ASEN 4018 Senior Projects Fall 2017
Preliminary Design Review

COHRINT

RAVEN

Rover and Air Visual Environment Navigation

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CUSTOMER: NISAR AHMED

ADVISOR: TORIN CLARK

Agenda

Project Description	Ryan Wall and Rolf Andrada
Tracking	Ian Loefgren and Rolf Andrada
Power	Brendan Boyd
Communications	Ryan Blay
Conclusion	Ryan Blay and Ryan Wall

Acronyms

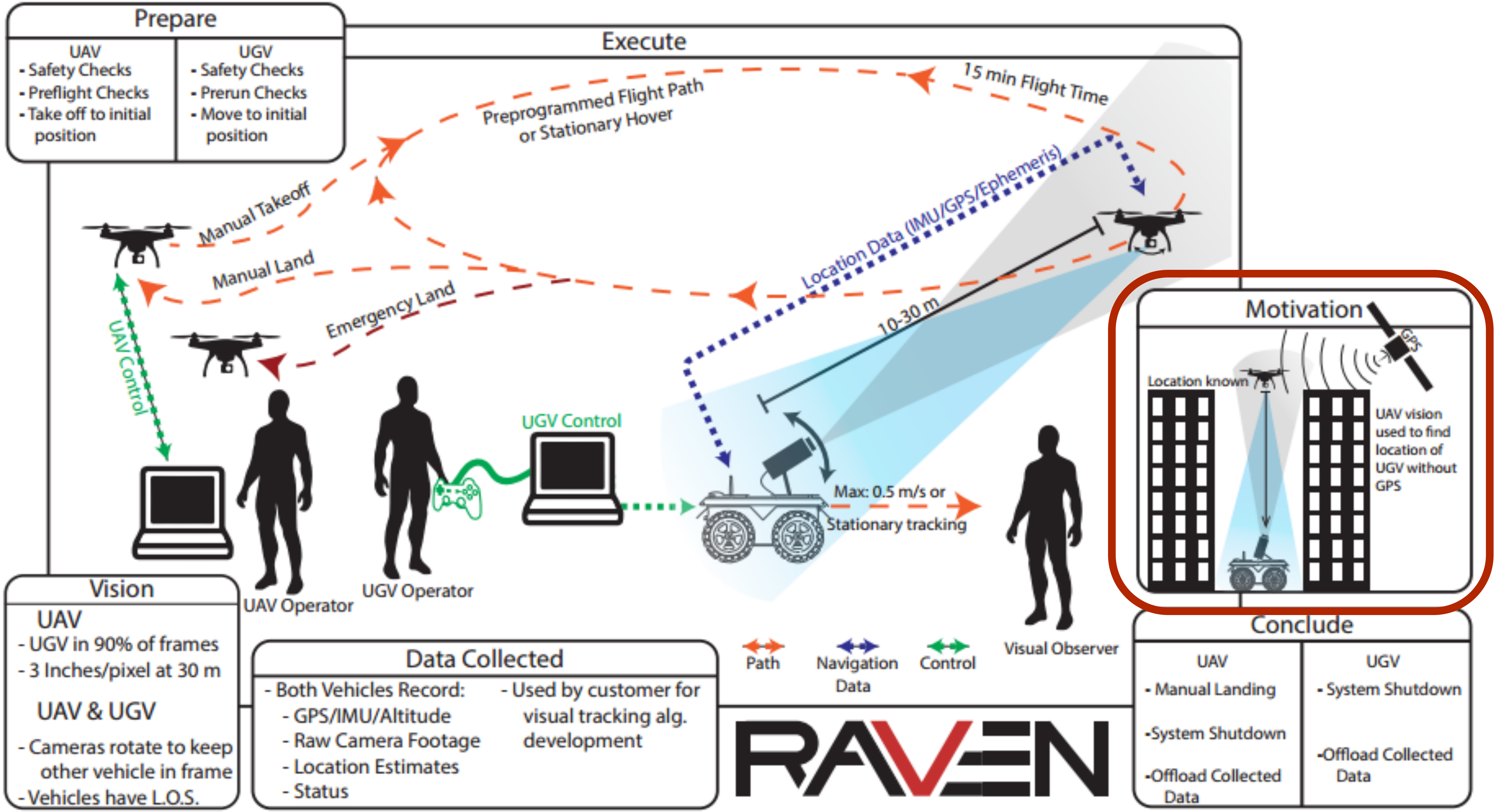
- AOV: Angle of View
- AR: Augmented Reality
- AUW: All Up Weight
- CEP: Circular Error Probable
- CPU: Central Processing Unit
- EPS: Electrical Power System
- ESC: Electronic Speed Control
- FC: Flight Controller
- FOV: Field of View
- GCS: Ground Control Station
- GPS: Global Positioning System
- IMU: Inertial Measurement Unit
- ISM: Industry Science Medicine
- LiPo: Lithium Polymer
- LOS: Line of Sight
- MCU: Microcontroller Unit
- MP: Megapixel
- PWM: Pulse Width Modulation
- RF: Radio Frequency
- RTK: Real Time Kinematics
- UAV: Unmanned Aerial Vehicle
- UGV: Unmanned Ground Vehicle
- UI: User Interface

Project Objectives

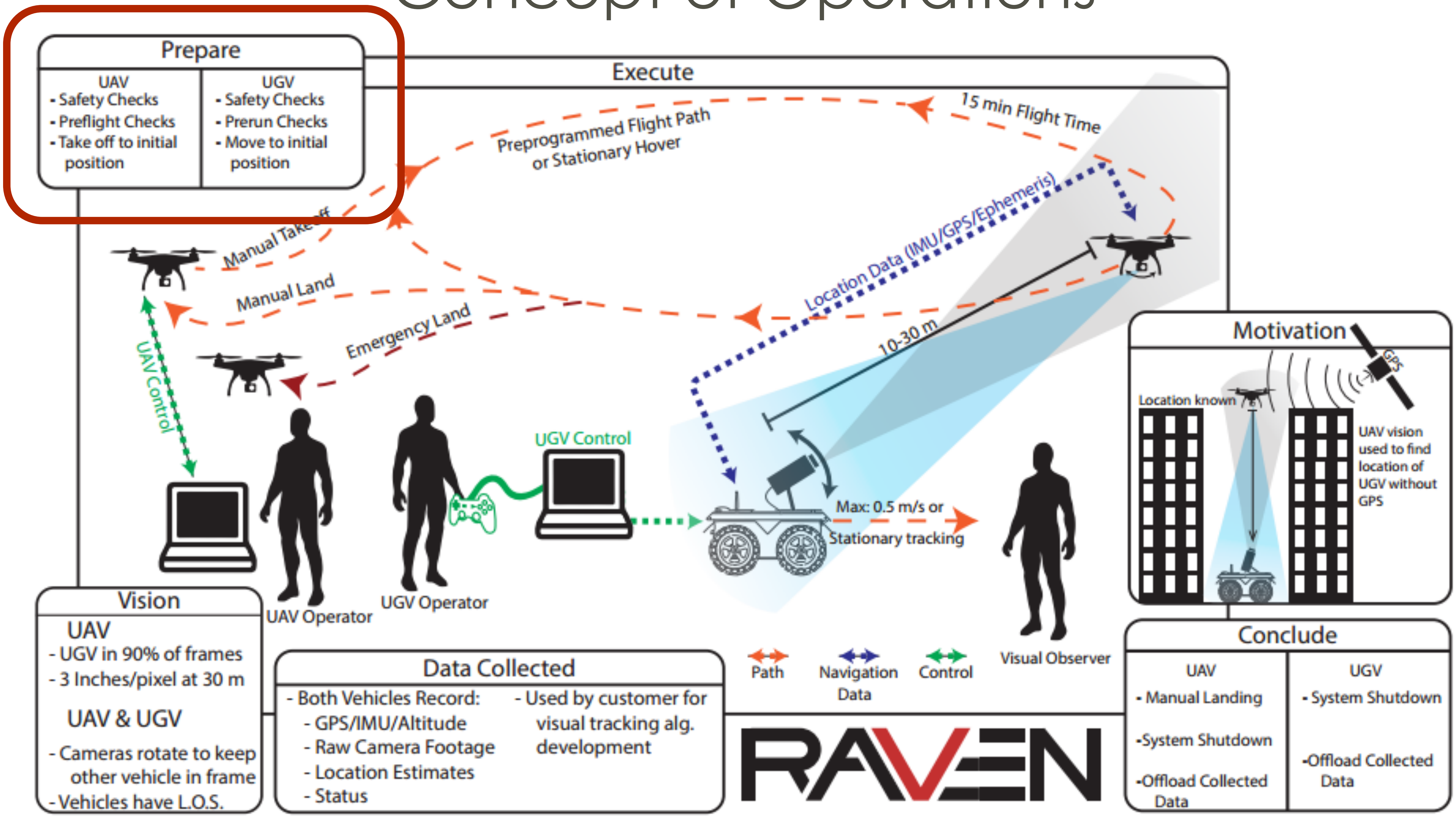
Mission Statement: RAVEN will develop a testbed that will collect image, position, and sensor data to be used by the customer for the verification of customer developed cooperative localization algorithms.

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

Concept of Operations



Concept of Operations



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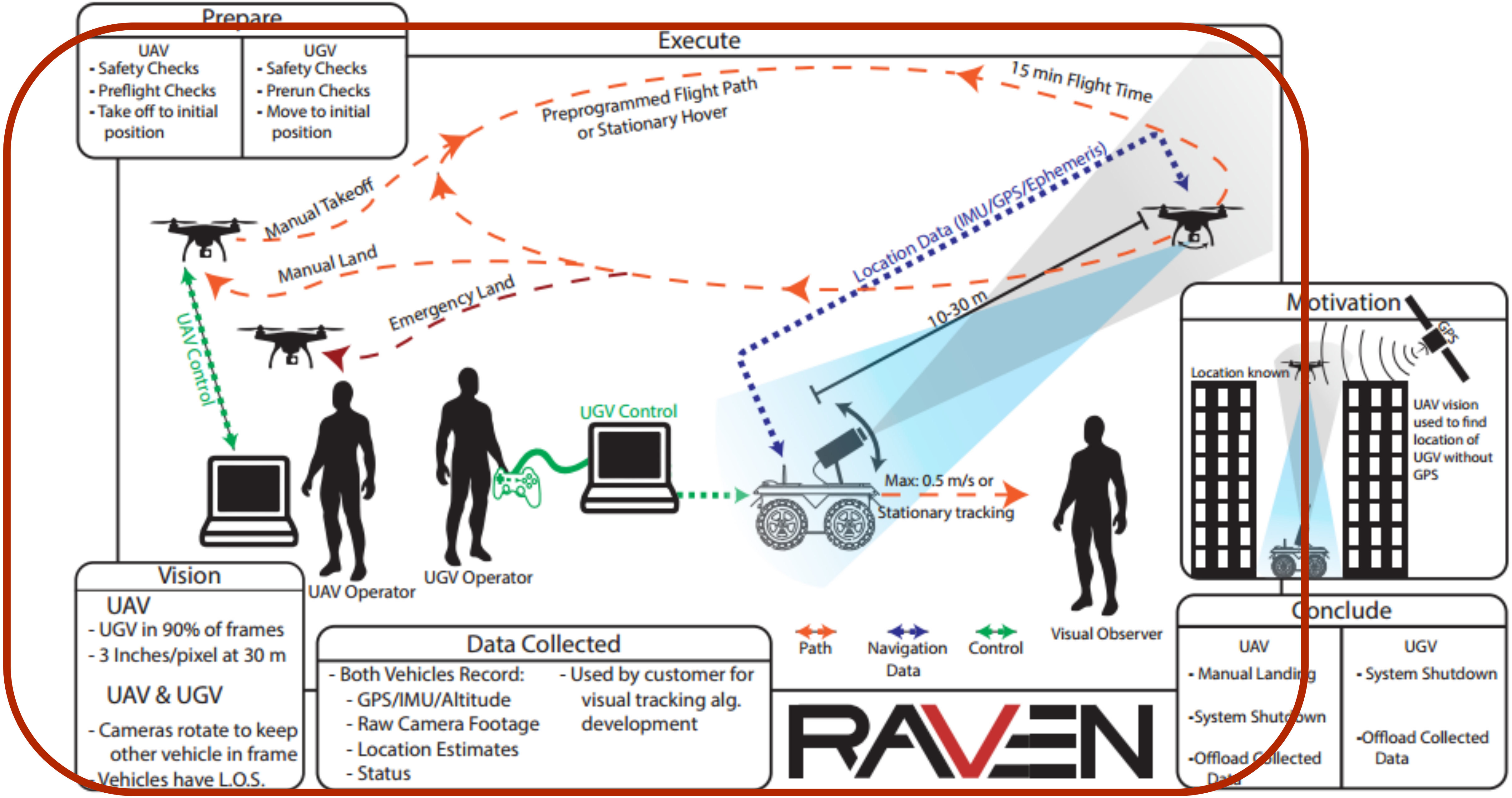

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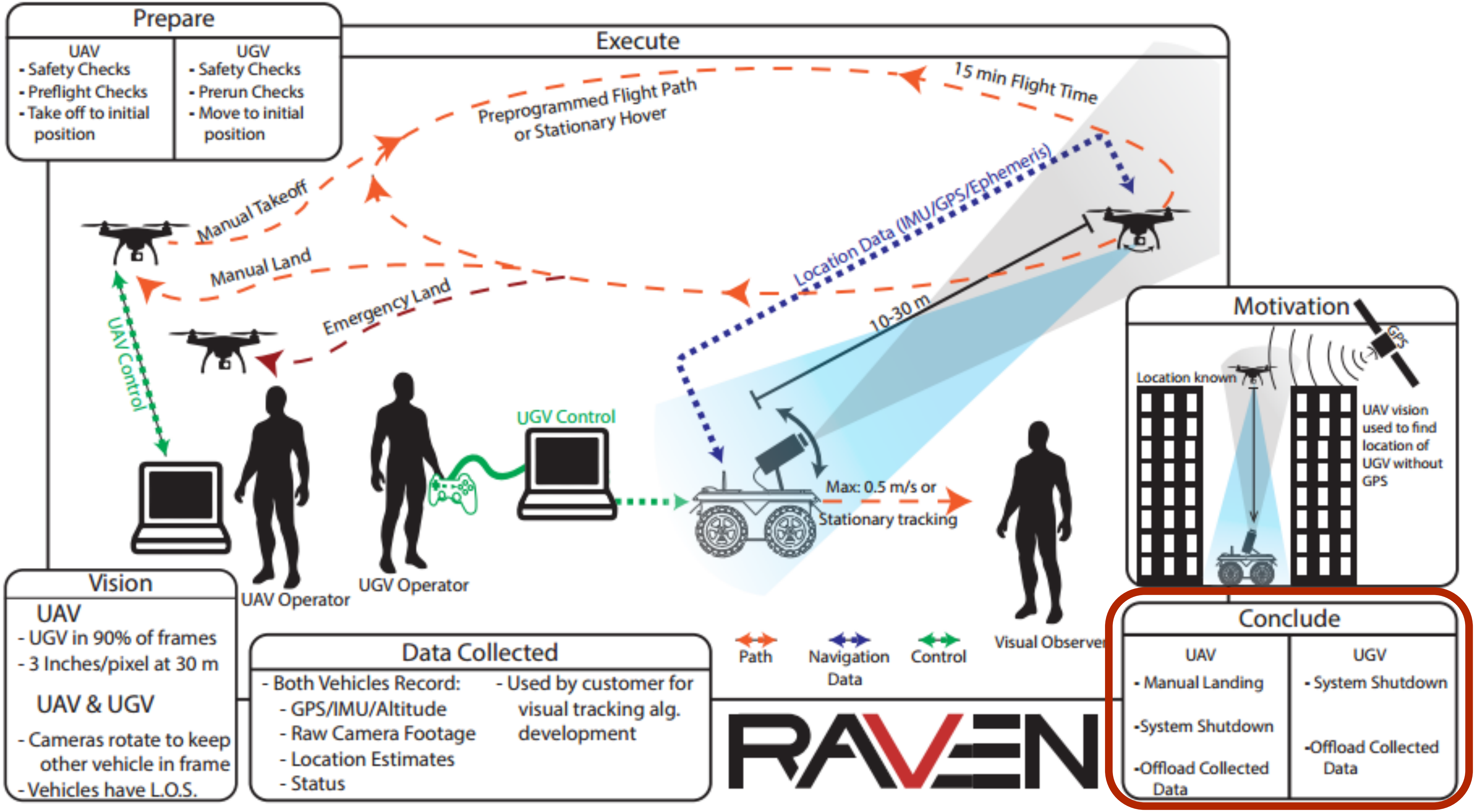
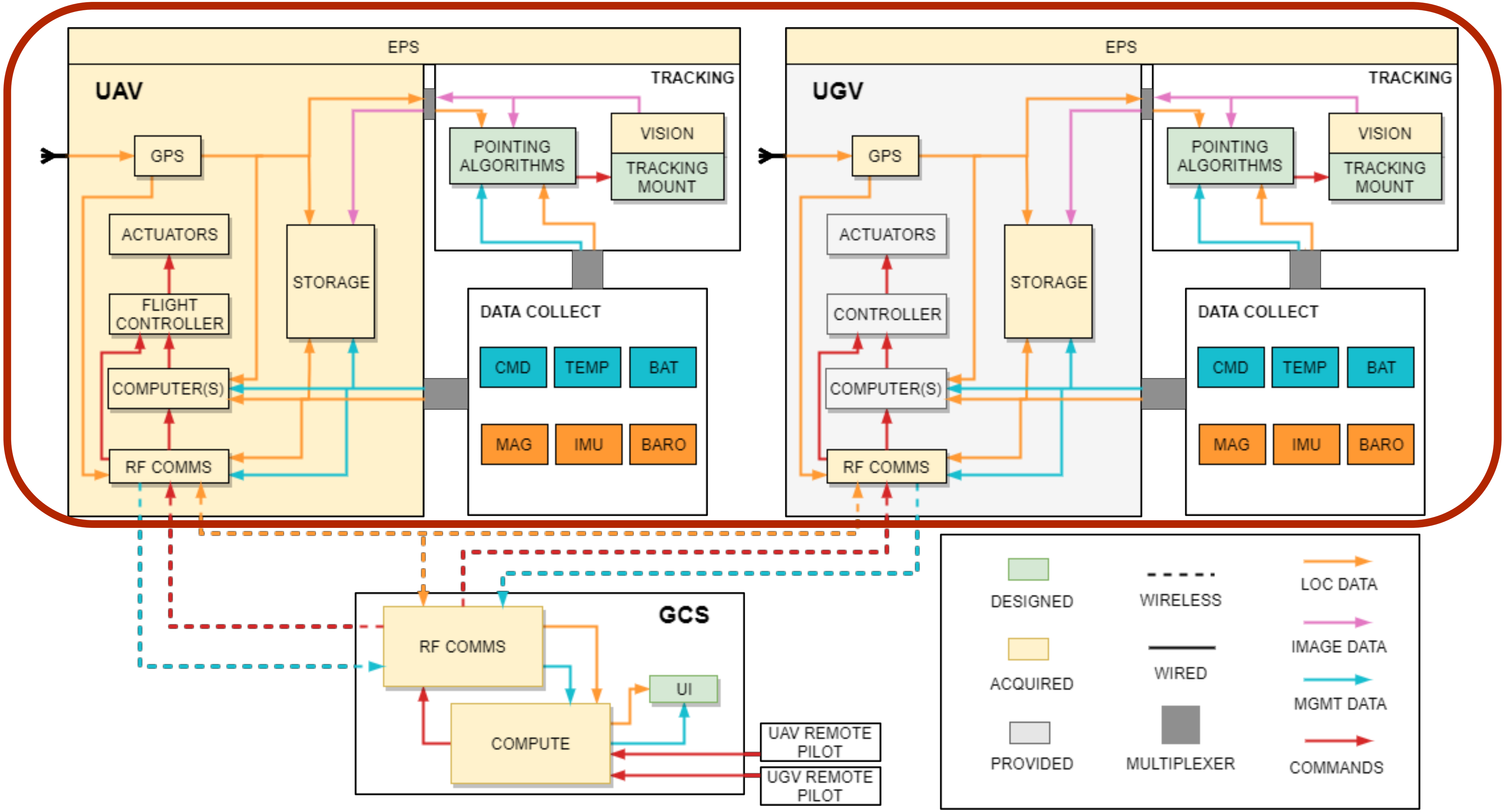


Functional Requirements

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.

System Level Functional Block Diagram



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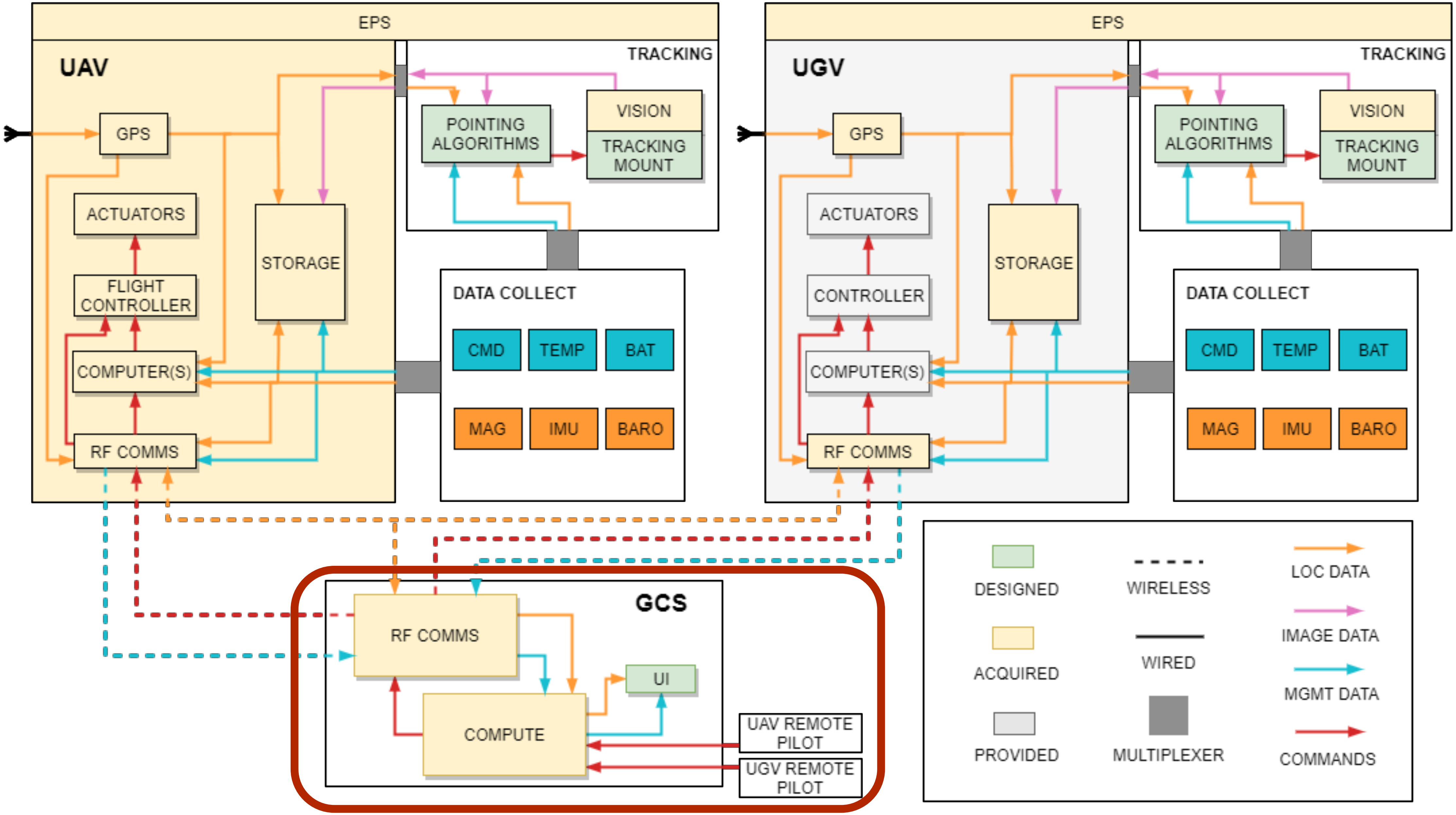
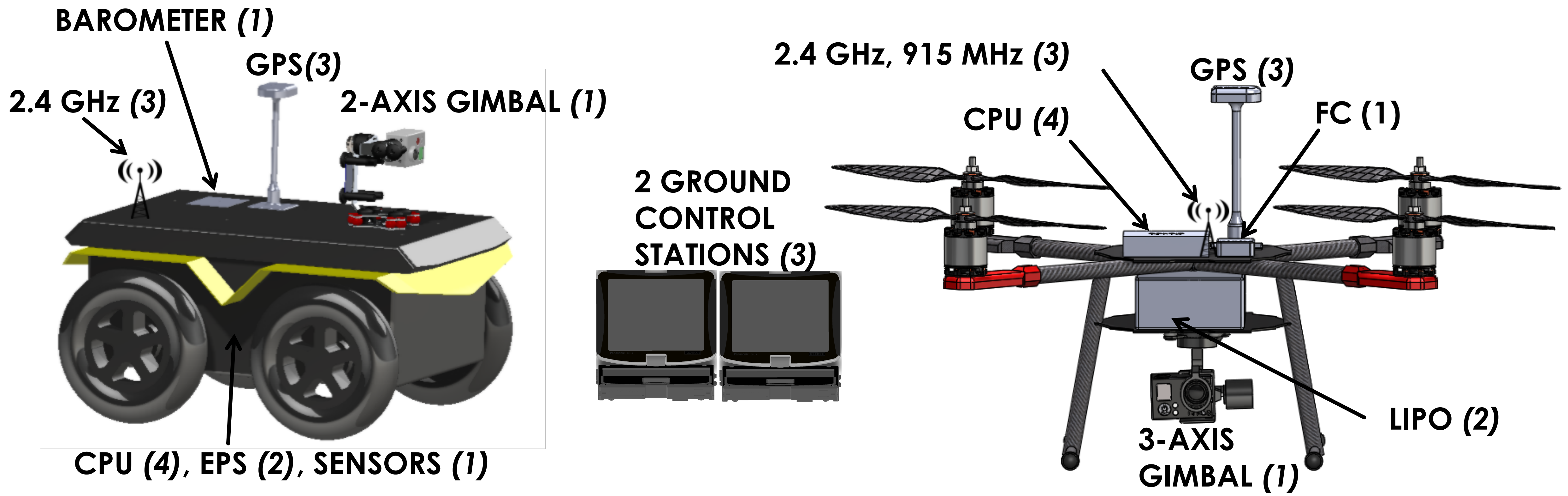


Baseline Design Choices and CPEs

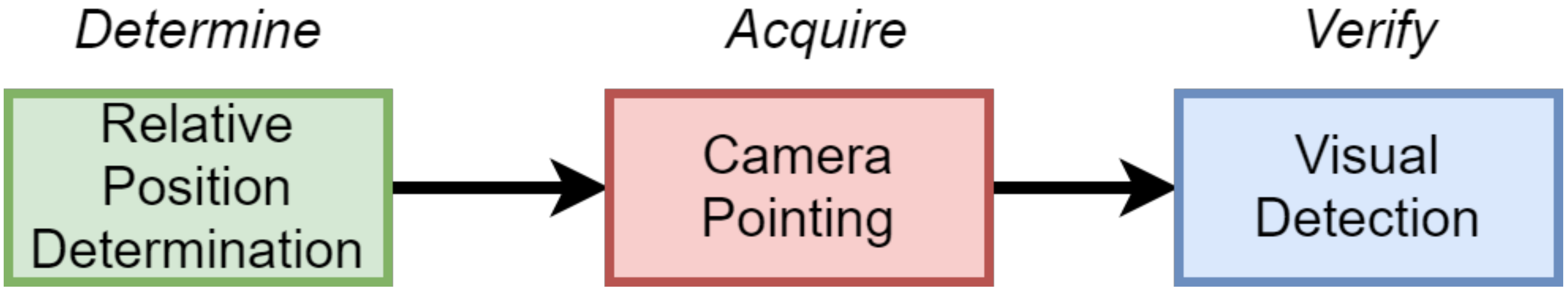


(1) Tracking Systems | (2) Power Systems | (3) Communications | (4) Data Collection

UAV/UGV gimbals, GCS Models courtesy of GrabCAD
UGV model courtesy of ClearPath Robotics

Tracking Method

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 three inches per pixel at a distance of 30 m.



