RAMROD

REMOTE AUTONOMOUS MAPPING OF RADIO FREQUENCY OBSTRUCTION DEVICES

Team: Jorgen Baertsch, Ian Cooke, Kennedy Harrmann, Mary Landis, Sarah Larson, Harrision Mast, Ethan Morgan, Selby Stout, Jake Ursetta, Justin Williams, Samantha Williams

Sponsor: Dennis Akos

Advisor: Jade Morton

ACRONYM TABLE

Acronym:	Meaning:
AGC	Automatic Gain Control
ET	**Emerging Threat**
FAA	Federal Aviation Administration
GNC	Guidance Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	**Inertial Measurement Unit**
INS	**Inertial Navigation System**
MCU	Microcontroller
PDOA	**Power Difference of Arrival**
PPD	**Personal Privacy Device**
RFI	**Radio Frequency Interference**
UAS	Unmanned Aerial System

AGENDA

1. Project Purpose and Objectives
2. Design Solution
3. Critical Project Elements
4. Design Requirements and Their Satisfaction
5. Risk Analysis
6. Verification and Validation
7. Project Summary

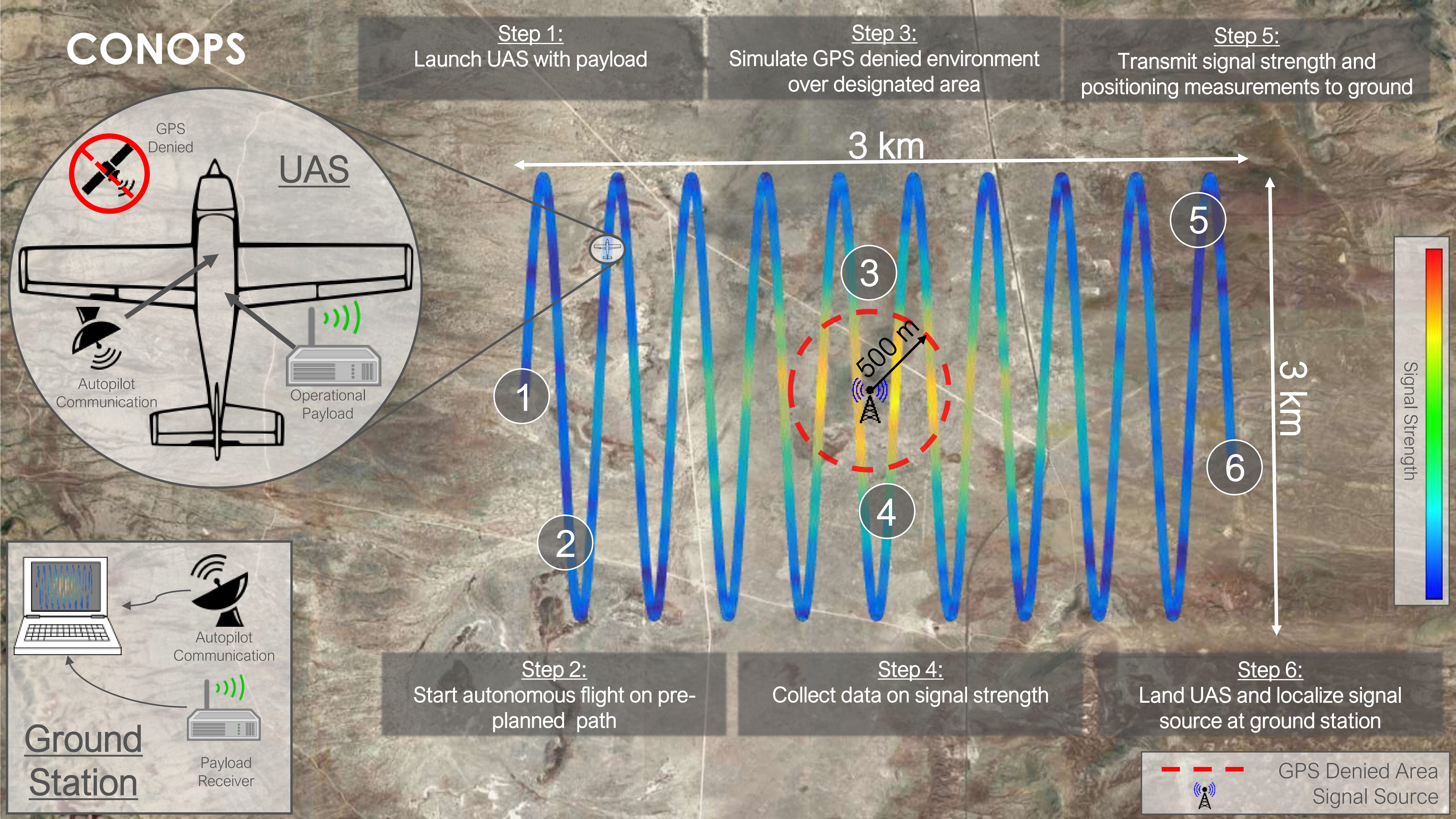
MISSION STATEMENT

RAMROD will utilize an autonomous **UAS** and self-contained **sensor payload** to **localize** Radio Frequency Interference and Emerging Threat sources in a **GPS-denied environment** to allow civilian and military GNSS endeavors to continue without disruption.

BACKGROUND AND MOTIVATION

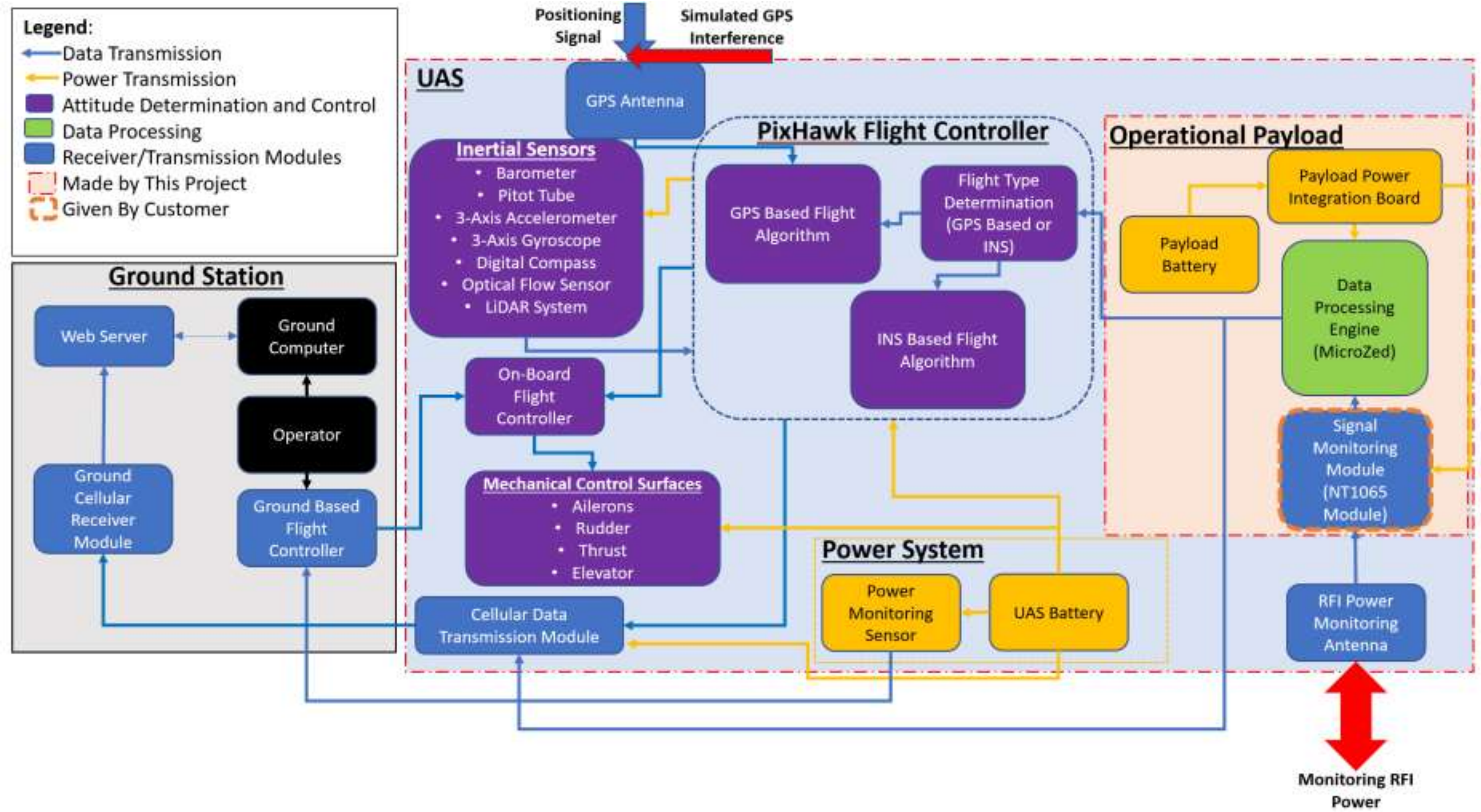
- Personal Privacy Devices and Emerging Threats (spoofers) are interrupting civilian and military GNSS endeavors
- Utilizing a UAS is the most efficient method for rapidly localizing these RFI sources
- Flying a UAS in GPS-denied conditions is problematic due to most autopilots reliance on GNSS

GPS Emerging Threat



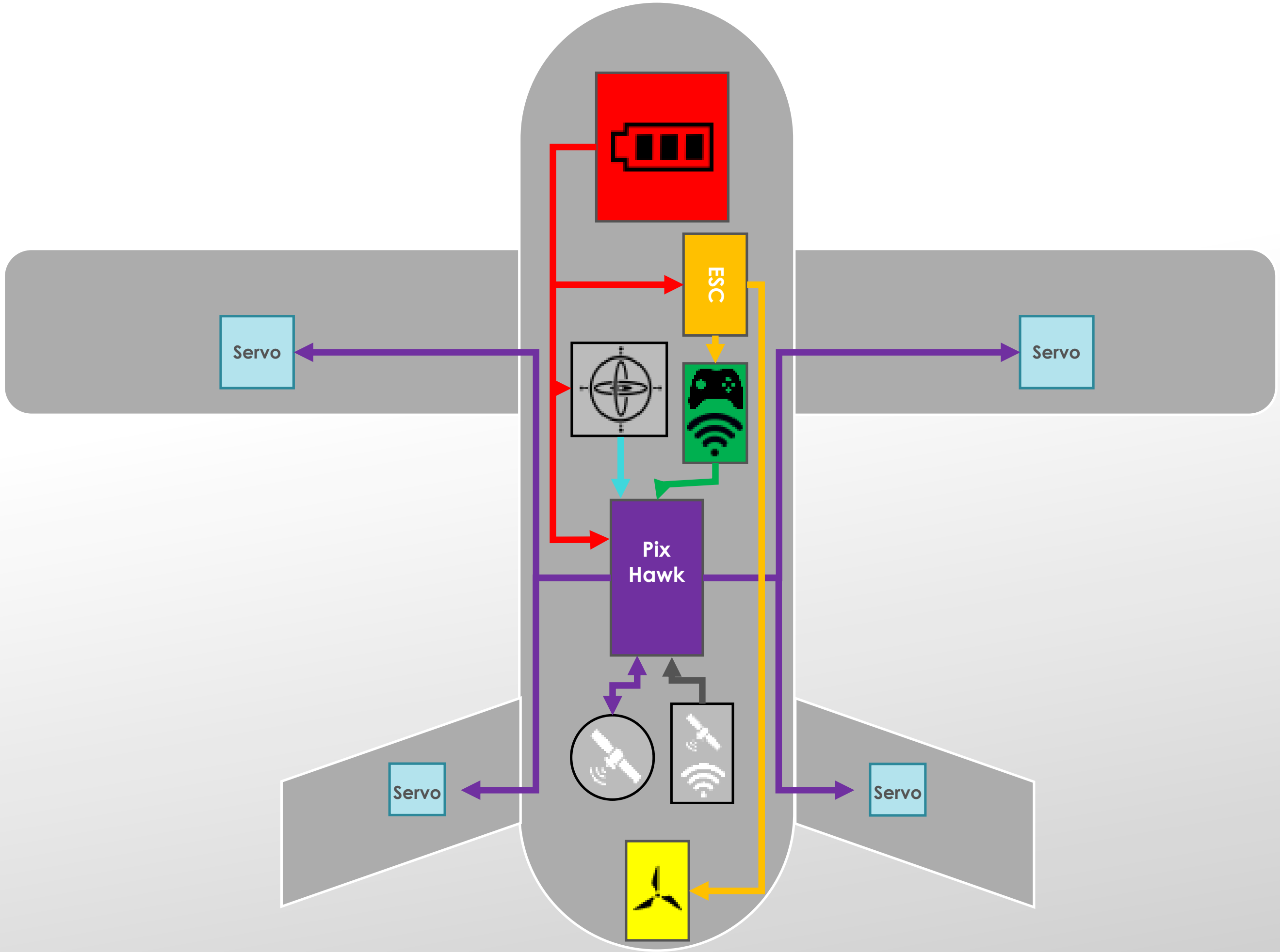
CONOPS
Step 1:
Launch UAS with payload
Step 3:
Simulate GPS denied environment over designated area
Step 5:
Transmit signal strength and positioning measurements to ground
GPS Denied
UAS
Autopilot Communication
Operational Payload
3 km
3 km
500 m
1
2
3
4
5
6
Signal Strength
Autopilot Communication
Payload Receiver
Ground Station
Step 2:
Start autonomous flight on pre-planned path
Step 4:
Collect data on signal strength
Step 6:
Land UAS and localize signal source at ground station
GPS Denied Area
Signal Source

