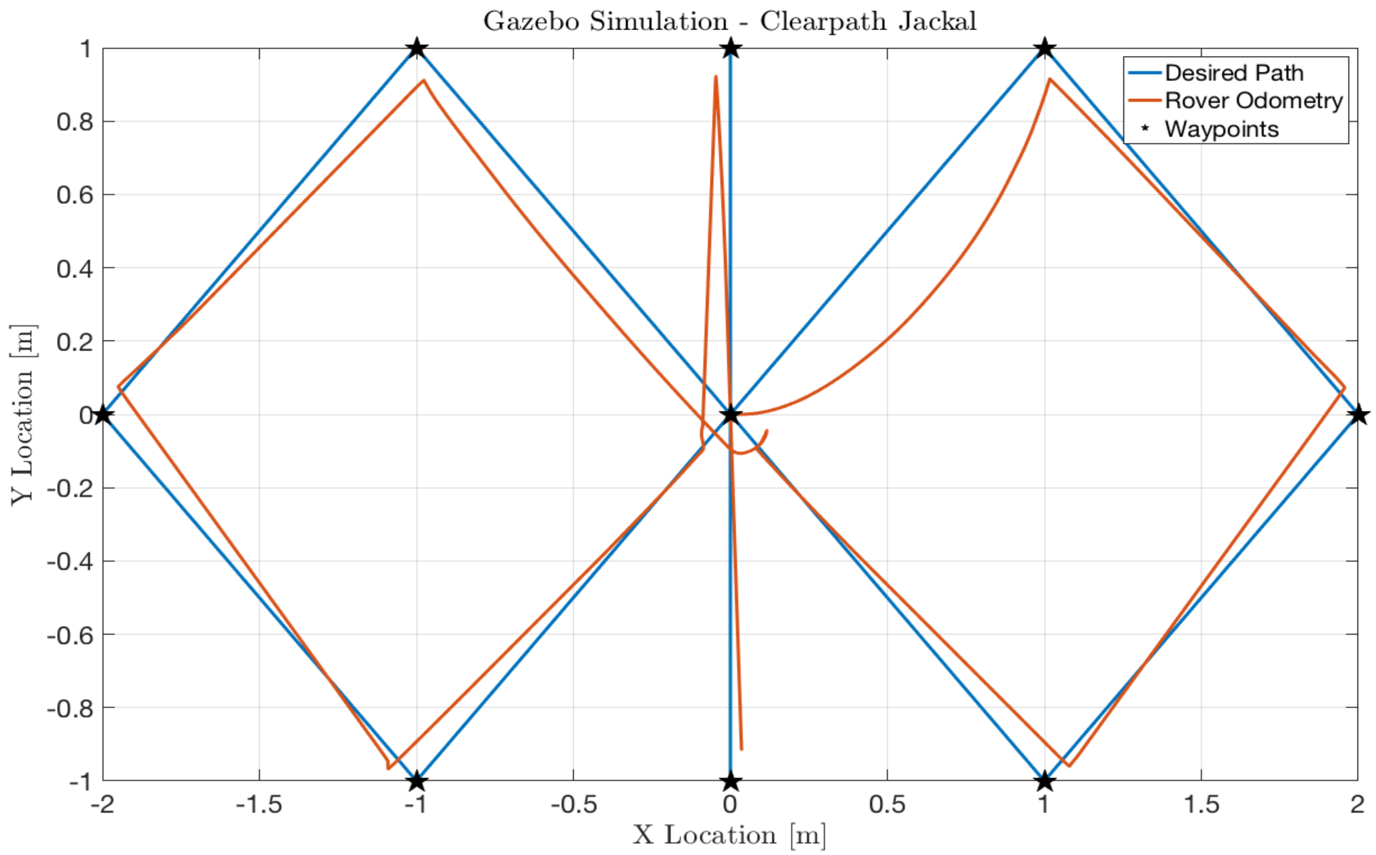
Navigation Feasibility - Simulated Test Path

Test Path Format

- Simple Figure-8 pattern with 10 total waypoints
- Rover physics simulator models basic rover behavior/ports directly to Jackal

Design Parameters

- XY distance/yaw tolerance
- Any number of waypoints
- Controller and map update frequencies

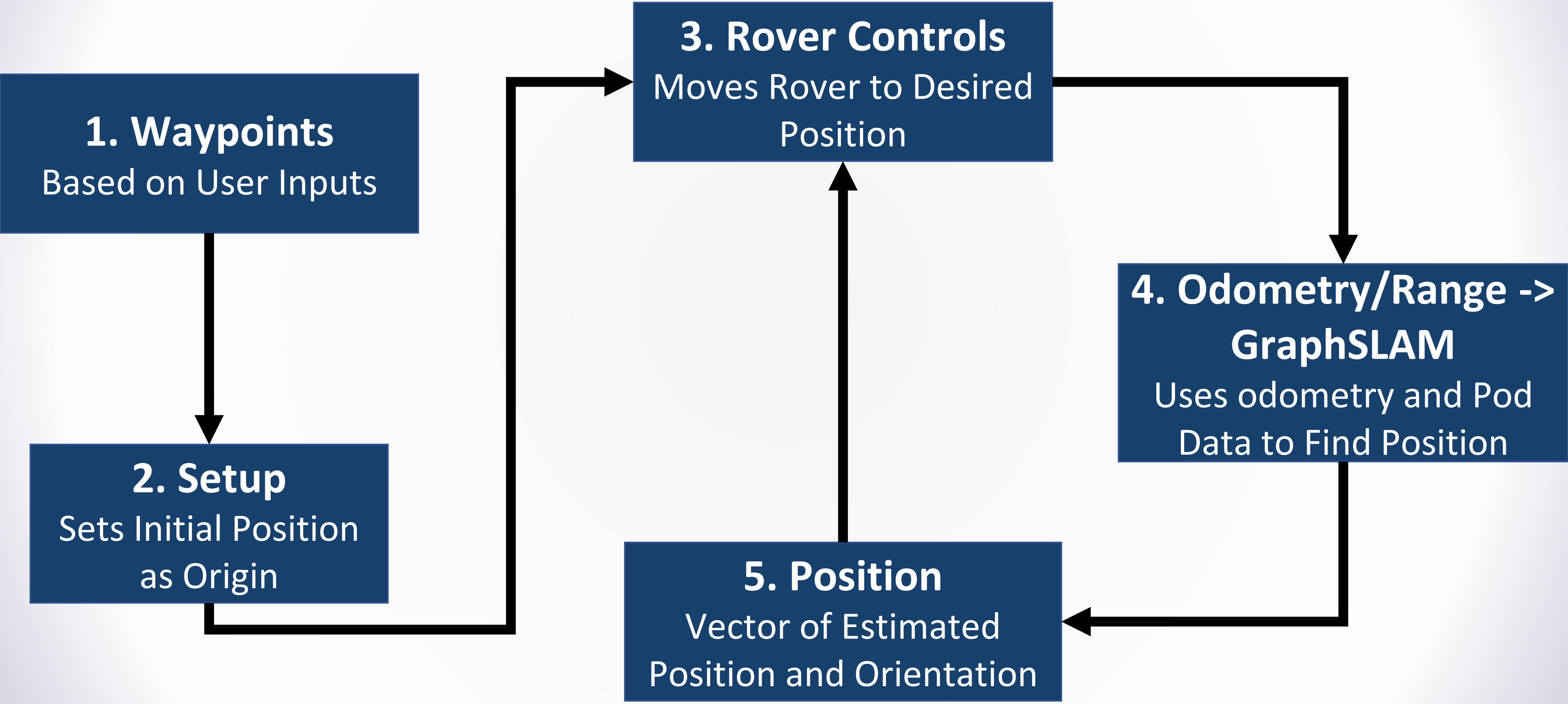


10 Waypoint Figure 8 Path

Navigation Feasibility - COHRINT Test

S1.2.1	Software shall be capable of controlling rover's physical motion through wheel actuators/ROS nodes	✓

Navigation Subsystem - Control Layout

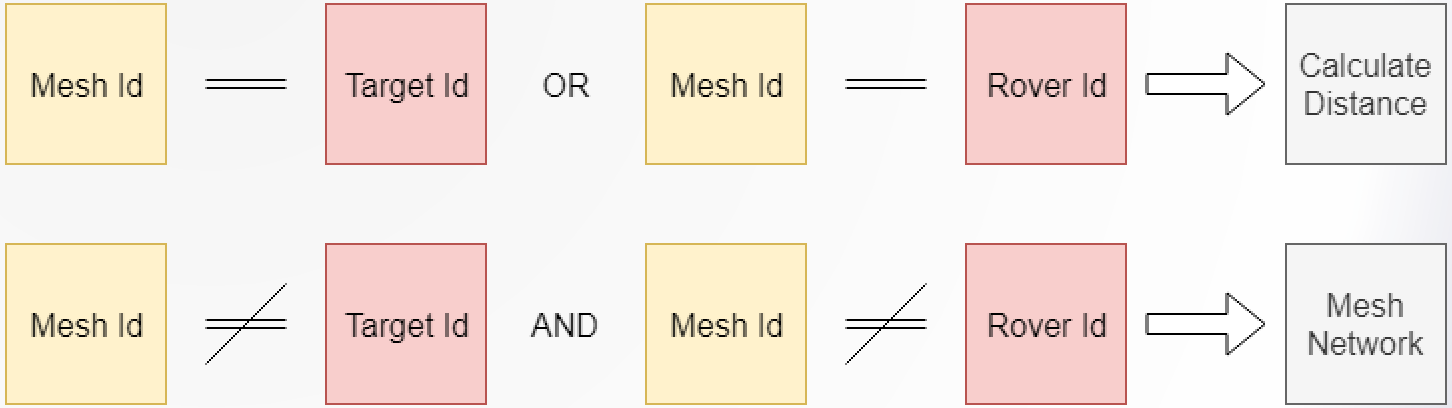


B: Pod Electronics

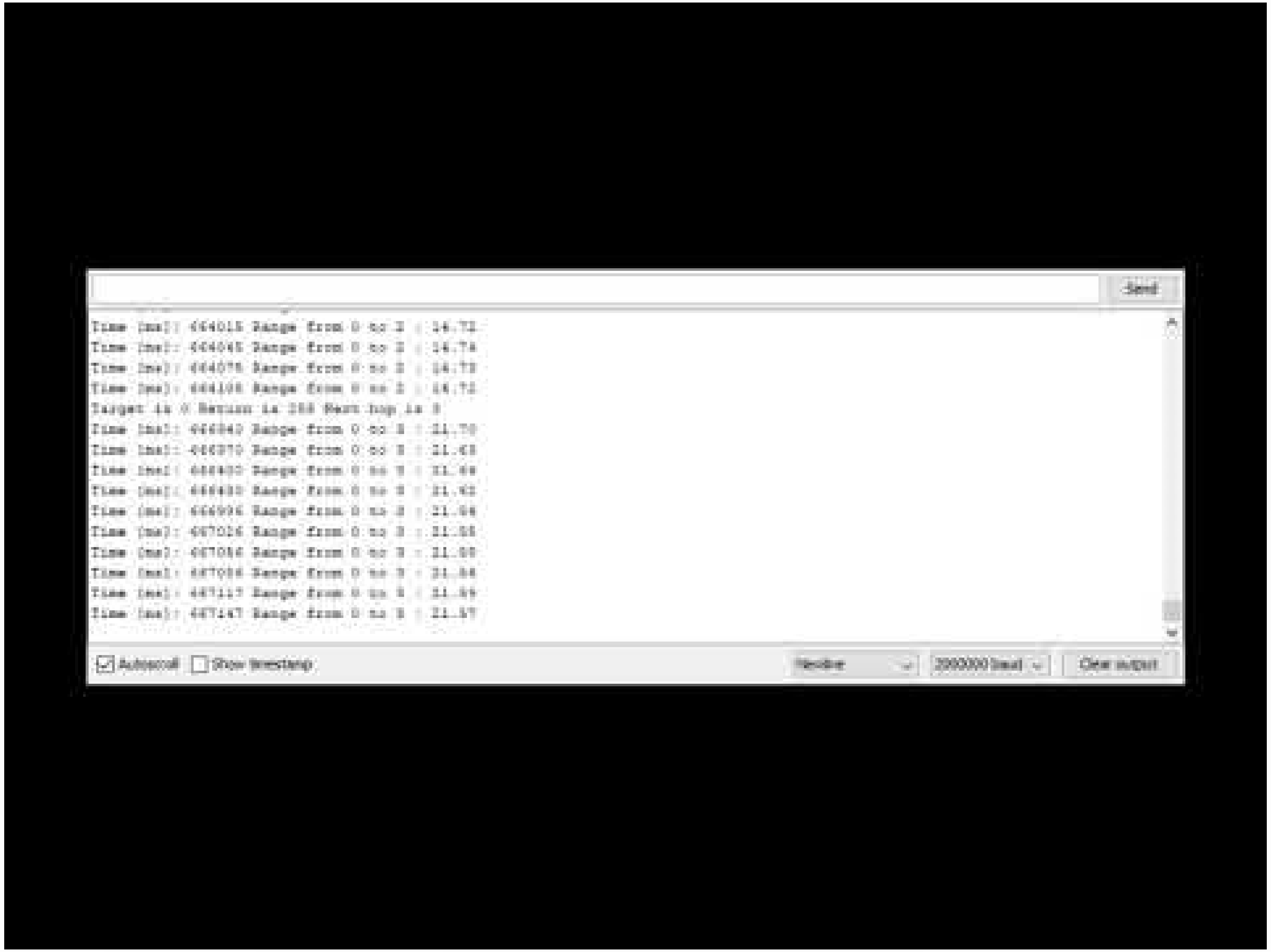
Mesh Network Design

- Purpose:
  - Calculated distances between rover and pods as well as distances from different pods
- Design:
  - Use a DWM1000 RF module with a STM32 Processor
- Specs:
  - Able calculate 30 distance measurements per input with minimal timeouts

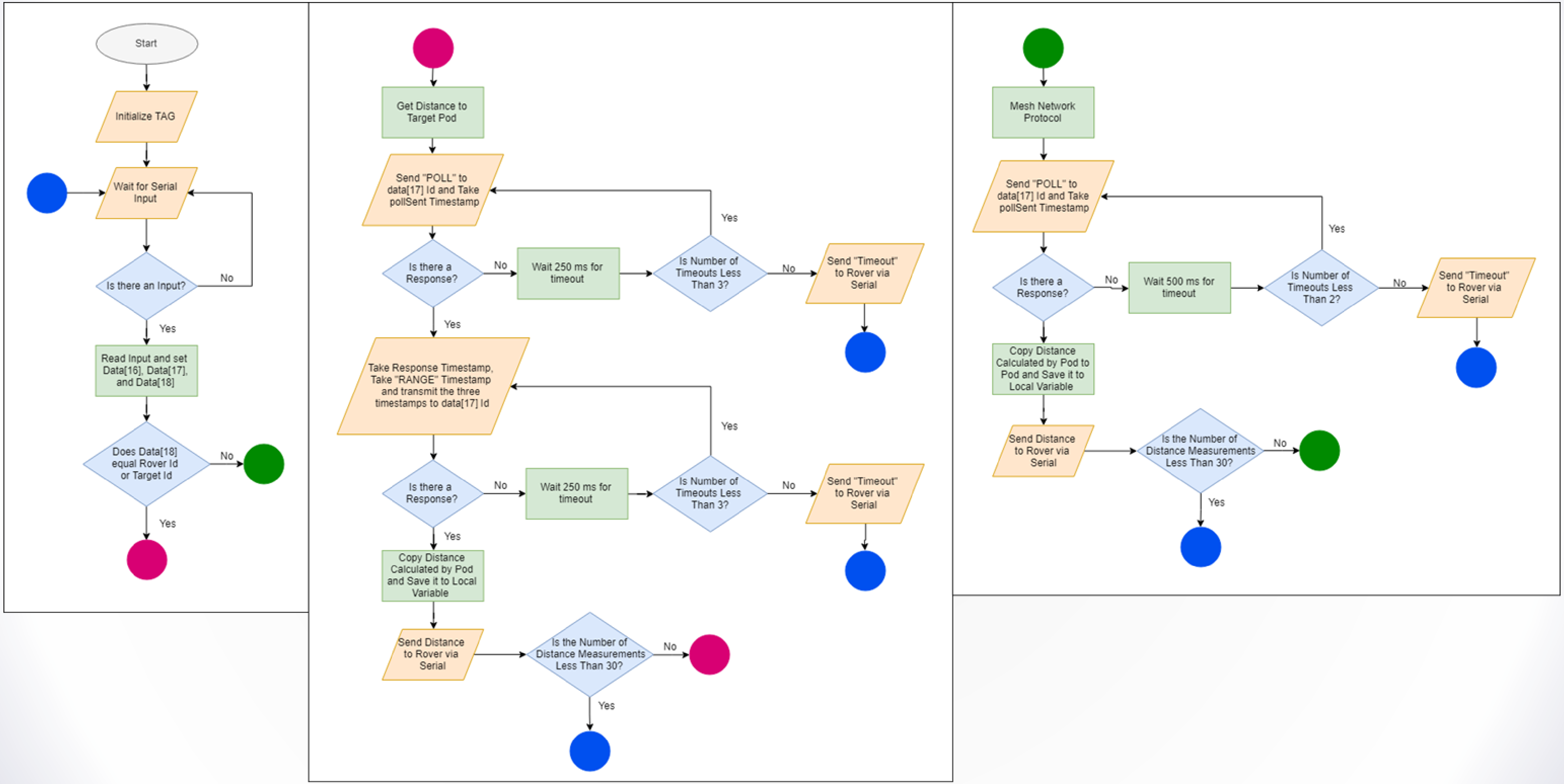
Data[0]	Data[1]	Data[2]	...	Data[14]	Data[15]	Data[16]	Data[17]	Data[17]
Signal Instruction	Reserved For Timestamp Transmit and Distance Calculation Transmit					Return Id	Target Id	Mesh Id