Relative Position Determination

Collect position data using sensor suite

Share position data between vehicles*

Determine relative position using shared information

*Will be focused on in communications section

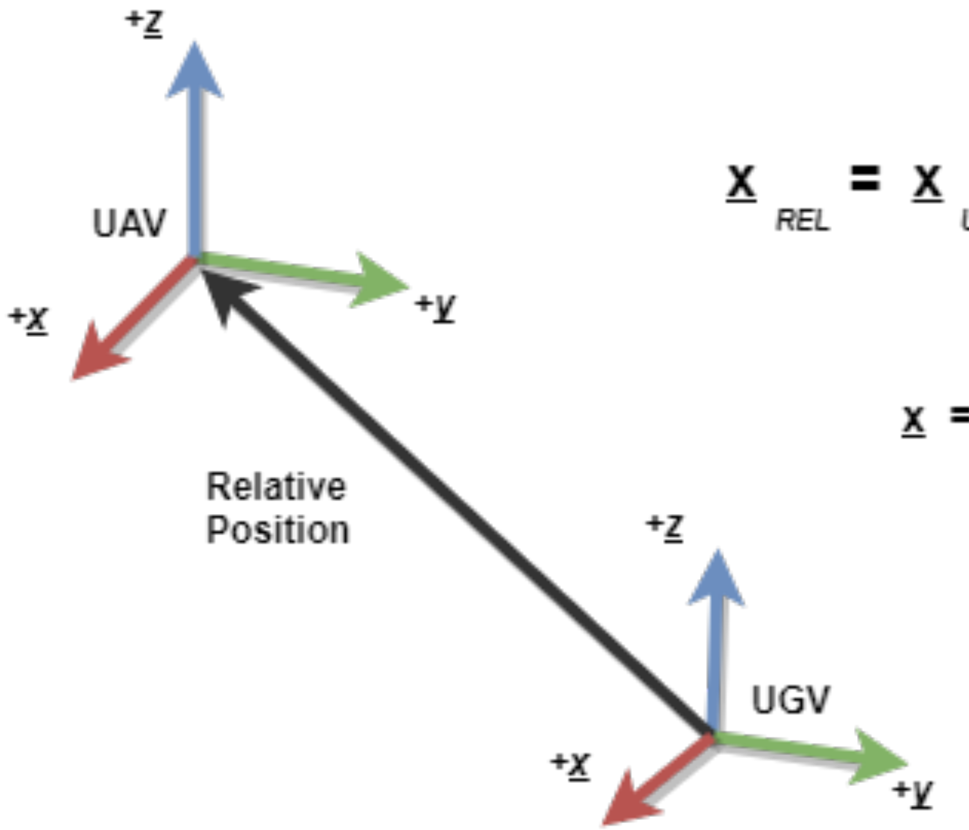
Relative Position Determination: Collect

Vehicle Sensors

State Variable	GPS*	Barometer	IMU	Magnet-ometer
x	✔			
y	✔			
z		✔		
Φ (Roll)			✔	
Θ (Pitch)			✔	
Ψ (Yaw)				✔

*DGPS with RTK engine provides high (cm) accuracy for relative positions

Relative Position Determination: Determine



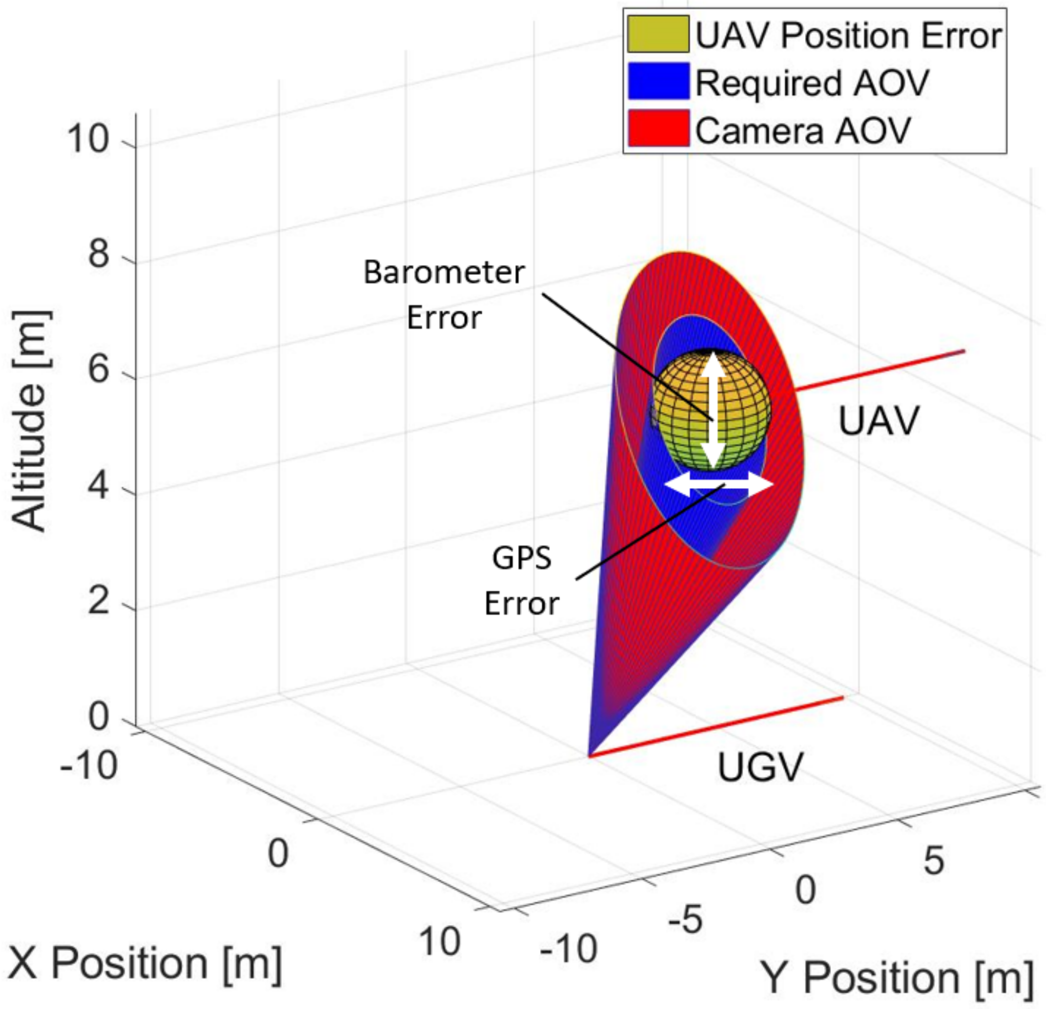
$$\underline{x}_{REL} = \underline{x}_{UAV} - \underline{x}_{UGV}$$

$$\underline{x} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Vehicle Location Error Model

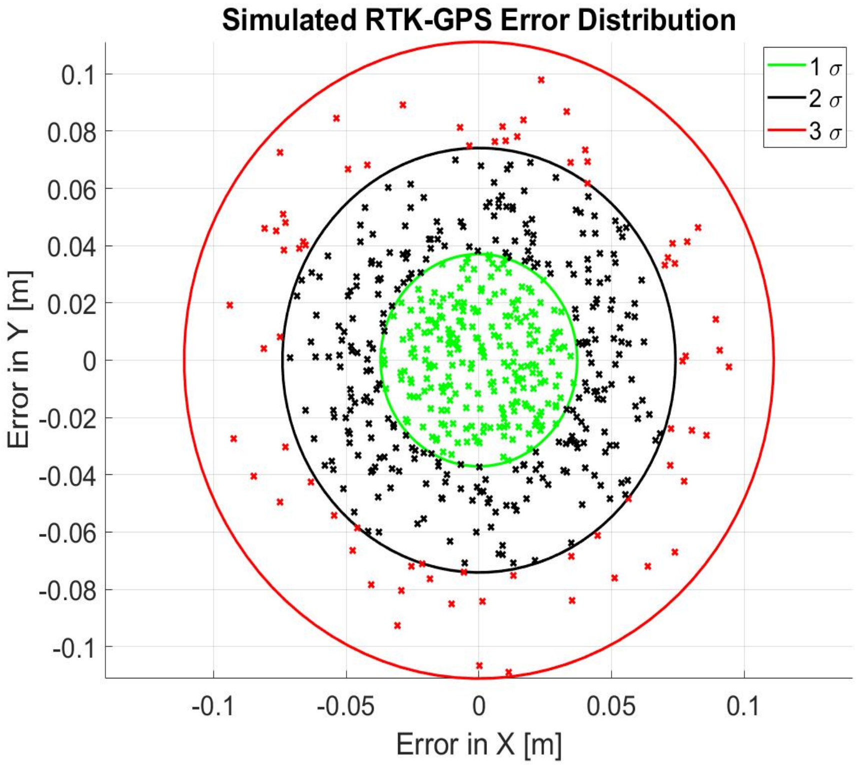
- Purpose
  - Gaussian distributed error based on sensor datasheets
  - Determine required Angle of View accounting for sensor errors
  - Justification of RTK capable GPS

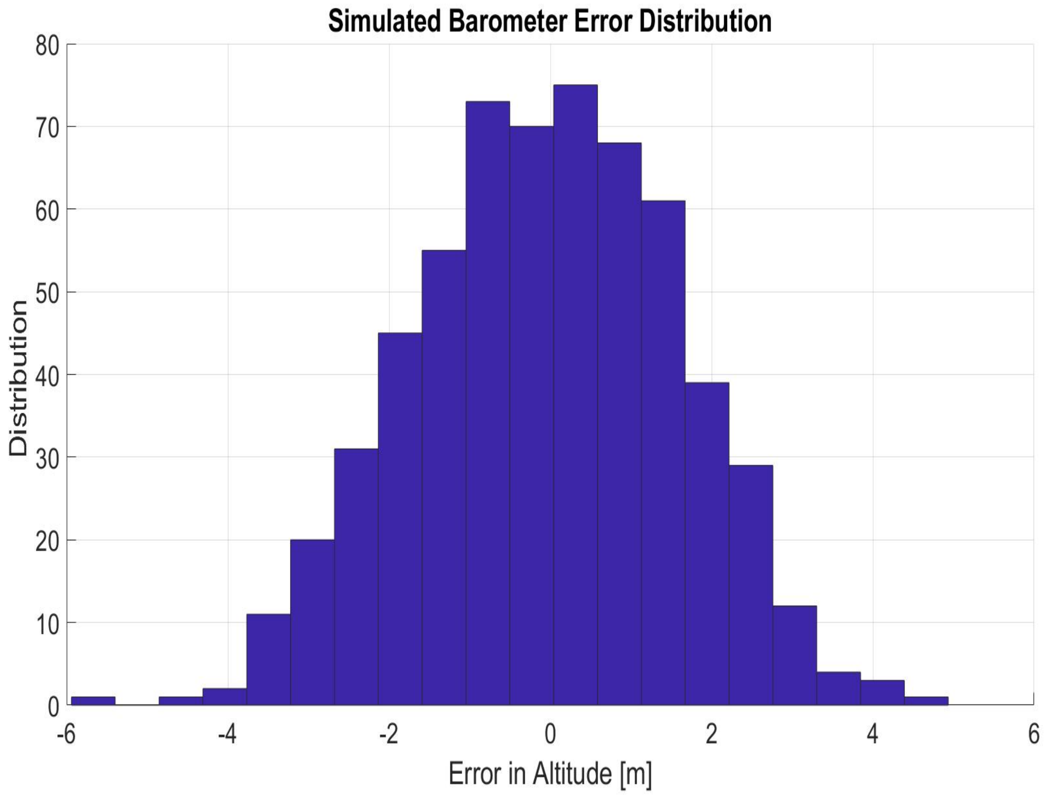
- Assumptions
  - Constant velocity orbit
  - Circular Orbit
  - Constant Altitude



Vehicle Location Error Model (cont.)

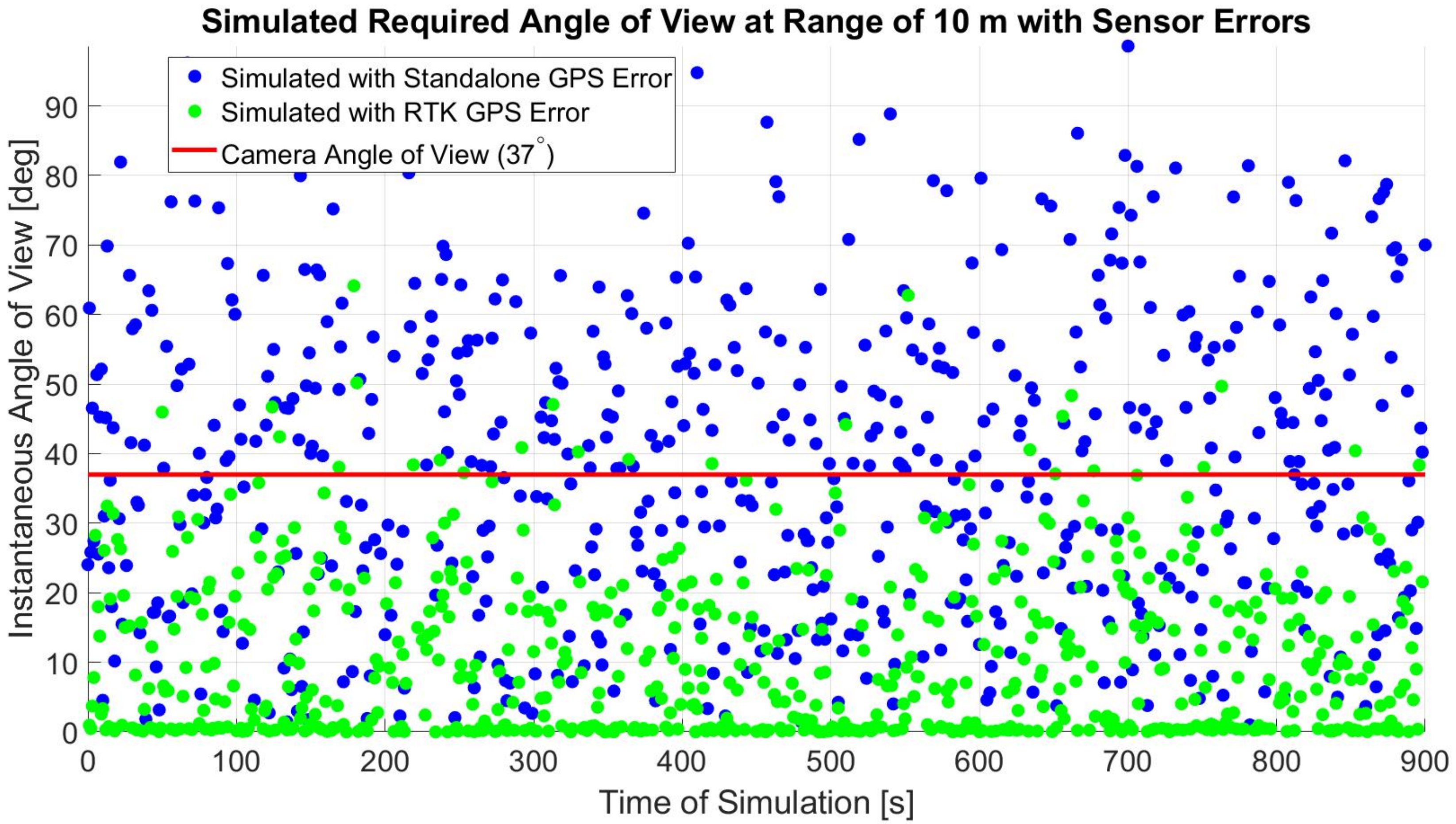
- UAV location error based on GPS and barometer
- Assumption: error has Gaussian distribution
- NEO-M8P u-blox M8 High Precision GNSS Module with RTK [1]
  - Listed Error: 0.025 m CEP
- MS5611 Barometer [2]
  - Listed Max Error: ±0.5 mbar





Vehicle Location Error Model – Required AOV

- RTK-GPS results in >90% within AOV constraints



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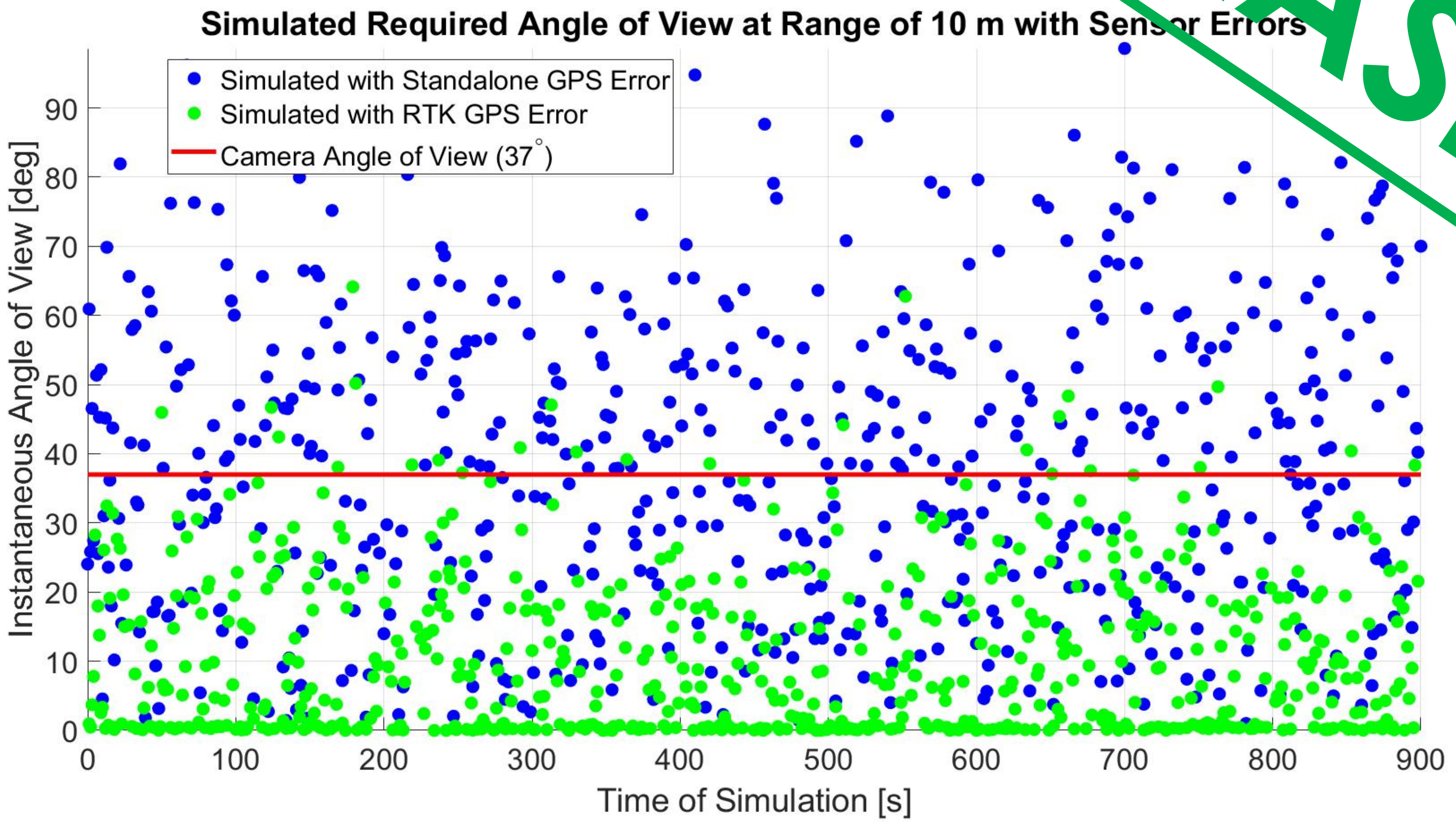

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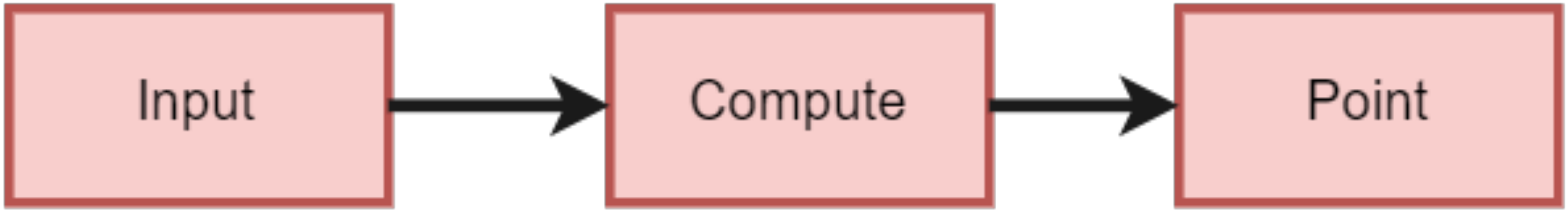
Project Overview | Tracking | Power | Communication | Conclusion

Camera Pointing



Input collected sensor data (with relative position computed)

Compute coordinate transformations

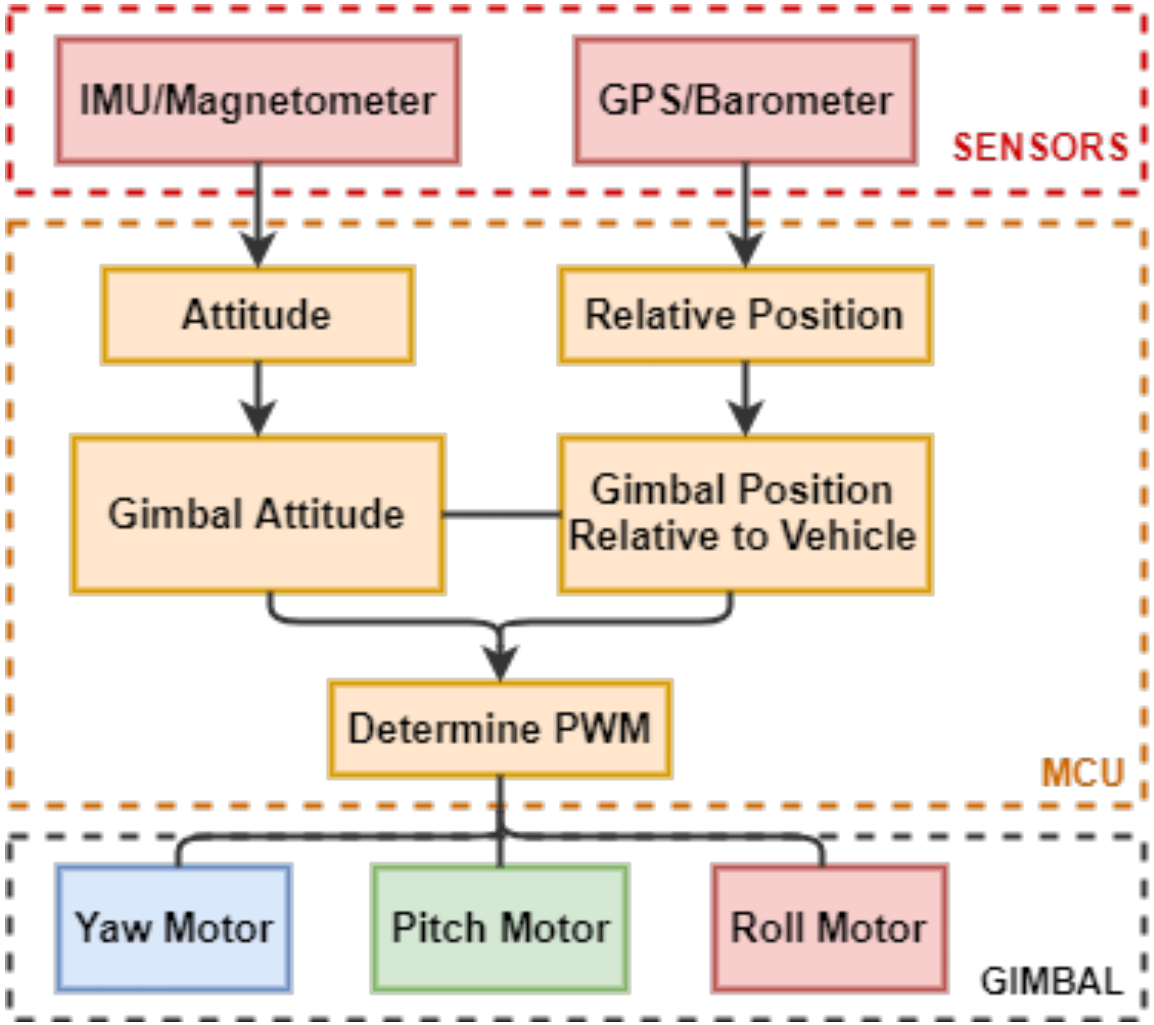
Point camera

Camera Pointing – Gimbal Model

- UAV: 3-axis gimbal
  - Control Yaw, Pitch, Roll
- UGV: 2-axis gimbal
  - Control Yaw, Pitch
  - UGV on "level" surface
- Need:
  - Relative Position (GPS, Barometer, AR)
  - Attitude (IMU and Magnetometer)

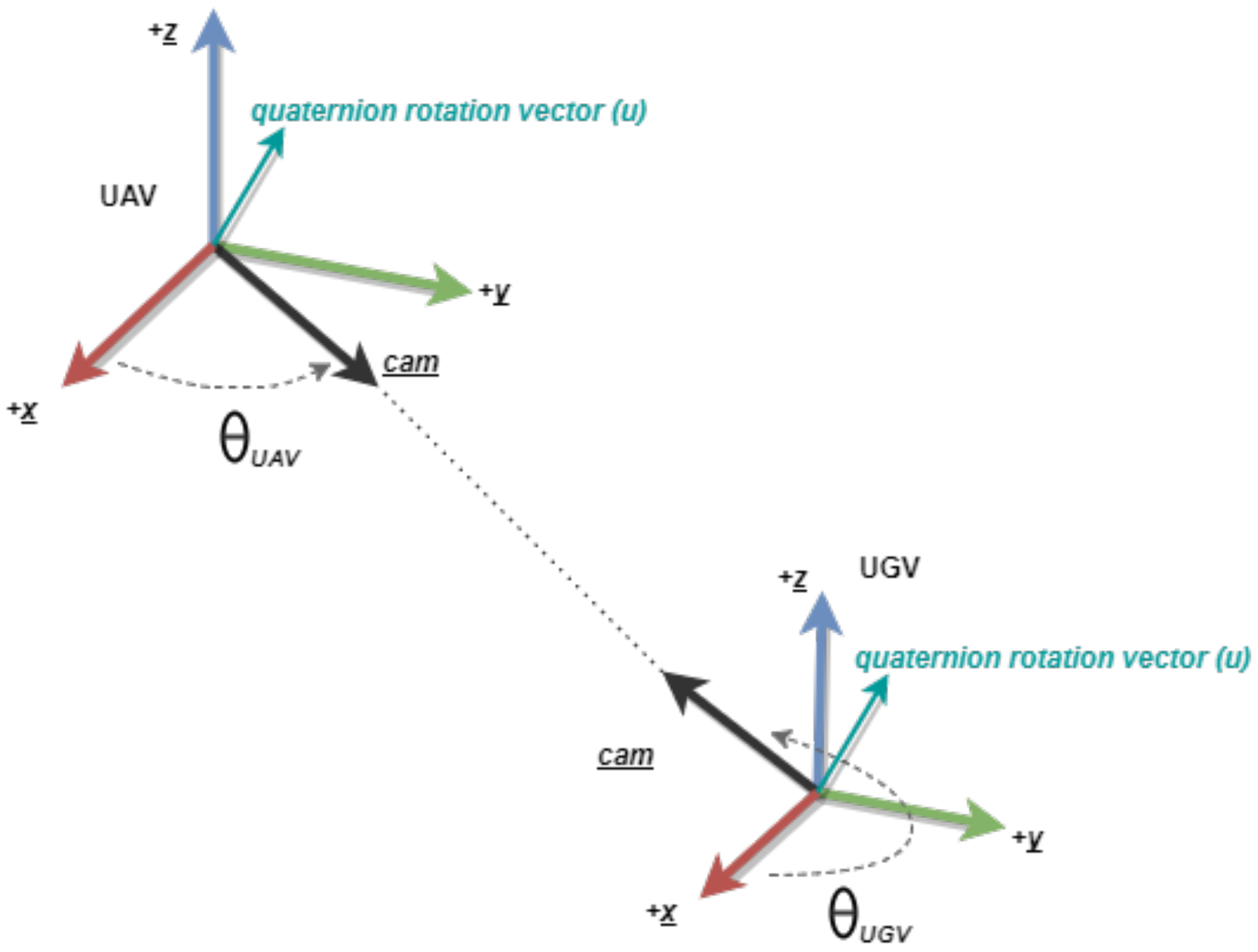
Courtesy of Hobby King

Gimbal Control Diagram



Pointing Model

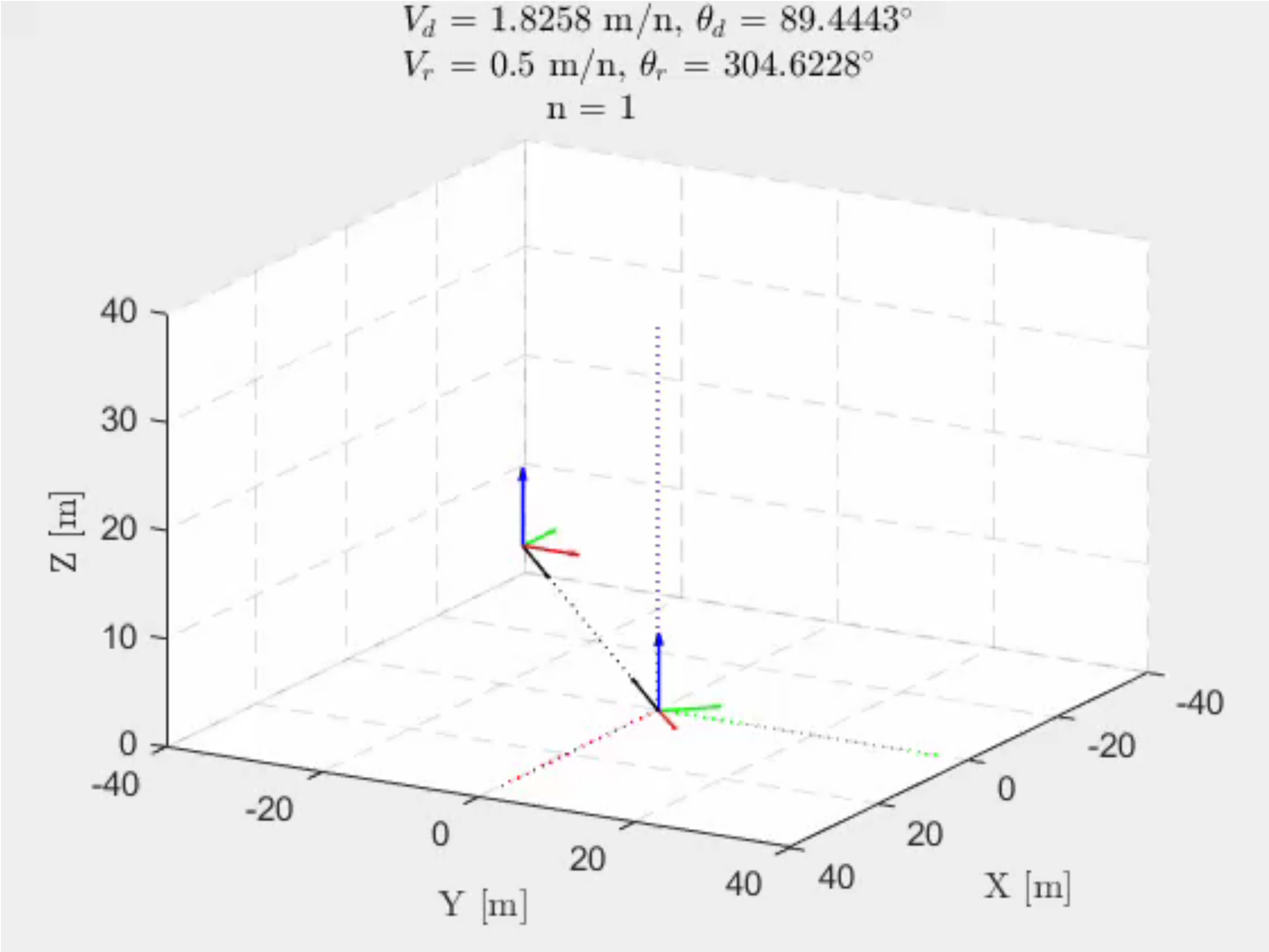
- Quaternion rotation scheme
  - Vehicle body to camera frame
  - One axis of rotation and rotation angle
- Break down rotation into Euler angles:
  - UAV: 3-2-1
  - UGV: 3-2
- Gimbal Lock (+Pitch 90˚ on UAV)
  - UAV gimbal will be prevented from pointing straight down
  - FOV will handle overhead pointing