FUNCTIONAL BLOCK DIAGRAM

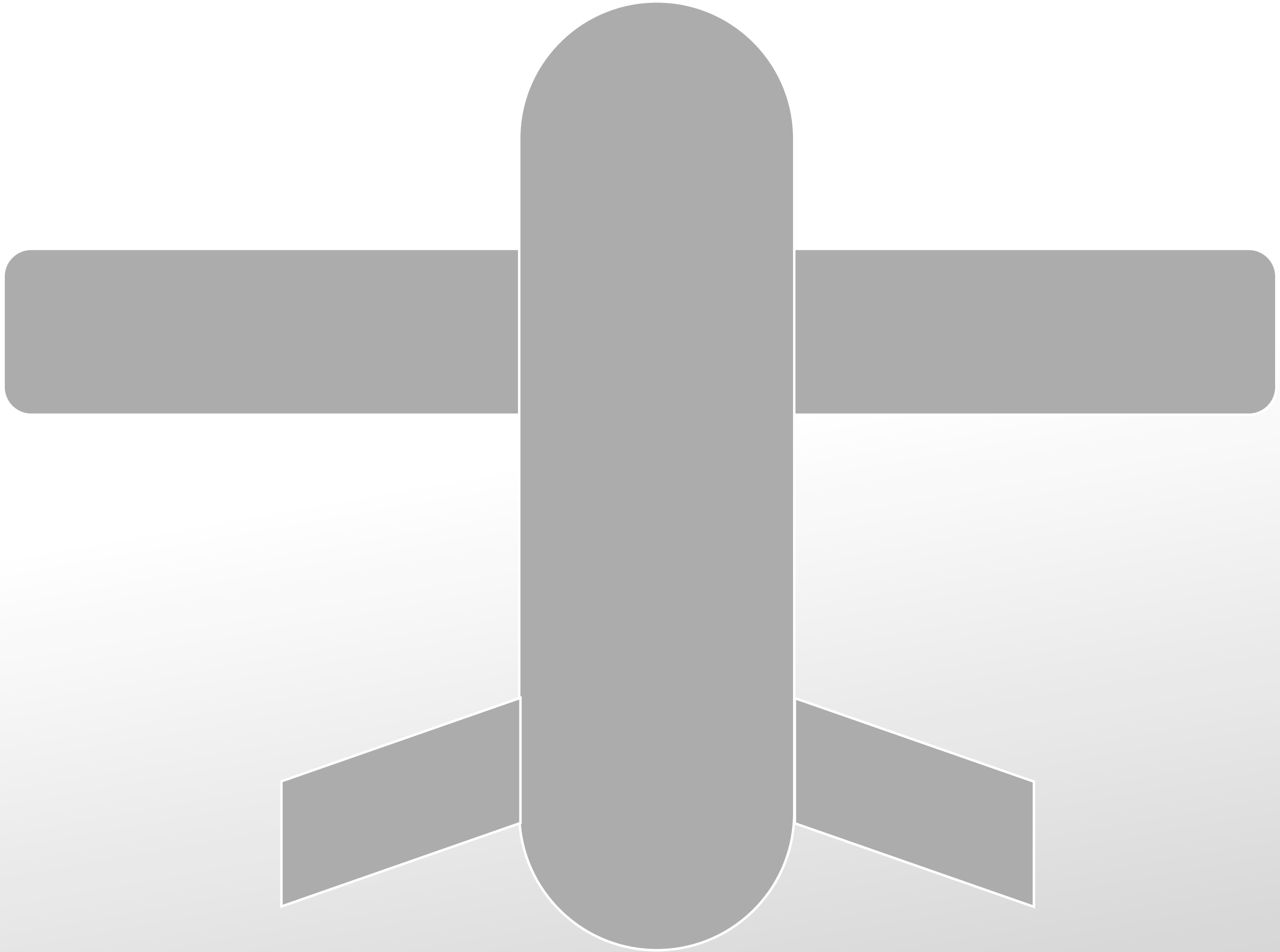


DESIGN SOLUTION

UAS PLATFORM SOLUTION



UAS PLATFORM SOLUTION



Airframe

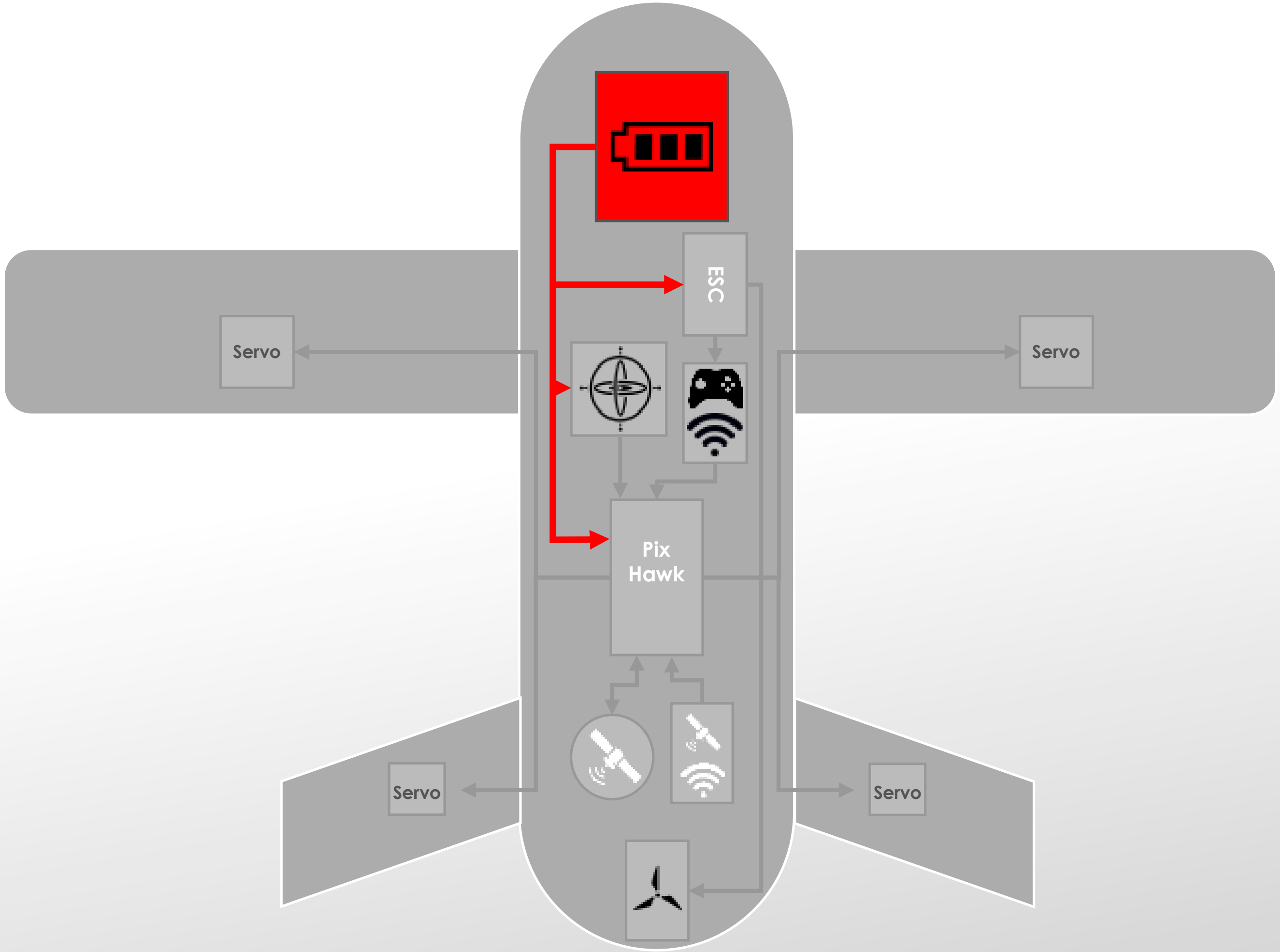
Name: X-UAV Talon

Wing Span: 1718 mm

Empty Weight: 1050 g

Configuration: V-tail

UAS PLATFORM SOLUTION

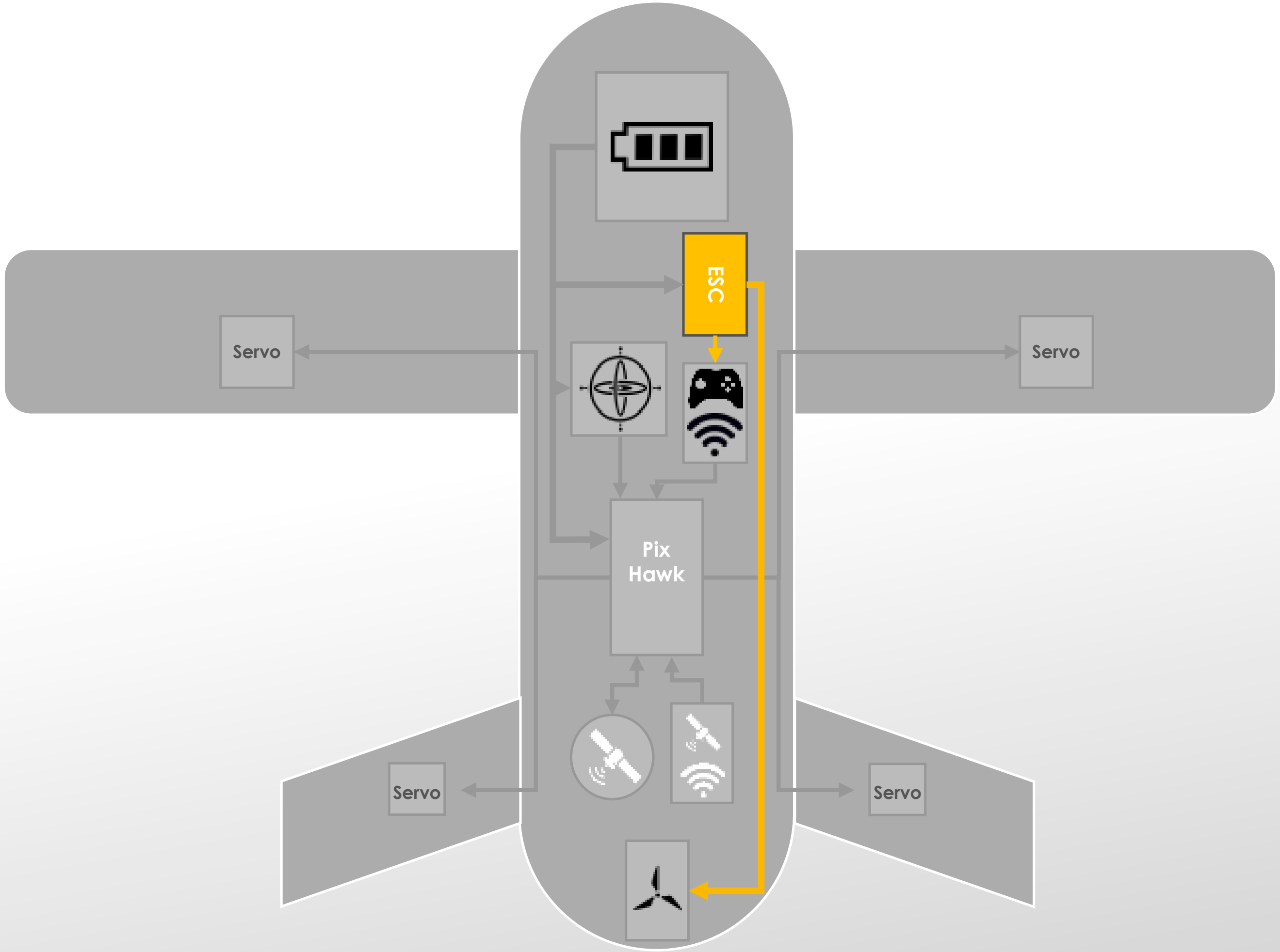


Power System
Name: Thunder Power TP700

Type: High Voltage LiPo
Capacity: 2x 3s 7000 mAh
Output: EC3/EC5

Mass: 423 g
Dimensions: 27 x 69 x 110 mm

UAS PLATFORM SOLUTION

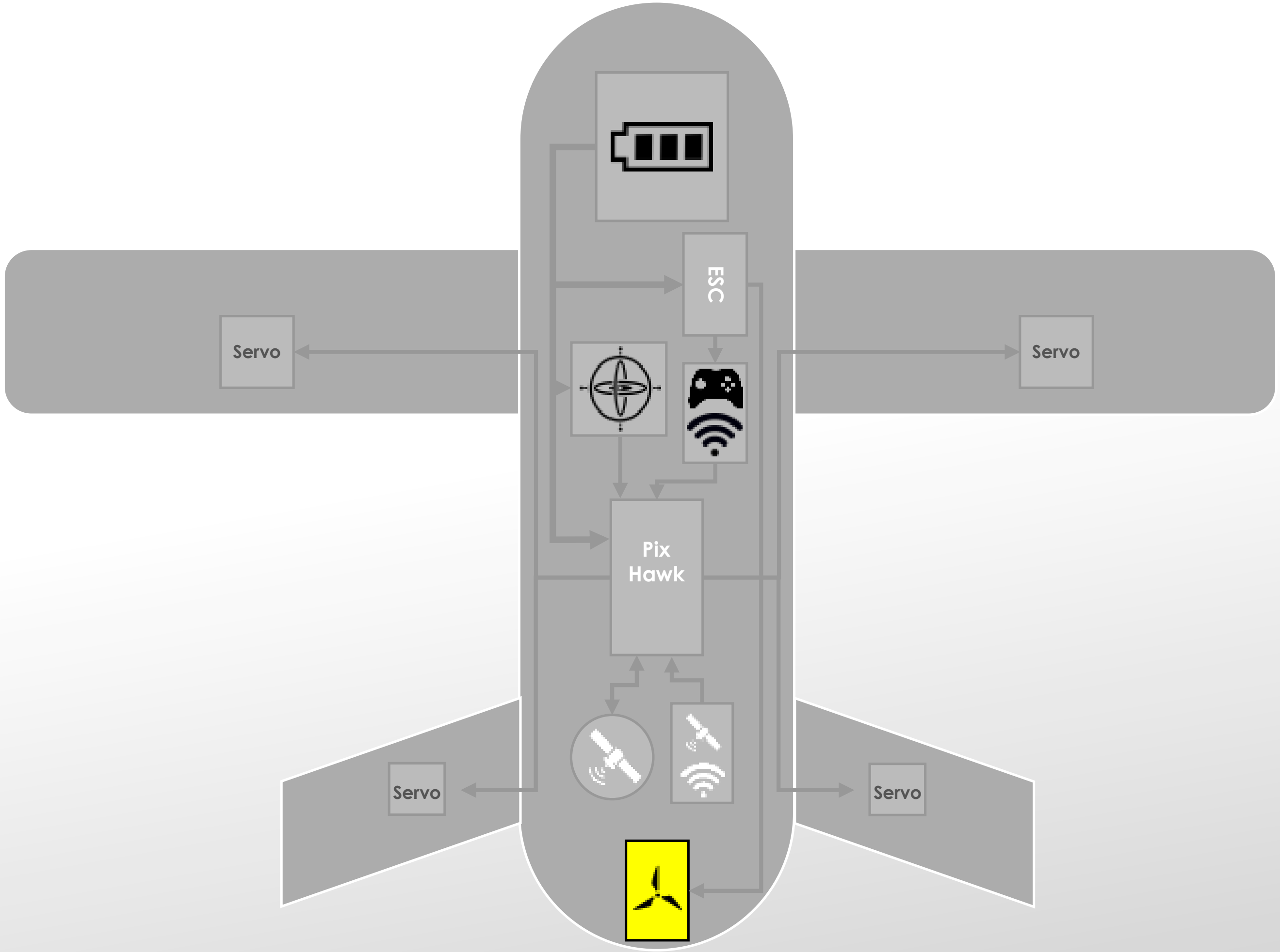


Electronic Speed Control
Name: E-Flite Pro

Rating: 60-Amp – 13 AWG
Input: EC3/EC5
Output: 3.5mm Bullet

Mass: 75g
Dimensions: 73 x 33 x 15.5 mm

UAS PLATFORM SOLUTION

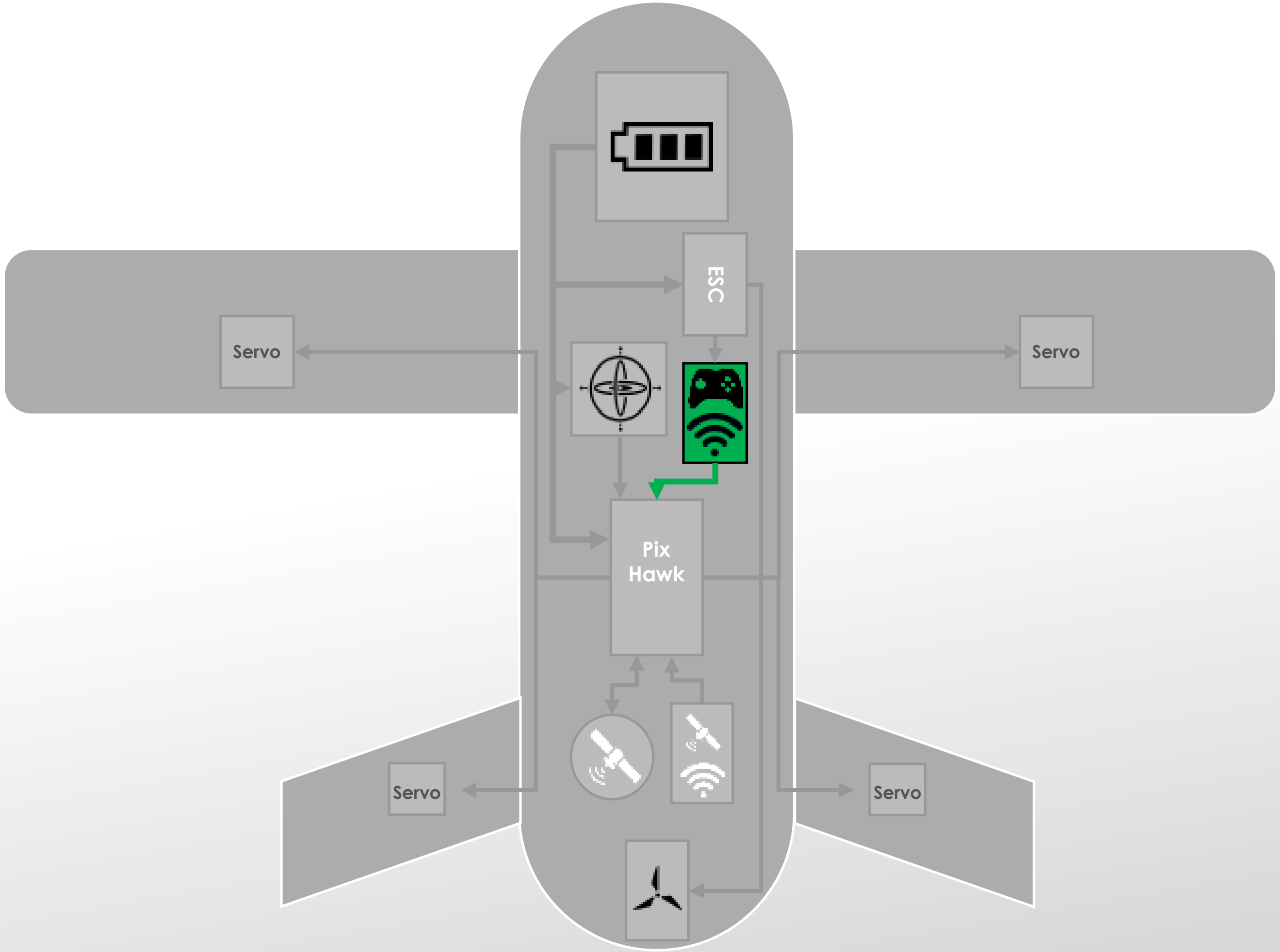


Motor
Name: E-Flite Power 25 BL

