ASEN 4018 Senior Projects Fall 2017
Critical Design Review

RAVEN

Rover and Air Visual Environment Navigation

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Agenda

Purpose and Objectives	4	Ryan Wall, Rishab Gangopadhyay
Design Solution	7	Torfinn Johnsrud, Nikolas Setiawan, Alexander Swindell
Critical Project Elements	17	Alexander Swindell
Design Requirements	19	Nikolas Setiawan, Alexander Swindell, Torfinn Johnsrud, Rishab Gangopadhyay, Nathan Levigne
Risk Management	62	Rishab Gangopadhyay
Verification and Validation	64	Cody Charland
Project Planning	76	Ryan Wall

Project Purpose and Objectives

<u>Mission Statement:</u> RAVEN will develop a testbed that will collect image, position, and sensor data to be used by the customer for the verification of customer developed cooperative localization algorithms.

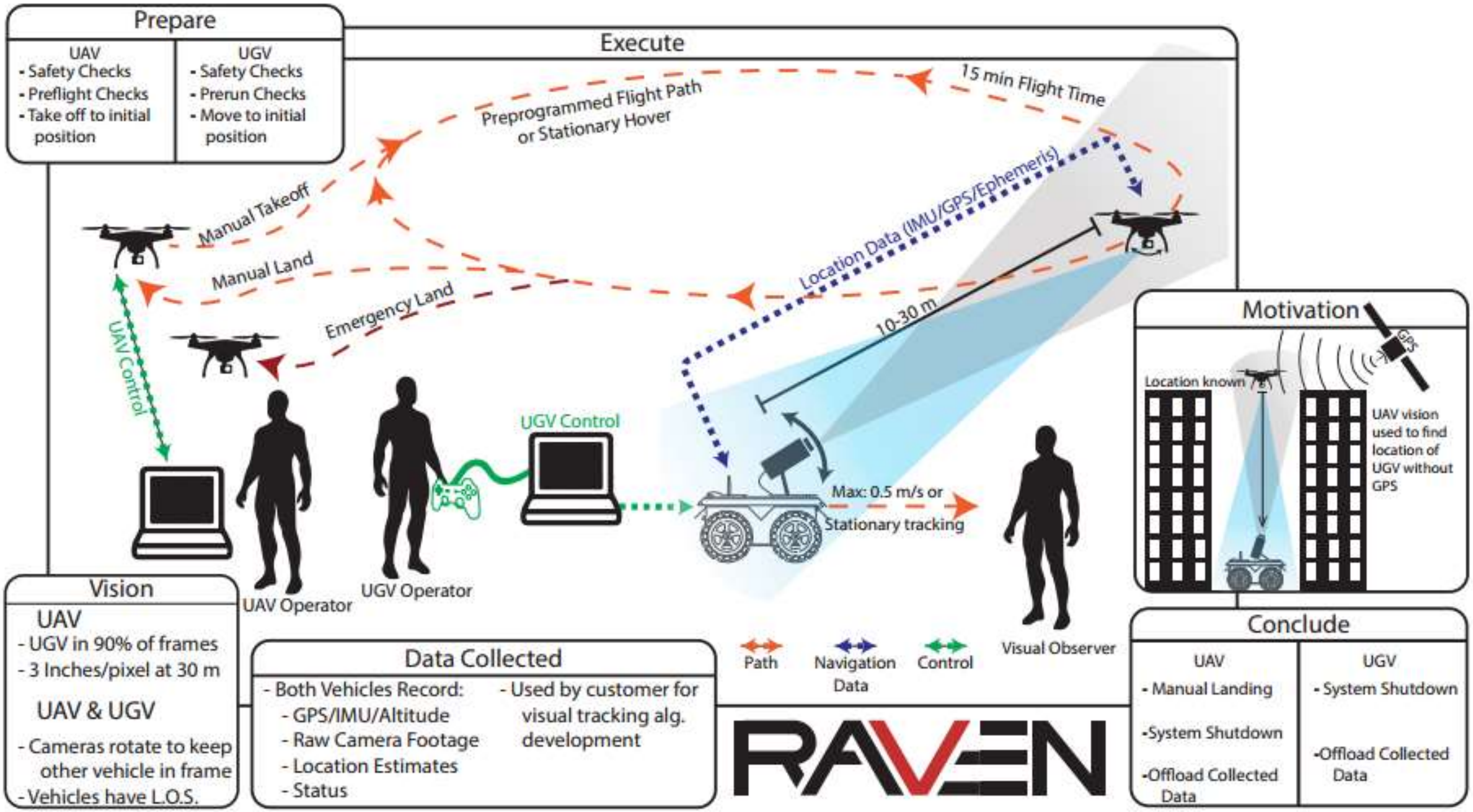
- Provide the customer with an **UAV and UGV** pair **testbed**.
- Record **image, position, and sensor** data.
- **Deliver** recorded information, including **collected GPS data**, and UAV/UGV pair to customer.

Motivation

- **Scenario:** Teams of humans and robots in a GPS-denied environment
- Localize team members without reliable GPS
- However, RAVEN will not be simulating a GPS-denied environment

Squad X concept, courtesy DARPA

Concept of Operations

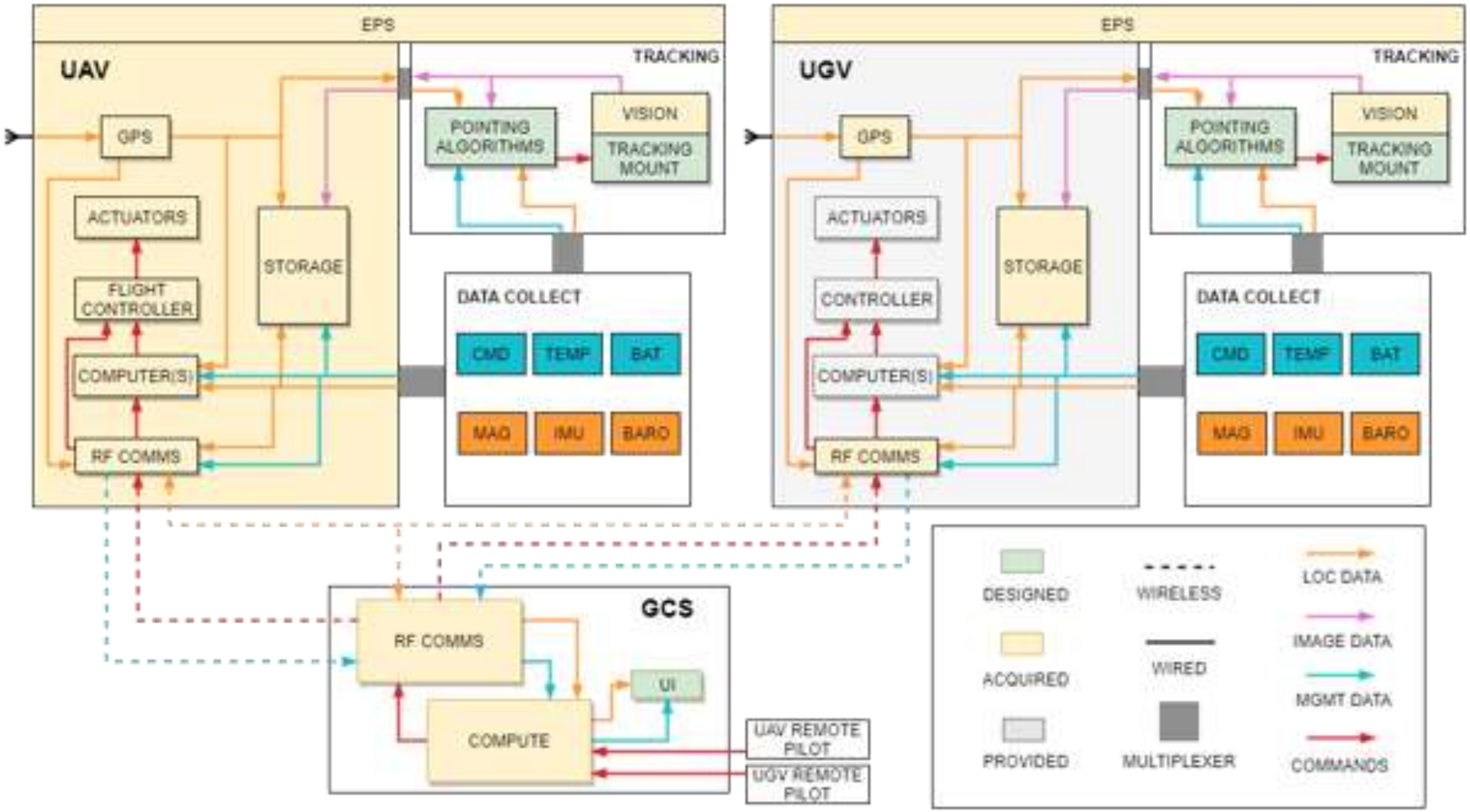


Functional Requirements

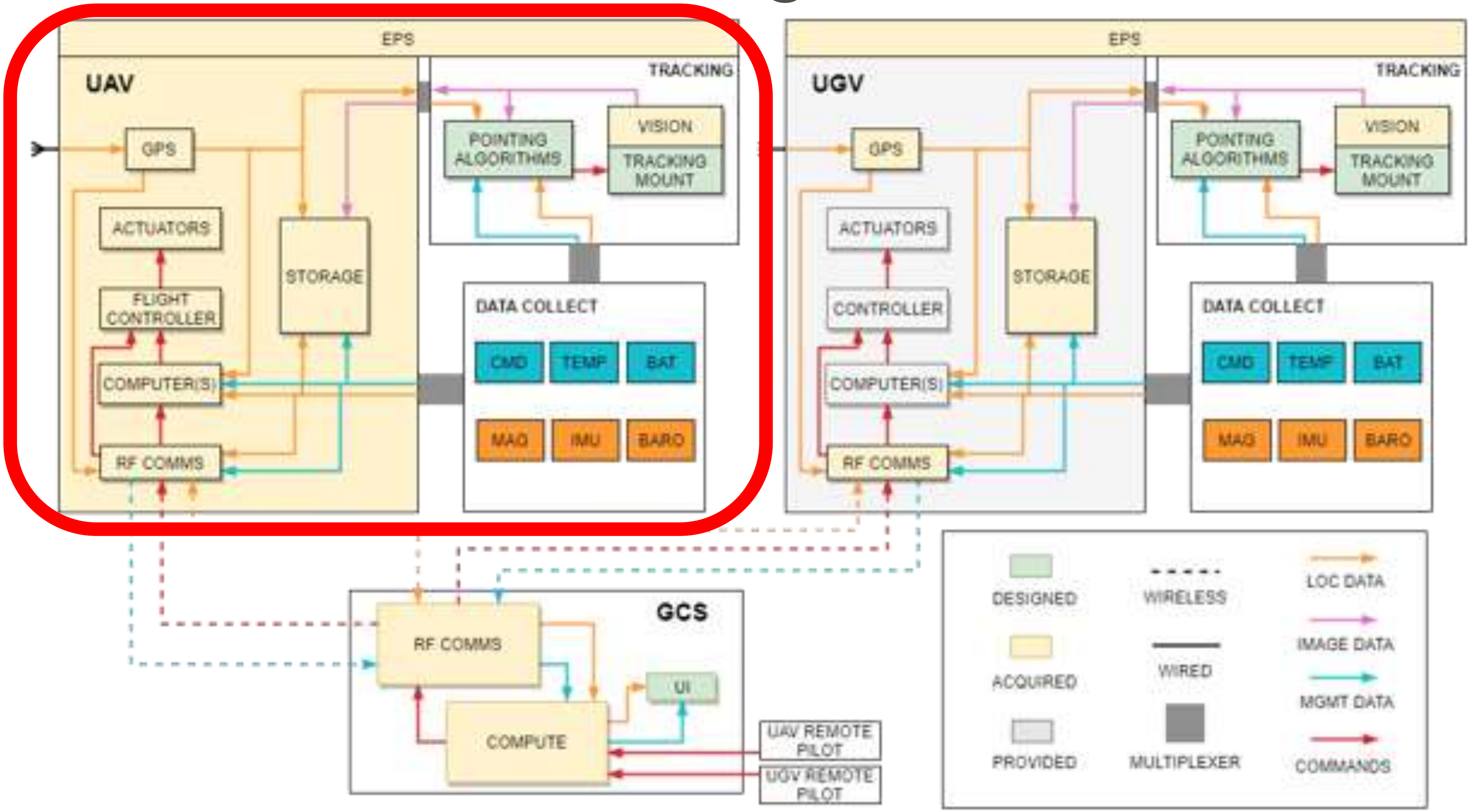
Functional Requirement	Description
FR 1.0	**RAVEN shall perform data collection for 15 minutes.**
FR 2.0	RAVEN shall have a removable data storage system on both the UAV and UGV.
FR 3.0	**UAV and UGV visual data shall contain the other vehicle in 90% of frames and shall not take more than three seconds of frame data without the other vehicle in frame.**
FR 4.0	**UAV & UGV visual data shall have a minimum resolution of 3 inches per pixel at a distance of 30 m.**
FR 5.0	RAVEN shall operate outside on a fair-weathered day (i.e., no wind, no precipitation).
FR 6.0	RAVEN shall comply with Army Memorandum (DAMO-AV).
FR 7.0	RAVEN shall utilize the customer-provided Clearpath Jackal UGV.
FR 8.0	**The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other.**
FR 9.0	**RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM Radio Frequency.**
FR 10.0	Vision system shall use customer specified interfaces.