Pointing Simulation

- Pointing using quaternions

- Legend (body frame):
  - Black – camera pointing vector
  - Red – x
  - Green – y
  - Blue – z



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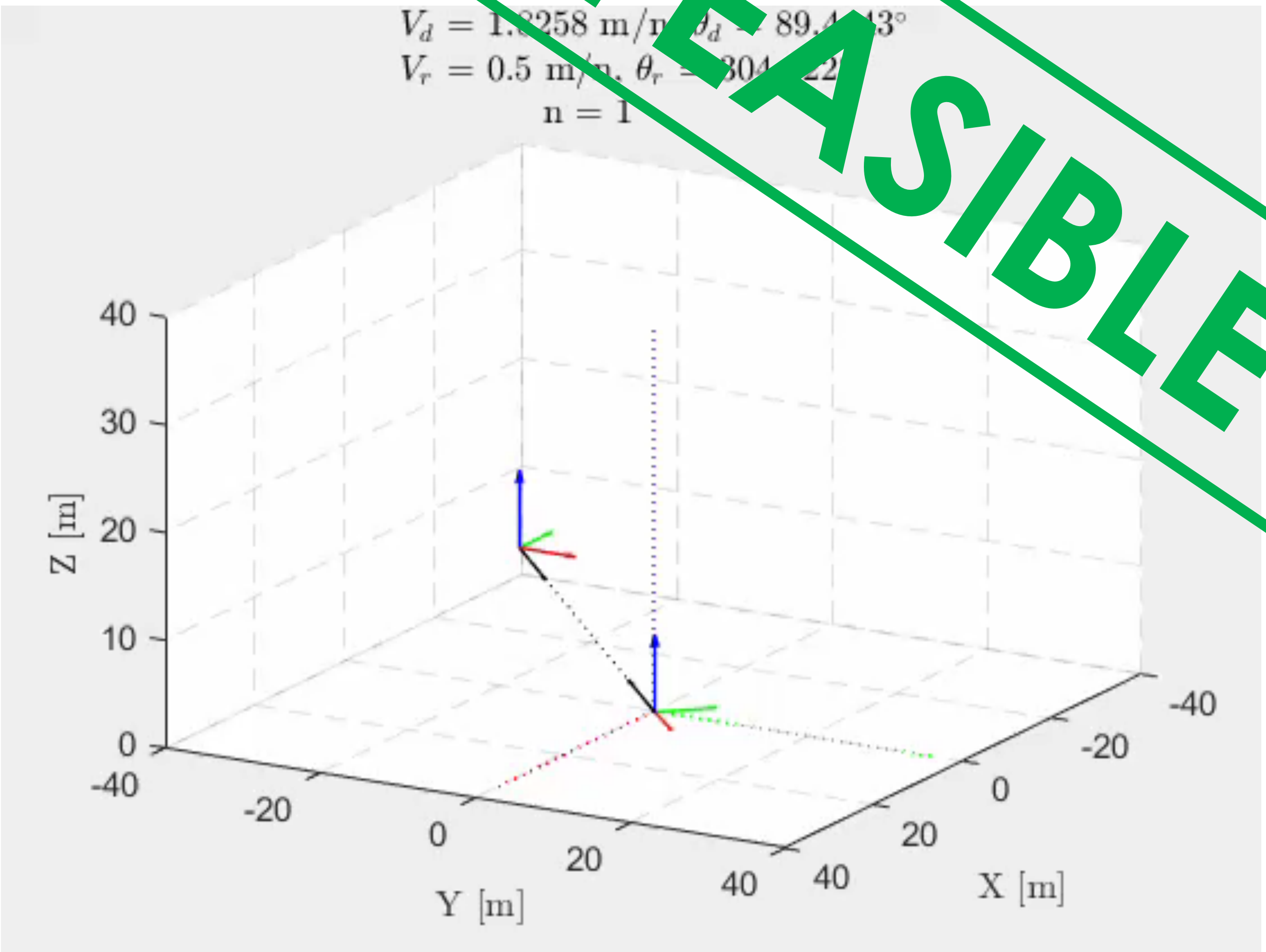
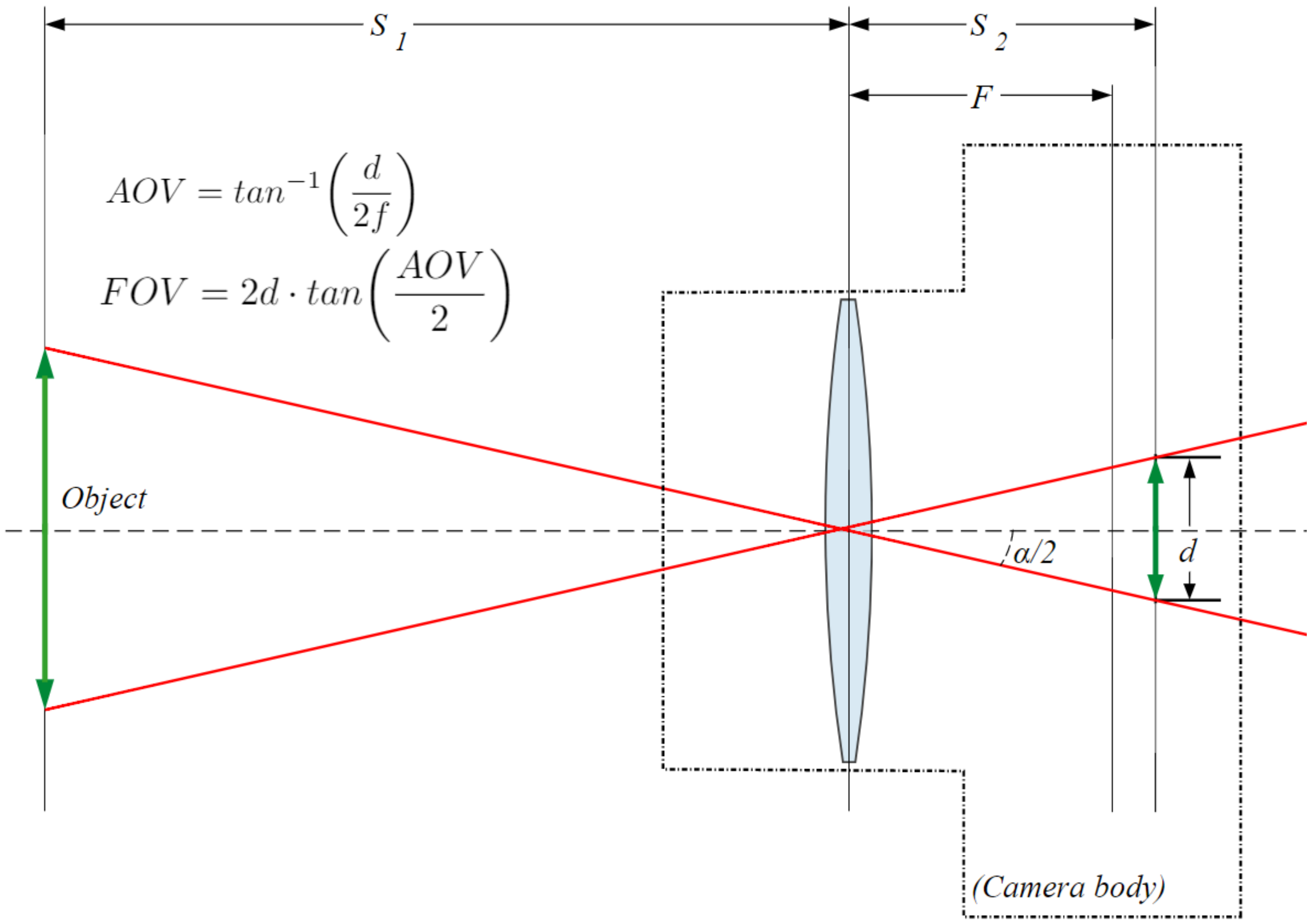


Visual Detection – Verification

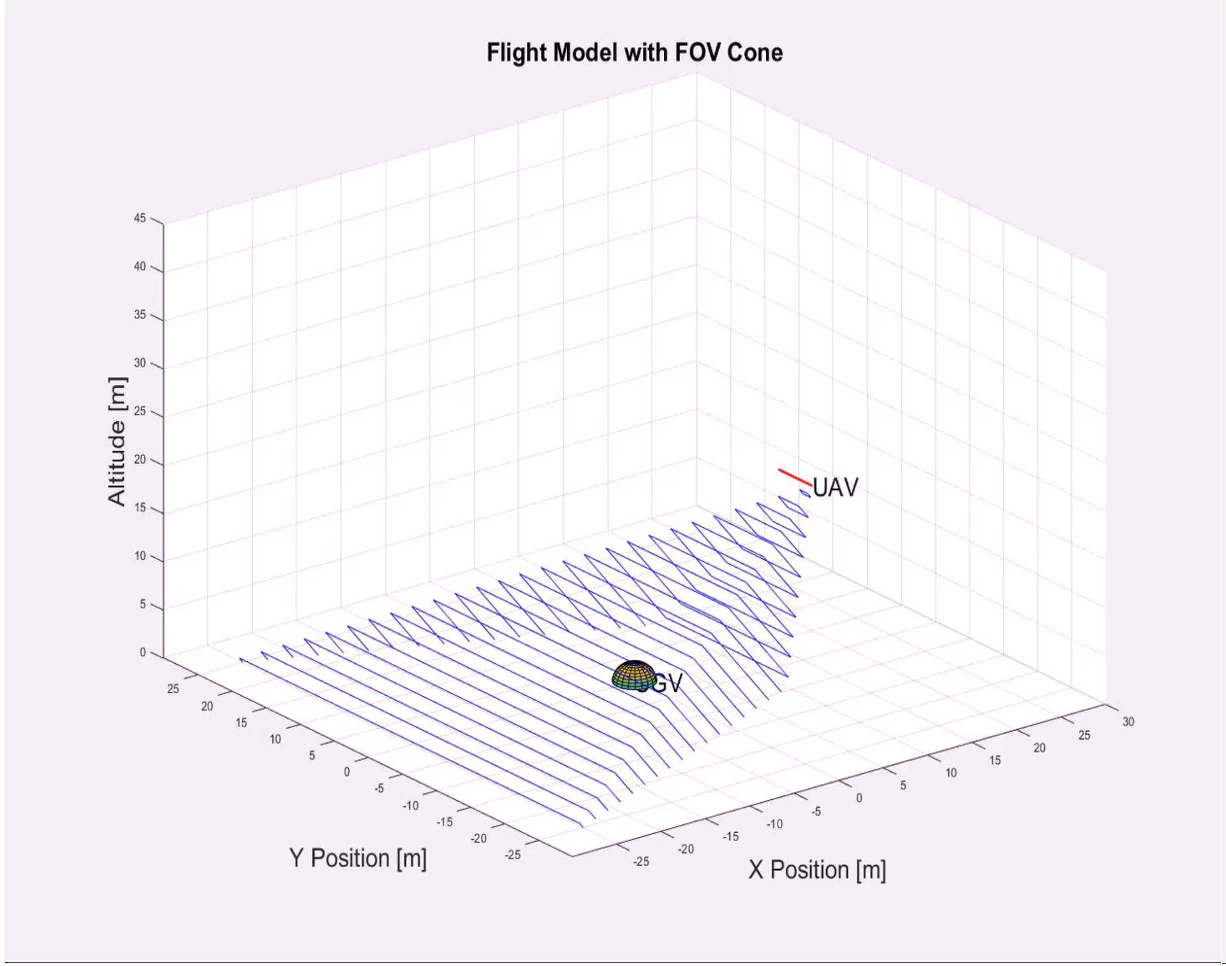
- Visual detection is used to verify target is within image frame
- Visual detection methods are susceptible to environmental conditions, e.g. lighting
- Camera resolution will need to be high enough to meet FR 4.0
- Visual detection split into two groups: ground to air, and air to ground
  - Air to ground validation accomplished with AR tags
  - Ground to air validation accomplished with blob detection

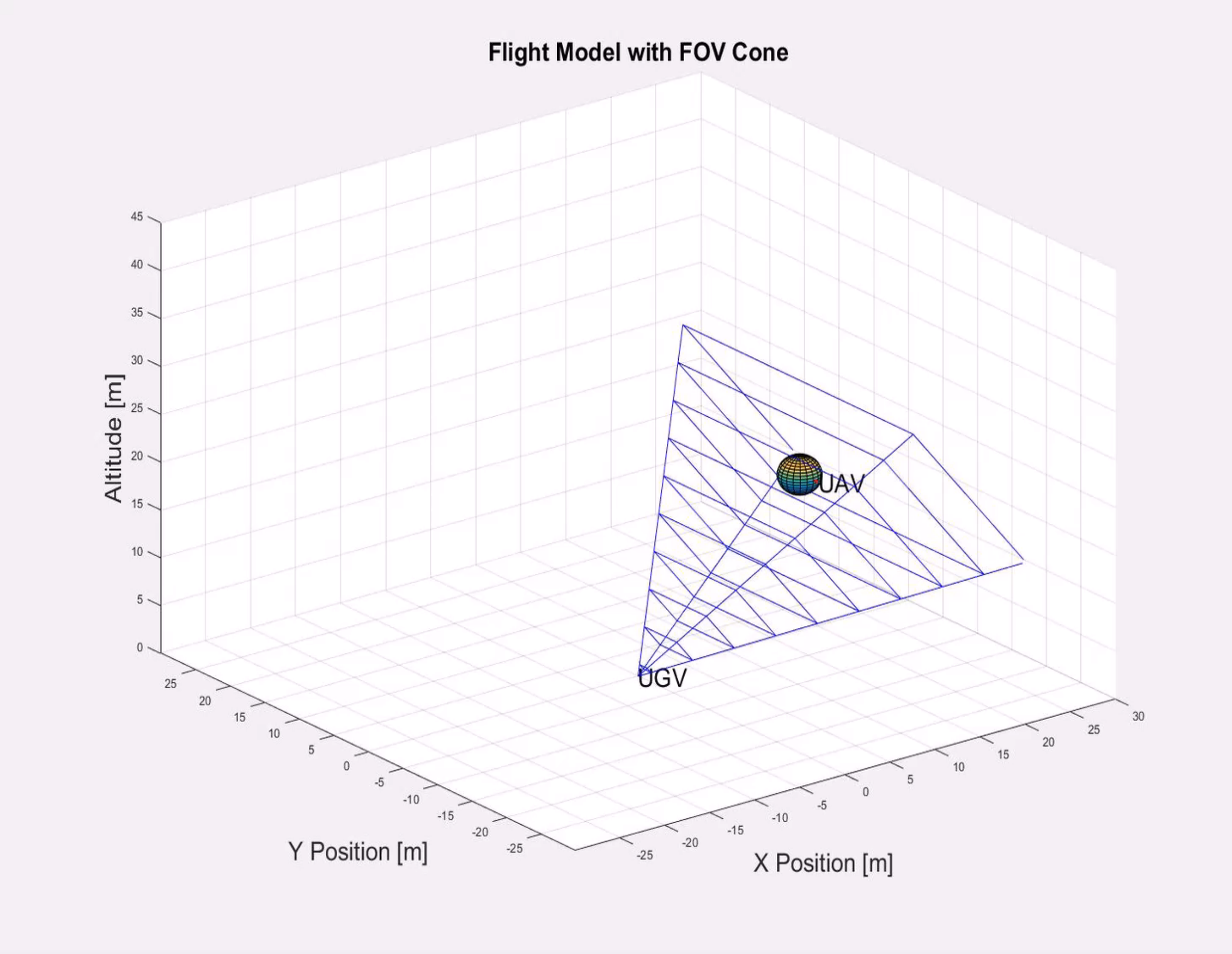
Resolution Model

- Purpose:
  - Feasibility of camera and lens choice
  - Satisfy FR 4.0 (3 in/pix at 30 m)
  - Latency impact
- FLIR Blackfly 2.3 MP & 12 mm lens[3]:
  - Resolution: 1920 x 1200
  - Focal Length *(f)*: 12 mm
  - Sensor Type: 1/1.2" (10.67 mm x 8 mm)
- Pixel Density:
  - Compute by dividing FOV by resolution
  - At 30 m: **0.467 in/pix**



Resolution Model





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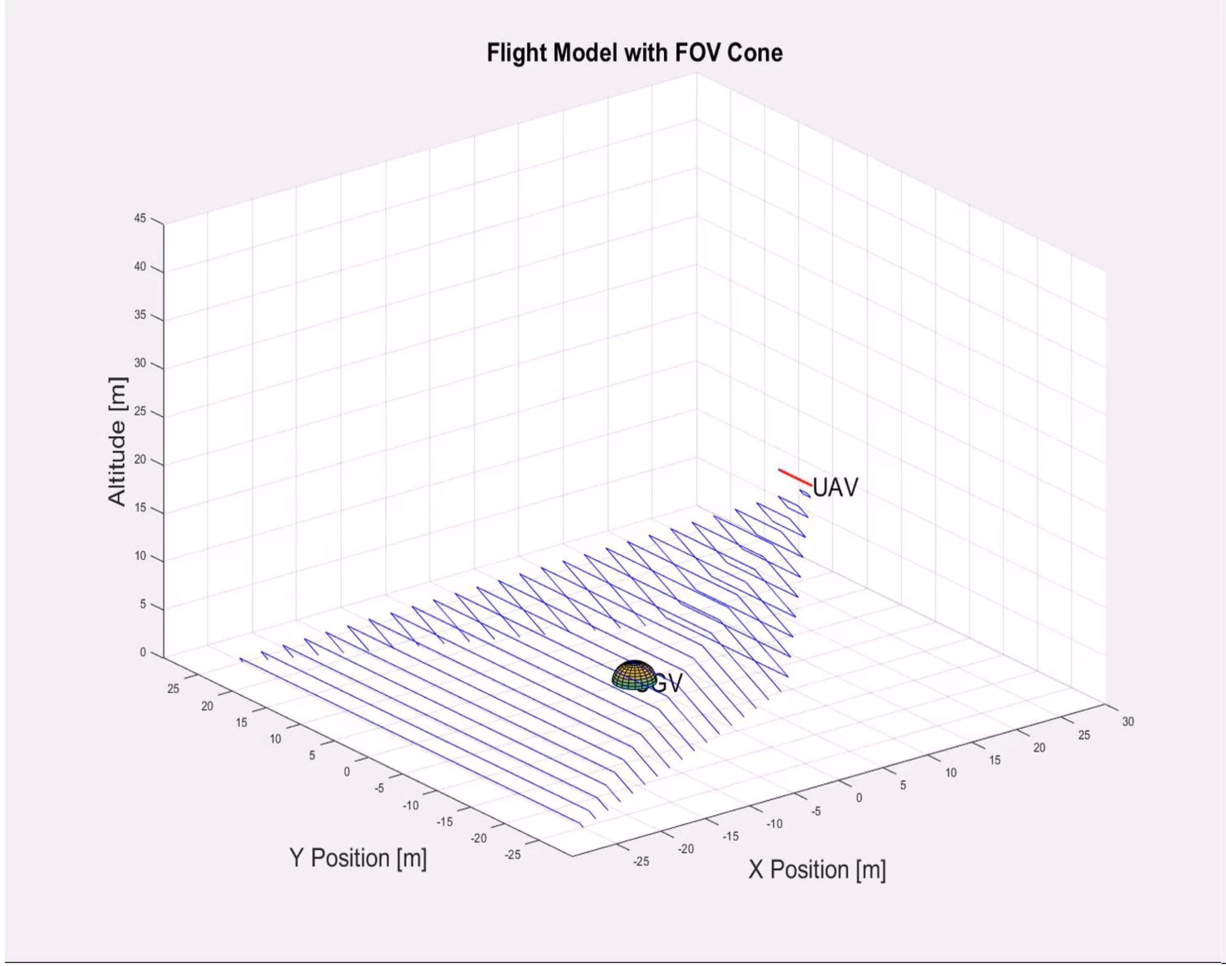
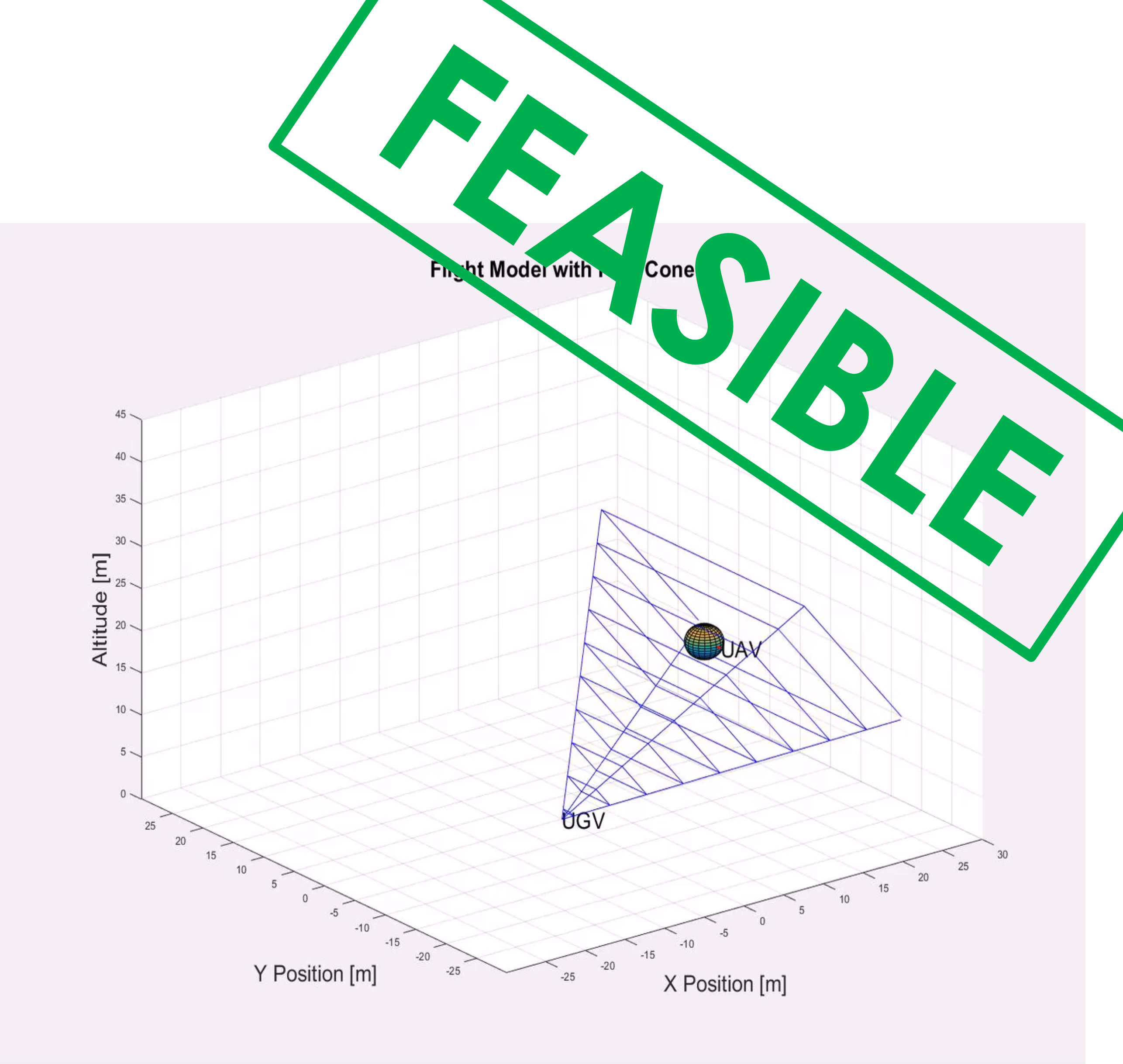
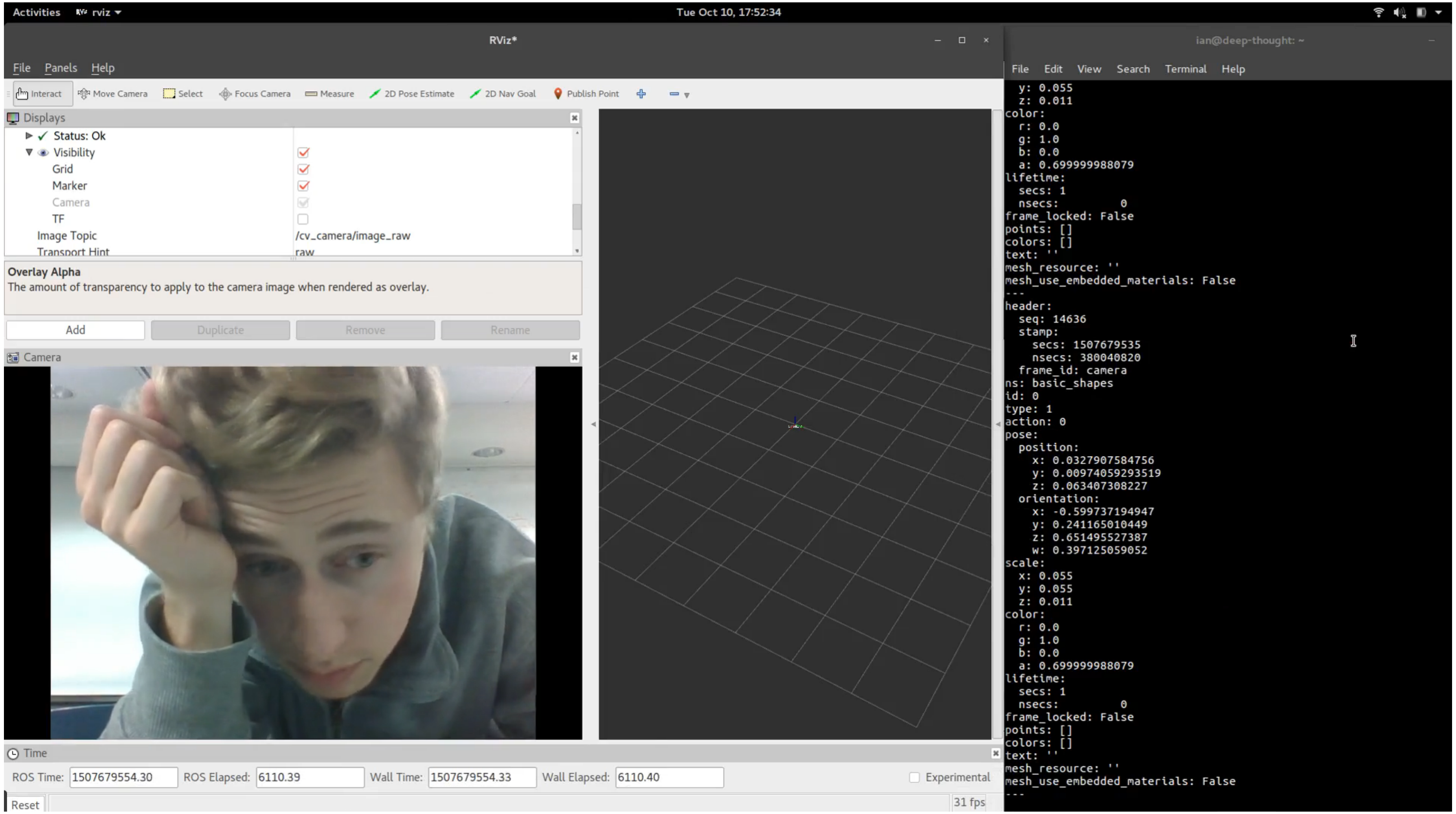




AR Tag Proof of Concept

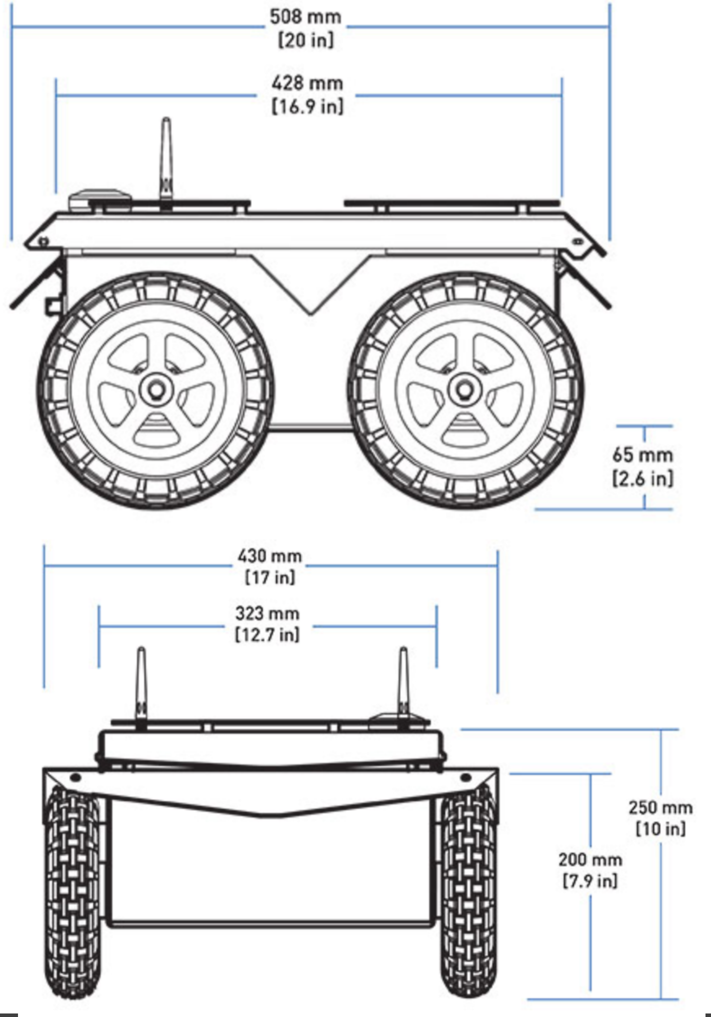
- High-contrast binary patterns with unique features
- Robust to lighting changes
- Implementations exist in ROS packages
- Able to estimate position and orientation from tags

AR Tag Proof of Concept



AR Tag Required Size Estimate

Courtesy of Clearpath Robotics



- Trial Run (Laptop Webcam):
  - Resolution: 640 x 480
  - AOV: ~64°
  - Identified: 5.5 cm AR tags up to 2.5 m range
- Implies:
  - Tracking limit: 11 pixels per linear dimension of the tag
  - Tag size: ~18 cm (7 in) for 2.3 MP sensor (extrapolating linearly assuming no distortion effects)