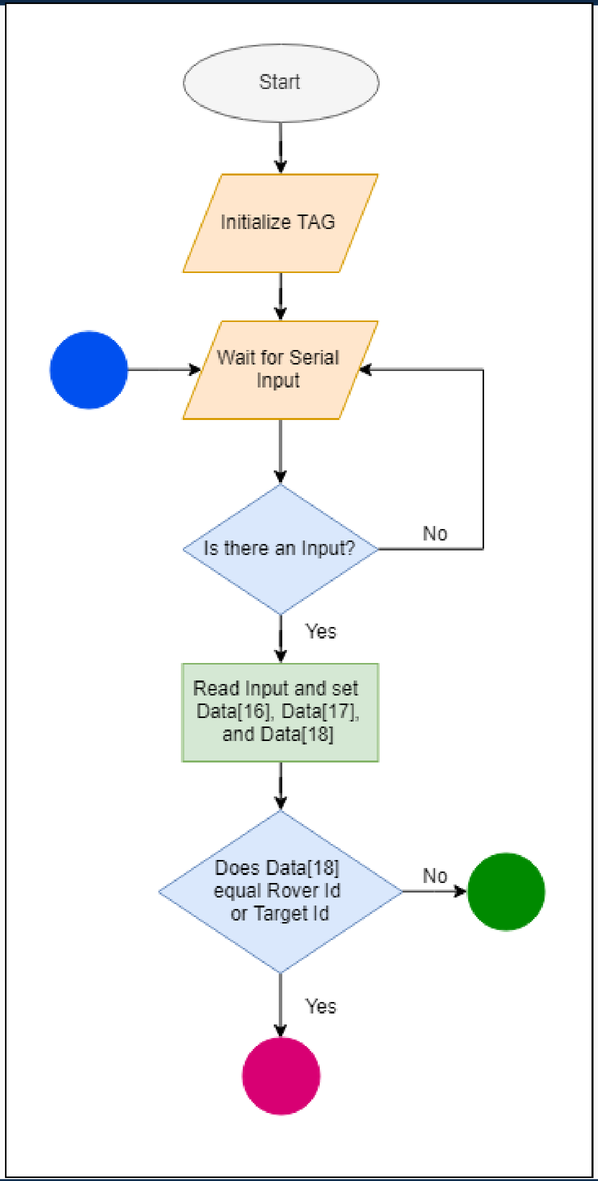
Mesh Network Test



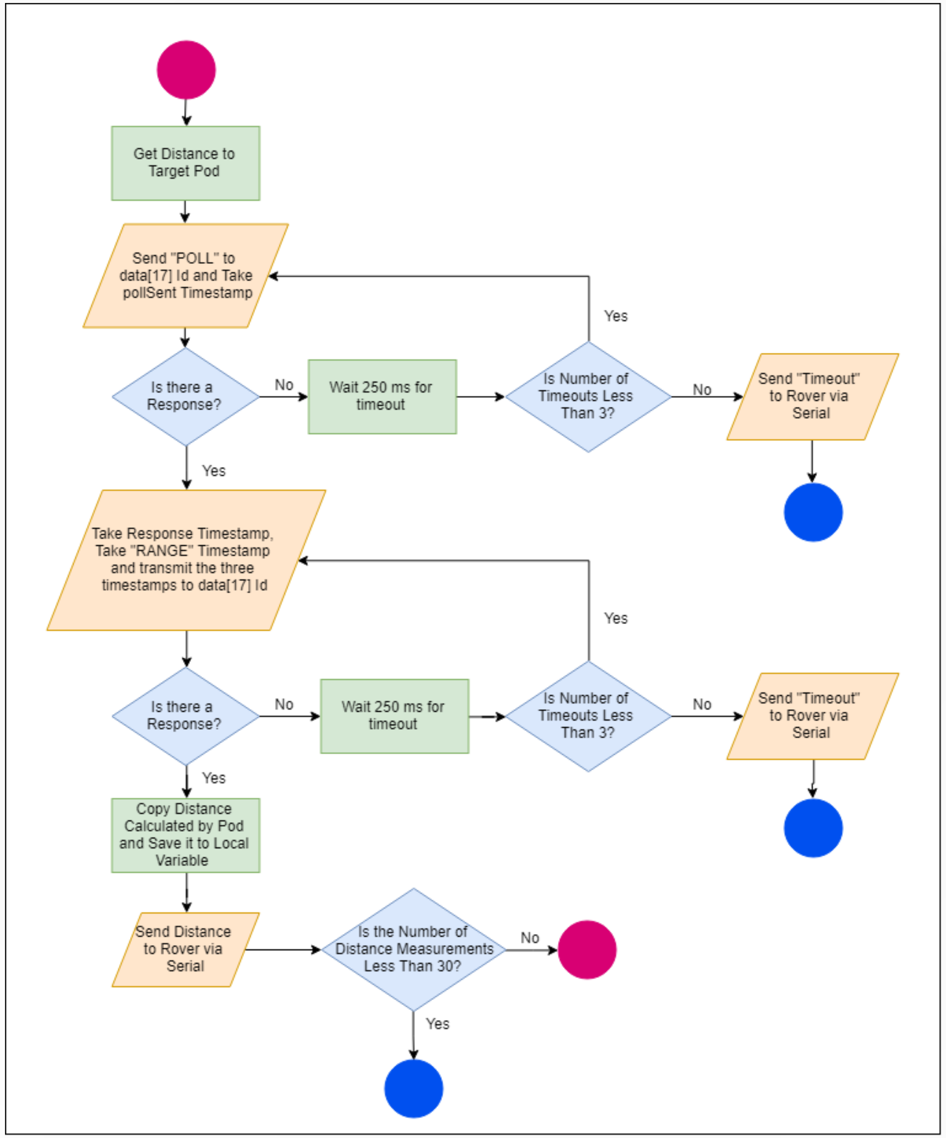
Tag (Rover Beacon) Flowchart



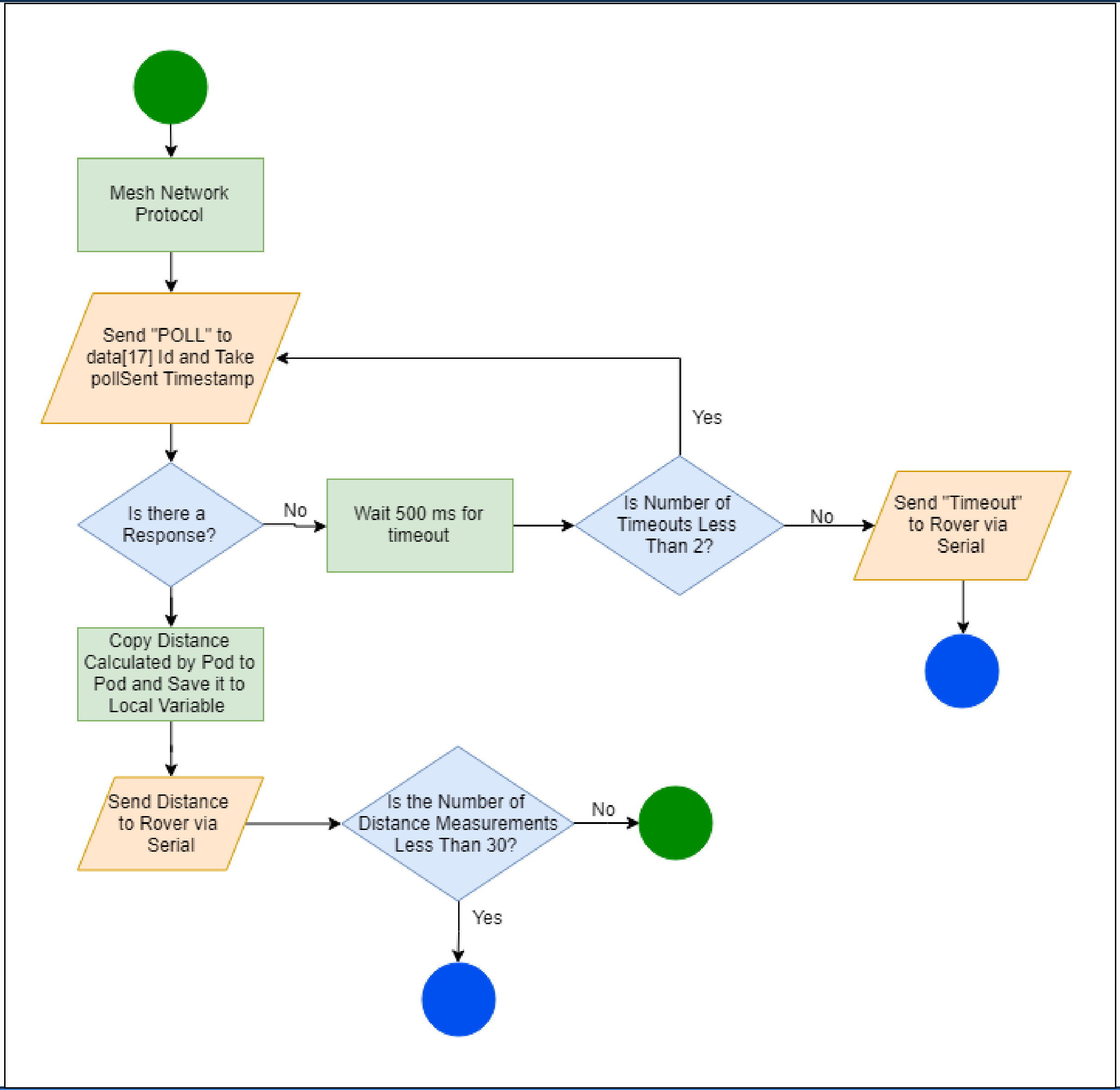
Tag (Rover Beacon) Flowchart



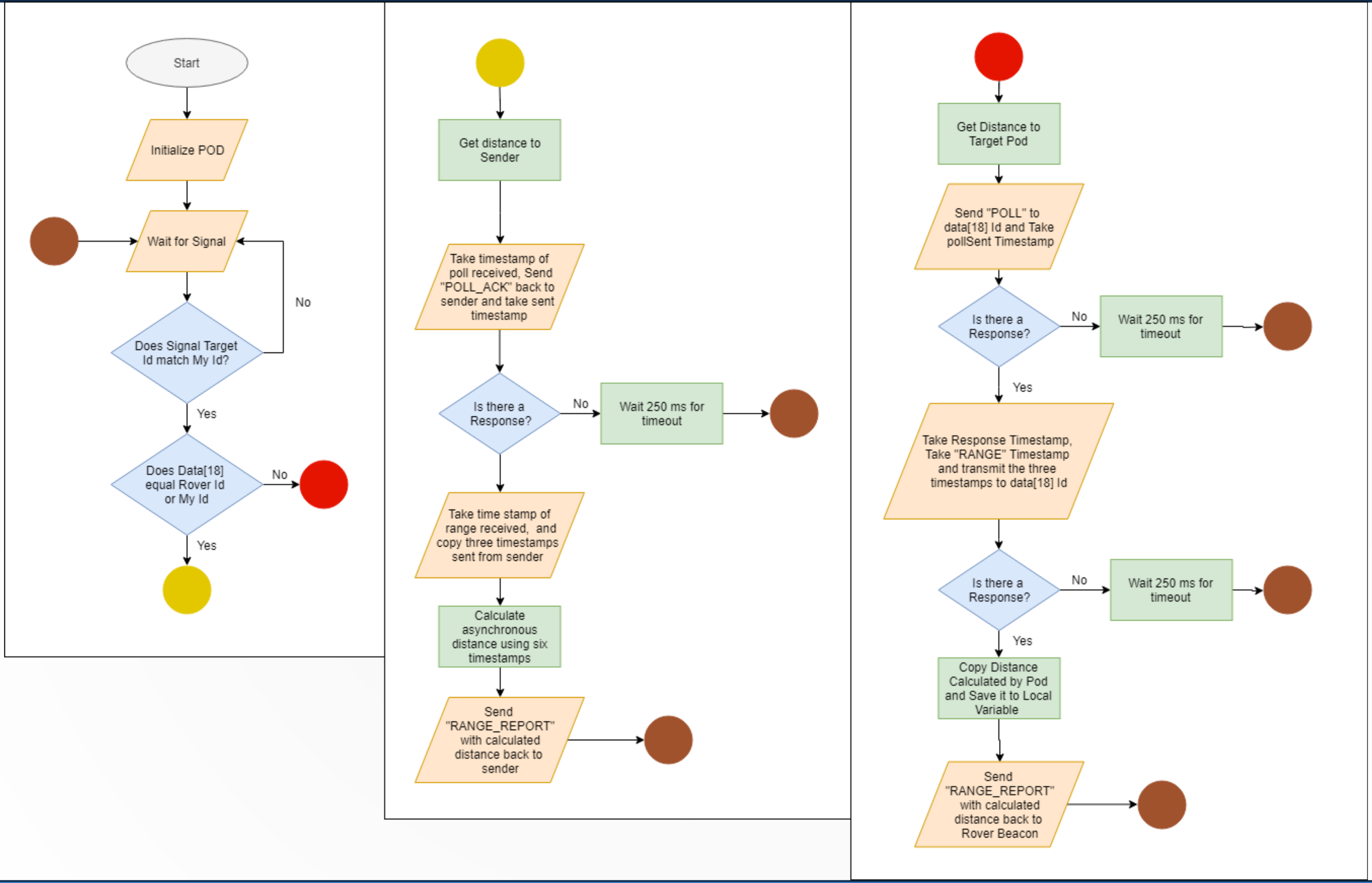
Tag (Rover Beacon) Flowchart



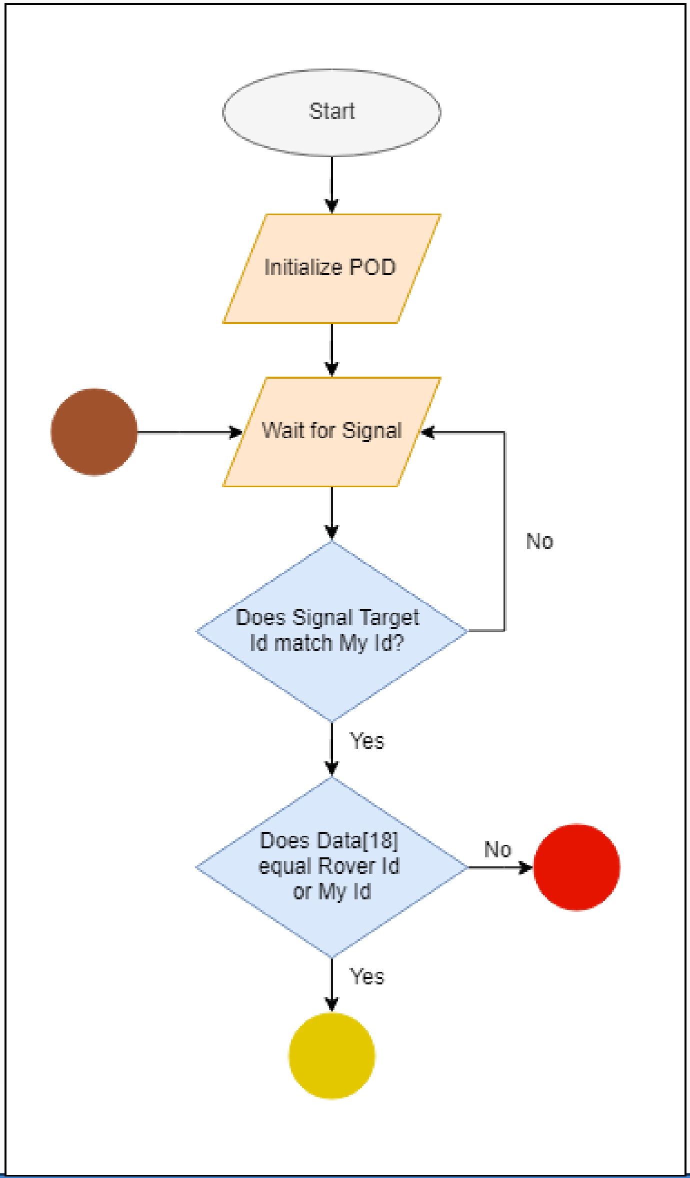
Tag (Rover Beacon) Flowchart



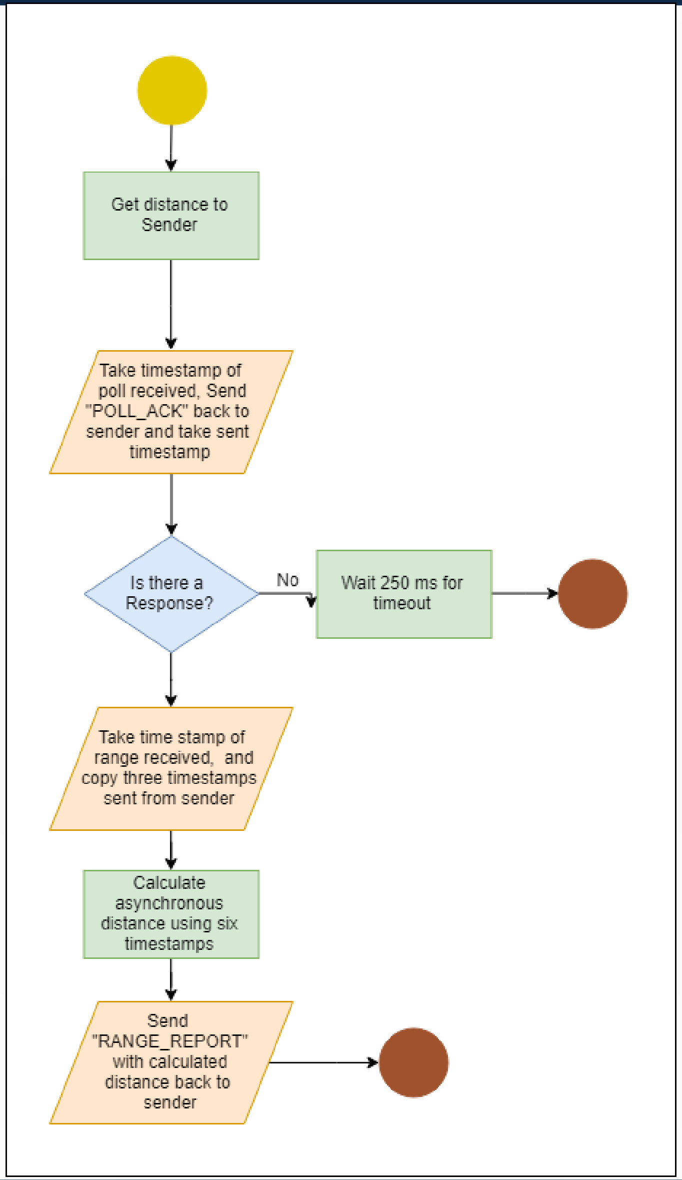
Pod Flowchart



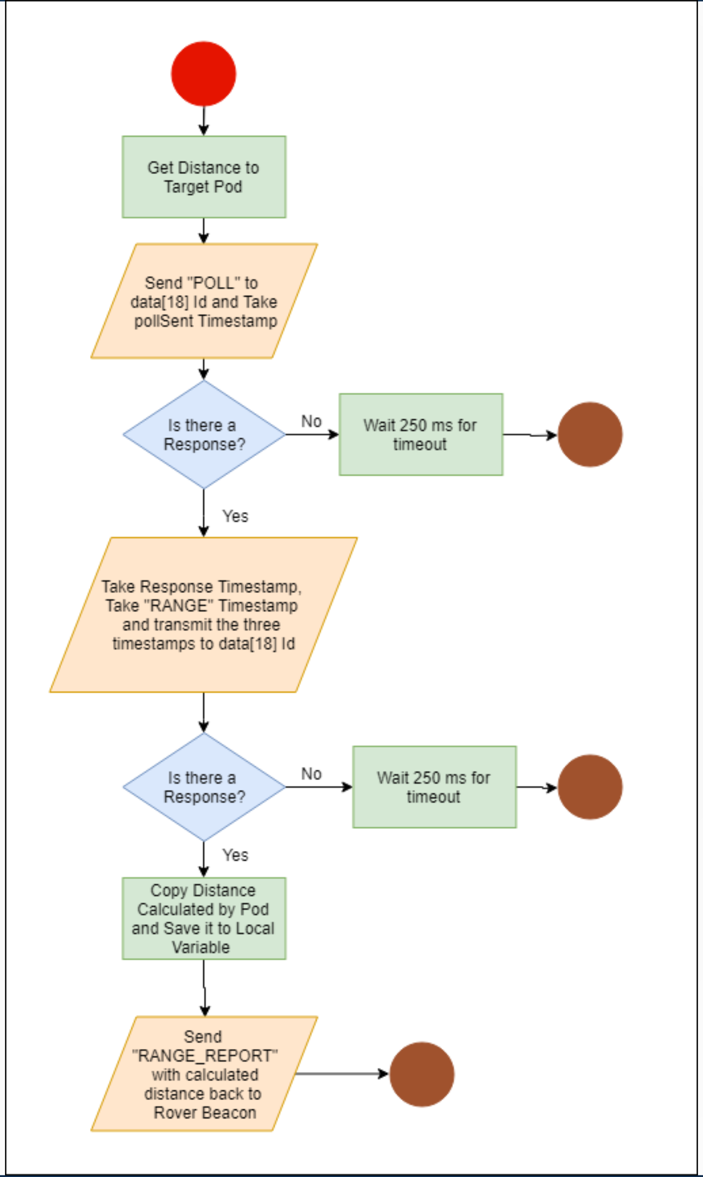
Pod Flowchart



Pod Flowchart



Pod Flowchart



Mesh Network Background

- DSDV
  - Table Routing Routine
  - No Multicasting
  - Network hops are known sequences
  - Low complexity with known number of nodes.
  - With 10 nodes(pods) less than 100 combinations are needed for rover to pod to pod communications