Rating: 1250 Kv, 14AWG
Input: 3.5mm Bullet

Mass: 221
Dimensions: 5 x 14 x 5 mm

UAS PLATFORM SOLUTION



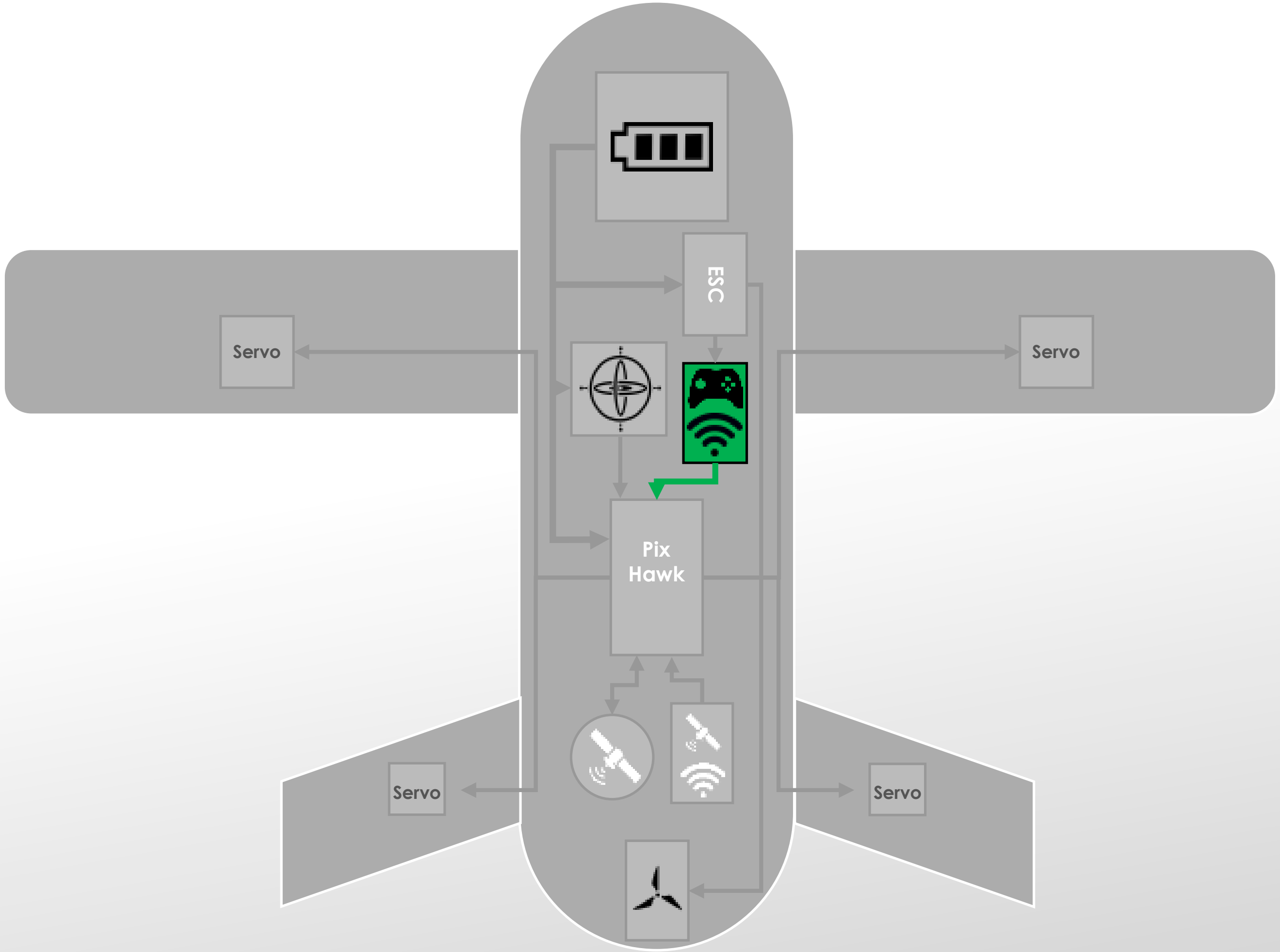
Transmitter

Name: Spektrum DX6i

Range: 3 km

Channel: 6

UAS PLATFORM SOLUTION



Receiver

Name: Spektrum AR7700

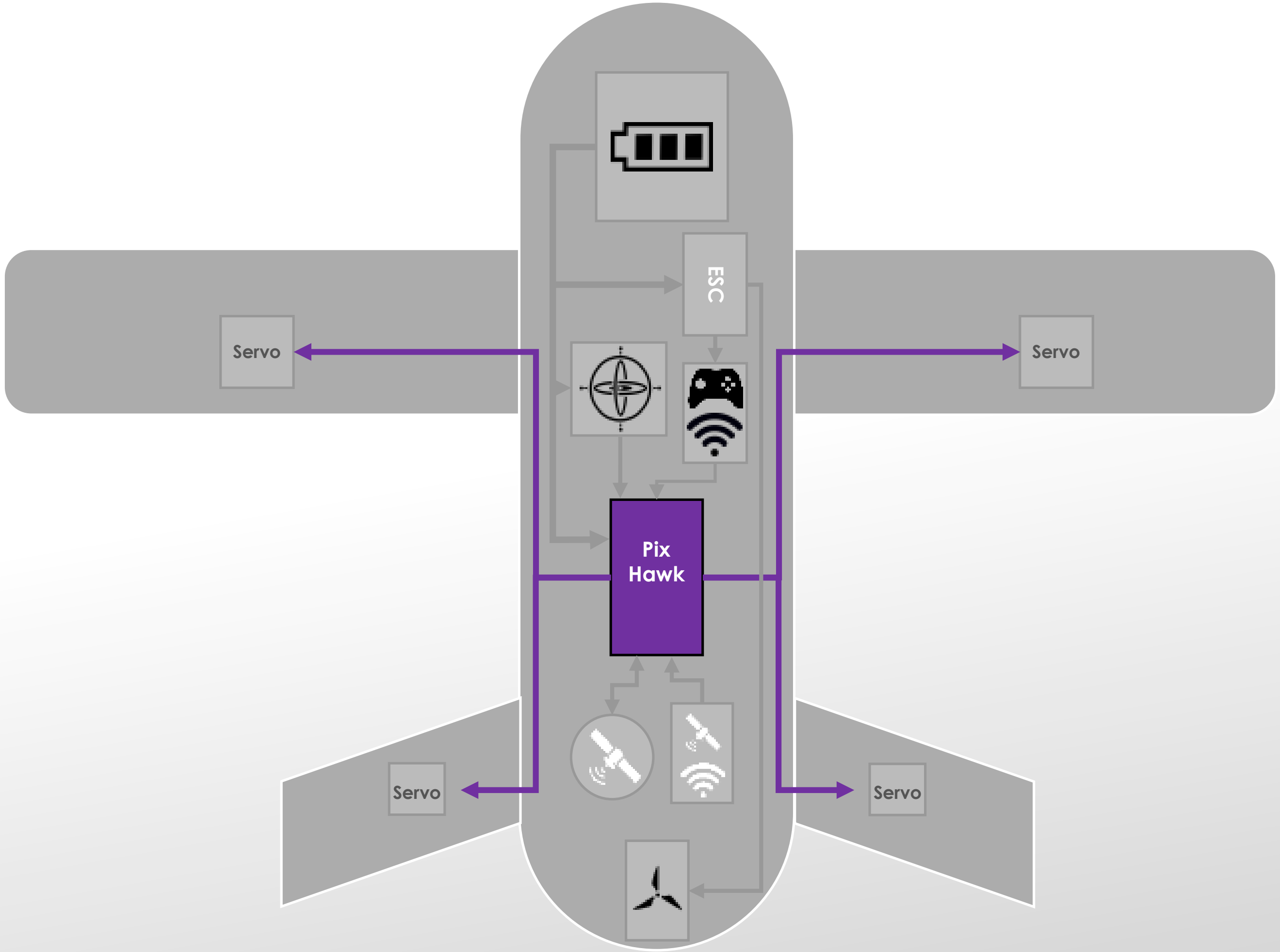
Type: Serial Output (PixHawk)

Channel: 7

Mass: 8.9g

Dimensions: 29.2 x 34.3 x 11.4 mm

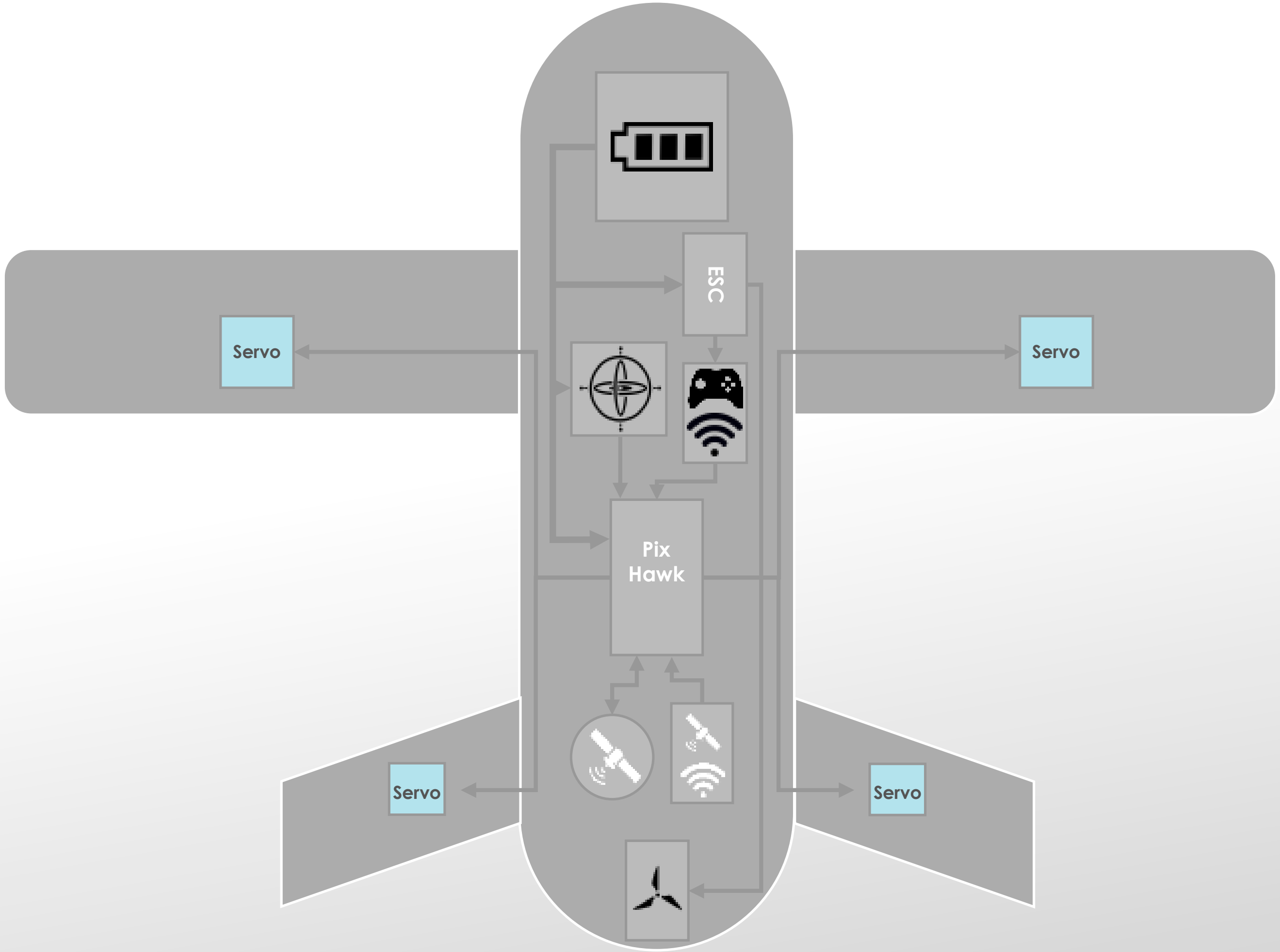
UAS PLATFORM SOLUTION



Auto-Pilot
Name: PixHawk

Mass: 39 g
Dimensions: 95 x 45 x 21 mm

UAS PLATFORM SOLUTION

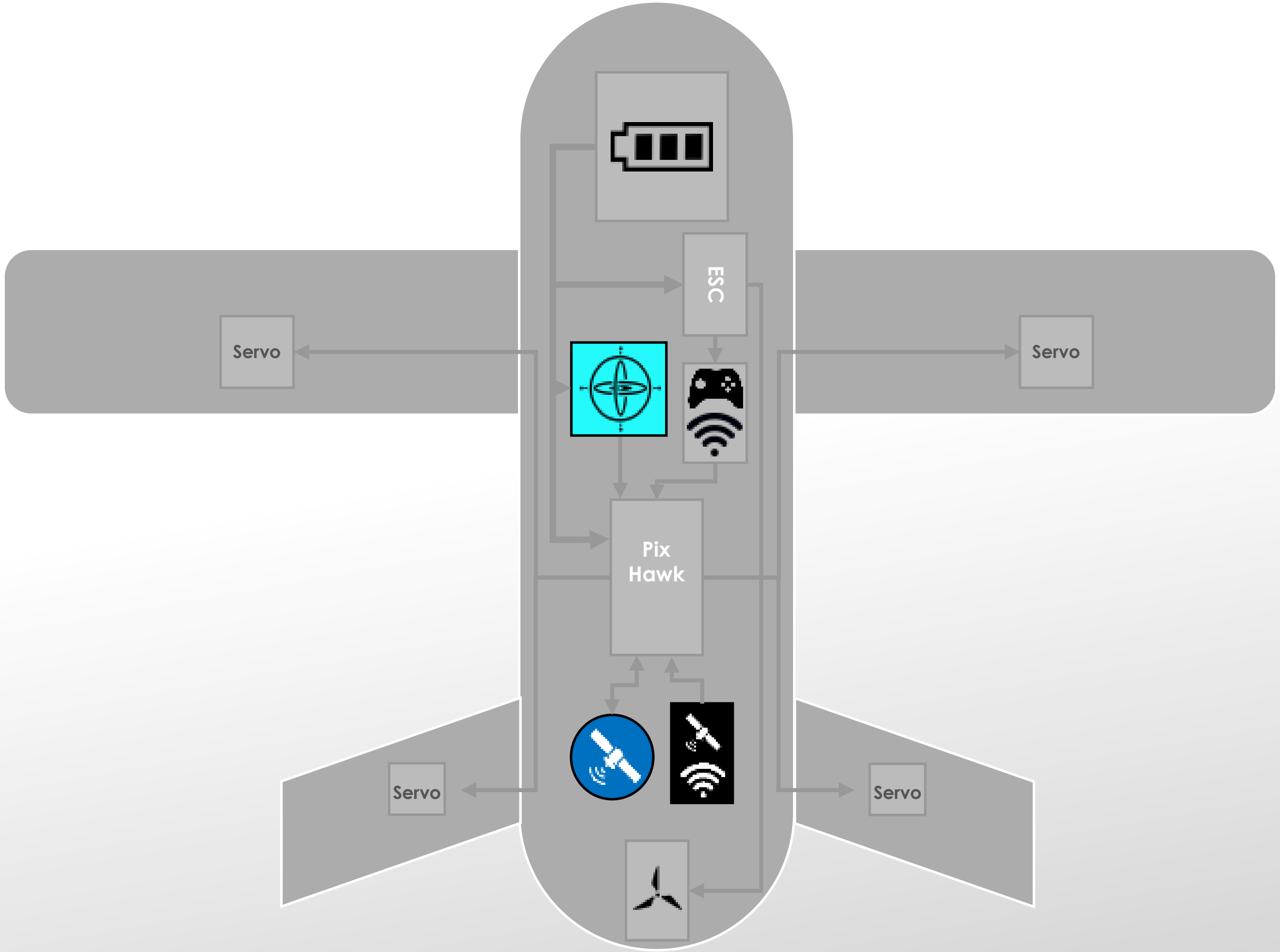


Servos

<u>Main</u>
Name: HS-5065MG
Mass: 11.9g
Dimensions: 23.6 x 11.6 x 24 mm

<u>Tail</u>
Name: HS-5055MG
Mass: 9.5g
Dimensions: 22.8 x 11.6 x 24 mm

UAS PLATFORM SOLUTION



Other Systems:

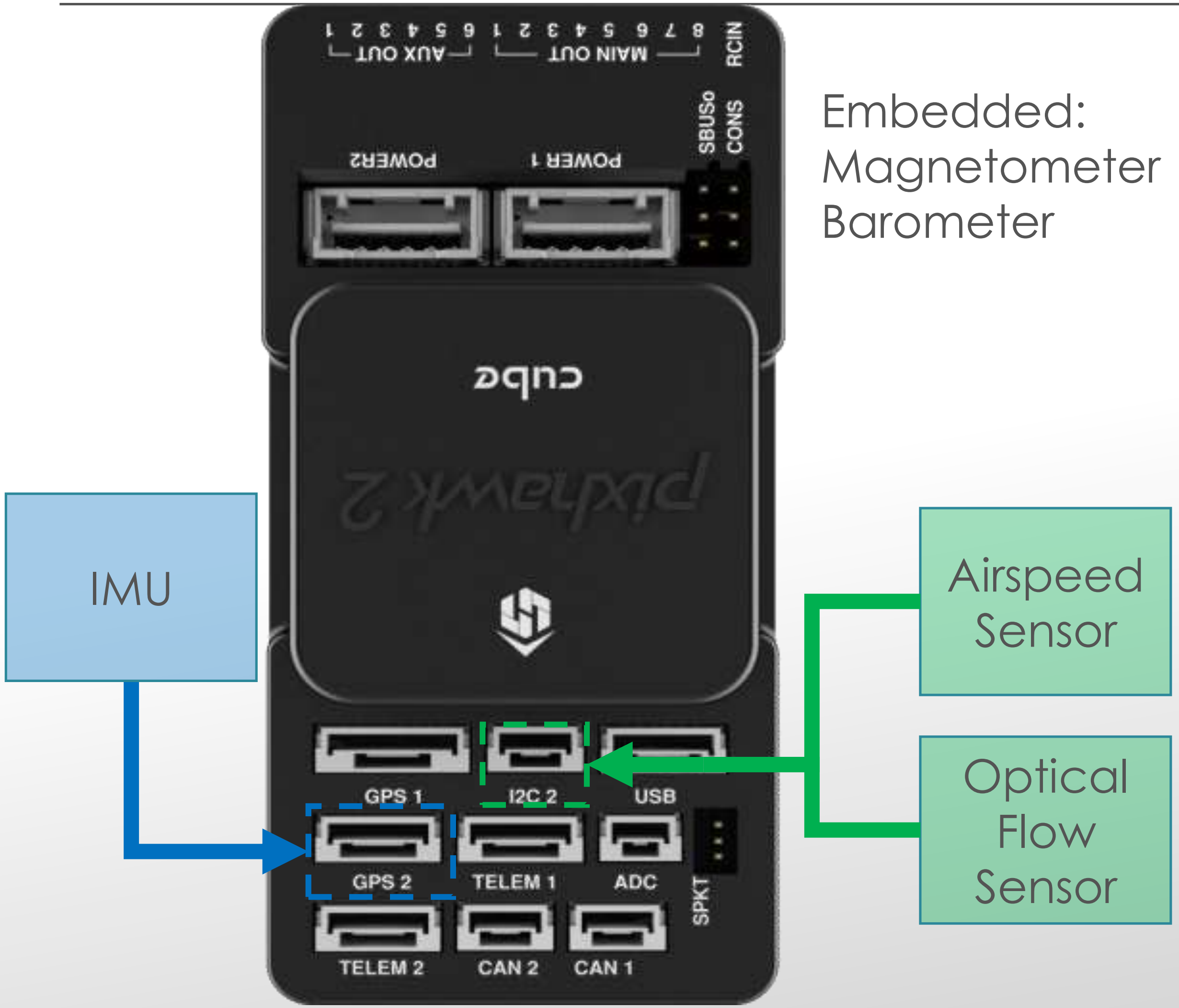
IMU
Silicon Sensing DMU 11

LIDAR
Garmin LiDAR Lite

GPS Module
"Here" GPS Module

Operational Payload
Designed by RAMROD

INERTIAL NAVIGATION SYSTEM



Embedded:
Magnetometer
Barometer

Component	Contribution to EKF
IMU	Angular rate: 3 axes Acceleration: 3 axes
Optical Flow	Relative motion of UAS
Airspeed sensor	True airspeed
Magnetometer	Magnetic heading
Barometer	Altitude

Component outputs are fused and integrated with the onboard EKF

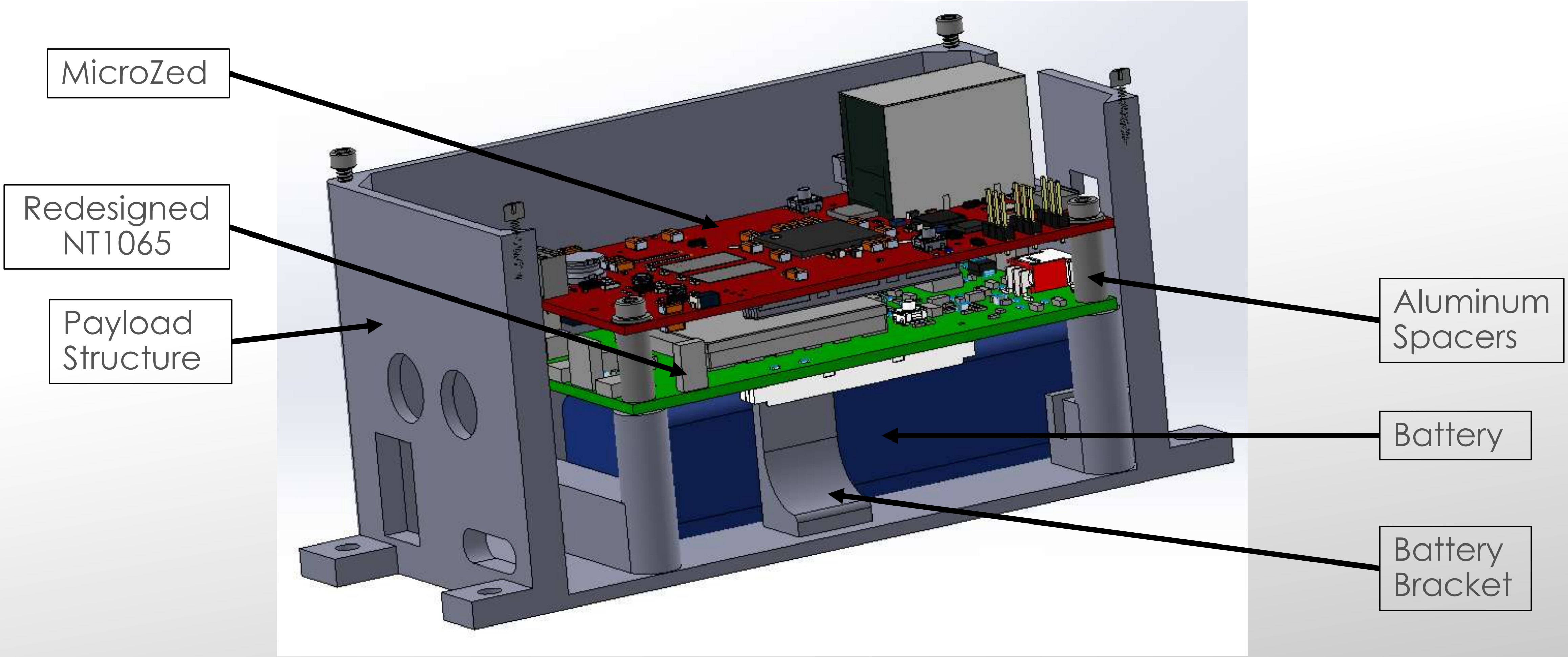
IMU HARDWARE

DMU11 From Silicon Sensing

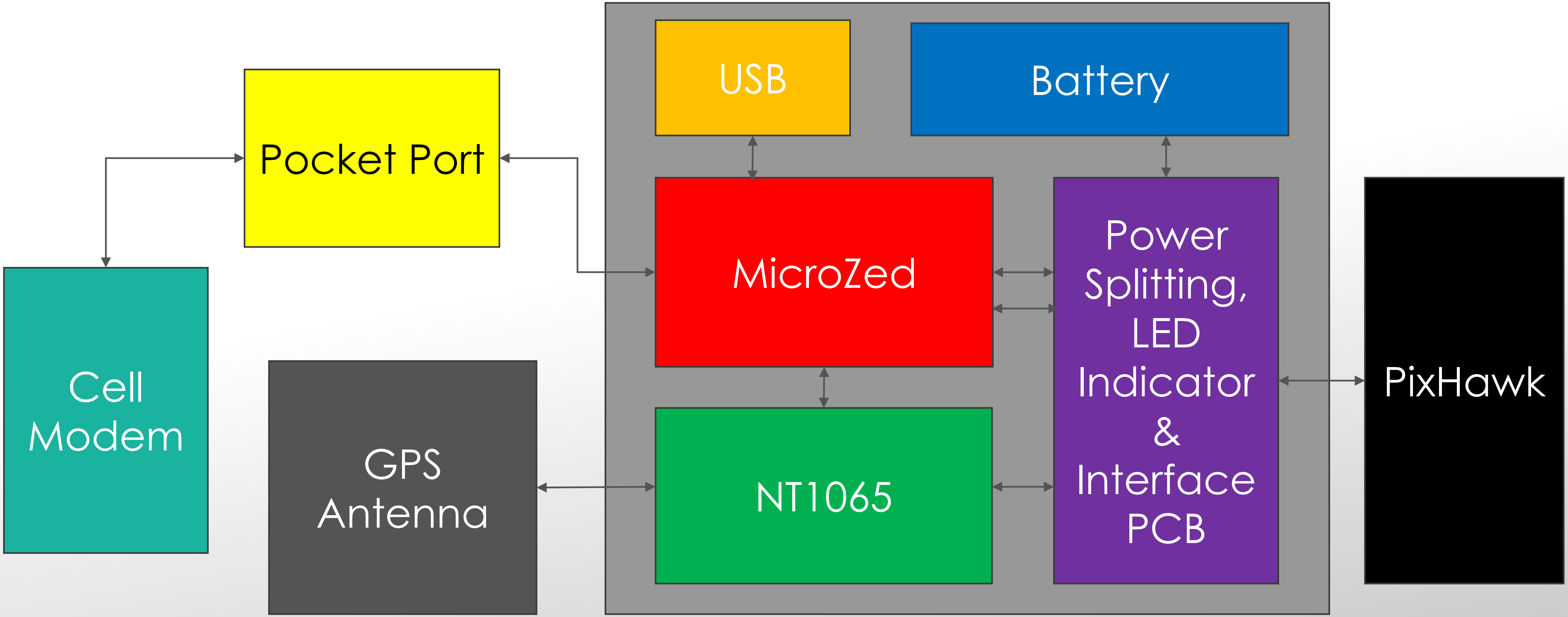
Features:

- Low cost
- High precision
- Low noise
- Internal temperature compensation
- 1000Hz sensor sample rate
- 200Hz data output
- Supporting evaluation kit and test software