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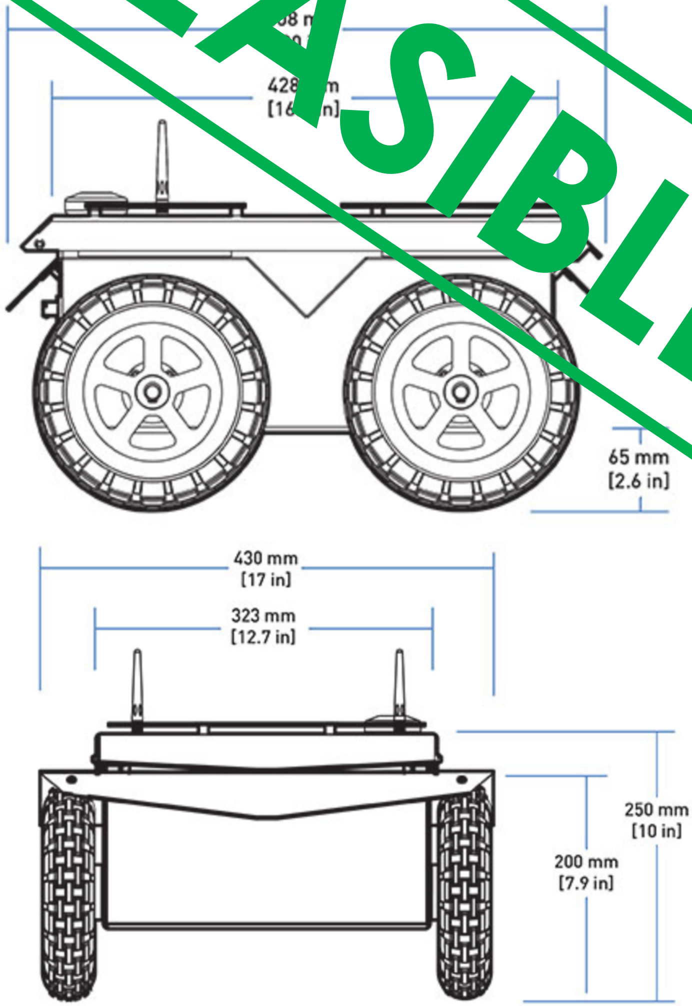
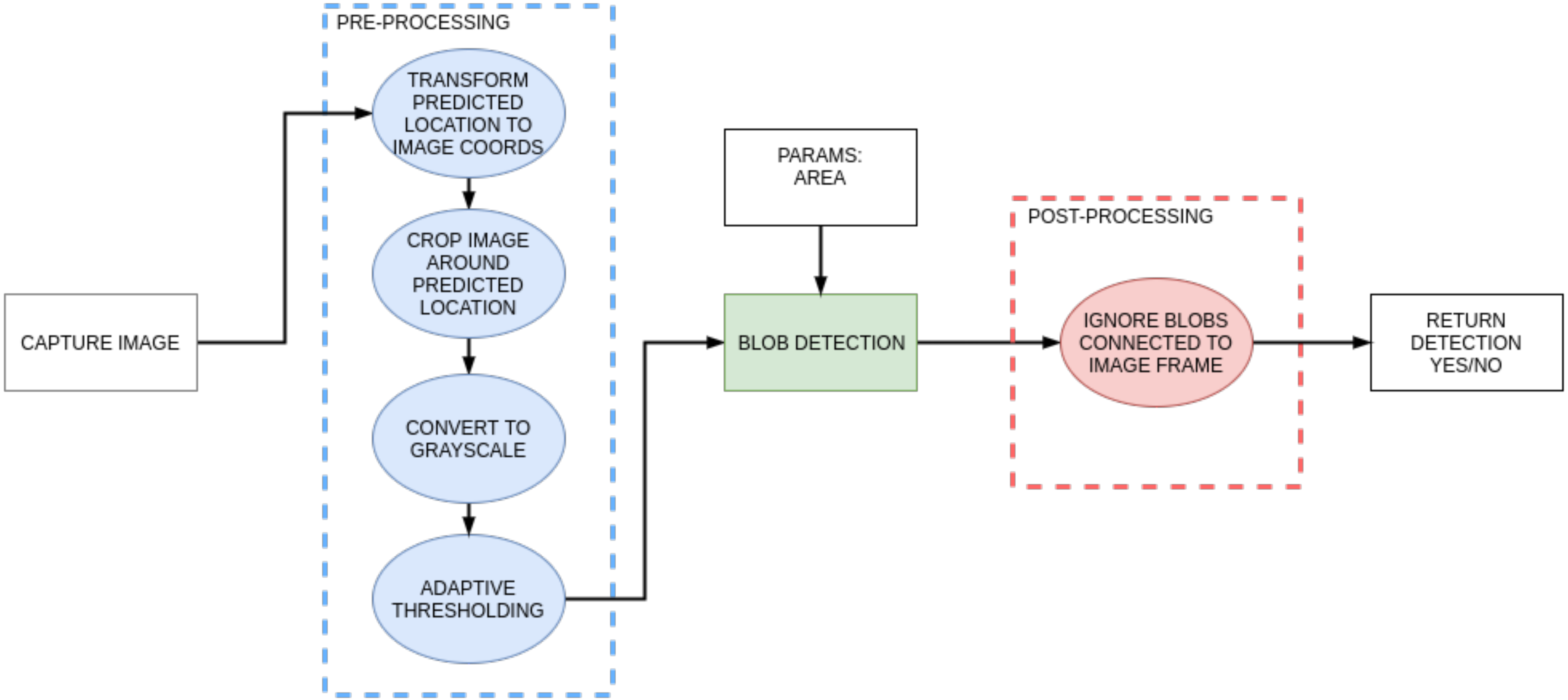


Ground to Air Detection

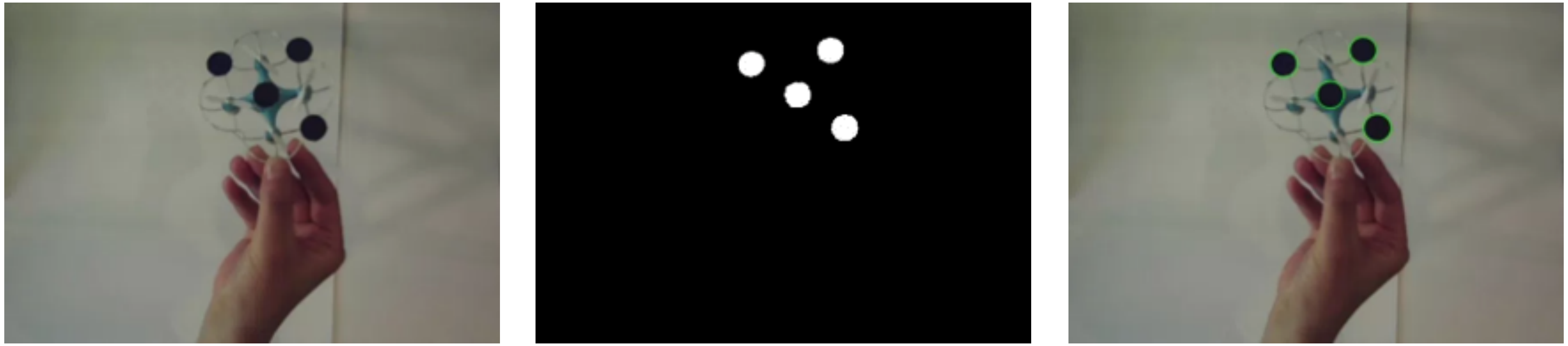
- AR tags would be too large to attach to the UAV
- Assumptions made to constrain problem:
  - High contrast between target and background
  - Accurate information about target location and motion relative to camera
  - Background features are connected to edges of image frame (e.g. trees, buildings)
- Blob detection: identify clusters of pixels with similar characteristics, e.g. color, intensity

Ground to Air Detection (cont.)



Ground to Air Detection (cont.)

- Similar method used by Krukowski et al.[4]
- OpenCV libraries for blob detection, pre and post-processing steps [5]
  - Eases implementation



Courtesy of makehardware.com

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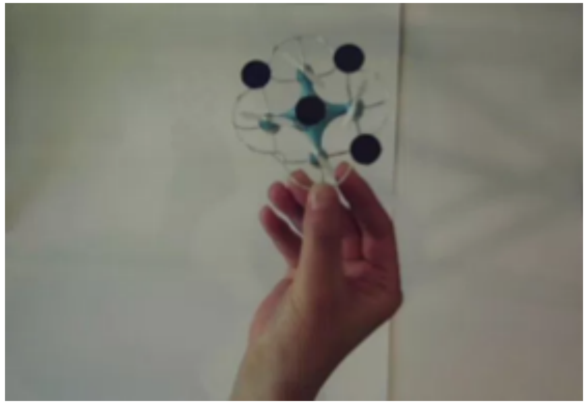
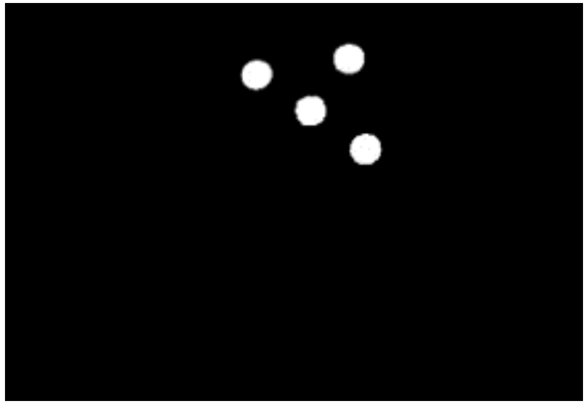
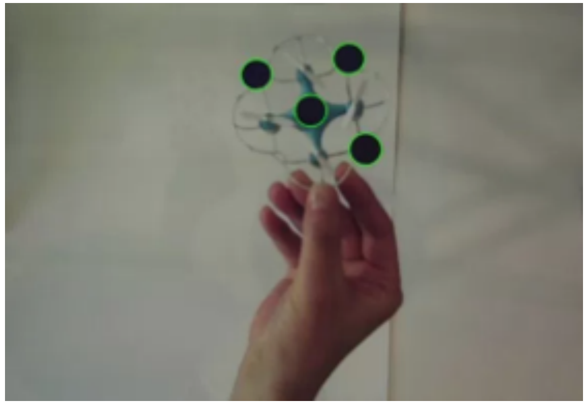






Courtesy of makehardware.com

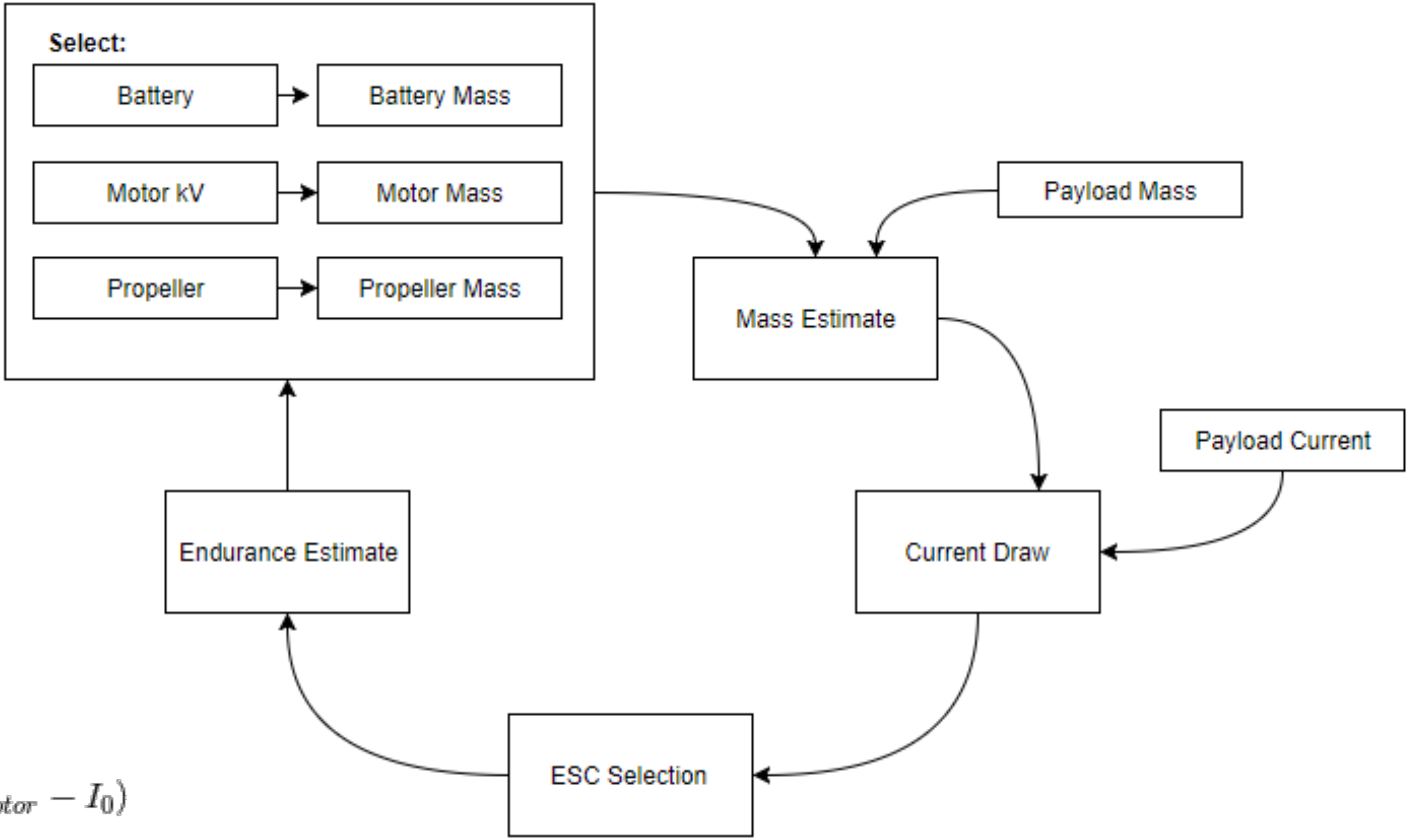
UAV Power Requirements

FR 1.0	RAVEN shall perform data collection for 15 minutes.

Power

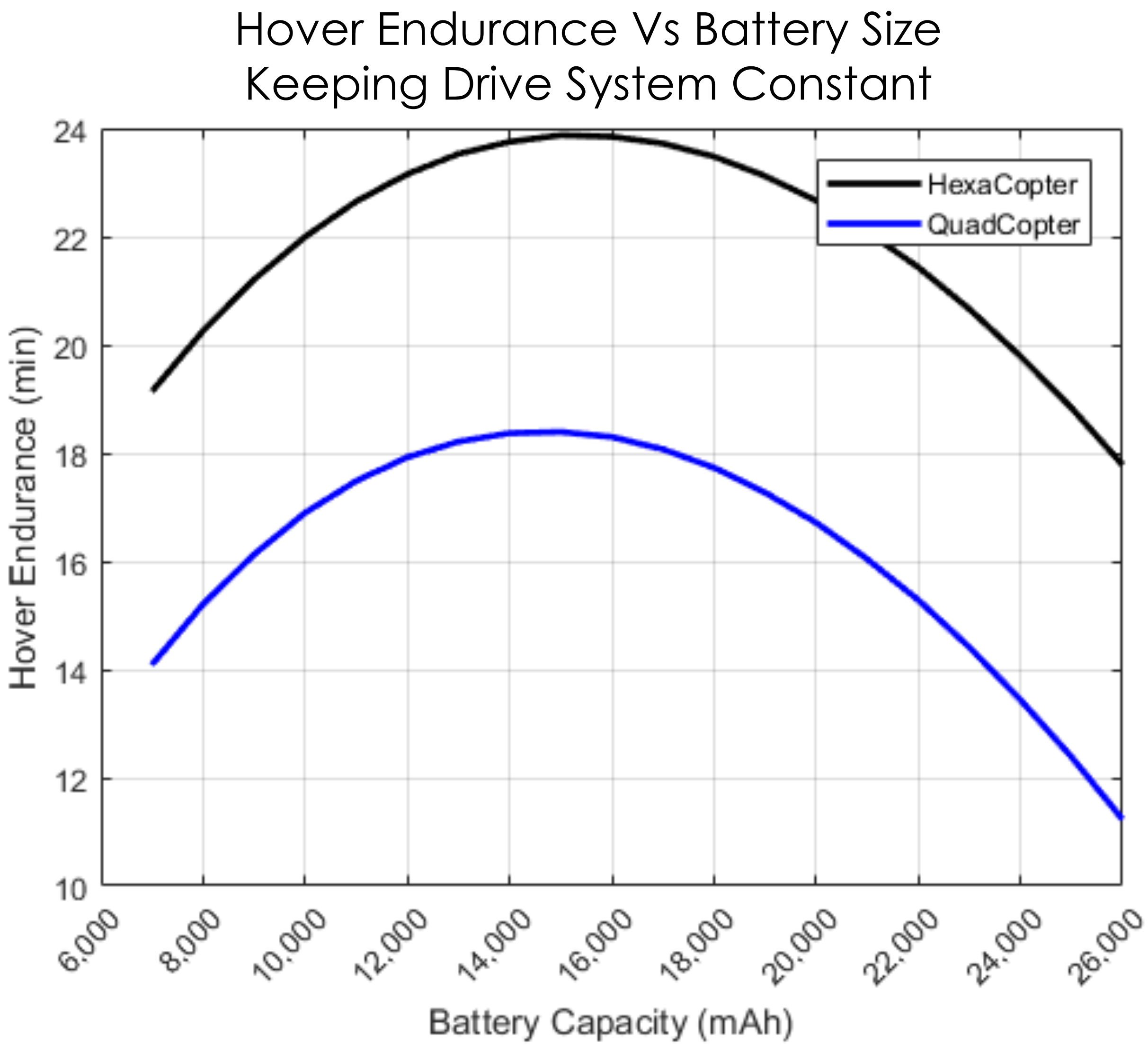
- Assumptions:
  - 85% Battery Discharge
  - Voltage Linearly Depends on Charge
  - Wire Resistance Negligible
  - Payload Current Draw Constant (6A)
  - Wires 5% of All Up Weight
  - Flying at 5280 ft, 60° F
  - No Airframe Drag

$$T = \frac{1}{2}\rho A V^2$$
$$V_{air} = \sqrt{\frac{2T}{\rho A}}$$
$$P_{prop} = T V_{air}$$
$$P_{mech} = (V_{batt} - R_{motor} I_{motor})(I_{motor} - I_0)$$
$$V_{air} = \omega \times pitch \times (\frac{0.0254}{60})$$
$$I_{tot} = NumMotors \times I_{motor} + I_{payload}$$



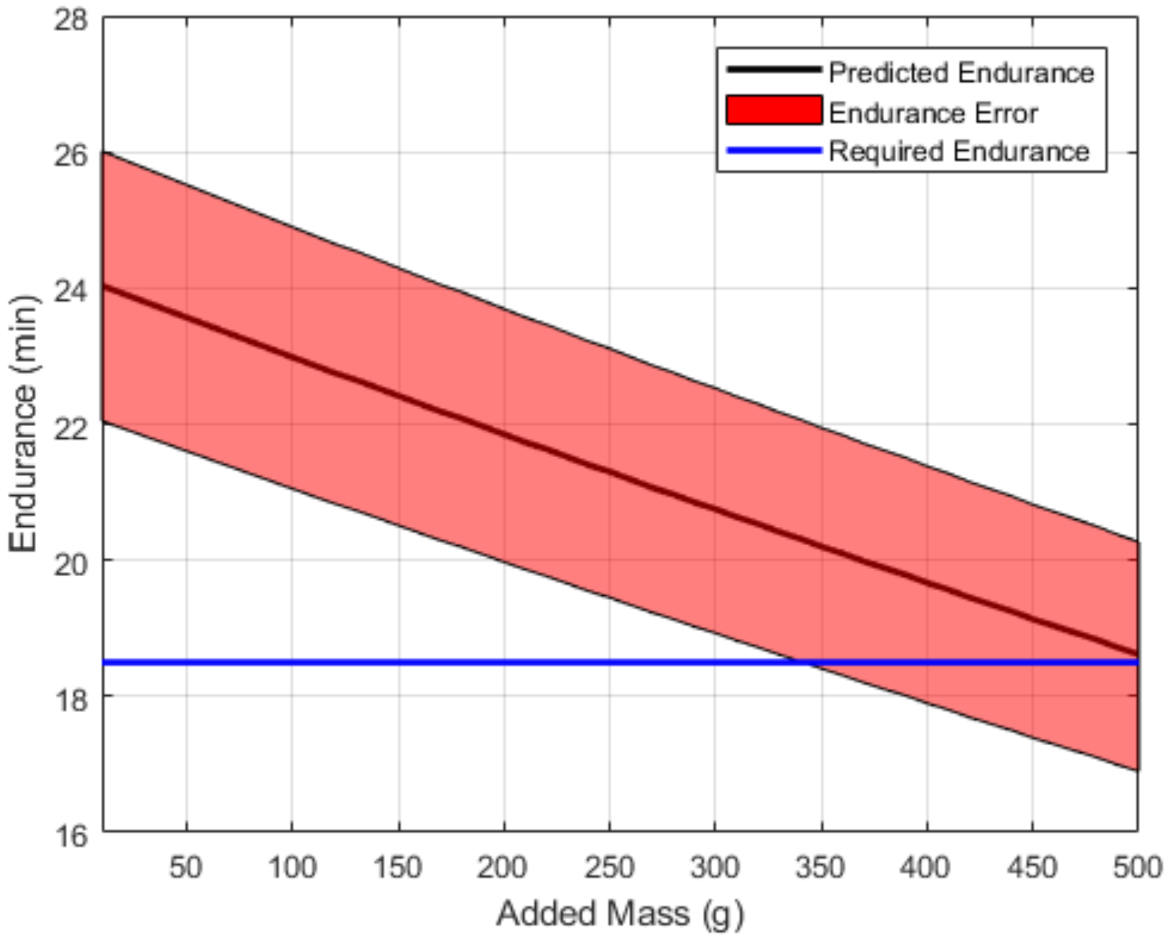
Quad vs HexaCopter

	QuadCopter	HexaCopter
Max Hover Endurance	18 min	24 min
Mixed Flight Endurance	15.3 min	20.4 min
All Up Weight	4.3 kg	4.65 kg
Controllable with rotor failure	No	Yes
Max Amp Draw	80 A	113 A
Ideal Battery	5s – 14,000 mAh	5s – 16,000 mAh



UAV Configuration

	Configuration
Number of Rotors	6
Hover Endurance	24 (min)
Battery	5s-16000 mAh Li-Po



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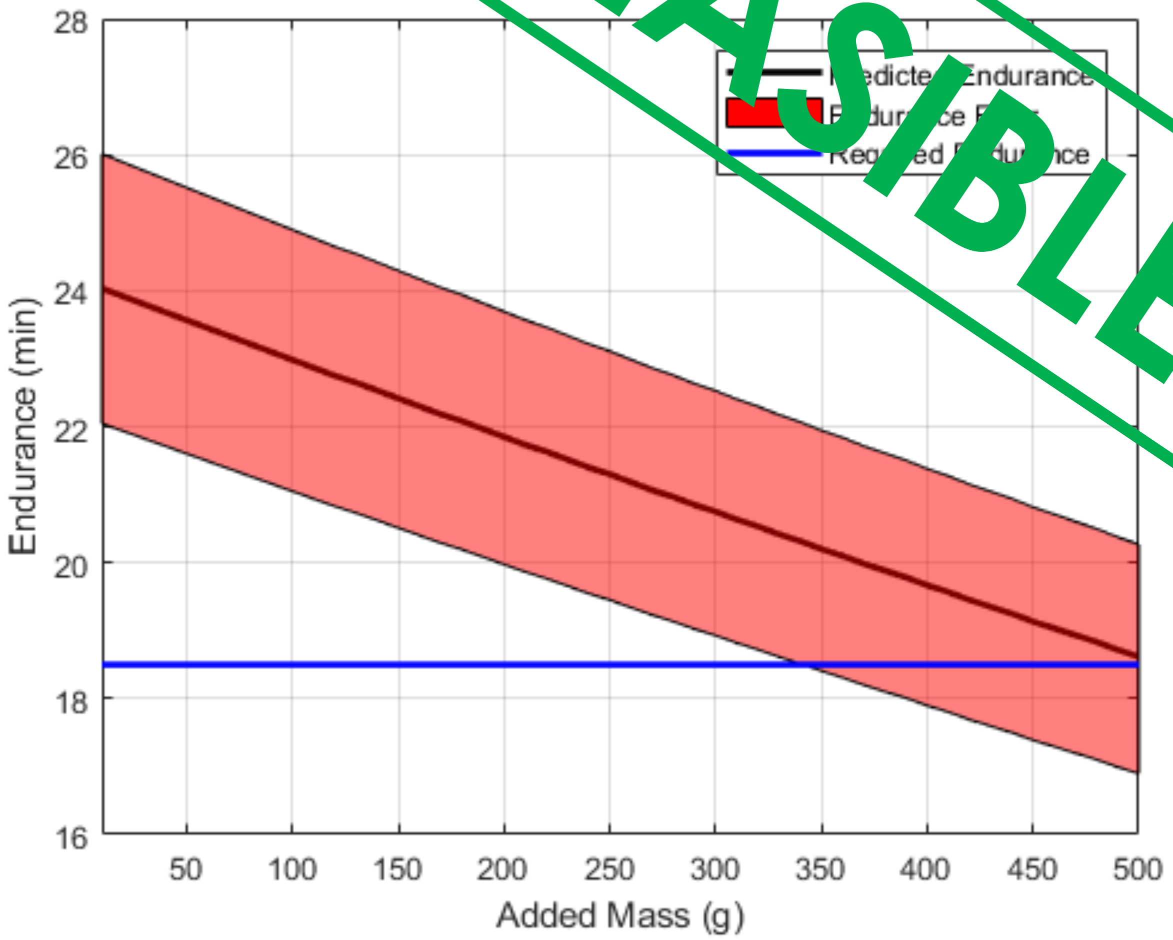

FEASIBLE

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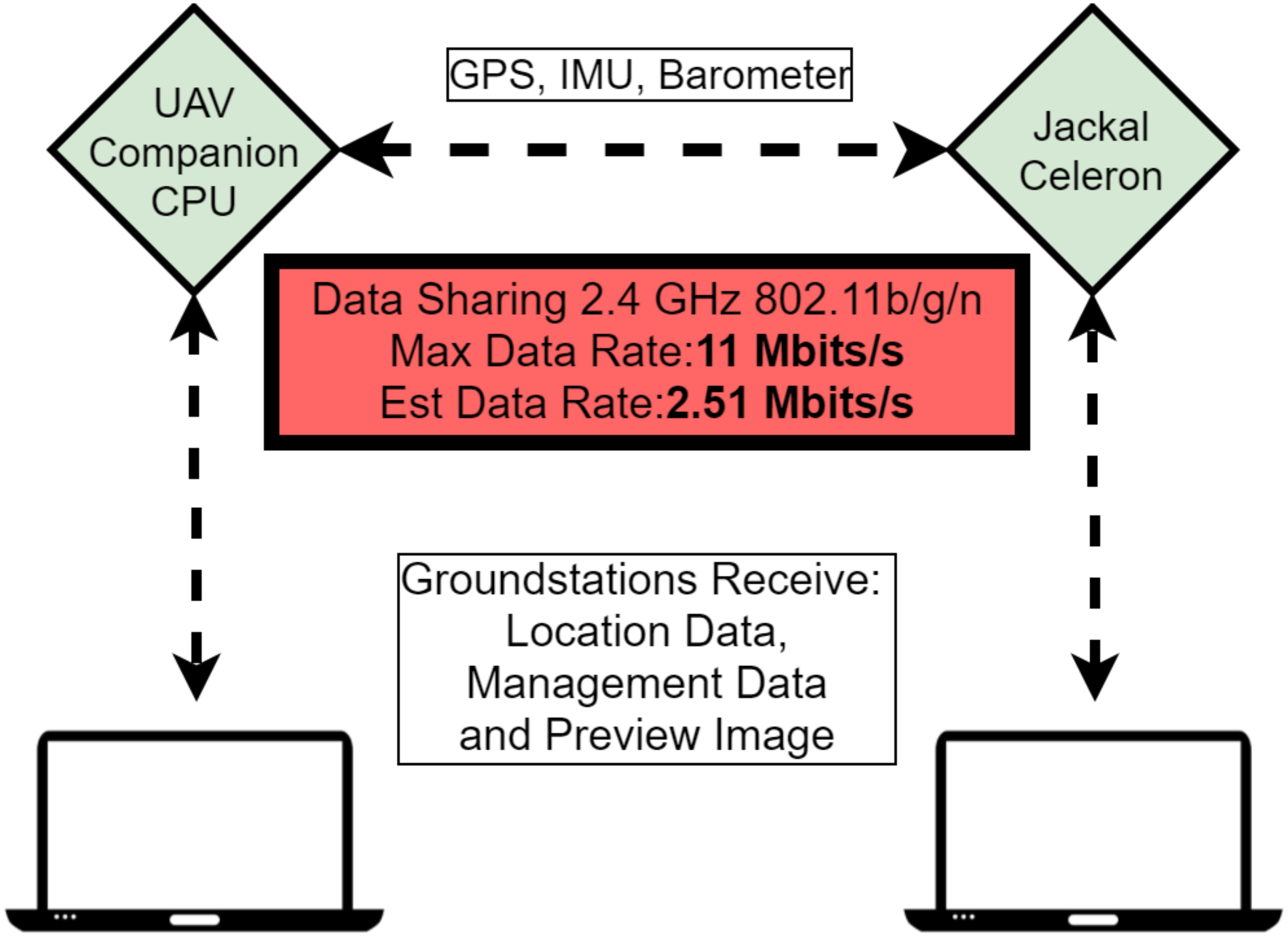
FR 9.0	RAVEN shall communicate flight/drive commands from ground stations to and from their respective vehicle over an ISM radio frequency.