Reference Schematic - DWM1000

5.2 Application Circuit Diagram

A simple application circuit integrating the DWM1000 module need only power the device and connect the device to a host controller, see Figure 10.

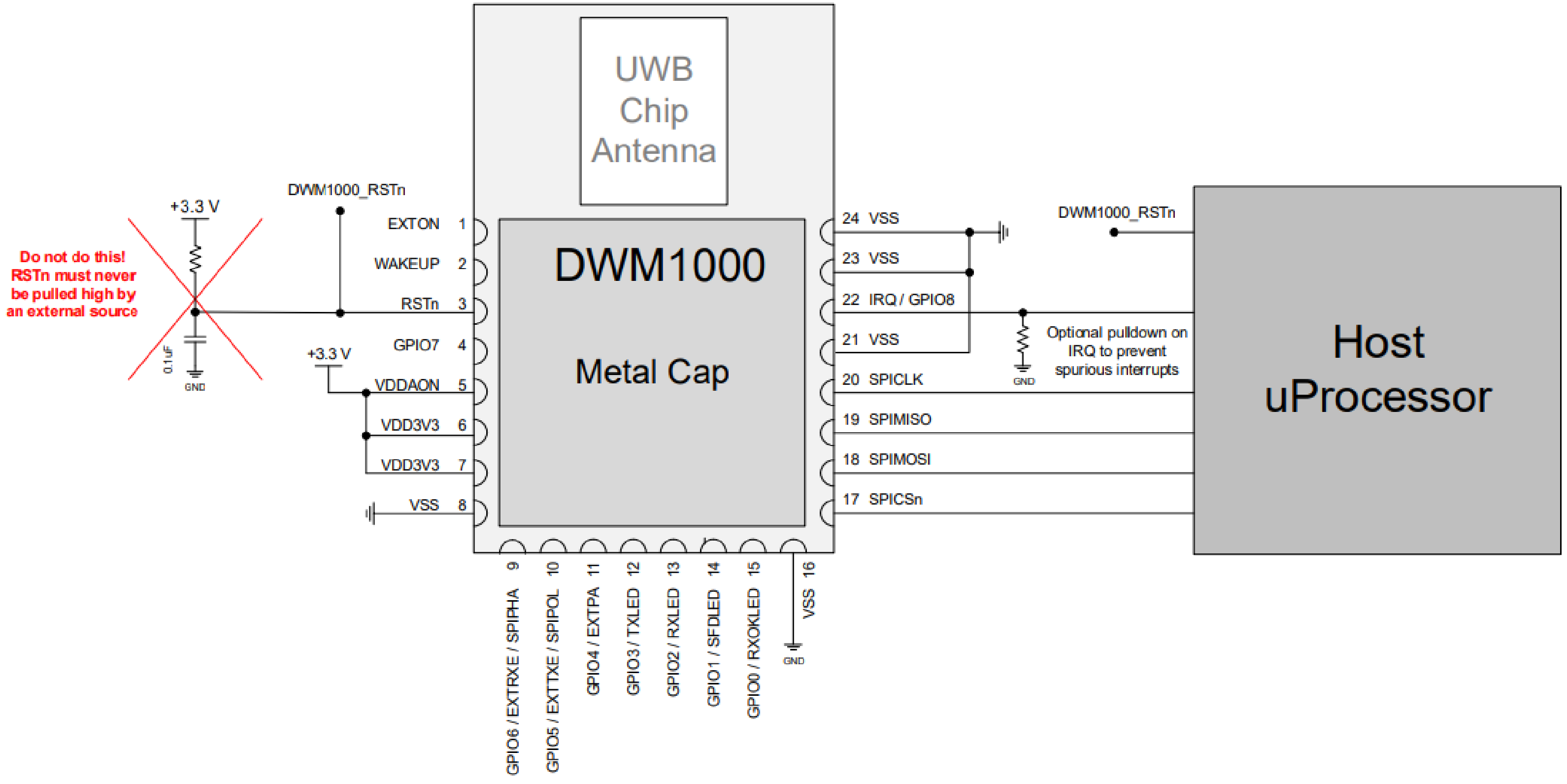
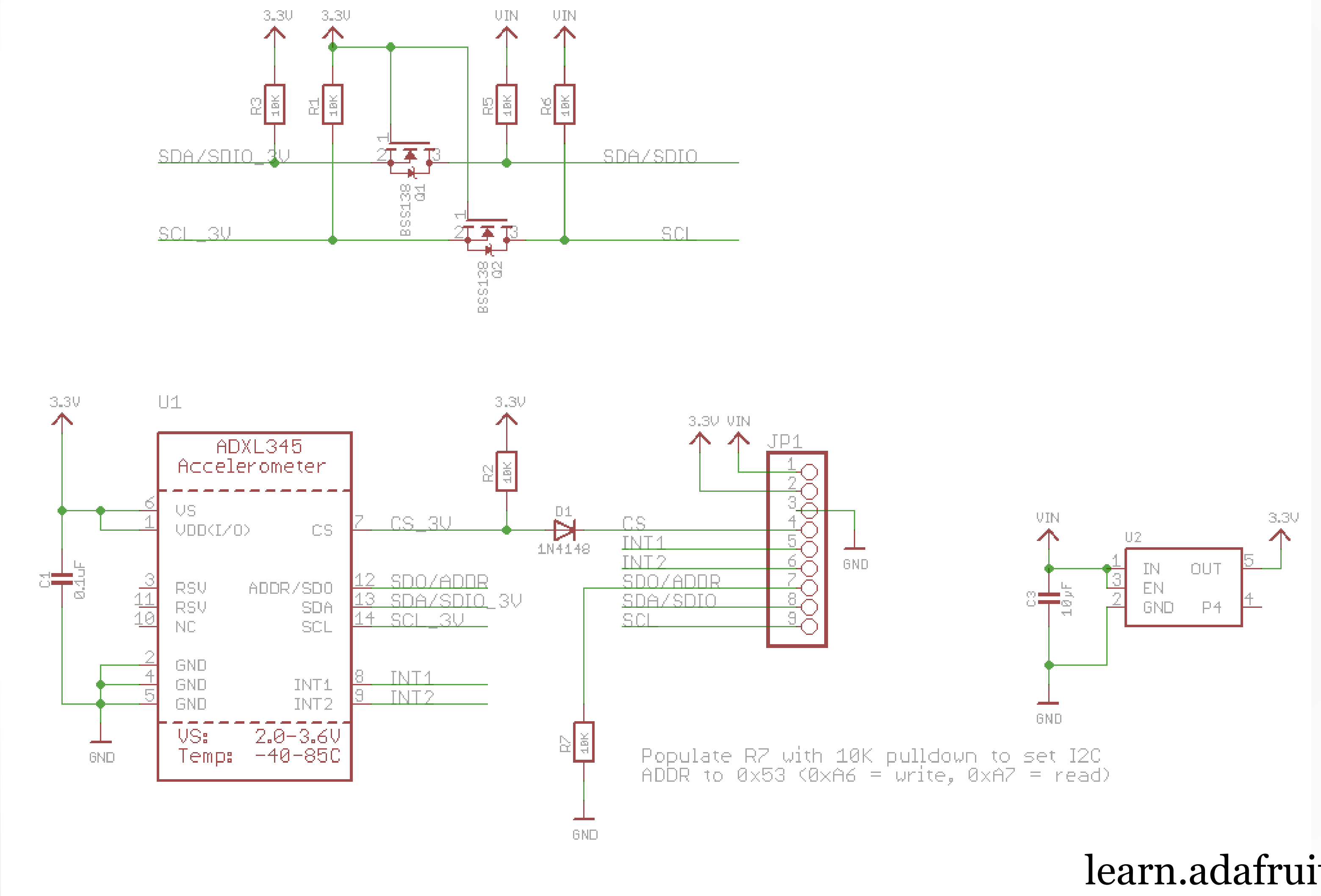


Figure 10: Example DWM1000 Application Circuit

https://www.decawave.com/sites/default/files/resources/dwm1000-datasheet-v1.3.pdf

Reference Schematic - Accelerometer



https://cdn-learn.adafruit.com/assets/assets/000/036/127/original/adafruit_products_schem.png?1475251909

Reference Schematic - Altimeter

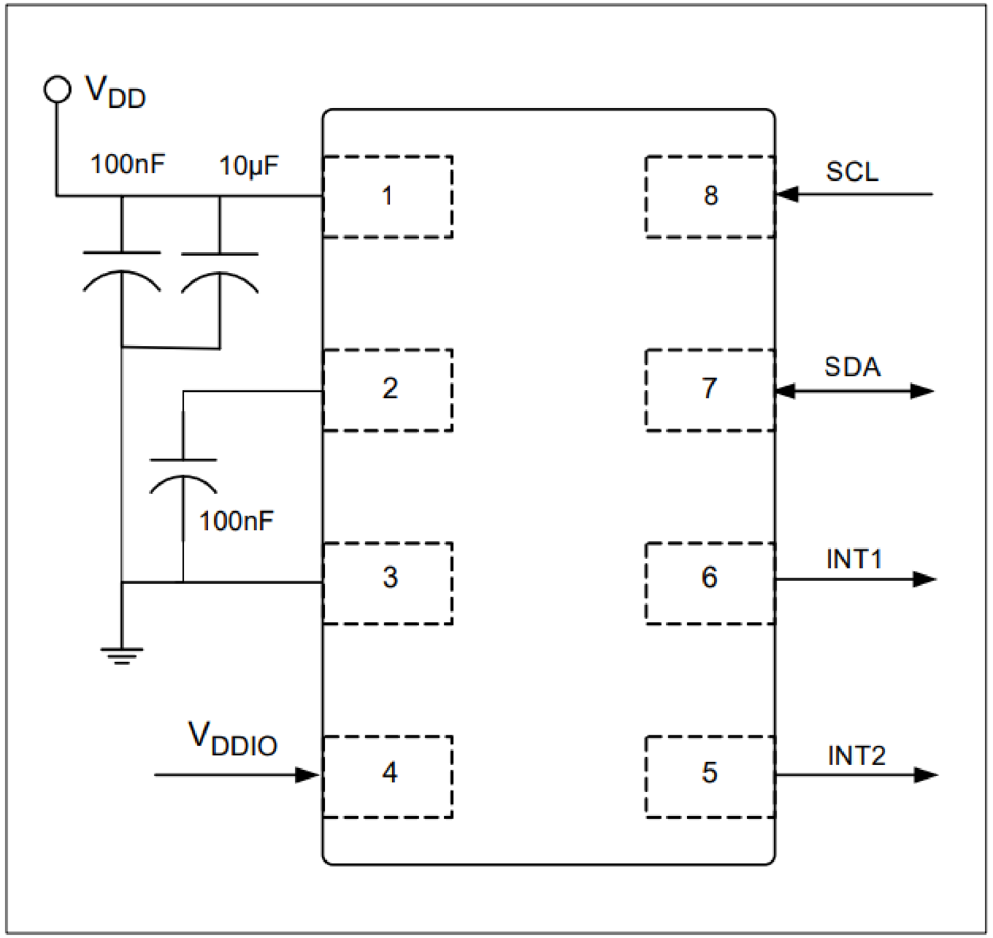
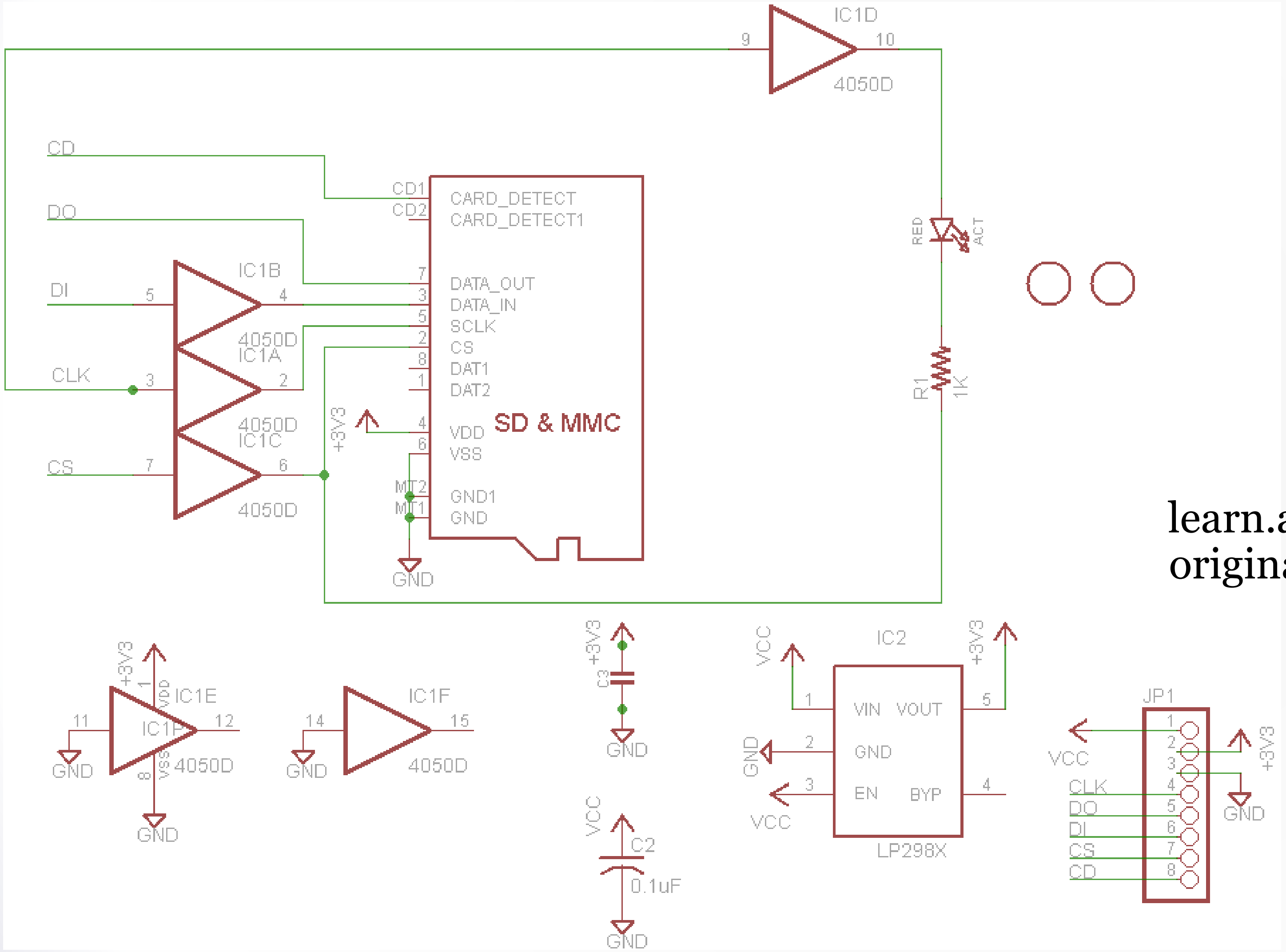