Design Solution

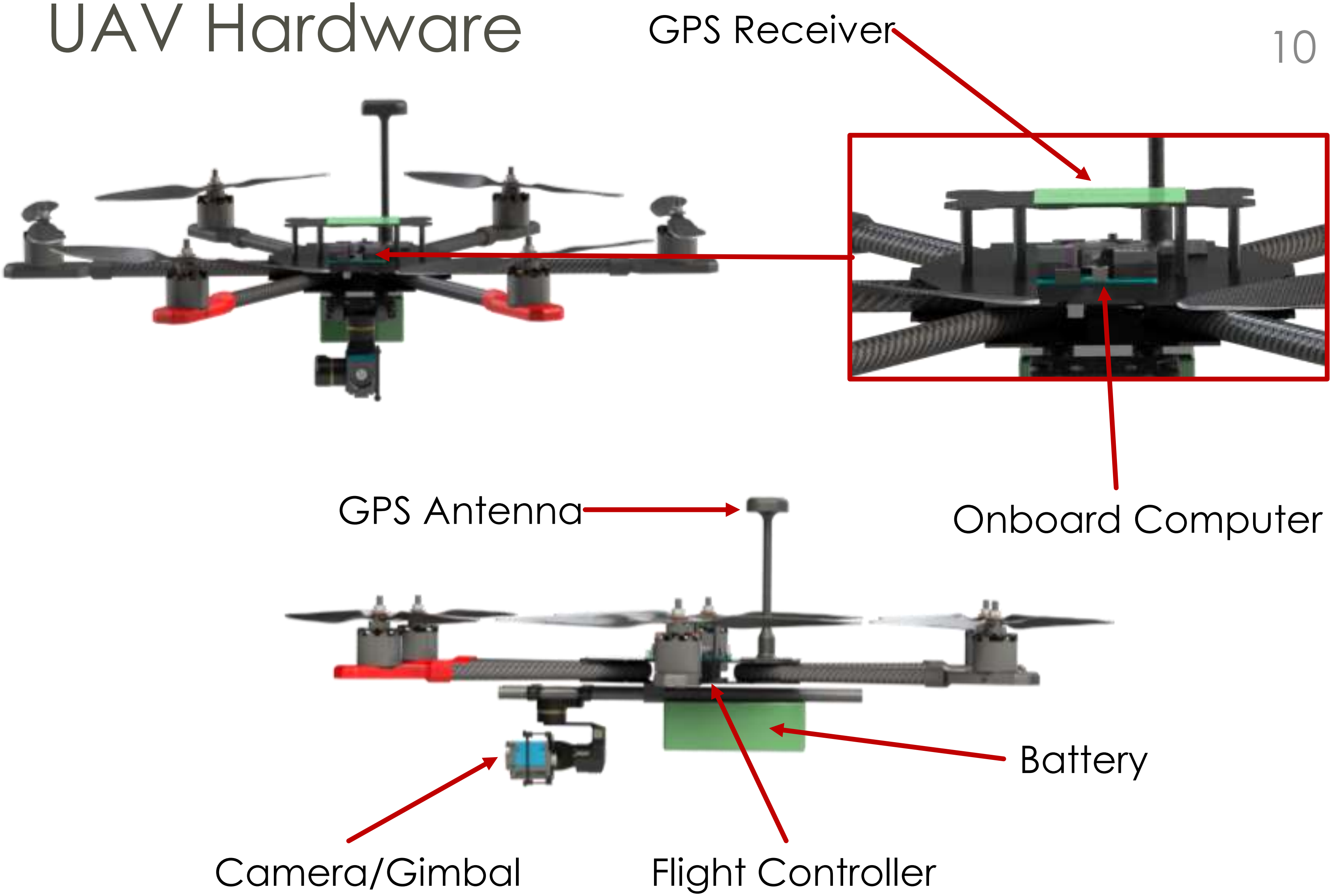
Functional Block Diagram



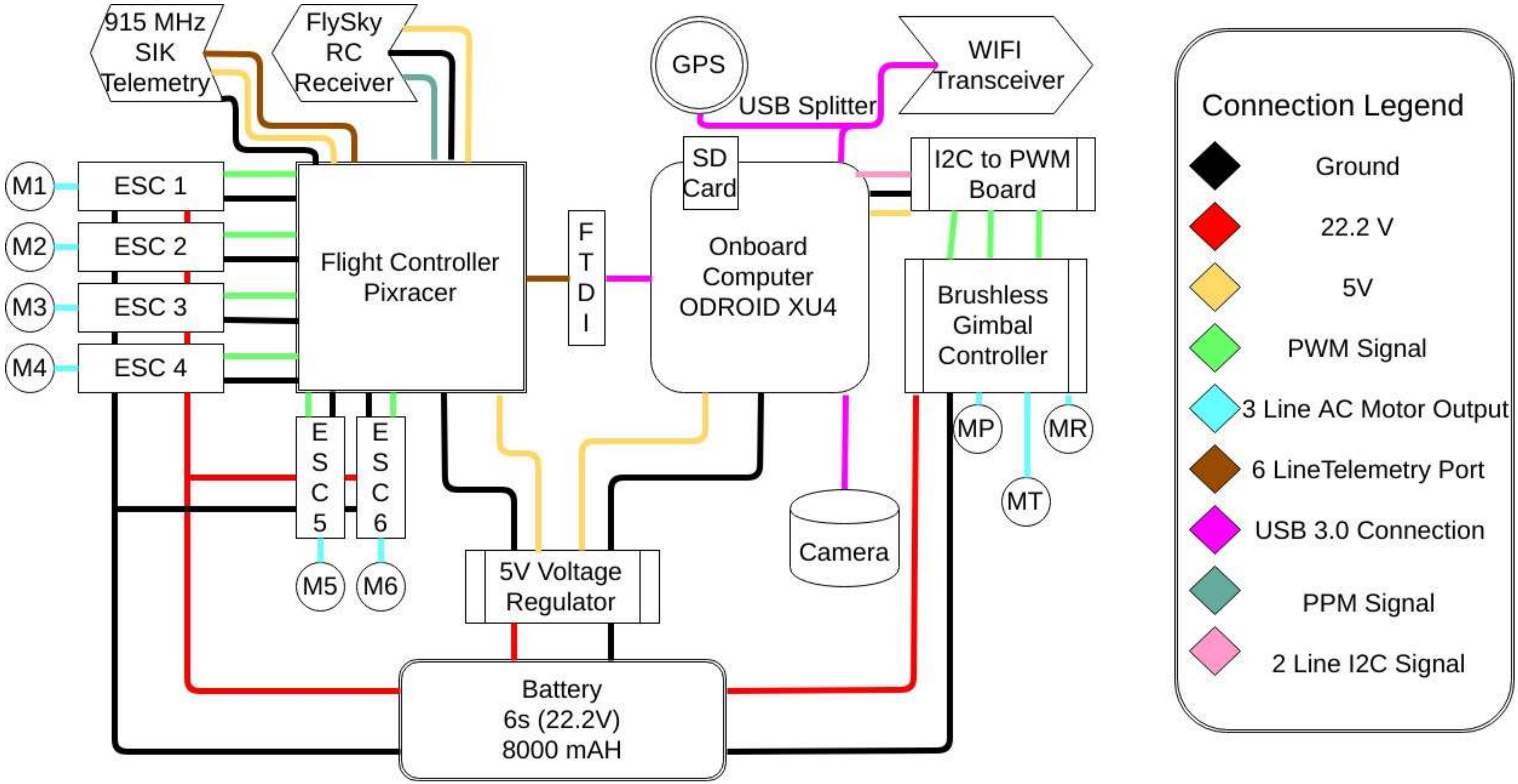
Functional Block Diagram



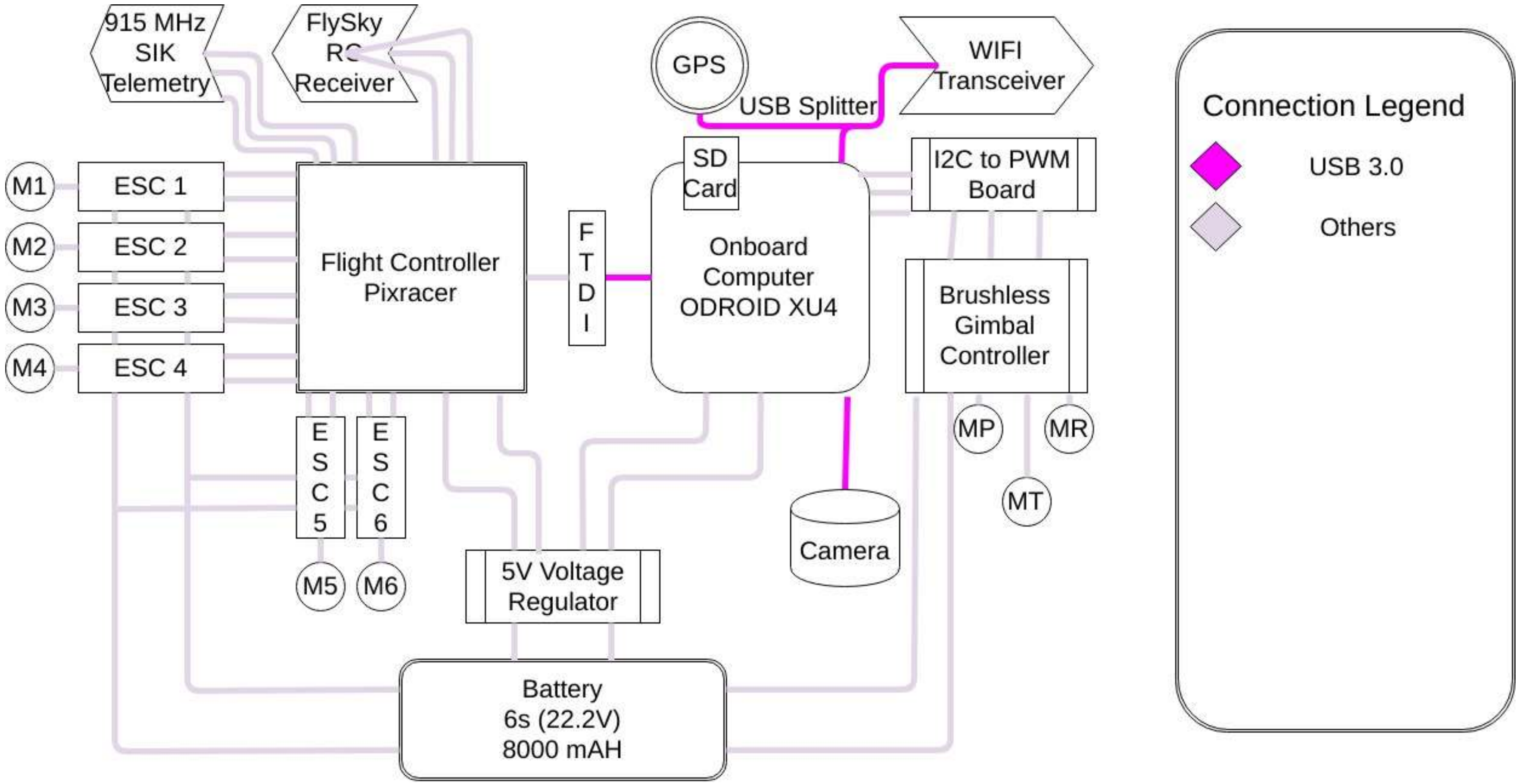
UAV Hardware



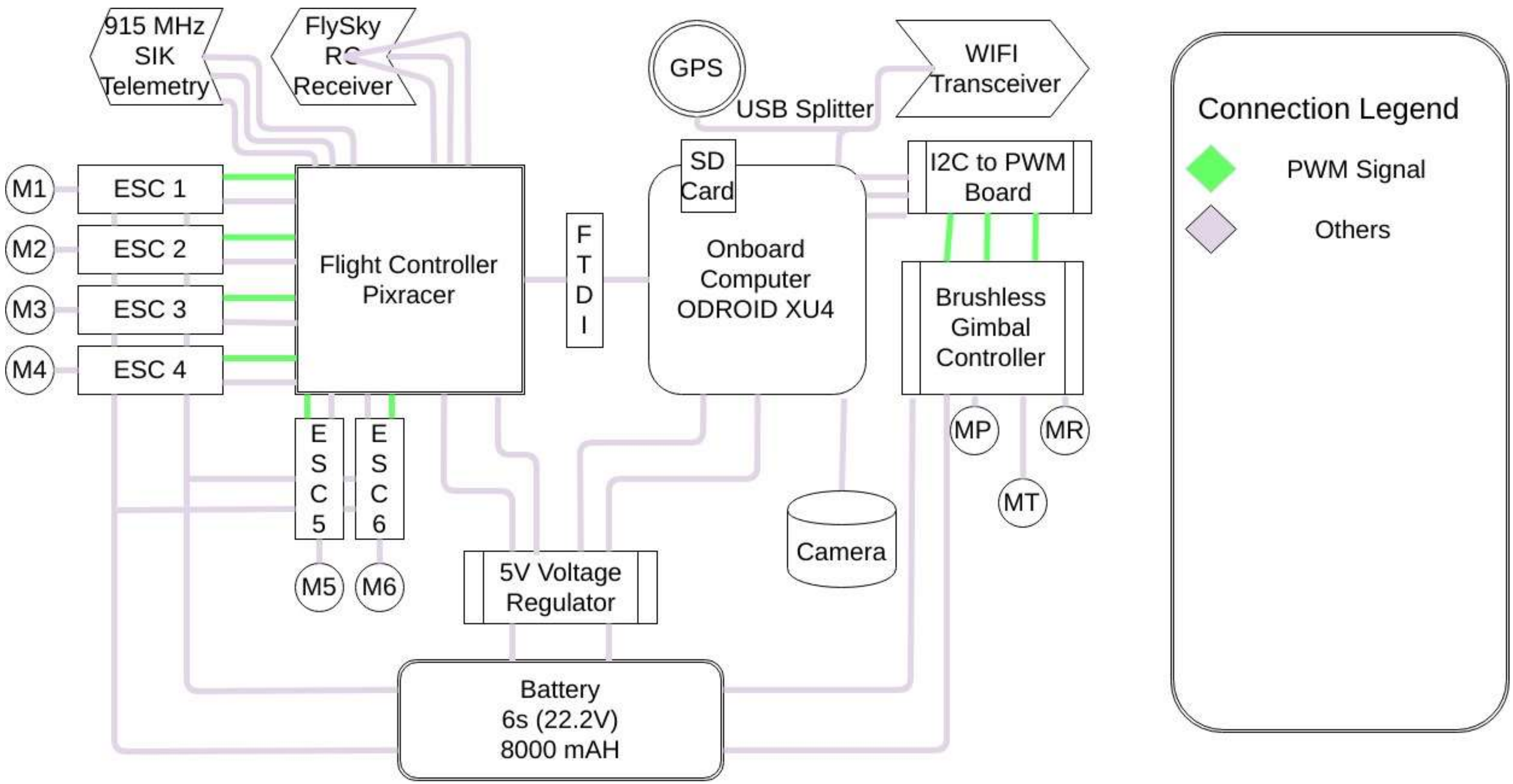
UAV Electronics Wiring



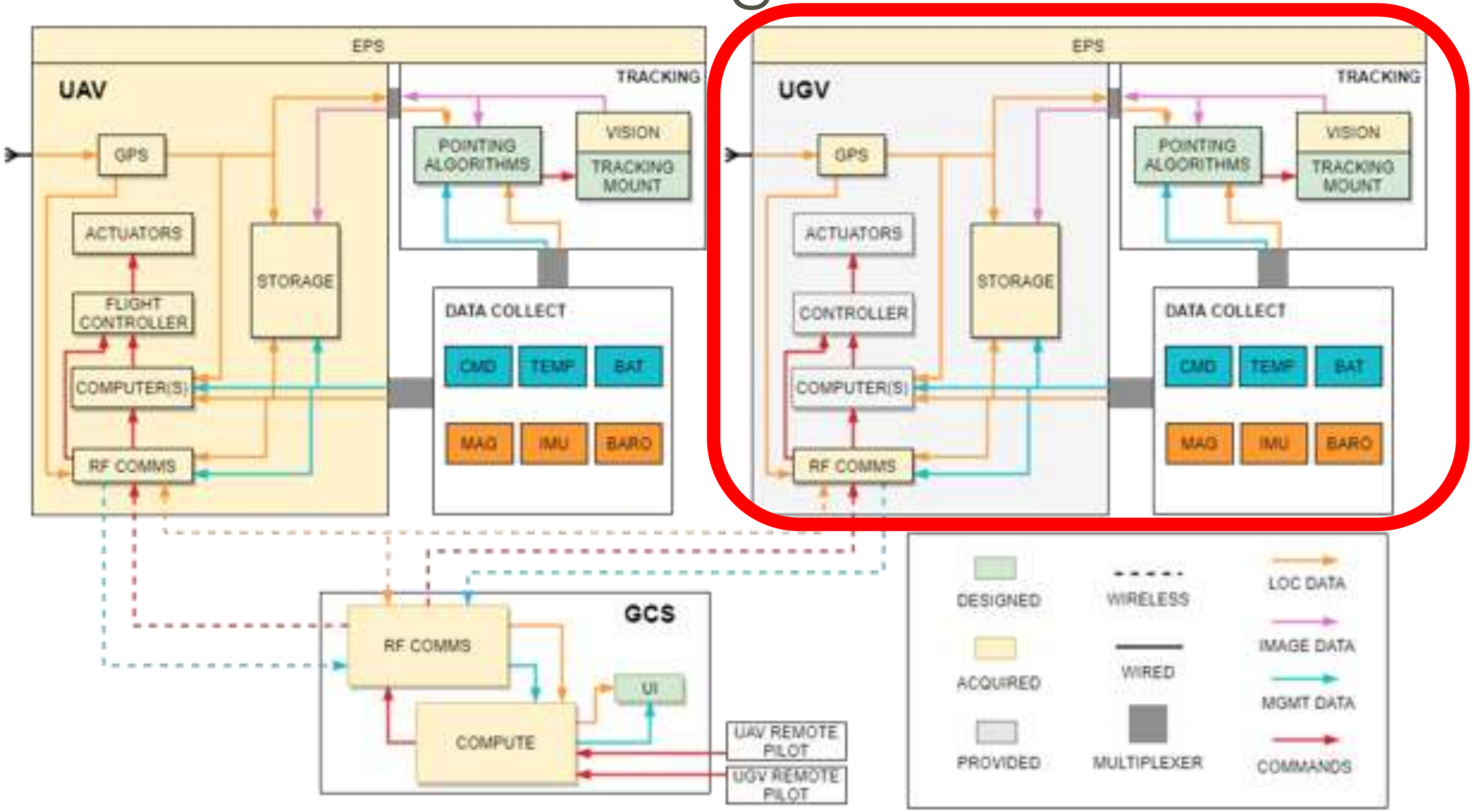
UAV Electronics Wiring



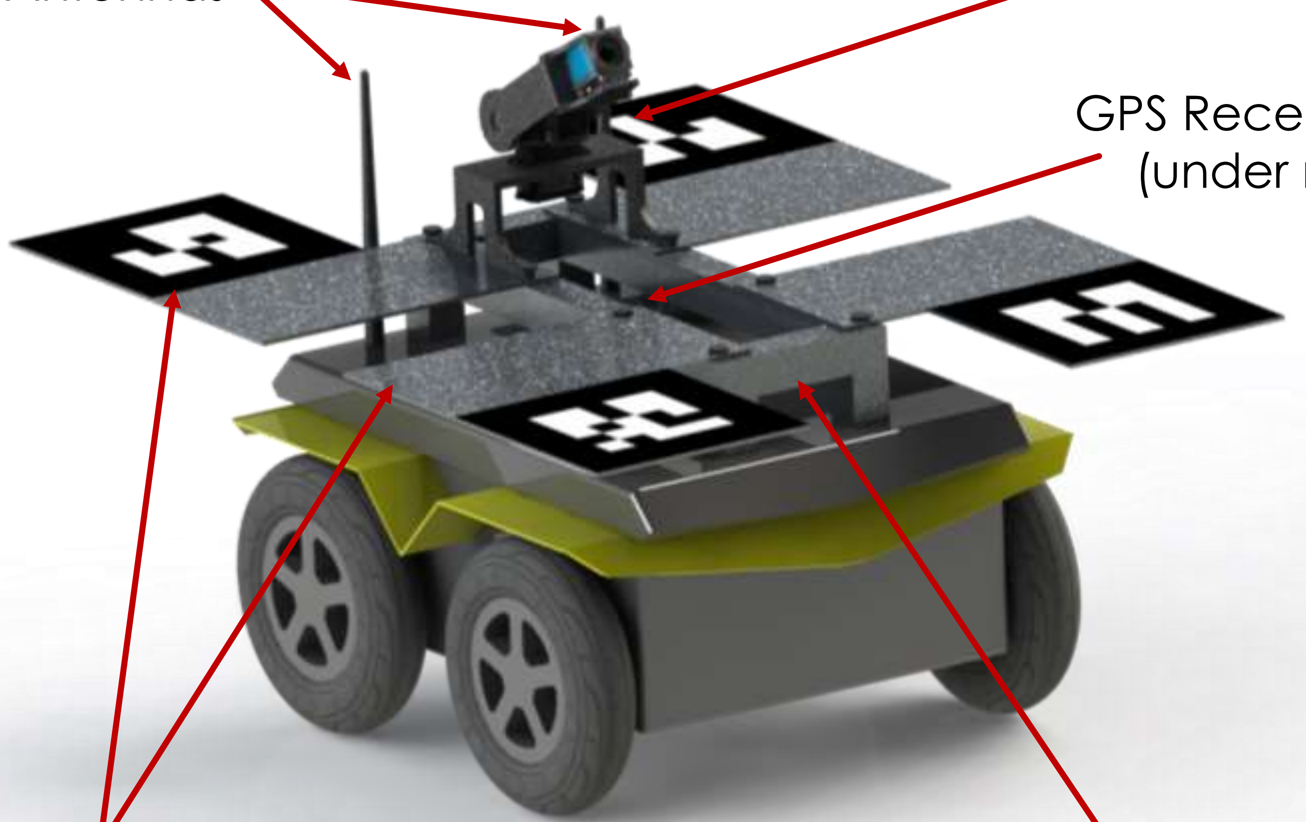
UAV Electronics Wiring



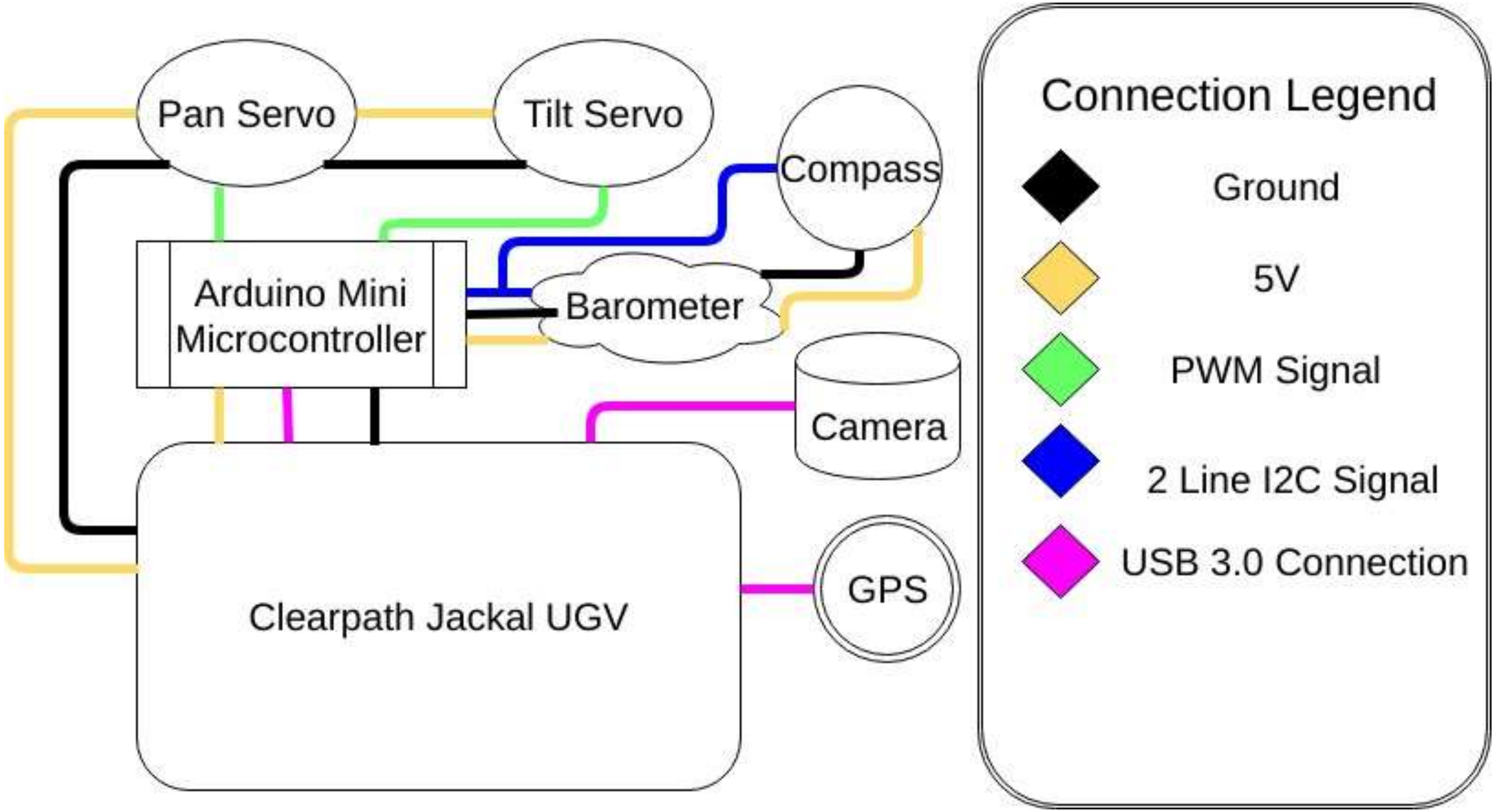
Functional Block Diagram



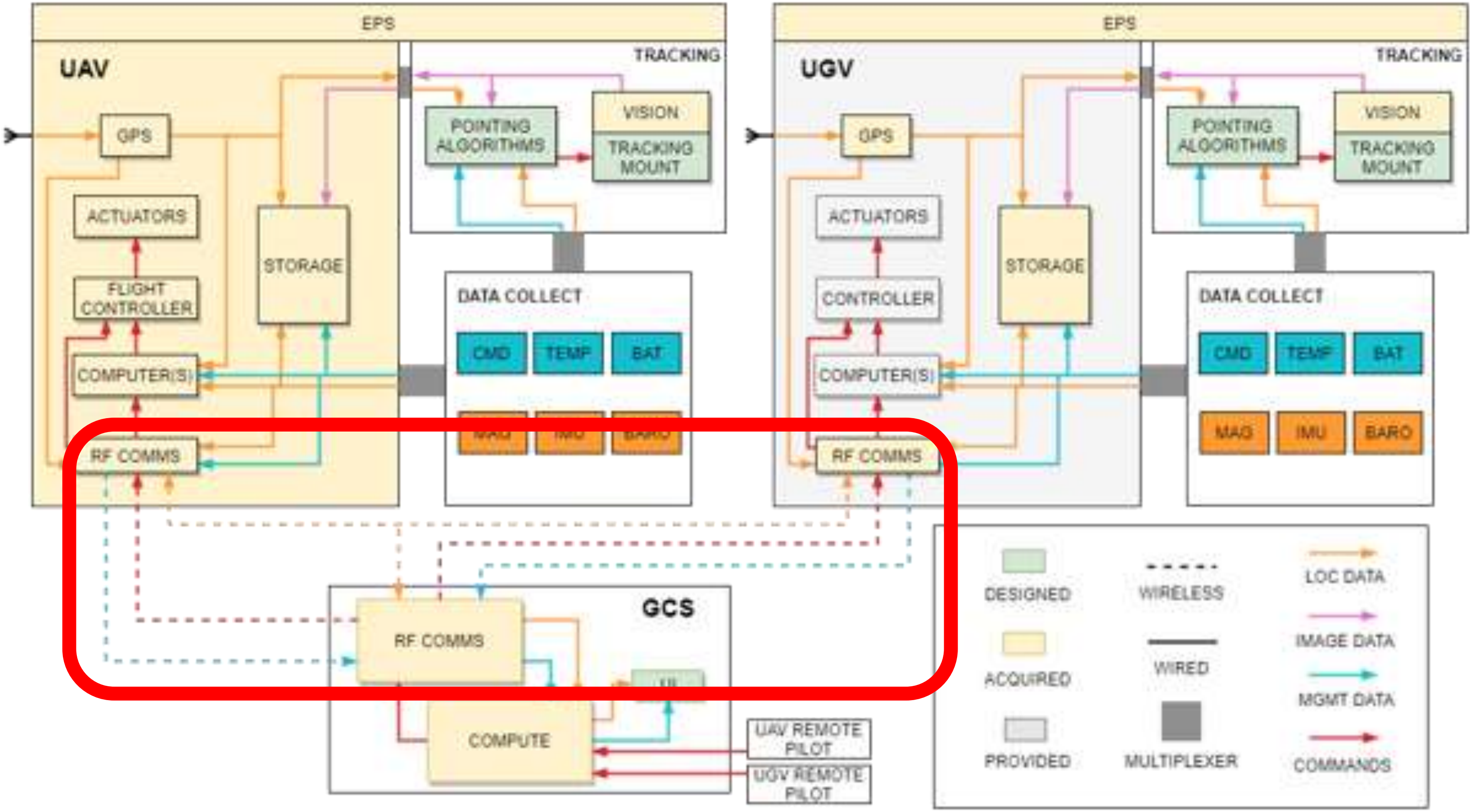
UGV Hardware Overview



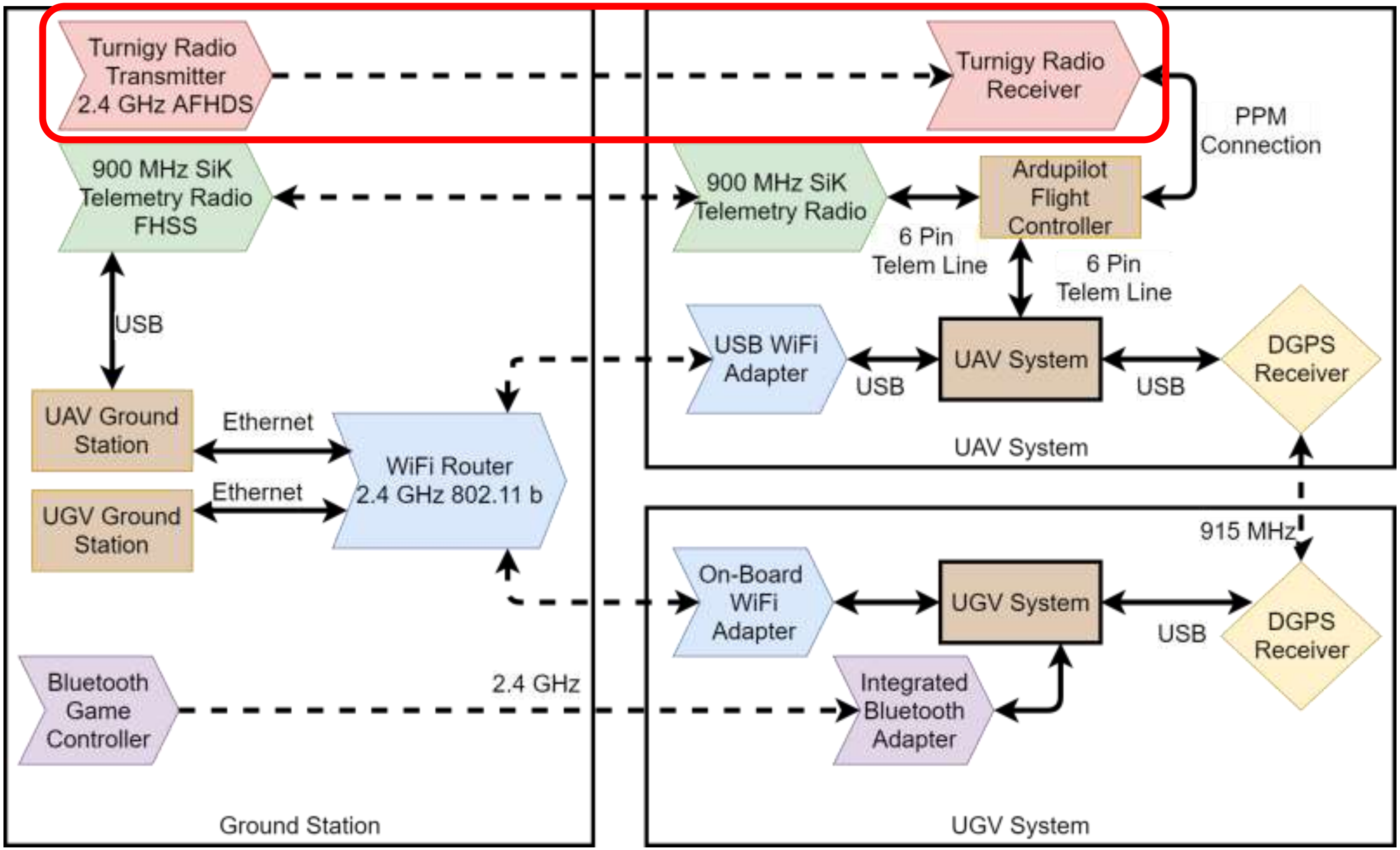
UGV Electronics Wiring



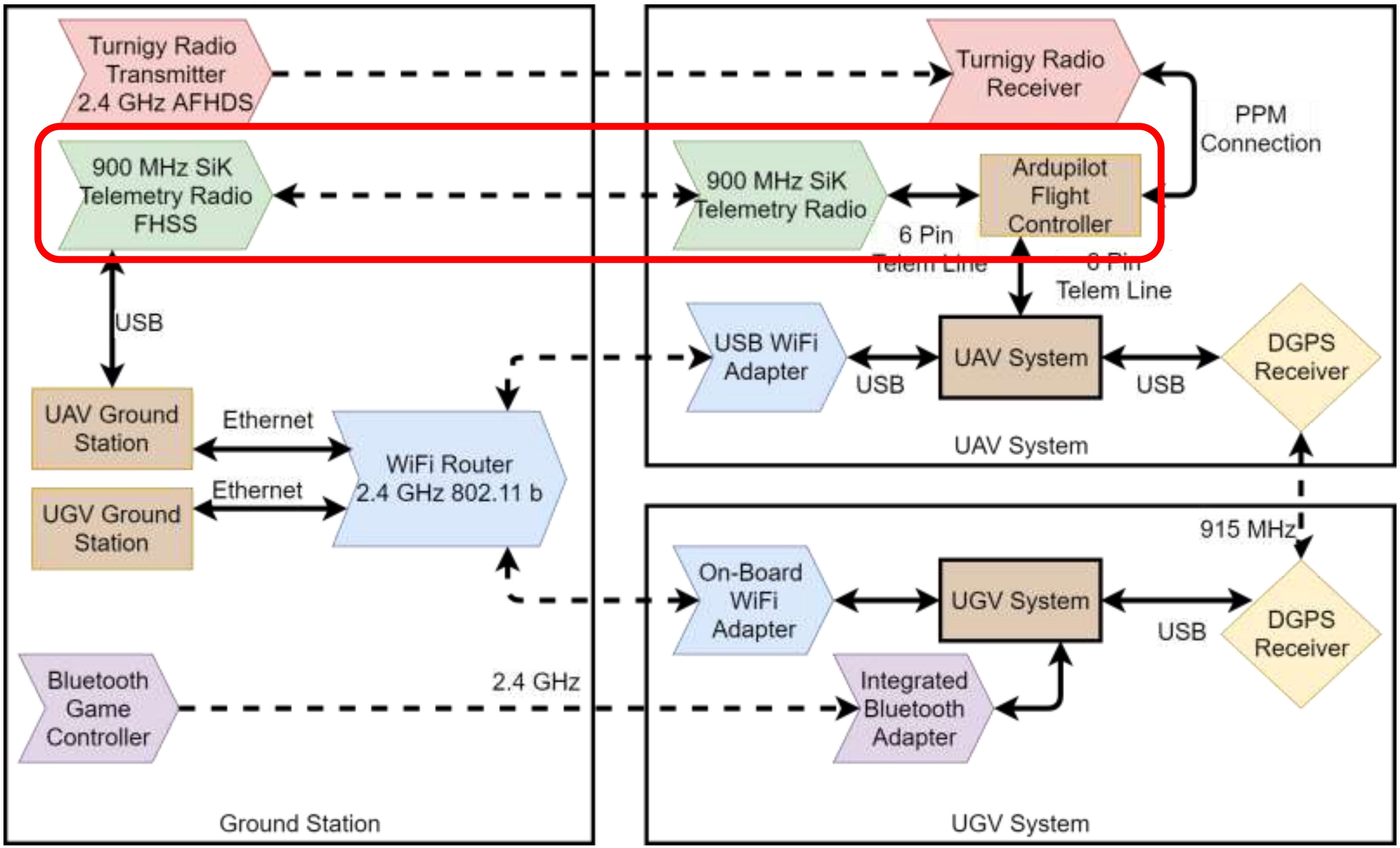
Functional Block Diagram



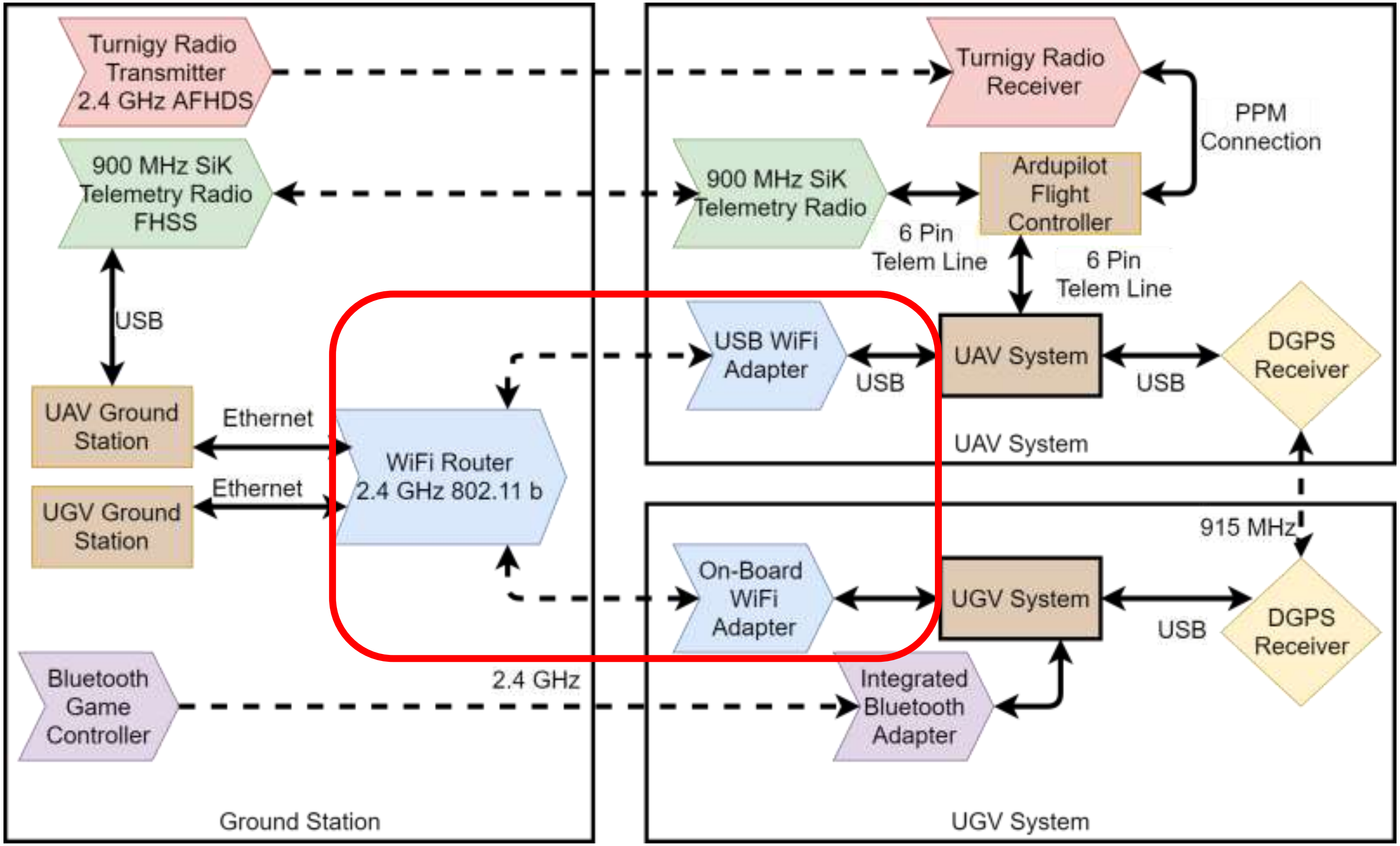
Communications



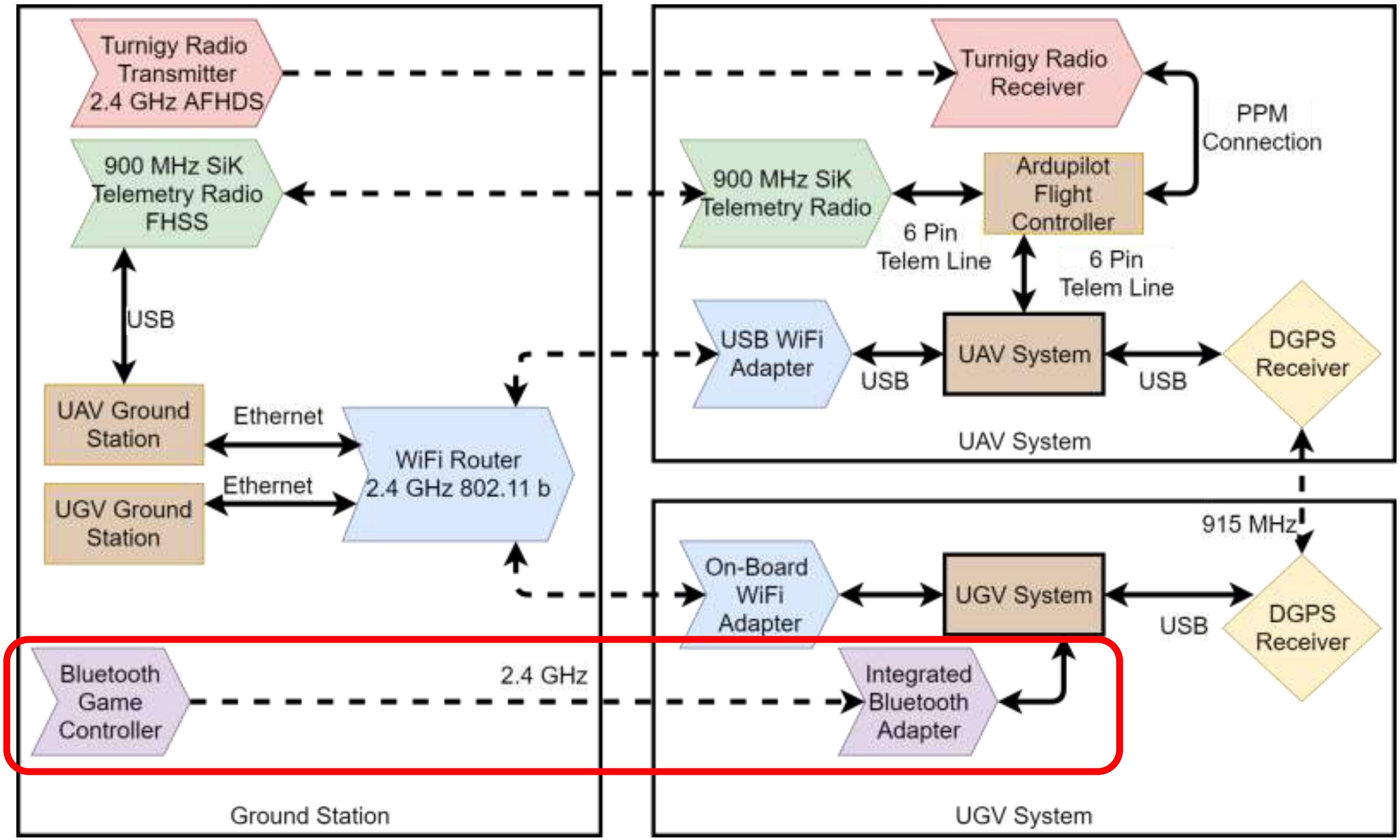
Communications



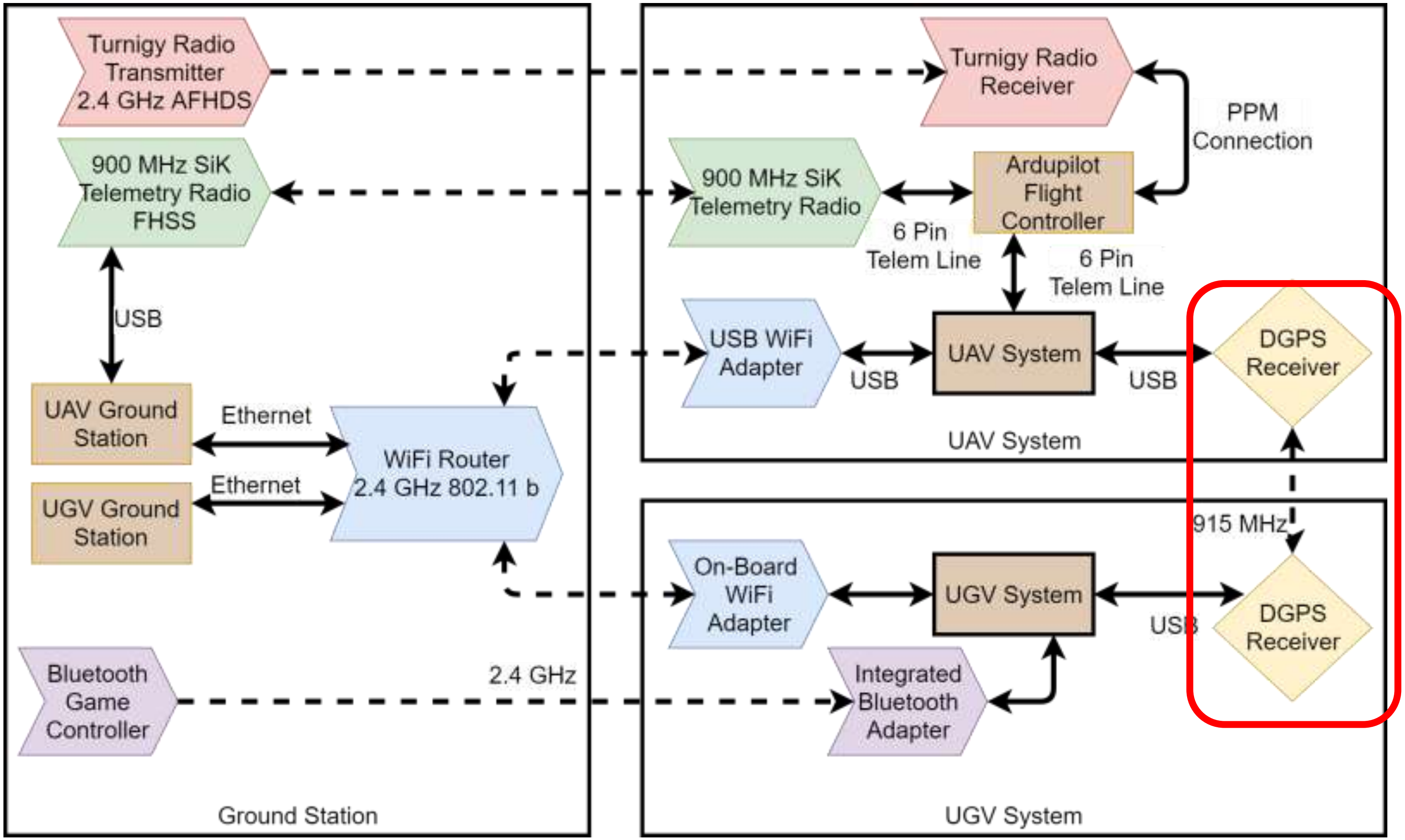
Communications



Communications

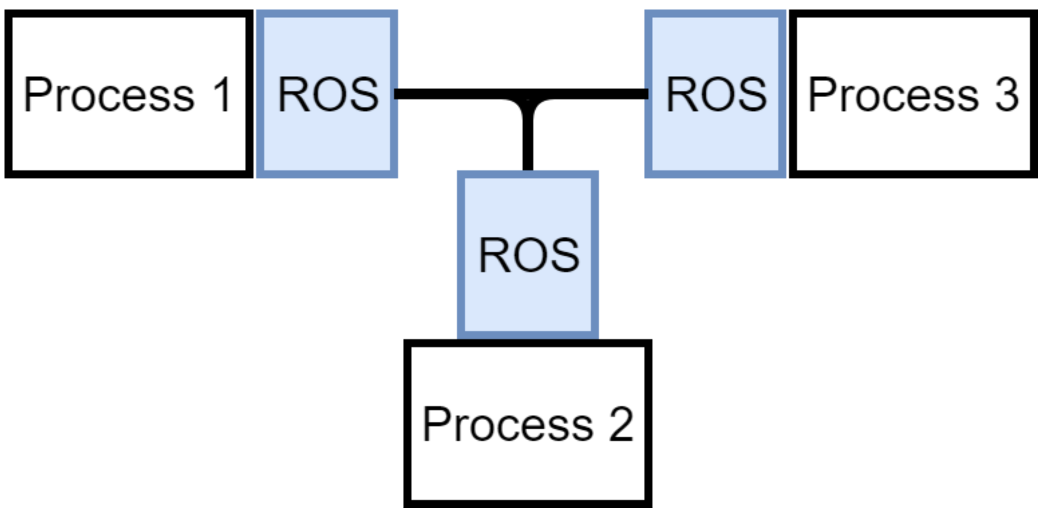


Communications

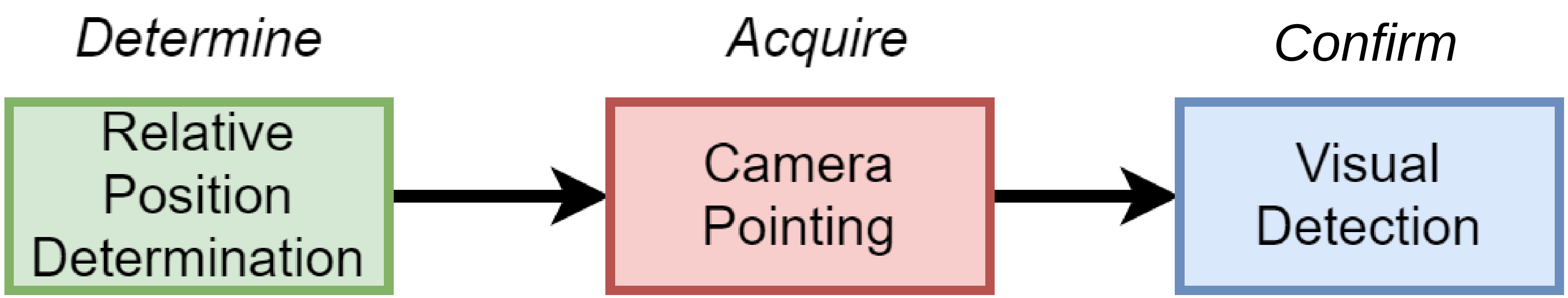


Robot Operating System (ROS)

- Open-source meta-operating system that provides:
  - Tools and libraries for interfacing with robotic systems and their components
  - Communication framework for distributed computing over network



Tracking Method



Determine

- Use GPS to find relative vector between vehicles.

Acquire

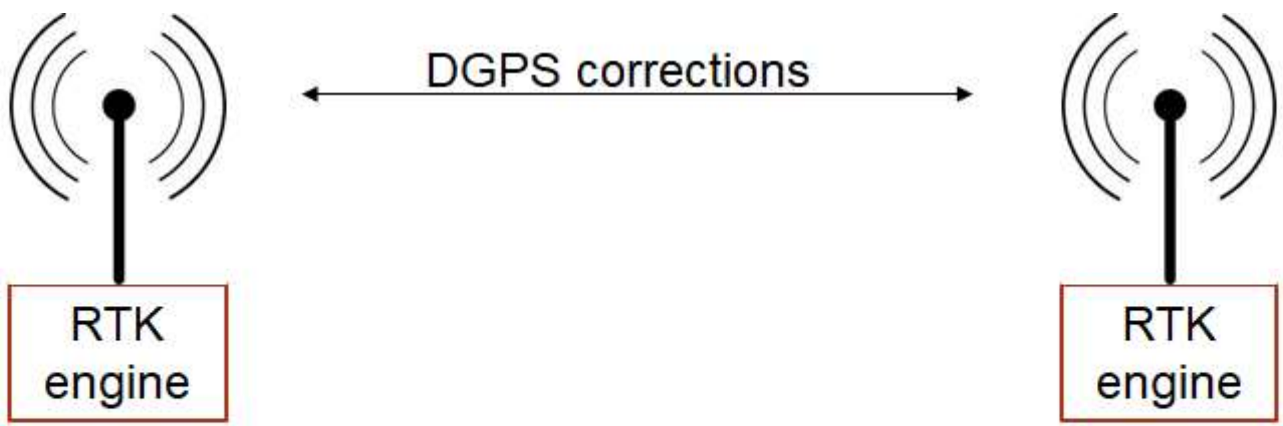
- Point Gimbal using GPS data to command servo.

Confirm

- UAV and UGV detection using AR tag and blob detection

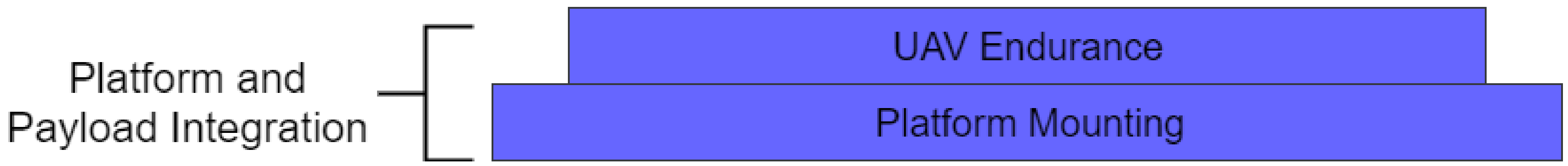
Determination Overview

- GPS receivers on each vehicle will communicate with each other and use **Differential-GPS (DGPS)** and **Real-Time Kinematics (RTK)** to reduce error considerably
- **DGPS** - method of removing shared errors from both GPS receivers
- **RTK** - ability to converge to a much higher precision using carrier-phase tracking (requires DGPS)

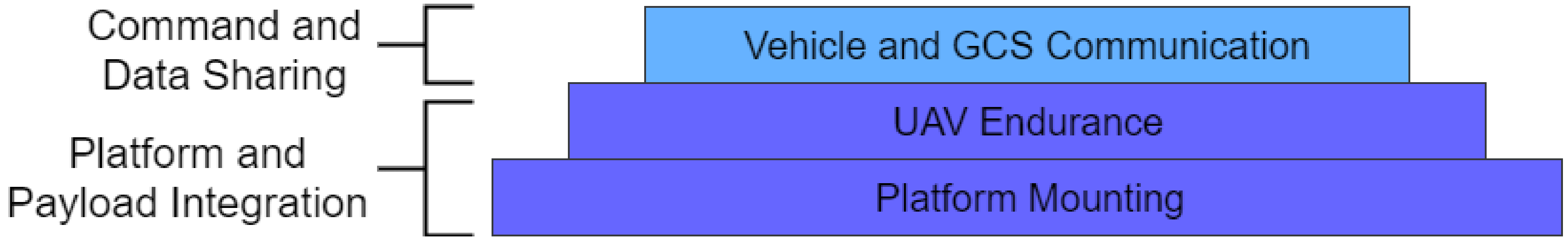


Critical Project Elements

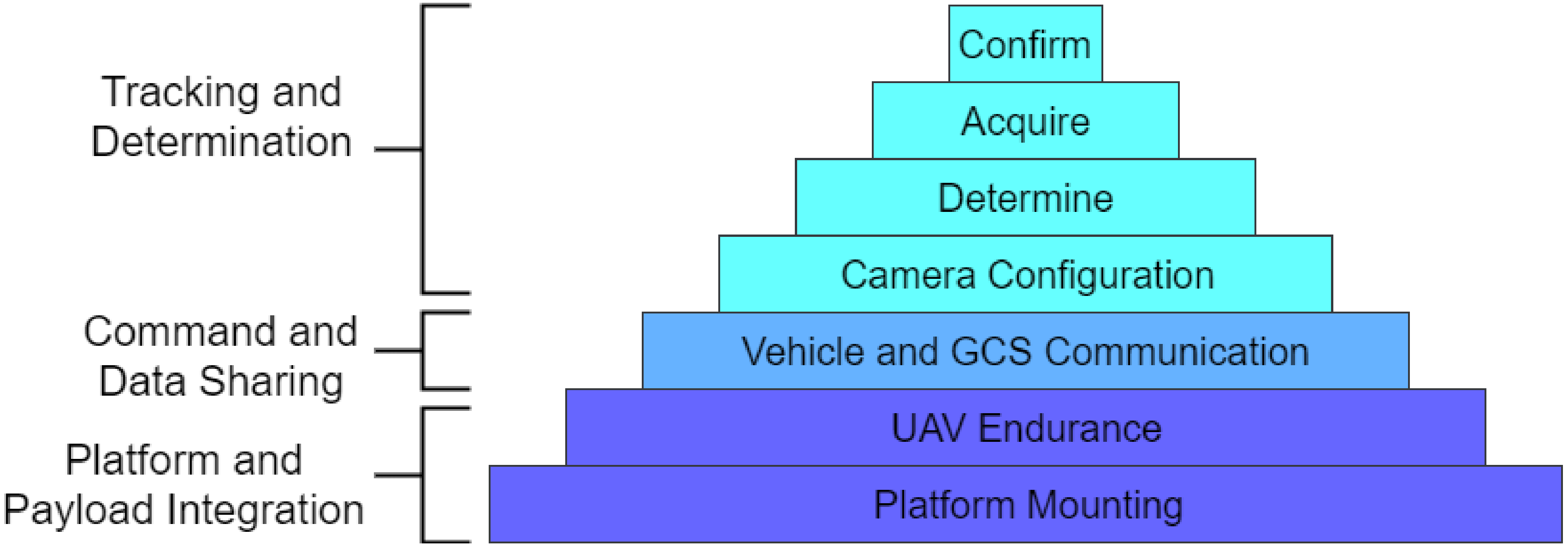
Critical Project Elements Breakdown



Critical Project Elements Breakdown



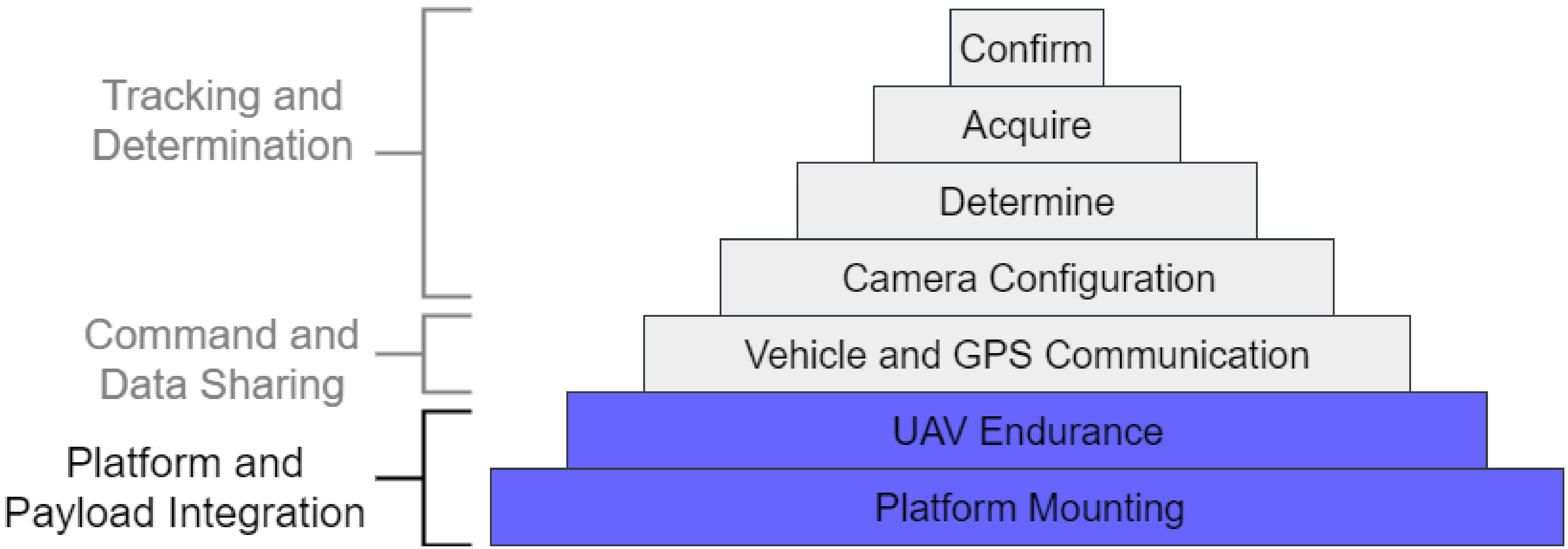
Critical Project Elements Breakdown



Design Requirements and Satisfaction

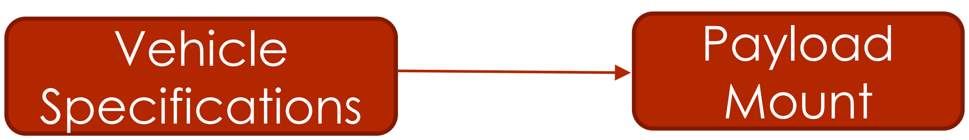
Payload and Platform Integration

Functional Requirement	Description
FR 1.0	RAVEN shall perform data collection for 15 minutes.
FR 7.0	RAVEN shall utilize the customer-provided Clearpath Jackal UGV.

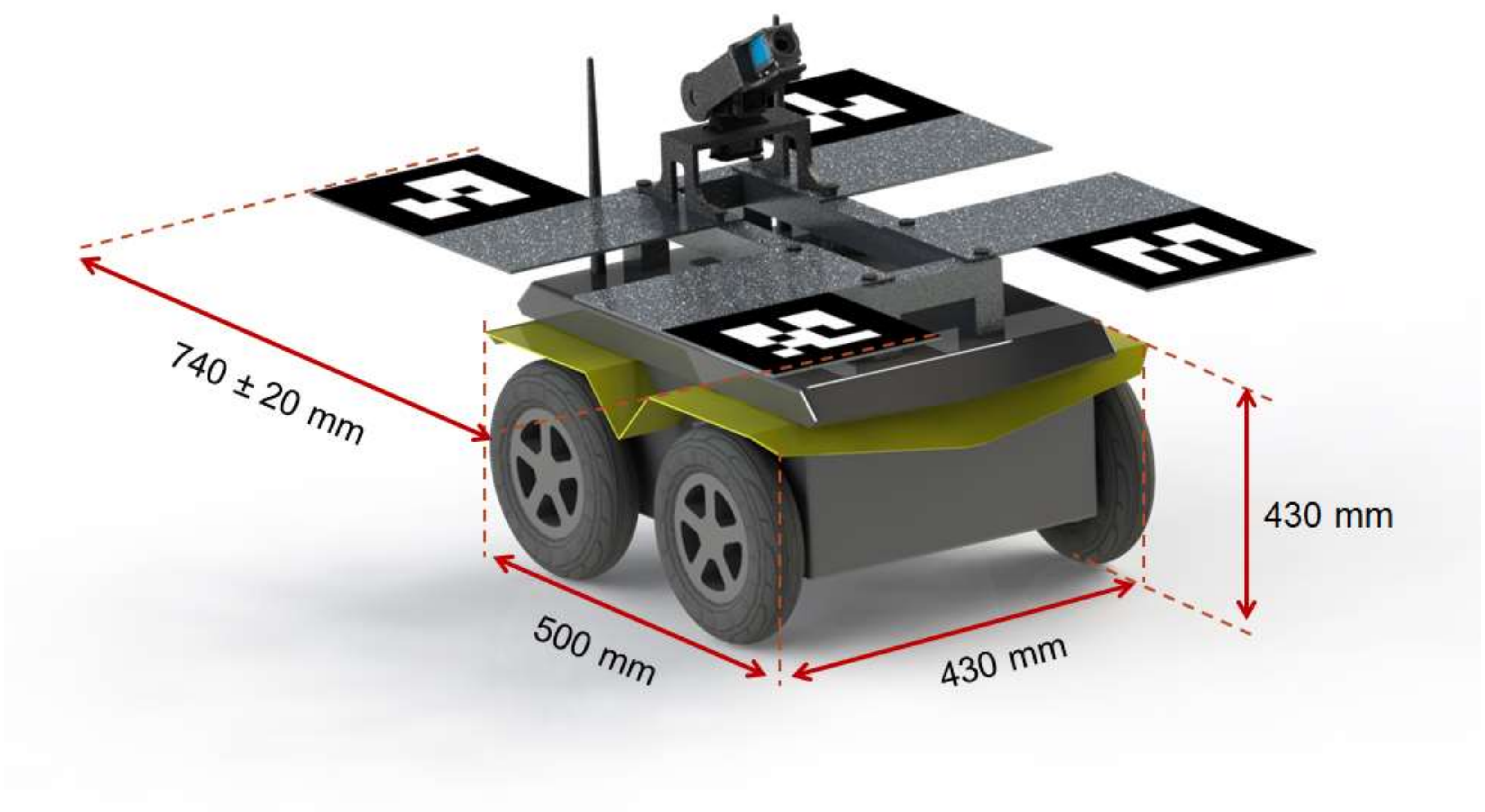


Platform Mounting

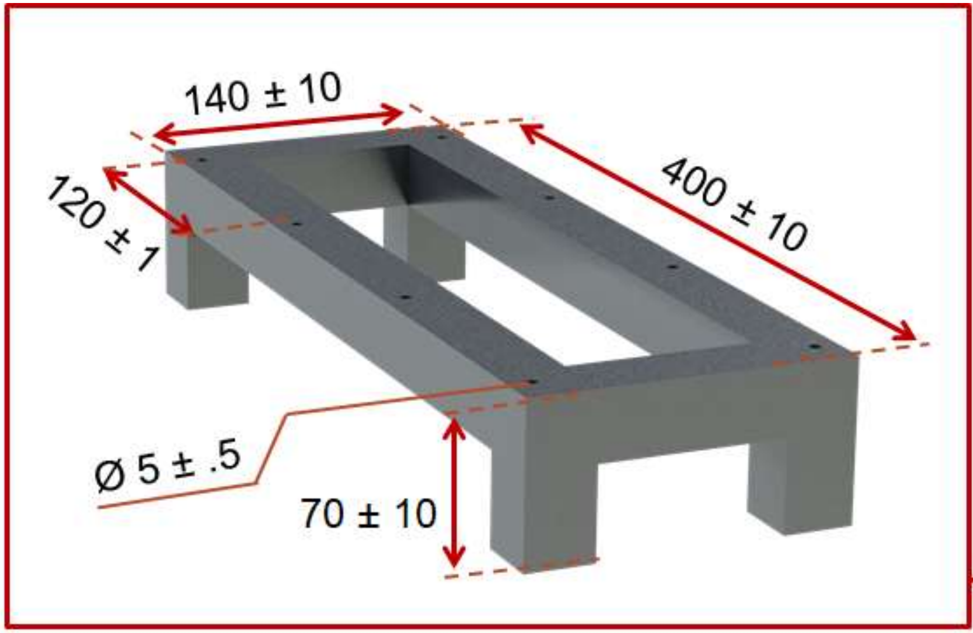
Design Requirement	Description
DR 1.2	UAV payload shall mount to UAV platform.
DR 7.1	UGV payload shall mount to 5 mm diameter holes spaced 120 mm x 120mm.
DR 7.4	UGV payload shall weigh less than 44 lbs.



UGV Specifications

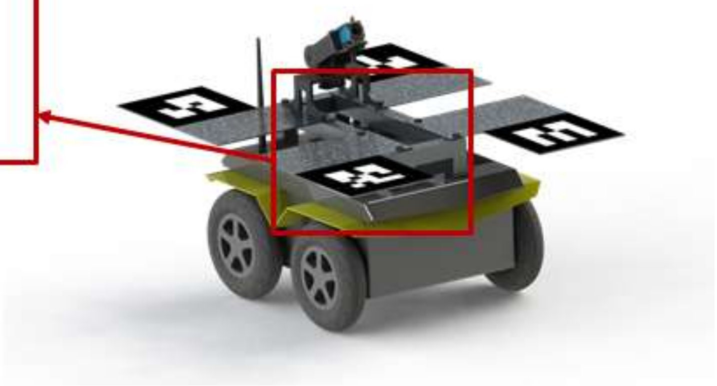


UGV Mounting Rails Specifications



*Dimensions in mm

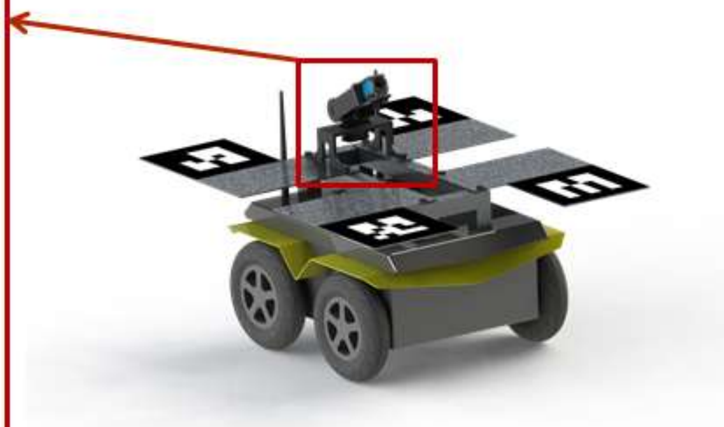
Extruded aluminum used to mount the gimbal and AR tag plates



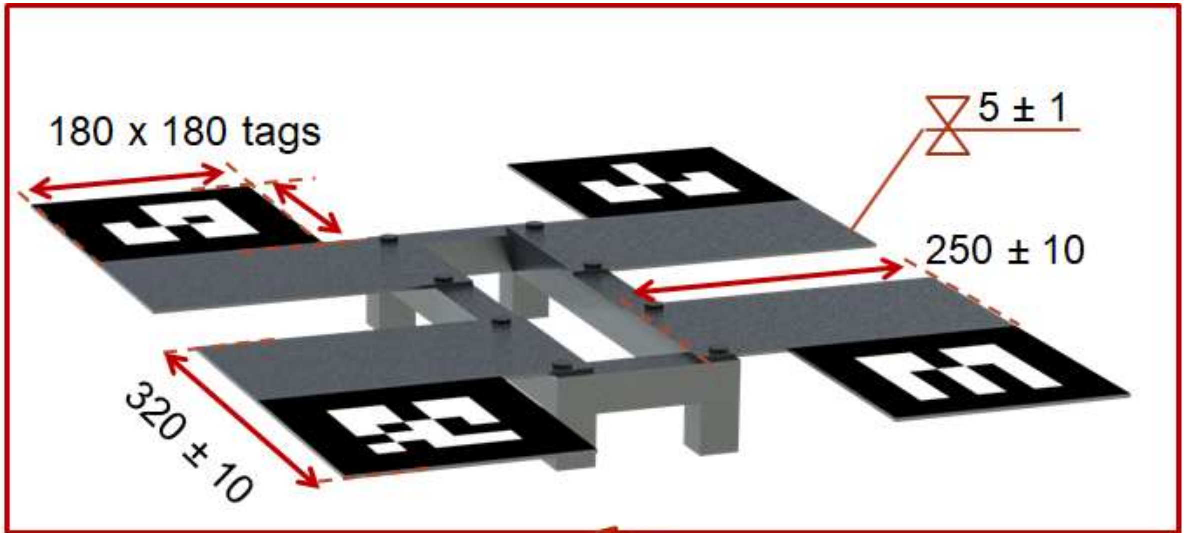
UGV Gimbal Specifications

*Dimensions in mm

Aluminum
servo and camera
mounts

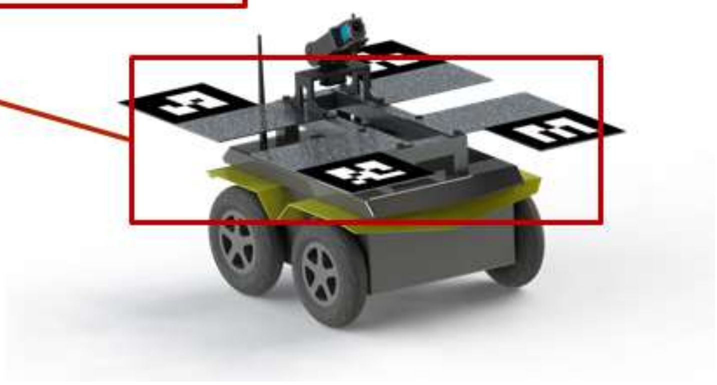


UGV AR Plate Specifications

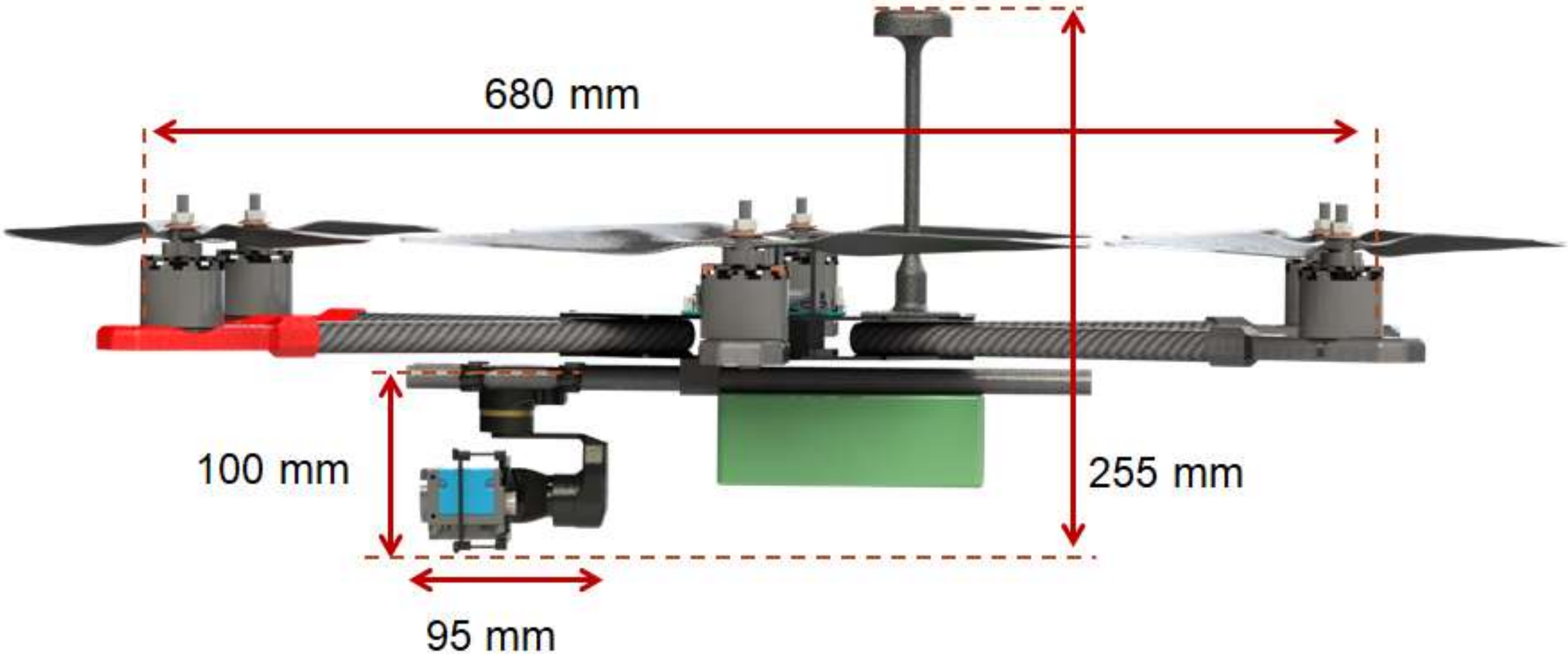


*Dimensions in mm

4 aluminum sheets to house the 4 AR tags

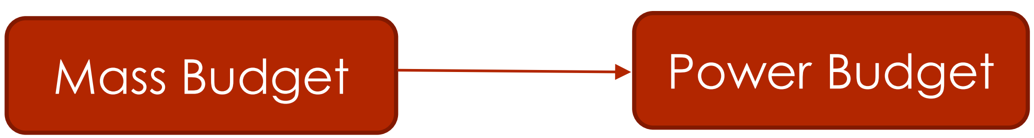


UAV Specifications



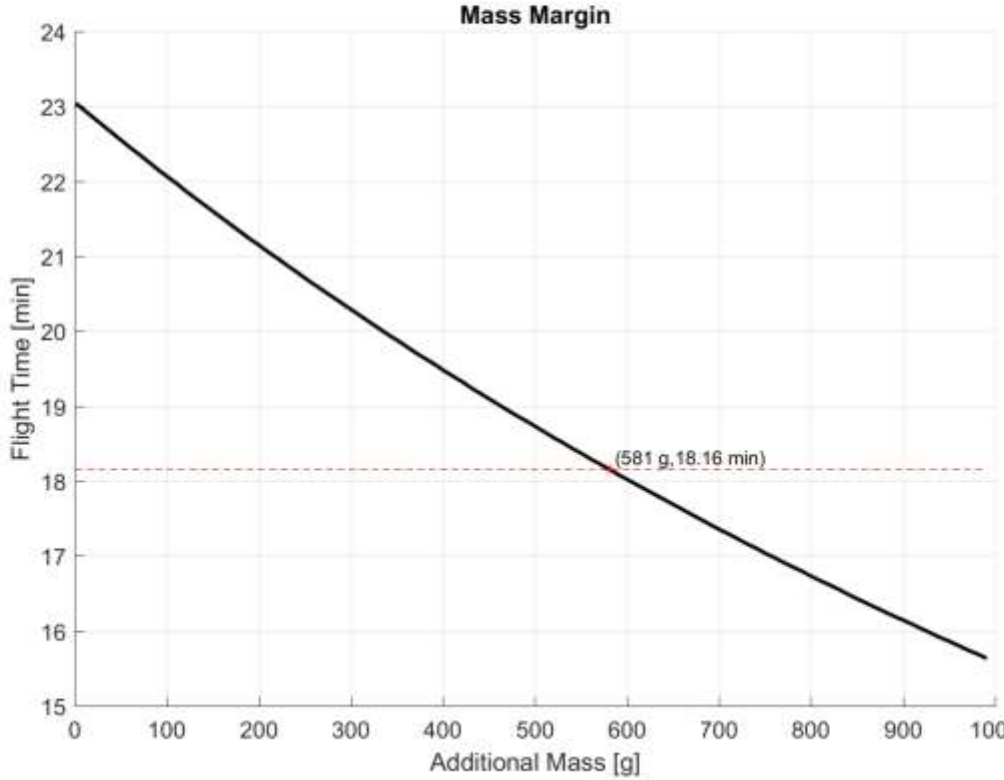
UAV Endurance

Design Requirement	Description
DR 1.1	EPS shall provide power to all electronic subsystems for a minimum of 15 minutes.