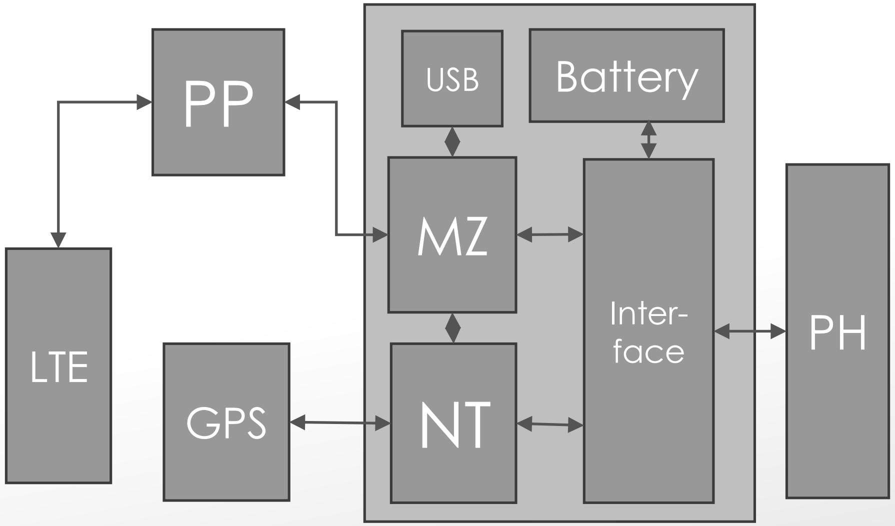
PAYLOAD ASSEMBLY



OPERATIONAL PAYLOAD



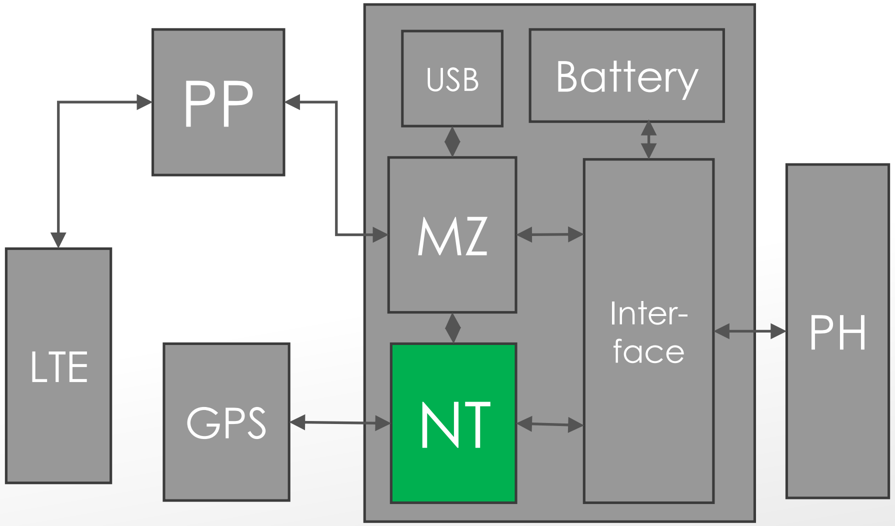
OPERATIONAL PAYLOAD
STRUCTURE



PAYLOAD STRUCTURE

3D printed from Nylon X

OPERATIONAL PAYLOAD
NT1065

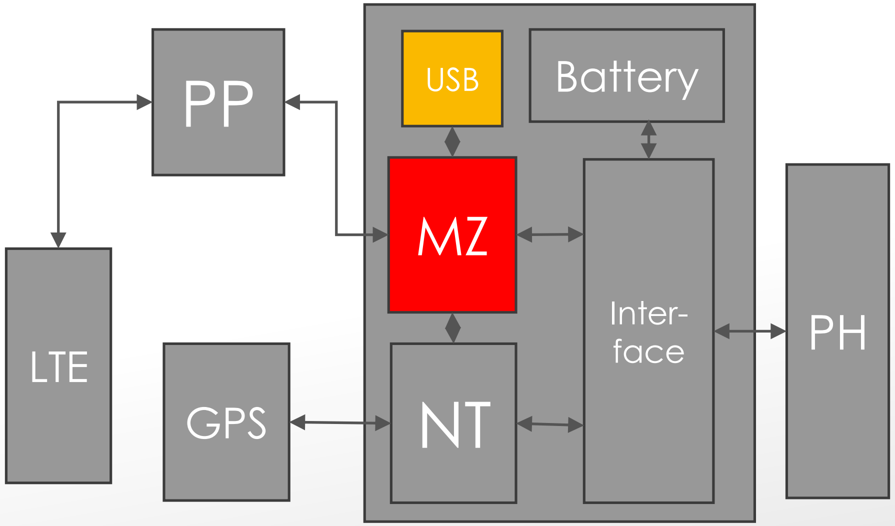


NT1065

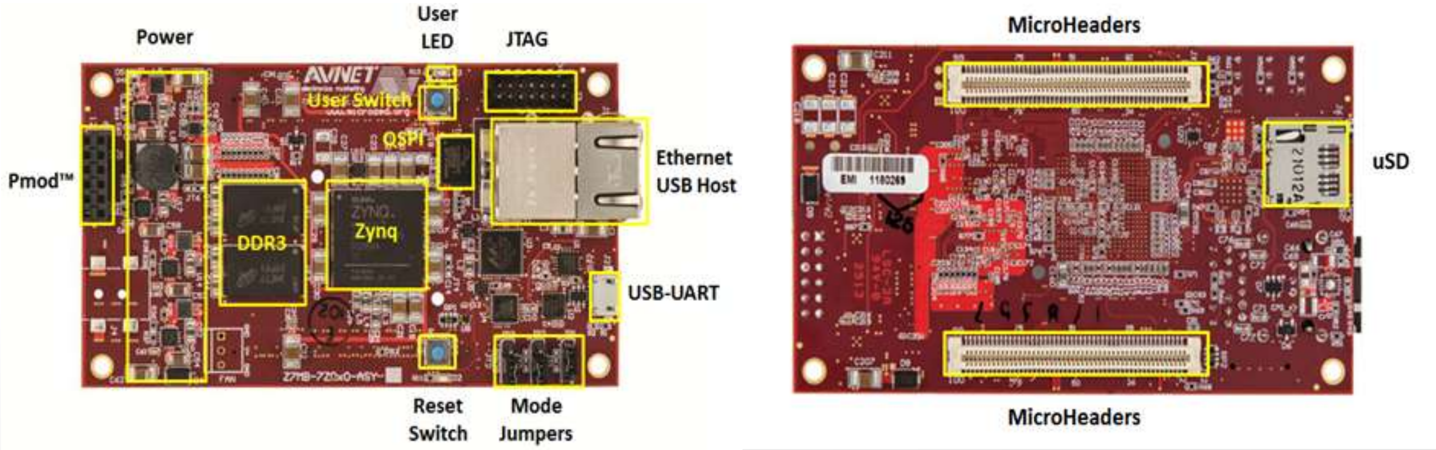
Measures an RFI power source on multiple GPS bands

Board must be redesigned to have internal splitting

OPERATIONAL PAYLOAD
MICROZED



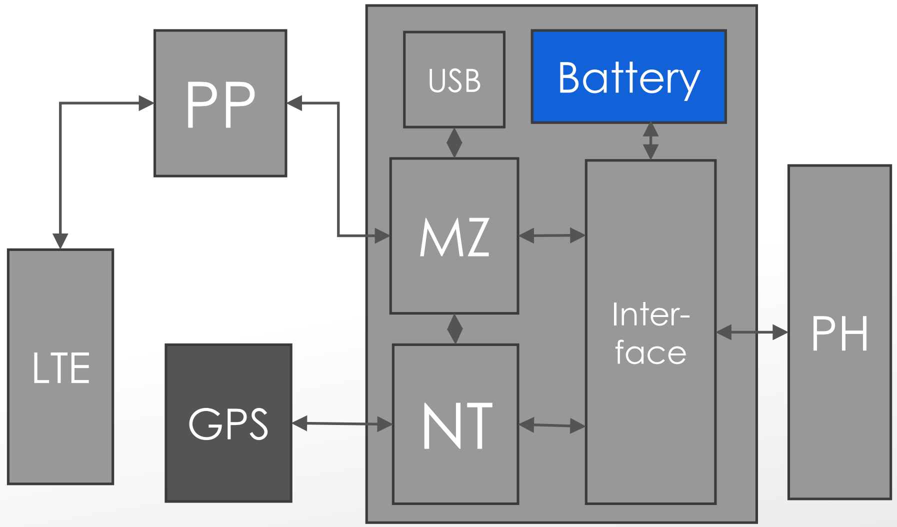
MicroZed



Stores data from NT1065 on USB drive

Interface with cellular modem, NT board, and PixHawk 2

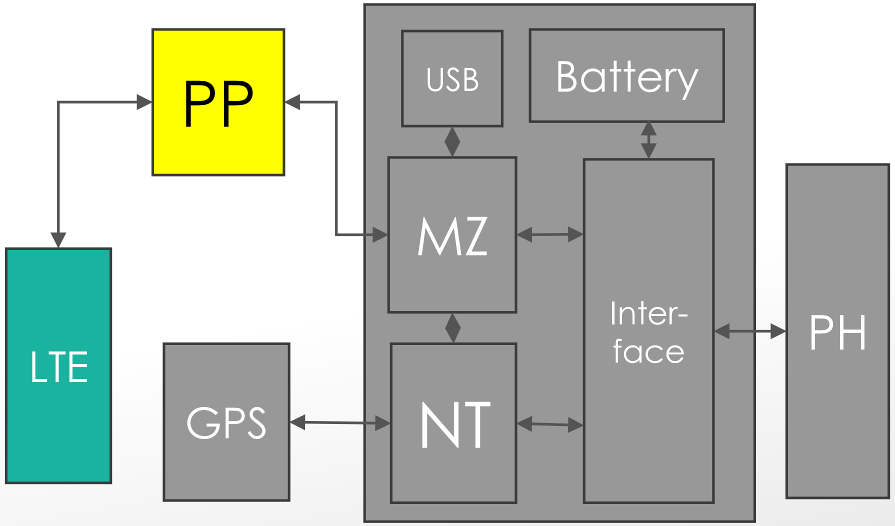
OPERATIONAL PAYLOAD
BATTERY AND GPS ANTENNA



Battery
2200 mAh
5V, 1A, USB3
Lithium Ion Battery

GPS Antenna
Name: TW7872 Magnetic Mount Dual Band GNSS Antenna
Mass: 180 g
Dimensions: 69mm Diameter, 22mm height

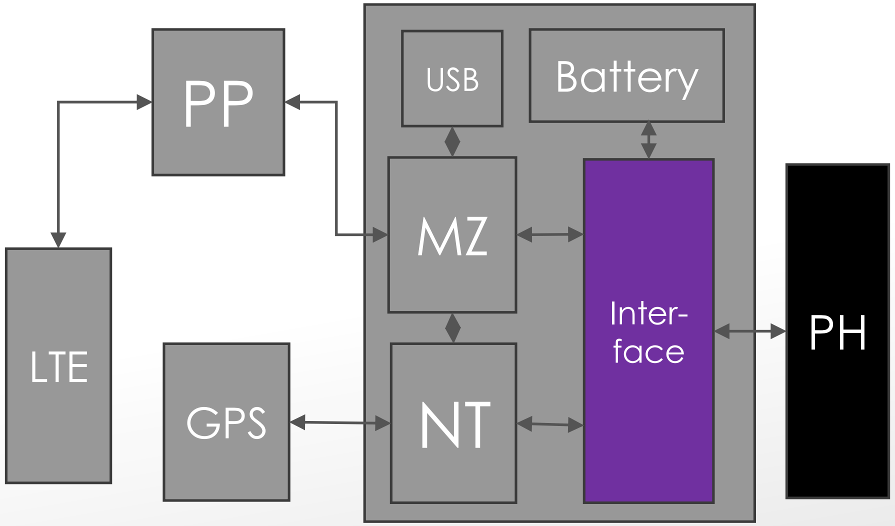
OPERATIONAL PAYLOAD
LTE MODEM



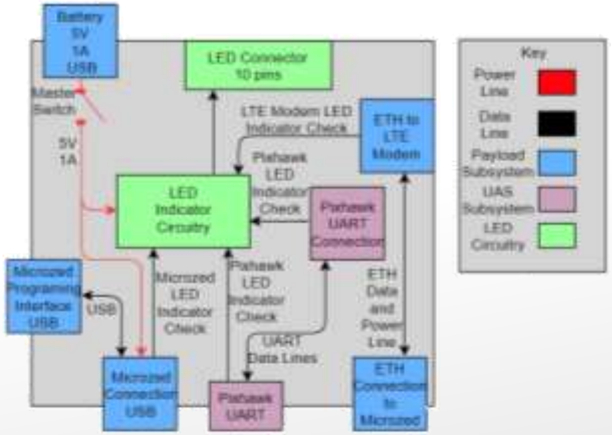
LTE Modem:
Pantech UML290 Global 4G LTE Modem
Network: Verizon Wireless

Cellular Modem Bridge:
Proxicast PocketPORT2 Ethernet to USB converter

OPERATIONAL PAYLOAD
INTERFACE BOARD



Interface Board – PCB Design

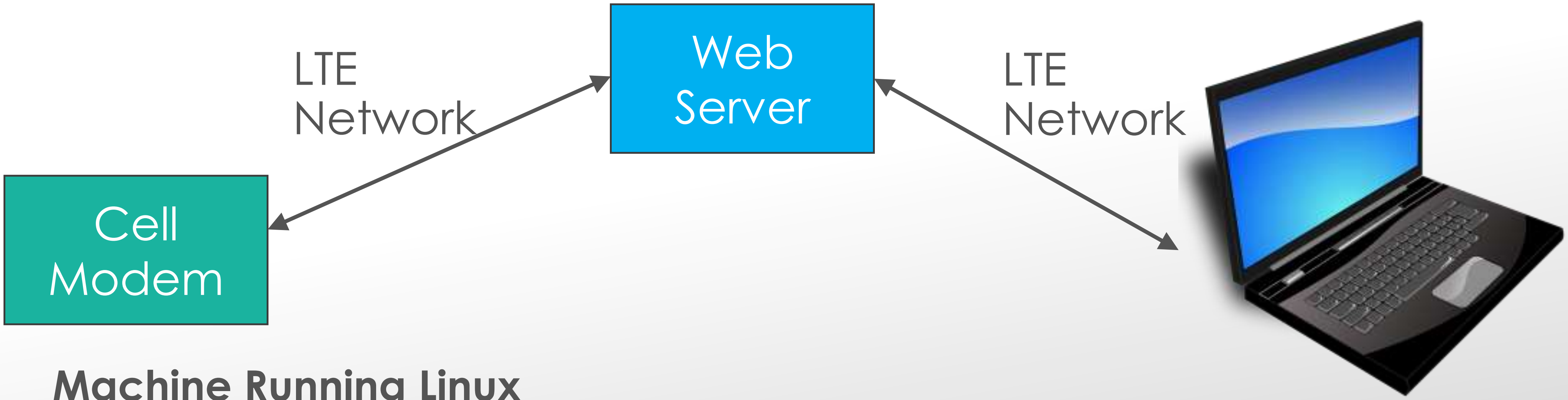


Splits power between different components in payload

Connection between MicroZed and PixHawk

Indicators to show what's connected

GROUND STATION



Machine Running Linux

- 2 GB RAM and 50 GB Storage
- Capable of running MATLAB
- Connected through a publicly accessible IP address
- Listening on an open port above 1024

CRITICAL PROJECT ELEMENTS

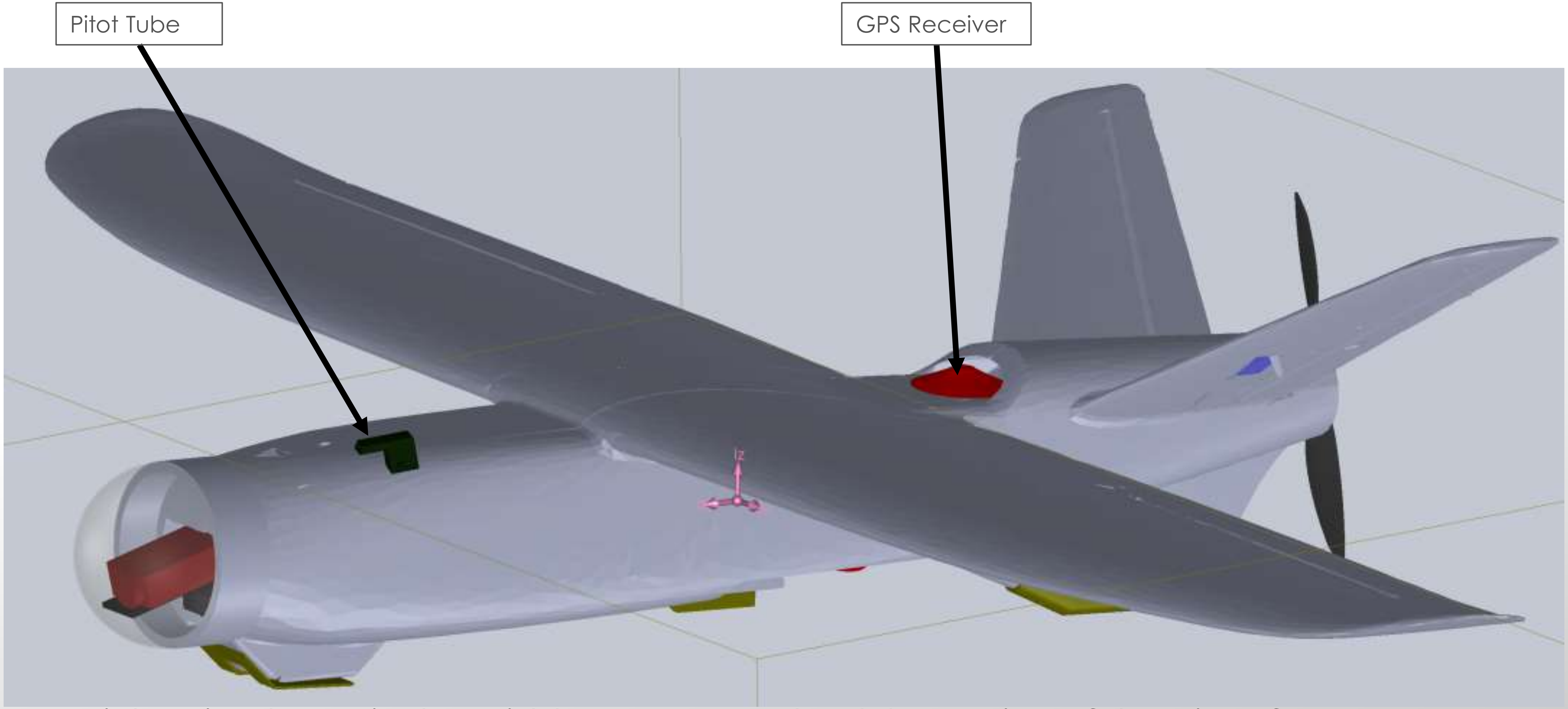
CPE	Description	Reason
Payload	Self-powered **sensor payload** that can monitor, store and **transmit RFI signal data** while interfaced with the UAS platform	A self-contained payload is necessary to measure necessary data and feed into the autopilot, as well as downlink the data to a ground station.
UAS	Develop a **UAS platform** capable of maintaining flight in a **GPS denied environment** while supporting all RFI measuring equipment	Measuring the RF profile over a large area will require an efficient means of surveying the area. A UAS capable of supporting the necessary sensors is the best means of covering this area.
Algorithm	Maintain **autonomous flight** while in a simulated **GPS denied environment** for an extended period of time	A PPD or ET will cause GPS data to be inaccurate. Flying through the affected area will require an autonomous flight mode that is **not reliant on GPS**