Figure 2. Pin Connections

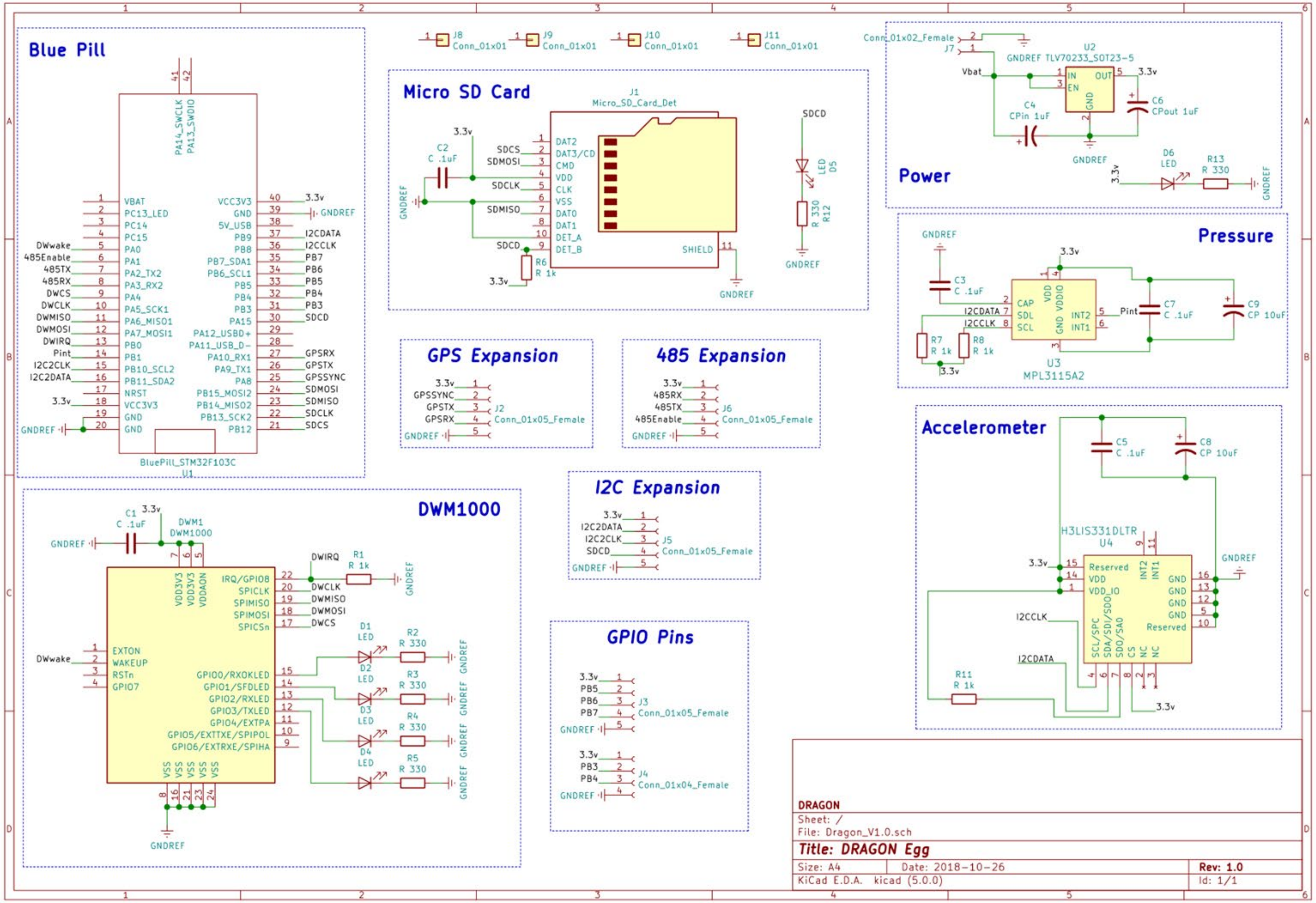
https://cdn-learn.adafruit.com/assets/assets/000/036/127/original/adafruit_products_schem.png?1475251909

Reference Schematic - SD Card Reader



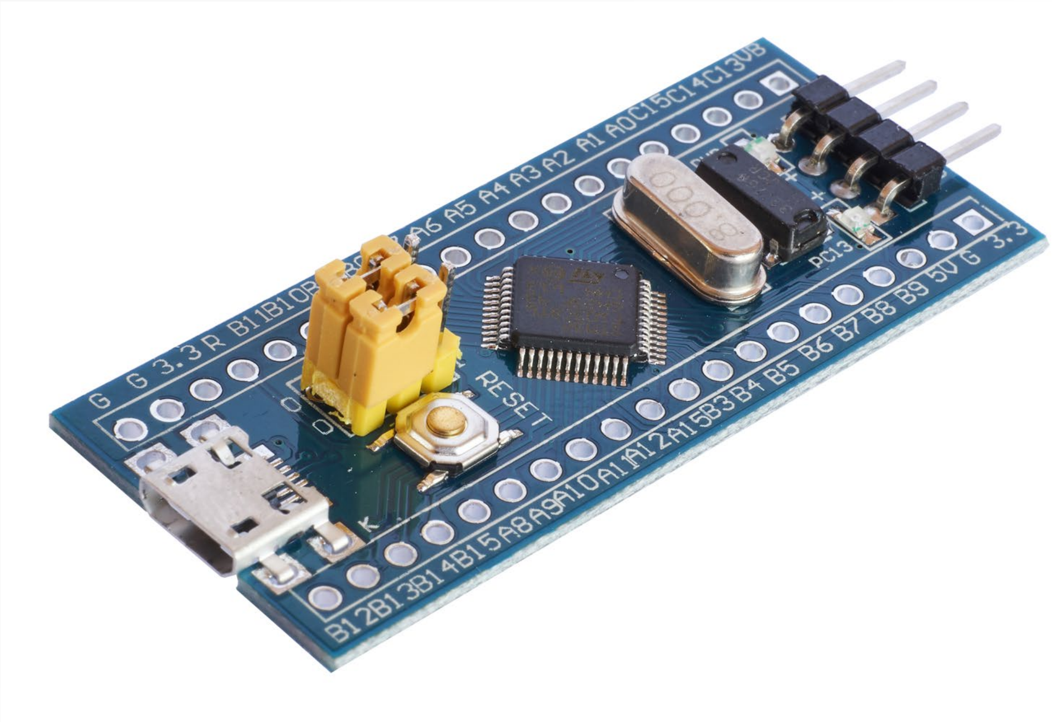
https://cdn-learn.adafruit.com/assets/assets/000/035/635/original/adafruit_products_schem.png?1473451805

Custom PCB Design Schematic



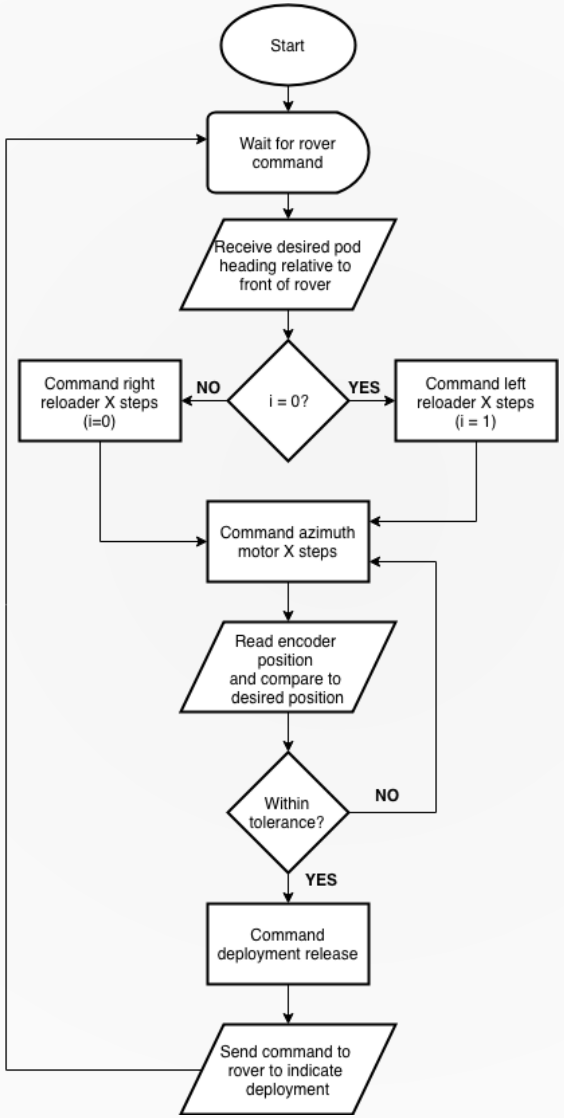
What is a Blue Pill?

- Purpose:
  - Breaks out the STMF103C8 Microcontroller into pinouts that can be used without having to account for support components.
- Design:
  - Give direct access to the chip pins without worry of improper support components.
- Specs:
  - Are ~$3/each, which is cheaper than just buying the processor



Blue Pill

Deployment Module Design: Software



Power Budget For Pods

D5.3.2	Battery shall have sufficient capacity to meet a 5% duty cycle between low and high power mode for 2 hour duration test	✓

Component	Current [mA]	Duration [minutes]	Usage [mAh]
Blue Pill (STMF32)	50	120	100
DWM1000	140	120	280
Sensor Breakout	0.04	120	0.08
Accelerometer	0.145	120	0.19
SD Card Reader	100	120	200

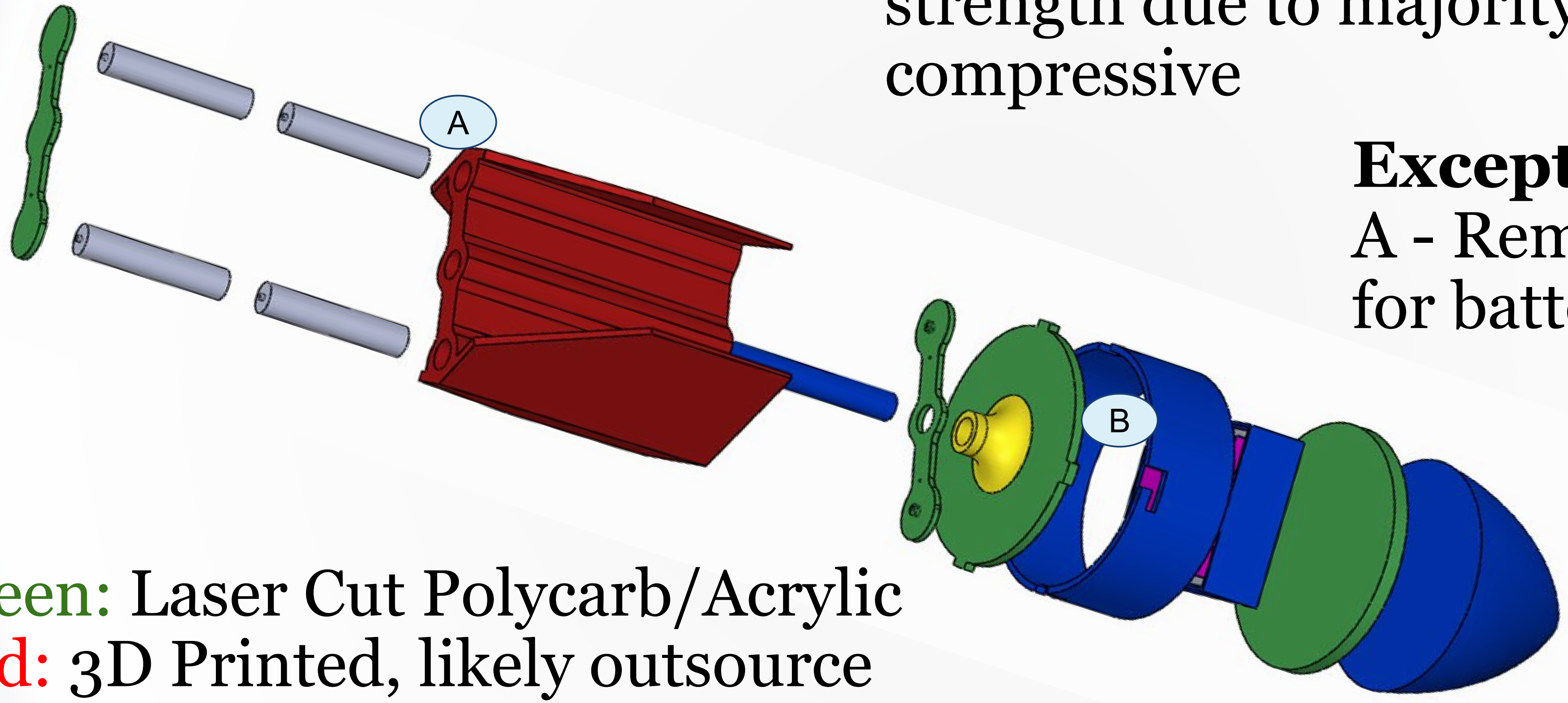
Total Usage: 580.27 [mAh]

AAA Battery Capacity: 1100[mAh]

B2: Pod Structure

Pod Structural Design: Manufacturing

All joints bonded with epoxy, sufficient strength due to majority of stress being compressive



Exceptions:

A - Removable hardware for battery swap

B - Friction rotation slot-lock for electronics access, can pin if needed

Green: Laser Cut Polycarb/Acrylic
Red: 3D Printed, likely outsource
Blue: COTS, modified
Yellow: COTS, add-on
Yellow:

P5.3.1 P5.4.7	P - Battery hot swap & rechargeable P - Pods can be serial manufactured	✓

Pod Structural Design: Mass and size

- Purpose:
  - Lower mass minimizes impact force, improves range
- Design:
  - High strength plastics (polycarbonate)
  - Little to no metal (obstructs antenna)
  - Lightweight foam, and material removal wherever possible
  - Using high strength adhesives (epoxy) rather than hardware
- Specs:
  - Mass model: 500 grams with 30g ballast margin
  - Length = 24cm, Diameter 8.5cm

Mass properties of pod_new_new_new_new
Configuration: Default
Coordinate system: -- default --

Mass = 468.41 grams

Volume = 449.38 cubic centimeters

Surface area = 1563.93 square centimeters

Center of mass: (centimeters)
X = 2.76
Y = 12.64
Z = 7.08

Principal axes of inertia and principal moments of inertia: (grams * square centimete
Taken at the center of mass.
Ix = (0.01, 1.00, 0.00)   Px = 3979.06
Iy = (-0.95, 0.01, -0.31)   Py = 20353.18
Iz = (-0.31, 0.01, 0.95)   Pz = 21879.14

Moments of inertia: (grams * square centimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 20496.22	Lxy = 210.79	Lxz = 448.09
Lyx = 210.79	Lyy = 3981.79	Lyz = -33.87
Lzx = 448.09	Lzy = -33.87	Lzz = 21733.37