Mass Budget

Component	Mass
Frame	600 g
Driving Components	709 g
Battery	956 g
Payload	531 g
Wiring	139 g
Total	**2935 g**
Max Takeoff Weight	3516 g
Margin	581 g

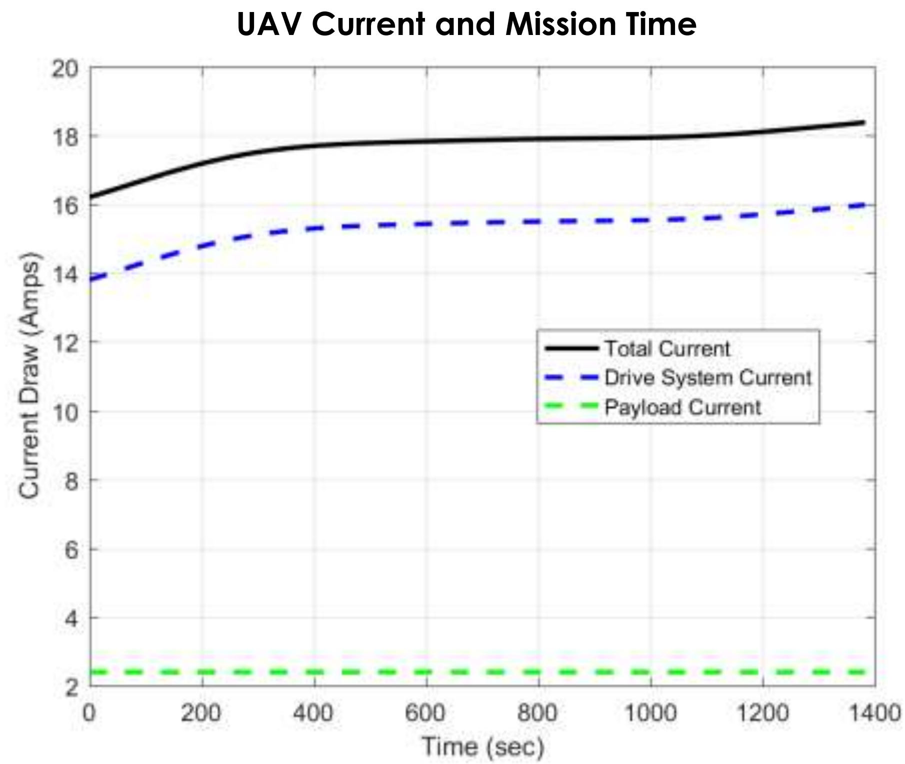


Conclusion:
- 17% mass margin
- DR 1.1 satisfied

Power Budget

- Battery: Turnigy 8,000 mAh 6S Li-po
- 18.15 minute endurance required

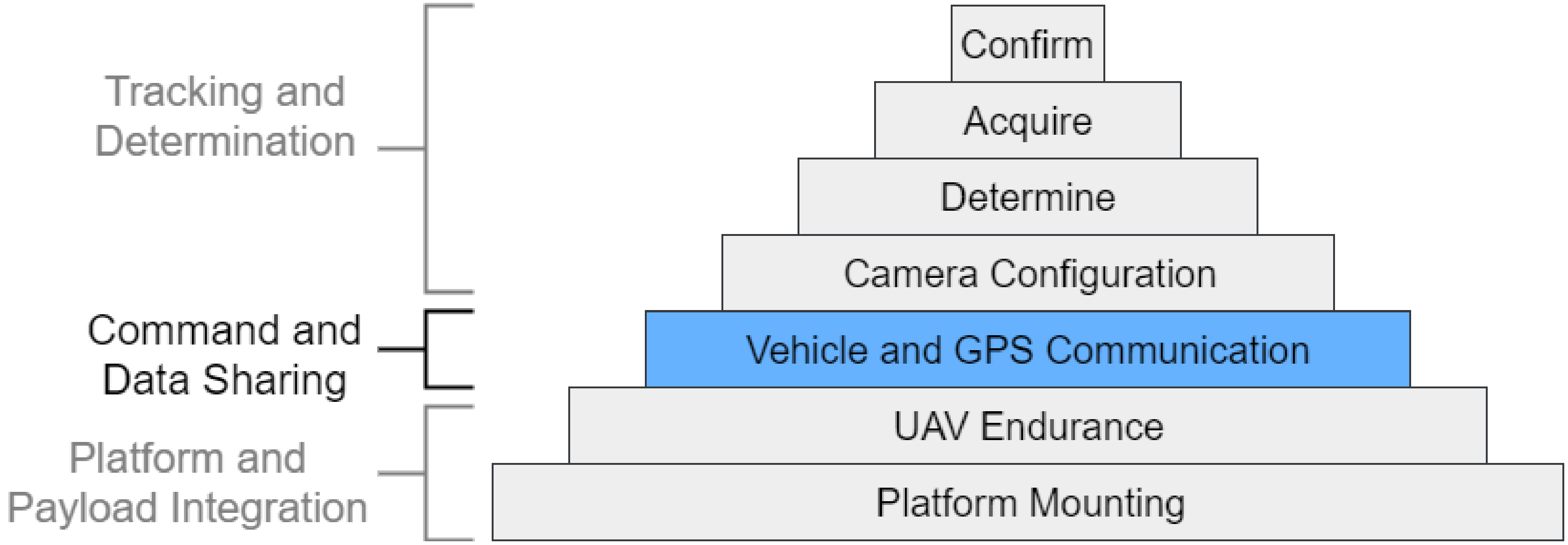
Component	Amperage
Camera	0.25 A
Computer	1.00 A
GPS	0.50 A
Flight Controller	0.50 A
Gimbal	0.15 A
Propulsion	16.0 A
Total	18.4 A



Conclusion:
- 25% charge margin after 18.15 min mission
- DR 1.1 satisfied

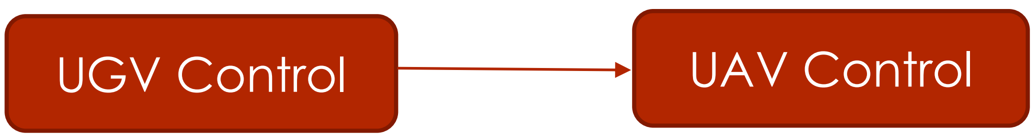
Command and Data Sharing

Functional Requirement	Description
FR 8.0	The UAV and UGV shall communicate flight and navigation status data to their respective ground stations (GCS) and to each other.
FR 9.0	RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM Radio Frequency.



Vehicle Controls

Design Requirement	Description
DR 9.2	Shall be able to transmit user pilot controls to the UAV and UGV.
DR 9.2.1	Vehicles shall be pilotable by generic controllers

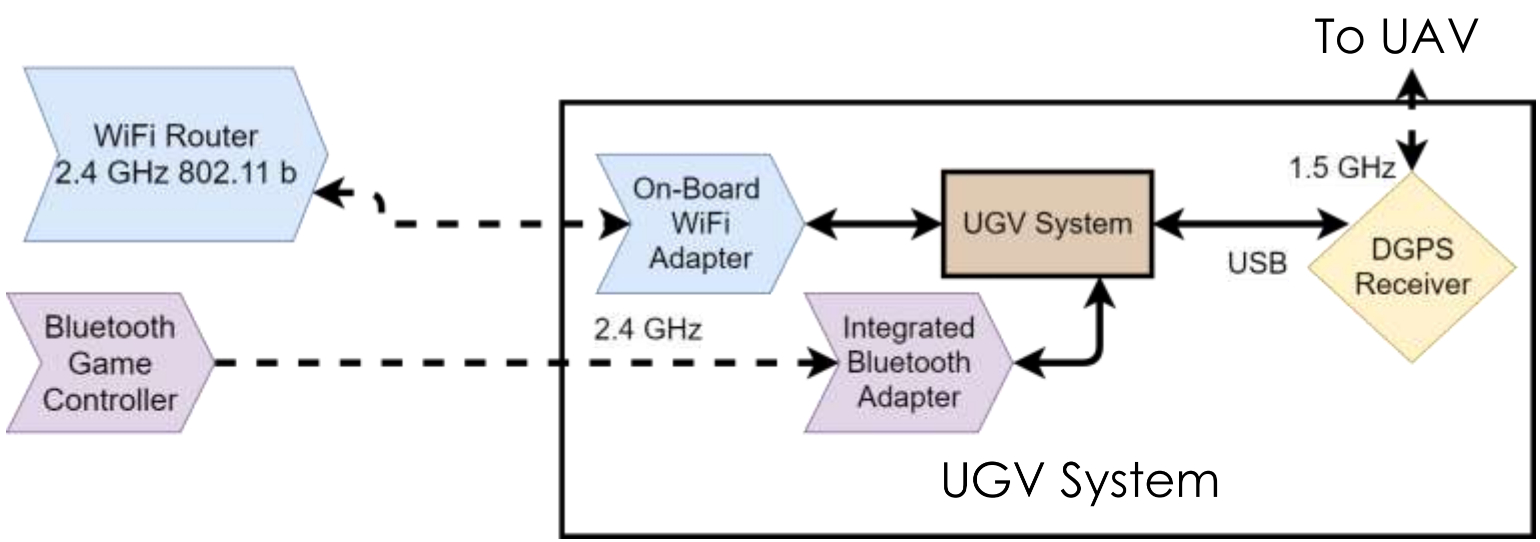


UGV Control

- To satisfy DRs 9.2 & 9.2.1 within test area, UGV must be controllable within 40 meters.
- Bluetooth game controller (provided with Jackal) tested to have range of 45.7 meters.
- Backup is to piggy back controller signal over WiFi data network.

Req. Range	Control Range
40 m	45.7 m

Conclusion:
- Satisfies DR 9.2, 9.2.1
- UGV will be controllable in operation area

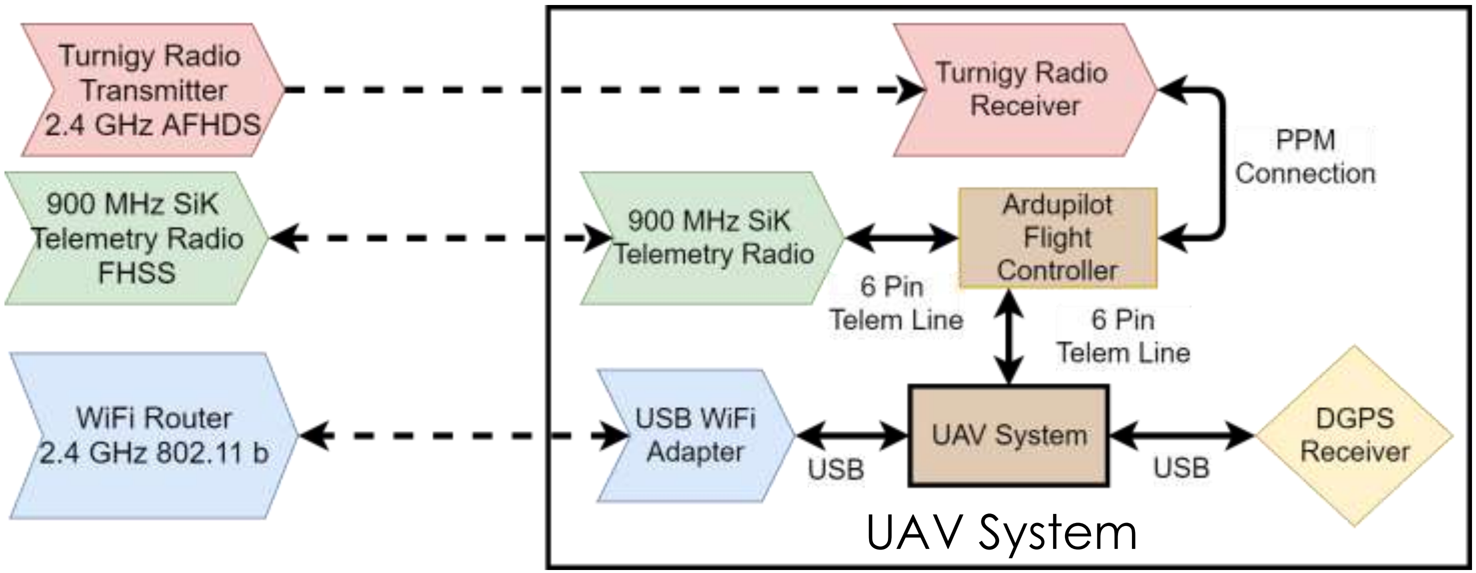


UAV Control

Req. Range	Control Range
65 m	1000 m

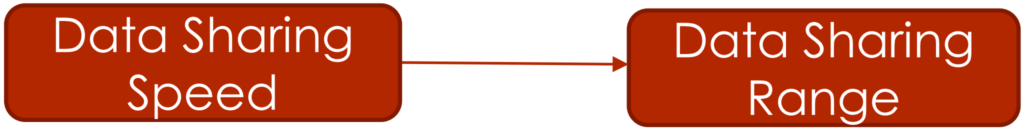
- To satisfy DRs 9.2 & 9.2.1 within test area, UAV must be controllable within 65 m of the user.
- Transmitter: Turnigy i6s 2.4 GHz

Conclusion:
- Satisfies DR 9.2, 9.2.1
- UAV will be controllable in operation area



Data Sharing

Design Requirement	Description
DR 8.1	Both vehicles shall communicate navigation data to their respective ground station.
DR 8.2	Vehicles shall be able to share data between each other
DR 8.3	Both vehicles shall communicate visual tracking data to GCS.
DR 8.4	Vehicles shall share live GPS data.
DR 8.5	Vehicles shall share live IMU, magnetometer and barometer data



Data Sharing Speed

- To satisfy DRs 8.1 – 8.5:
  - The data sharing network (using IEEE 802.11 b standard) must have the bandwidth to carry all aforementioned data.
  - UAV, UGV, and CGS must all be connected to the data sharing network

Item	Data rate
Preview Image	3.05 Mbits/s
Navigation Data	153.6 kbits/s
Management Data	25 kbits/s
Total Data Rate	3.231 Mbits/s
802.11 b Maximum Throughput	11 Mbits/s
Margin	7.769 Mbits/s

Connection	Device
Network Hub	Netgear Nighthawk AC1750 WiFi Router
UGV Connection	Built-in WiFi adapter
UAV Connection	ODROID WiFi Module 3
Ground Stations	Ethernet

Conclusions:
Total network demand is less than the network throughput and all nodes connected to network, satisfying DR 8.8

Data Sharing Range

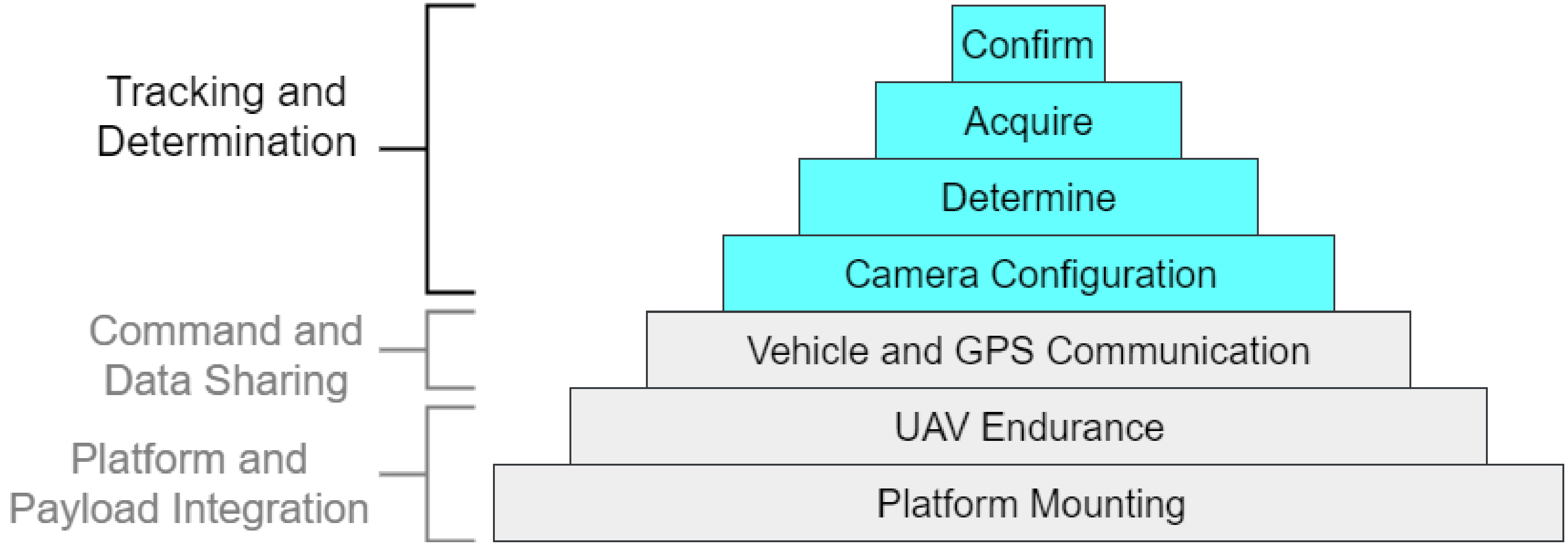
- To satisfy DR 8.1 – 8.5:
  - The data sharing network must function within the entire test area (radius of 30 m)
- Testing done using consumer grade hardware: ZyXEL C1100Z Router, Intel integrated WiFi adapter

Required Range	Estimated Range
30 m	55 m

Distance	Strength	Share Status
1 m	-20 dBm	Stable
55 m	-64 dBm	Stable
118 m	-80 dBm	Slight Delay

Tracking and Determination

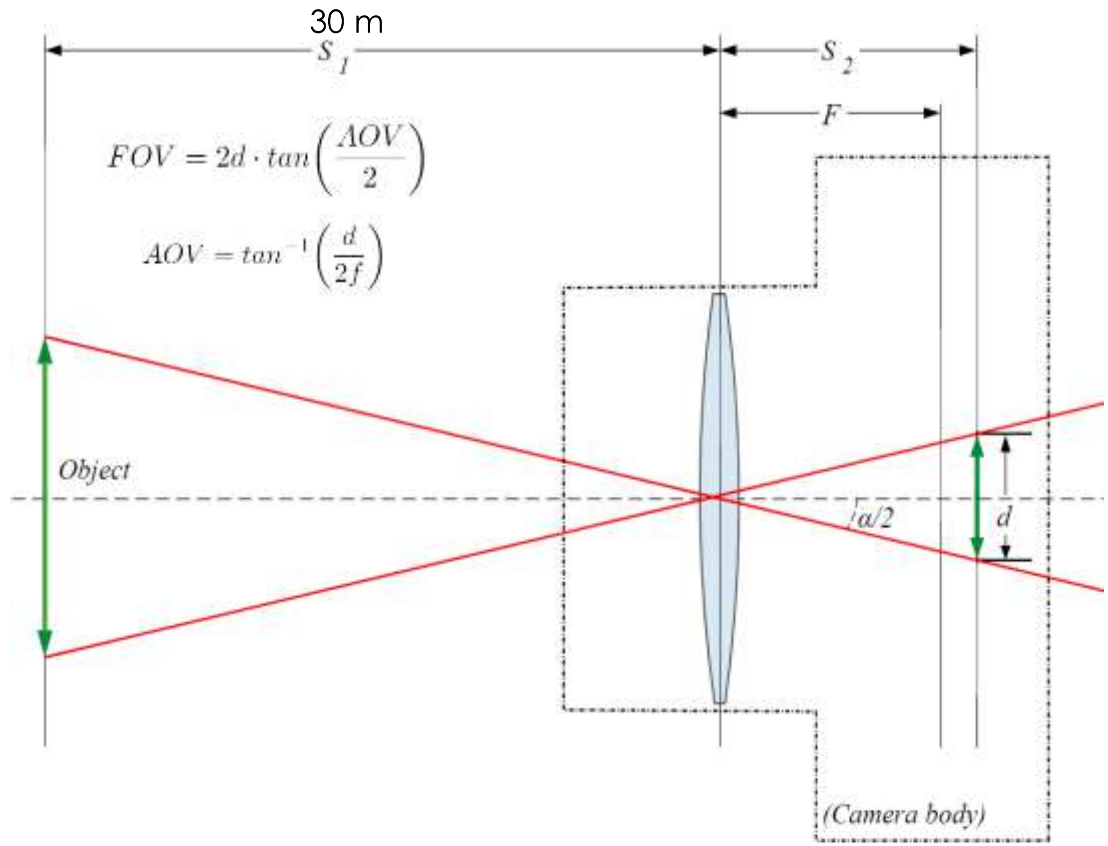
Functional Requirement	Description
FR 3.0	UAV and UGV visual data shall contain the other vehicle in 90% of frames and shall not take more than three seconds of frame data without the other vehicle in frame.
FR 4.0	UAV and UGV visual data shall have a minimum resolution of 3 in/pixel at a distance of 30 m.



Camera Configuration

Design Requirement	Description
DR 4.1	Camera resolution shall be greater than 1920x1080 with at least a 25 mm focal length (35 mm equivalent)

- DFK 33UX249 and 16mm lens:
  - Resolution: 1920 x 1200
  - AOV: 28 x 36.8 degrees
- Pixel Density:
  - At 30 m: **0.451 in/pix**



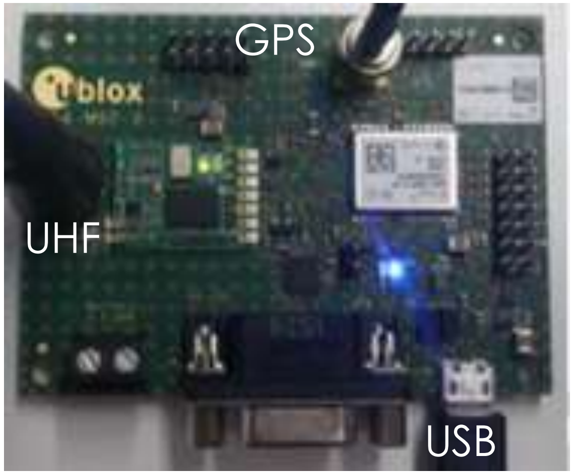
Conclusion:
- Camera has a pixel density less than 3 in/pixel @ 30 m
- DR 4.1 satisfied

Determination of Location

Design Requirement	Description
DR 3.2	UAV mounted vision tracking system shall be able to track UGV at ground speed of 0.5 m/s and range of 10 m.
DR 3.4	UGV mounted vision tracking system shall be able to track UAV at ground speed of 0.5 m/s and range of 10 m.
DR 8.4	Vehicles shall share live GPS data.

Chosen GPS Solution

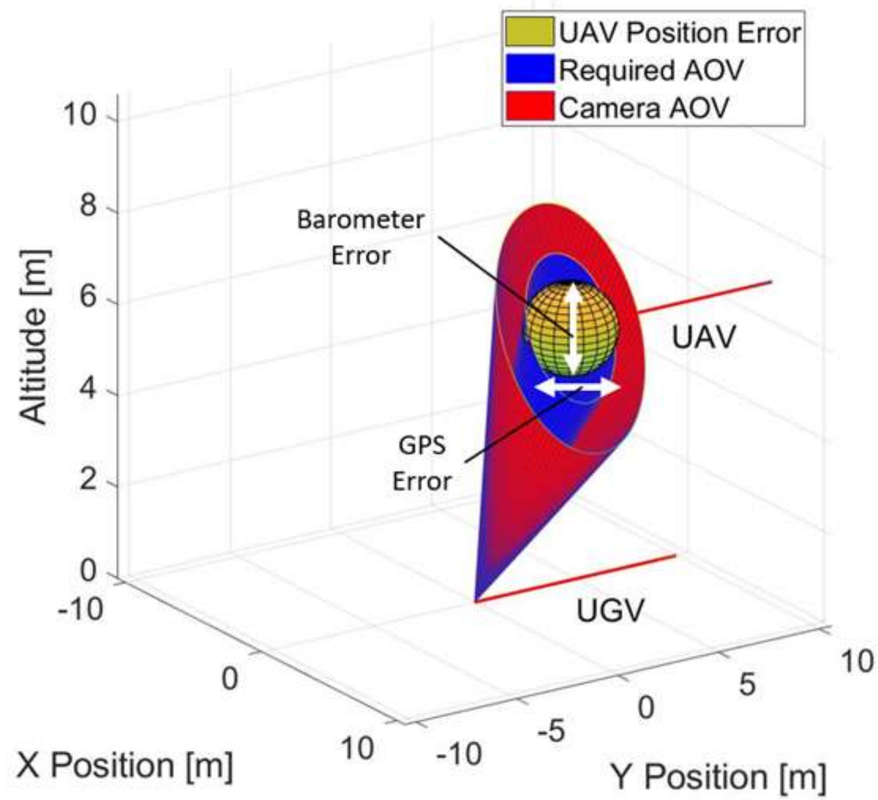
- GPS Receiver: NEO-M8P integrated on C94-M8P application boards
- C94 boards can communicate with each other over UHF (ultra-high frequency) to communicate DGPS corrections
- The receivers use RTK (Real-time Kinematic) that allow cm-level relative accuracy



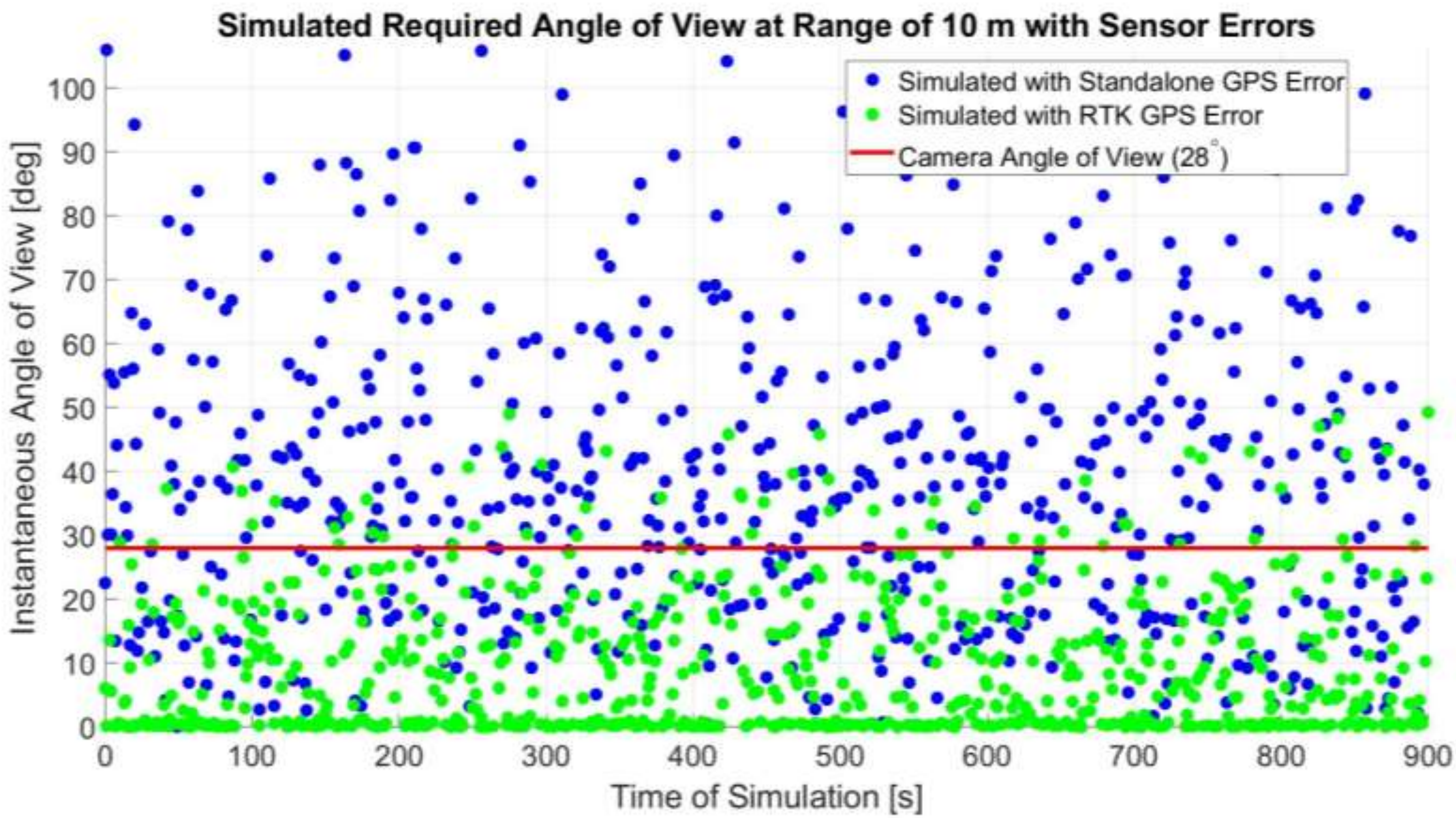
http://www.luohanjie.com/2017-07-24/configuration-method-of-ublox-c94-m8p-application-board.html

Vehicle Location Error Model

- Purpose
  - Gaussian distributed error based on sensor datasheets
  - Determine required Angle of View accounting for sensor errors
  - Justification of RTK capable GPS
- Assumptions
  - Constant velocity orbit
  - Circular orbit
  - Constant altitude



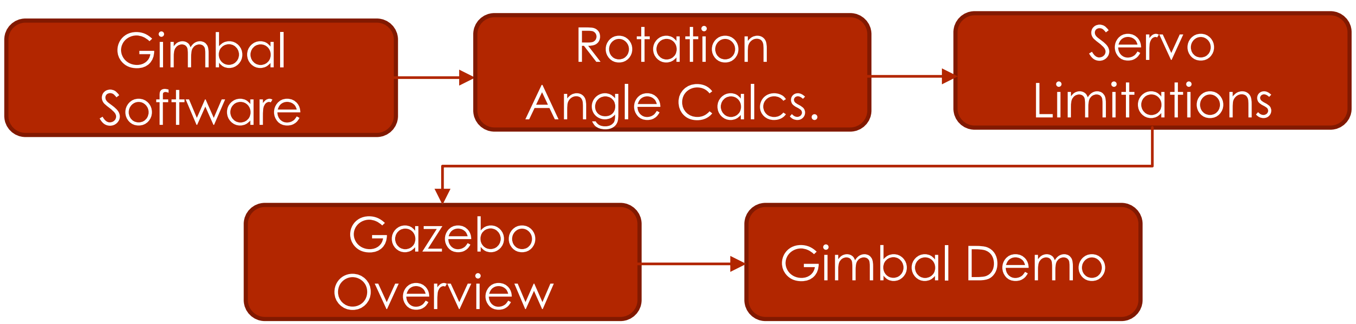
RTK Accuracy



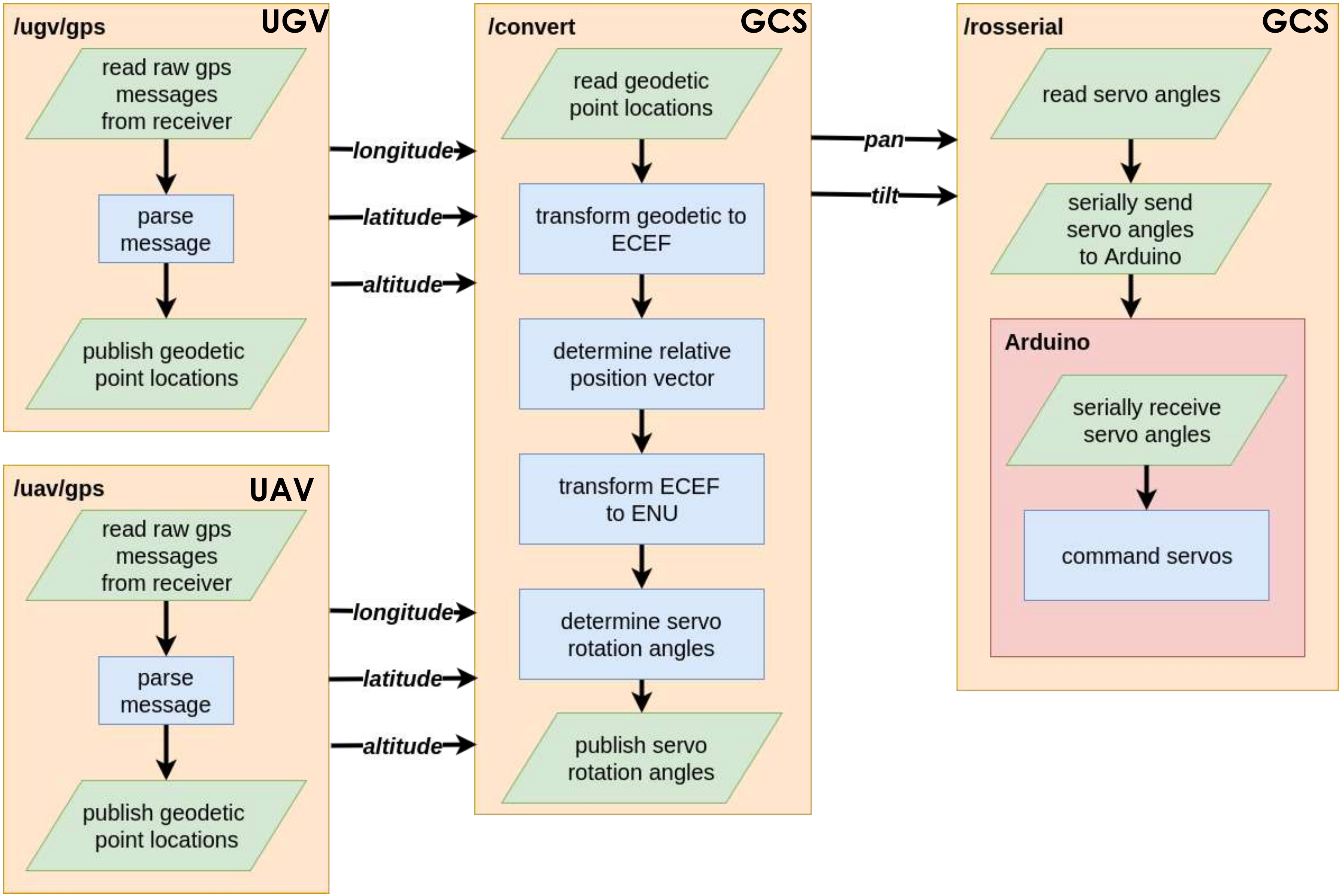
- Over 90% of simulated RTK data points are within angle of view.

Acquisition of Target

Design Requirement	Description
DR 3.2	UAV mounted vision tracking system shall be able to track UGV at ground speed of 0.5 m/s and range of 10 m.
DR 3.4	UGV mounted vision tracking system shall be able to track UAV at ground speed of 0.5 m/s and range of 10 m.



Gimbal Software Flowchart

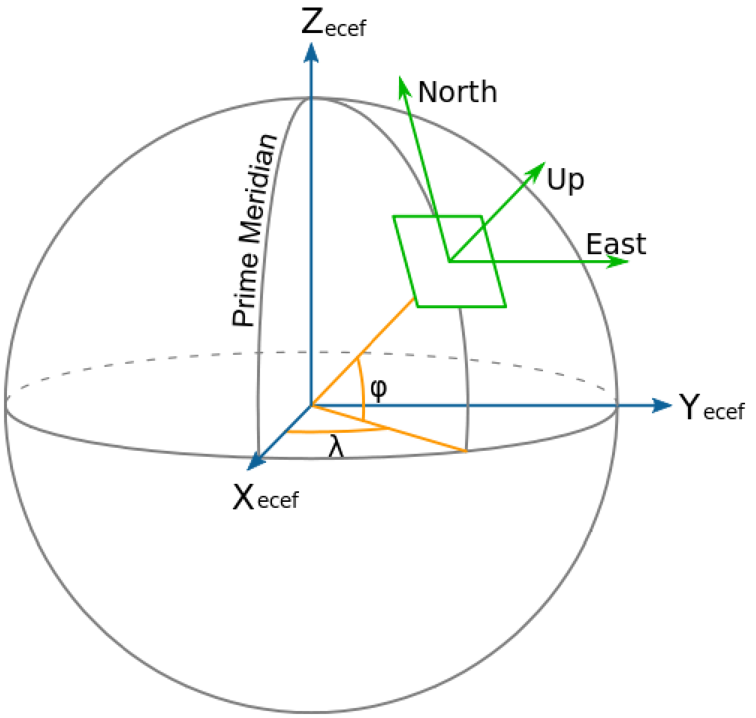


Calculating Servo Rotation Angles

- **Goal:** convert inertial geodetic coordinates into East-North-Up coordinates to determine gimbal rotation angles
- **Step 1:** convert inertial geodetic to Earth centered Earth Fixed (ECEF)

$$N = \frac{a}{\sqrt{1 - e^2 sin^2(\phi)}}$$

$$\vec{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (N+h)cos(\phi)cos(\lambda) \\ (N+h)cos(\phi)sin(\lambda) \\ ((1-e^2)N+h)sin(\phi) \end{bmatrix}$$

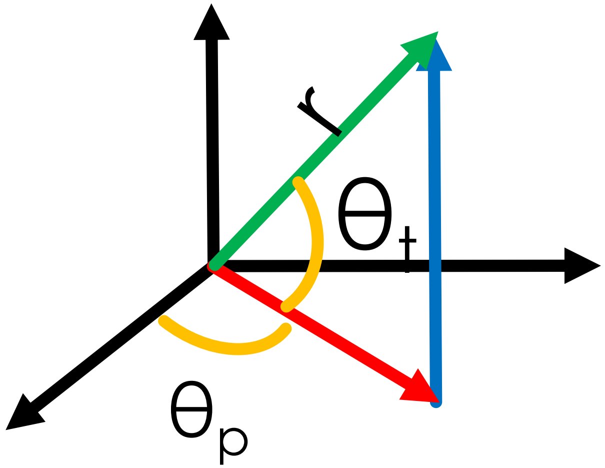


Calculating Servo Rotation Angles Cont.