Data Storage Feasibility

Name	Data Rate
Camera	114 MB/s
IMU	~4 kB/s
GPS	2.4 kB/s
Barometer	~0.13 kB/s
Total Data Rate	115 MB/s
USB 3.0 Flash Write Speed	150 MB/s

Storage Time	Storage Needed	Storage Capacity
900 s (15 min)	101.1 GB	128 GB

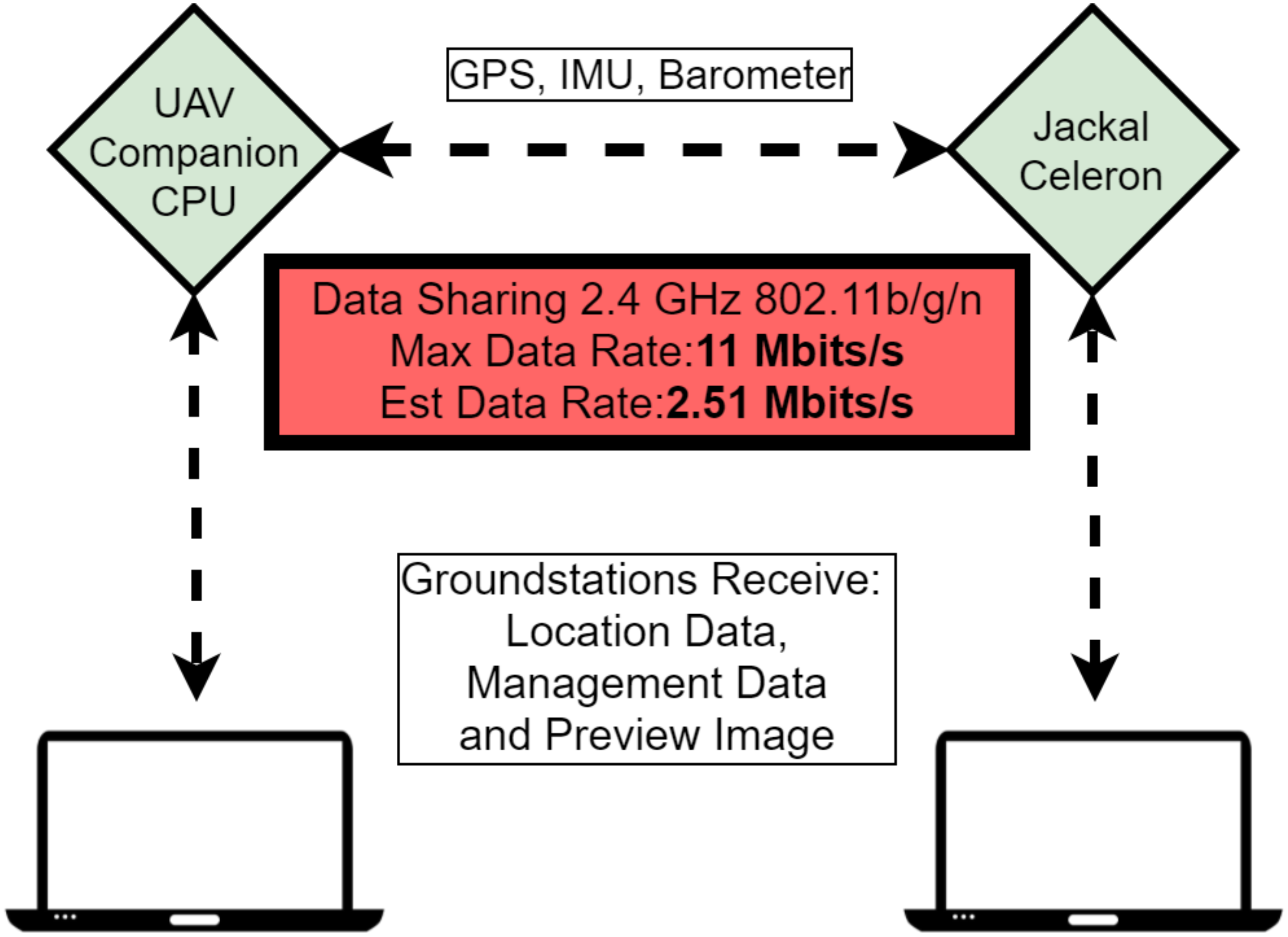
Data Sharing



Item	Data rate
Preview Image	2.50 Mbits/s
Navigation Data	75 kbits/s
Management Data	20 kbits/s
Total Data Rate	**2.51 Mbits/s**
Maximum Throughput	**11 Mbits/s**

Data Sharing

FEASIBLE



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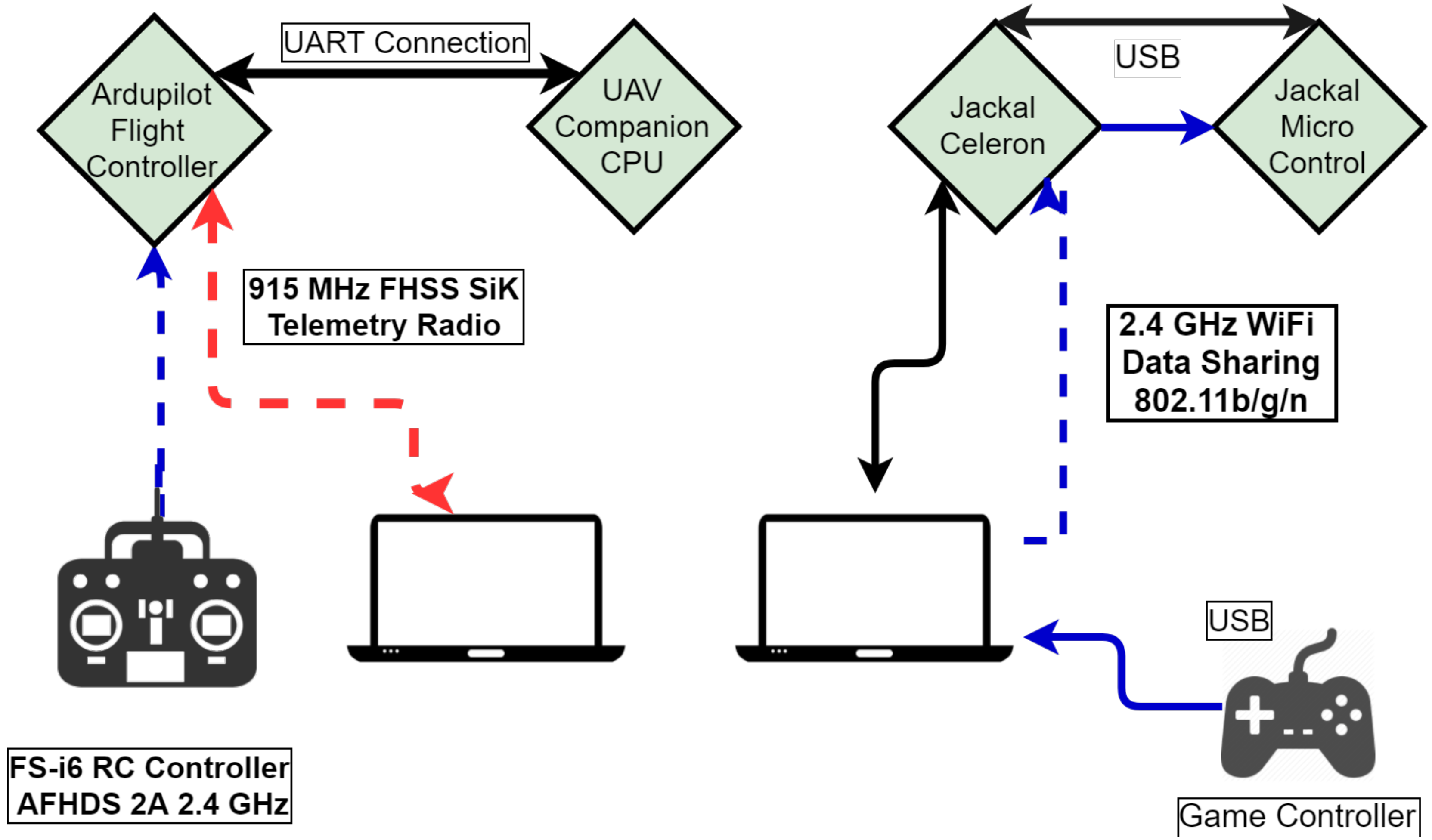
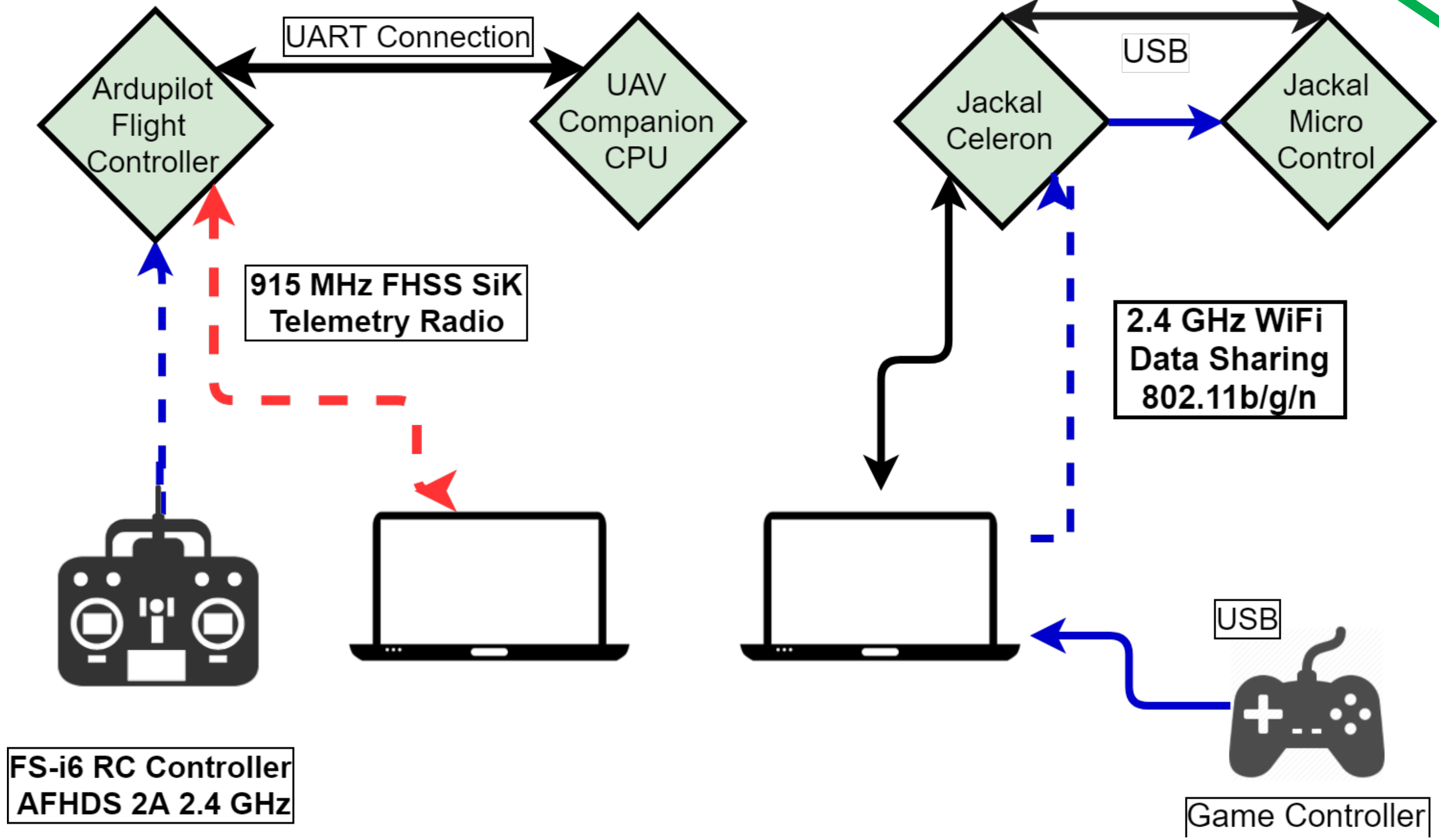
Commands



Component	Manufacturer Range
FS-i6 Controller	1.0 km
915 MHz SiK Telemetry	500 m
2.4 GHz WiFi 802.11	125 m

Commands

FEASIBLE



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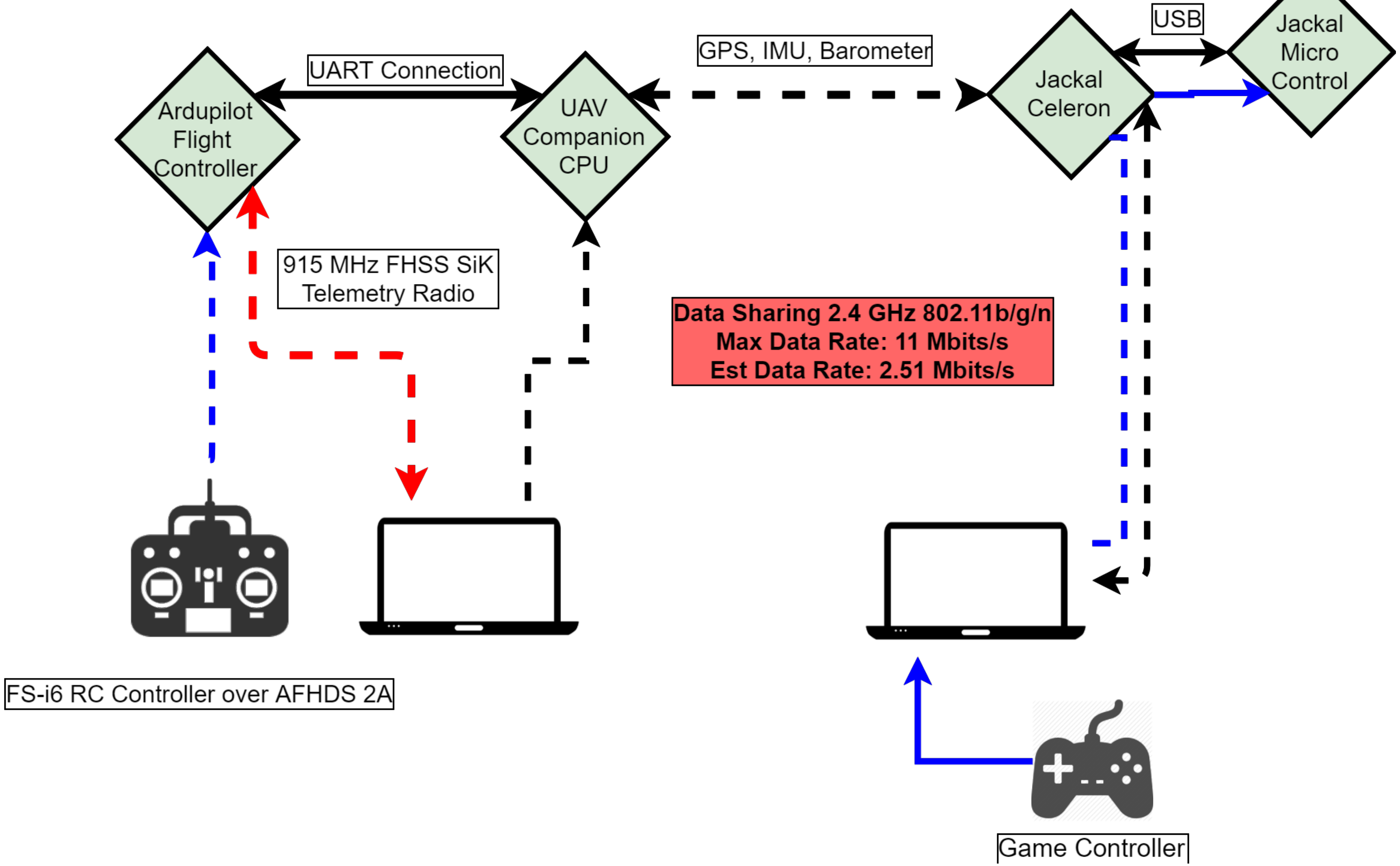
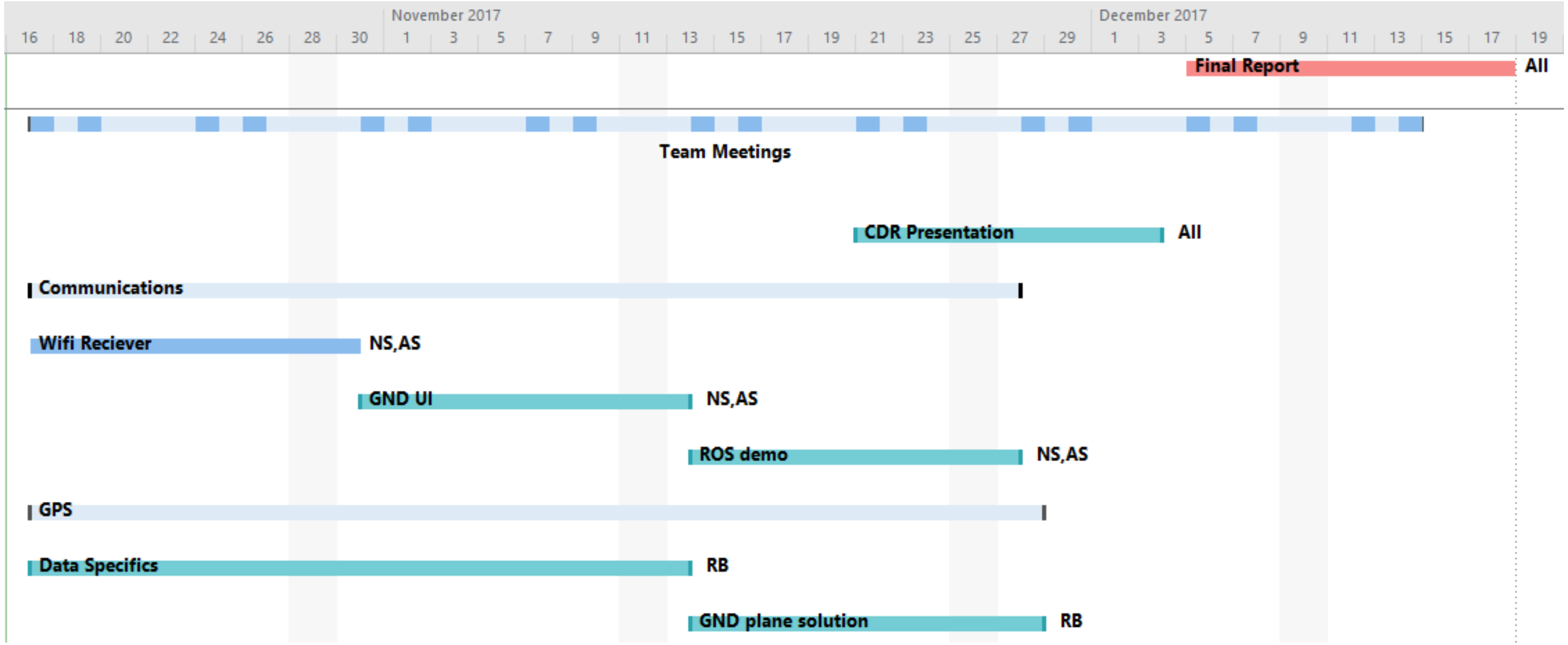
All Communications



Conclusions

Objective	Requirement	Verified?
Tracking Method	Sensor requirements for state determination	✔
	Camera pointing, gimbal actuation, and camera resolution	✔
	Visual detection methods	✔
UAV Power	Requirement of hexacopter baseline decision	✔
	Endurance capabilities of baseline design	✔
Communications	Data storage requirements	✔
	Data sharing	✔
	Command sharing	✔

Schedule to CDR



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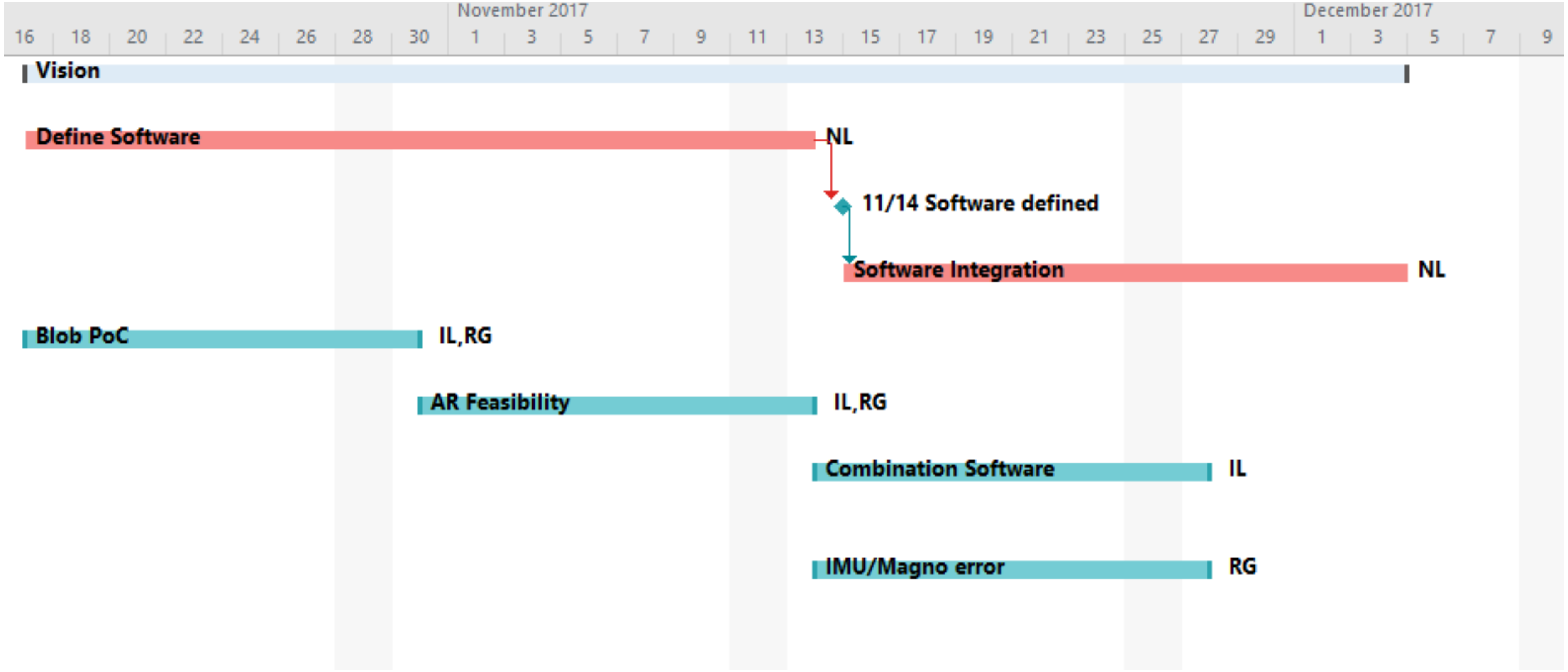
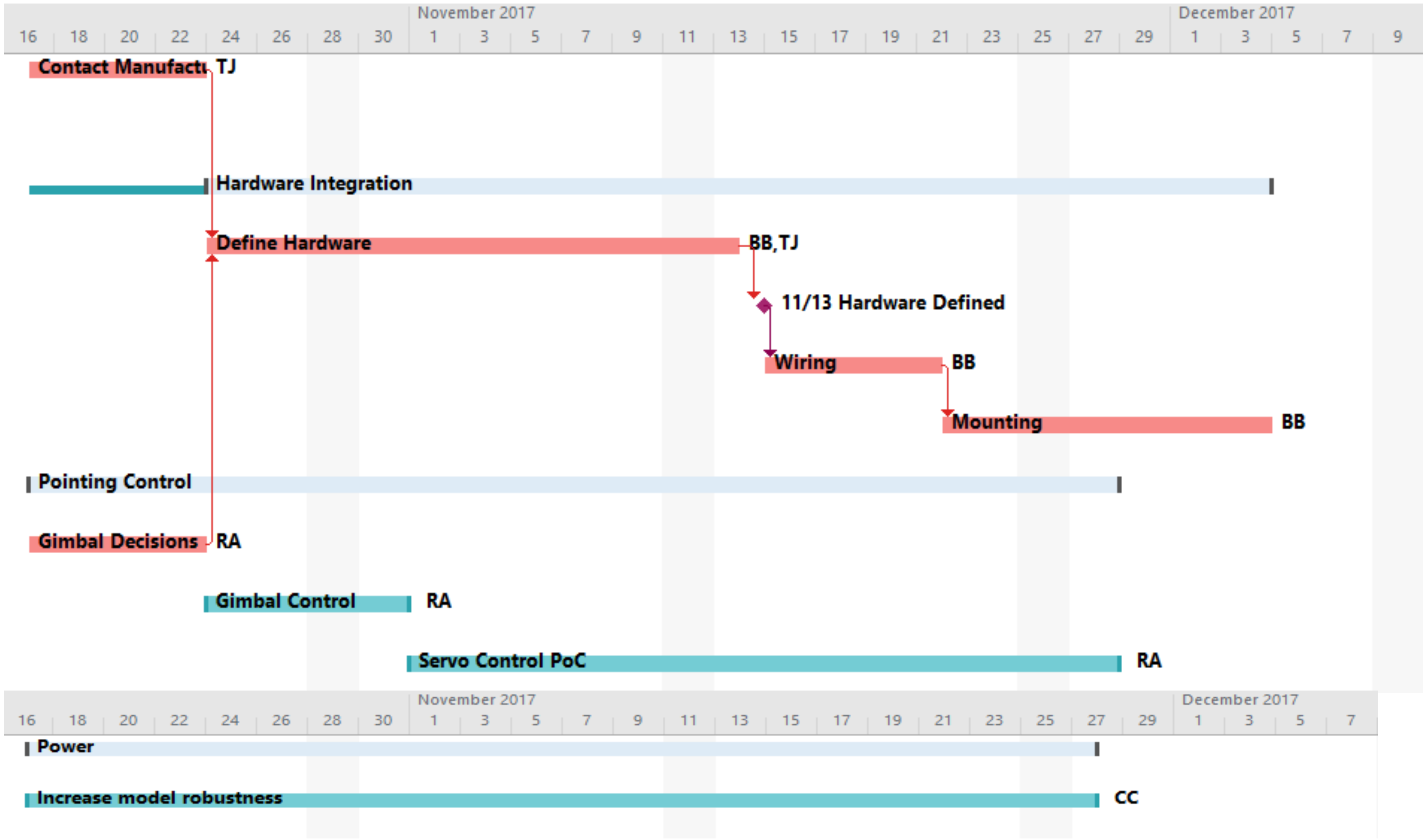


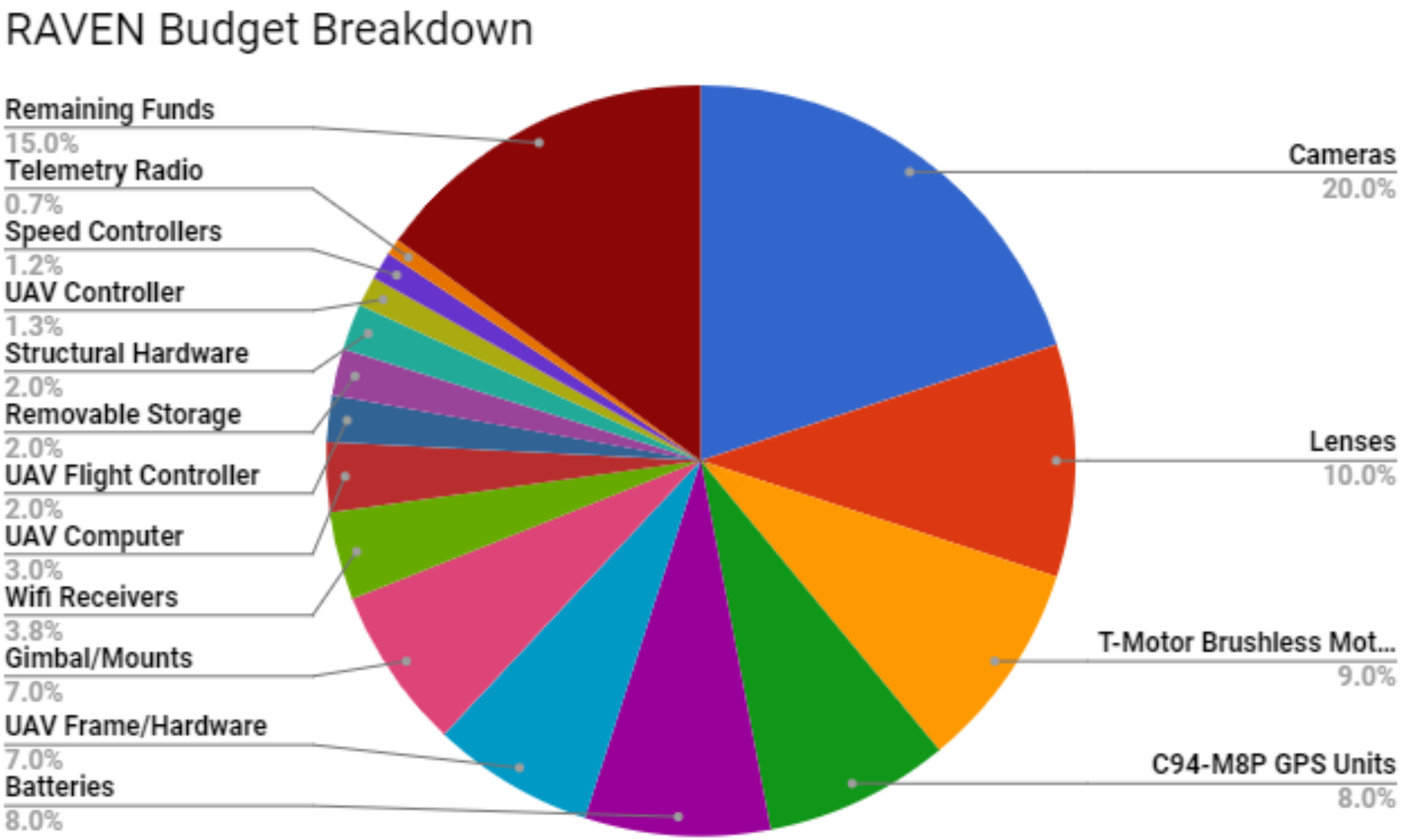
Schedule to CDR



Project Overview | Tracking | Power | Communication | Conclusion

Budget

Financial Summary	
System	Cost
Cameras	$ 1,000.00
Lenses	$ 500.00
T-Motor Brushless Motors	$ 450.00
C94-M8P GPS Units	$ 400.00
Batteries	$ 400.00
UAV Frame/Hardware	$ 350.00
Gimbal/Mounts	$ 350.00
Wifi Receivers	$ 190.00
UAV Computer	$ 150.00
UAV Flight Controller	$ 100.00
Removable Storage	$ 100.00
Structural Hardware	$ 100.00
UAV Controller	$ 65.00
Speed Controllers	$ 60.00
Telemetry Radio	$ 35.00
Remaining Funds	**$ 750.00**
Total	**$ 5,000.00**



Questions?