Solidworks Mass Prop. Table and Major Pod Dimensions

P5.1.1	P - Pods under 600 grams	✓
P5.1.2	P - Pods <9cm diameter	

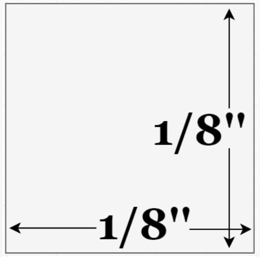
Pod Locking Mechanism

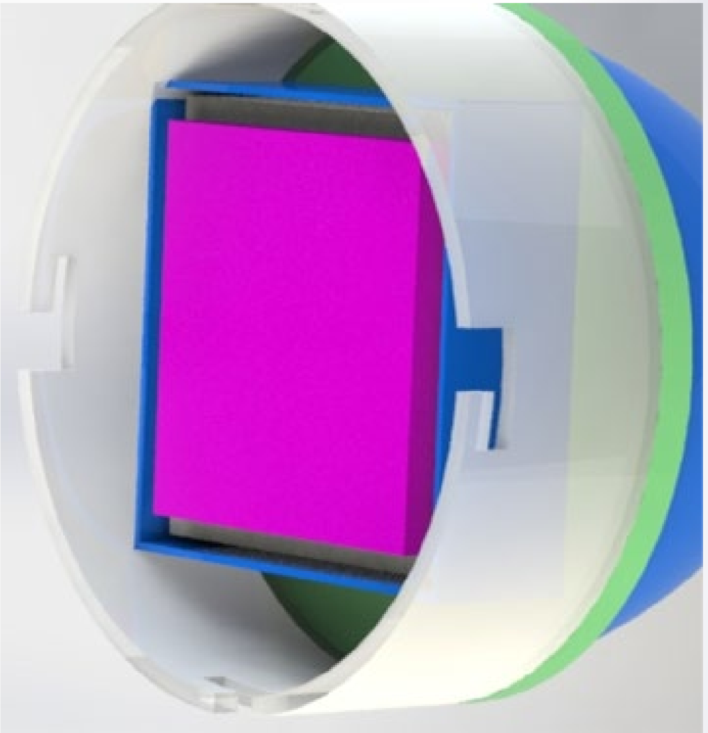
<u>Shear Analysis</u>

τ_y = 6000 psi (Polycarbonate)

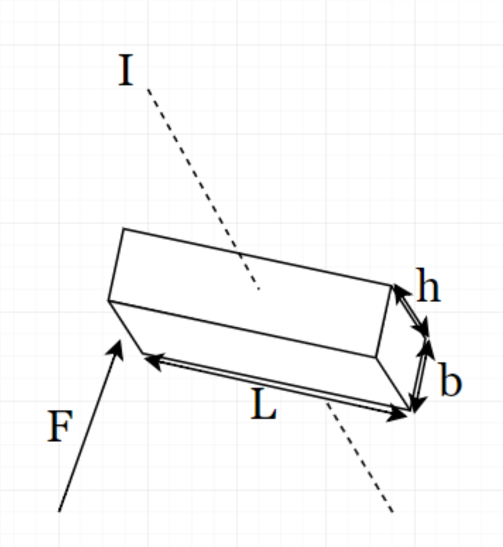
A = 1/64” n = 4 F = 300 lbs

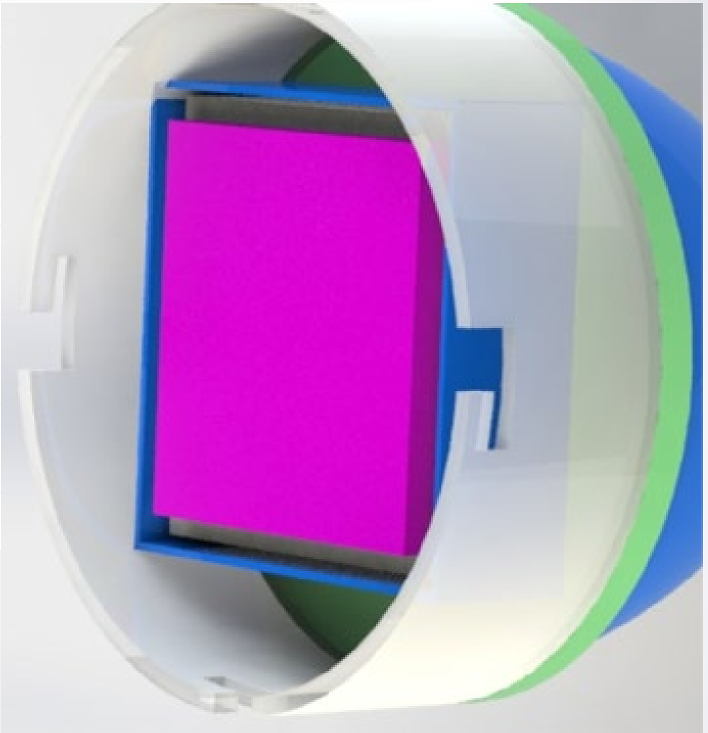
$$\tau = \frac{F}{nA} = \frac{300}{4(1/64)} = 4800 \text{ psi}$$





Pod Locking Mechanism





Bending Moment

σ_y = 13,500 psi (Polycarbonate)

F = 300

b=h=⅛”

$$I = \frac{1}{12} b h^2$$

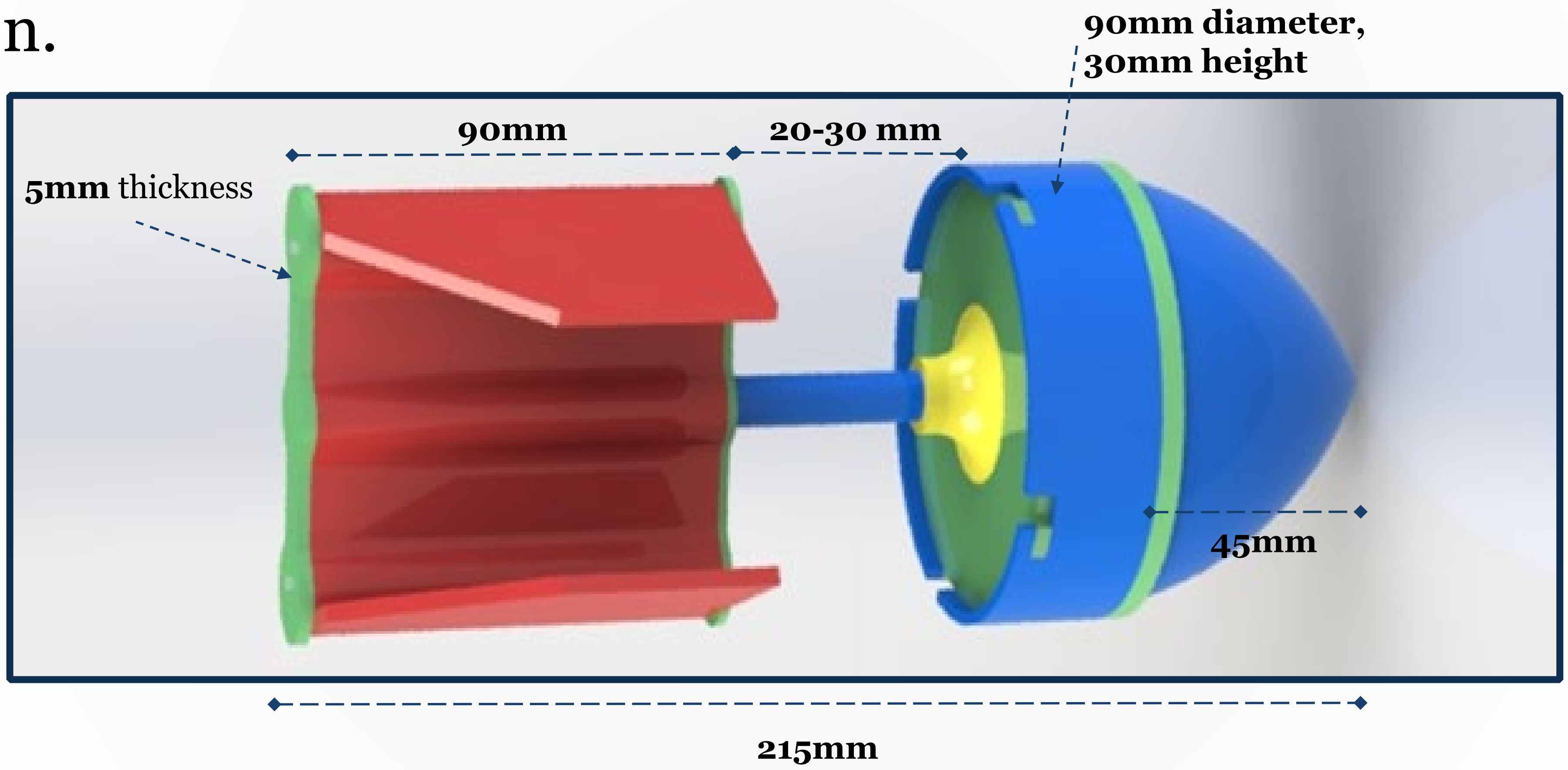
$$M = F \frac{L}{2}$$

$$\sigma = \frac{Mc}{I} = \frac{F(\frac{L}{2})(\frac{b}{2})}{\frac{1}{12} b h^2} = 57600L$$

$\sigma \leq \sigma_y$ ⟹ $L \leq 0.2343$ [in]

Pod Structure Design

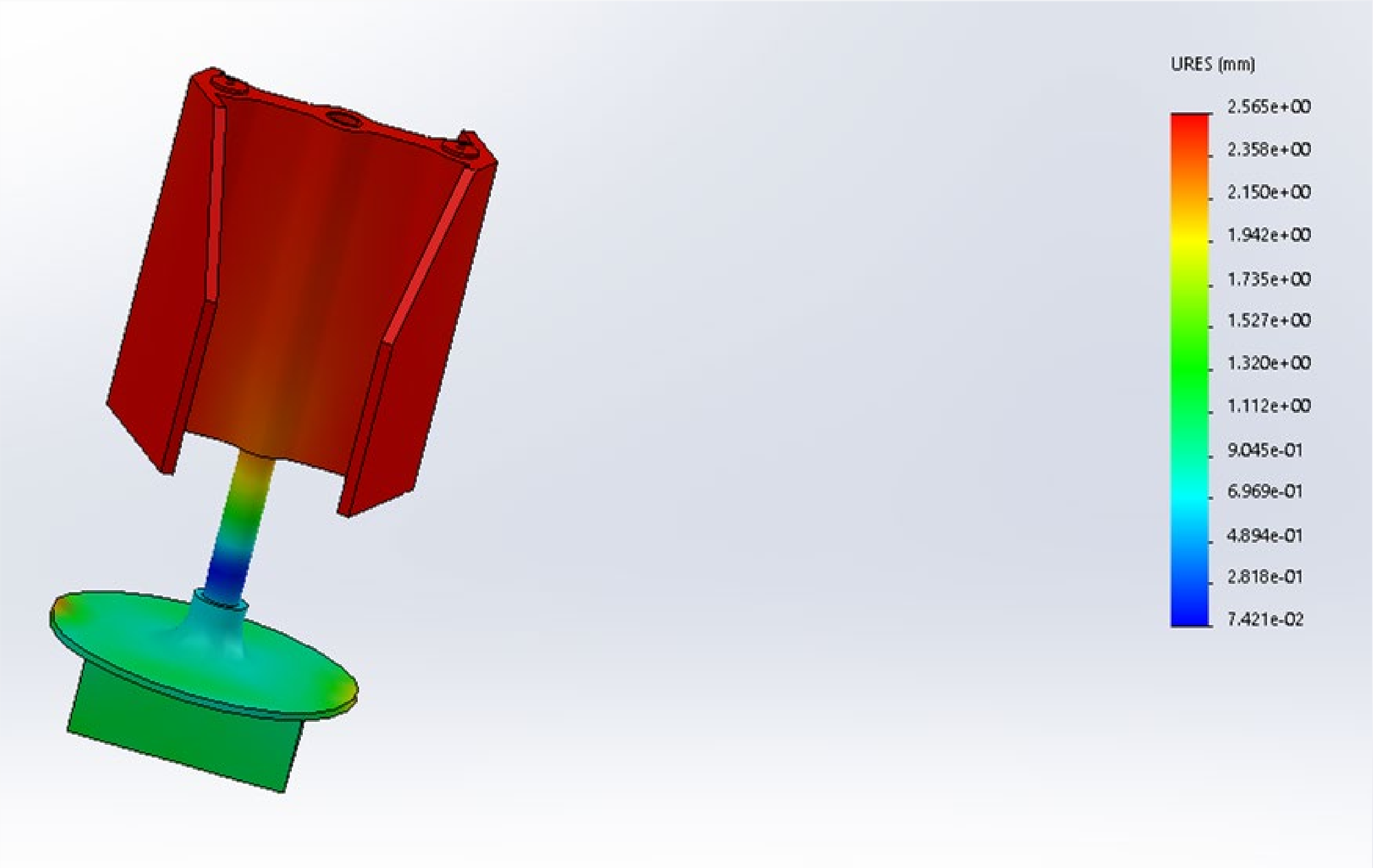
Pod structure contains the ranging electronics which are deployed from the cannon.



Pod Tail-Boom Structural Analysis

Under worst case impact:

tail boom was able to deflect top of fuselage by up to 2mm. Additional height was included to permit this flexure.



Pod Structural Design: Mech/Aero

Mass properties of pod_new_new_new_new
Configuration: Default
Coordinate system: -- default --

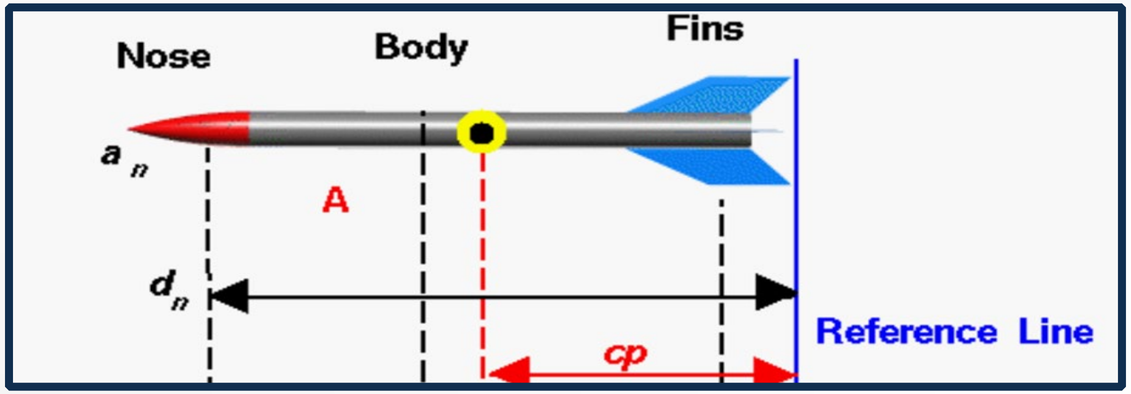
Mass = 468.41 grams

Volume = 449.38 cubic centimeters

Surface area = 1563.93 square centimeters

Center of mass: (centimeters)
X = 2.76
Y = 12.64
Z = 7.08

- **Purpose:** Cannon compatibility
- **Design:** Low mass bonded plastics
- **Specs:**
  - Mass: 500 grams with 30g ballast
  - Length: 21.5cm
  - Diameter 8.5cm

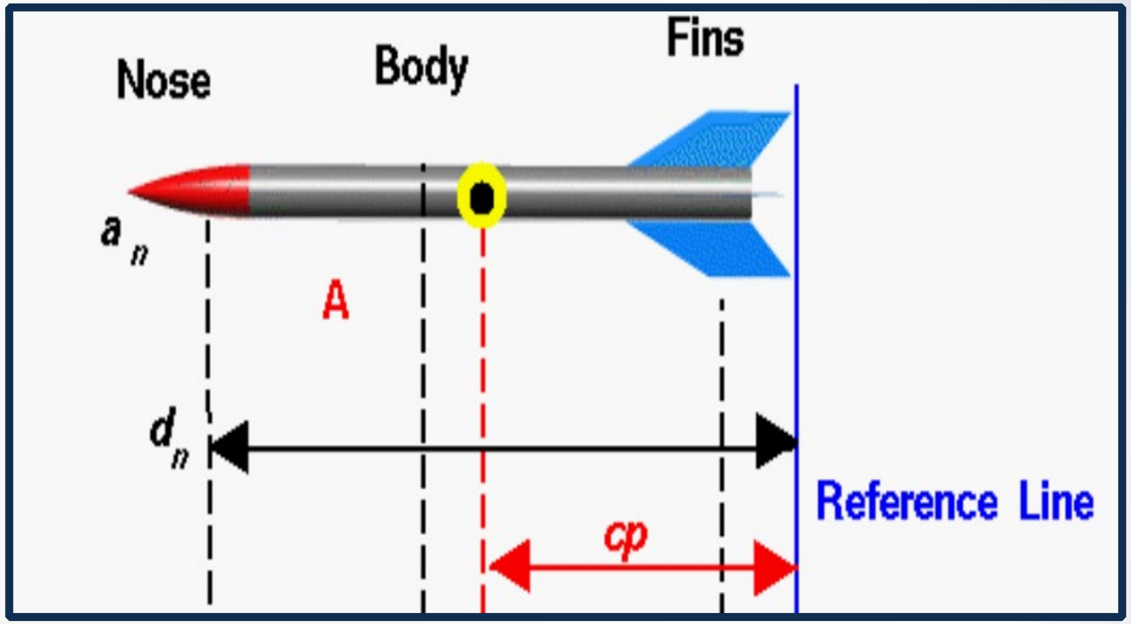


- **Purpose:** Minimize drag, maximize stability
- **Design:** Area rule, swept surfaces, Cg < Cp
- **Specs:**
  - From Nose: Cp = 11.1cm, Cg = 11.0cm,
    - with ballast Cg = 10.5cm = stable
  - cD of 0.25 was calculated via CFD