- **Step 2:** convert ECEF to ENU using direction cosine matrix (DCM)

$$DCM = \begin{bmatrix} -sin(\lambda) & -cos(\lambda)sin(\phi) & cos(\lambda)cos(\phi) \\ cos(\lambda) & -sin(\lambda)sin(\phi) & sin(\lambda)cos(\phi) \\ 0 & cos(\phi) & sin(\phi) \end{bmatrix}$$

- **Step 3:** calculate servo rotation angles using projections

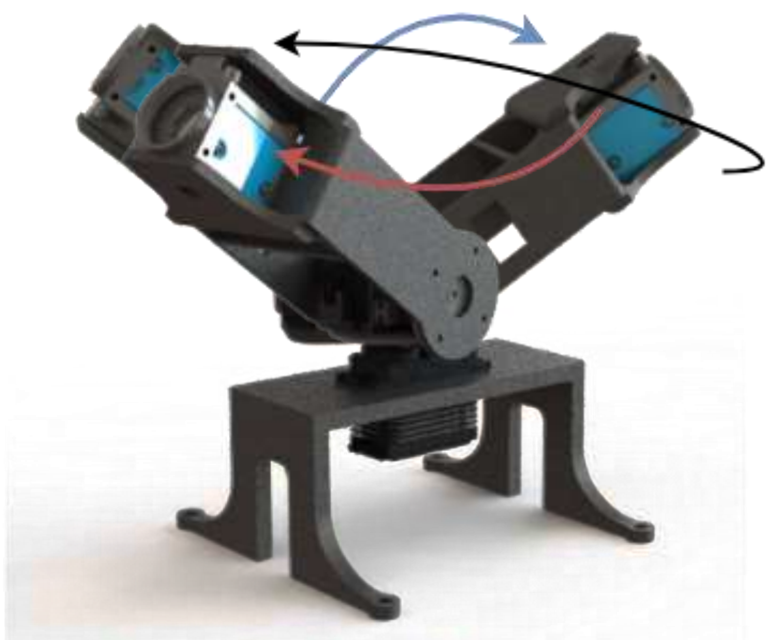


$$\theta_p = tan^{-1}\left(\frac{r_n}{r_e}\right)$$

$$\theta_t = tan^{-1}\left(\frac{r_u}{\sqrt{r_e^2 + r_n^2}}\right)$$

Accounting for Servo Limitations

- "Figure 8" method
  - Pan servo resets to initial position (like a sprinkler)
  - Tilt servo flips to the other side
- Solves wire wrap issue from using continuous rotation
- Maneuver completes within a single second



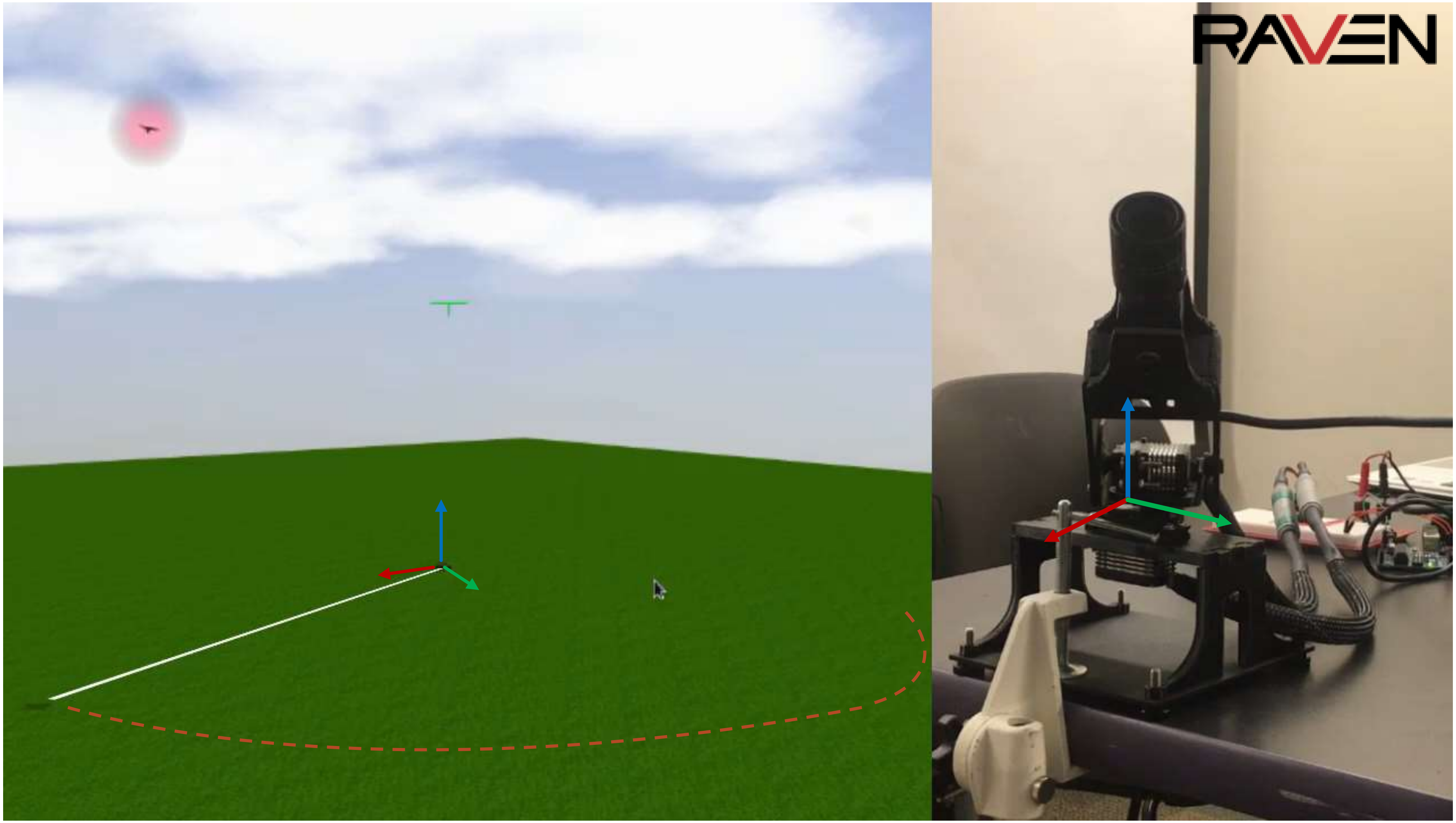
Gazebo Overview

- ROS Simulation Tool
- Provides 3D visualization of systems
- Allows sensor emulation
- Simulates reasonable approximations of dynamics
- **Allows prototyping of RAVEN network**

Gazebo Assumptions

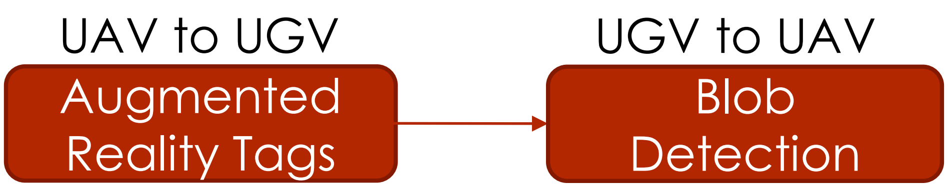
- Sensors are emulated
  - Sensor traits are not yet configured
  - Sensor data source will change
- Physical characteristics
  - Magnitude of losses are unknown
  - Can change with environment

UGV Gimbal Demonstration



Confirm - Visual Detection

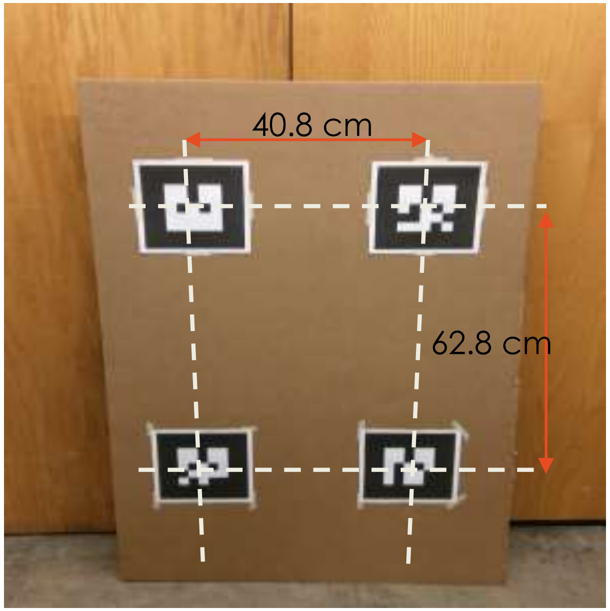
Design Requirement	Description
3.1	UAV mounted vision tracking system shall be able to identify presence of UGV in frame.
3.3	UGV mounted vision tracking system shall be able to identify presence of UGV in frame.



Augmented Reality (AR) Detection

Overview:

- Orientable high contrast binary patterns.
- Robust to lighting changes.
- Easily implemented in ROS. (ar_track_alvar)
- AR tag bundle improves accuracy.



Testing:

Need:

- Characterize the maximum AR detection range.

Method:

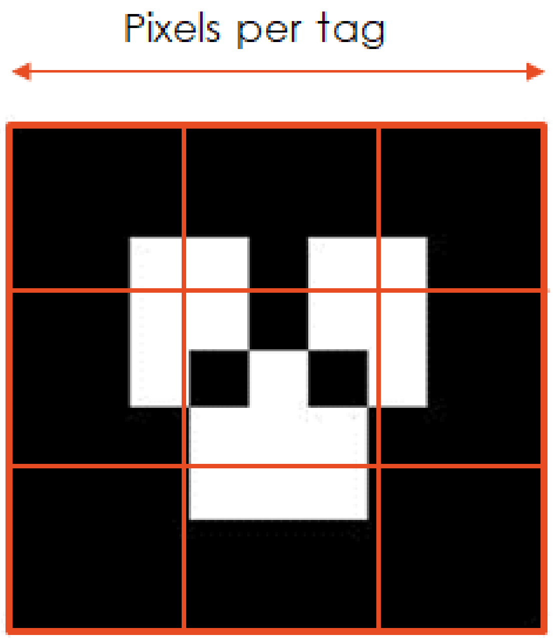
- Testing performed with Flir Flea3 Machine vision camera.
- 10cm tags and 18cm tags used.

Performance Metric:

- Number of pixels per linear tag dimension.

AR Testing Results

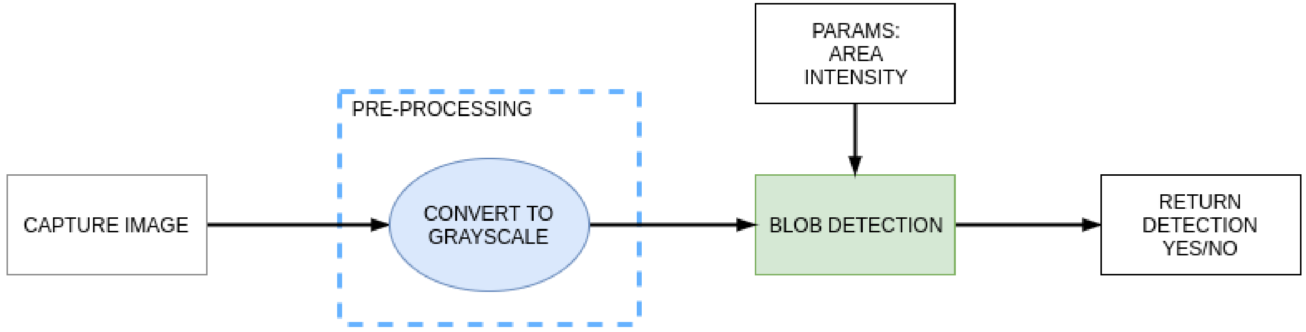
Test	AR Tag Size	Max Detection Range	Pixels per tag
Webcam (PDR) 5.5cm	5.5 cm	2.5 m	27.9 pix
Flea 3	10 cm	25.3 m	29.7 pix
Flea 3	18 cm	35.6 m	37.7 pix
DFK 33UX249 w/ 16mm lens	18 cm	>30 m	39.9 pix (@ 30 m)



- DFK 33UX249 with 16 mm lens using 18 cm tags
  - Will have more pixels per tag than Flea 3
- Detection threshold is exceeded.

Blob Detection - Overview

- Blob (binary large object) detection: identify clusters of pixels with similar characteristics, e.g. color, intensity
- OpenCV libraries for blob detection, and processing steps
- Assumptions made to constrain problem:
  - High contrast between target and background
  - Accurate information about target location and motion relative to camera
  - Background features are connected to edges of image frame (e.g. trees, buildings)

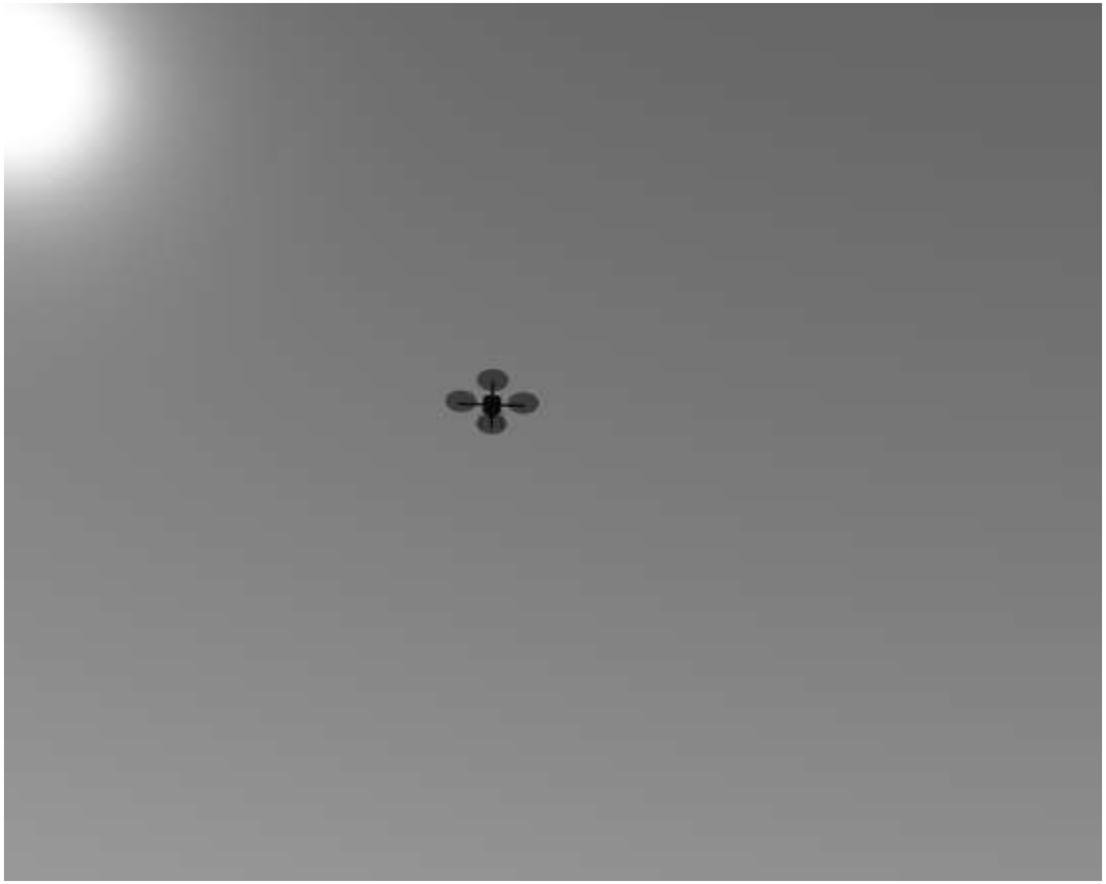


Blob Detection -- Process

Initial image

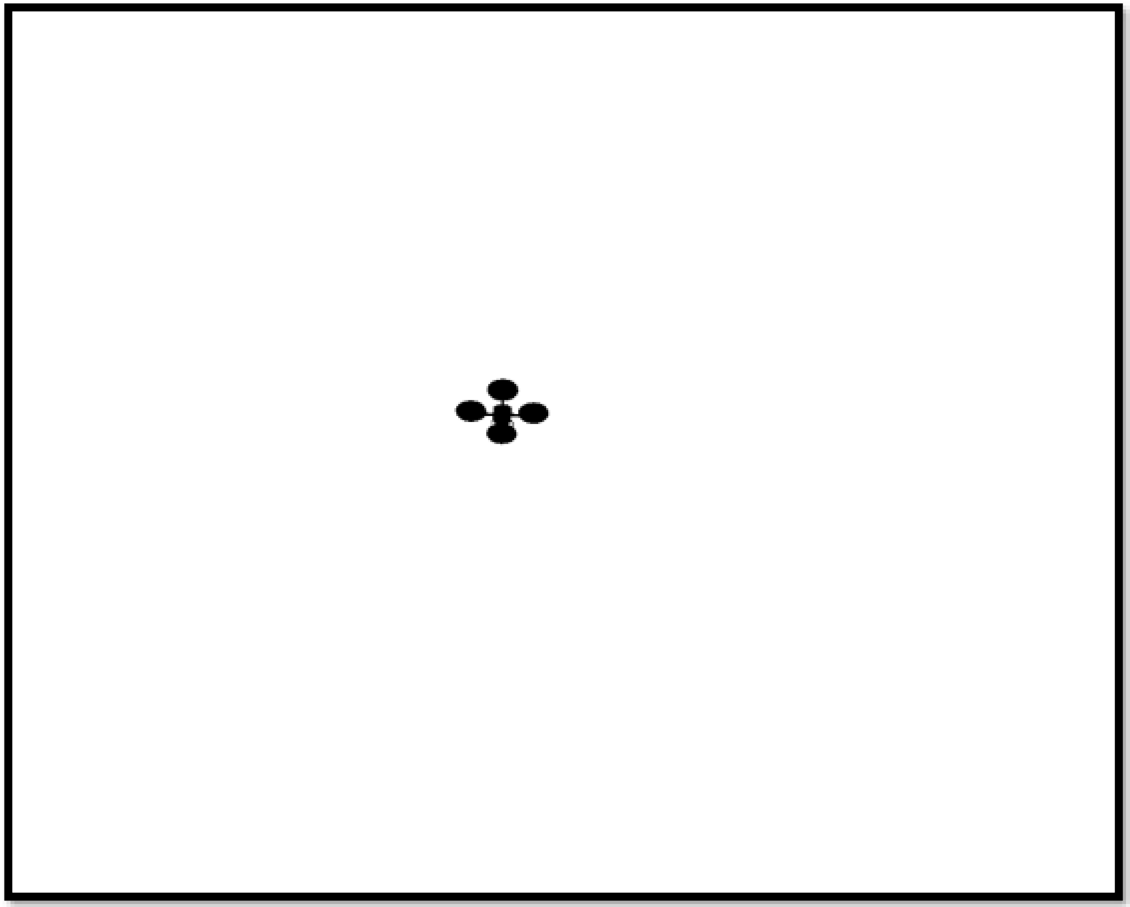
Blob Detection -- Process

Convert to grayscale



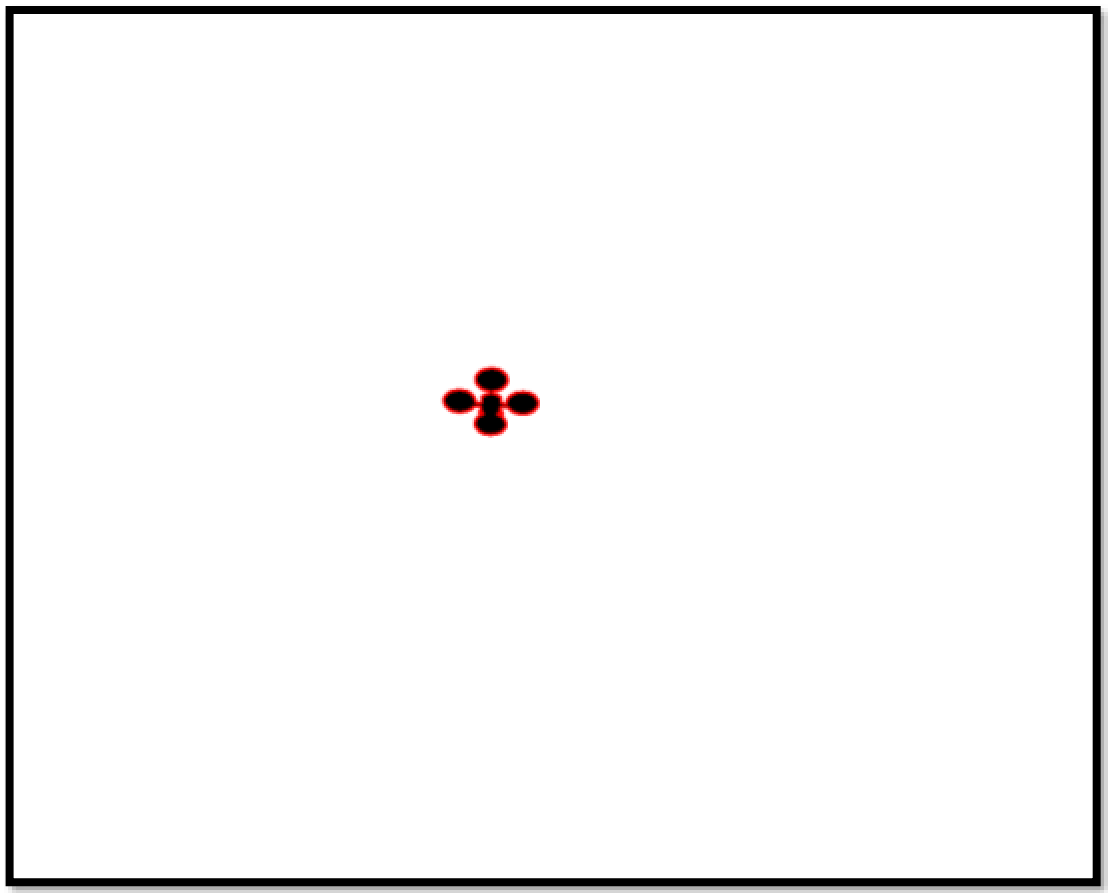
Blob Detection -- Process

Threshold for binary image



Blob Detection -- Process

Find contours



Blob Detection -- Process

Find center and mark detection

Blob Detection - Demonstration

Conclusions:

- For blue sky, and sun in frame:
- DR 3.3 satisfied

Project Risks

Significant Project Risks

Risk	Description	Mitigation
1	UAV stability is poor	Incremental build up with proxy masses
2	Field of view is insufficient	Lens and camera combination FOV will be determined before integration via testing
3	Noise affecting GPS accuracy	Antenna design and electronics placement will reduce interference
4	Pulse Width Modulation not working	PWM motor control will be ground tests
5	Communication between Ardupilot and ODROID fails	Confirmation in testing of serial to USB data transfer
6	Lead times for products	Suppliers have been contacted to check stock, parts have been identified so ordering can occur immediately

Likelihood						
80-100%	10					
60-80%	8					
40-60%	6				1,3	
20-40%	4			4	2,5,6	
0-20%	2					
		2	4	6	8	10
Severity		Insignificant	Minimal	Moderate	Significant	Catastrophic

Conclusions:

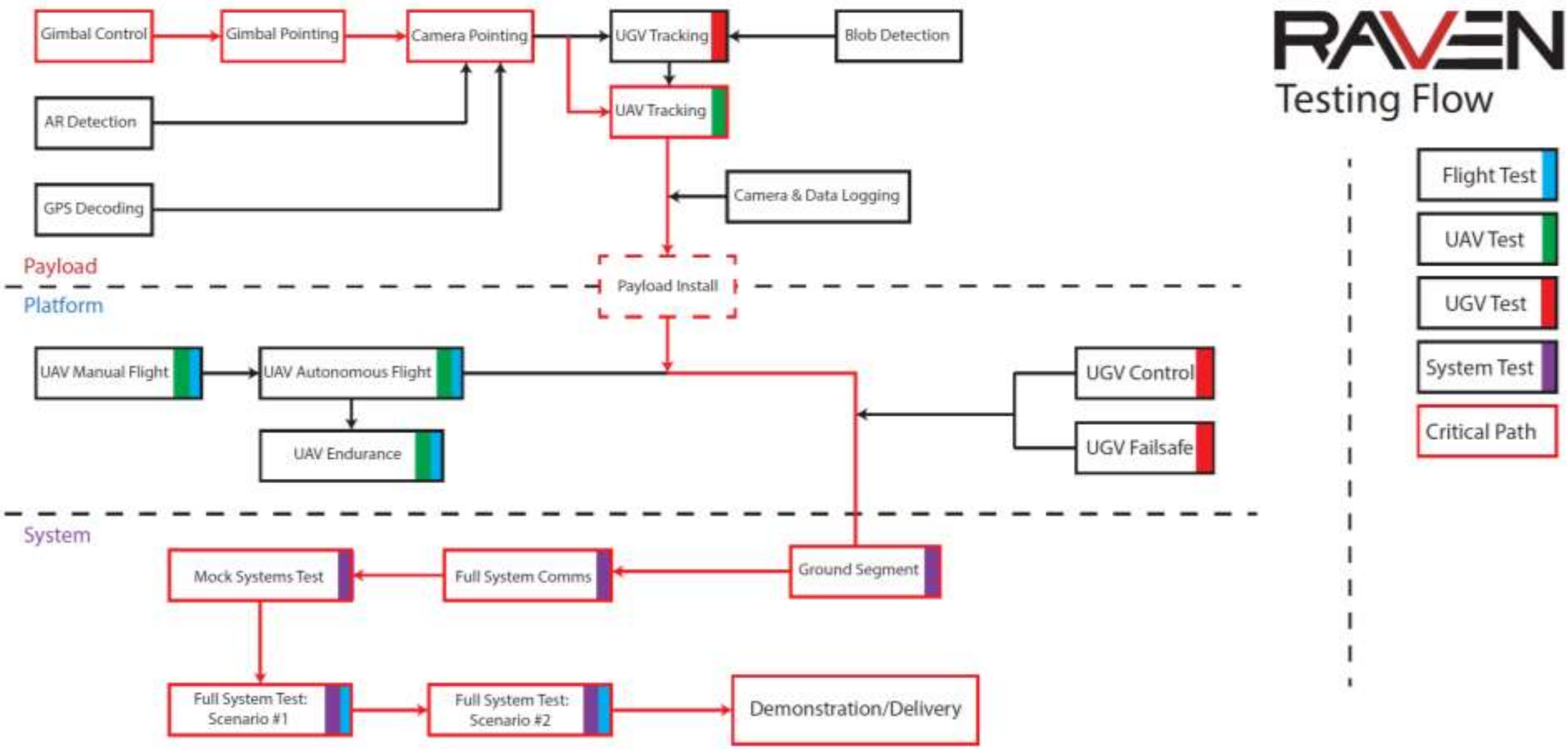
- Quantify GPS accuracy early to facilitate project success
- Lead times must be accounted for by ordering before break
- Communication between hardware must be confirmed as soon as possible

Testing, Verification & Validation

Testing Methodology/Approach

- Incremental Test Buildup to minimize risks
  - Using weights to simulate payload when not needed
- Indoor testing whenever possible
  - RECUV indoor flight Space (Allows more testing flexibility)
- Parallelize platform from payload to allow multiple teams to work on hardware at the same time

Testing Flow



Conclusions:

- Critical intermediary testing must begin soon
- Rigorous scheduling to keep testing on track
- Able to parallelize platform and payload effectively

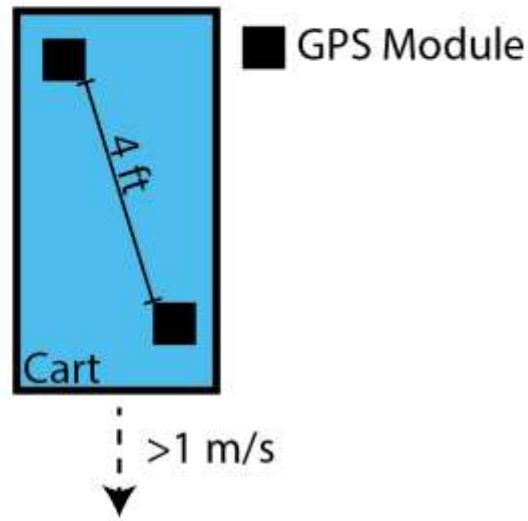
Verification Methods

FR	Summary	Verification Method	Testing Required
1.0	Collect for 15 min	UAV Endurance, Full System Test	✓
2.0	Removable Storage System	Inspection	
3.0	Other vehicle in 90% of frames, no more than three seconds without other vehicle in frame	GPS Characterization, Full System Test	✓
4.0	Minimum resolution of 3 inches/pixel	Camera Characterization	✓
5.0	Operate on a fair weathered day	Full System Test	✓
6.0	Do not use any DJI products	Inspection	
7.0	Use Clearpath Jackal	Inspection	
8.0	Communicate flight and navigation data to ground stations	Communications test, Full system test	✓
9.0	Communicate over ISM frequencies	Inspection	
10.0	System shall use customer specified interfaces	Inspection	

Conclusion:
Full system test and GPS characterization critical to system success

GPS Characterization

- Executed on the business field
- Verify GPS error model
  - DRs: 3.1, 8.4
- Overview:
  - Two modules on a cart, moving across field
  - Modules are a known, fixed distance apart (4 ft)
  - Both logging GPS location



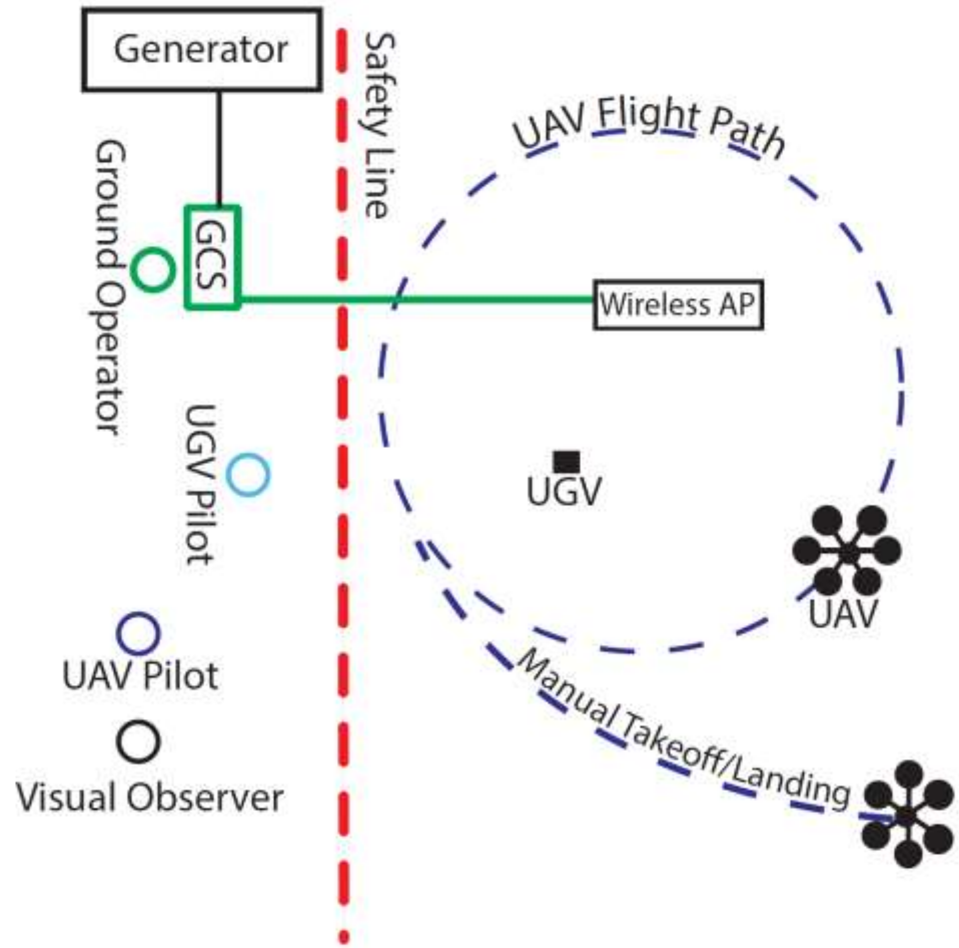
- Measuring:
  - GPS Location (1 Hz)
  - Distance Between modules (Ruler)

- Allows relative position error to be measured using known difference in position.

Conclusions:
- Validate GPS error model
- Verify DGPS/RTK operation

Full System Test

- Executed at CU Boulder South Campus
- UGV placed in operation area
- Integrated system is validated against mission profile
- Collecting:
  - Flight Time (Stopwatch)
  - GPS (1 Hz)
  - Vision Data (10 Hz)
    - Must have vehicle in frame 90% of time
  - Status (1 Hz)
  - Navigation Data (10 Hz)

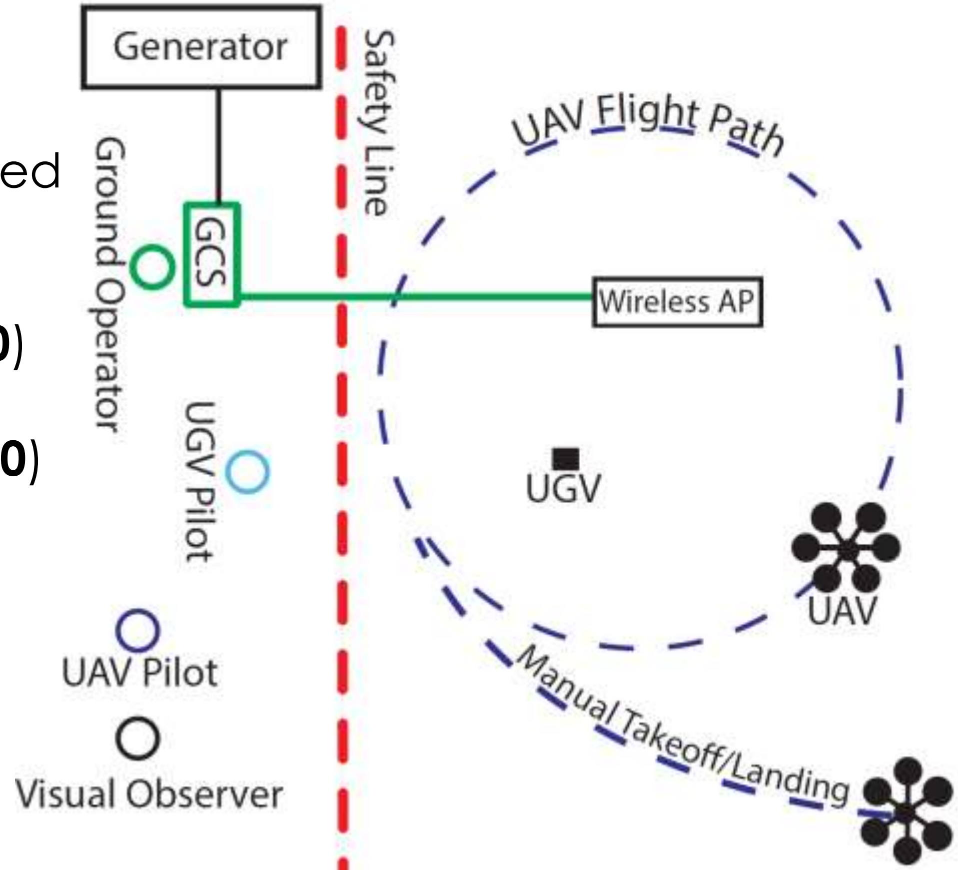


Full System Test Procedure

Approx time: Operation
T – 10:00 UGV Powered and positioned
T – 5:00 Payload Powered on (**FR 4.0**)
T – 2:30 Operation area live
T – 2:00 Transmission Begins (**FR 8.0,9.0**)
T – 1:00 UAV Takeoff
T + 0:00 Data Collection Begins (**FR 3.0**)
T + 15:00 Data Collection Ends
T + 15:30 UAV Lands
T + 16:00 All Stop
T + 17:00 All Safe Call

Data offloaded (**FR 2.0**)

Verify data collected meets requirements



Conclusions:
- Full System Test able to verify operation of system
- Test site available
- Detailed procedure in work

Major Testing Risks

Risk	Description	Mitigation
1.1	UAV crash with major damage	Incremental Build Up and testing, Spare structural carbon rods
1.2	UAV crash with catastrophic damage, irreparable damage to the UAV system or payload	
2.0	Component damage	Payload installed only when required
3.0	Testing takes too long	Margin in testing schedule
4.0	Li-Po damage	Observed charging, charging in Li-Po sack

Likelihood						
80-100%	10					
60-80%	8				1.1	
40-60%	6					
20-40%	4		3.0	4.0		1.2
0-20%	2					2.0
		2	4	6	8	10
Severity		Insignificant	Minimal	Moderate	Significant	Catastrophic

Conclusions:
- ► Flying UAV is inherently risky
- ► Some components are irreplaceable due to budget
- ► Project must be able to pivot testing strategies if failure occurs

Project Planning

Organizational Structure

RAVEN

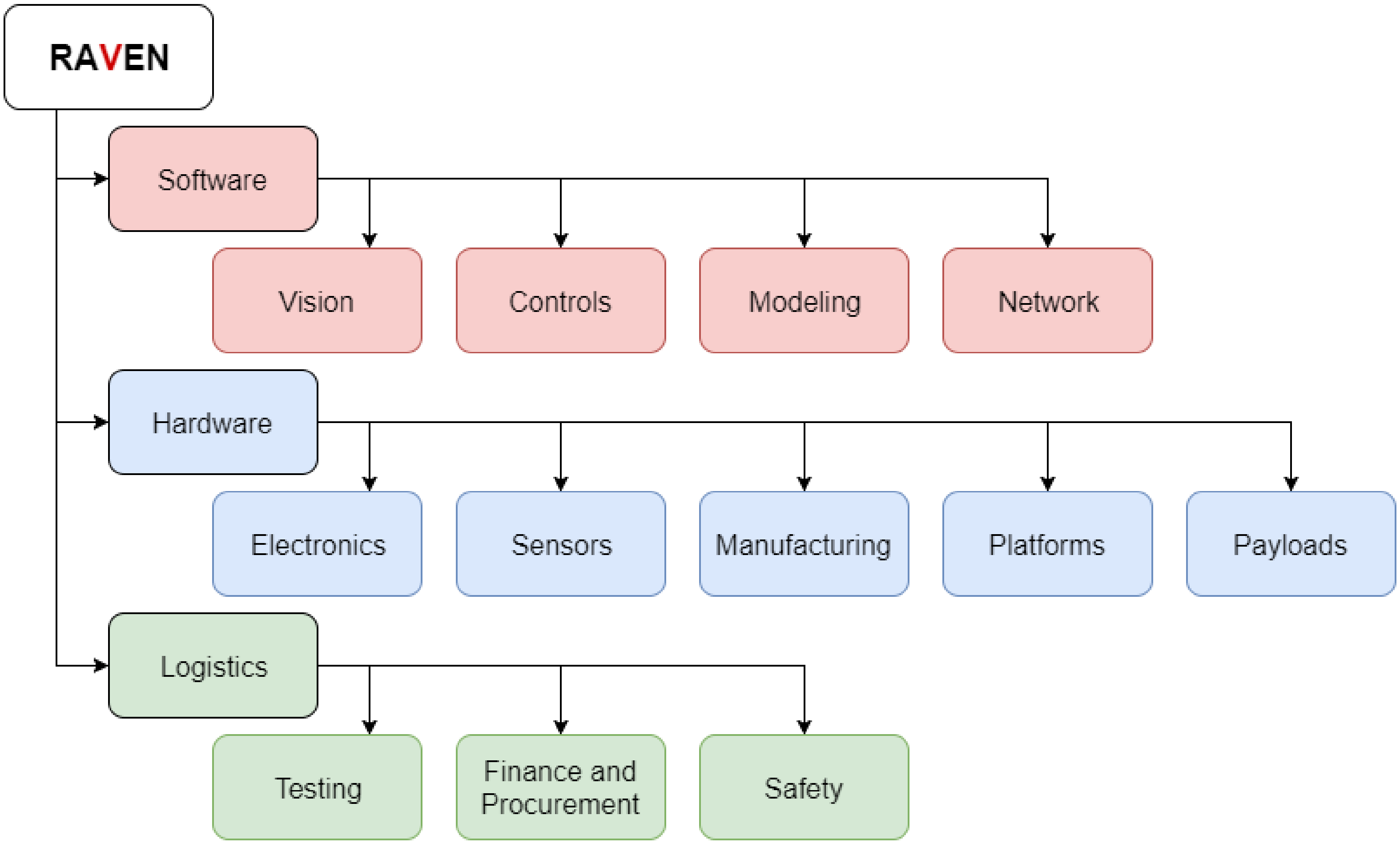
- Customer: Nisar Ahmed
- Director: Dale Lawrence
- Advisor: Torin Clark

- PM: Ryan Wall
- Testing: Cody Charland
- CFO: Ryan Blay
- Systems Eng.: Brendan Boyd
- Safety: Alex Swindell

- Software: Nathan Levigne
- Hardware: Rolf Andrada

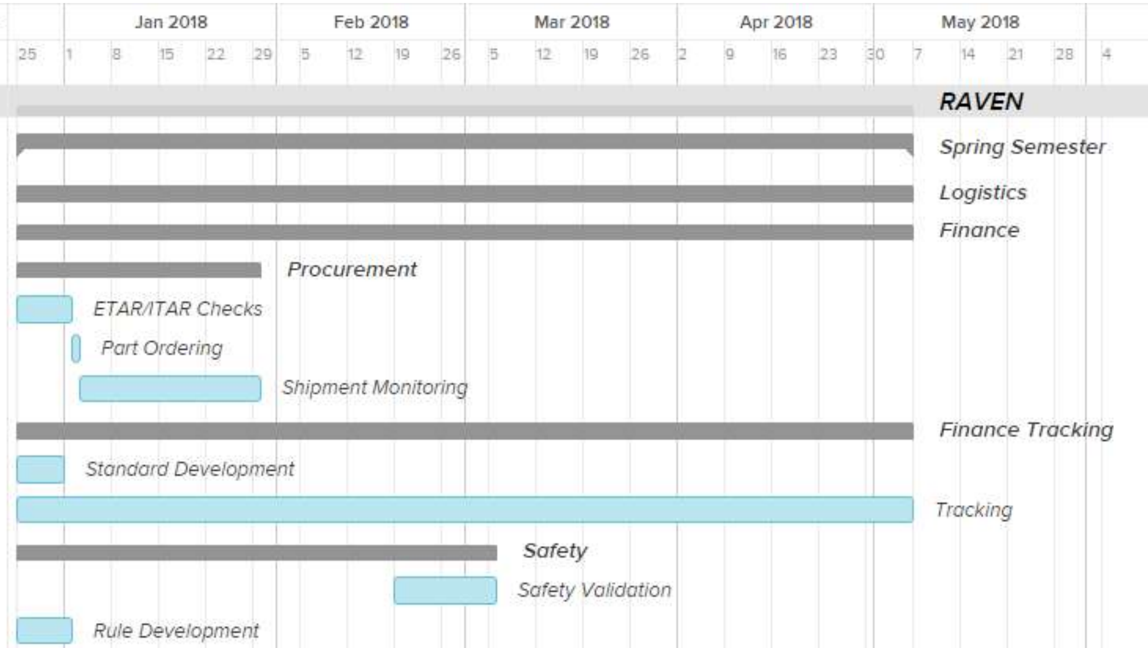
- Vision: Ian Loefgren
- Network: Alex Swindell
- Modeling: Rishab Gangopadhyay
- Electronics: Nikolas Setiawan
- P & P: Torfinn Johnsrud
- Sensors: Ryan Blay

Work Breakdown Structure - Overview



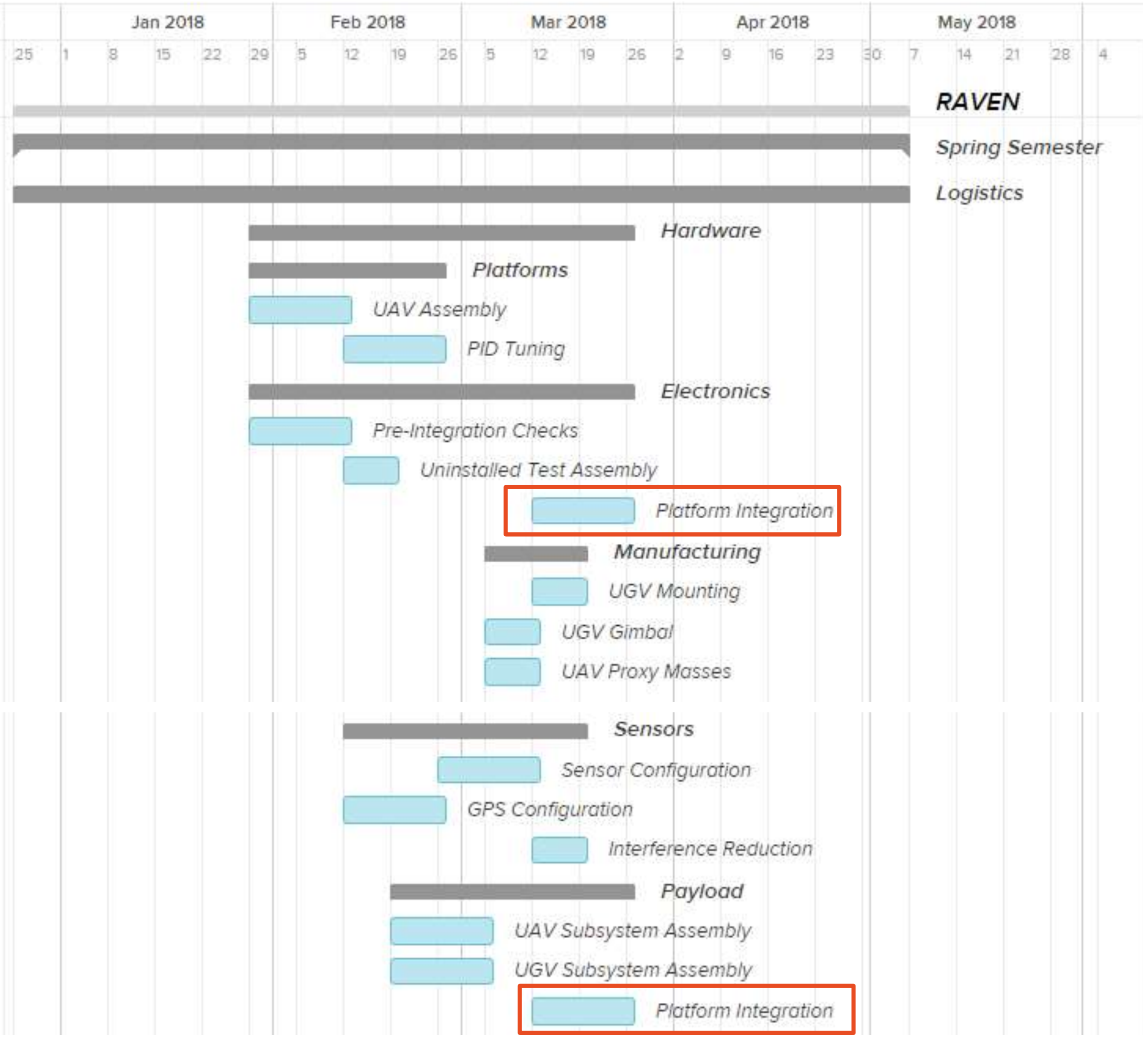
Work Flow - Logistics

	People Assigned	% Complete
RAVEN		0%
▼ Spring Semester		0%
▼ Logistics		0%
▼ Finance		0%
▼ Procurement		0%
ETAR/ITAR Checks	Brendan Boyd, Ryar	0
Part Ordering	Brendan Boyd, Cody	0
Shipment Monitoring	Ryan Blay	0
▼ Finance Tracking		0%
Standard Development	Ryan Blay	0
Tracking	Ryan Blay	0
▼ Safety		0%
Safety Validation	Alexander Swindell,	0
Rule Development	Alexander Swindell	0