References

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2. "SS CAP ALTIMETER PRESSURE SENSOR." *Board Level Pressure Sensors*, TE Connectivity.
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5. Lady, M H. "Blob Detection With Python and OpenCV." *MakeHardware*, 19 May 2016.
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8. Bershadsky, Dmitry, et al. "Electric Multirotor UAV Propulsion System Sizing for Performance Prediction and Design Optimization." *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2016, doi:10.2514/6.2016-0581.

Index (Presentation)

Index (Backup Slides)

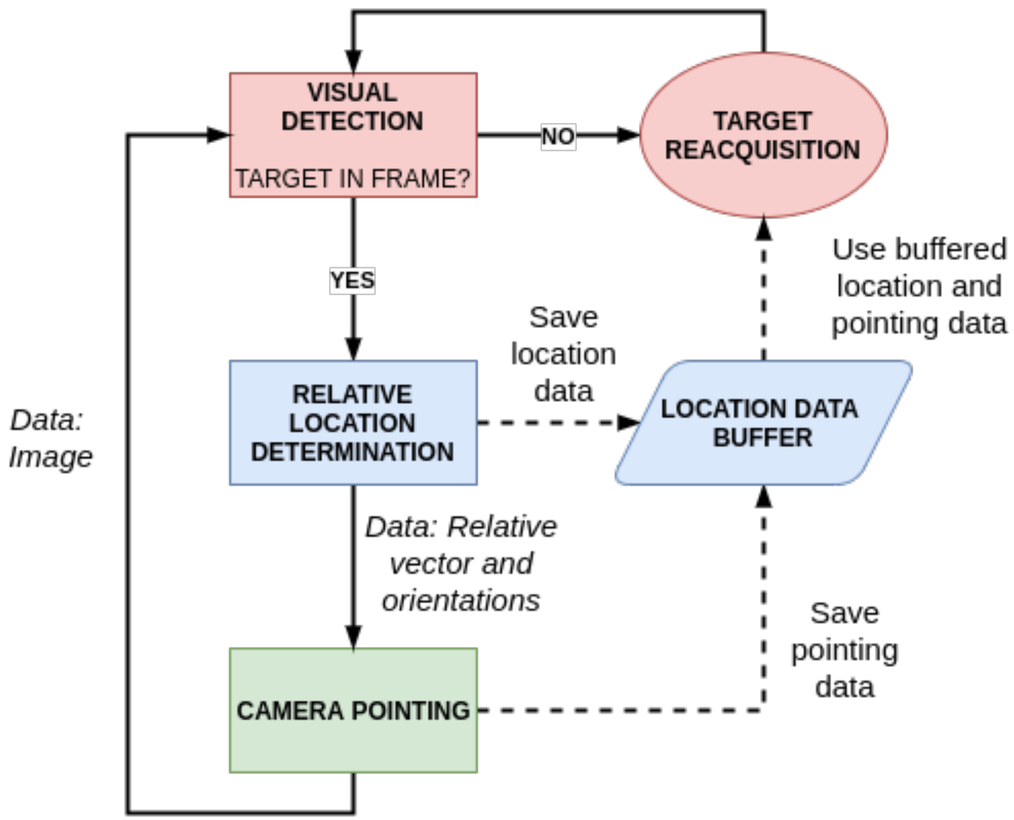
Detailed Baseline Design Choices

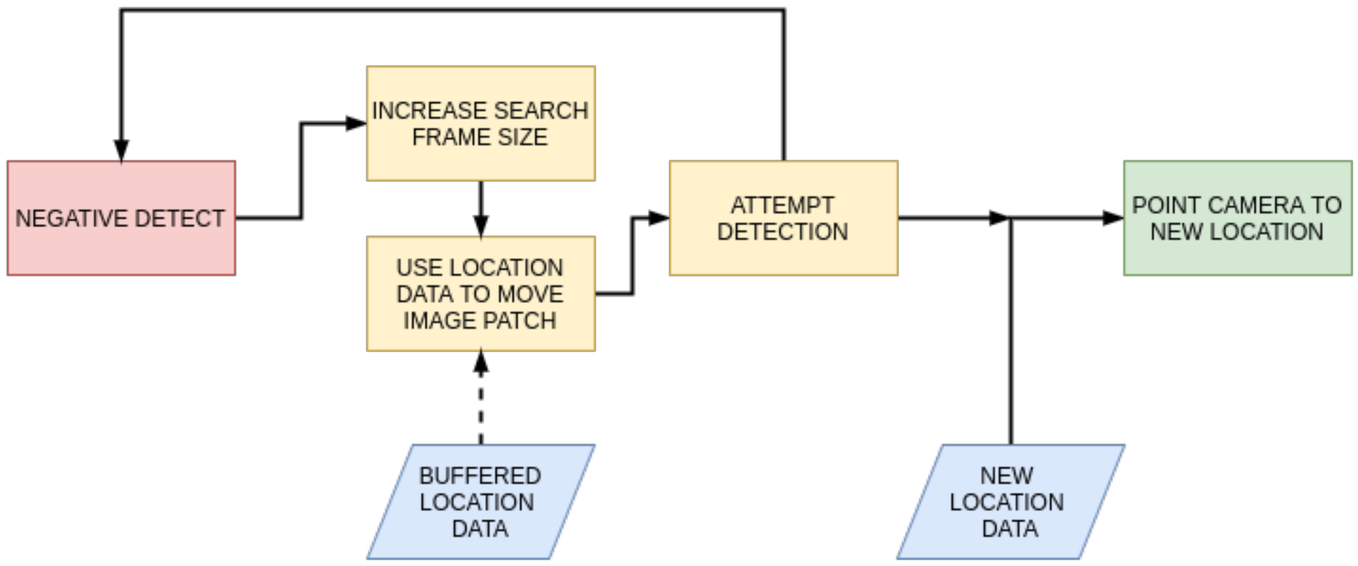
- UAV
  - 3 Axis Brushless Gimbal
  - Lithium Polymer Battery
  - External Computer
  - Vision System
    - Global Shutter Camera
    - Monocular
    - Color
    - Prime Lens
  - Communication Bands
    - 2.4 GHz Navigation
    - 915 MHz Controls
  - External Integrated GPS Board
  - Multirotor Frame
- UGV
  - 2 Axis Servo Gimbal
  - Vision System
    - Global Shutter Camera
    - Monocular
    - Color
    - Prime Lens
  - Communication Bands
    - 2.4 GHz Navigation & Command
- Ground Station
  - Dual Ground Station

Motivation

- As long as there are GPS denied environments there will be a need to circumvent GPS denial. In these situations, precise localization must be maintained by other means. To deliver precise location data, a cooperative localization method using aerial drones and ground units has been developed. The drone is able to access GPS signal by flying out of the denied zone and transmitting its location to any ground units. The relative position of the drone can then be found using cooperative localization.

Reacquisition of Target





Sensor Error Calculations and Assumptions

- NEO-M8P u-blox M8 High Precision GNSS Module
  - Standalone: 2.5 m CEP → $\sigma = 2.5/0.6745$ (Gaussian Distributuion at 50%)
  - RTK: 0.025 m CEP → $\sigma = 0.025/0.6745$ (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
  - $\sigma = 5/3$ (Gaussian Distribution at 99.7%)
  - Both barometers operate in similar environments
    - Barometer drift due to environment ignored for relative altitude
- 3-Axis Digital Compass IC HMC5983 [7]
  - 1° to 2° Compass Heading Accuracy
  - $\sigma = 2/3$ (Gaussian Distribution at 99.7%)

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

Data Filter Considerations

- Considered using an Extended Kalman Filter (EKF)
- Advantages:
  1. Useful for estimation and prediction of future states
  2. Useful for sensor fusion of multiple sensors for single metric
  3. Useful to clean noisy sensor data in real time
- Disadvantages
  1. Difficult to implement
  2. Computationally costly

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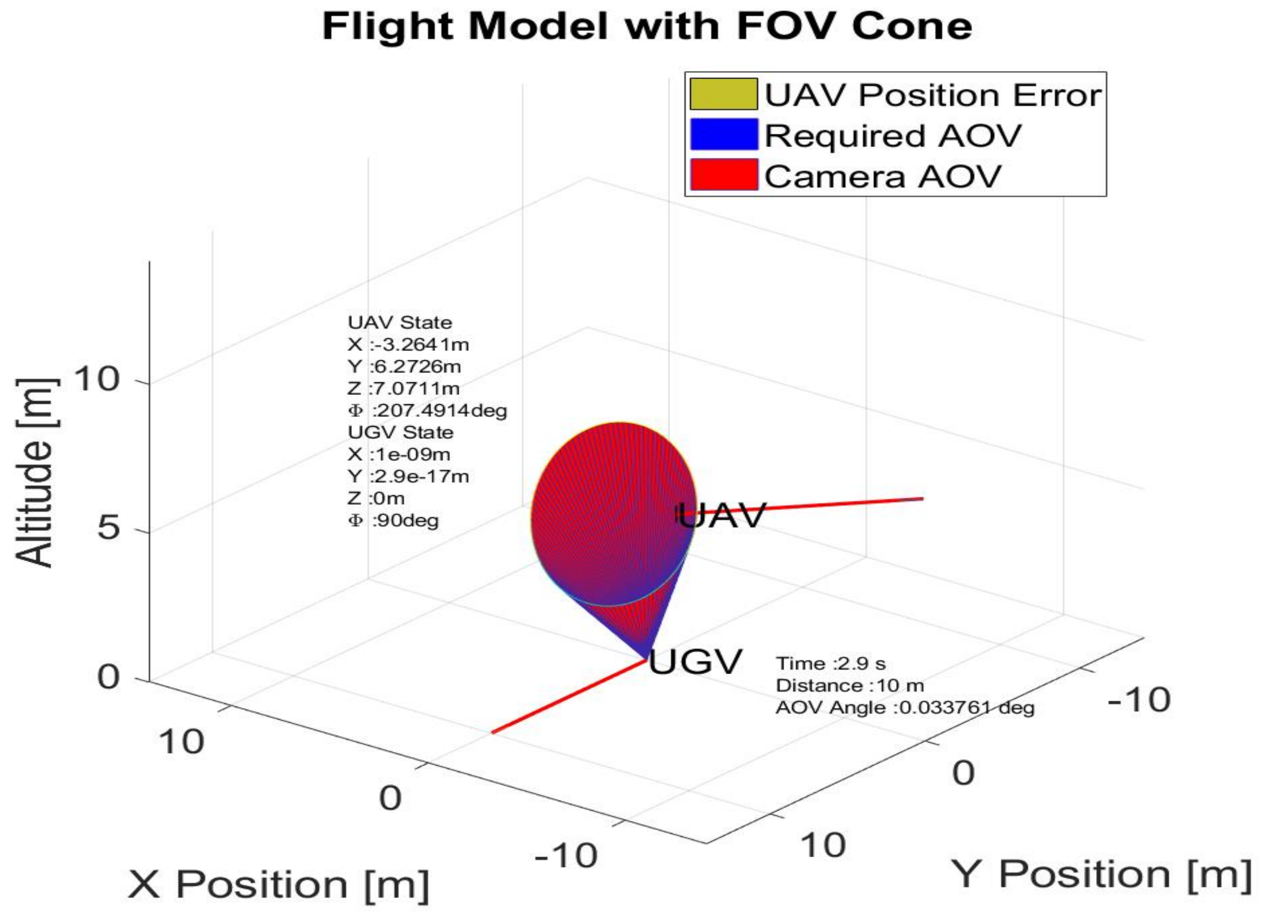
➢ State Estimation was considered to account for latency in relative position transmission
➢ Latency of 0.5 seconds would still allow UAV to be In-View*



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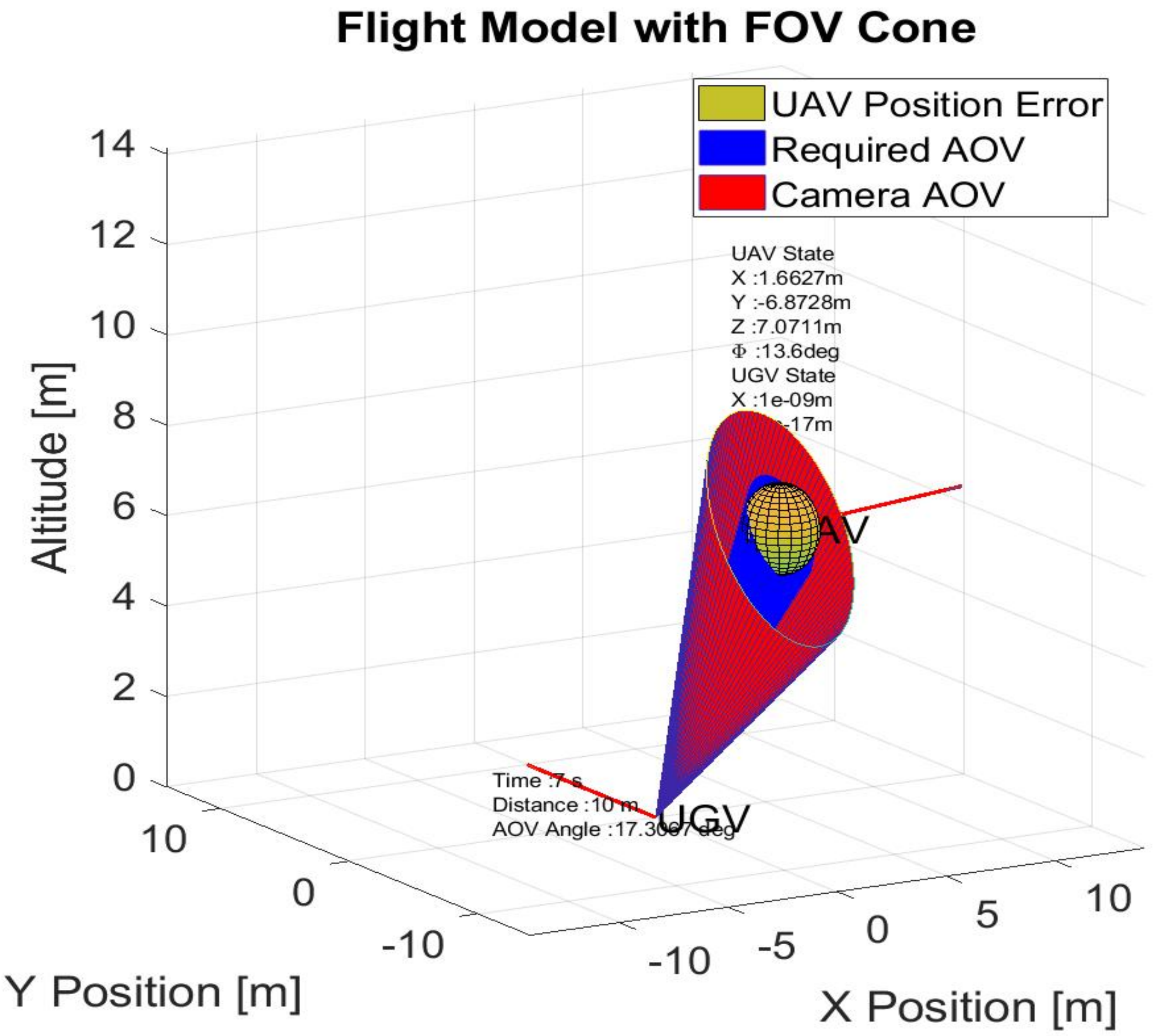
  3. Useful to clean noisy sensor data in real time
- Disadvantages
  1. Difficult to implement
  2. Computationally costly

> - No state variables are being measured by multiple sensors
> - Therefore weighted sensor fusion using a Kalman filter is not necessary

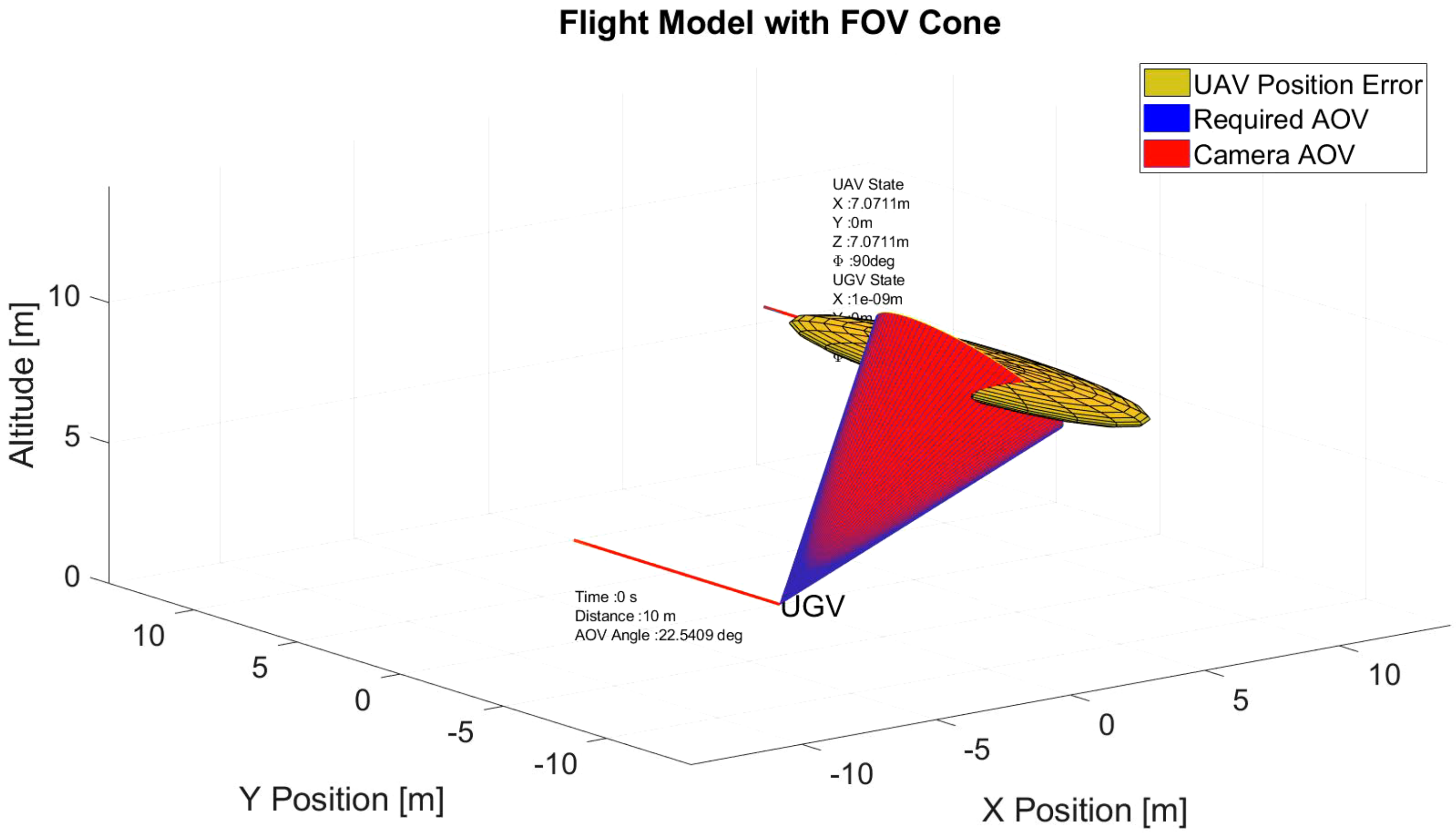
State Variable	GPS	Barometer	IMU	Magnet-ometer
x	✔			
y	✔			
z		✔		
Φ (Roll)			✔	
Θ (Pitch)			✔	
Ψ (Yaw)				✔

Justification of Requirement of RTK Capable GPS

- Error of NEO-M8P GNSS Module:
  - Standalone: 2.5 m CEP
  - RTK: 0.025 m CEP
- Assumptions:
  - Gaussian Distribution of Error
  - UGV is Stationary
  - Constant Velocity Circular UAV Orbit at 10 m (Closest mission range)
  - No latency in pointing

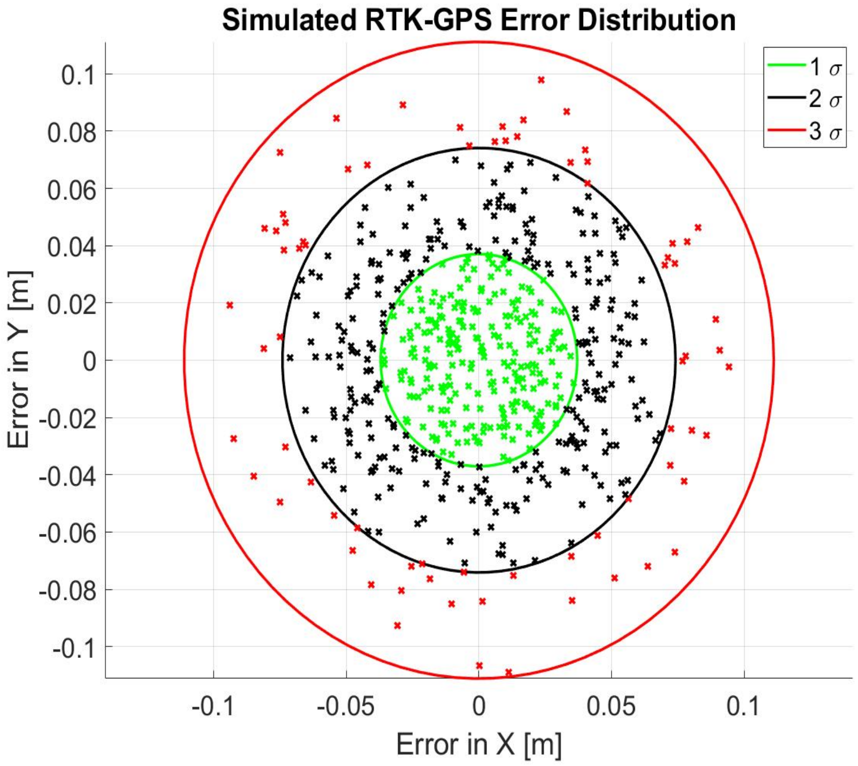


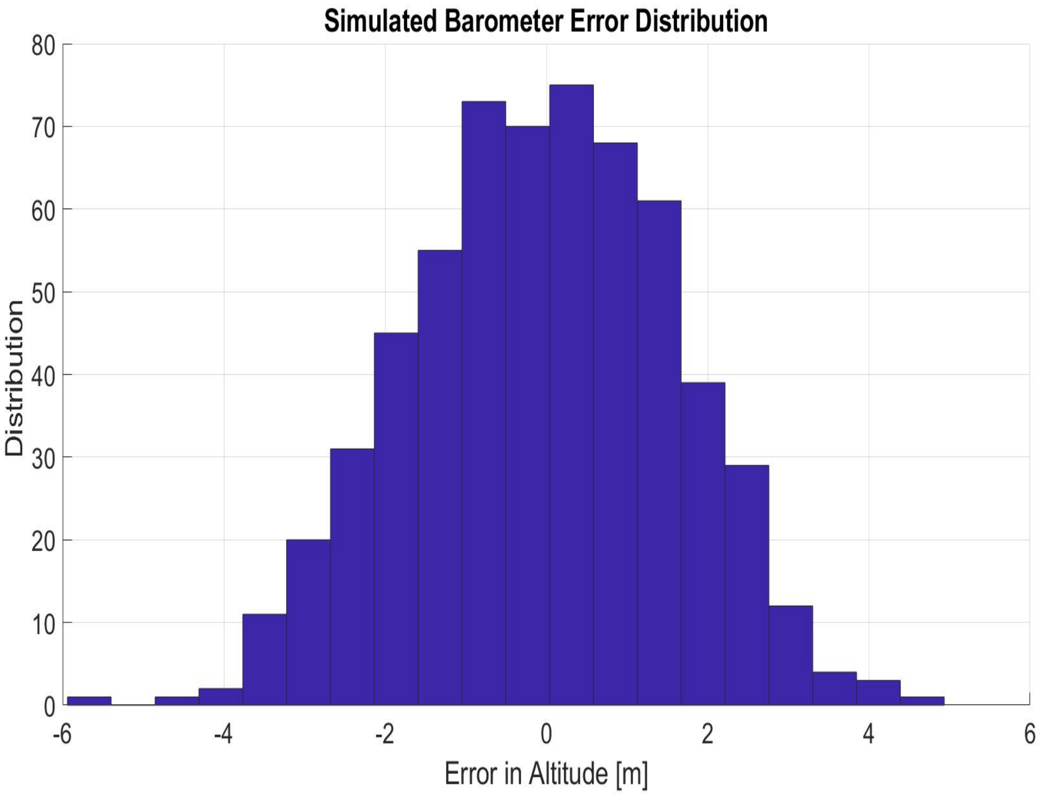
Justification of Requirement of RTK Capable GPS



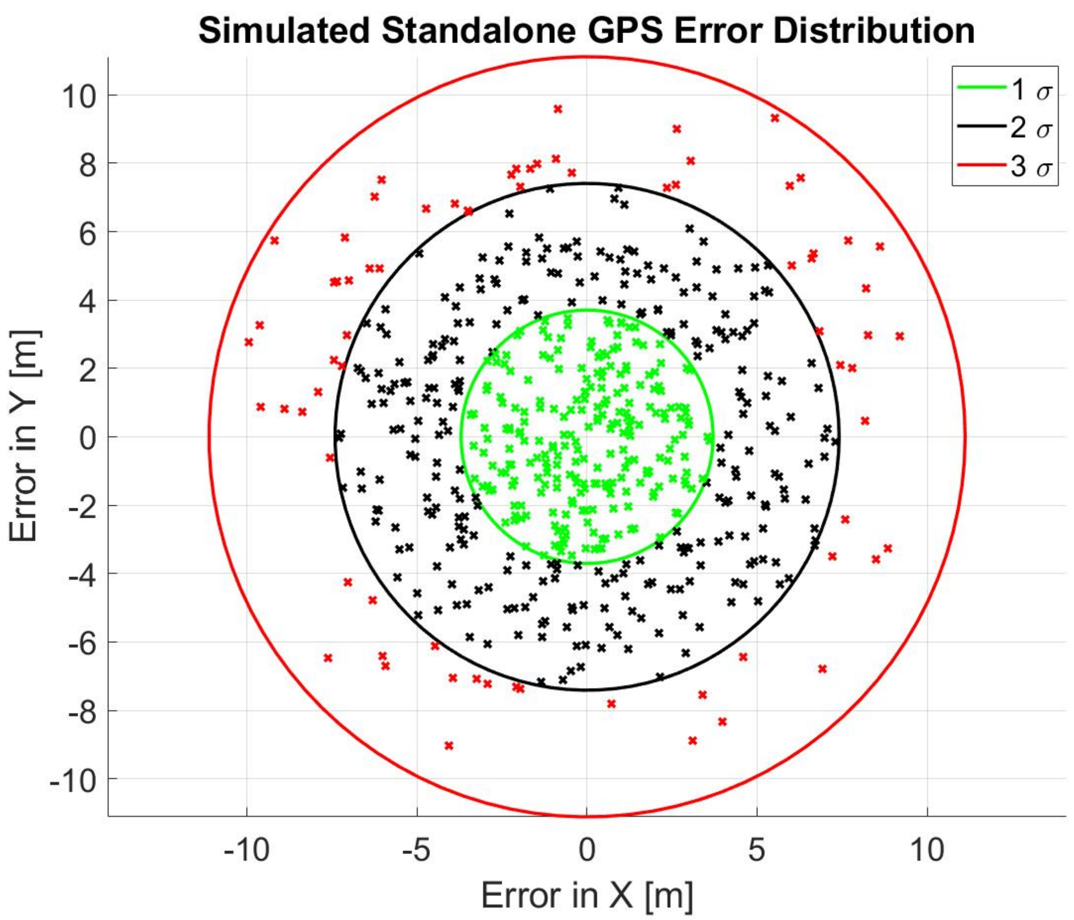
Vehicle Location Error Model (cont.)