P5.1.1	P - Pods under 600 grams	✓
P5.1.2	P - Pods <9cm diameter	
P5.4.6	P - Pods shall be stable to promote range and impact orientation	

Pod Structural Design: Aerodynamics

- Purpose:
  - Minimize aerodynamic drag
  - Maximize aerodynamic stability
- Design:
  - Cp is behind the Cg, aerodynamic stability is achieved
  - Minimizing drag: area rule, sweeping fins, and minimizing area
  - Fins also provide spin stability



$$cp\,A = d_n a_n + d_b a_b + d_f a_f$$

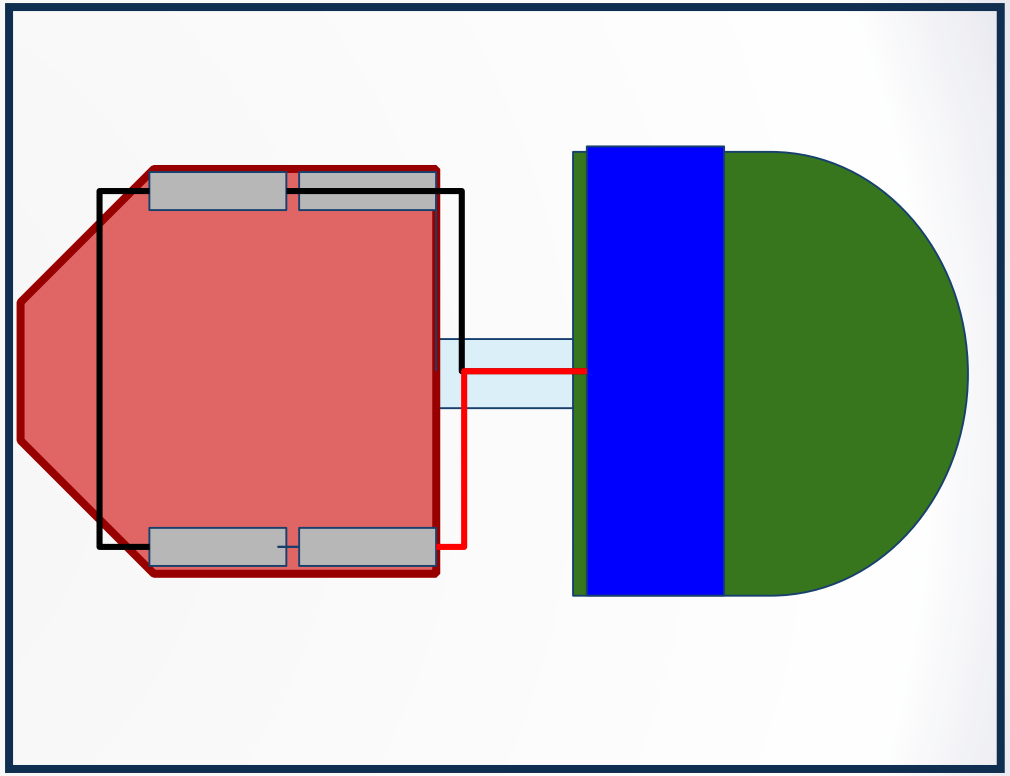
Simplified cP calculation, validated via CFD

- Specs:
  - From Nose: Cp = 11.1cm, Cg = 11.0cm, **with ballast Cg = 10.5cm = stable**
  - A cD of 0.25 was calculated via CFD

P5.4.6	P - Pods shall be stable to promote range and impact orientation	✓

Pod Structural Design: Power Connect.

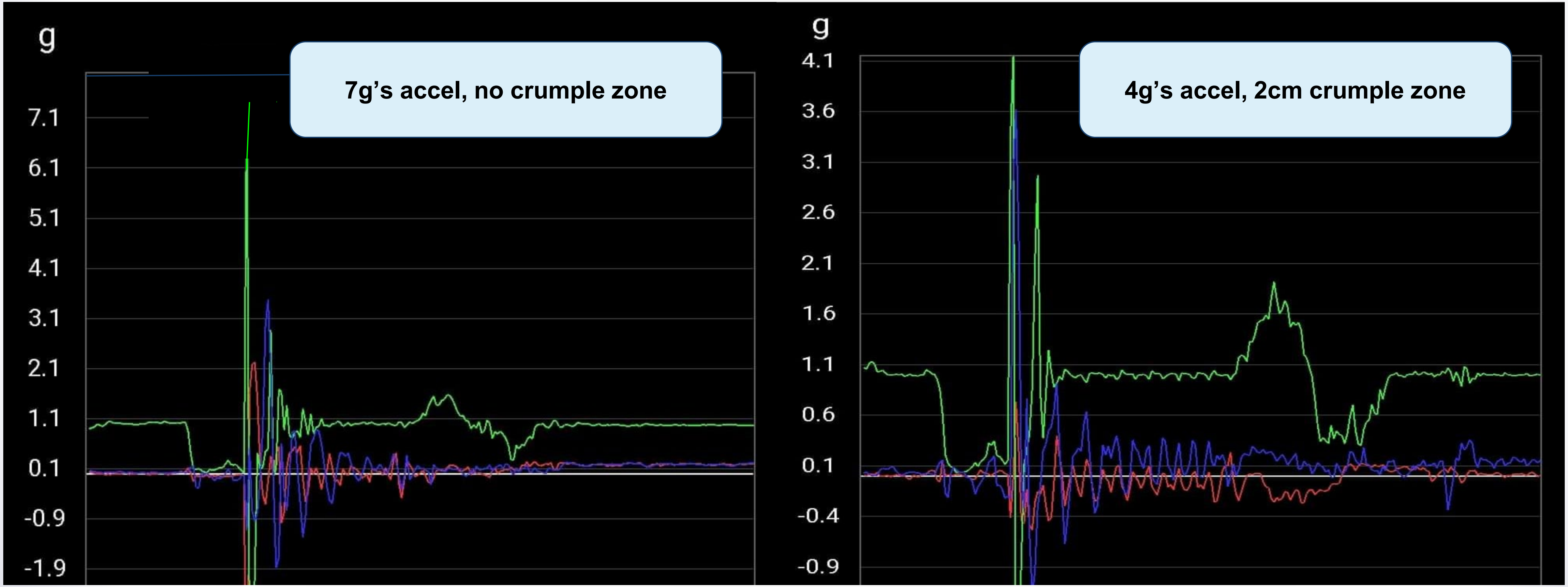
- Purpose:
  - Secure batteries, connect them to board securely
- Design:
  - Spring tension on batteries to maintain connection
  - Hot-swappable from end of tail
  - Twisted pairs to prevent signal interference
- Specs:
  - 3 AAA in series (4 avail but unneeded)
  - 1100 mAh
  - 3.6V



Wiring diagram

Pod Structural Design: Crumple Zone

- **Real:** Drop Test 2m/s



Decreases acceleration by factor of 2

C: Pod Deployment

DRAGON

Deployment Module: Budgets

Component	Power Draw [W]	Duration [minutes]	Energy [Watt minutes]
24V Compression Motor	33.6	1.72	0.97
Nema 23 Stepper Motor	5.7	5	12.83
Nema 17 Stepper Motors (x2)	5	40	3.33
Sensors (Photo interrupter, etc.)	0.5	20	0.17

Total: 19.21kg

Total: 20.63 watt hour

Component	Weight (kg)
Pods	5
Motors	1.86
Gears (1018 Carbon steel)	2.36
Base Plates and Lazy Susan (Polycarbonate and Aluminum)	5.4
Barrel and Funnel (Polycarbonate)	1.25
Launch Plate and Rack (6061 Aluminum)	0.25
Base Support (6061 Aluminum)	0.8
Reloading Material	0.9
Spring	0.39
Binding Materials	1

Total: 19.21kg

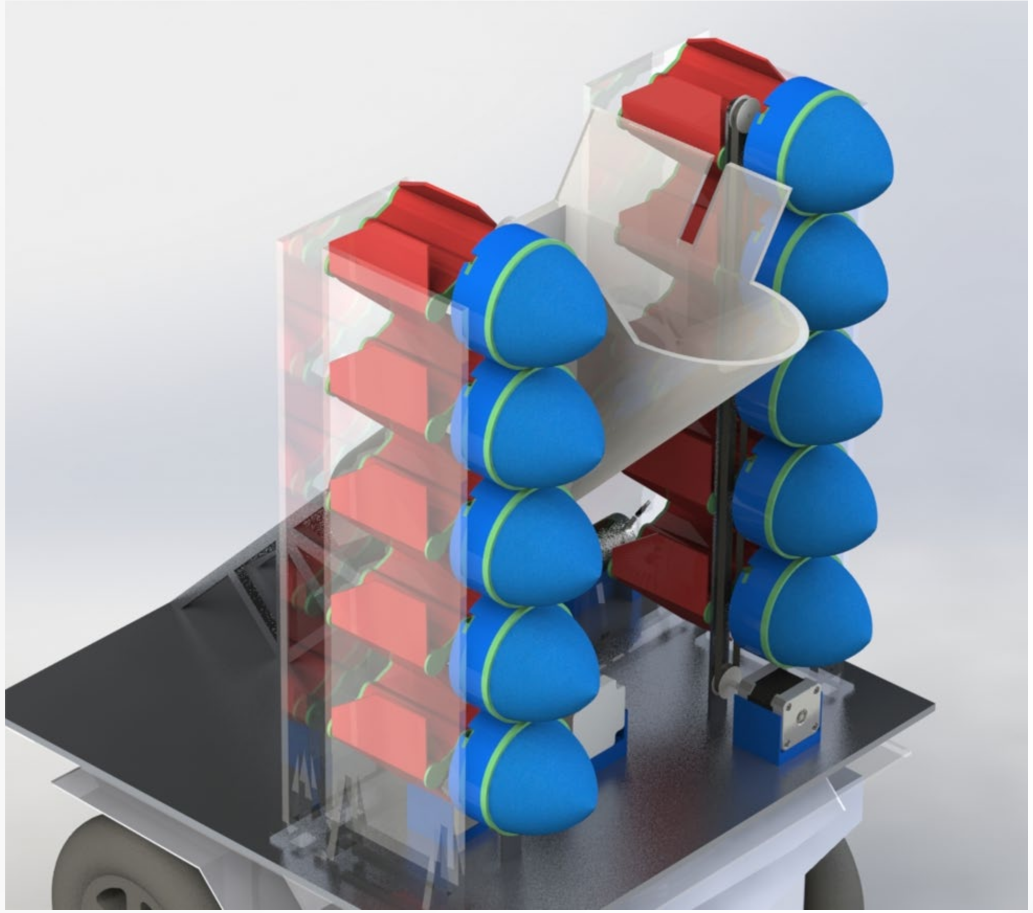
D4.1.2	Module and pods shall weigh less than 20kg together	✓
D8.3.1	Deployment module shall be compatible with provided onboard power (270 watt hour)	✓

Manufacturing

Component	Material	Process	Allotted Time
Cannon Barrel	Plexiglass/Acrylic	Band Saw	2 days
Plates (Mounting, base, support structure, etc.)	Plexiglass/Acrylic , Aluminum	Band Saw	1 week
Rack	Aluminum	CNC	1 day
Reloading Support	Aluminum		2 days
Spring Cannon Base Support	Aluminum	CNC	1 week
Motor Mounts	Acrylic?		1 day
Funnel	Acrylic		1 week
Launch Plate	Aluminum	CNC	1 day

Deployment Module Design: Reloading Mechanism

- Purpose:
  - Feed pods into the cannon barrel
- Design:
  - Twin NEMA 17 stepper motor
  - Timing belt, conveyor system
- Specs:
  - Loading time: 5 seconds
  - Maximum Power Draw: 5W



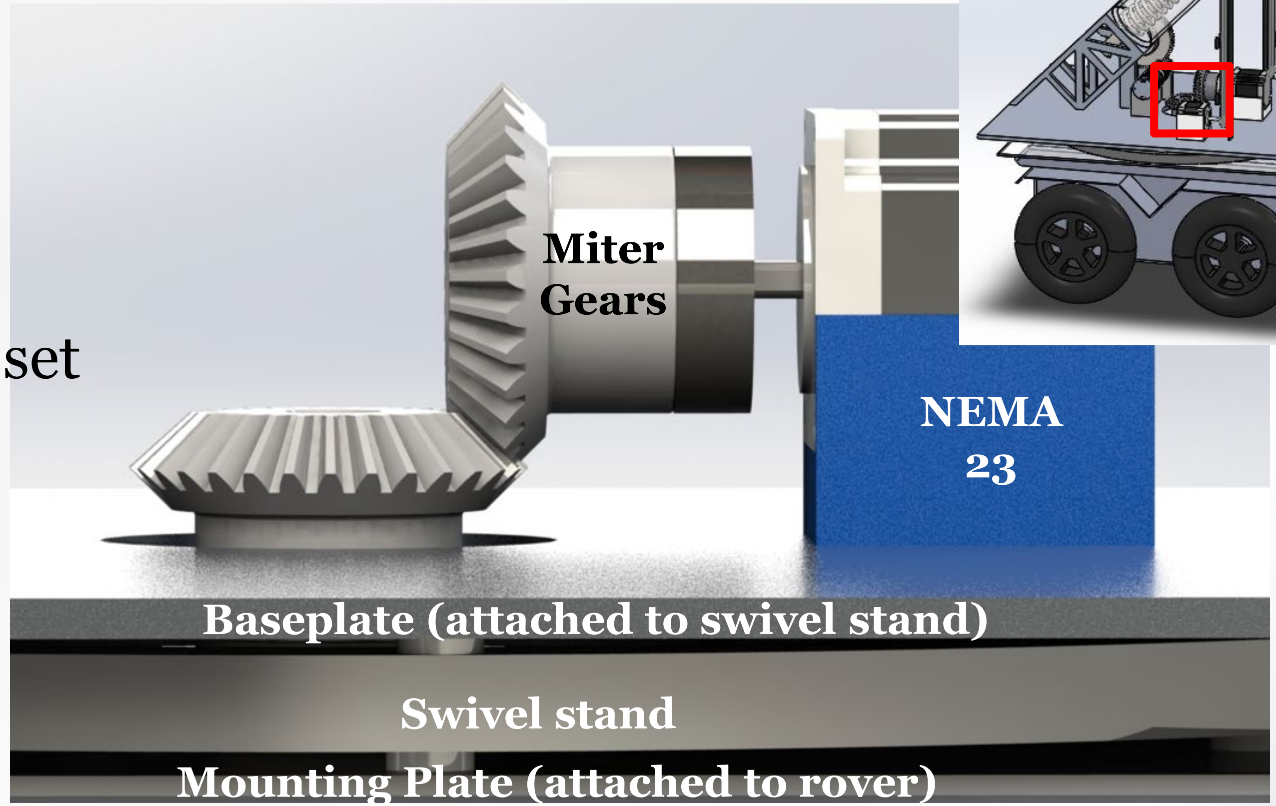
Reloading Mechanism: Funnel

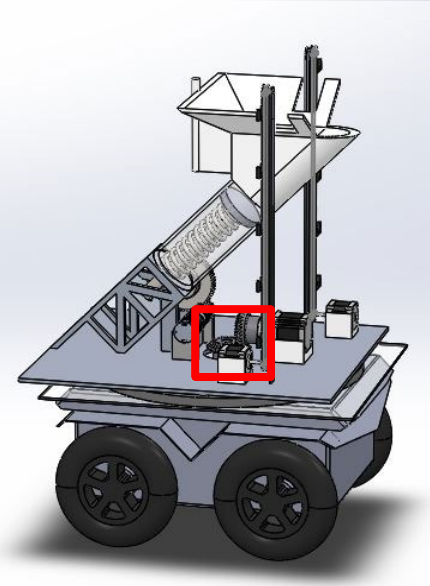
D3.5.1	DM shall be capable of reloading and deploying a new pod every 2 minutes	

- Test: Do pods jam? If so, when?
- Results:
  - If pods are oriented properly, no jamming occurs and they slide tail first into tube
  - Jams if:
    - Fin catches on ramp
    - Fin catches on top of barrel
  - **Mitigation**: Arm holding pod releases pod above edge of ramp, also moved forward on ramp

Deployment Module Design: Azimuth Control

- Purpose:
  - Rotate the cannon from -140° to 140° relative to rover
- Design:
  - Rotating base plate mounted to a swivel stand
  - NEMA 23 motor drives a bevel gear set
  - Photo interrupter used to reset step count
- Specs:
  - Pointing Accuracy: 12°
  - Maximum Power Draw: 5.7W