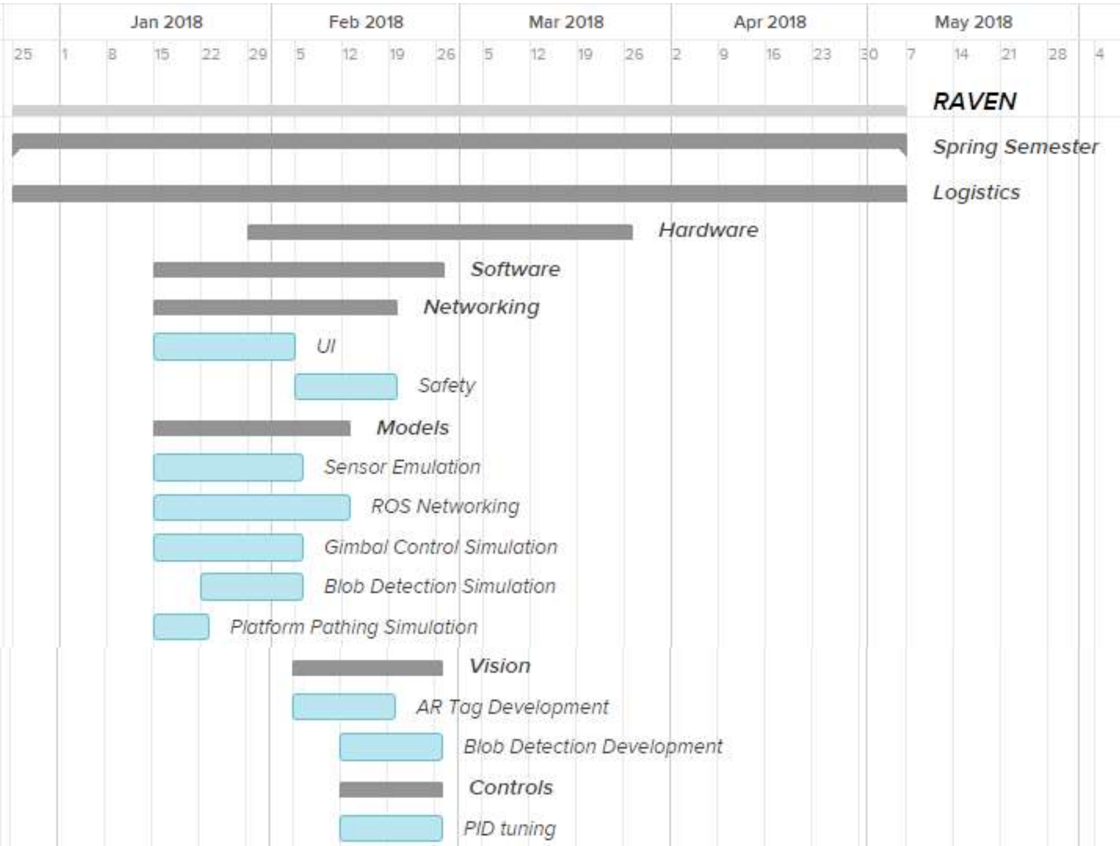
Work Flow - Hardware

	People Assigned	% Complete
RAVEN		0%
▼ Spring Semester		0%
▶ Logistics		0%
▼ Hardware		0%
▼ Platforms		0%
UAV Assembly	Brendan Boyd, Cod	0
PID Tuning	Brendan Boyd, Rolf	0
▼ Electronics		0%
Pre-Integration Checks	Nikolas Setiawan, R	0
Uninstalled Test Assembly	Nikolas Setiawan, R	0
Platform Integration	Brendan Boyd, Cod	0
▼ Manufacturing		0%
UGV Mounting	Rolf Andrada, Torfin	0
UGV Gimbal	Nathan Levigne, Rol	0
UAV Proxy Masses	Cody Charland, Rolf	0
▼ Sensors		0%
Sensor Configuration	Nathan Levigne, Rya	0
GPS Configuration	Nathan Levigne, Rya	0
Interference Reduction	Ryan Blay	0
▼ Payload		0%
UAV Subsystem Assembly	Alexander Swindell,	0
UGV Subsystem Assembly	Alexander Swindell,	0
Platform Integration	Alexander Swindell,	0



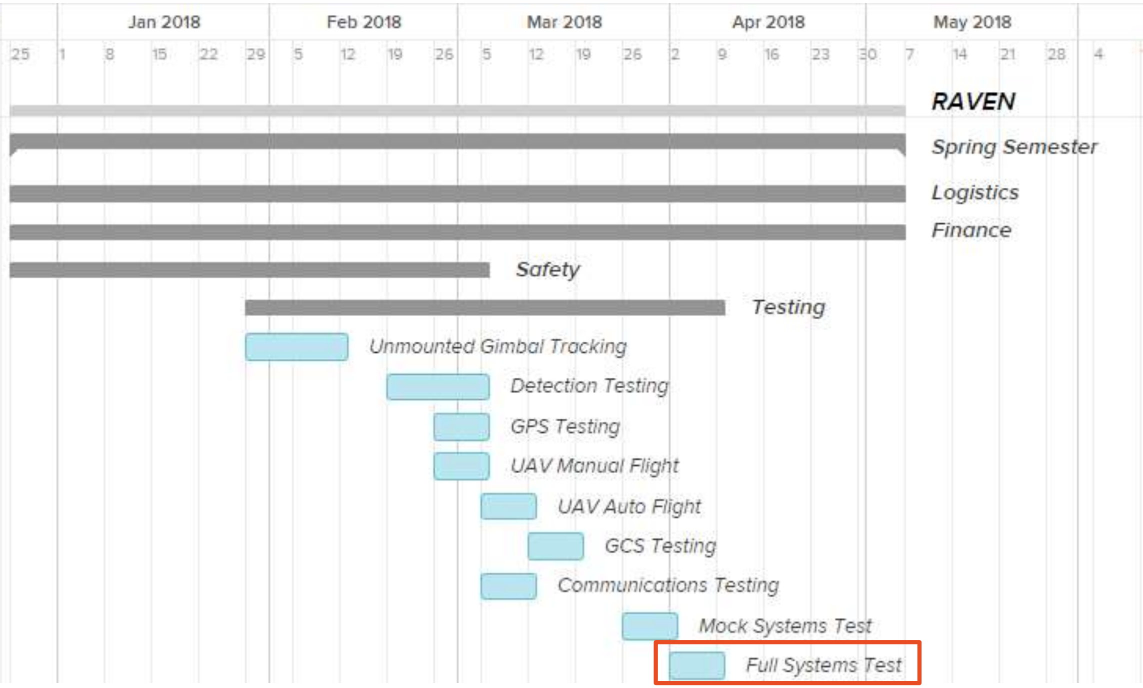
Work Flow – Software

	People Assigned	% Complete
RAVEN		0%
▼ Spring Semester		0%
▶ Logistics		0%
▶ Hardware		0%
▼ Software		0%
▼ Networking		0%
UI	Alexander Swindell	0
Safety	Alexander Swindell	0
▼ Models		0%
Sensor Emulation	Rishab Gangopadhy	0
ROS Networking	Alexander Swindell,	0
Gimbal Control Simulation	Ian Loefgren, Natha	0
Blob Detection Simulation	Ian Loefgren, Rishab	0
Platform Pathing Simulation	Rishab Gangopadhy	0
▼ Vision		0%
AR Tag Development	Ian Loefgren, Torfinn	0
Blob Detection Development	Ian Loefgren, Torfinn	0
▼ Controls		0%
PID tuning	Nathan Levigne, Rol	0



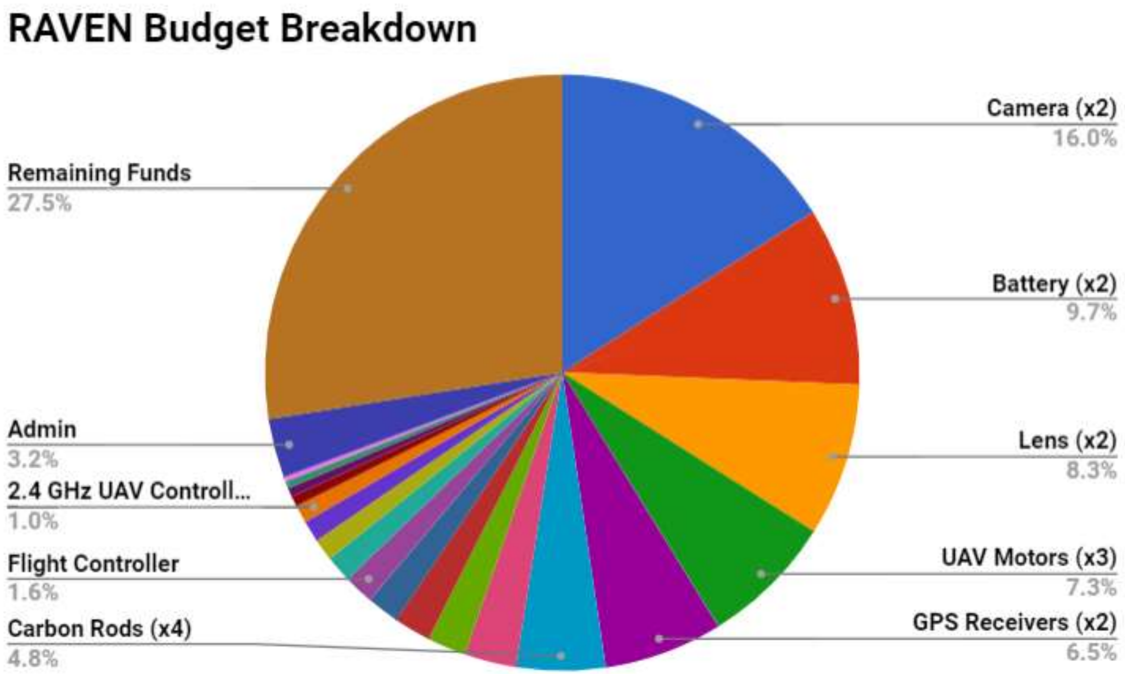
Test Plan

	People Assigned	% Complete
RAVEN		0%
▼ Spring Semester		0%
▼ Logistics		0%
▶ Finance		0%
▶ Safety		0%
▼ Testing		0%
Unmounted Gimbal Tracking	Ian Loefgren, Natha	0
Detection Testing	Ian Loefgren, Rishab	0
GPS Testing	Cody Charland, Rya	0
UAV Manual Flight	Cody Charland, Niko	0
UAV Auto Flight	Alexander Swindell,	0
GCS Testing	Alexander Swindell,	0
Communications Testing	Alexander Swindell,	0
Mock Systems Test	Alexander Swindell,	0
Full Systems Test	Alexander Swindell,	0



Cost Plan

Financial Summary	
System	Cost
Cameras (x2)	$ 990.00
Batteries (x2)	$ 600.00
Lenses (x2)	$ 515.00
T-Motor Brushless Motors (x3)	$ 450.00
C94-M8P GPS Units (x2)	$ 400.00
Carbon Rods (x4)	$ 300.00
UAV Gimbal	$ 175.00
UAV CPU (x2)	$ 130.00
UAV Frame	$ 125.00
Router	$ 110.00
UAV Flight Controller	$ 100.00
Data Storage (x2)	$ 90.00
Propellers (x18)	$ 75.00
ESC (x6)	$ 72.00
UAV Controller	$ 60.00
Telemetry Radio	$ 35.00
Voltage Regulators	$ 30.00
Ethernet Cables	$ 24.00
UAV Transceiver	$ 15.00
Admin	$ 200.00
Remaining Funds	$1,704.00
Total	$ 6,000.00



Engineering Excellence Fund

EEF grant: $1000

Questions?

References

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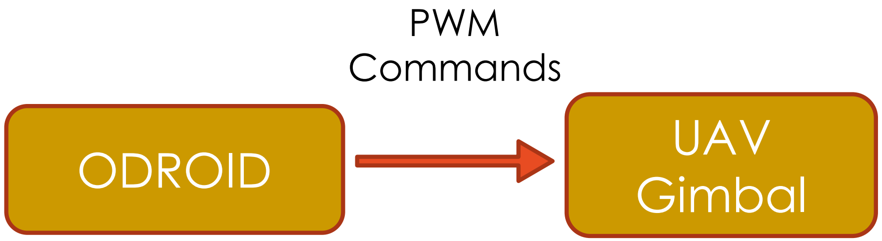
Index

Back up Slides

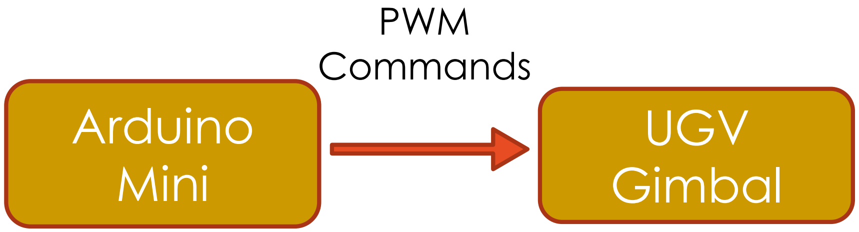
Index

Acquisition Overview

- ODROID XU4 sends PWM commands to Feiyu-Tech 3-axis gimbal controller



- Arduino Mini 05 sends PWM commands to 2 x 180° servos
  - Hitec HS-7950TH servos
  - Implement "Figure 8" method due to 180° limit



Communications System Test

- Conducted at South Boulder Campus
- Verify data/telemetry/command range
  - DR 8.2, 8.3, 8.5
- Validate data models
  - DR 9.1, 9.2
- Assess flight ready status of communications system

Overview:

1. Props off, UGV on blocks
2. UAV moved to >30 m from GCS and UGV
3. UAV commanded to take off
4. Auto flight sequence commenced
5. Auto/Manual flight toggled
6. Emergency land command sent
7. UAV moved and sequence repeated until COMMS unreliable or ROS node failure

Data collection performed by RAVEN natively, external data collection systems unnecessary

Conclusions:

- Assess flightworthiness of comms
- Verify operational range of system

Project Development: Communications

Design	PDD	CDD	PDR	CDR	Decision
Ground Control	-	2 ground stations	-	-	Team Provided
Network Configuration	-	2.4 GHz and 902 MHz	2.4 GHz, 2.4 GHz, and 915 MHz	-	Sik Telemetry Radio V2 TGYi 6s
GPS	-	Integrated Board	Integrated RTK GPS boards	-	C94-M8P-2
Ground UI	-	-	-	QT	QT
Storage	Micro SD	Micro SD	Micro SD / Flash USB	Micro SD	EVO Select

Project Development: Vehicle Hardware

Design	PDD	CDD	PDR	CDR	Decision
UAV Frame	-	Quadrotor	Hexarotor	-	TAROT FY 690s
UAV Gimbal	-	3 axis, brushless	-	-	FY MiNi 3D Pro
Onboard CPU	-	External	-	-	Odriod XU4
UAV Battery	-	LiPo	-	-	
UGV	Customer Provided	-	-	-	Clearpath Jackal
UGV Gimbal	-	2 axis, servo	-	-	In House
Flight Controller	-	Autonomous	-	-	Pix Racer

Project Development: Vision System

Design	PDD	CDD	PDR	CDR	Decision
Camera Shutter	-	Global Shutter	-	-	DFK 33Ux249
Camera Configuration	-	Monocular	-	-	" "
Color Response	-	Color	-	-	" "
Lens	-	Prime Lens	12 mm Prime Lens	-	M112FM12
UAV Tracking Method	-	GPS, Sensor, and Visual Tracking	Combined w/ AR Tags	-	Combined w/ AR Tags
UGV Tracking Method	-	GPS, Sensor, and Visual Tracking	Combined w/ Blob Detection	-	Combined w/ Blob Detection

Critical Project Elements

Integration

- Payload & Platform Hardware Integration
- Hardware Compatibility
- Software Architecture

Communications

- Command and Data Sharing

Tracking and Detection

- Determine
- Acquire
- Verify

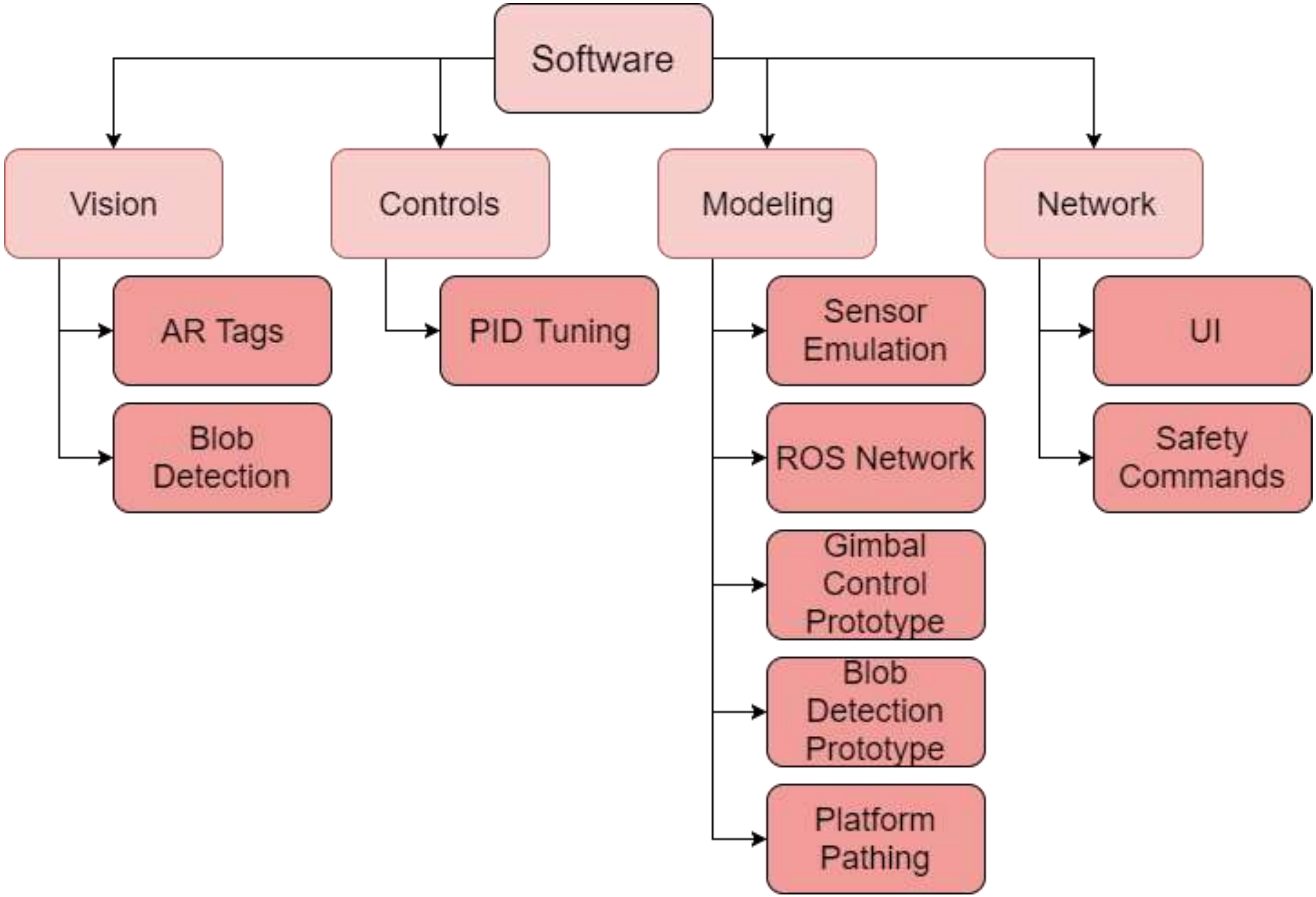
Critical Project Elements

Integration	Communications	Tracking and Detection
• Payload & Platform Hardware Integration • Hardware Compatibility • Software Architecture	• Command and Data Sharing	• Determine • Acquire • Verify

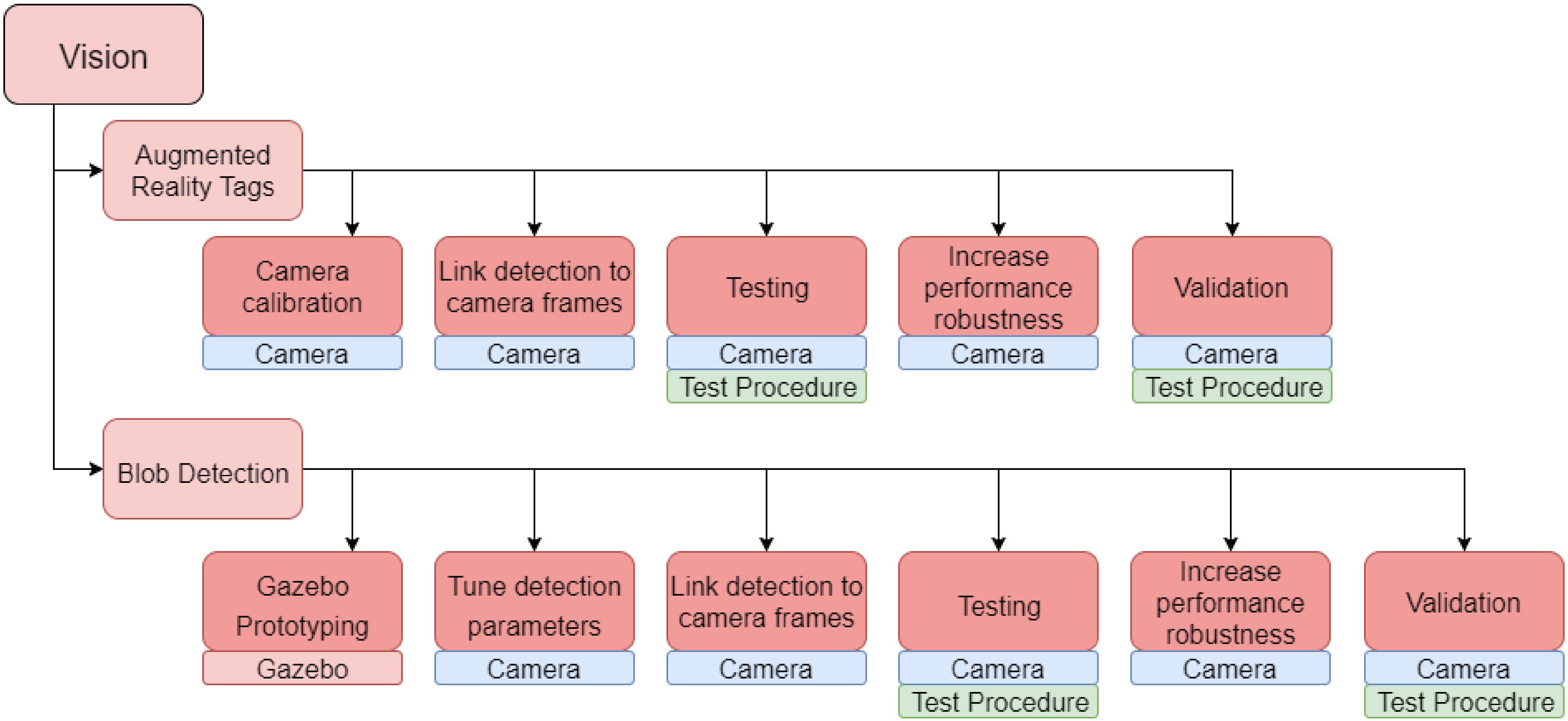
Critical Project Elements

Integration	Communications	Tracking and Detection
• Payload & Platform Hardware Integration • Hardware Compatibility • Software Architecture	• Command and Data Sharing	• Determine • Acquire • Verify