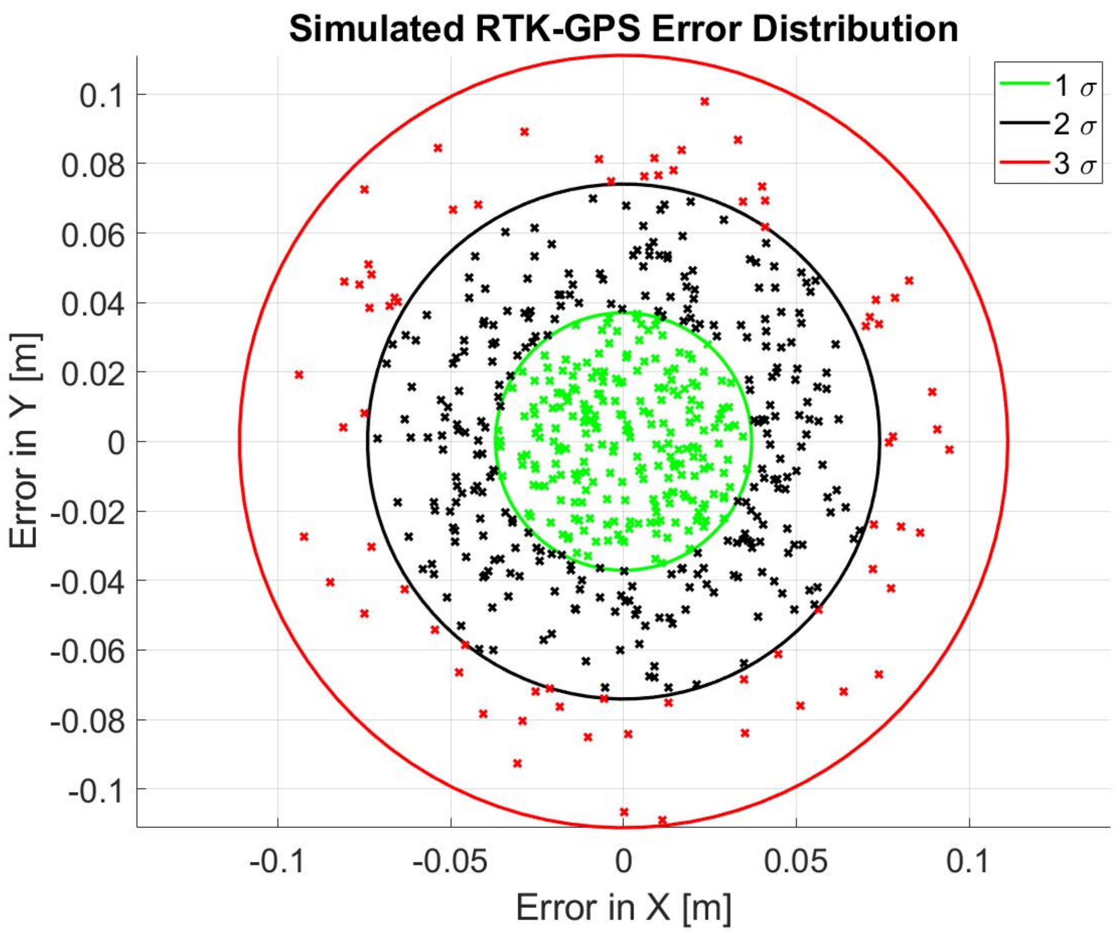
- UAV location error based on GPS and barometer
- Assumption: error has Gaussian distribution
- NEO-M8P u-blox M8 High Precision GNSS Module with RTK [1]
  - Listed Error: 0.025 m CEP
  - σ = 0.025/0.6745
  - (0.025 m at 0.6745 σ)
  - Gaussian Distribution at 50%
- MS5611 Barometer [2]
  - Listed Max Error: ±0.5 mbar
  - σ = 5/3 (5 m at 3 σ)
  - Gaussian Distribution at 99.7%





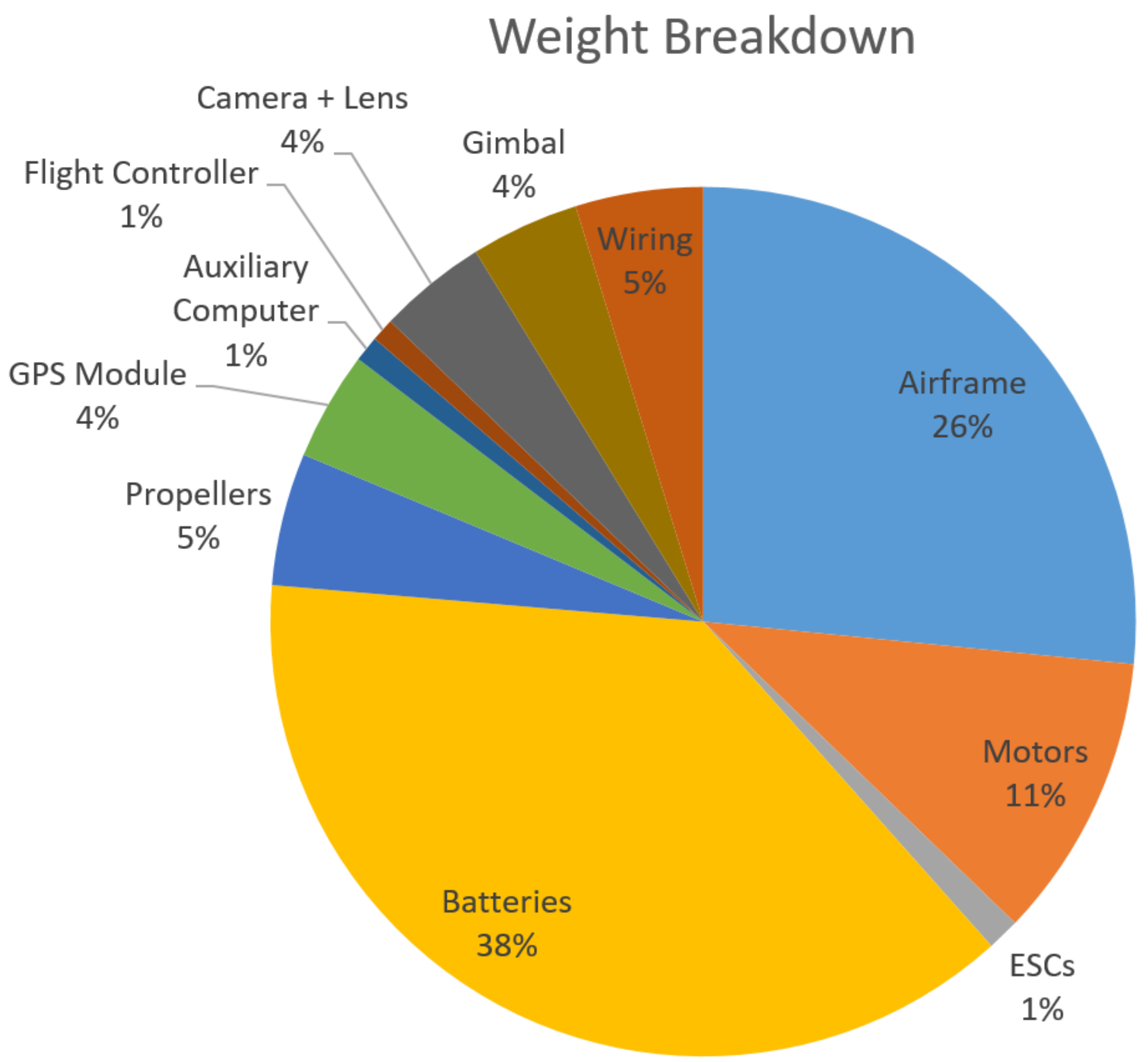
Justification of Requirement of RTK Capable GPS Module (cont.)





UAV Mass Budget

Object	Mass (g)	Qty	Total (g)
Airframe	1050	1	1050
Motors	70	6	420
ESCs	23	6	138
Batteries	1800	1	1800
Propellers	32.5	6	195
GPS Module	160	1	160
Auxiliary Computer	38	1	38
Flight Controller	34	1	34
Camera + Lens	160	1	160
Gimbal	160	1	160
Wiring	5% AUW	1	188
AUW			4153



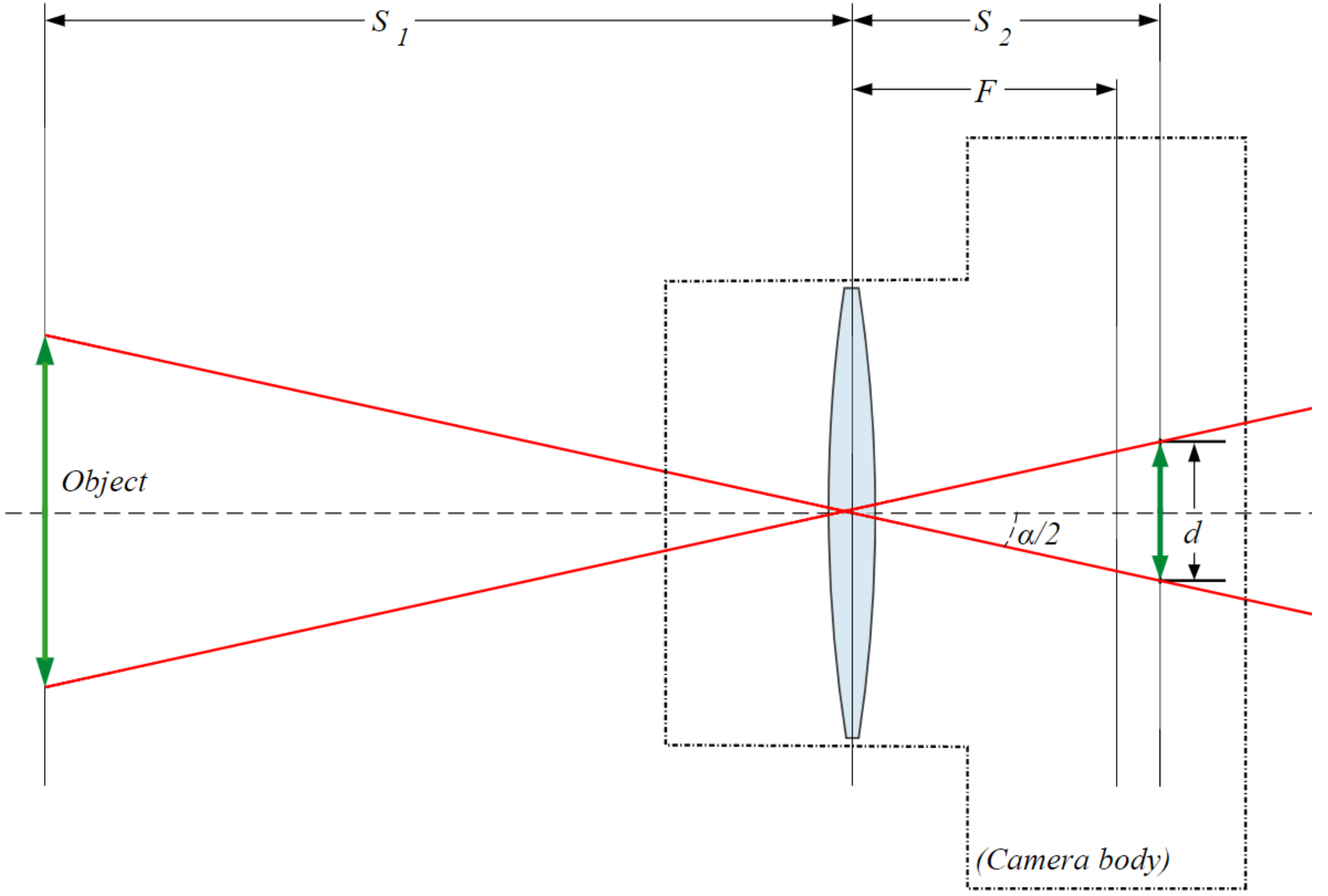
Angle of View Calculations

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 Flir Blackfly 2.3MP, a 12mm lens gives a 37 degree vertical AOV and a 48 degree horizontal AOV



Chosen GPS Receiver: C94-M8P

- The C94-M8P integrates the UBlox's high-precision NEO-M8P chip with UHF antennas and an RTK engine.
- The UHF antennas allow Differential-GPS to obtain cm-level accuracy (0.025 m + 1 ppm CEP).
- Only $400 for two integrated boards and associated hardware.
- However, it will add 160 grams and the antenna will require to be elevated on a ground plane.

https://www.u-blox.com/en/product/c94-m8p

UAV Interference model

- GPS is greatly impacted from noise that can result from the camera system as well as the EPS.
- To mitigate, it is necessary to keep the GPS receiver and antenna as far from the camera and battery as possible.
- Insulating the camera and cables in a low-cost solution such as Aluminum foil will act as a Faraday cage and reduce interference.
- Having a ground plane isolates the GPS receiver and improves the signal-to-noise ratio and satellites it can acquire.

Example ground plane with 6 in diameter

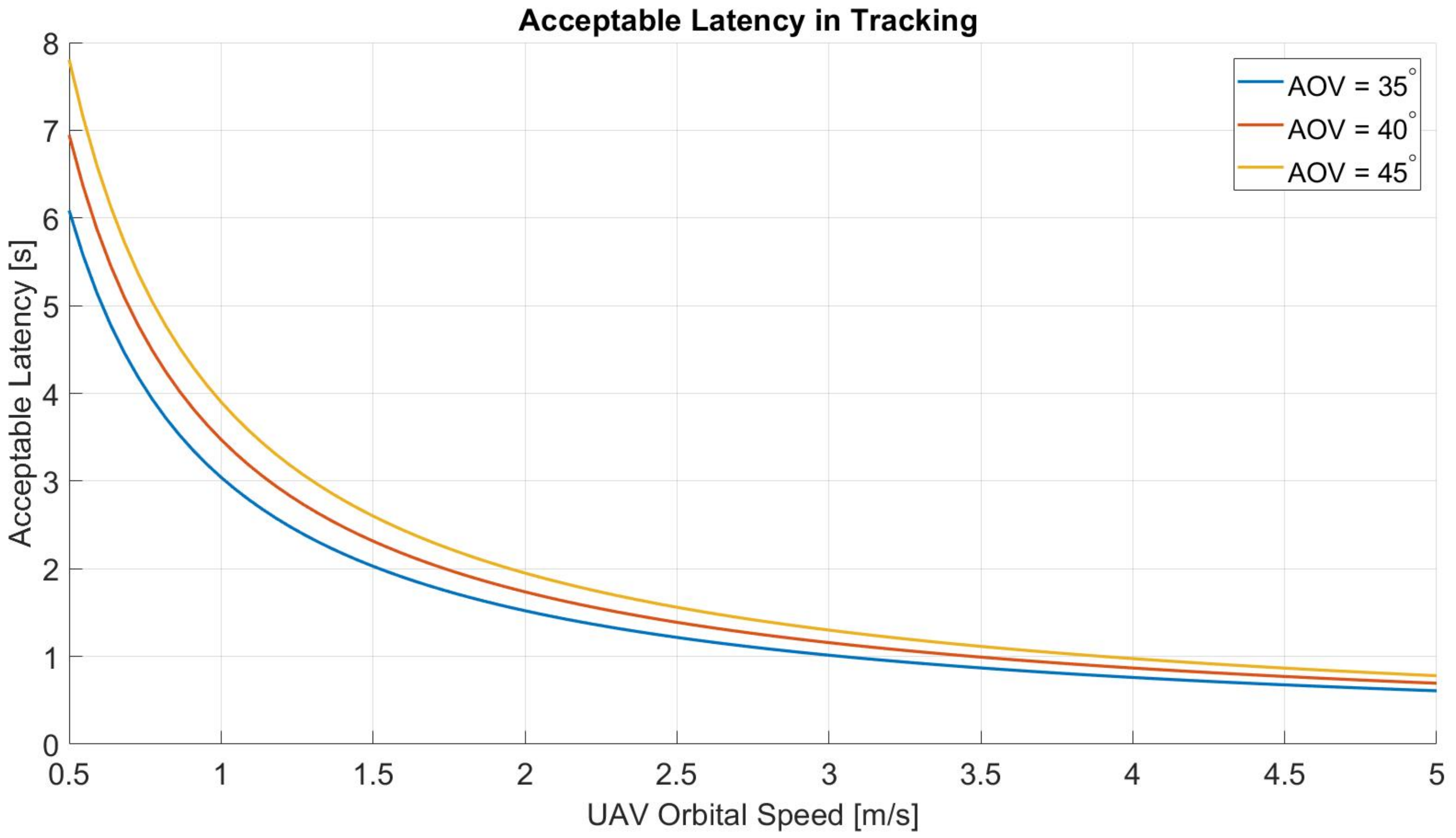
Latency Model

In order to feel confident in the ability to visually track, the latency should be within constraints. The big question is: Is our system fast enough?

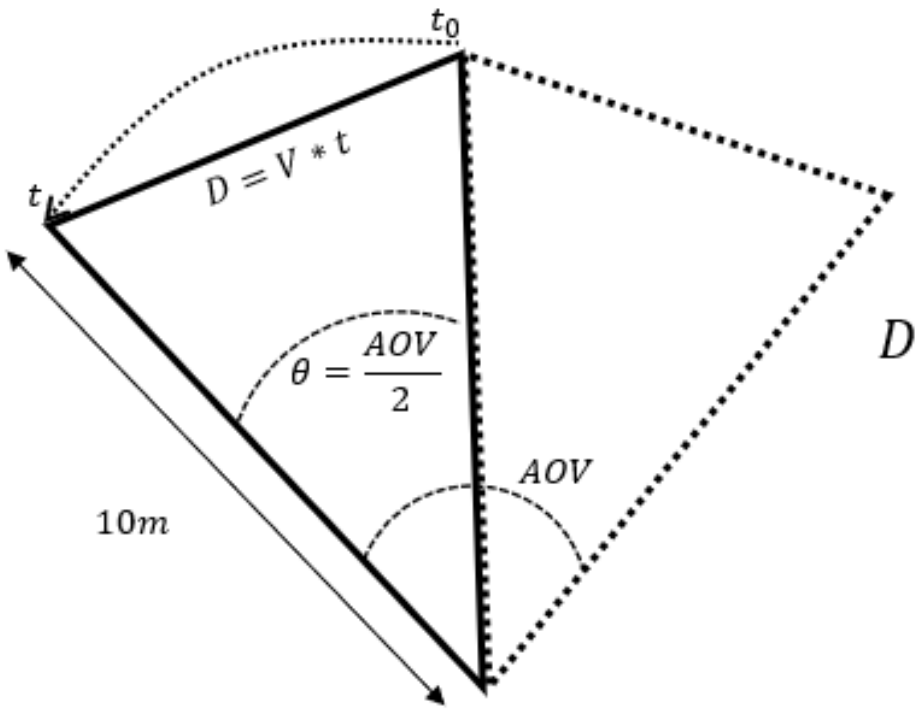
Capture Data	Process Data	Transmit/ Receive	Process Data	Use Data
GPS/IMU	Parse Lat/Long & raw ephemeris. Calculate state estimates.	Send data <30 meters	Calculate relative location and angle to turn camera.	Activate servos to turn camera.
100 ms (10 Hz)	10 ms	20 ms	TBD ms	TBD ms

Latency Model

- Calculated Latency is time between pointing states
- Includes position transmission, processing, pointing commanding, and actuation



Latency Model



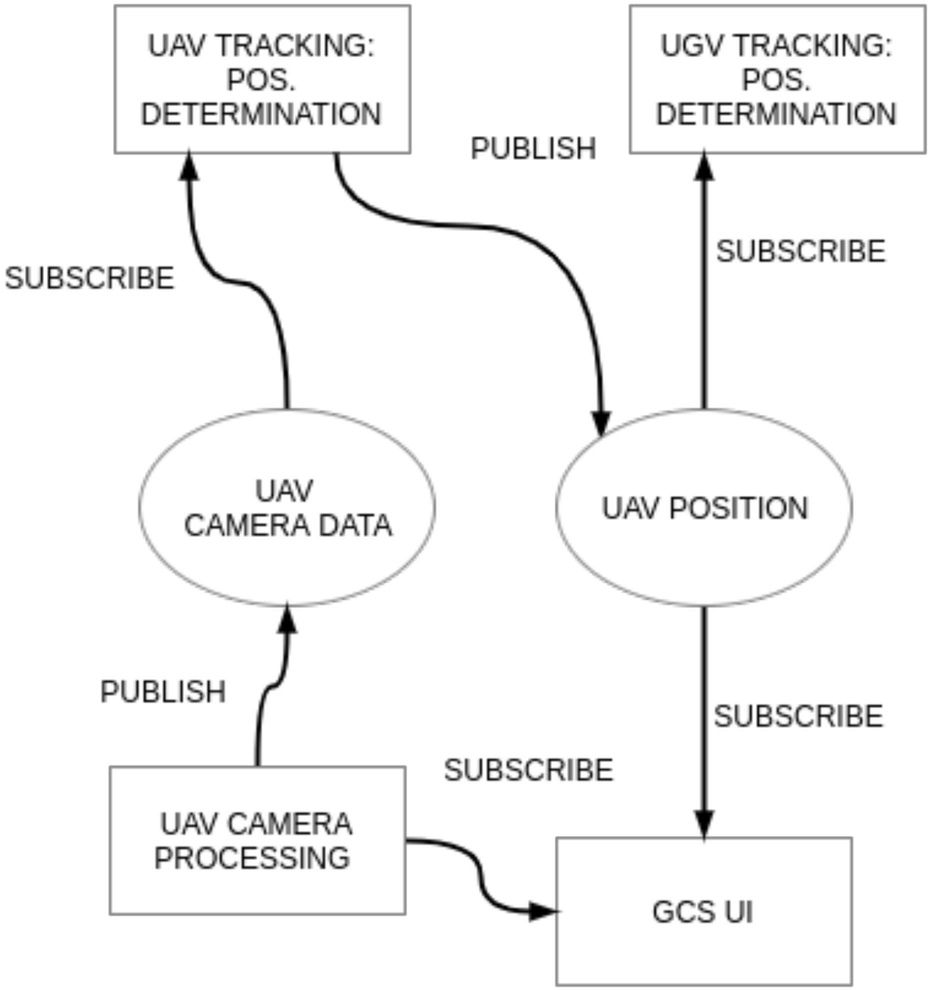
$$t - t_0 = t_{lat}$$
$$D = V * t_{lat}$$
$$D = 2 * 10m * \sin\left(\frac{\theta}{2}\right) = 2 * 10m * \sin\left(\frac{AOV/_2}{2}\right)$$
$$V * t_{lat} = 2 * 10m * \sin\left(\frac{AOV/_2}{2}\right)$$
$$\boldsymbol{t_{lat} = \frac{2}{V} * 10m * sin\left(\frac{AOV/_2}{2}\right)}$$

Calculating Transmit/Receive Latency

- This latency boils down to the time it takes to deliver a message.
  - Packet Delivery Time = Transmission Time + Propagation Delay = 10 ms + 250 ns = 10 ms
  - Roundtrip Time = 2*Packet Delivery Time + Processing Delay = 2*10 ms + 20 ms = 40 ms
  - Network Throughput = Window Size/Roundtrip Time = 32 Kbit / 40 ms = 800 bit/ms
  - Message Delivery Time = Message Size/Network Throughput = 19.2 Kb/800 bit/ms = 24 ms

ROS Overview

- The Robot Operating System (ROS) is a abstraction for data communication between machines
- Data is packaged as messages based on primitive data types
- Chunks of code can be made Nodes, which Publish messages to and Subscribe to receive messages from Topics
- Topics are a kind of message exchange for one type of message
- Any Node can Subscribe to any topic, and Publish to any topic
- Does not matter if Nodes are on the same machine or different machines
- Custom messages can be created using other message types



Communications Data Rate Calculations

Name	Data Size	Event Rate	Data Rate
Camera	1920x1200 [pixels]*(1.3-2.0) [bytes/pixel in RAW] =2.8-4.4 MB/frame	41 frames/s	114-180*MB/s
IMU	20 [values]*16[bit/value] = 320 bits	I2C Connection Dependent (100 Hz)	~4.0 kB/s
GPS	Ublox NMEA output: 19.2 kbits	1 Hz	19.2 kbits/s
Barometer	7 bits	I2C Connection Dependent (100 Hz)	~1 kbit/s
Preview Image	160x160 pixel jpeg image: 20 kB (rough estimate)	4Hz/vehicle	1.25 Mbits/s

*SD cards limited to about 90 MB/s write speed: alternates are high speed USB 3 Flash drives @ 150-300 MB/s -needs to be verified. Or Removable SSD. FlashDrive SD Card RemovableSSD

RF Link Budget model

Connection Name	Frequency	Protocol	Data Type	Estimated Data Rate	Max Data Rate	Transmitter Power	Receiver Sensitivity	Range
UAV Controller	2.408 ~ 2.475 GHz	AFHDS 2A	Manual Controller Commands to FC	N/A	N/A	19 dBm	-105 dBm	1 km
SiK Telemetry Radio	915 MHz	FHSS	MAVLink GCS1 to FC	Varies: N/A during flight	250 Kbits/s	100mW (20 dBm?)	-117dBm	500 m
Data Network	2.4 GHz	802.11g/n	*	2.75 Mbits/s	54-> 11 Mbits/s	14 dBm	-68 dBm	125 m

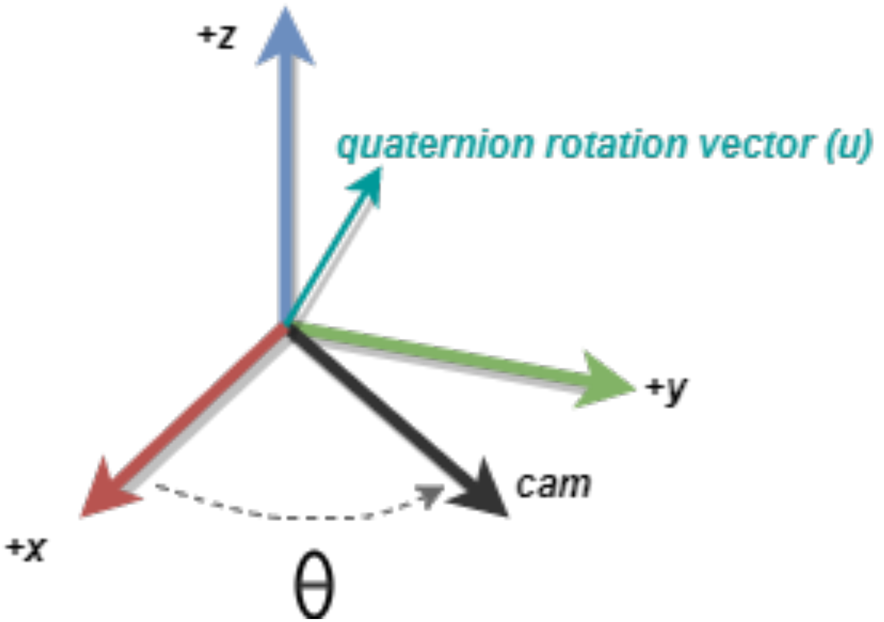
* UAV - UGV [GPS, IMU, Bar, State Estimation]
UAV-GCS1 [GPSx2, IMUx2, Barx2, State Estimationx2, Housekeeping, Preview Image, Control Relay]
UGV-GCS2 [GPSx2,IMUx2,Barx2,State Estimationx2,Housekeeping, Preview Image, UGV Manual Controls]

Camera Specifications

- Flir Blackfly 2.3MP Color:
  - Resolution: 1920x1200
  - Weight: 36 g
  - Size: 29 x 29 x 30 mm
  - FPS: 41
  - Power consumption: < 3 W
  - Cost: $495
  - Interface: USB 3.1 gen 1
  - Global Shutter
  - 10 bit and 12 bit ADC

Quaternion Rotation Calculation

- Determine relative position and attitude of vehicle
- Cross relative position vector and body x-axis for rotation axis
- Determine desired angle by taking the inverse cosine of the dot product of the relative position and body x-axis divide by the product of their magnitudes
- Calculate quaternion with unitized rotation vector and rotation angle
- Determine 3-2-1 Euler Sequence for gimbal control (3-2 for UGV)



$$q = q_0 + \boldsymbol{q} = \cos\frac{\theta}{2} + \hat{\boldsymbol{u}}\sin\frac{\theta}{2}$$

$$\begin{bmatrix}\phi \\ \theta \\ \psi\end{bmatrix} = \begin{bmatrix}\arctan\frac{2(q_0q_1+q_2q_3)}{1-2(q_1^2+q_2^2)} \\ \arcsin(2(q_0q_2-q_3q_1)) \\ \arctan\frac{2(q_0q_3+q_1q_2)}{1-2(q_2^2+q_3^2)}\end{bmatrix}$$

Euler Angles for 3-2-1 Rotation Sequence

Simulation Rotation Scheme

- Takes quaternion *(q)* and calculates rotation matrix *(R)*
- Multiply *R* with vehicle x-axis to get pointing vector

$$R = \begin{bmatrix} 1 - 2(q_2^2 + q_3^2) & 2(q_1 q_2 - q_0 q_3) & 2(q_0 q_2 + q_1 q_3) \\ 2(q_1 q_2 + q_0 q_3) & 1 - 2(q_1^2 + q_3^2) & 2(q_2 q_3 - q_0 q_1) \\ 2(q_1 q_3 - q_0 q_2) & 2(q_0 q_1 + q_2 q_3) & 1 - 2(q_1^2 + q_2^2) \end{bmatrix}$$

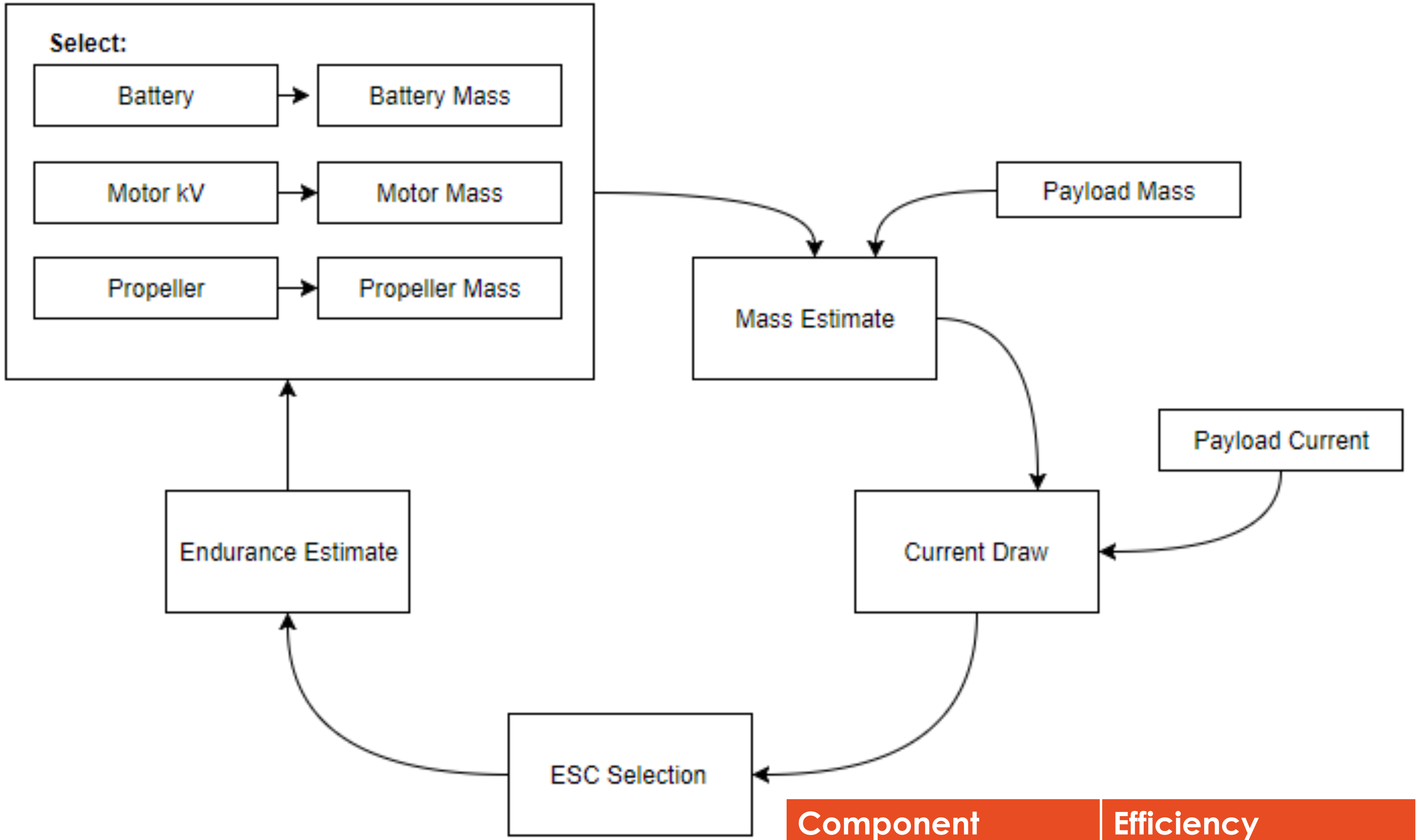
Avoiding Gimbal Wire Wrap

- Vehicles should yaw around body z-axis if approaching gimbal yaw limit (gimbal dependent)
- Skid steering on UGV, manually controlled
- Should not be an issue due to low vehicle speeds (no jerking motion to yaw)