DESIGN REQUIREMENTS AND THEIR SATISFACTION

FUNCTIONAL REQUIREMENTS

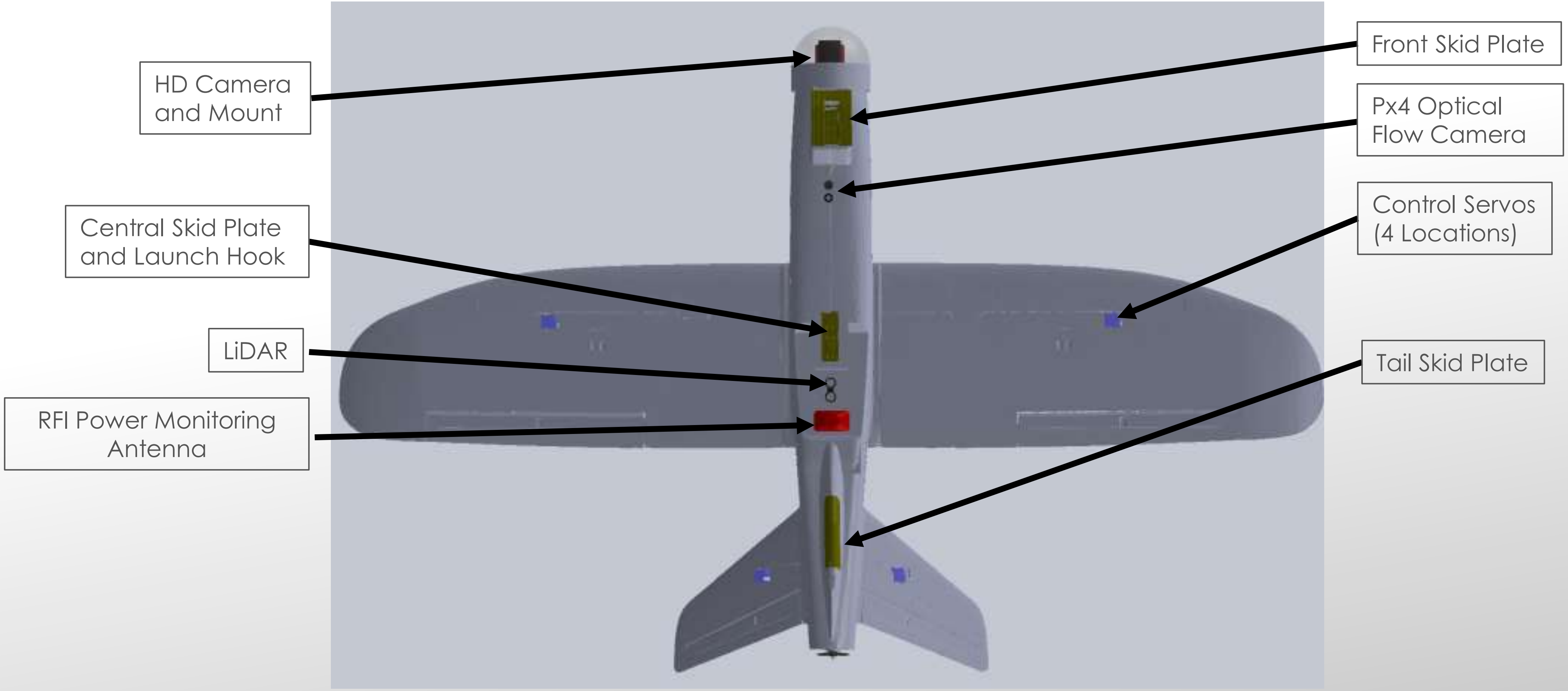
FR	
FR1	The UAS shall have a flight time of 60 minutes.
FR2	The UAS shall fly in maximum winds of 30 km/hr.
FR3	The UAS shall fly in GPS denied environment for a linear distance of up to 2 km and a time of 200 seconds.
FR4	The UAS shall support all flight hardware and instrumentation.
FR5	The UAS and its testing shall adhere to FAA and CU Boulder regulations.
FR6	The UAS shall be capable of flying the operational payload.
FR7	The system shall fly autonomously given a pre-programmed flight plan.
FR8	The system shall have the ability to seamlessly switch between GPS and GPS-denied flight.
FR9	The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.
FR10	The system shall create a profile of RF signal power.
FR11	The payload components shall be fully functional in a self-contained structure.
FR12	The payload shall have the ability to measure and localize an RFI source in GPS-denied environments.

UAS ASSEMBLY

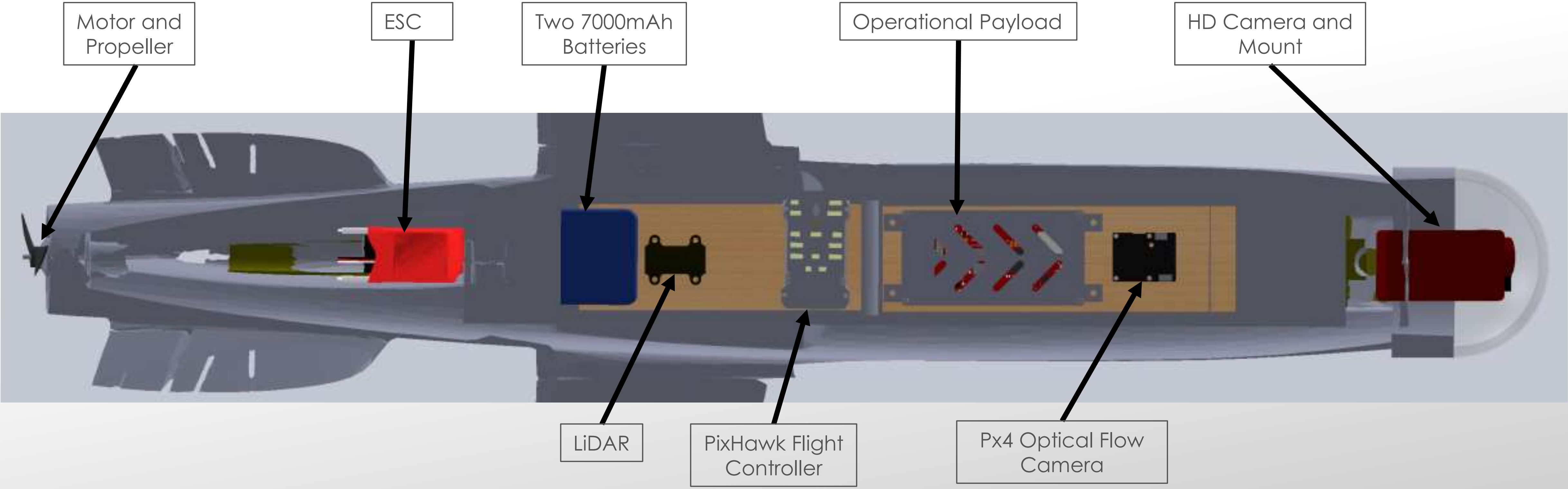


Note: Pink point shown in the middle represents the CG location of the aircraft

UAS ASSEMBLY

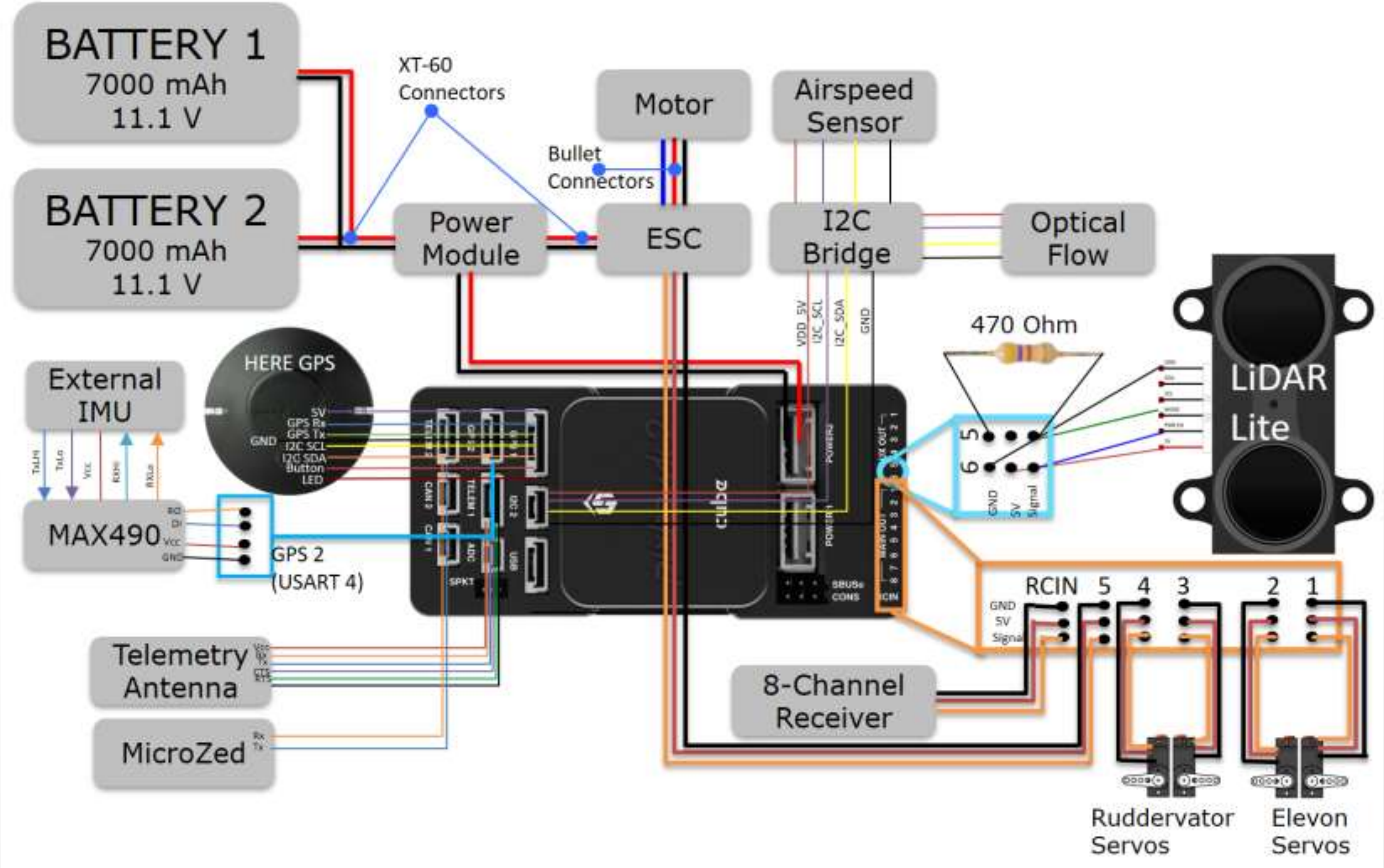


UAS ASSEMBLY



Note: Only large and critical components were modelled and shown; however, all components were considered for the CG calculation. The non-modelled components were assumed to be evenly distributed throughout the payload bay and thus their CG was located at the airframe CG

UAS WIRING DIAGRAM



UAS REQUIREMENTS

Requirement	Satisfaction
FR 4: The UAS shall support all flight hardware and instrumentation.	The UAS Payload Bay and inserts can support all hardware and instrumentation as shown in in the CAD model
FR 5: The UAS and its testing shall adhere to FAA and CU Boulder regulations.	The UAS complies with FAA weight and size requirements and testing will also comply with FAA regulations.
FR6: The UAS shall be capable of flying the operational payload.	The operational payload fits within the payload bay and is under the total weight requirement for the UAS

FUNCTIONAL REQUIREMENTS

FR	
FR1	The UAS shall have a flight time of 60 minutes.
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FR5	The UAS and its testing shall adhere to FAA and CU Boulder regulations.
FR6	The UAS shall be capable of flying the operational payload.
FR7	The system shall fly autonomously given a pre-programmed flight plan.
FR8	The system shall have the ability to seamlessly switch between GPS and GPS-denied flight.
FR9	The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.
FR10	The system shall create a profile of RF signal power.
FR11	The payload components shall be fully functional in a self-contained structure.
FR12	The payload shall have the ability to measure and localize an RFI source in GPS-denied environments.

UAS WEIGHT BREAKDOWN

System	Weight [g]
Flight System (FS)	2398
Autopilot (AP)	242
Operational Payload (OP)	536
Miscellaneous (MS)	140
Structural Components (SC)	155
TOTAL	**3471**

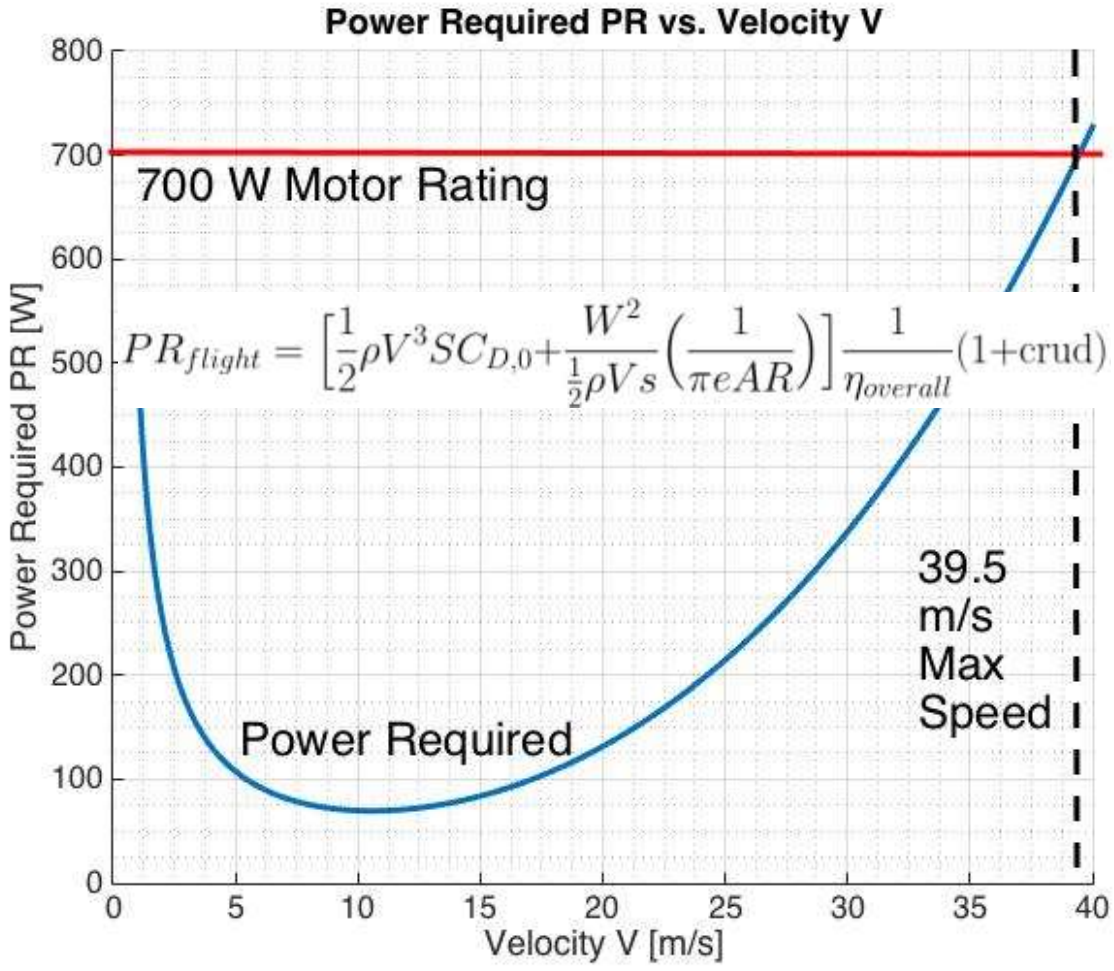
Requirement	Satisfaction
DR 5.1: The UAS shall weigh less than 25 kg	The UAS weighs 3.471 kg
DR 6.2: The operational payload shall weigh less than 1kg	The payload and additional connected antenna only weight 536 g