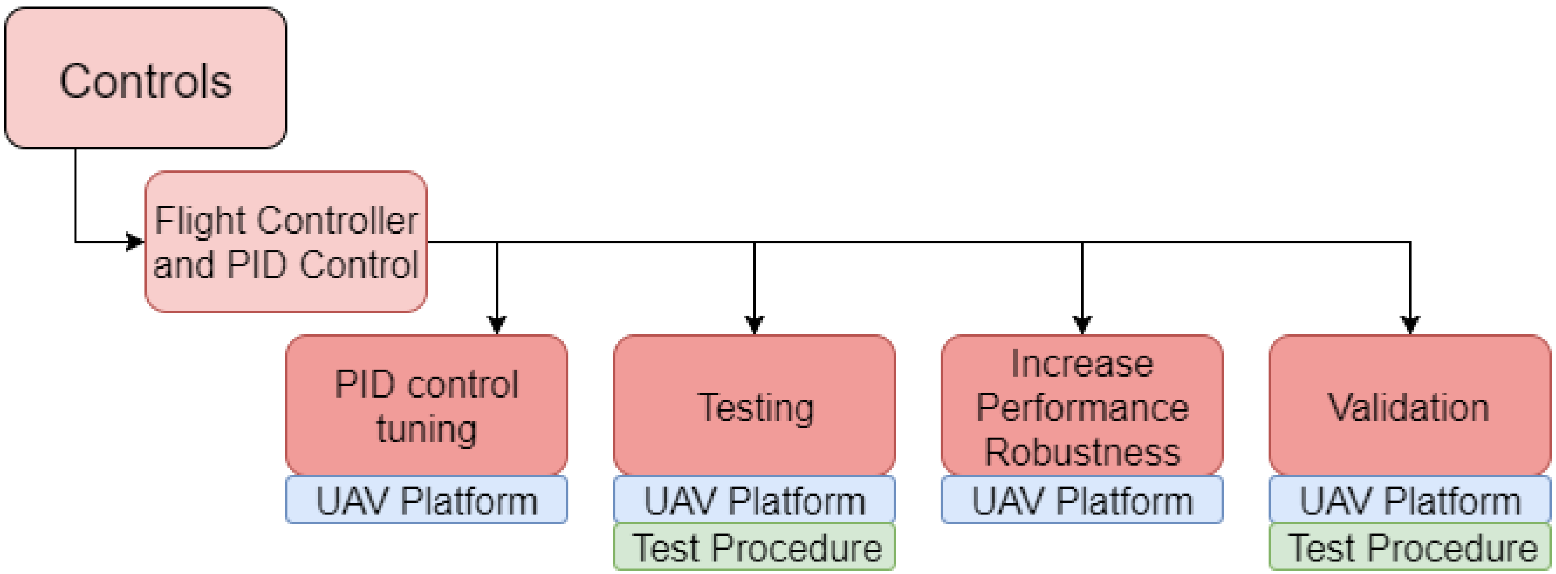
WBS - Software



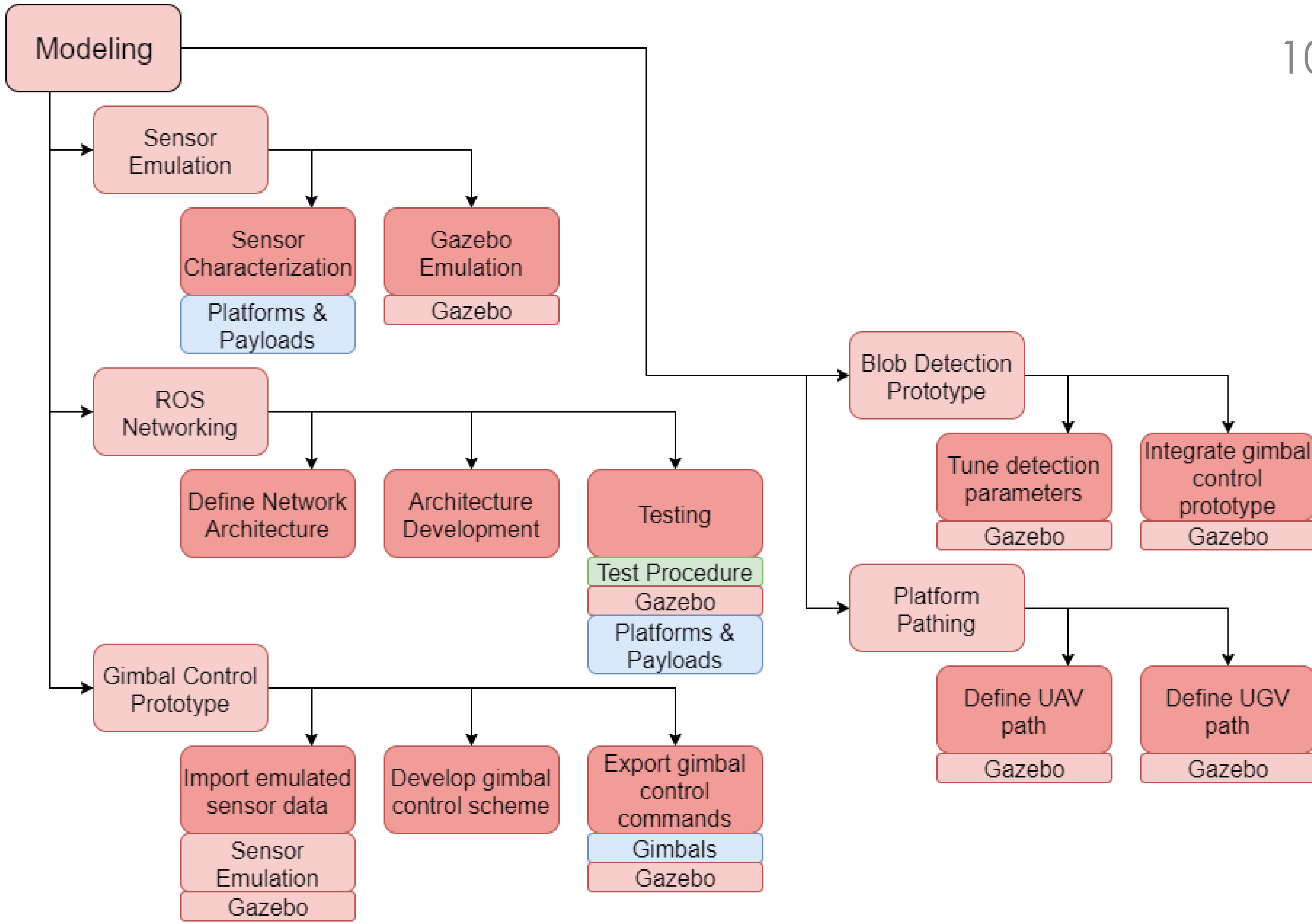
Work Breakdown Structure - Software



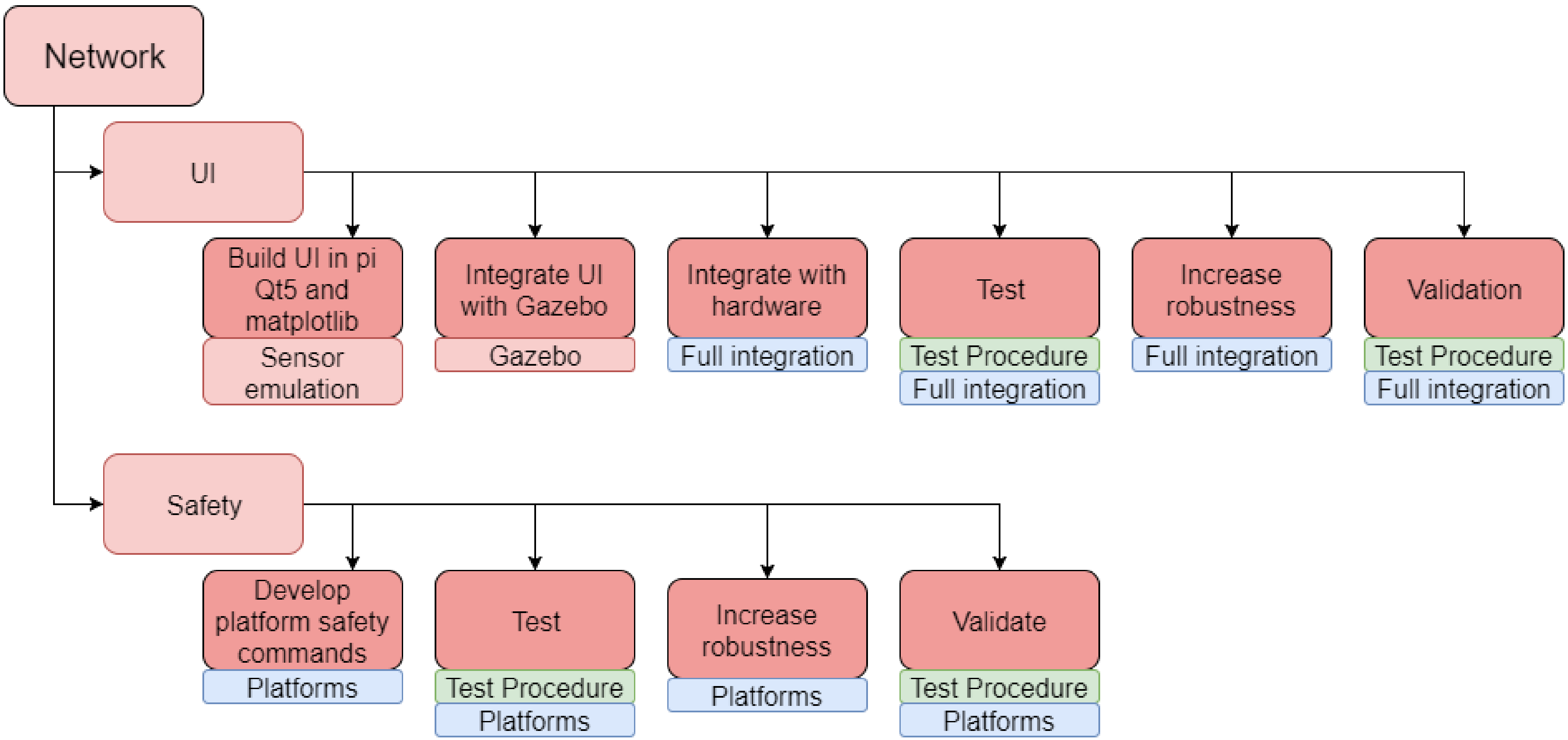
Work Breakdown Structure - Software



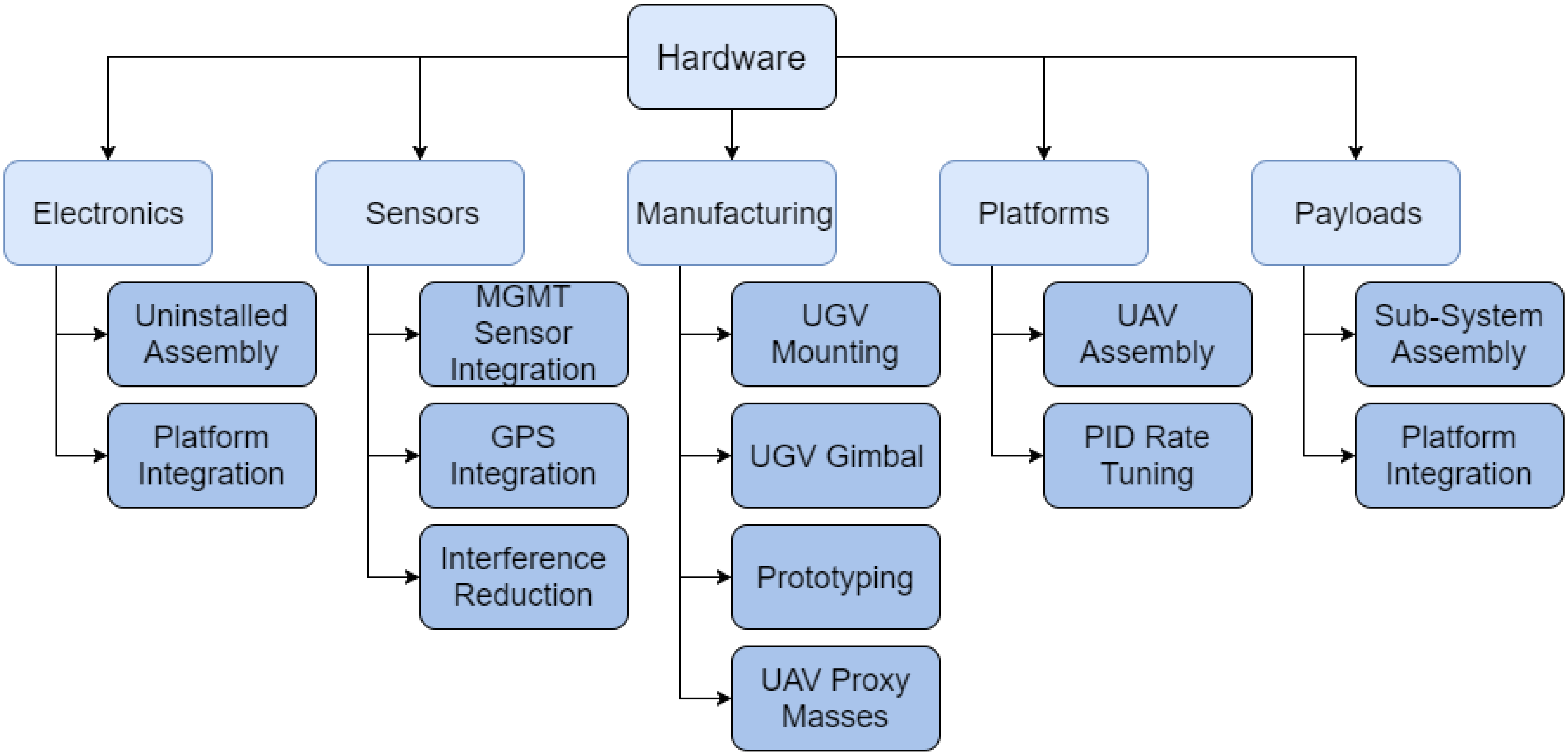
Work Breakdown Structure - Software



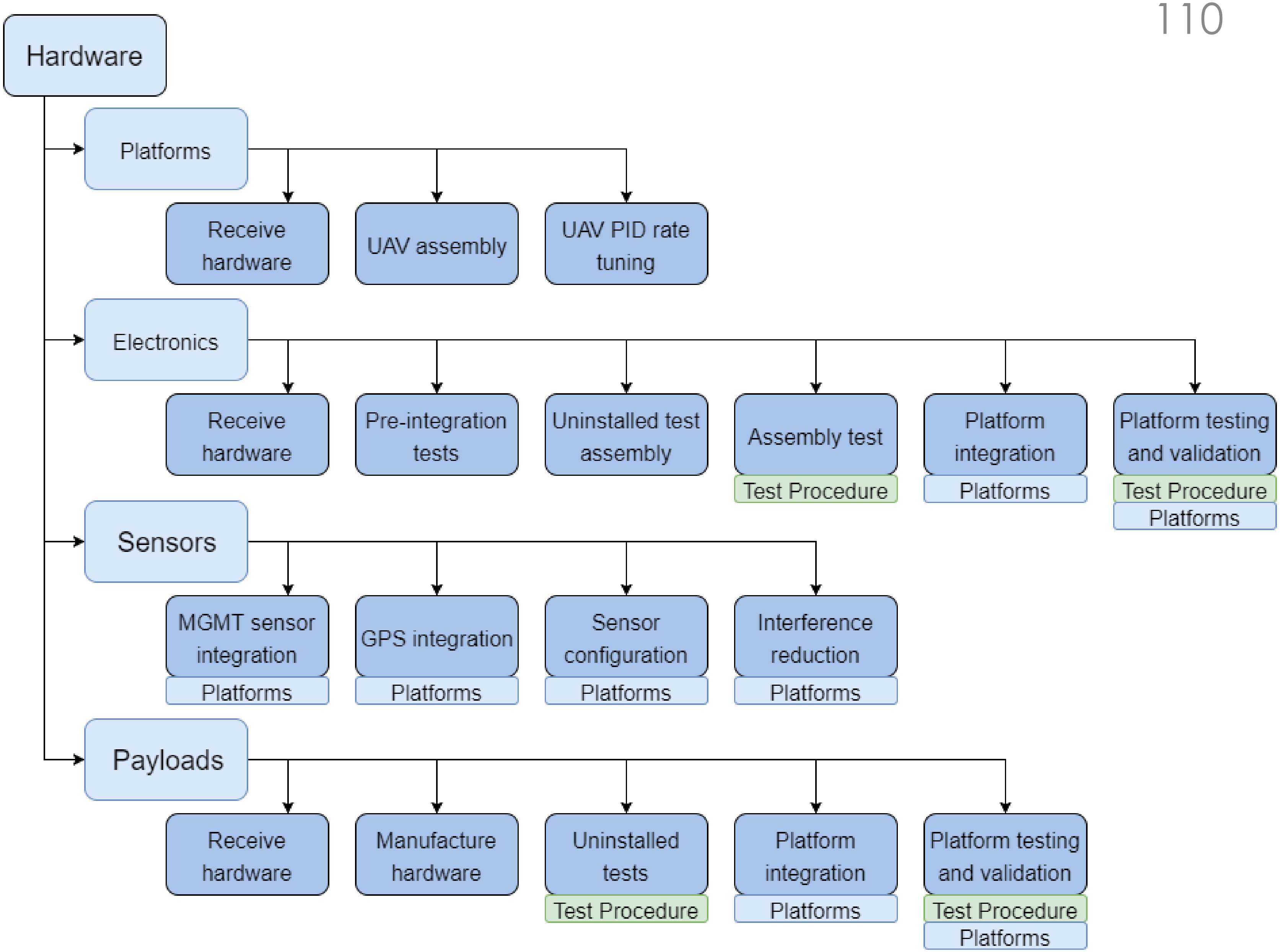
Work Breakdown Structure - Software



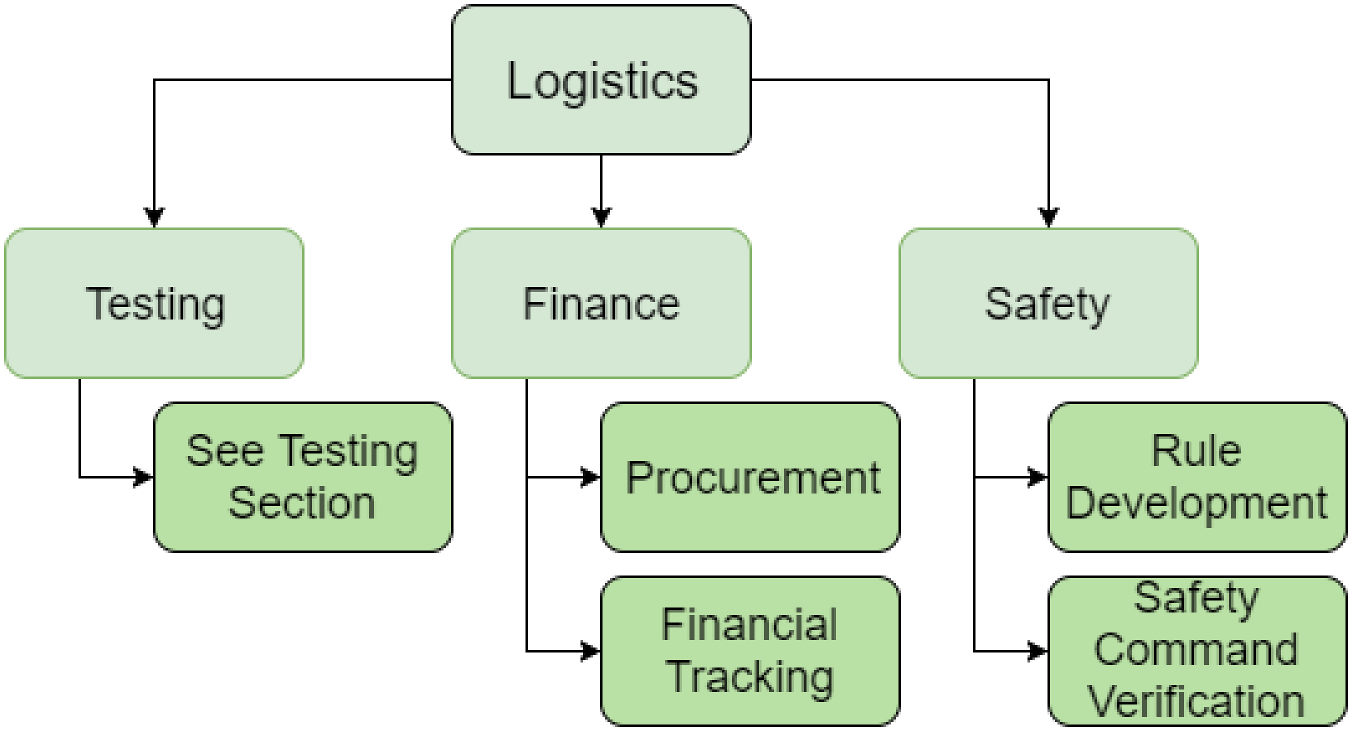
WBS - Hardware



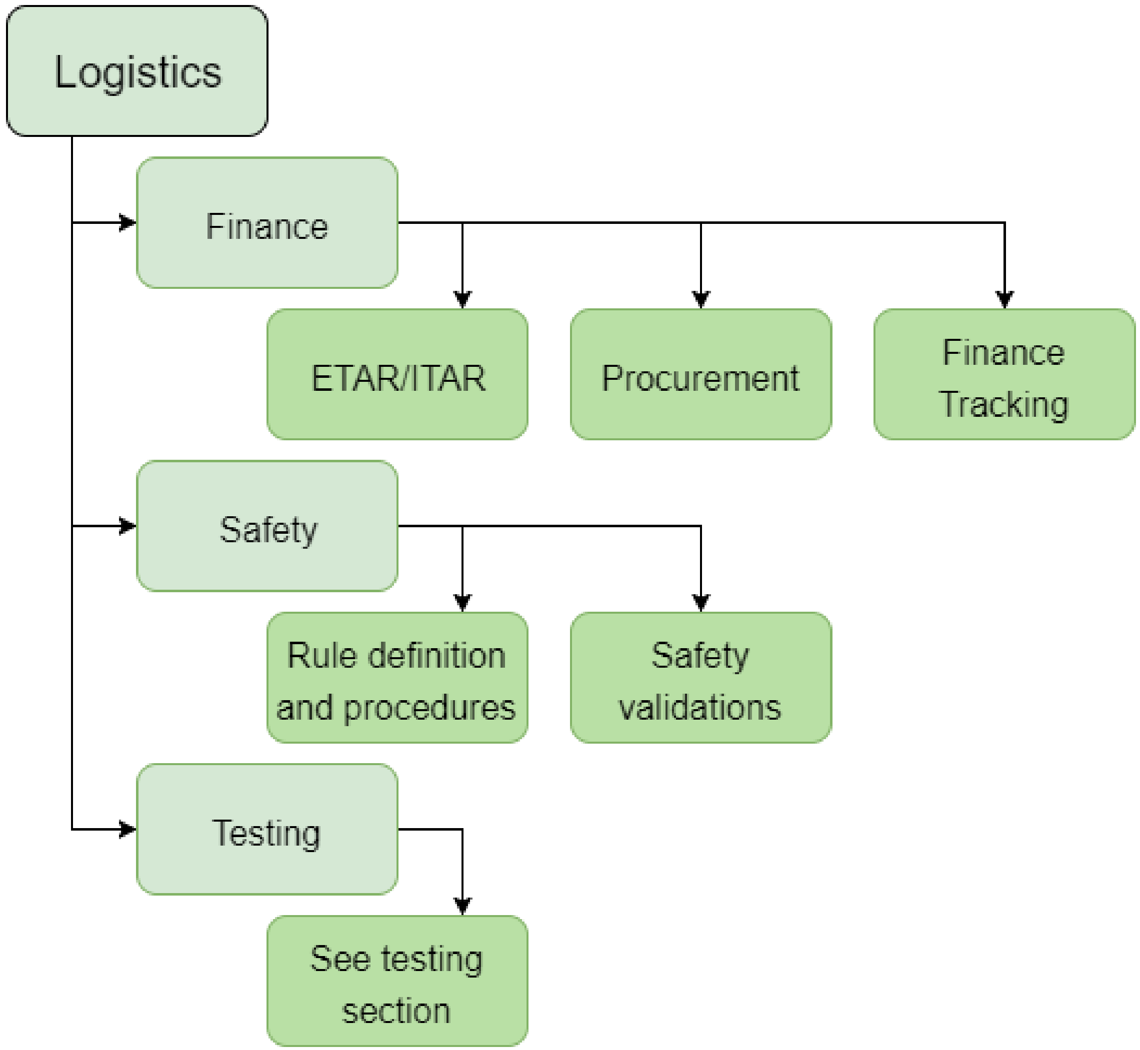
Work Breakdown Structure - Hardware



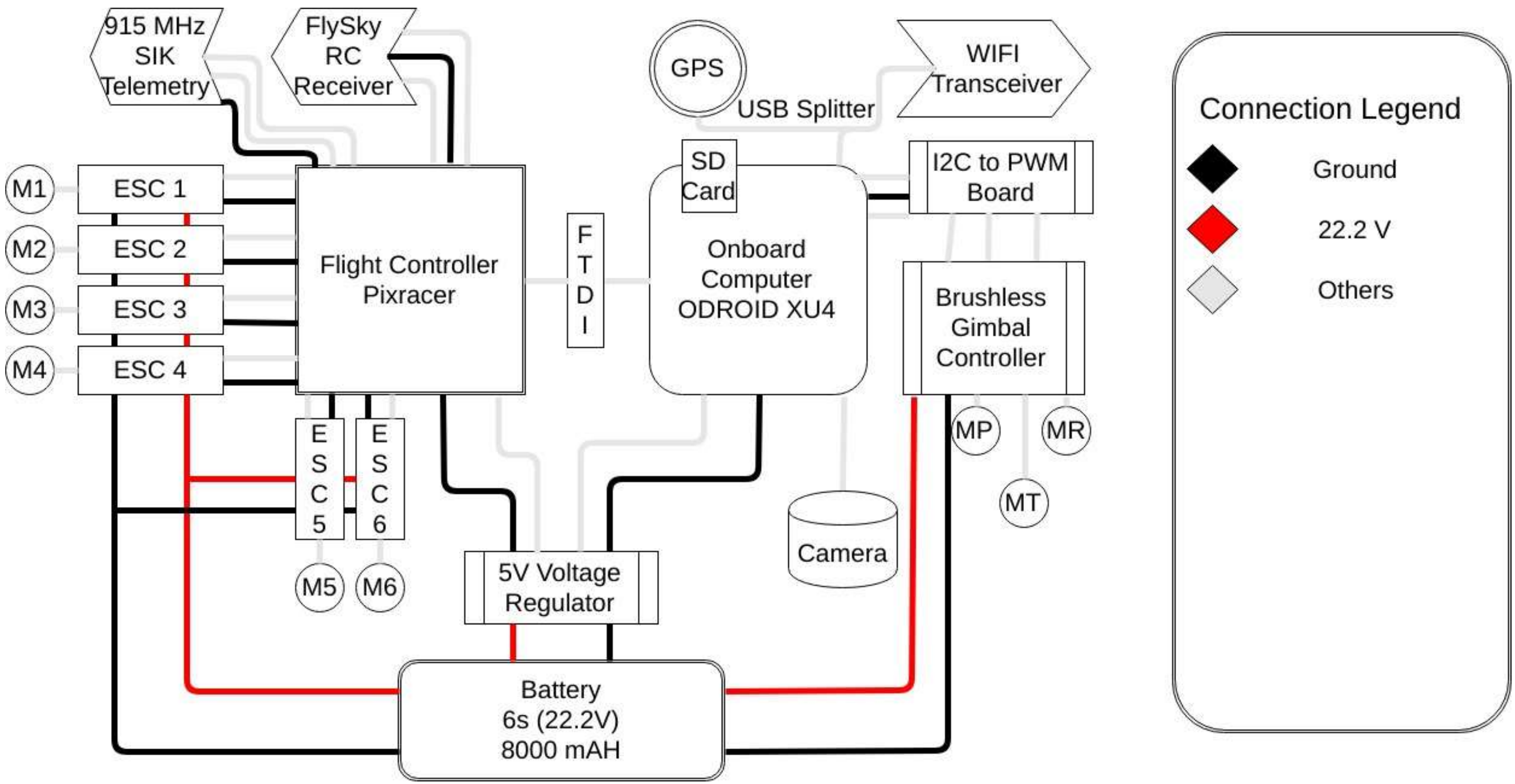
WBS - Logistics



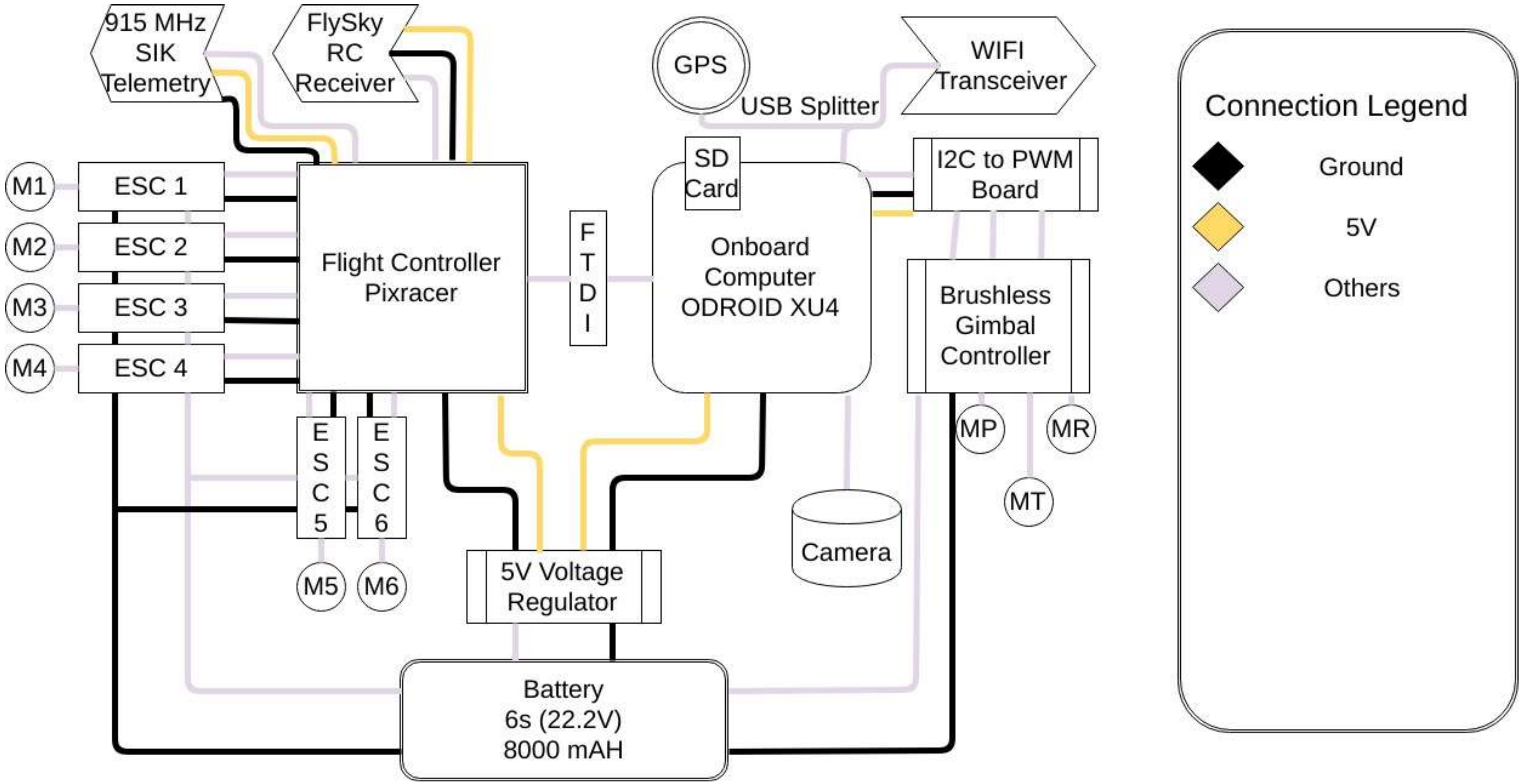
Work Breakdown Structure - Logistics



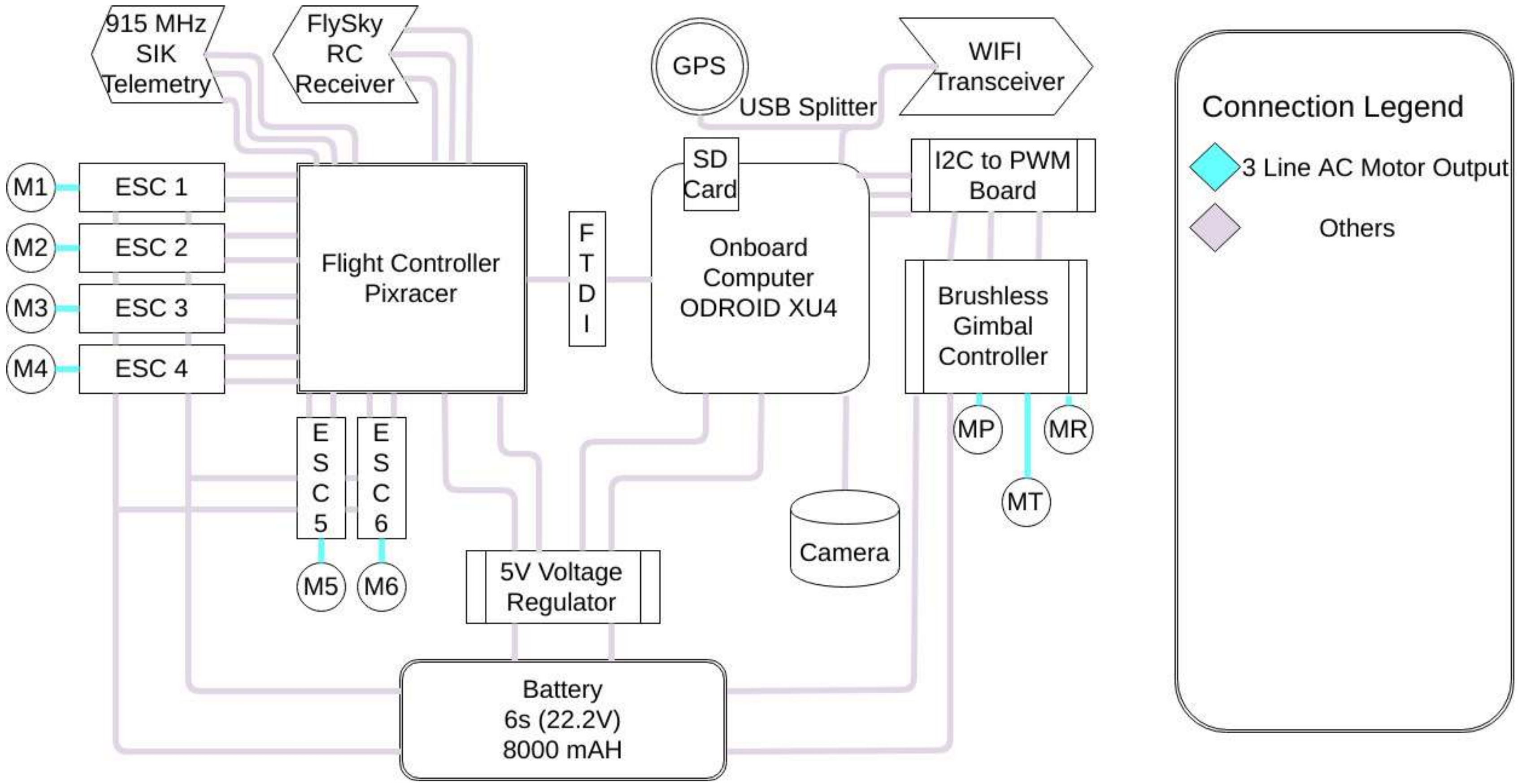
UAV Electronics Wiring



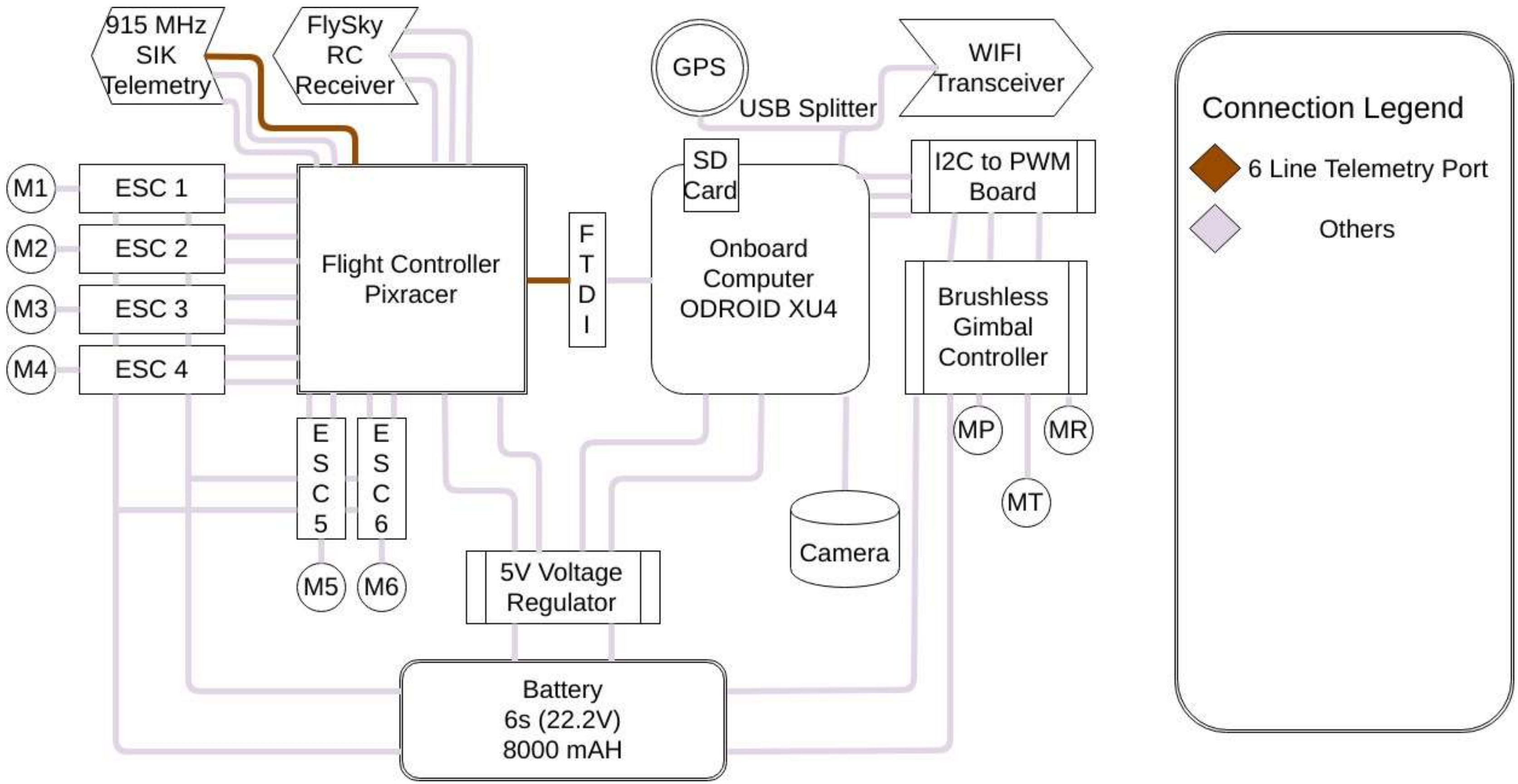
UAV Electronics Wiring



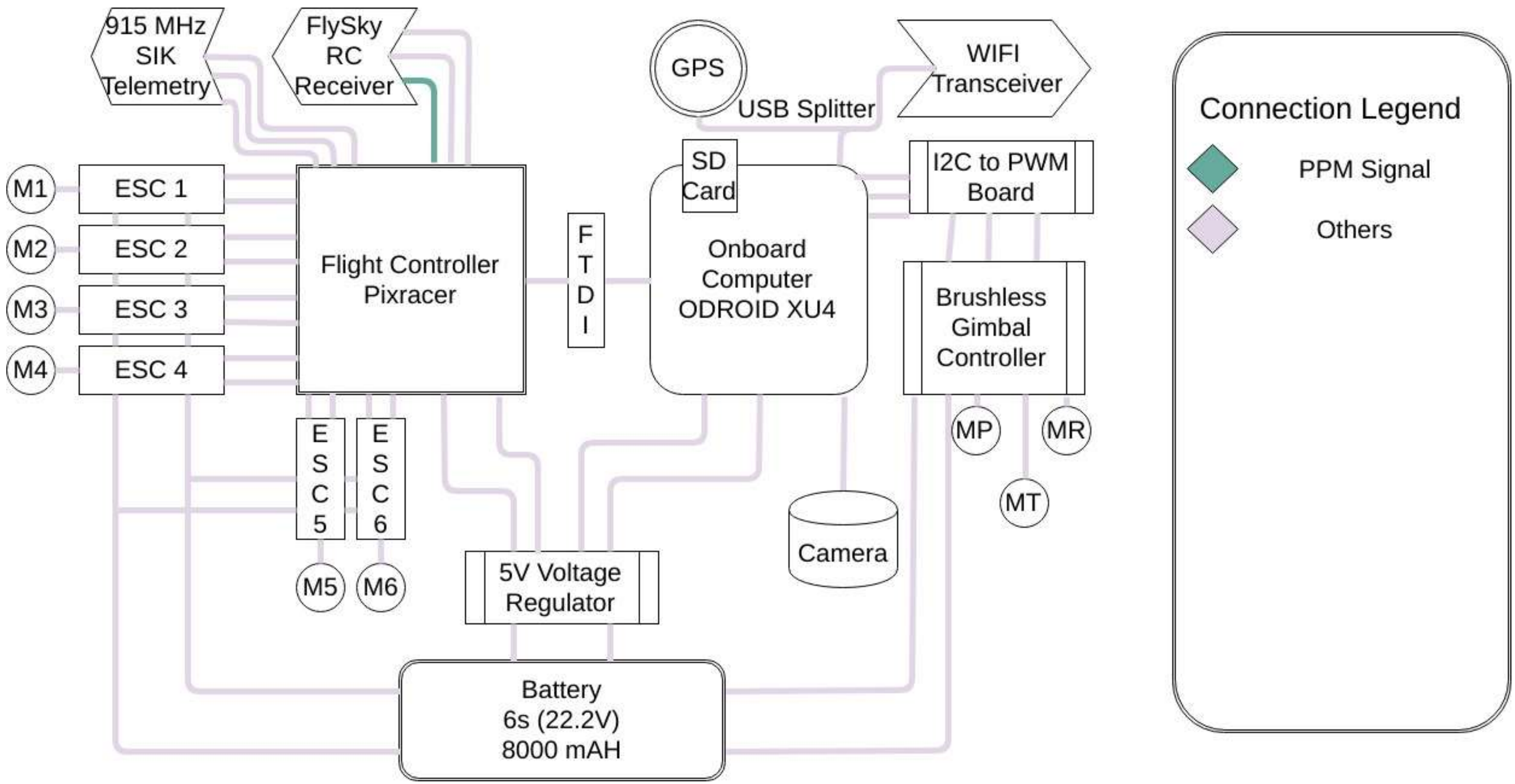
UAV Electronics Wiring



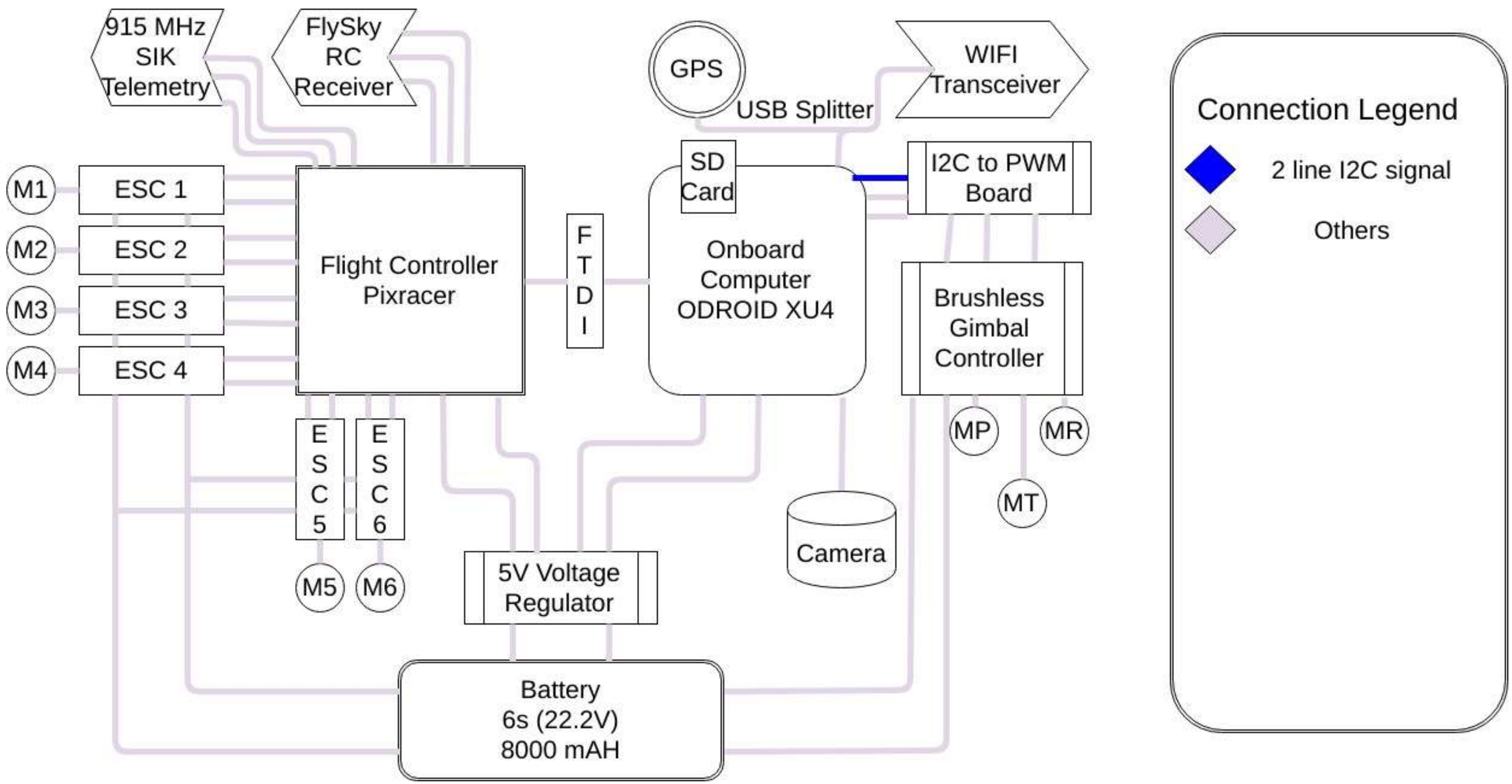
UAV Electronics Wiring



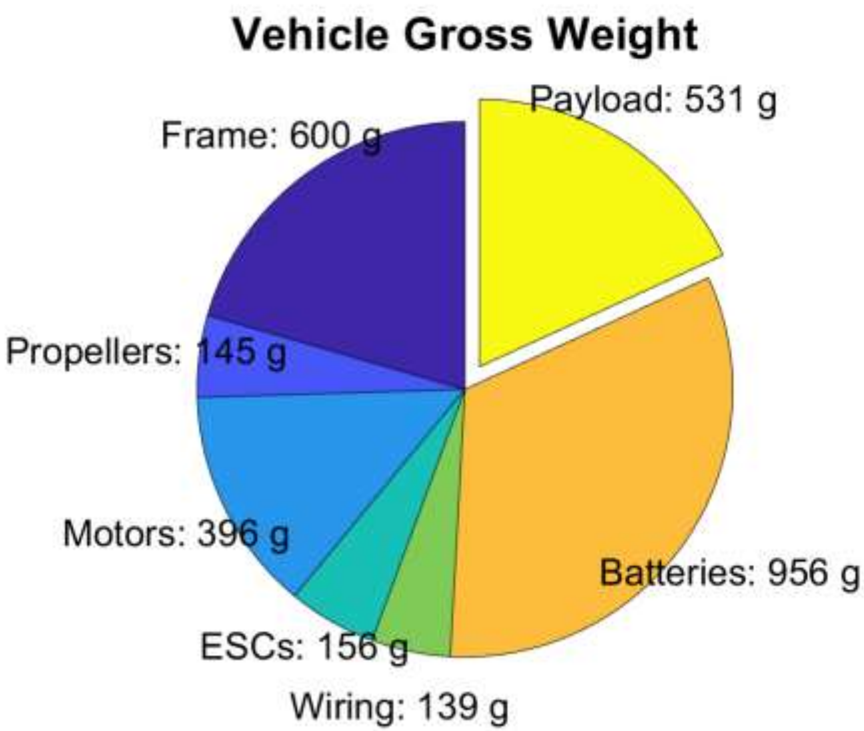
UAV Electronics Wiring

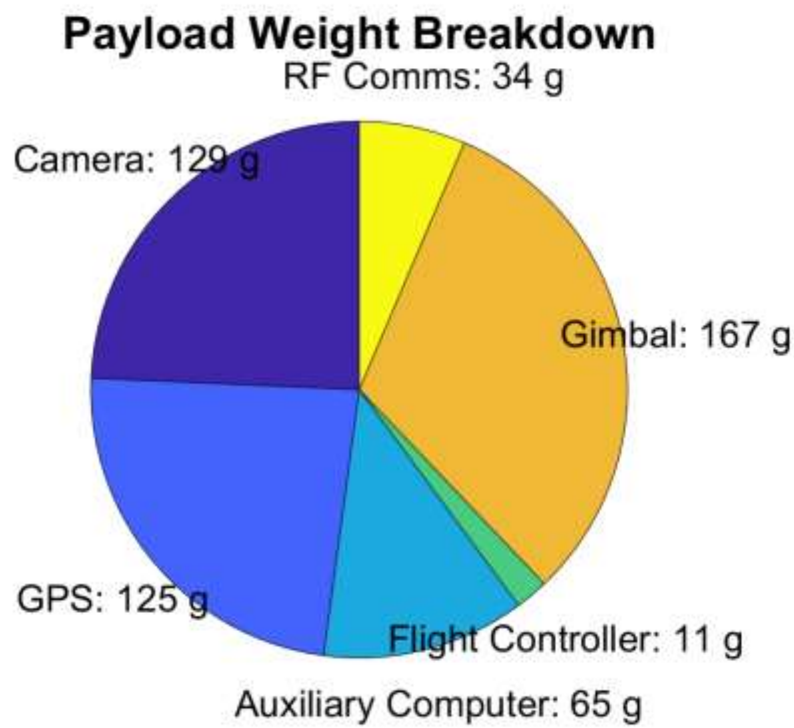


UAV Electronics Wiring



Mass Breakdown





Total Weight: 2,935 g

Citations: Frame, Battery, Propellers, Motors, ESCs, Camera, Lens, Gimbal, Odroid, PixRacer, GPS Main Module, GNSS Antenna, UHF Antenna, Control Receiver, Nav Receiver, Nav Antenna

Detailed Mass Breakdown

Item	Part	Mass	Quantity	Total
Frame	Tarot FY680S	600 g	1	600 g
Battery	Turnigy, 8,000 mAh 6S Li-po	956 g	1	956 g
Propellers	APC MR 13x5.5	24.1 g	6	144.6 g
Motors	T-Motor Antigrav 4006, 380 kV	66 g	6	396 g
ESCs	Hobbywing, 40 A 2-6 S ESC	26 g	6	156 g
Gimbal	FY Mini 3D Pro	167 g	1	167 g
Flight Controller	PixRacer	10.9 g	1	10.9 g
GPS	uBlox C94-M8P	125 g	1	125 g
RC Reciver	Redcon CM 703	12 g	1	12 g
Data Reciver	ODROID WiFi Module 3	14 g	1	14 g
Telemetry Radio	3DR Telemetry Kit	14 g	1	14 g
Camera	DFK 33UX249	65 g	1	65 g
Lens	TAMRON M112FM12	64 g	1	64 g
Aux Computer	ODRIOD XU4	65 g	1	65 g
Wiring Mass	5% AUW	139 g	1	139 g
TOTAL				**2928 g**

Negligible Drag Validation

1 Airframe drag on props

$$D_V = \frac{C_d F_{prop} S}{A_{disk}} \quad (1)$$

Where
D_V = Vertical Drag
C_d = Total fuselage drag coefficient
F_{prop} = Propellor thrust
A_{disk} = Propellor disk area
S = Projected area of affected components

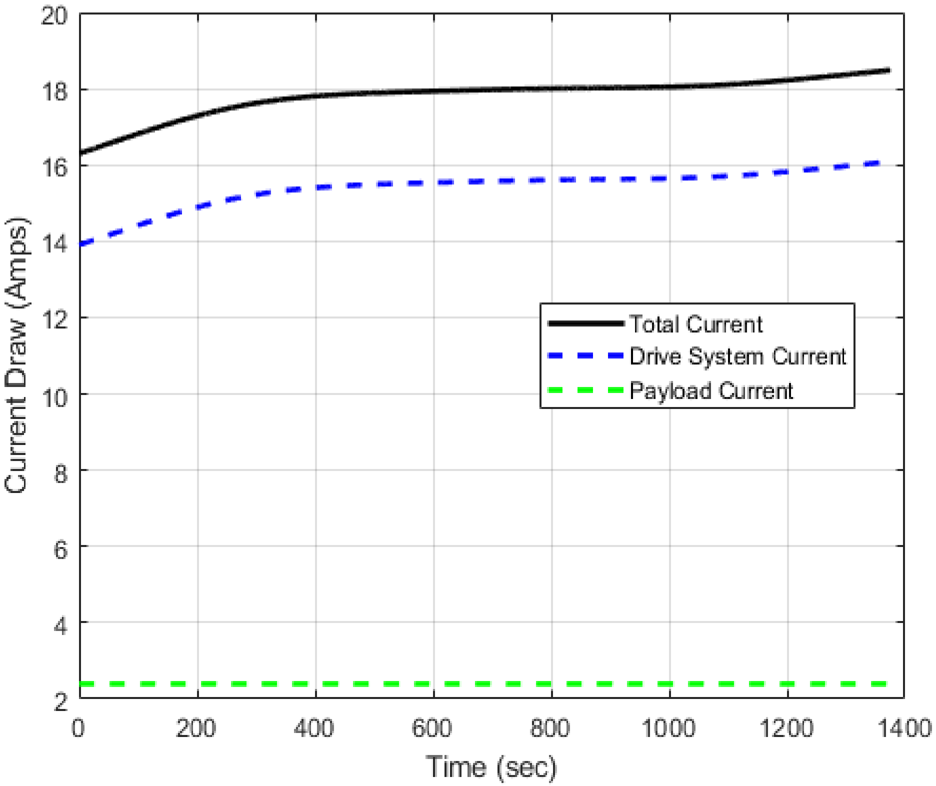
$$F_{prop} = \frac{mg}{N} \quad (2)$$

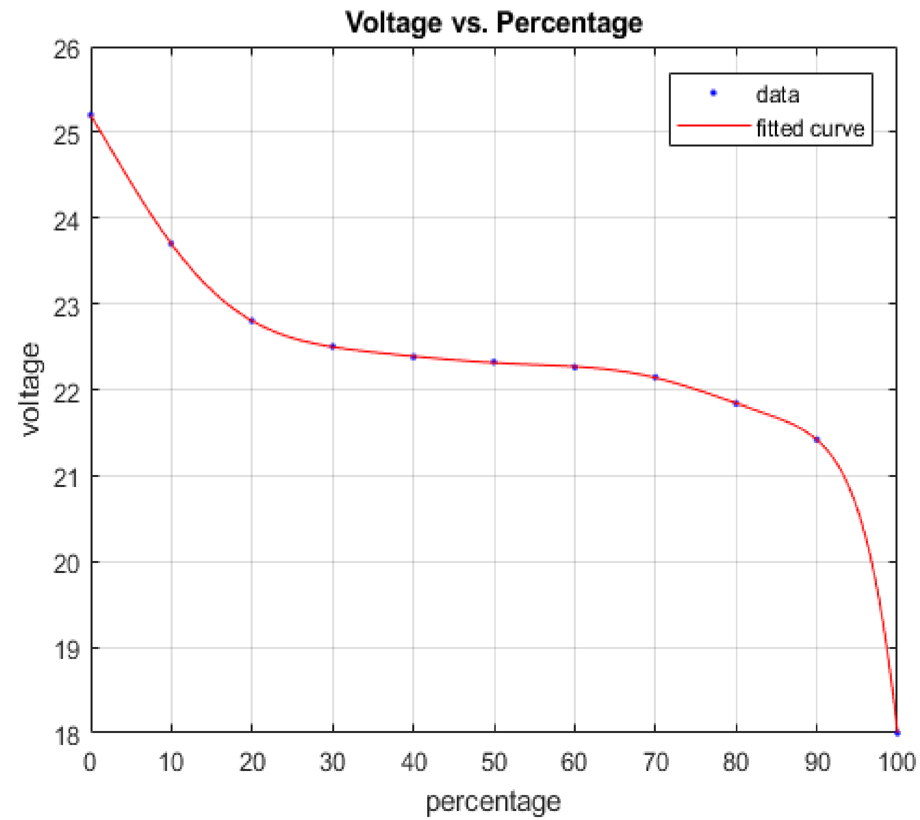
$m \approx 3.166kg$
$g = 9.81\ m/s^2$
N = number of propellors (6)
$C_d \approx 0.2$

S is calculated using the motor diameter of 44.35mm, so $S \approx 0.00154482m^2$. A_{prop} is calculated using the propellor radius and has a value of 0.0410433 m^2 for the 4.5" props and 0.0506707 m^2 for the 5.5" props. Plugging these values into the vertical drag equation above we get $D_V < 0.04N$, which is negligible.

Citations:
Vertical Drag Equation
Drag Coefficient Value

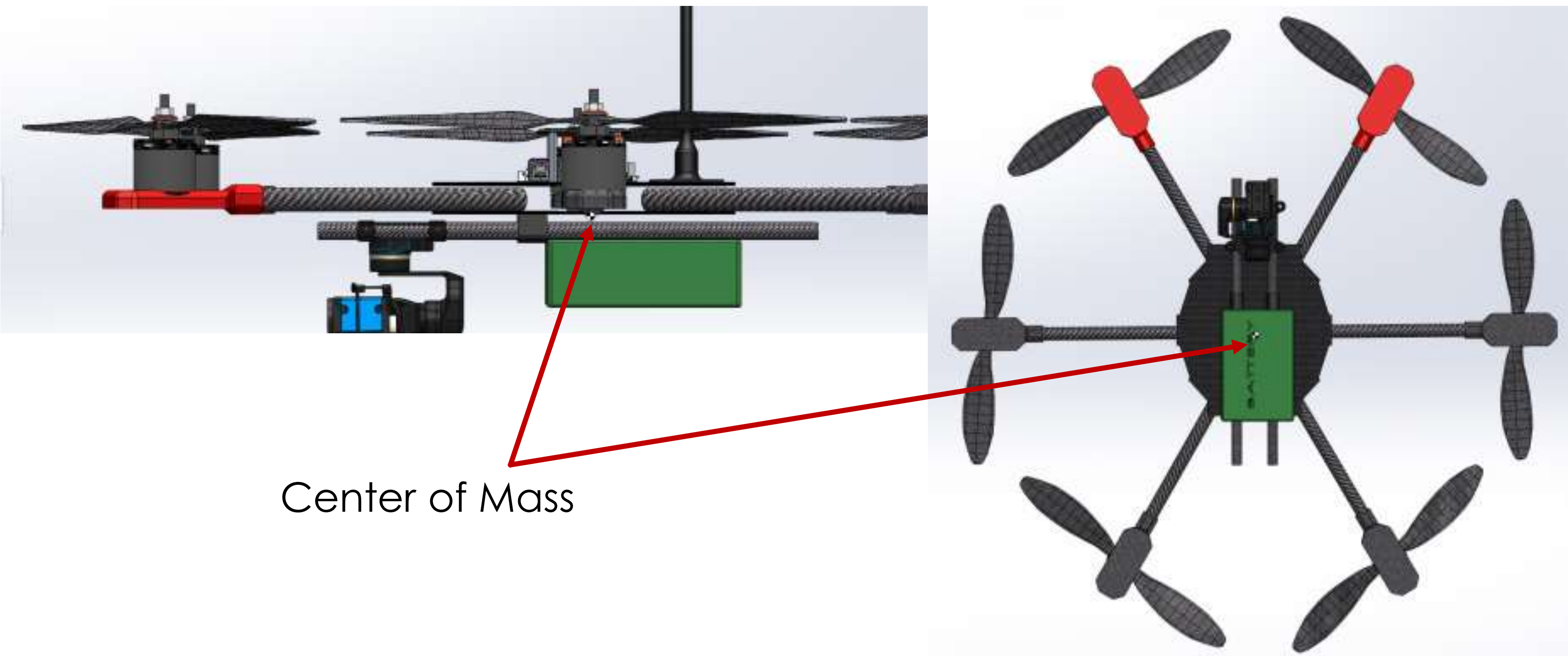
Battery Life





UAV Stability Properties

- Calculate moments of inertias via SolidWorks' mass evaluation tool, in order to characterize stability
- **Desired:** center of mass below propeller plane
- Achievable from SolidWorks center of mass viewer



UAV Stability Properties

Mass = 2794.25 grams

Volume = 1797243.37 cubic millimeters

Surface area = 1247463.35 square millimeters

Center of mass: (millimeters) X = 13.78 Y = 4.76 Z = 14.52

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)

Taken at the center of mass.

Ix = (-0.05, -0.02, 1.00)	Px = 54613492.77
Iy = (1.00, 0.01, 0.05)	Py = 62719545.61
Iz = (-0.01, 1.00, 0.02)	Pz = 104795258.94

Moments of inertia: (grams * square millimeters)

Taken at the center of mass and aligned with the output coordinate system.