Power

- Assumptions:
  - 85% Battery Discharge
  - Voltage Linearly Depends on Charge
  - Wire Resistance Negligible
  - Payload Current Draw Constant (6A)
  - Wires 5% of All Up Weight
  - Flying at 5280 ft, 60° F
  - No Airframe Drag

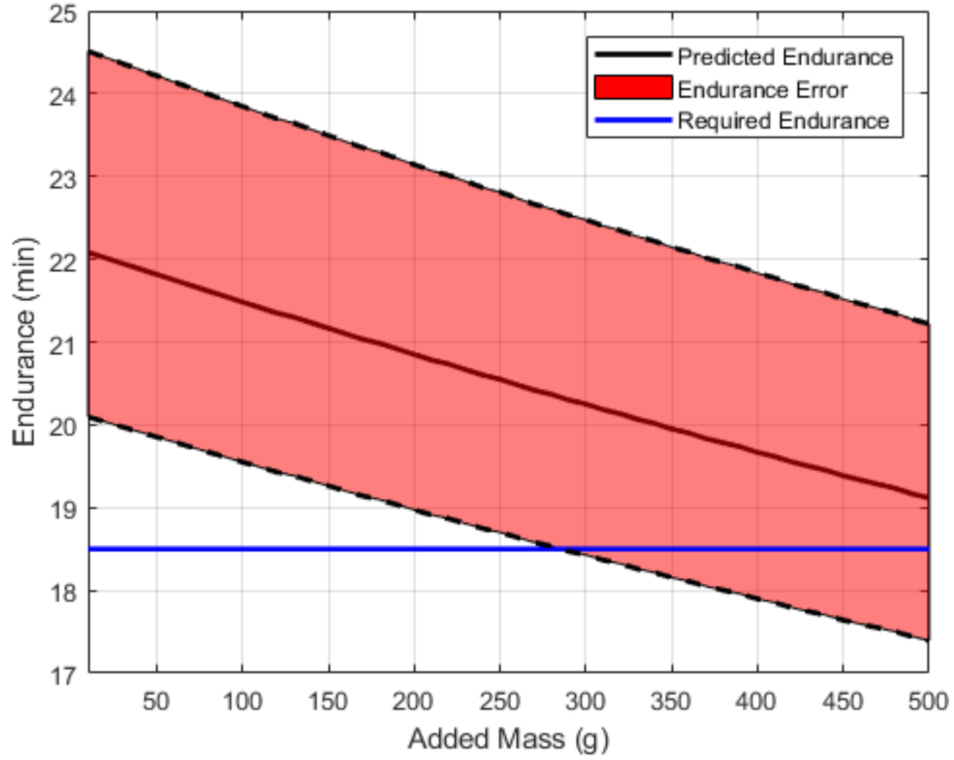
$$T = \frac{1}{2}\rho A V^2$$
$$V_{air} = \sqrt{\frac{2T}{\rho A}}$$
$$P_{prop} = TV_{air}$$
$$P_{mech} = (V_{batt} - R_{motor}I_{motor})(I_{motor} - I_0)$$
$$V_{air} = \omega \times pitch \times (\frac{0.0254}{60})$$
$$I_{tot} = NumMotors \times I_{motor} + I_{payload}$$



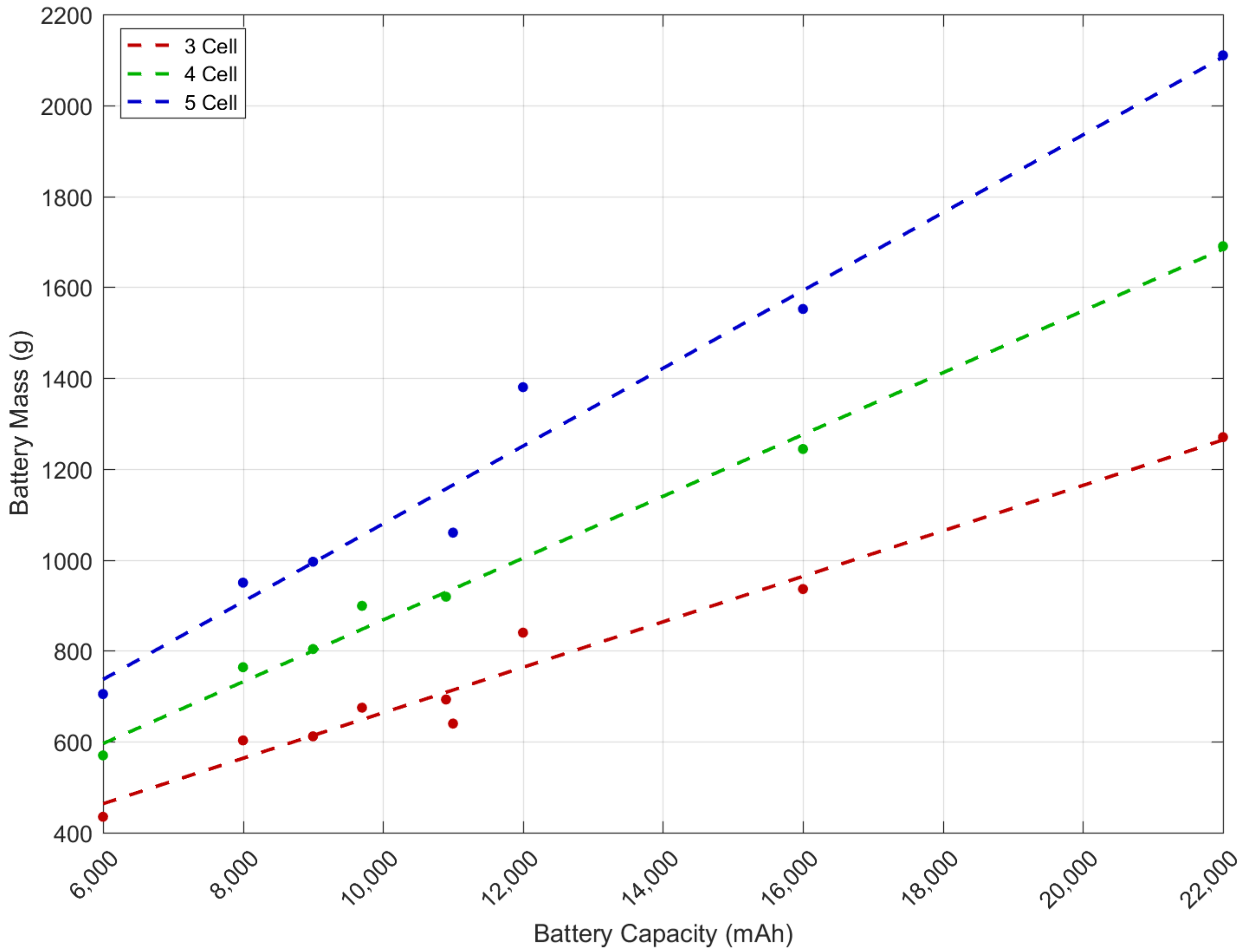
Component	Efficiency
ESCs	97%
Motors	80% (hovering)
Propellers	70% (hovering)

UAV Configuration

	Configuration
Number of Rotors	6
Hover Endurance	24 (min)
Battery	5s-16000 mAh Li-Po
Motor	~400-500 kV, 250+ Watt
Propeller	18x5.5 Carbon Props
Max Current Draw	120 (A), 19 Amp/motor
Hover Current Draw	6 Amp/Motor
Max Wattage	1500 Watts
Hover Wattage	550 Watts
Full Throttle Endurance	9 min
Battery Discharge Rating	23C+
All up Weight	4.65 (kg)



Mass Budget Calculations



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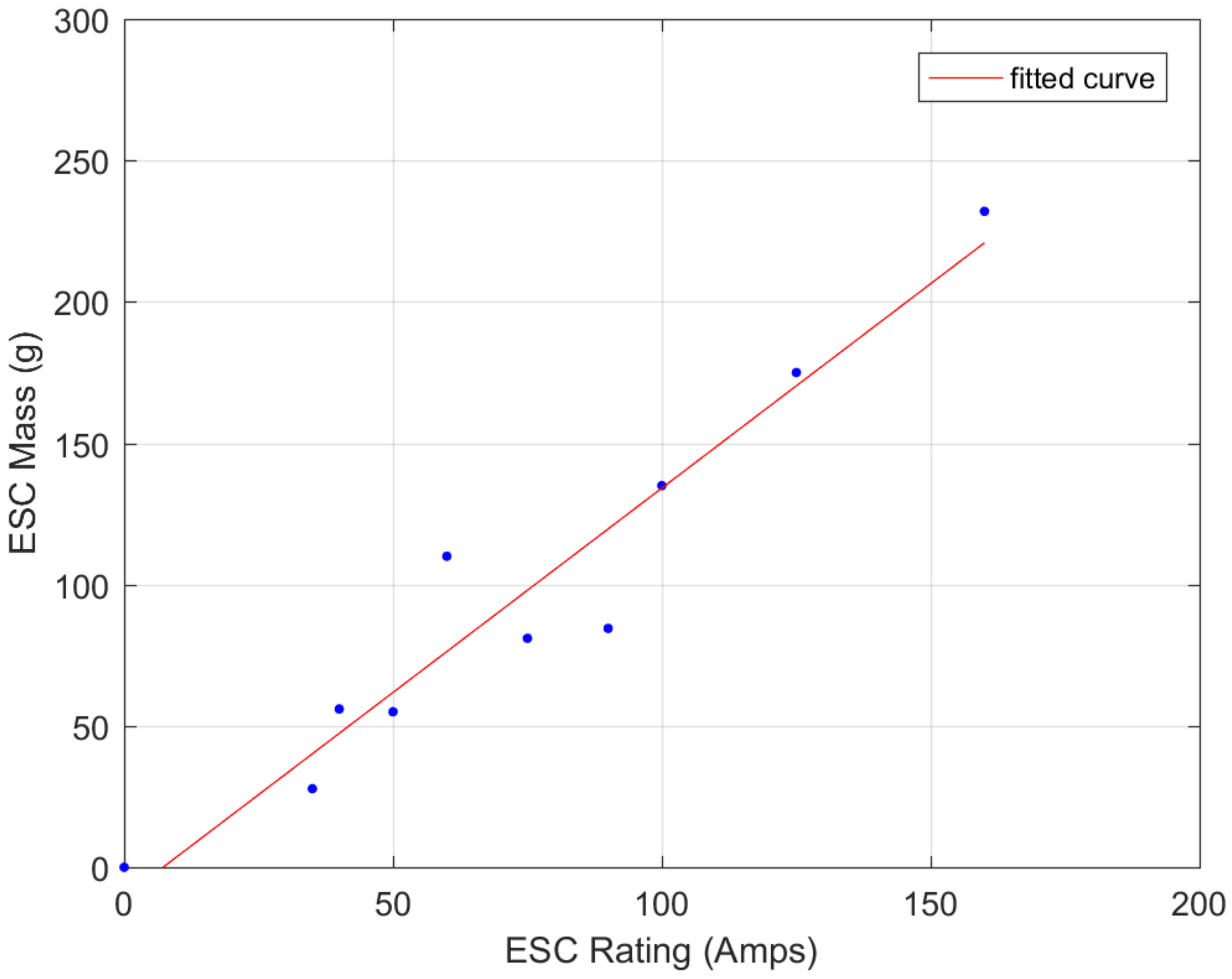

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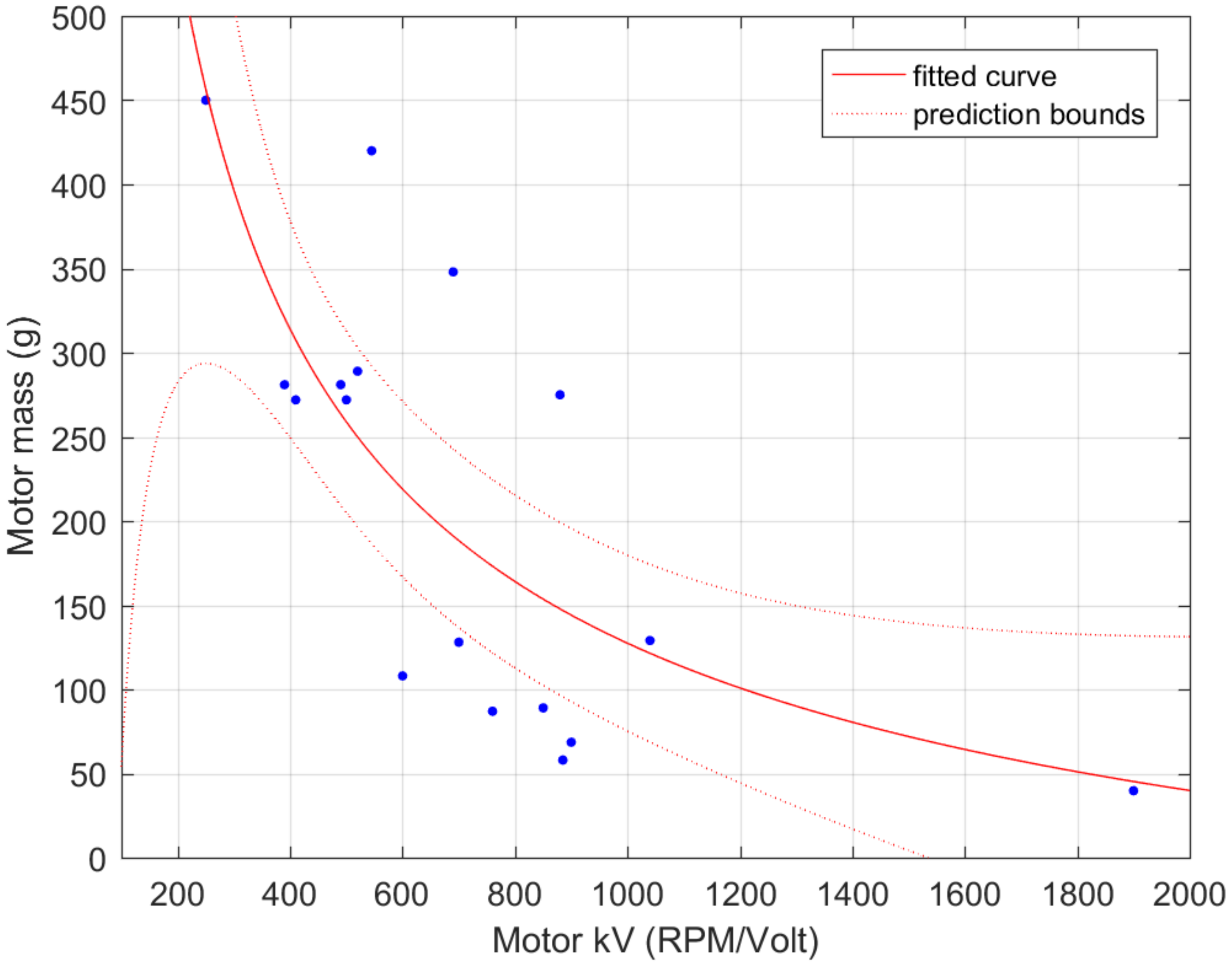
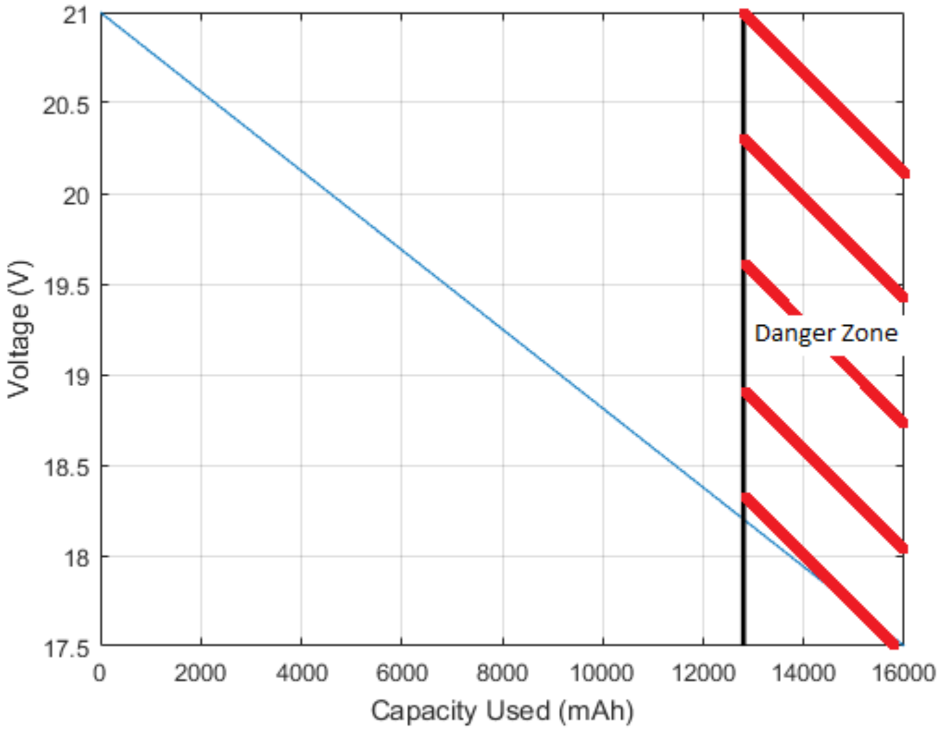
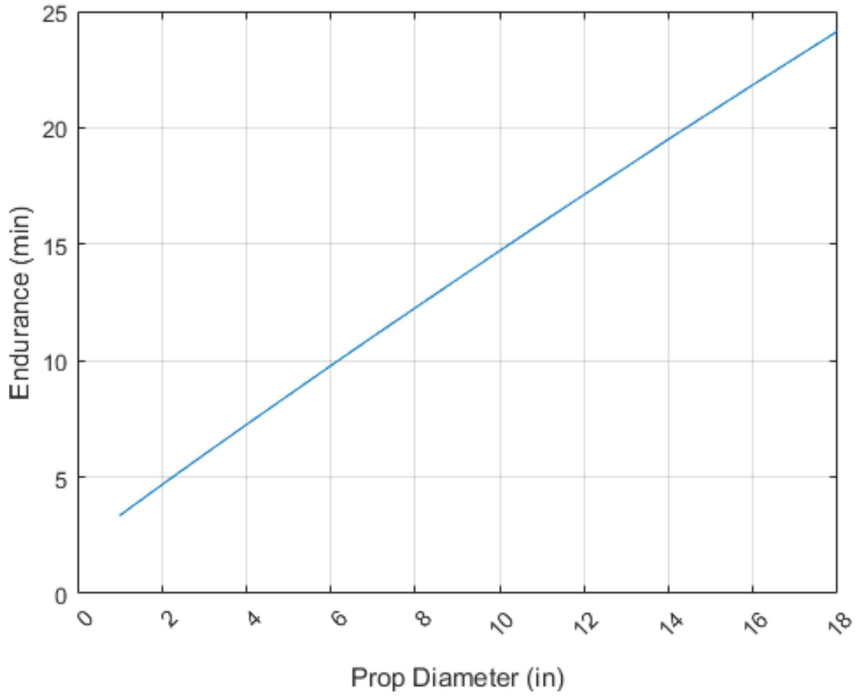


Power Graphs





$$T = \frac{1}{2}\rho A V^2$$

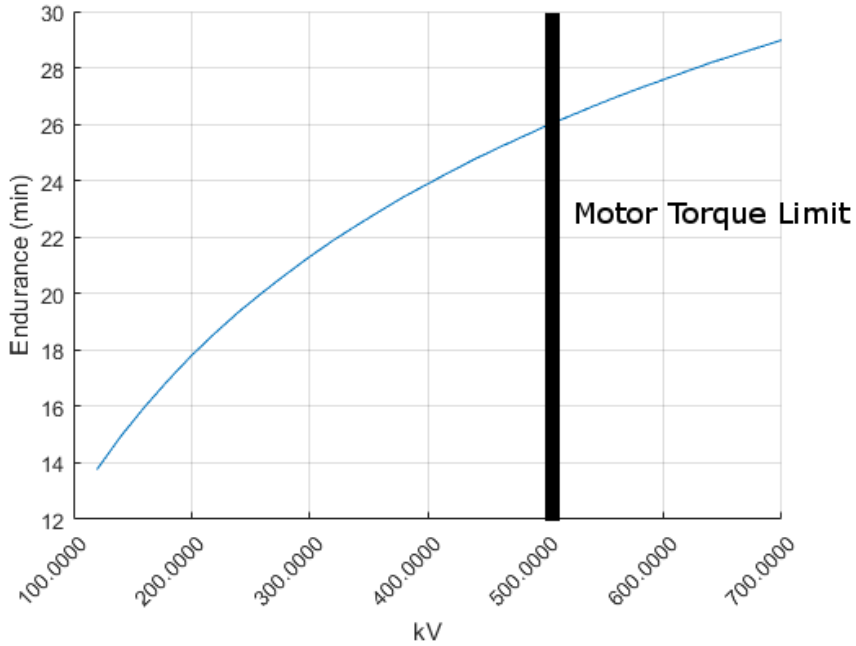
$$V_{air} = \sqrt{\frac{2T}{\rho A}}$$

$$P_{prop} = T V_{air}$$

$$P_{mech} = (V_{batt} - R_{motor} I_{motor})(I_{motor} - I_0)$$

$$V_{air} = \omega \times pitch \times (\frac{0.0254}{60})$$

$$I_{tot} = NumMotors \times I_{motor} + I_{payload}$$



UGV Power

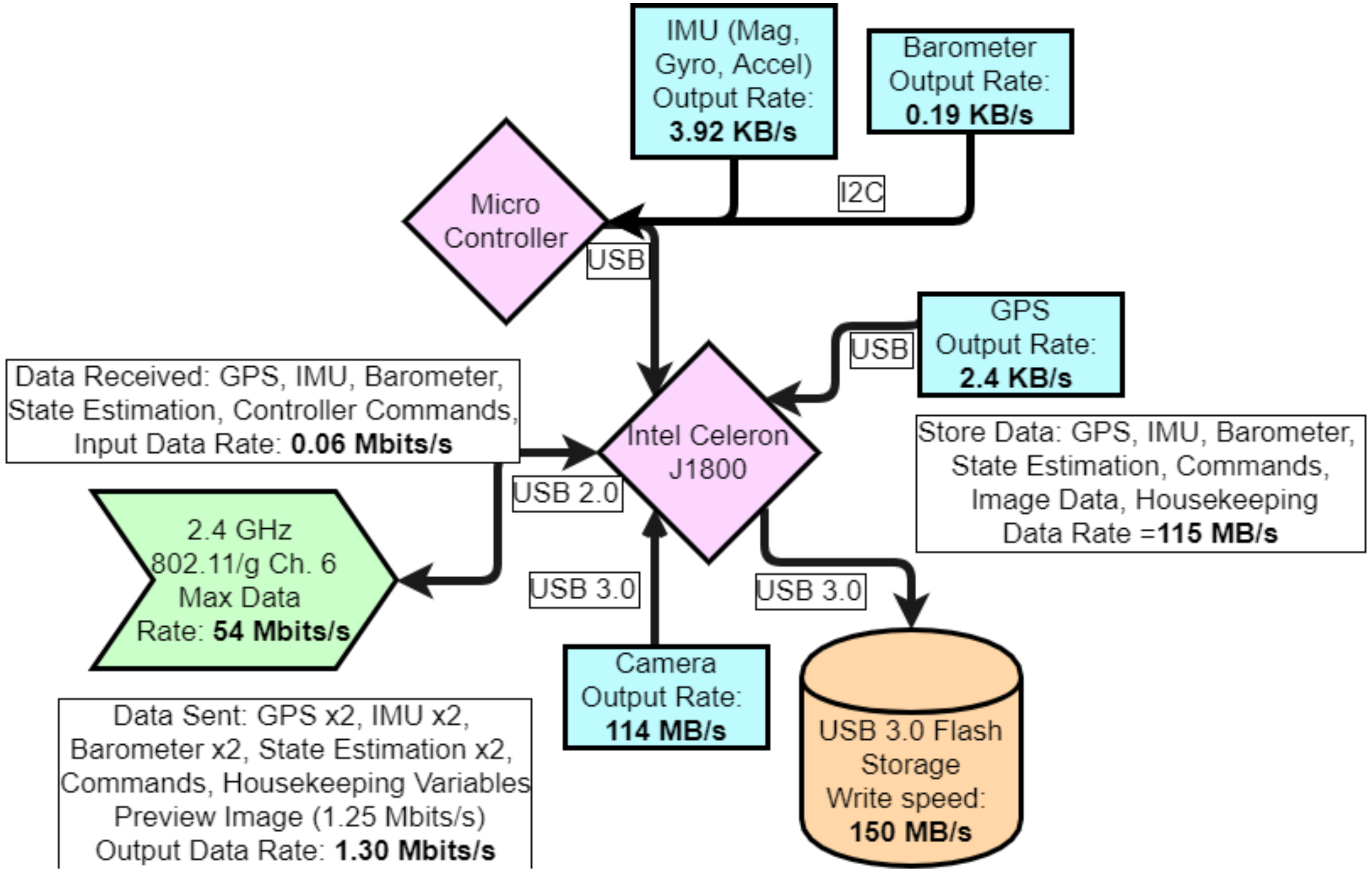
At Max Power Draw	Power Draw
Onboard Computer	60 W
Drive System	500 W @ Full throttle
Payload	50 W max
Total	610 W
Endurance	~25 Min

Stationary Tracking	Power Draw
Onboard Computer	60 W
Payload	100 W Max
Drive System	0 W
Total	160 W
Endurance	~100 min

Note Power Consumption occurs when rover is driving top speed while spinning gimbal at full speed and stress testing CPU simultaneously. Not representative of RAVENs use of the system, expecting more than 2 hrs of battery life while testing.

Courtesy of Clearpath Robotics

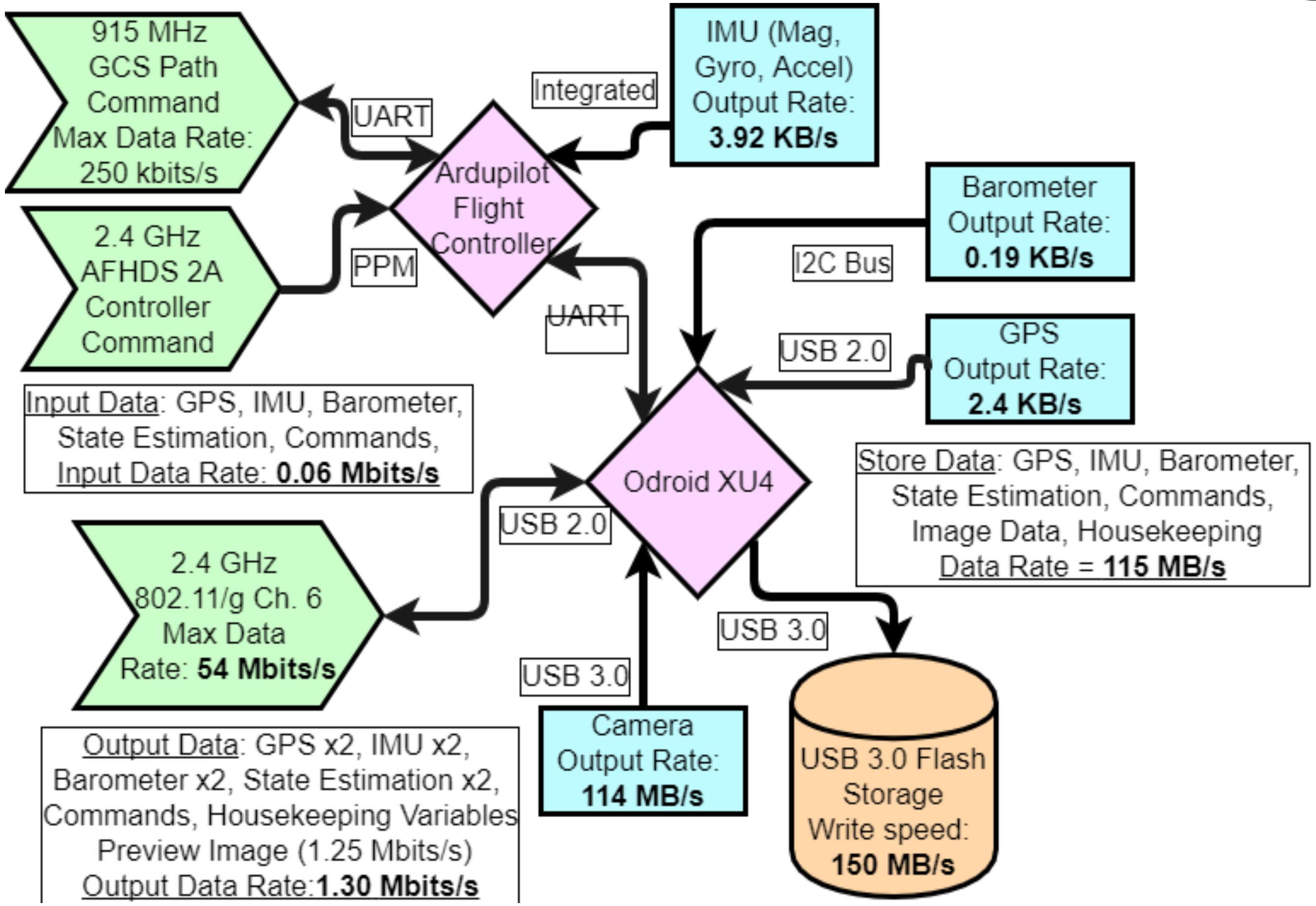
Internal UGV Link Budget model



Property	Estimate	Limit
Storage Write Speed	115MB/s	150 MB/s
Output Network Data Rate	2.25 Mbits/s	54 Mbits/s: Network Pend
Incoming Network Data Rate	0.06 Mbits/s	54 Mbits/s: Network Depend

RF Component	Purpose
Bluetooth PlayStation Controller	Pre-installed manual control remote. (Not used)
2.4 GHz 802.11g/n	Receive nav data from UAV. Send nav data to UAV. Send nav & state data to GCS.

Internal UAV Link Budget model



Property	Estimate	Limit
Storage Write Speed	115 MB/s	150 MB/s
Output Network Data Rate	1.30 Mbits/s	54 Mbits/s: Network Pend
Incoming Network Data Rate	0.06 Mbits/s	54 Mbits/s: Network Depend

RF Component	Purpose
915 MHz GCS Path Command	Upload flight path to FC from GCS
2.412 GHz AFHDS 2A Controller Command	Upload Manual Commands Directly to FC
2.4 GHz 802.11g/n	Receive nav data from UGV. Send nav data to UGV. Send nav & state data to GCS.

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