MAXIMUM SPEED

Motor: E-flite Power 25 BL

Maximum Speed Achieved When Velocity Causes Power Required = 700 W

Requirement	Satisfaction
FR 2: The UAS shall fly in winds of 30 km/h	The UAS has a max speed of 148 km/h
DR 2.1: The UAS shall have a max speed of at least 45 km/h	The UAS has a max speed of 148 km/h



FLIGHT SYSTEM COMPONENT SELECTION

$$PR_{max} = 671\ W$$

↓

Requirement	Satisfaction
DR 1.2: The UAS propulsion System shall be electrically powered	The UAS runs on an electric motor
DR 1.2.1: The electric power source shall be a battery	The UAS power source is a battery

E-flite Power 25 BL 1250 Kv – 700 W (Same as RECUV Talon)

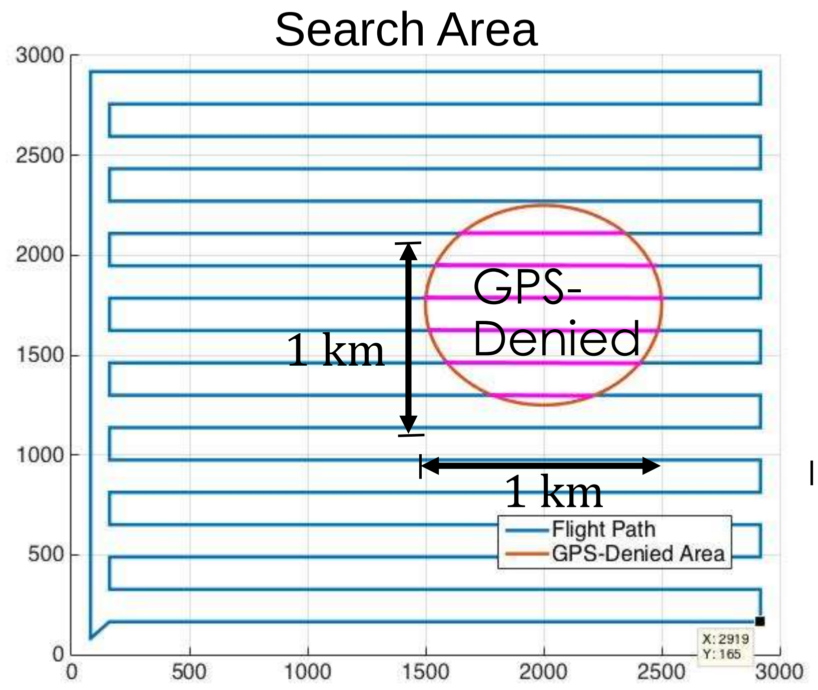
→

E-flite 60-Amp ESC (recommended for motor)

→

2x Thunder Power RC 7000 mAh 3S LiPo batteries (Same as RECUV)

TIME AND DISTANCE COVERED IN GPS-DENIED ENVIRONMENT

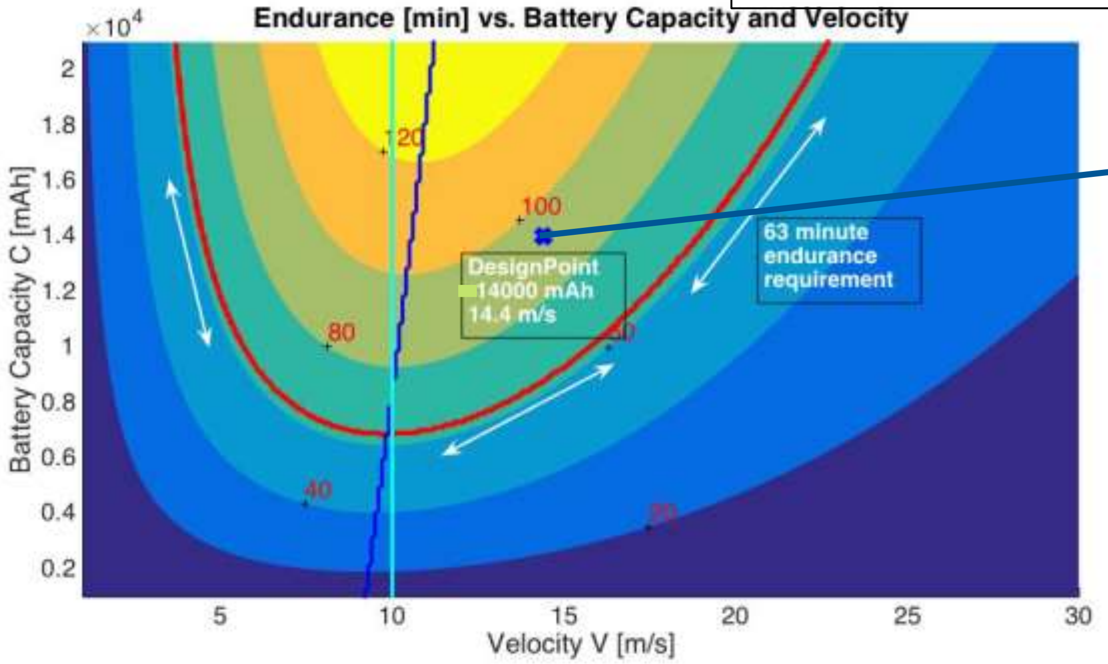


- Distance Covered in GPS-Denied Area = **4.5 km**
- $V_{cruise} = 14.4\ \mathrm{m/s}$
- Time Spent in GPS-Denied Area = **315 s**
- Total Flight Path Length = **57.14 km**
- Flight Time: **66.1 minutes**

Requirement	Satisfaction
FR 1: The UAS shall have a flight time of 60 minutes	The UAS has a flight time of 66.1 minutes
FR 3: The UAS shall fly in a GPS-denied area for at least 2 km and 200 seconds	The UAS will spend 4.5 km and 315 s in GPS-denied area, with max single stretch of 69 s and 1 km

ENDURANCE

With cruise speed = 14.4 m/s, can the UAS fly for at least 66 minutes?



- Predicted Endurance @ 14.4 m/s and 14000 mAh LiPo Battery Capacity: 93 minutes
- Predicted power required during cruise: 78 W

Requirement	Satisfaction
DR 1.2.2: The battery shall power the UAS for 60 minutes	The battery's 14000 mAh capacity provides 93 minutes of flight time

$$E = \frac{3.6 C v_b D_b \eta_{overall}}{\left[\frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)\right](1 + \text{fudge})}$$

FUNCTIONAL REQUIREMENTS

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FR12	The payload shall have the ability to measure and localize an RFI source in GPS-denied environments.

INERTIAL NAVIGATION SYSTEM

DMU11:
Raw angular rate and linear acceleration

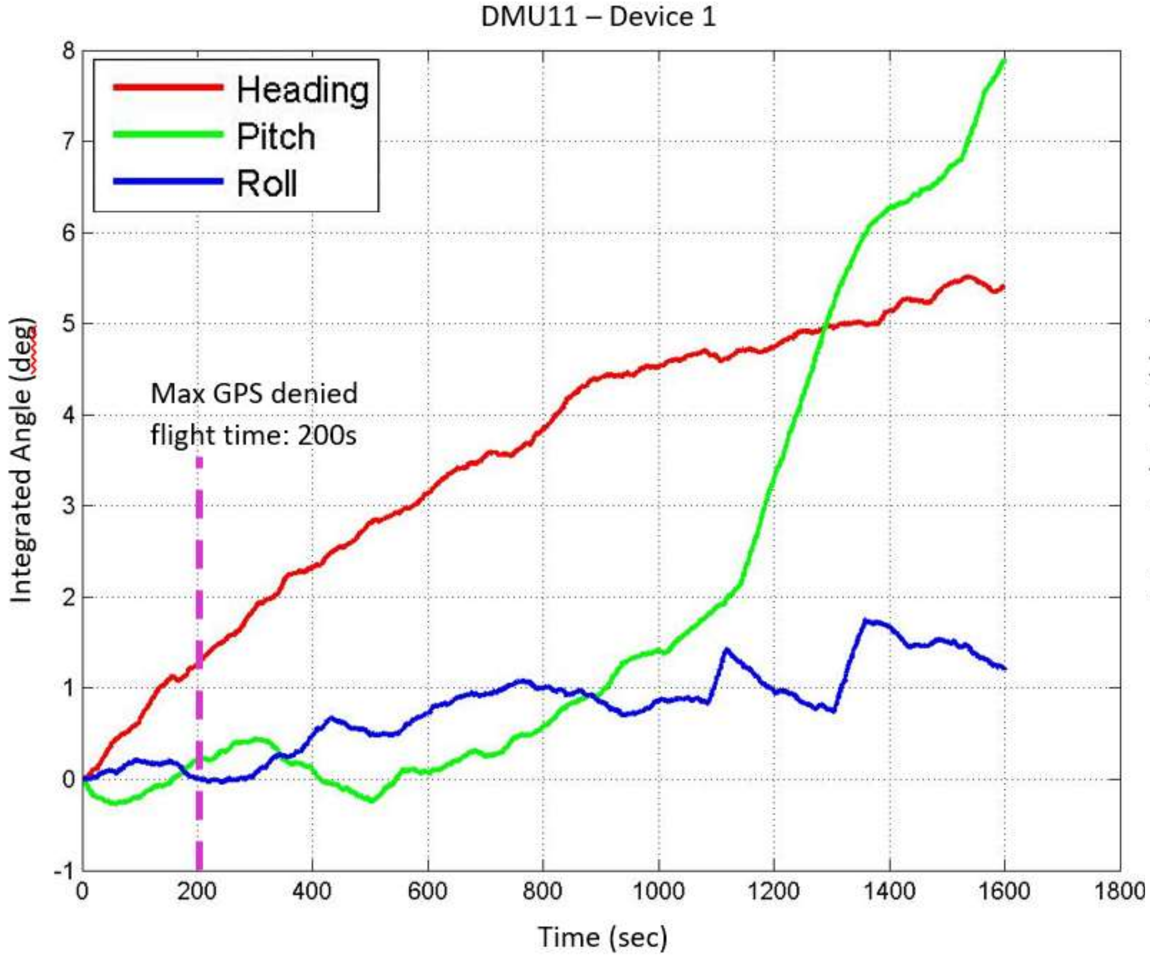
Magnetometer:
Constrains heading
Barometer:
Constrains altitude

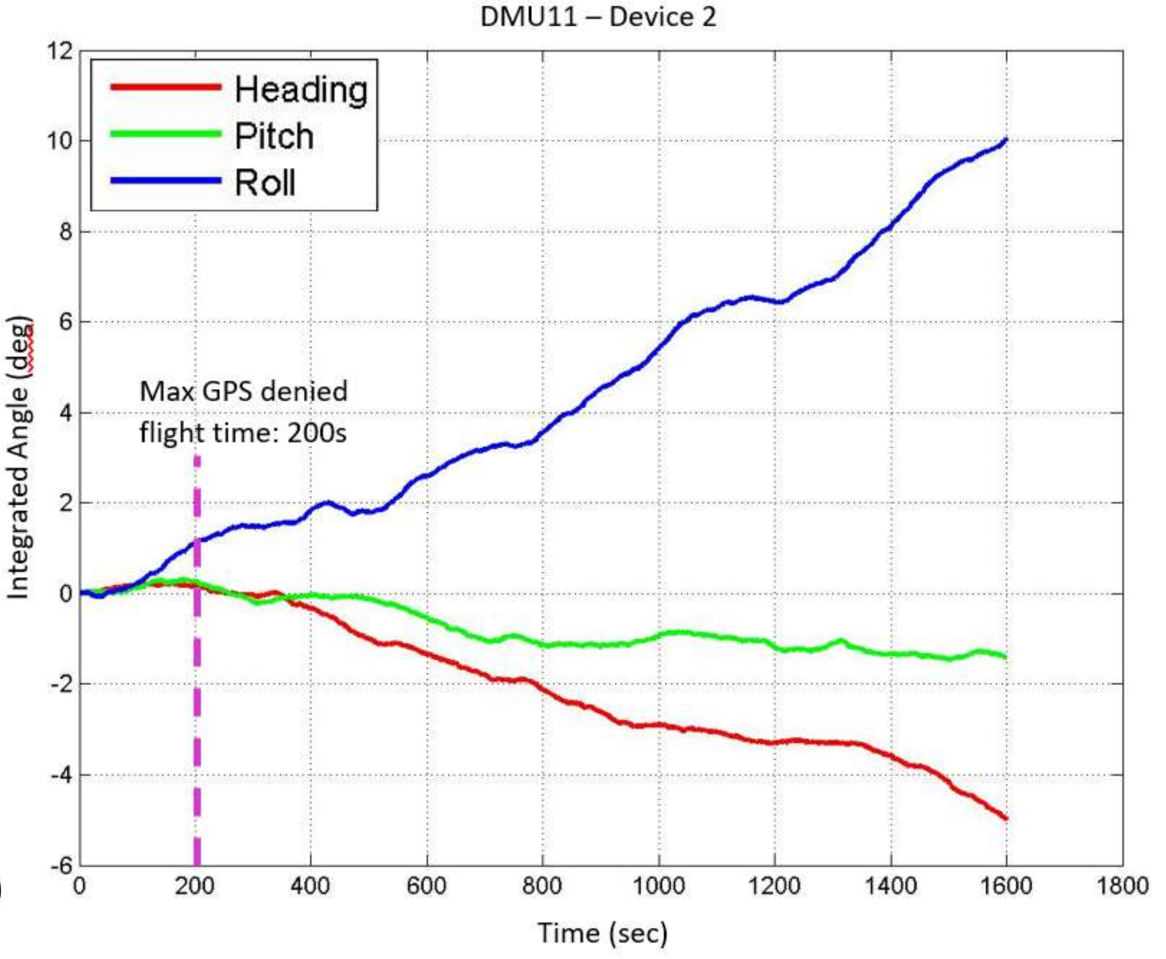
PX4FLOW:
Ground speed

Digital airspeed sensor:
True airspeed

Requirement	Satisfaction
FR 3: The UAS shall fly in a GPS denied environment for a linear distance of up to 2 km and a time of 200 seconds.	The DMU11 accumulates an error of < 2°after 200 seconds of operation, and the additional sensors will enhance operation to allow for accurate flight.
FR 9: The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.	The INS provides inertial data on all six degrees of freedom to be fused and recorded by the PixHawk.