Azimuth Control

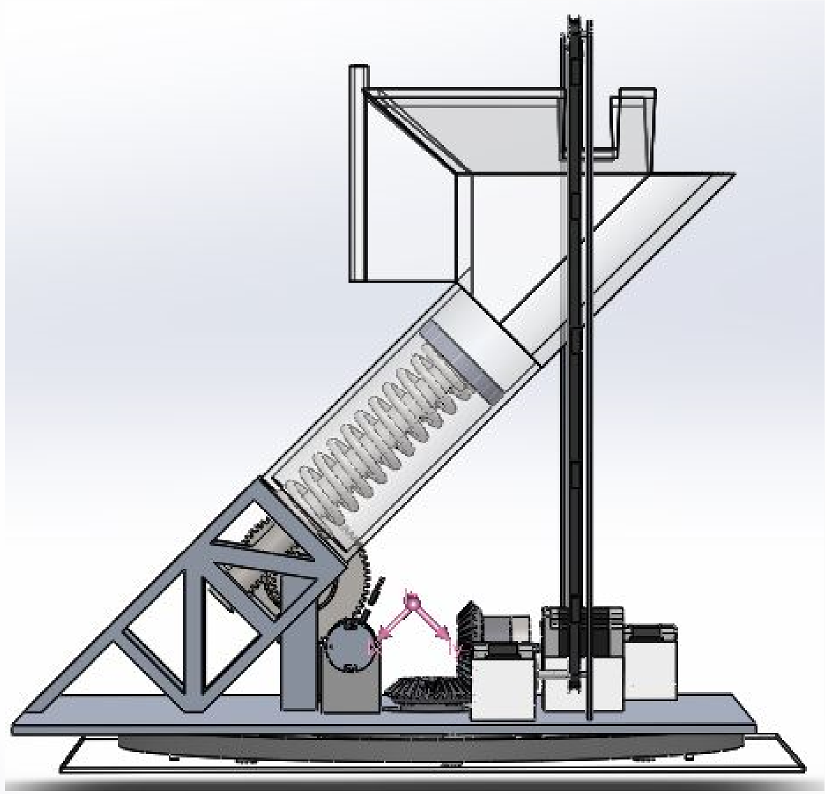
M3	The deployment mech shall have capability to deploy pods to software defined locations	✓

- Why?
  - Pods must be placed at locations that will not always be in line with the rover's direction of travel
- Designs Driven:
  - Allows for one stationary hub with the cannon and reloading mechanism rotating around the center gear
- Demonstration Method:
  - Lazy susan used to minimize torque requirement needed to rotate the base plate

Reloading Mechanism: Center of Mass

D4.1.1	DM and mounting interface shall not modify Jackal's center of gravity to a point where it cannot sustain 30 degree slope in any orientation.	✓

CG Location without Pods

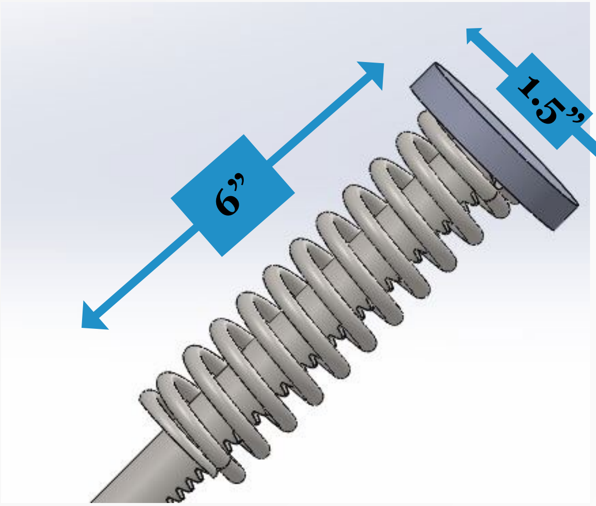


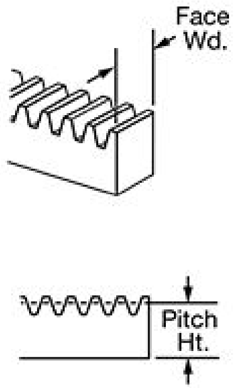
CG Location without Pods

Spring Compression Device

Constraints for the rack and launch plate:

- Mass **[250g]**
- Spring inner diameter
- Beam deflection
- Tensile Stress





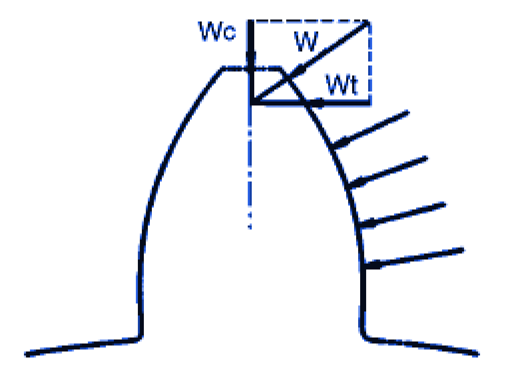
Design Parameters

- Pitch height
- Face width
- Length

Spring Compression Device

Tensile Stress Calculations

$$\sigma_t = \frac{W_t P_d}{FY}$$



- Wt is the tangential load [lbs]
- Pd is the diametral pitch [in^{-1}]
- F is the face width [in]
- Y is the Lewis form factor (dimensionless)

Mass/Volume Constraint Calculations

$$w = \frac{m}{\rho l h}$$

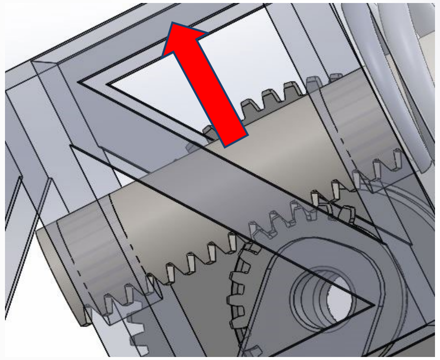
- m is the maximum allowable mass
- ρ is the density [lbs/in^3]
- l and h are length and pitch height respectively [in]

Beam Deflection Calculations

$$I = \frac{1}{12} w h^3$$

- I is moment of inertia [in⁴]
- w is face width
- h is diametic height

$$\sigma_b = \frac{F_R l^3}{3EI}$$

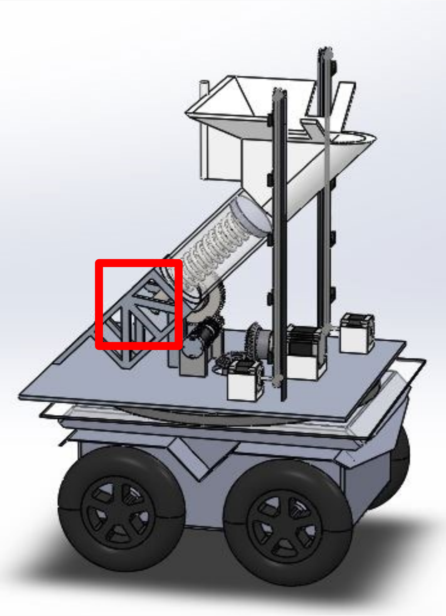


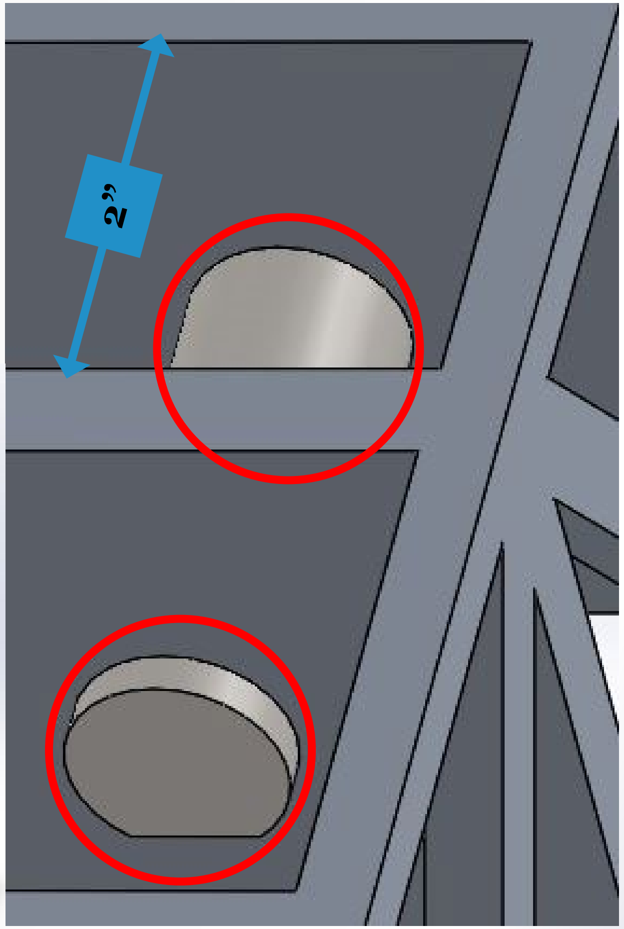
- σb is beam deflection (constrained to 0.01 [in])
- FR is radial load
- l is length [in]
- E is the Young's modulus [psi]

Rearrange to solve for deflection as a function of face width and height

Deployment Module Design: Rack Support

- Purpose:
  - Guide rack during compression and decompression
- Design:
  - Two linear ball bearings
  - Support beam to prevent beam deflection
- Specs:
  - Maximum dynamic load: 353lbs
  - ID Tolerance: +/-.0004
  - Steady state speed: 83.3 in/sec





Deployment Module: Safety

- Why:
  - Prevent unwanted deployment, safely store the rover, indicate safe state to approach rover
- Designs Driven:
  - Multiple safety inhibits
  - Lights to indicate safety state
  - Defined states with corresponding safety procedures

Inhibit Type	Description
Mechanical	Pin to keep baseplate from rotating (also used for storage)
Electrical	Prevents motors from moving (remove before flight pin)
Remote Kill Switch	PS4 controller to send kill command to rover (COHRINT provided)

Indicator Type	Description
Green Light	Safe state to approach rover
Red Light	Unsafe state to approach rover, corresponding to State 1-3

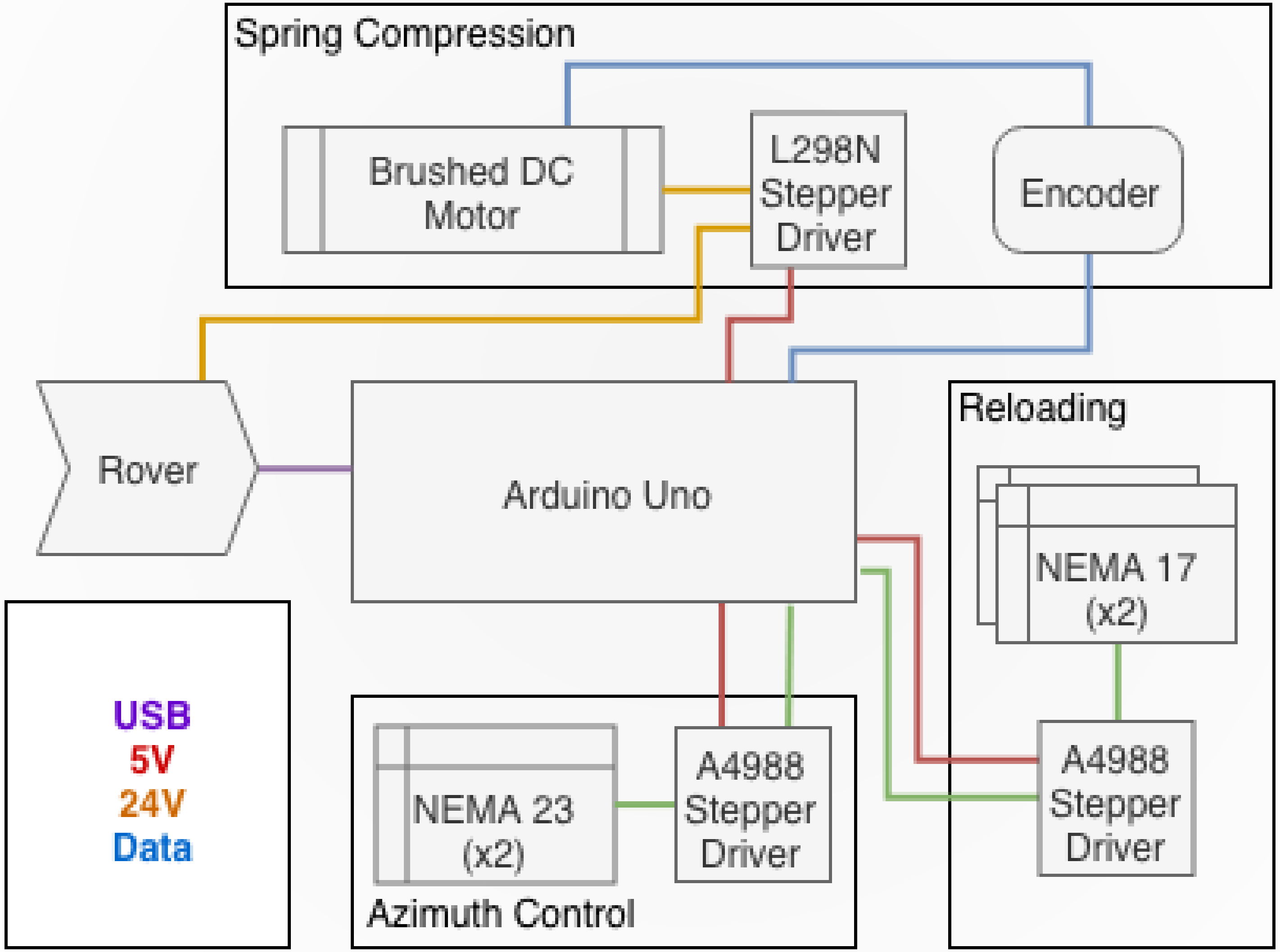
D4.4	DM shall have a remote safety inhibit, such as an arm/disarm, to enable safe approach to rover.	✓

Deployment Module: Safety States

State	**Description**	Steps to abort	Notes
1	Pod in tube, electrical inhibit OUT, spring **compressing**	1) Send software stop 2) Send software command to reverse motor direction 3) Proceed from State 2.2	Front of rover clear at all times. Red light ON
2	**Pod in tube**, electrical inhibit OUT, spring uncompressed	1) Send software stop 2) Place electrical inhibit IN 3) Remove pod from tube	Front of rover clear until after step 2. Red light ON
3	No pod in tube, electrical inhibit **OUT**, spring uncompressed	1) Place electrical inhibit IN	Red light ON
4	No pod in tube, electrical inhibit IN, spring uncompressed	None	Safe state to transport rover and upload MIP. Green light ON

*Azimuth control occurs between State 1 and 2. State 2 is considered fire-ready and full range safety measures are to be in place.