Lxx = 62699632.99	Lxy = 378729.63	Lxz = -424409.54
Lyx = 378729.63	Lyy = 104767875.86	Lyz = -1100133.13
Lzx = -424409.54	Lzy = -1100133.13	Lzz = 54660788.47

UAV Product Choices Overview/TOC

UAV Hardware	See next slide
Camera	DFK 33UX249
Lens	TAMRON M112FM12
Gimbal	Feiyu Tech FY MiNi 3D Pro
Processor	ODROID XU4
Flight Controller	Pix Racer
IMU	Included in FC
Barometer & Magnetometer	Included in FC
GPS	C94-M8P-2
2.4 GHz Channel 1 (data)	Steve provided
2.4 GHz Channel 2 (controller)	DSMX receiver/transmitter
915 MHz Channel (Mavlink)	SIK telemetry radio

Frame: Tarot FY690s

Props	6x High Pitch – 13x5.5" APC 6x Low Pitch – 13x4.5" APC
Motors	Antigravity 4006 KV380 by T-MOTOR
Battery	Multistar 8000mAh 6S
ESC	2-6S 40A
Micro SD (Storage)	Samsung Evo Select

Camera: DFK 33UX249

Resolution	1,920×1,200 (2.3 MP)
FPS	48
Interface	USB 3
Lens mount	C/CS
Current Consumption	~250 mA @ 5 VDC
Dimensions	H: 29 mm, W: 29 mm, L: 43 mm
Mass	65 g
Mounting	Mounting plate included, 29x43mm
Price	

Lens: M112FM12

Mount Type	C
Dimensions	H: 7.5cm, W: 10cm, L: 10cm
Mass	64 g
Price	

Gimbal: Feiyu Tech FY MiNi 3D Pro

Working Voltage	7-17V (8.4V)
Dimensions	H: 130 mm, W: 74 mm, L: 50 mm
Mass	167 g
Mounting	Mounting hooks included (53.4mm width apart)
Price	$203.15
Interfaces	

Processor: ODROID XU4

Power Source	5V/4A DC Power Source
Dimensions	H: 20 mm, W: 58 mm, L: 83 mm
Mass	65 g
Mounting	Holes in corners for screws/bolts
Ports	eMMC – Boot loader USB 3 – Camera USB 3 – Data Channel USB 2 – GPS Ethernet HDMI 1.4a 42 pins – 12 for FC
OS	Linux Kernel 4.9 LTS, ARM compatible
Price	$59.00

Flight Controller: Pix Racer

URL	https://store.mrobotics.io/mRo-PixRacer-R14-Official-p/auav-pxrcr-r14-mr.htm
Operating voltage	5 VDC
Dimensions	H: ~ mm, W: 36 mm, L: 36 mm
Mass	10.54 g
Mounting	Screw holes in corners
Price	$99.00
Interfaces	See site

GPS: C94-M8P-2

Module Mass	35g
GNSS Antenna	Tallysman TW2406 (35g)
UHF Antenna	Included in package (50g)
Ground Plane	5g
Price	$400

UAV Sensor Overview

State Variable	Sensor	Listed Accuracy	Std. Dev.	Units	Notes
$\boldsymbol{x}, \boldsymbol{y}$	uNEO-M8P u-blox M8 High Precision GNSS Module	0.025 m CEP	0.037	m	With RTK
$\boldsymbol{z}$	MS5611 Barometer	Max Total Error Band w/ Autozero @ 25°C = ±0.5 mbar	1.6667	m	From PixRacer Autopilot
$\boldsymbol{\phi}, \boldsymbol{\theta}$	MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device	Total RMS noise = 0.1deg/s RMS	0.1	°/s	From PixRacer Autopilot
$\boldsymbol{\psi}$	u3-Axis Digital Compass IC HMC5983	1° to 2° Compass Heading Accuracy	0.666666	°	From PixRacer Autopilot
$\dot{\boldsymbol{x}}, \dot{\boldsymbol{y}}, \dot{\boldsymbol{z}}$	MPU-9250 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device	Total RMS noise 8 mg-rms	0.008	g	From PixRacer Autopilot
$\dot{\boldsymbol{\phi}}, \dot{\boldsymbol{\theta}}, \dot{\boldsymbol{\psi}}$	MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device	Total RMS noise = 0.1deg/s RMS	0.1	°/s	From PixRacer Autopilot

- Assumptions: Error is Gaussian
- Specific characteristics such as drift and bias must be determined experimentally

UGV Sensor Overview

State Variable	Sensor	Listed Accuracy	Std. Dev.	Units	Notes
x, y	uNEO-M8P u-blox M8 High Precision GNSS Module	0.025 m CEP	0.037	m	With RTK
z	Adafruit BMP280 I2C or SPI Barometric Pressure Altitude Sensor	Typical Abs. Acc. = ±1 hPa	3.2333	m	Integrated w/ I2C to Arduino
ϕ, θ	MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device	Total RMS noise = 0.06deg/s RMS	0.06	°/s	Standard on Jackal
ψ	Honeywell HMC5883L Digital Compass IC	1° to 2° Compass Heading Accuracy	0.666666	°	Integrated w/ I2C to Arduino
$\dot{x}, \dot{y}, \dot{z}$	MPU-9150 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device	Total RMS noise 4 mg-rms	0.004	g	Standard on Jackal
$\dot{\phi}, \dot{\theta}, \dot{\psi}$	MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device	Total RMS noise = 0.06deg/s RMS	0.06	°/s	Standard on Jackal

- Assumptions: Error is Gaussian
- Specific characteristics such as drift and bias must be determined experimentally

Sensor Error Calculations and Assumptions

- NEO-M8P u-blox M8 High Precision GNSS Module
  - Standalone: 2.5 m CEP → σ = 2.5/0.6745 = 3.706 (Gaussian Distribution at 50%)
  - RTK: 0.025 m CEP → σ = 0.025/0.6745 = 0.003706 (Gaussian Distribution at 50%)
- MS5611 Barometer
  - Max Total Error Band with Autozero at Pressure Point, at 25°C = ±0.5 mbar
  - Pressure at 5450 ft = 828.901 mbar [6]
  - Pressure Altitude at 828.901 + 0.5 mbar = 5433.95 ft
  - Error of ~ 17 ft ~ 5 m
  - σ = 5/3 = 1.66667 m (Gaussian Distribution at 99.7%)
    - Barometer drift due to environment ignored for relative altitude

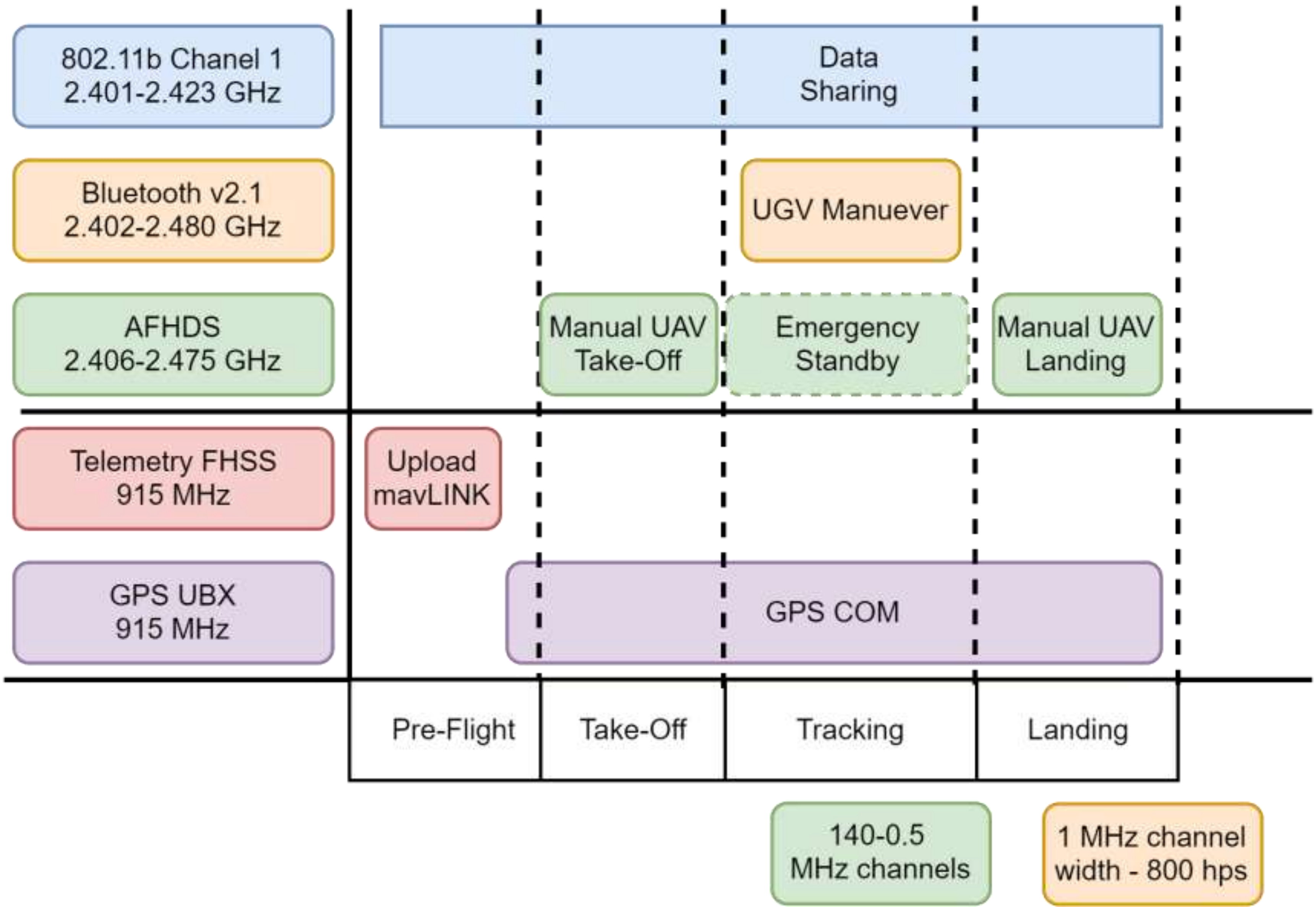
$$h_{alt} = \left(1 - \left(\frac{P_{sta}}{1013.25}\right)^{0.190284}\right) \times 145366.45$$

- Adafruit BMP280 I2C or SPI Barometric Pressure Altitude Sensor
  - Typical absolute accuracy from 0-40°C = ±1 hPa
  - Pressure at 5450 ft = 828.901 mbar = 828.901 hPa
  - Pressure Altitude at 828.901 + 1 hPa = 829.901 hPa = 829.901 mbar = 5417.9
  - Error of ~ 32 ft ~ 9.7 m
  - σ = 9.7 /3 = 3.2333 m (Gaussian Distribution at 99.7%)

Sensor Error Calculations and Assumptions

- 3-Axis Digital Compass IC HMC5983 [7]
  - 1° to 2° Compass Heading Accuracy
  - σ = 2/3 = 0.66667° (Gaussian Distribution at 99.7%)
- Honeywell HMC5883L Digital Compass IC
  - 1° to 2° Compass Heading Accuracy
  - σ = 2/3 = 0.66667° (Gaussian Distribution at 99.7%)
- MPU-9250 Nine-Axis (Gyro) MEMS MotionTracking™ Device
  - Total RMS noise = 0.06 °/s - rms
  - σ = 0.1°
- MPU-9250 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device
  - Total RMS noise = 8 mg – rms
  - σ = 0.008 g
- MPU-9150 Nine-Axis (Gyro) MEMS MotionTracking™ Device
  - Total RMS noise = 0.06 °/s - rms
  - σ = 0.06°
- MPU-9150 Nine-Axis (Accelerometer) MEMS MotionTracking™ Device
  - Total RMS noise = 4 mg – rms
  - σ = 0.004 g

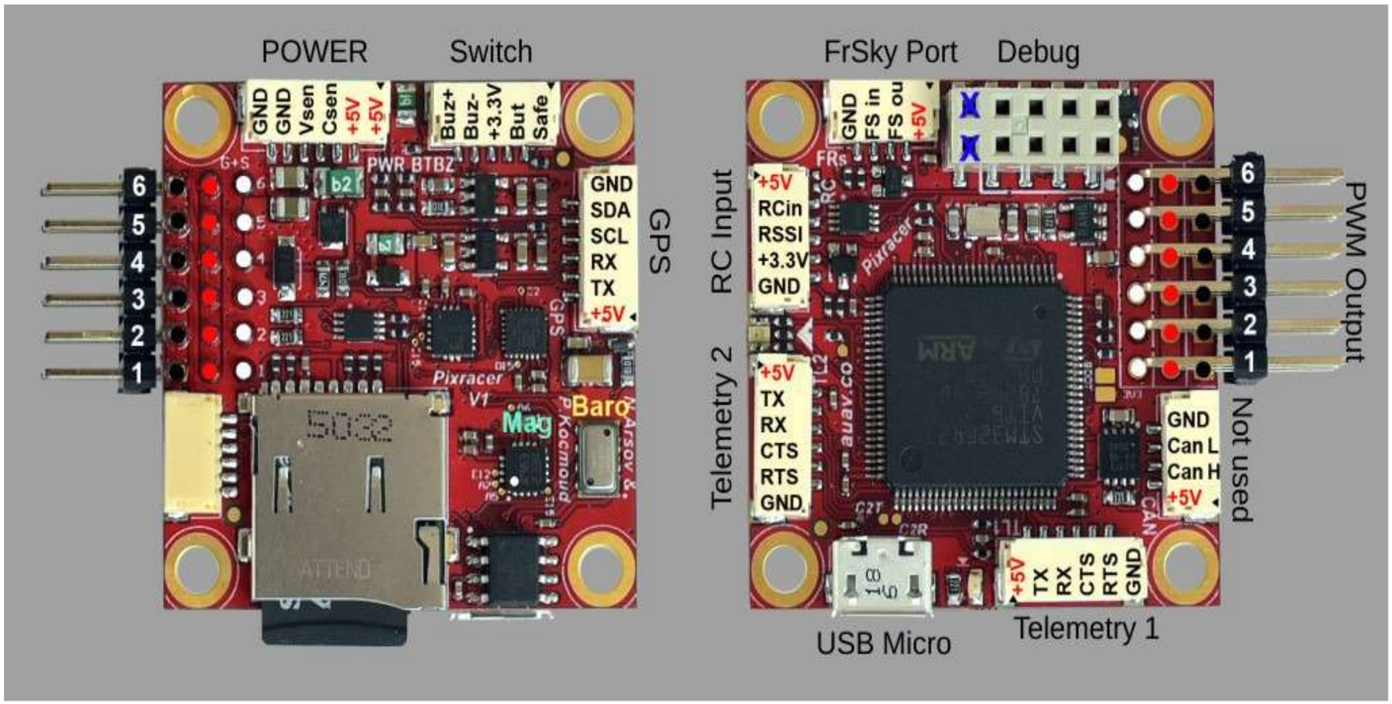
Interference



Interference

- RAVEN testing location at CU South Campus is 400+ meters from any houses, mitigating residential WiFi interference.

Pixracer Connection



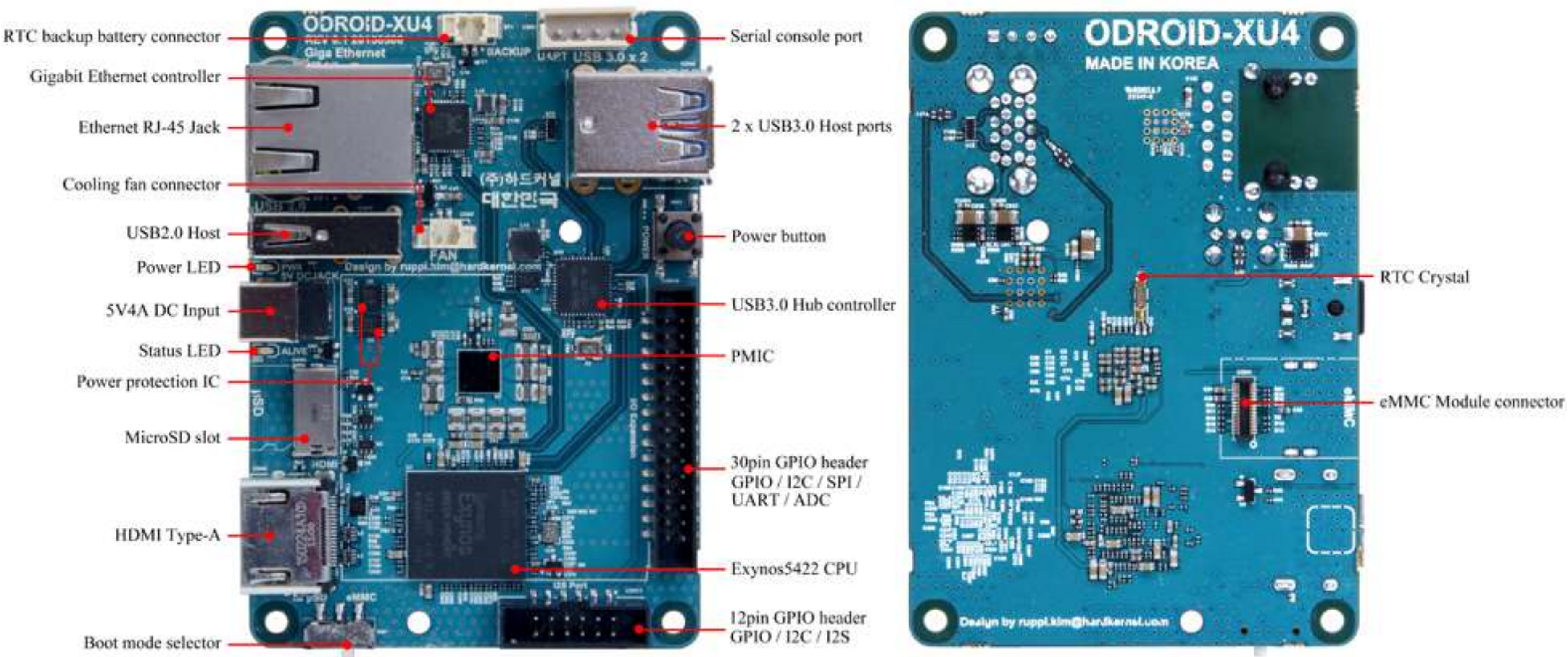
Pinouts

TELEM1, TELEM2+OSD ports

Serial (TTL Level)

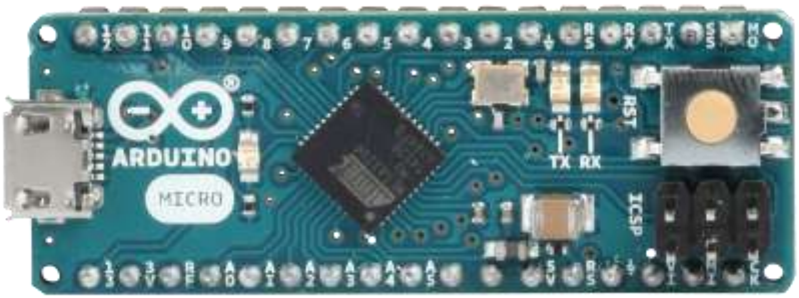
Pin	Signal	Volt
1 (red)	VCC	+5V
2 (blk)	TX (OUT)	+3.3V
3 (blk)	RX (IN)	+3.3V
4 (blk)	CTS (IN)	+3.3V
5 (blk)	RTS (OUT)	+3.3V
6 (blk)	GND	GND

ODroid Connection

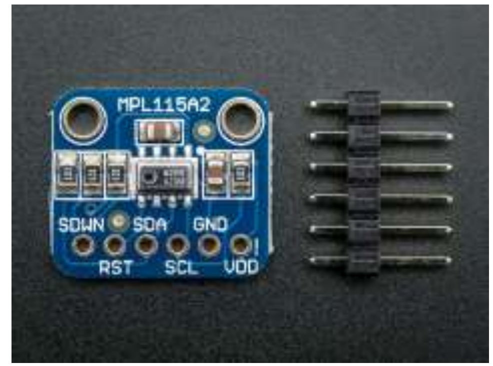


Extra Electronics 1

- Arduino Micro



I2C Barometer

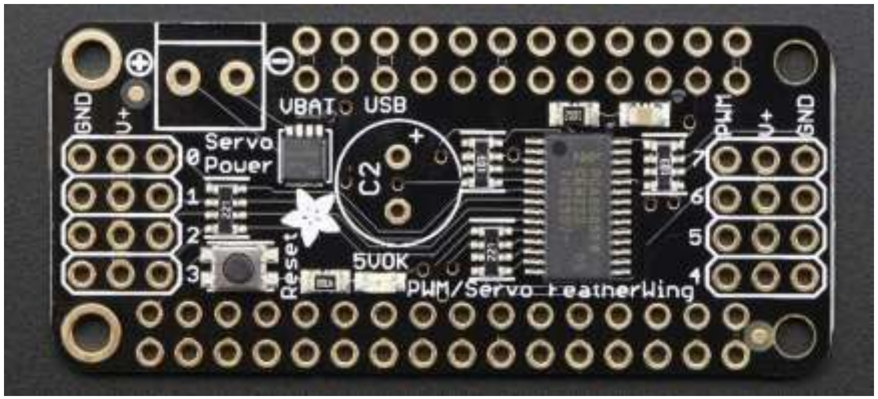


Sik Telemetry Radio

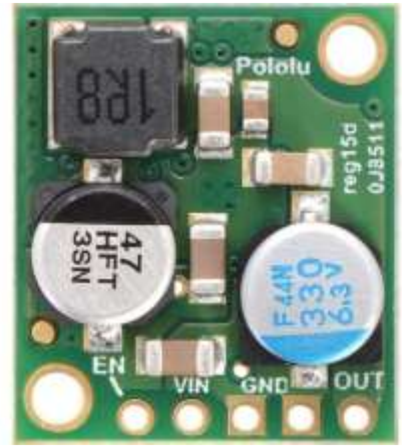
3 Axis Gimbal

Extra Electronics 2

Servo Motor Driver



Voltage Regulator



Turnigy RC Receiver

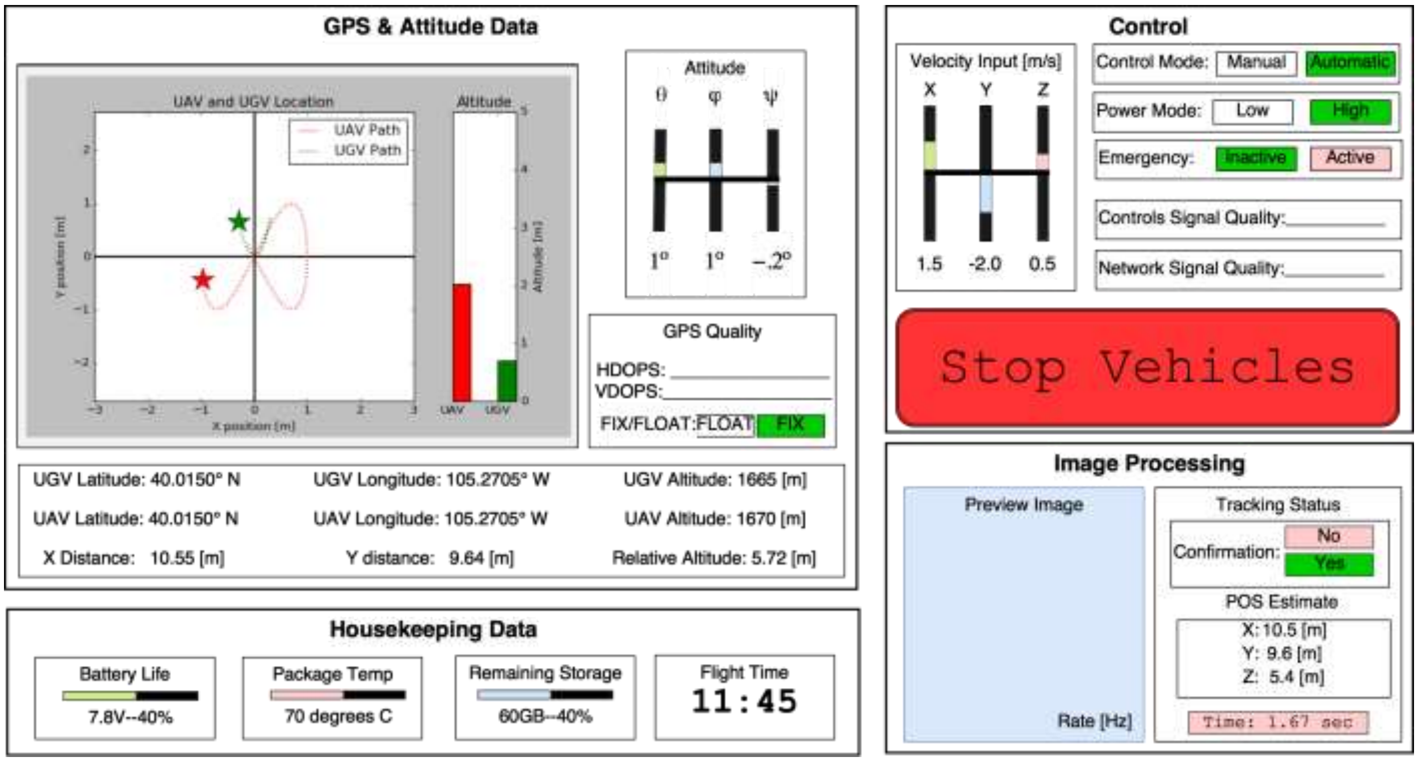
Servo Motor

Extra Cables

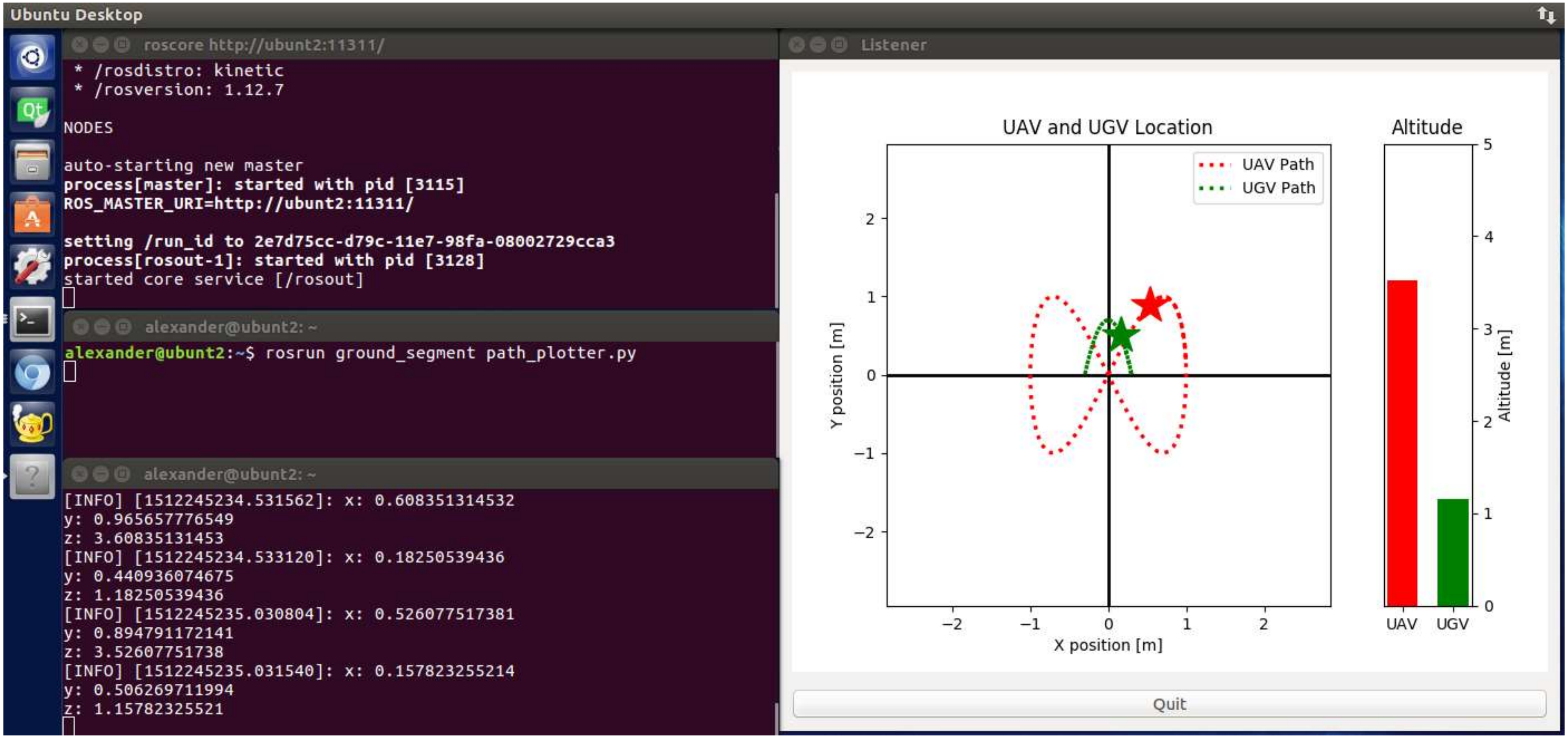
- FTDI Cable

USB Splitter

UI Mockup

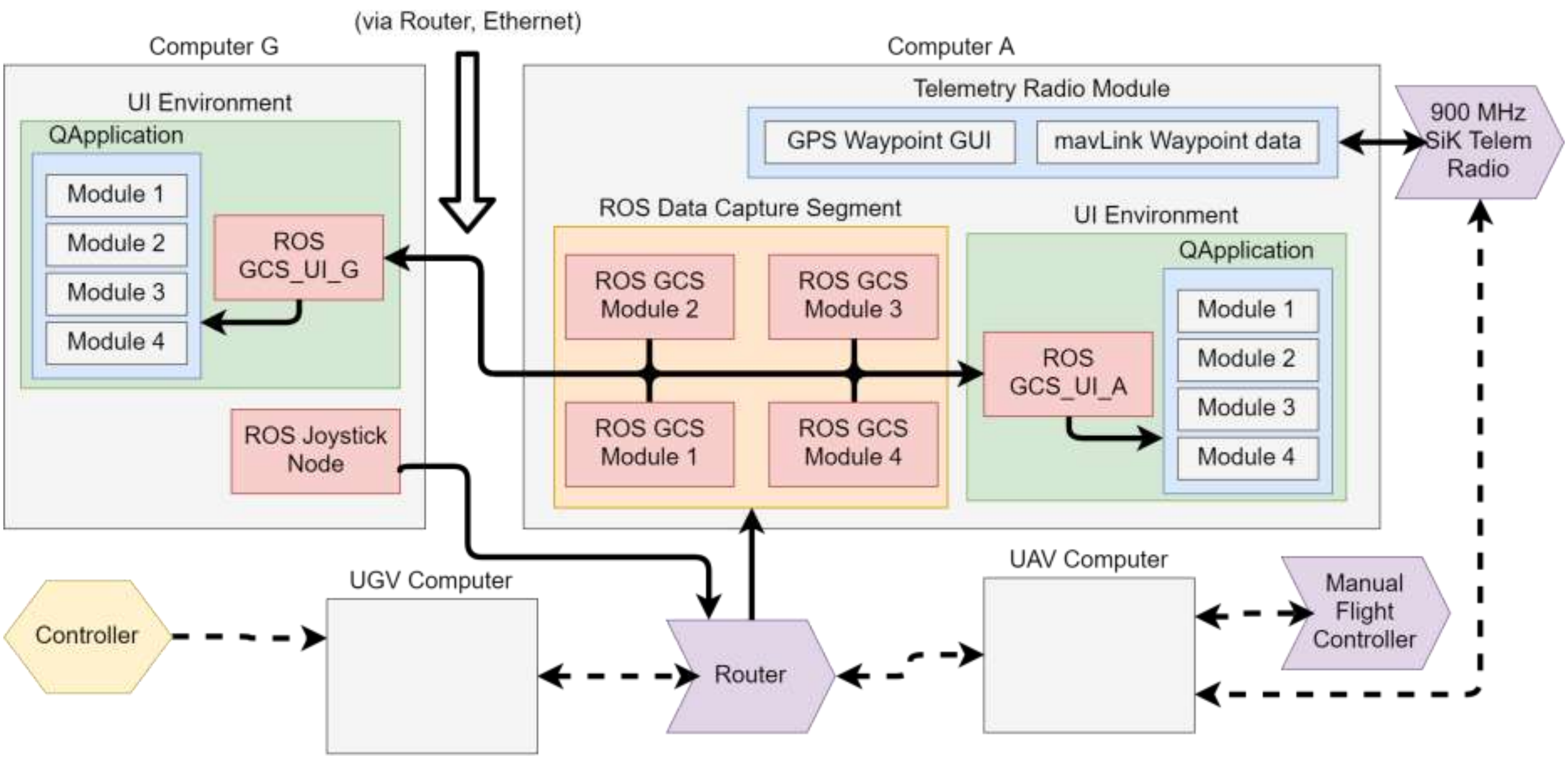

GPS & Attitude Data
UAV and UGV Location
UAV Path
UGV Path
Y position [m]
X position [m]
Altitude
Altitude [m]
UAV
UGV
Attitude
θ
φ
ψ
1°
1°
−.2°
GPS Quality
HDOPS:
VDOPS:
FIX/FLOAT: FLOAT
FIX
UGV Latitude: 40.0150° N
UGV Longitude: 105.2705° W
UGV Altitude: 1665 [m]
UAV Latitude: 40.0150° N
UAV Longitude: 105.2705° W
UAV Altitude: 1670 [m]
X Distance: 10.55 [m]
Y distance: 9.64 [m]
Relative Altitude: 5.72 [m]
Control
Velocity Input [m/s]
X
Y
Z
1.5
-2.0
0.5
Control Mode:
Manual
Automatic
Power Mode:
Low
High
Emergency:
Inactive
Active
Controls Signal Quality:
Network Signal Quality:
Stop Vehicles
Housekeeping Data
Battery Life
7.8V--40%
Package Temp
70 degrees C
Remaining Storage
60GB--40%
Flight Time
11:45
Image Processing
Preview Image
Rate [Hz]
Tracking Status
Confirmation:
No
Yes
POS Estimate
X: 10.5 [m]
Y: 9.6 [m]
Z: 5.4 [m]
Time: 1.67 sec

UI + ROS Demonstration



UI + ROS Demonstration

UI Planning



(via Router, Ethernet)
Computer G
UI Environment
QApplication
Module 1
Module 2
Module 3
Module 4
ROS
GCS_UI_G
ROS Joystick
Node
Computer A
Telemetry Radio Module
GPS Waypoint GUI
mavLink Waypoint data
900 MHz
SiK Telem
Radio
ROS Data Capture Segment
ROS GCS
Module 2
ROS GCS
Module 3
ROS GCS
Module 1
ROS GCS
Module 4
UI Environment
QApplication
ROS
GCS_UI_A
Module 1
Module 2
Module 3
Module 4
Controller
UGV Computer
Router
UAV Computer
Manual
Flight
Controller

Camera Image size approximation:

- Flea image size: 1,314,816 bytes
- Flea Resolution: 1280 *1024
- Total # of pixels: 1310720
- Flea bytes per pixel: 1.003
- Cam resolution: 1920*1200=2304000
- Size of image file: 2310912 bytes /10^6 =
- 2.311 MB/image

Preview Image approximation

- 384*240 = 92160 pixels
- Worst case scenario, no compression: 1.033 bytes/pixel
- Image size = 95 kB = 761 kb/image
- 11mb/761kb = 6.9% (approx 0.069 seconds to send one preview image over network)

Controller Power

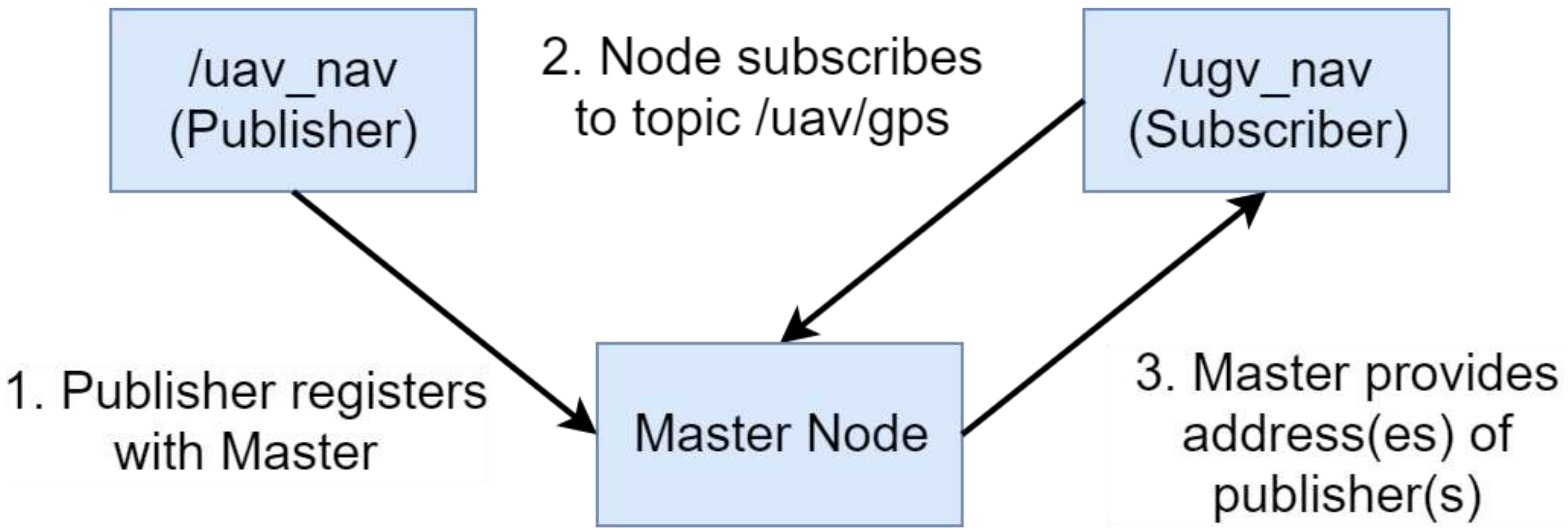
Transmitter Name	Protocol	Frequency	Sensitivity	Output Power (max)	Estimated Range	Hardware Connection	Data Rate	Error Tolerance	Channels
SiK Telemetry Radio	FHSS	900 MHz	-121 dBm	20 dBm	300+ m (out of box)	6 pin (UART + I2C)	250 kbps	25%	
TGY-i6 Transmitter Radio	AFHDS	2.4 GHz		20 dBm	1 km		N/A		6
Netgear R6700 WiFi Router	802.11 b	2.4-2.4835GHz		14 dBm	90 m		11 mb/s		13
Bluetooth Controller		2.4 GHz					19.2 kB/s		
Ublox GPS Radio		1.5 GHz							

ROS Overview

- Robot Operating System
- Open-source communication framework
  - Commonly used in robotics research
- Distributed network of independent processes
  - Processes called “nodes”
- Synchronous communication over “*services*”
- Asynchronous communication over “*topics*”

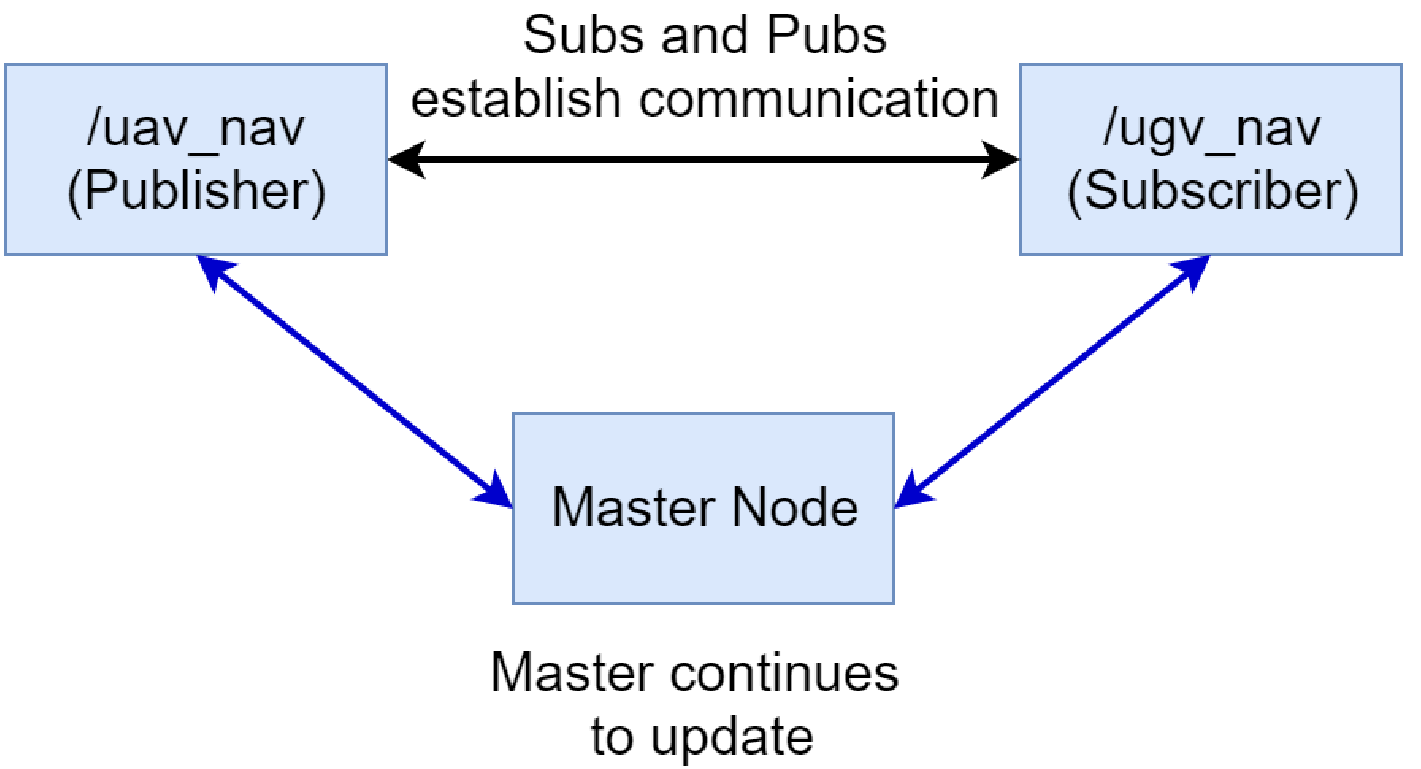
ROS Overview

- All nodes register with the master node.



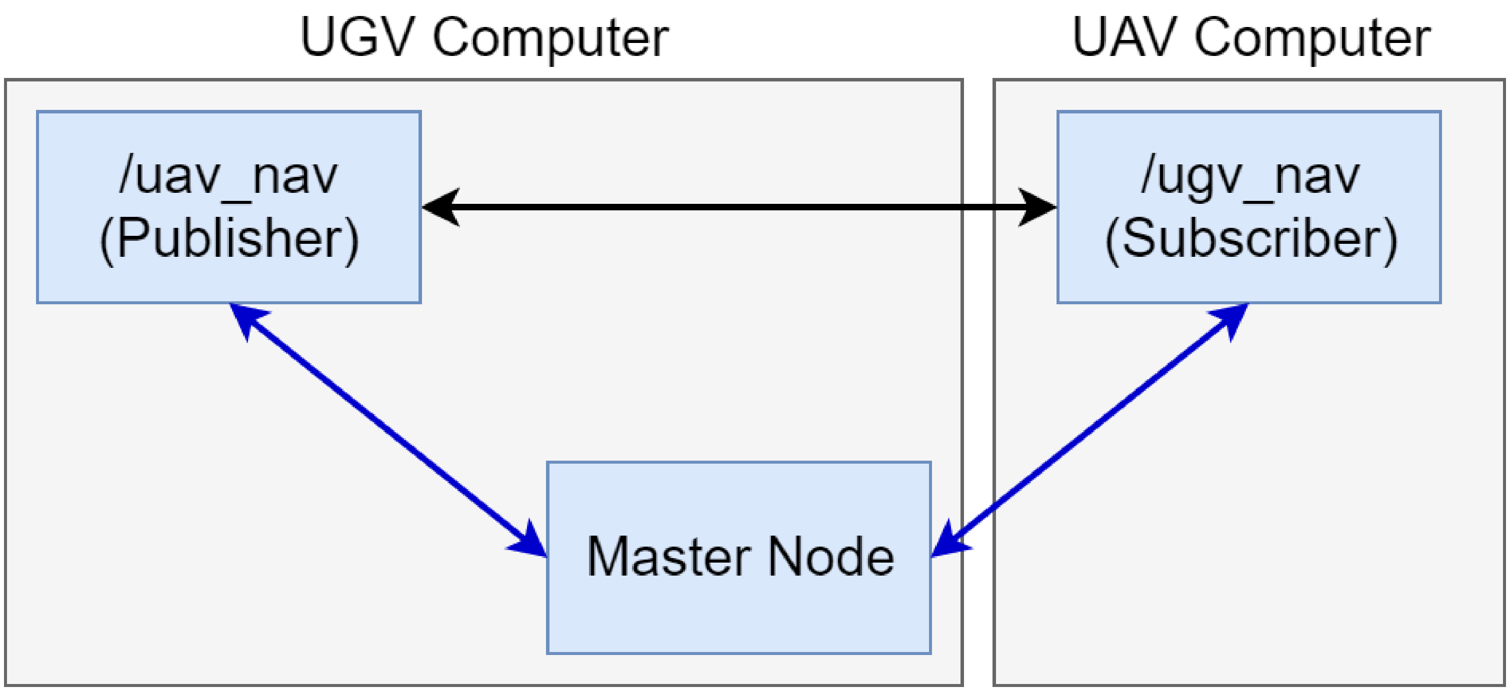
ROS Overview

- Subscribers and publishers communicate directly, messages sent when a topic published to.

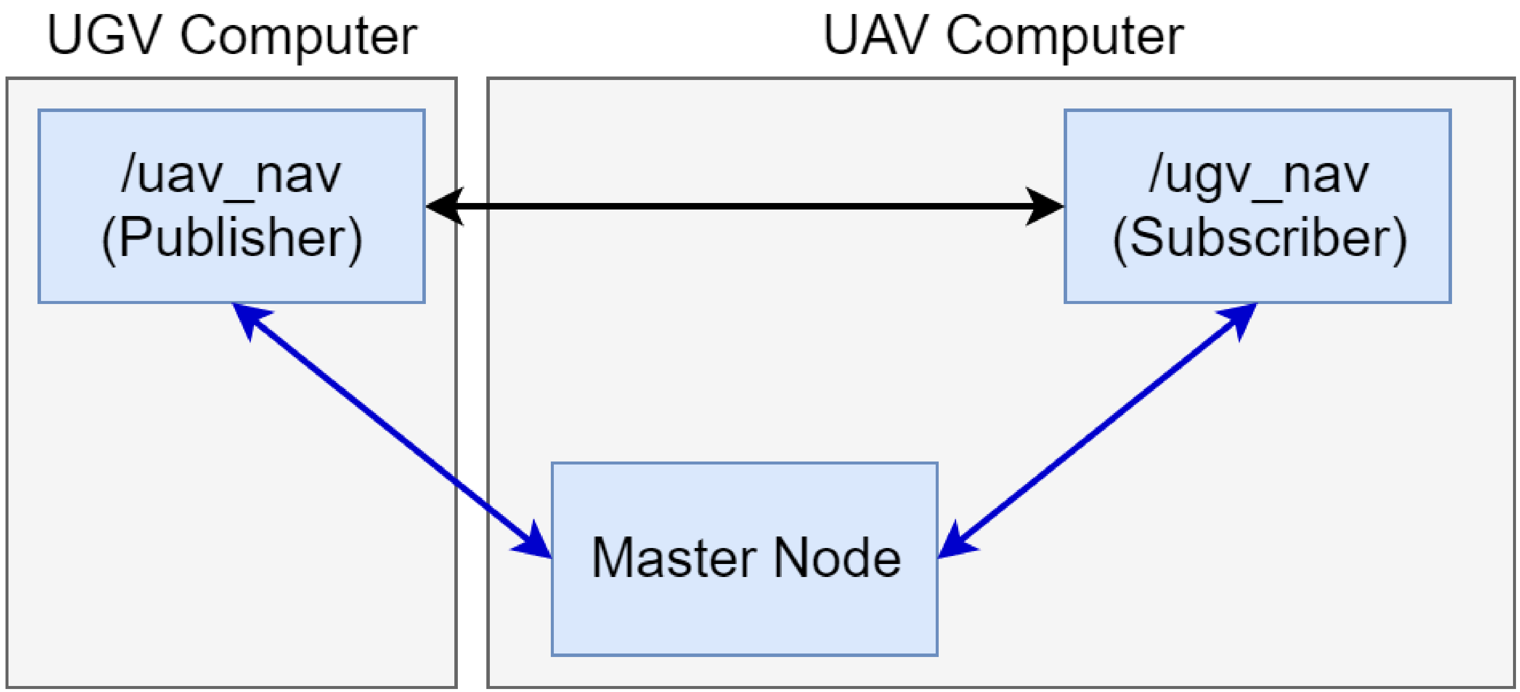


ROS Overview

- Physical node locations do not matter, but all nodes must be on the same network.



ROS Overview



ROS Overview

- *ROS topic monitoring can be used to determine data rates used by individual topics.*
- *ROS Bags subscribe to topics and provide a record of sent data*
  - *This will be utilized to store all sensor, navigation, image and housekeeping data.*

GPS Configuration

- The GPS receiver will output following UBX messages:
  - GPS Fix: UBX-NAV-HPPOSLLH
  - GPS Raw Ephemeris: UBX-NAV-ORB
  - Satellite Geometric Quality (DOP): UBX-NAV-DOP
  - Relative position in NED frame: UBX-NAV-RELPOSNED
  - Velocity in NED frame: UBX-NAV-VELNED
  - Time of GPS Fix: UBX-NAV-TIMEUTC

- Update Rate of 1 Hz at 19200 Baud.

GPS Interference

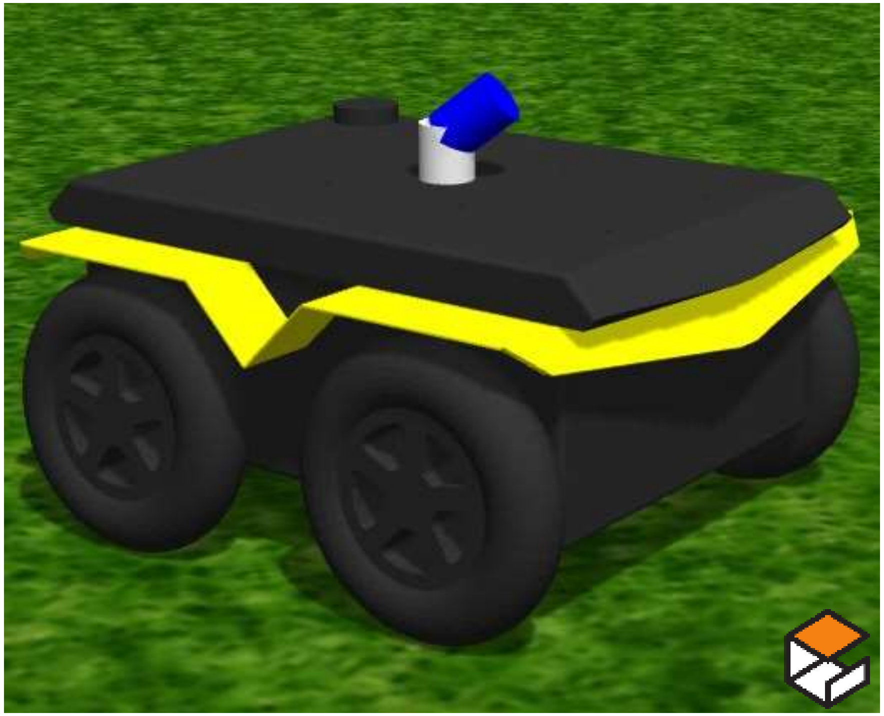
- To combat noise from camera and electronics:
- Antenna will be elevated with ground plane.
- Camera and electronics will be wrapped with aluminum to act as a faraday cage.

Pointing Potential Improvements/Changes

- GPS Unit could potentially send messages with ECEF coordinates.
- If GPS update rate is too slow then path prediction will need to be implemented using velocity solutions from the GPS unit.
- Further UGV gimbal development to minimize size and jitter for the selected camera.

Simulated Camera and Mount

- Gazebo plugin for camera
  - Parameters
    - View distance
    - Resolution
    - Field of view
- Gazebo plugin for mount control
  - Modeled by two intersecting cylinders
  - Manually command pan and tilt joints to angles
  - Still to implement: mount tracks UAV by sharing GPS, more realistic model for camera and mount



Gazebo Playback

- A ROS Bag records ROS messages for topics that the bag is subscribed to, as well as a time record of the message.
- Using ROS playback, tools these messages can be played back in real time.
- Utilizing the Gazebo model, and replaying all ROS messages, the test conditions and results can be played back.
  - There are some limitations, based on the time difference between when a topic was published to, and when the value was processed.

Gazebo Simulation Orbit Parameters

	Pointing	Blob Detection
Distance	21.2 m	14.1 m
Radius	15 m	10 m
Altitude	15 m	10 m
Speed	3.93 m/s	0.873 m/s

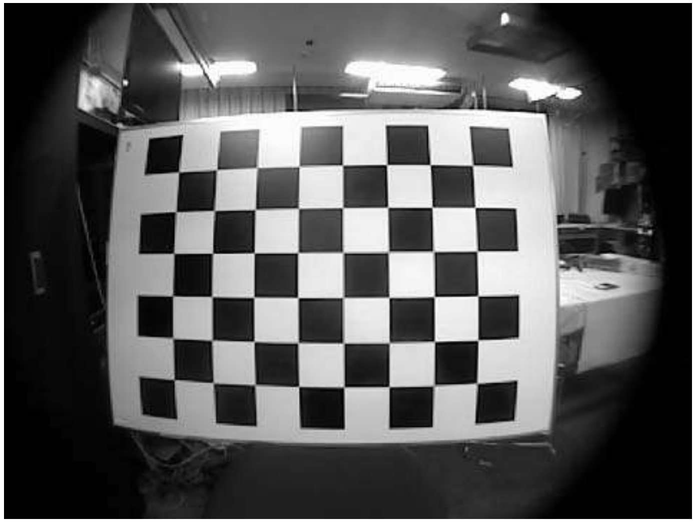
Camera Distortion Model

- Correction matrix created by checkerboard and Brown-Conrady model.
- Tangential distortion assumed zero.

[1]

$$\breve{x} = x + x[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2]$$
$$\breve{y} = y + y[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2]$$

- Model corrects for radial distortion.
- Corrected Image will have parallel lines.



*Courtesy SWARD Camera Calibration Toolbox

Camera Calibration

- Camera matrix:

$$P = K[R \mid -RC]$$

- Intrinsic matrix multiplied by the Extrinsic matrix.
- Extrinsic matrix can be expressed as:

$$[R \mid \boldsymbol{t}] = \left[\begin{array}{ccc|c} r_{1,1} & r_{1,2} & r_{1,3} & t_1 \\ r_{2,1} & r_{2,2} & r_{2,3} & t_2 \\ r_{3,1} & r_{3,2} & r_{3,3} & t_3 \end{array}\right]$$

- Where the right block is camera rotation relative to world coordinates and left block is camera translation in world coordinates.
- World coordinate origin is target.

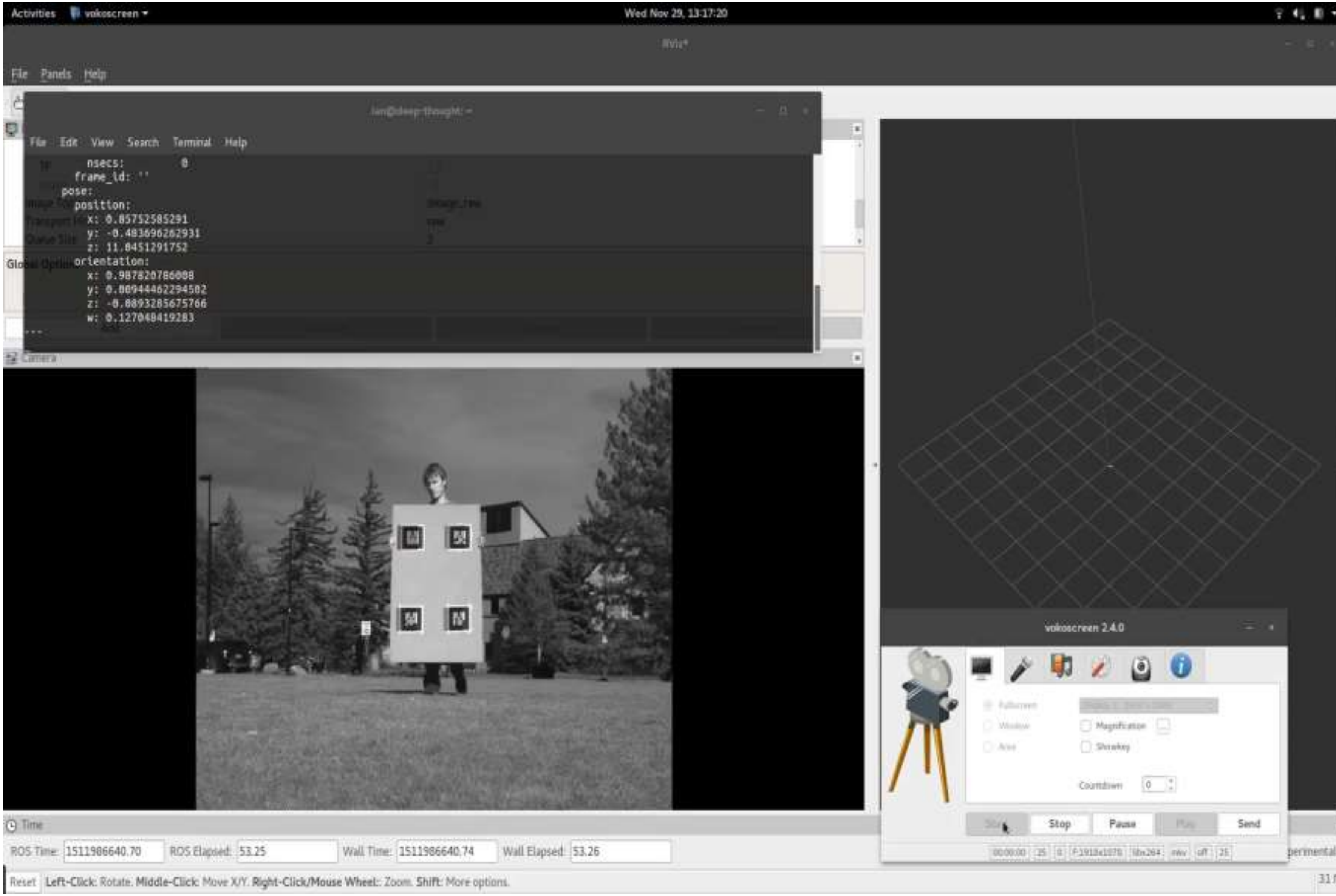
Camera Matrix

- A “principal point” is assumed the center of the distortion.

$$K = \begin{pmatrix} f_x & s & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}$$

- f_x and f_y are the focal lengths for the sensor (assumed equal).
- x_0 and y_0 are offsets for principal point.
- S is axis skew or distortion, or a shear.

AR Tag Test Video



Camera Solution

- DFK 33UX249 (1920x1200).
- Tamron M112FM16 16mm lens.
- Second choice from trade study.

Parameter	Value
Vertical Angle of View	28 degrees
Horizontal Angle of View	36.8 degrees
Maximum fps	48 fps
Lens Mount	C/CS
Sensor Format	1/1.2”

*Courtesy of rmaelectronics.com and theimagingsource.com

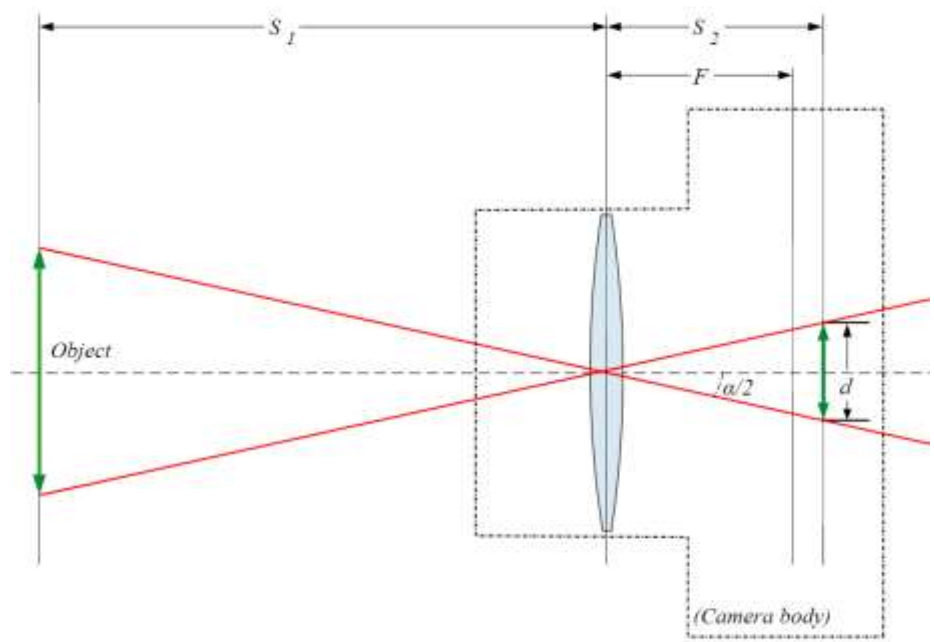
Angle of View Calculations

Angle of view is calculated from the sensor dimension, d, and the focal length of the lens, f

$$AOV = tan^{-1}\left(\frac{d}{2f}\right)$$

$$FOV = 2d \cdot tan\left(\frac{AOV}{2}\right)$$

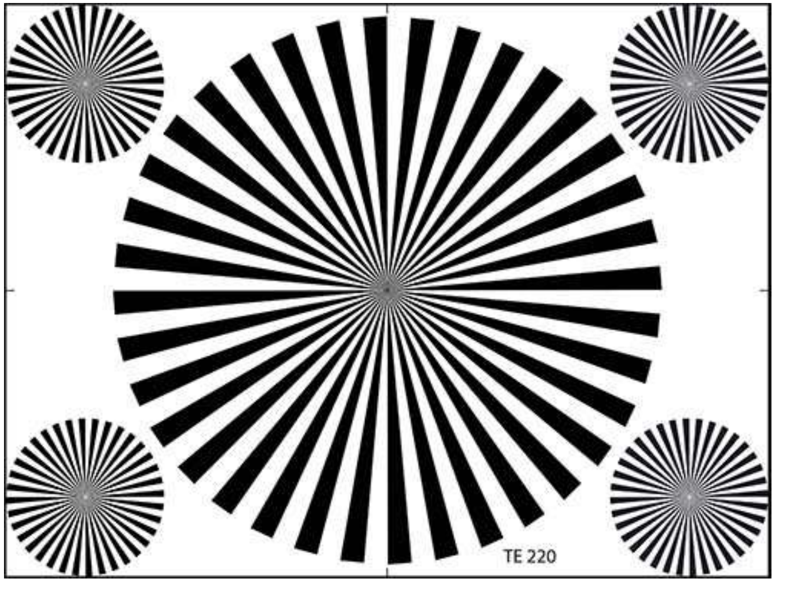
For the 1/1.2" sensor (10.67 x 8.00 mm) on the DFK 33UX249, a 16mm lens gives a 28 degree vertical AOV and a 36.8 degree horizontal AOV



Testing Improvements

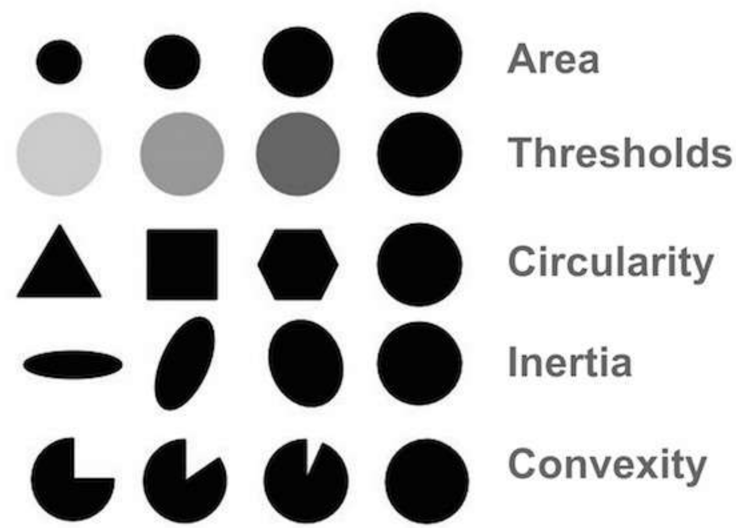
- Camera calibration with larger checkerboard.
- Precise spacing and printing of tags.
- Focus calibration.

*Courtesy of Image Engineering



OpenCV Blob Detection – Tunable Parameters

- OpenCV library class SimpleBlobDetector
- Parameters available to tune for optimal performance
  - Color/threshold – define desired intensity range
  - Area (blobs detected will be between min and max area) in pixels
  - Circularity
  - Inertia ratio (measure of eccentricity of blobs, min and max)
  - Convexity

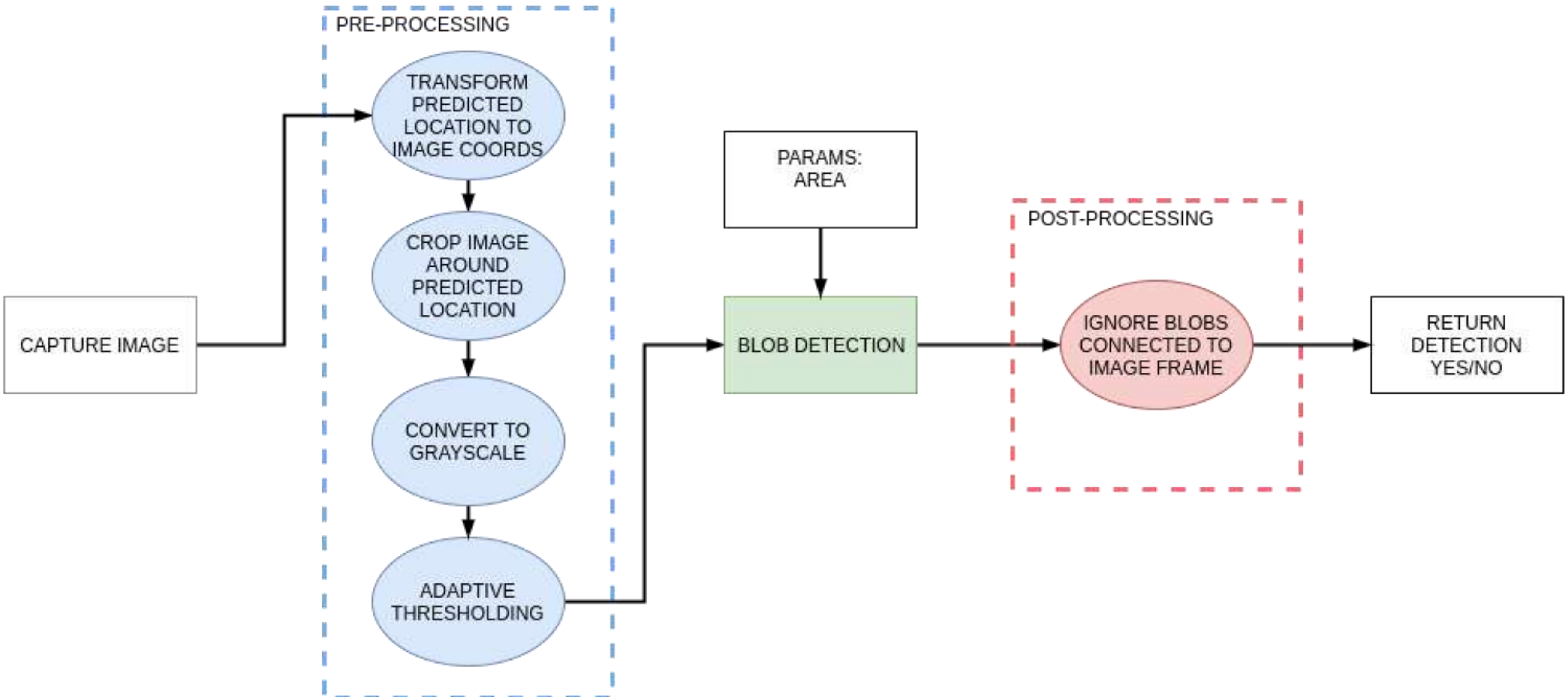


Courtesy of learnopencv.com

Blob Detection Demo Parameters

- Threshold (intensity 0 – 255)
  - Minimum value: 0
  - Maximum value: 127
- Area of blobs (pixels)
  - Minimum value: 100
  - Maximum value: 10000

Blob Detection Flowchart -- PDR



Detection of small target

Testing Design Requirements and Models

Subsystem Test	Design Requirements	Model to Validate
Camera Pointing	DR 3.1	AOV Model
GPS Accuracy	DR 3.1, 8.4	GPS Error
Tracking	FR 3.0	Gazebo
UAV Manual Flight	DR 5.1	-
UAV Auto Flight	DR 9.3	-
UAV Endurance	DR 1.1, 7.1, 7.4	Power Model
Comms Test	DR 8.2, 8.4	Range
Full System Test	DR 4.1	Gazebo

Key
Payload
Platform
System

Conclusions:
- Gazebo model contains many project elements
- Many UAV tests required to build up to test readiness

Risks

Failure Mode	Cause	Likelihood	Effect	Severity	Total	Mitigation
Testing						
- UAV Crash: No Damage	User Error or Code Failure	10	Reset Test	2	20	Incremental Build Up, Spare carbon structural rods for quick repairs
- UAV Crash: Minor Damage	User Error or Code Failure	10	Repair Damage Reset Test	4	40	
- UAV: Crash Major Damage	User Error or Code Failure	8	Repair Damage Reset Test	8	64	
- UAV Crash: Catastrophic	User Error or Code Failure	4	Re-factor testing plans	10	40	
- Li-Po Damage	Operator Error	4	Use other batteries	4	16	Observed Charging, Charging in Li-Po sack
- Testing takes too long to complete	Long Prep Times	4	Schedule Slide	4	16	Properly plan testing for efficiency, plan for schedule slip due to weather
- UGV Crash	Operator Error	2	Reset Test	2	4	Only authorized personnel drive vehicle
- ODROID doesn't meet performance requirements	Underestimation of the complexity of algorithms	6	Change visual detection strategy	2	12	Scale the image processing
- Unable to meet endurance requirement	Model Inaccuracies	2	Mission duration shortened	2	4	Connect two cells in parallel
- Bad Data	Incorrect sensor selection, too much sensor noise	2	Implement filtering, refactor data collection strategy	6	12	Characterize sensors to determine what filtering needs to occur
- Camera Breaks	UAV Crash, operator error	2	Transfer camera to UAV, continue testing without UGV camera	10	20	Payload only installed when required
- Short Electronics	Operator Error	2	Replace broken electronics	6	12	Order spare ODROID and build from schematics
- Testing doesn't substantiate claims	Insufficient testing, incorrect test plans	2	Refactor testing plan, retest system	8	16	Peer review test plans among team and faculty

Risks

Failure Mode	Cause	Likelihood	Effect	Severity	Total	Mitigation
Hardware						
- Too heavy	Inaccurate weight estimates	2	UAV may crash or have reduced endurance	8	16	UAV will be flown with proxy weights for testing.
- Payload doesn't mount	Insufficient modelling	2	Will have to redesign mounting solution	4	8	Solidworks modelling to ensure payload will mount
- C/G Stability is poor	Payload weight is not correctly distributed	6	UAV may crash	8	48	Incremental build up with proxy masses.
- Field of View	Lens and camera combination result in insufficient field of view	4	Target vehicle will not be In image	8	32	Lens and camera combination FOV will be determined
- Jitter	Gimbal mount not manufactured properly	2	Target vehicle will not be in frame	4	8	Machining gimbal mount from aluminum
- Compression	ODROID does not have computational power to compress images	2	Data storage solution will not store all images from tracking run.	2	4	Confirm ODROID has builtin hardware JPEG encoder.
- Endurance	Extra weight, insufficient battery capacity or motor power	4	System will not fulfill 15 minute tracking requirement.	4	16	Incremental build-up to confirm endurance.

Risks

Failure Mode	Cause	Likelihood	Effect	Severity	Total	Mitigation
Electronics						
- Splitting GPS data flow between ODROID and transmitter	Ardupilot data transfer capabilities are poor.	2	GPS data may not be recorded or shared between vehicle	4	8	Data transfer will be incrementally tested to determined thresholds.
- GPS noise affecting accuracy	Pointing system not accurate enough	6	Target vehicle will not be in frame.	8	48	Antenna design and electronics placement will reduce interference.
- Pulse Width Modulation does not work	Incorrect motor controller design	4	UAV may crash	6	24	PWM motor control will be ground tests.
Communications						
- WiFi range is not sufficient	UAV moves out of range of GCS station during test	4	Lose control over UAV, data communcation would fail	2	8	UAV will fly within predetermined constraints to maintain range within limits.
- UGV bluetooth connection fails	UGV moves out of range of GCS	2	Lose control over UGV	2	4	UGV will operate within predetermined constraints to maintain range within limits.
- Preview image does not get communicated to GCS	Communication system does not have bandwidth to send image in real time	4	GCS will not have preview image for operator	2	8	Preview image will be compressed and scaled down before transmission.
- Interference	Electrical components result in interference with comminications system.	2	Realtime data sharing during test is impacted	2	4	Electronics organization in payload is organized to mitigate interference.
- Communication between Ardupilot and ODROID fails	Protocol miscommunication	4	Flight data will not be shared with rest of network, resulting in failure to track.	8	32	Confirmation in testing of serial to USB data transfer

Risks

Failure Mode	Cause	Likelihood	Effect	Severity	Total	Mitigation
Tracking						
- Blob detection / AR detection fail	Environmental factors cause detection to fail, or algorithms are not refined enough	6	90% frame requirement will not be automatically verified; will have to be verified with manual review.	2	12	Blob/AR detection are not critical to tracking algorithm
Logistics						
- Lead times for products	Shipping errors or stocking issues	4	Parts do not show up on time resulting in physical integration and testing schedule being pushed back	8	32	Suppliers have been contacted to check stock, and parts have been identified so ordering can occur immediately.

Test Schedule

Test	Required Equipment	Personnel	Date
Gimbal Pointing	Gimbal, Servos, Arduino, Power Supply	R. Andrada, C. Charland, N. Levigne	12/1/17-12/15/17
Unmounted Tracking	Gimbal, camera, GPS Units	R. Andrada, N. Levigne, R. Blay	1/20/17-1/31/17
Detection Testing	Camera, Computer, AR Tags, UAV Analogue	I. Loefgren, N. Levigne	1/28/17- 2/4/17
GPS Test	2x GPS Units	R. Blay, C. Charland	1/12/17-1/18/17
UAV Manual Flight	UAV System, Transmitter	C. Charland, A. Swindell	2/5/17
UAV Auto Flight	UAV System, Transmitter	C. Charland, A. Swindell	2/19/17
GCS Test	GCS, UAV, UGV	C. Charland, A. Swindell, I. Loefgren	3/20/17
COMMS Testing	COMMS system, UAV, UGV, GCS, Payload	C. Charland, A. Swindell,	3/5/17-3/10/17
Mock Systems Test	UAV, UGV, GCS, Payload	C. Charland, A. Swindell	3/17/17
Full Systems Test #1 & #2	UAV, UGV, GCS, Payload	C. Charland, A. Swindell	4/6/17-4/8/17

Test Equipment & Facilities

Equipment/Facility	Status/Availability
South Boulder Campus	Available for use on 48 hour notice
RECUV VICON Space	Available for scheduling after safety brief
Measurement Tools	Purchased or borrowed from AES department
Sensors	Purchased, some borrowed from customer/ AES department for fall semester testing
Generator	Borrowed
UGV Gimbal Mount	Machined
UAV System Components	Purchased
UGV	On loan from customer

VICON System

- Motion capture system owned by RECUV
- Operational in indoor flight space (RIFLE)
- Allows precise position capture using multiple IR cameras and reflective tags affixed to vehicle
- Can convert position to UTM+13 (Universal Transverse Mercator)
  - Compatible with EME system used in RAVEN
- Low Latency data generation
- Act as a stand in for GPS data
- Build RAVEN to work with both GPS and VICON

Safety

- Safety when flying UAV is biggest concern
  - Follow American Modeler Associations Guidelines
  - Safety Line when flying the UAV
  - Pilot must be AMA certified
  - Props off whenever possible
  - Arming plug for UAV
  - Follow CU Flight Operations Manual
- Li-Po safety
  - Observed charging of Li-Po batteries
  - Charging in Li-Po sack
  - Low voltage alarms to avoid over discharging
- PPE when handling hazardous materials, e.g. cutting carbon fiber

Moving Forward

- Create detailed test procedures for testing
- Walk through testing with faculty
- Safety brief for the VICON space
- Complete preliminary testing with borrowed hardware

Payload Subsystem Test Breakouts

TEST	Level of Success	FR	Models
Gimbal Control	Vision L2	FR 3.0	Gimbal Model
Gimbal Pointing	Vision L2	FR 3.0	Gimbal Model
Camera Characterization	Vision L1	FR 4.0	-
IMU error	Captured Data L1	-	-
GPS Lock Time/ Position Error	Controls L1	-	-
Data Collection/ Compression	Captured Data L1	-	-
CPU Overhead	Electronics L3	-	-
Data volume	Captured Data L1	-	-

Platform Subsystem Test Breakouts

TEST	Level of Success	FR	Models
UAV manual flight and stability	Vision L1	FR 1.0	Gazebo Model
UAV Auto flight and stability	Controls L3	-	-
UAV endurance	Electronics L1	FR 1.0	UAV Power Model
GPS signal to ODROID	Captured Data L1	FR 8.0	-
GPS signal to flight controller	Captured Data L1	-	-
Flight controller to ODROID	Controls L3	-	-
Data logging	Captured Data L1	FR 2.0	Data Rates

COMMS Subsystem Test Breakouts

TEST	Level of Success	FR	Models
UAV → Ground	COMMS L1	FR 8.0	Data Rates/ Gazebo
UGV → Ground	COMMS L1	FR 8.0	Data Rates/ Gazebo
UAV → UGV	COMMS L2	FR 8.0	Data Rates/ Gazebo
Telemetry Radio	Controls L1	-	-
Bluetooth to UGV	Controls L3	-	-
GPS UHF	Electronics L1	-	DGPS Model

Vision Subsystem Test Breakouts

TEST	Level of Success	FR	Models
Blob detection	Vision L3	-	Gazebo
AR Tag detection	Vision L2	FR 3.0	Gazebo
UAV on a Stick	Vision L1	-	Gazebo

GCS Subsystem Test Breakouts

TEST	Level of Success	FR	Models
UI	Comms L1	FR 8.0	UI Mockup
Emergency Land	Controls L1	FR 9.0	-
Preview Image	Comms L3	-	-
Location Data	Comms L3	-	-
Mode Switching	Controls L1	-	-

Gimbal Pointing

OBJECTIVE

- Show gimbal can be pointed
- Quantify pointing error

FR: 3.0

Required Hardware:

- Gimbal
- Arduino
- Power Supply

Required Software:

- Pointing Algorithms
- Command Generator
- Pointing Model

Risks:

- Gimbal Damage
- Loaned Gimbal not representative of flight hardware

Environment:

- Lab Environment
- Gimbal mounted to table

Outcome:

- Able to quantify pointing error in gimbal commands
- Verify Pointing algorithms

Unmounted Tracking

OBJECTIVE

FR: 3.0

- Verify Operation of tracking using real hardware
- Identify Issues early

Required Hardware:

- Gimbal + Gimbal Controller
- Arduino
- AR Tags or Blob detect or 2x GPS Units
- Camera
- Power Supply

Required Software:

- GPS Decoding or Blob or AR Detection
- Pointing Control
- Camera Drivers

Outcome:

- Gimbal assembly able to track accurately
- Tracking error not a significant risk to project

Risks:

- Break Equipment

Environment:

- Lab Environment
  or:
- Outside (GPS)(On Campus)

UAV Manual Flight

OBJECTIVE

- UAV System is controllable and stable

FR: 1.0

Required Hardware:

- UAV System without payload installed
- Transmitter
- UAV Safety System

Risks:

- UAV Crash/Damage
- Li-Po Damage
- Injury to personnel

Required Software:

- Flight Controller Configs

Environment:

- RECUV VICON Space

Outcome:

- UAV able to hover for mission duration
- UAV able to orbit for mission duration
- UAV is stable during flight

UAV Auto Flight

OBJECTIVE

- Verify Auto-Flight Capability
- Hover/Orbit for mission duration
- Toggle between manual and automatic control

FR: 1.0, 5.0

Required Hardware:

- UAV System without payload

Required Software:

- Flight Controller configured
- Flight path definition
- GPS Decoding
- Auto/Manual Toggle

Outcome:

- UAV flies autonomously for mission duration
- Switching between auto/manual modes
- Smooth flight

Risks:

- UAV Crash Damage
- Li-Po Damage
- Weather Schedule Slippage

Environment:

- Outside, Clear Calm Day

GCS Test

OBJECTIVE

- Verify operation of GCS
- Verify:
  - ROS Package
  - COMMS
  - Visual Data
  - GPS Delivery
  - Pose Delivery
  - ISM Band

Required Hardware:

- GCS
- Fully integrated UAV/UGV

Required Software:

- GCS Software
- ODROID Running
- ROS Network

FR: 8.0, 9.0

Risks:

- Unable to reliably validate GCS
- Schedule Slippage

Environment:

- Lab Space

Outcome:

- Reliable GCS
- Checks all verify boxes in objective

COMMS Test

OBJECTIVE

- Ensure Comms system is flight ready
- ROS works
- Comms are reliable

Required Hardware:

- Router
- UGV/UAV
- GCS

Required Software:

- GCS
- ROS Nodes
- Comms Network

Outcome:

- All ROS Nodes can communicate
- Data latency does not pose risk to project
- Comms range is large enough to facilitate operation

FR: 8.0, 9.0, 10.0

Risks:

-

Environment:

- Lab Environment

Mock Systems Test

OBJECTIVE

- Determine Preparedness for FST

FR: 1.0, 3.0, 5.0, 6.0, 8.0, 9.0

Required Hardware:

- Fully Integrated UAV/UGV
- GCS
- Full System Ready

Risks:

- Schedule Slide
- Integration Failures

Required Software:

- UAV (Autopilot, Camera, ROS)
- UGV (Controls, Camera, ROS)
- GCS

Environment:

- RECUV VICON Space

Outcome:

- Ready for FST #1
- All systems Go

Full System Test #1 & #2

OBJECTIVE

- Show full system effectiveness
- Test both Scenarios

Required Hardware:

- Fully integrated UAV, UGV
- GCS
- Generator
- Router

Required Software:

-Completed system software

Outcome:

- System works and satisfies functional requirements

FR: All

Risks:

- System Damage
- Bodily Harm
- Weather Delays

Environment:

- South Boulder campus
- Calm, Clear day

Testing Risk Detailed Breakdown

Failure Mode	Cause	Likelihood	Effect	Severity	Total	Mitigation
UAV Crash						
- No Damage	User Error or Code Failure	10	Reset Test	2	20	Incremental Build Up, Spare carbon structural rods for quick repairs
- Minor Damage	User Error or Code Failure	10	Repair Damage Reset Test	4	40	
- Major Damage	User Error or Code Failure	8	Repair Damage Reset Test	8	64	
- Catastrophic	User Error or Code Failure	4	Re-factor testing plans	10	40	
Li-Po Damage	Operator Error	4	Use other batteries	4	16	Observed Charging, Charging in Li-Po sack
Testing Takes too Long	Long Prep Times	4	Schedule Slide	4	16	Properly plan testing for efficiency, plan for schedule slip due to weather
UGV Crash	Operator Error	2	Reset Test	2	4	Only authorized personnel drive vehicle
Odroid doesn't meet performance requirements	Underestimation of the complexity of algorithms	6	Change visual detection strategy	2	12	Scale the image processing
Unable to meet endurance requirement	Model Inaccuracies	2	Mission duration shortened	2	4	Connect two cells in parallel
Bad Data	Incorrect sensor selection, too much sensor noise	2	Implement filtering, refactor data collection strategy	6	12	Select sensors to
Camera Breaks	UAV Crash, operator error	2	Transfer camera to UAV, continue testing without UGV camera	10	20	Payload only installed when required
Short Electronics	Operator Error	2	Replace broken electronics	6	12	Order spare Odriod, build from schematics
Testing doesn't substantiate claims	Insufficient testing, incorrect test plans	2	Refactor testing plan, retest sys	8	16	Peer review test plans among team and faculty

UAV Crash
- No Damage

Description:

- UAV crash that requires repair
- New props or minor fixes

Rating: **20**

Likelihood: 10

Impact: 2

Mitigation:

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

UAV Crash
- Minor Damage

Description:

Rating: **40**

- UAV crash that requires repair
- New props or minor fixes

Likelihood: 10

Mitigation:

Impact: 4

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

UAV Crash - Major Damage

Description:

- UAV crash that requires complex repair
- New parts that aren't on hand

Rating: 64

Likelihood: 8

Impact: 8

Mitigation:

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods
- Spare companion computer
- Follow AMA Guidelines

UAV Crash
- Catastrophic Damage

Description:

- UAV crash that cannot be repaired

Rating: **40**

Likelihood: 4

Mitigation:

- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans

Impact: 10

Camera Breaks

Description:

- Camera breaks due to UAV crash or operator error
- Would force removal of camera from UGV for use on UAV

Mitigation:

- Camera payload will only be installed when required for testing
- Only certified pilot will fly UAV

Rating: **20**

Likelihood: 2

Impact: 10

UAV Stability is Poor

Description:

- UAV flight stability is poor due to poor weight distribution or C.G. location
- Would increase likelihood of a crash

Mitigation:

- Incremental build-up of components on UAV
- UAV testing with proxy weights

Rating: **48**

Likelihood: 6

Impact: 8

Field of View Insufficient

Description:

- Lens and camera combination result in an insufficient field of view
- Could result in failure to track target vehicle in 90% of frames

Rating: **32**

Likelihood: 4

Mitigation:

- Lens and camera combination angle of view will be confirmed through testing

Impact: 8

Noise affecting GPS accuracy

Description:

- Electronic equipment and environment worsen accuracy.
- High accuracy is required for tracking system

Mitigation:

- Electronics in payload will be arranged to minimize interference

Rating: **48**

Likelihood: 6

Impact: 8

Communication between ArduPilot and ODROID fails

Description:

- Protocol communication or bandwidth limitations prevent data transfer
- Tracking will fail without data sensor data

Mitigation:

- Testing of serial to USB protocol will confirm communication compatibility.

Rating: **32**

Likelihood: 4

Impact: 8

Lead Times for Products

Description:

- Shipping errors or product being out of stock could occur
- Would result in physical integration and testing schedule being pushed back.

Rating: **32**

Likelihood: 4

Mitigation:

- Specific components have been identified and are ready for order
- Suppliers have been contacted to confirm availability

Impact: 8

UAV Crash
- Minor Damage

Description:

Rating: **40**

- UAV crash that requires repair
- New props or minor fixes

Likelihood: 10

Mitigation:

Impact: 4

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods

UAV Crash
- Major Damage

Description:

- UAV crash that requires complex repair
- New parts that aren't on hand

Rating: **64**

Likelihood: 8

Mitigation:

Impact: 8

- Payload not installed when not needed
- UAV Safety system
- Spare Props and carbon rods
- Spare companion computer
- Follow AMA Guidelines

UAV Crash
- Catastrophic Damage

Description:

- UAV crash that cannot be repaired

Rating: **40**

Likelihood: 8

Impact: 8

Mitigation:

- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans

Li-Po Damage

Description:

- Cell Damage from:
  - Over discharging
  - Physical damage
  - Improper charging

Rating: 16

Likelihood: 4

Mitigation:

- Observed charging
- Charging in Li-Po sack
- Low voltage monitoring on UAV
- Team training on battery safety

Impact: 4

Testing Takes Too Long

Description:

- Testing Takes longer than expected
- Software not complete when needed
- Testing space not available

Rating: **16**

Likelihood: 4

Impact: 4

Mitigation:

- Schedule Margin for testing issues
- Parallelize testing as much as possible

UGV Crash

Description:

- UGV crashes into stationary object

Rating: **4**

Likelihood: 2

Mitigation:

Impact: 2

- Trained operators use UGV
- UGV not operated in spaces with many unmoving objects

ODROID does not meet performance requirements

Description:

Rating: **12**

- ODROID incapable of running required tasks
- ODROID processing not fast enough
- Unable to write to disk fast enough

Likelihood: 2

Mitigation:

Impact: 6

- Remove visual detection from ODROID
- Move gimbal control to Arduino
- Remove preview image downsampling

UAV Crash
- Catastrophic Damage

Description:

- UAV crash that cannot be repaired

Rating: **40**

Likelihood: 8

Mitigation:

Impact: 8

- Payload not installed when not needed
- Switch testing plans
- Build contingency testing plans