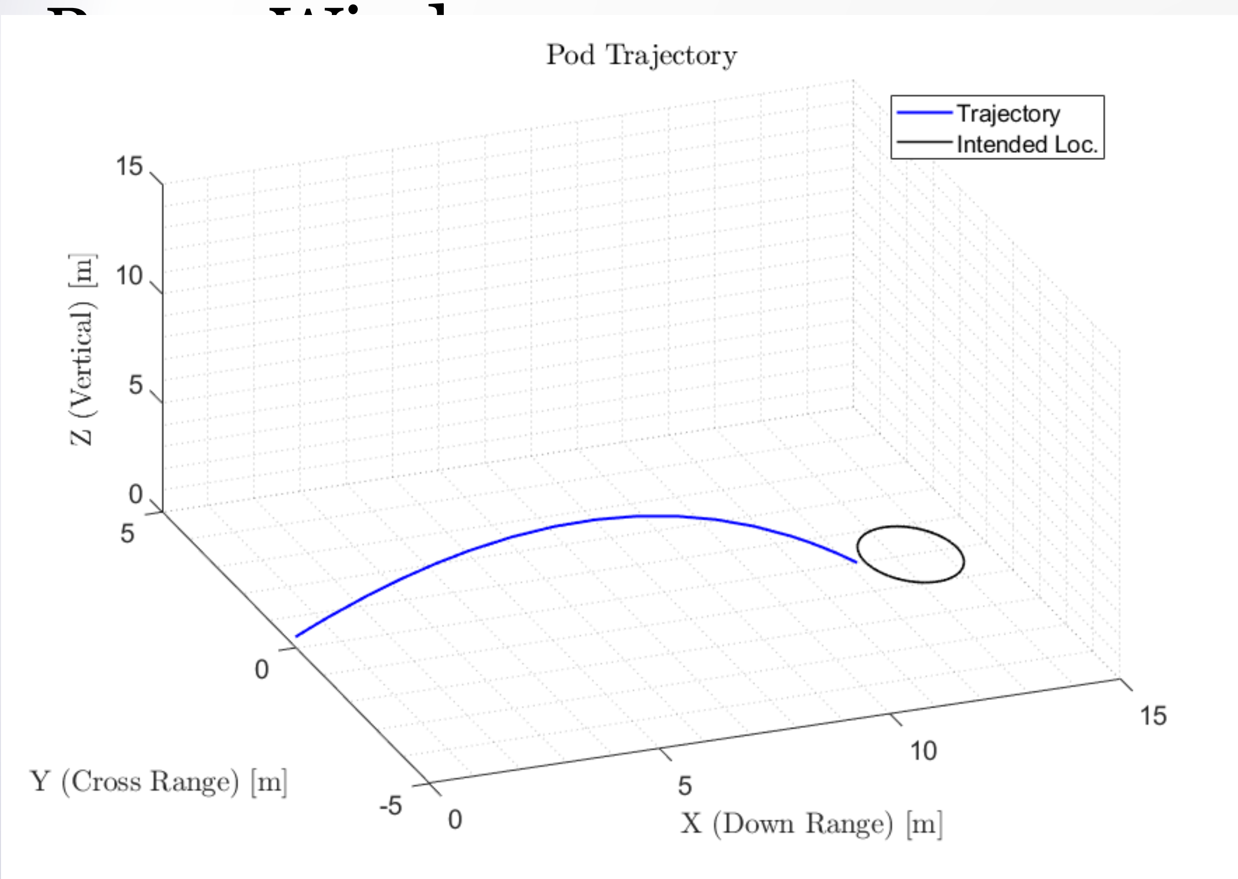
Deployment Module Design: Electronics

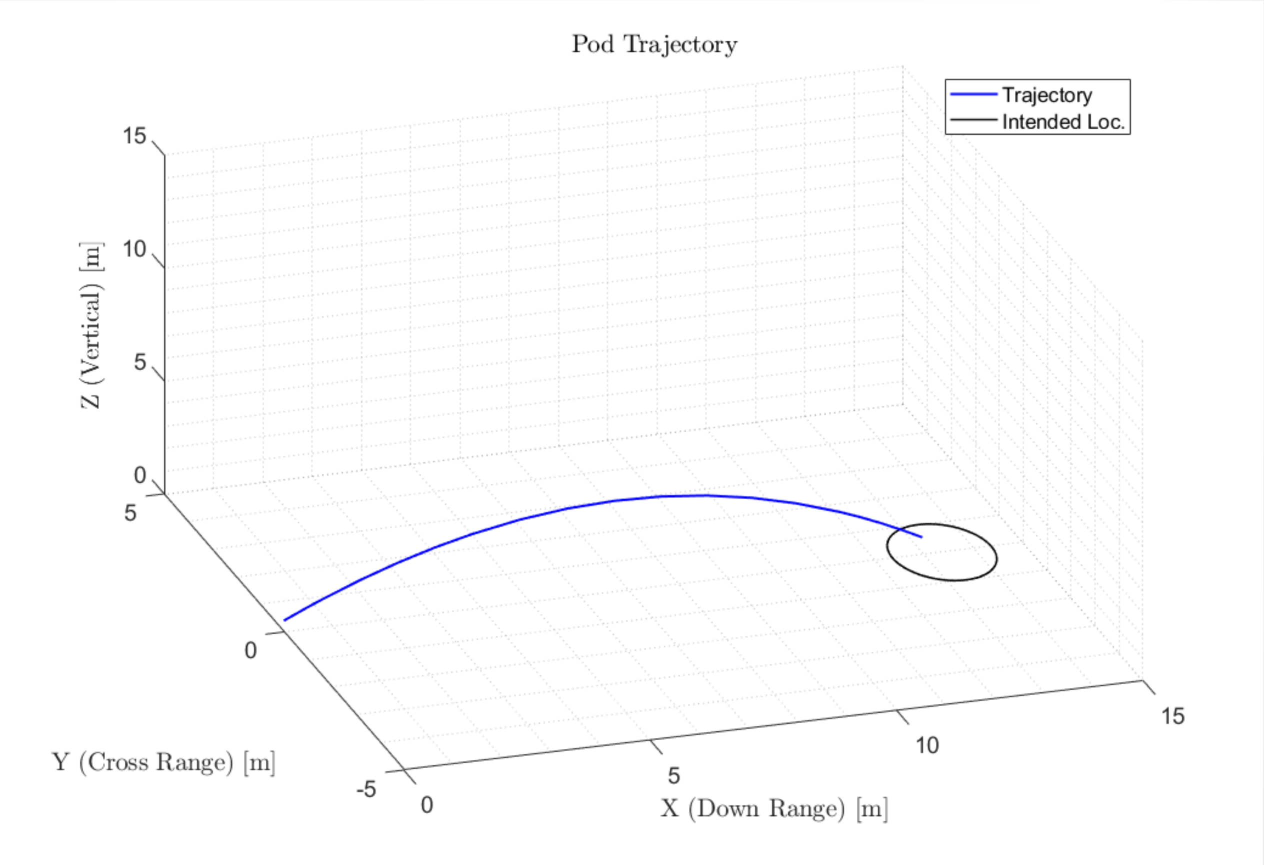


5 m/s of Wind (11.2 mph)

Opposing the Pod Trajectory

Cross

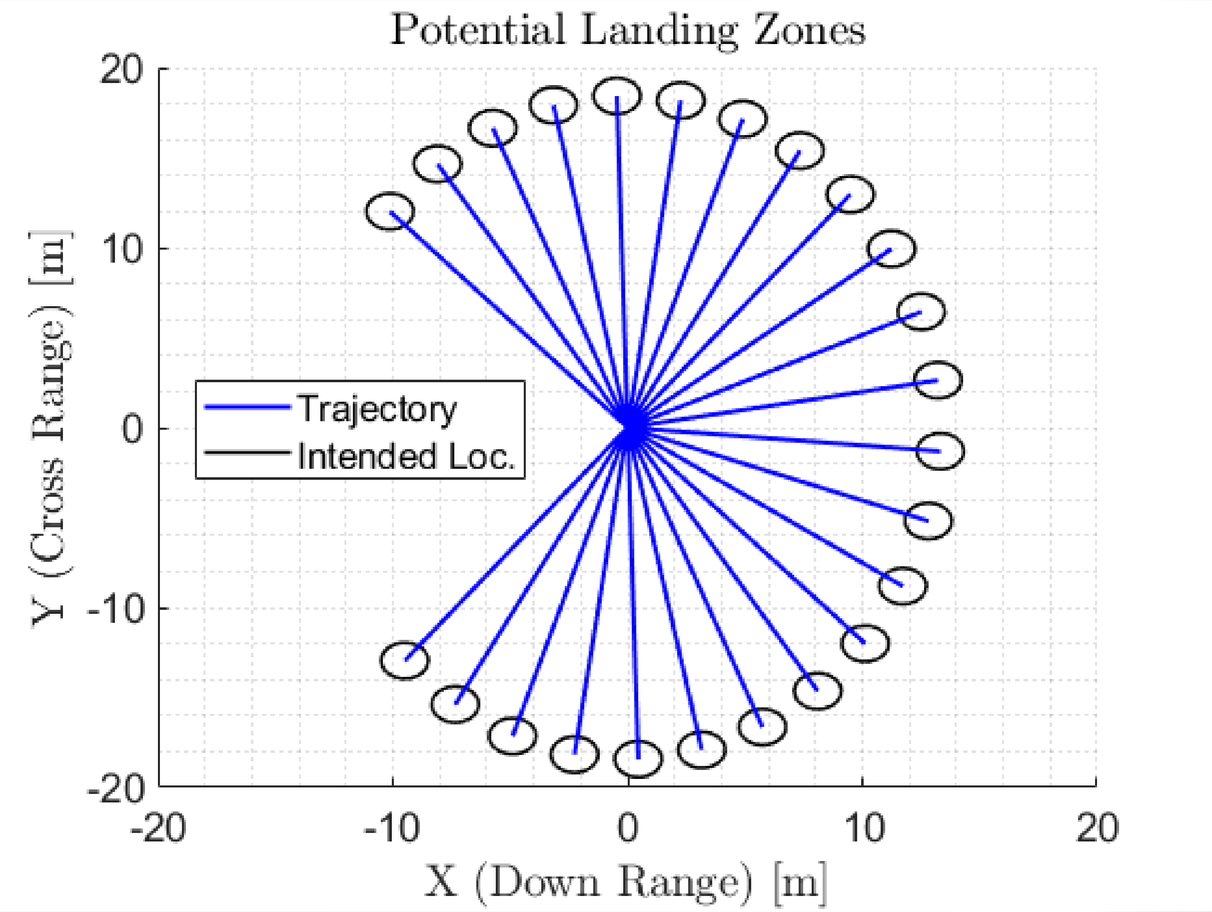




Pod Trajectories

Worst case: 12° azimuthal accuracy

- Discretized angles for launching



D: Risk Backup

Risk Descriptions

ID	Description
2	Mass too high
3	Antenna interference
6	Recoil forces
8	Potting material interference
9	Software development integration
10	Networking/Comm development

		Consequence				
		1	2	3	4	5
Likelihood	5				5	7
	4				1,9	4
	3			6	3,8	
	2					10
	1					2

ID	Description	Mitigation:
1	Electronics damage from deployment	- Compounding multiple methods for impact dampening - Drop tests have been performed to demonstrate survivability with some of the selected electronics.
4	Reloading jam or electrical complications	- Prototype built for demonstration. - Considerations included in design to provide a remote kill switch
5	Deployment unable to reach max range	- Significant range margin included in design which should surmount unanticipated parasitic forces. - Modelling efforts do have high fidelity and scaled testing.
7	PCB rev delays in schedule	- PCB boards have been designed and first rev printed pre-cdr - Testing commencing and expect to send 2nd rev before Dec 20 2018

Risk Matrix: Mitigation Results:

Pre-Mitigation

		Consequence				
		1	2	3	4	5
Likelihood	5				5	7
	4				1,9	4
	3			6	3,8	
	2					10
	1					2

Post-Mitigation

		Consequence				
		1	2	3	4	5
Likelihood	5			5		
	4					
	3				1	
	2			3,7	9	4
	1		6	2,10	8	

See Appendix D for mitigation plan of all risks

Risk Descriptions

Subsystem	ID	Rank: (L,C)	Description	Details
Pod Structure	1	4,4	Electronics damage from deployment	Electronics damage due to launch/impact acceleration will prohibit functionality
Pod Structure	2	1,5	Mass too high	Mass budget exceedance will inhibit max deployment distance
Pod Structure	3	3,4	Antenna interference	Antenna interference due to env. or pod structure could severely limit functionality and increase error
Deployment	4	4,5	Reloading jam or electrical complications	Reloading is a process which must succeed 10x in every mission, jamming or electronics complications can prevent every subsequent deployment
Deployment	5	5,4	Deployment unable to reach max range	Parasitic forces on deployment are difficult to predict. Current models account for many of them such as drag, friction, dead weight, but likely not all. An underestimate or misconception of the parasitic forces during deployment will lower range.
Deployment	6	3,3	Recoil forces	Recoil forces during launch may negatively impact the rover, by tipping or by unduly stressing the mounting fixtures of the cannon to the rover.
Pod Electronics	7	5,5	PCB rev delays in schedule	PCBs are known to take more revisions than expected, which can cause hardware damage, schedule slip, and stagnation of other subsystem progress.
Pod Electronics	8	3,4	Potting material interference	Potting material applied to the electronics boards can impact performance due to overheating, sensor blockage, and by limiting access to board level components.
Navigation SW	9	4,4	Disparate software development integration	Multiple methods of error reduction are being developed, integration of multiple methods can result in software that is complex, cumbersome, and difficult to diagnose.
Pod SW	10	2,5	Networking/Comm development	A complex mesh network and communication protocol must be developed to support localization

Risk Mitigation: Highest Risks Only

Subsystem	ID	Description	Effect	Mitigation
Pod Structure	1	Electronics damage during launch or landing	Ranging functionality failure, pod is unusable for localization	Compounding three methods for impact dampening is expected to be beyond sufficient, moreover, drop tests have been performed to demonstrate survivability with some of the selected electronics.
Deployment	4	Reloading: Jamming or difficulties in control	Failure to deploy, potentially unsafe stored energy, unexpected deployment	Prototype built for demonstration. Considerations included in design to provide a remote kill switch, and de-tension procedure for stored energy. Tube is clear so observers can monitor and kill a jam.
Deployment	5	Unmodeled parasitic forces reduce range	Limited range has a substantially negative impact on localization accuracy	Significant range margin included in design which should surmount unanticipated parasitic forces. Modelling efforts do have high fidelity and have already lead to several design changes.
Pod Electronics	7	PCB rev delays in schedule	Delay in electronics testing or development, impact other subsystems	PCB boards have been designed and first rev printed pre-cdr, testing commencing presently and expect to send 2nd rev before Dec 20 2018
Navigation Software	9	Combination of multiple error reduction methods	Complex, cumbersome, slow execution software product	Multiple error reduction methods have already been developed independently and are well understood. This provides additional integration time, and proves individual methods function correctly, thus the combination of all methods will be efficient and effective.

Risk Mitigation: Lower Risks

Subsystem	ID	Description	Effect	Mitigation
Pod Electronics	2	Mass too high	Mass budget exceedance will inhibit maximum range possible	A high-fidelity solidworks model was constructed and studied using the correct expected mass properties. Shows 80g of margin.
Pod Electronics	3	Antenna Obstruction or Interference	Unreliable high error measurements with limited ability to detect	Tests were performed to characterize environmental effects, the open air test range (think business field) will not impact signal. Pod is constructed of benign plastics and bonding (limited metal hardware), batteries will interfere with signal and antenna pattern is understood.
Deployment	4	Reloading jam or electrical complications	Failure to deploy will interrupt mission and require human intervention	A rough physical model of the feed system was built and tested with a high fidelity model of the pod, it showed promising functionality and highlighted areas of concern to be revised.
Deployment	6	Recoil forces	Rover tips over or has other unintended dynamic responses	Measurements of rover CG and expected forces to impart showed that significant margin exists against tipping. Design consideration towards using an outrigger system serves as a solution thus nullifying this risk.
Pod Electronics	8	Potting material interference	Potting it may impact signal, trap heat, and limit observational/debug access.	Research on heritage systems for material selection indicates several non-conductive options. 3D printed 'pour mold' to be developed which will prevent potting material seeping into undesired areas.
Pod SW	10	Mesh Network/Comms	Missing lower levels of success	The required hardware was procured in advance and a preliminary demonstration of the mesh network (on pod hardware only) was performed

E: Testing Additional

Verification Plan

Piecewise Testing → Subsystem Testing → Integration Testing → Full System Testing

Piecewise testing has been in progress for some time now. This type of testing consists of testing individual parts to prove their feasibility or functionality.

Tests performed pre-CDR

Pod Electronics: Test IDs: PT2, PT8

- 1 rover to 1 pod ranging: Demonstrated capability for pod electronics to communicate and range accurately.
- 1 rover to multi-pod ranging: Demonstrated capability for 'rover' to select which pod to communicate with.
- Mesh network ranging: Demonstrated the capability of rover-pod ranging, and rover-pod-pod ranging.

Deployment: Test IDs: DT2, DT5

- Test deployment range characterization: Demonstrates scale deployment model to reach correct (scaled) range.
- Pod drop testing of foam/potting: Demonstrates independent capability of suspension methods to protect elect.
- Pod reloading mechanism testing: Demonstrates pod into funnel without jamming, pod egress without jamming.

Navigation Software: Test IDs: NT10, NT1

- Software simulation of error propagation over time, incorporated minimization techniques and validated
- Rover path upload and follow using A* algorithm

Verification Plan

Piecewise Testing → **Subsystem Testing** → Integration Testing → Full System Testing

Subsystem tests consist of proving that all parts of a specific subsystem can combine and cooperate to function properly.

Pod Electronics New Rev Tests: Test ID PT7
- Receive and manufacture custom PCB with components, compare functionality to already functional non-custom hardware

Pod Power Draw Test: Test ID PT5
- With a near-flight-like electronics suite, characterize power draw over a simulated 2-hour mission duration

Deployment Safety Test: Test ID NT1,
- Demonstrate kill switch functionality, and decompression functionality.

Deployment Controls Test: Test ID DT4
- Demonstrate deployment mechanism can be installed to baseplate, and actuated via its microcontroller commands.

Deployment Range Test: Test ID DT2A
- Demonstrate using a mass-sim pod that the cannon can obtain the required range of +10m.
- This will also demonstrate pod structure's aerodynamic stability.

Pod Structure Test: Test ID PT2
- With 'Flight-like' pod manufactured, install latest-rev electronics into system, perform drop testing repeatedly and demonstrate board functionality pre/post each drop test.

Navigation Software Incorporation Test: Test ID NT7
- Using the pre-developed software simulation, test that error reduction methods functioning as intended and to the proper requirement levels even under worst case 3-sigma scenarios.
  - Push validation further by including monte-carlo test data and other non-optimal environmental factors.

Verification Plan

Piecewise Testing → Subsystem Testing → Integration Testing → Full System Testing

Integration Testing: The objective of integration testing is to demonstrate that subsystems have been successfully integrated together, and that all subsystems are functioning with the rover and overarching needs for mission success. They are defined based on key interfaces:

Navigation Software to Deployment: Test ID DT4

- Ensure that navigation software (on rover) can send data/commands to the deployment microcontroller (on cannon), demonstrate controlled deployment at specified attitude and that behavior is expected.

Deployment to Pod Structure: Test ID DT3, PT4

- Test deployment mechanism ability to reload and launch pods repeatedly. Test that any unexpected stresses on the pod do not damage internal electronics. Test robustness to jamming by moving rover throughout environment and inducing vibrations/off-nominal loading.

Navigation Software to Pod Electronics: Test ID FST3, FST4

- Test the interface which allows serial read/write commands between the rover and all pods on the network, demonstrate ability to collect ranging data from software-selected pods.

F: Budget Backup

Budget

*Notes:

- Budget based on estimated **12 pods + 4 pods for prototyping**
- Jackal Rover provided by customer