DMU11 PERFORMANCE



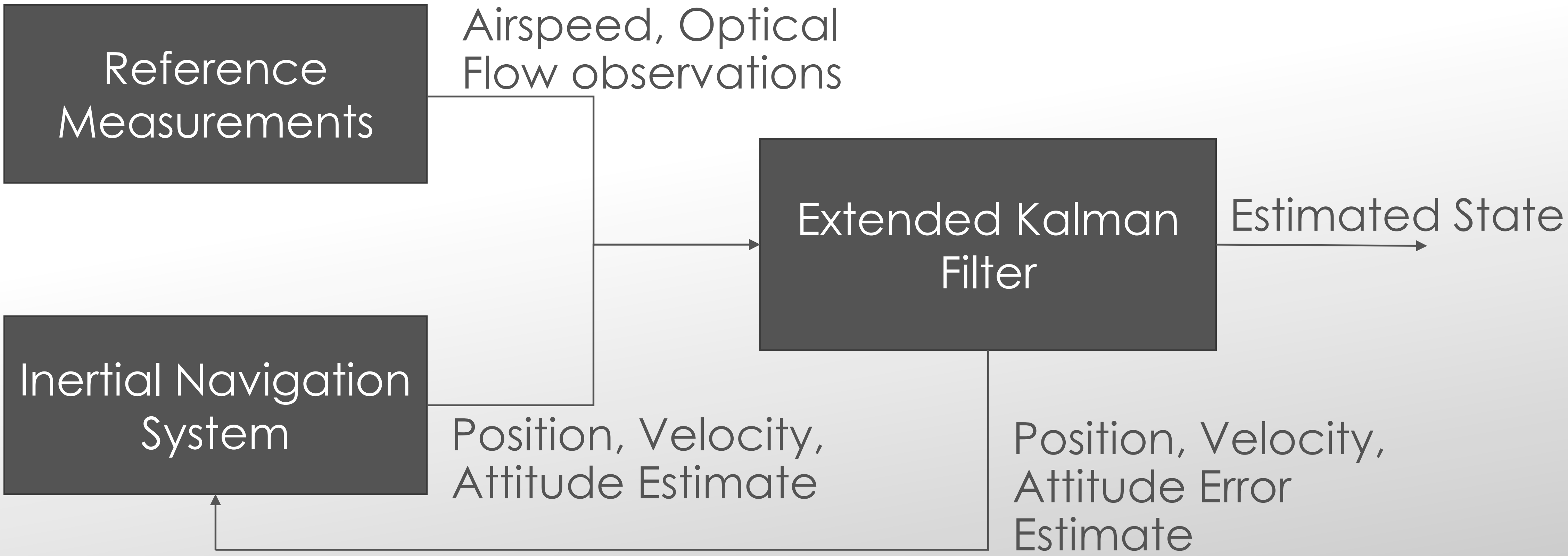


Data courtesy of Stephen Clarke, Silicon Sensing Systems Ltd.

EXTENDED KALMAN FILTER

- A nonlinear state estimation system
- Incorporates noisy and/or slightly inaccurate sensor data with prior knowledge of the dynamics of the system to create an estimate of the system state
- Uses “innovations” for tuning and data rejection
- Innovation variance tests to check filter health

EXTENDED KALMAN FILTER

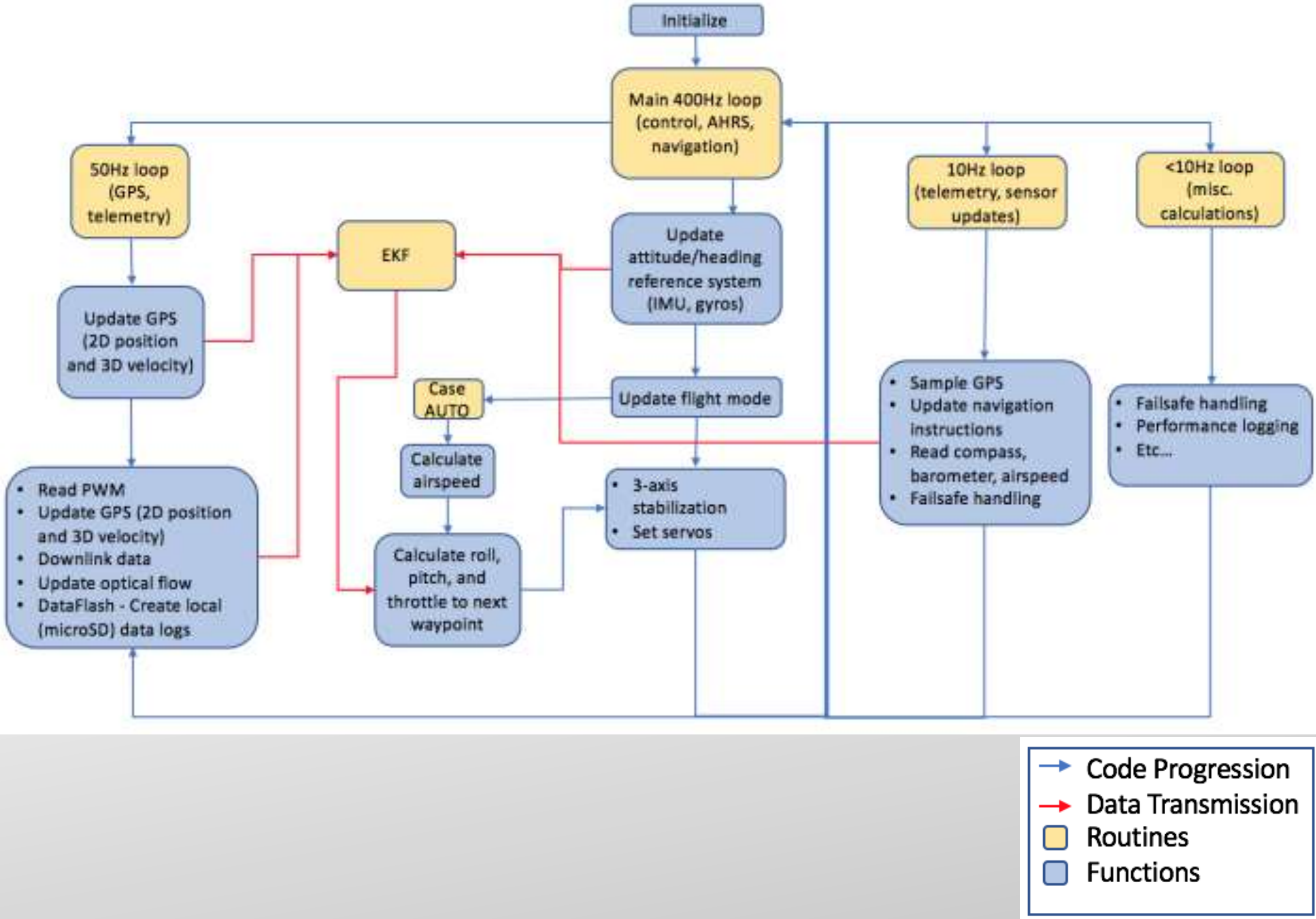


ARDUPILOT ESTIMATOR

- EKF2 Estimation System
- 24 state estimator
- Capable of processing data from multiple IMUs, increased chance of recovery from IMU fault
- Estimates error rotation vector, rather than quaternion orientation directly, resulting in faster and more efficient computations
- EK2_GPS_TYPE = 3

MODIFIED ARDUPILOT
FLYING WITH GPS – BLOCK DIAGRAM

- GPS-enabled flight uses ArduPilot AUTO flight mode
- Take off, fly through each waypoint, land
- GPS 2D position and 3D velocity data used in EKF state estimation

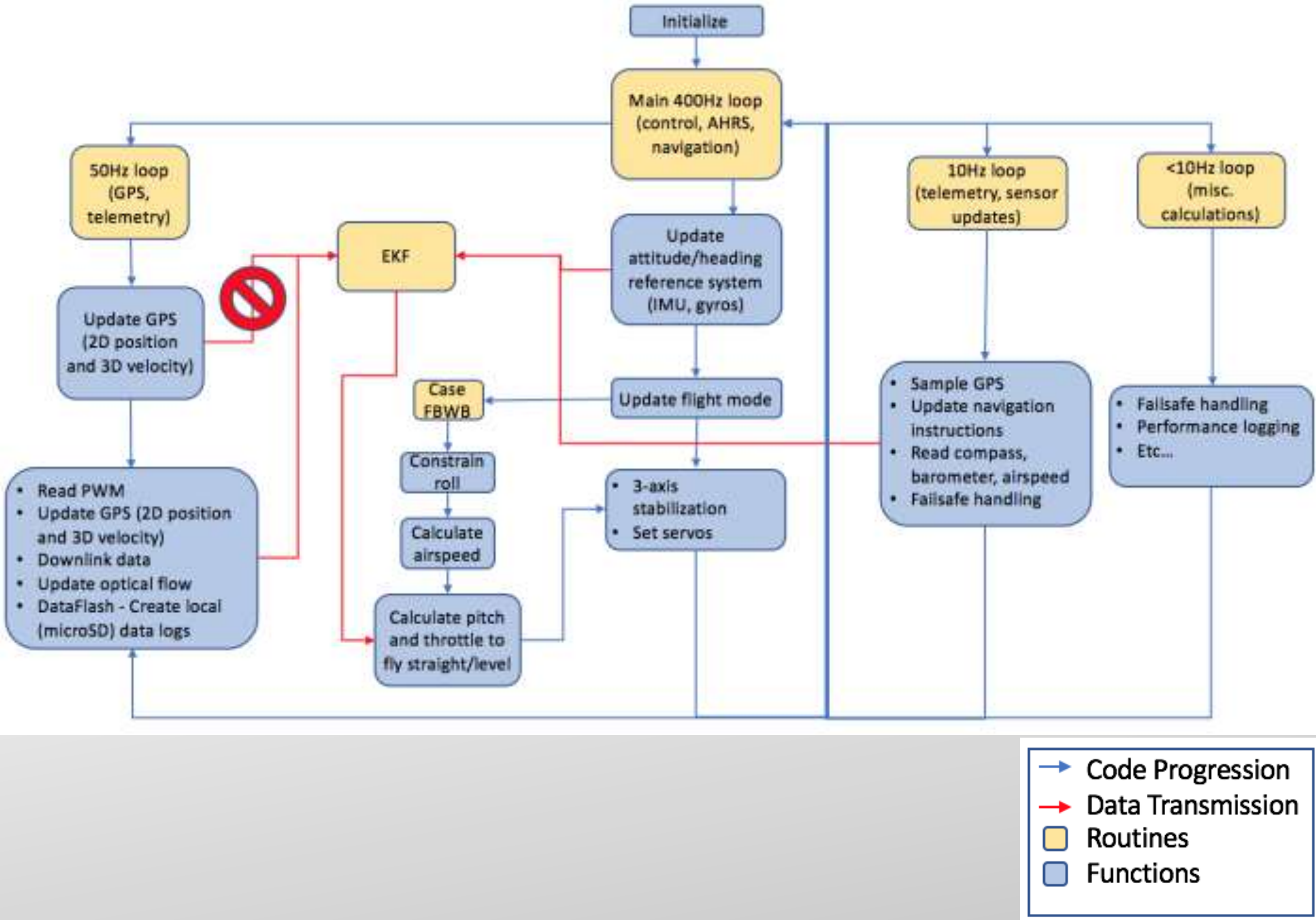


Requirement	Satisfaction
DR 7.1: The UAS system shall be able to fly autonomously with access to GPS data.	The AUTO flight mode flies autonomously using GPS

MODIFIED ARDUPILOT
FLYING WITHOUT GPS – BLOCK DIAGRAM

- GPS-disabled flight will use FLY_BY_WIRE_B flight mode
- Using Extended Kalman Filter state estimation, autopilot will hold altitude, roll, and pitch
- GPS input into EKF disabled, but Optical Flow enabled

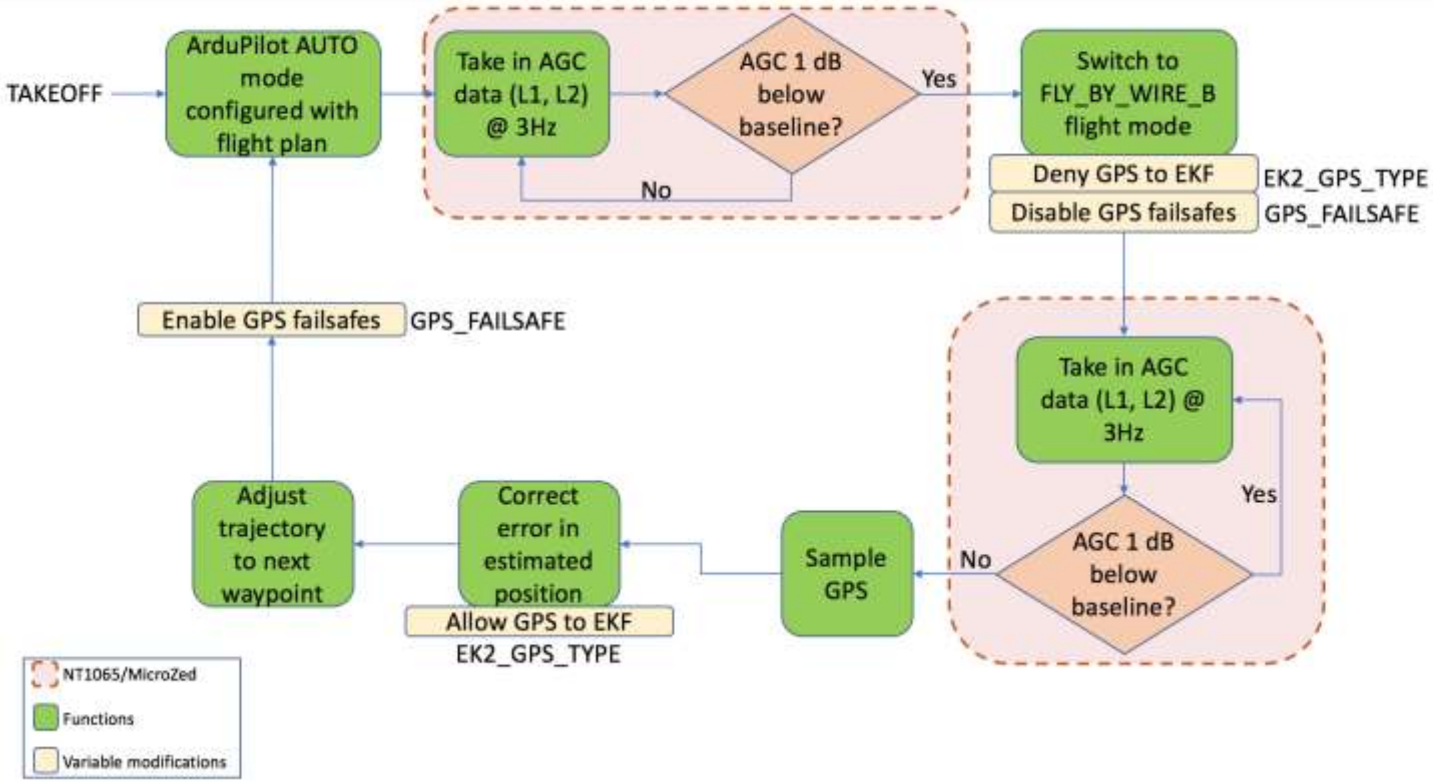
Requirement	Satisfaction
DR 7.2: The UAS flight system shall be able to fly autonomously without access to GPS data.	The modified FBW_B flight mode allows for autonomous flight without GPS



MODIFIED ARDUPILOT

GPS SWITCH – BLOCK DIAGRAM

- Payload sends a binary input to PixHawk @3Hz
  - 0: GPS available
  - 1: No GPS available
- For testing purposes, AGC data replaced with simulated WiFi power data
  - Flight software unchanged
- Flight mode switch will be written in existing function events.cpp (10Hz)



Requirement	Satisfaction
DR 8.1: The UAS flight system shall integrate with RF sensors in order to monitor RF power levels in real time.	The NT1065/MicroZed sample AGC in real time, transmitting to the PixHawk
DR 8.2: The UAS flight system shall utilize an RF signal power threshold to trigger a switch in flight modes.	The modified autopilot switches between flight modes based on AGC power data

SWITCH TIME

MicroZed/ NT1065

PixHawk

Sample GPS AGC at 3Hz

Serial Connection

Payload to PixHawk

Sample Payload Input at 10Hz

Switch Flight Modes at 10Hz

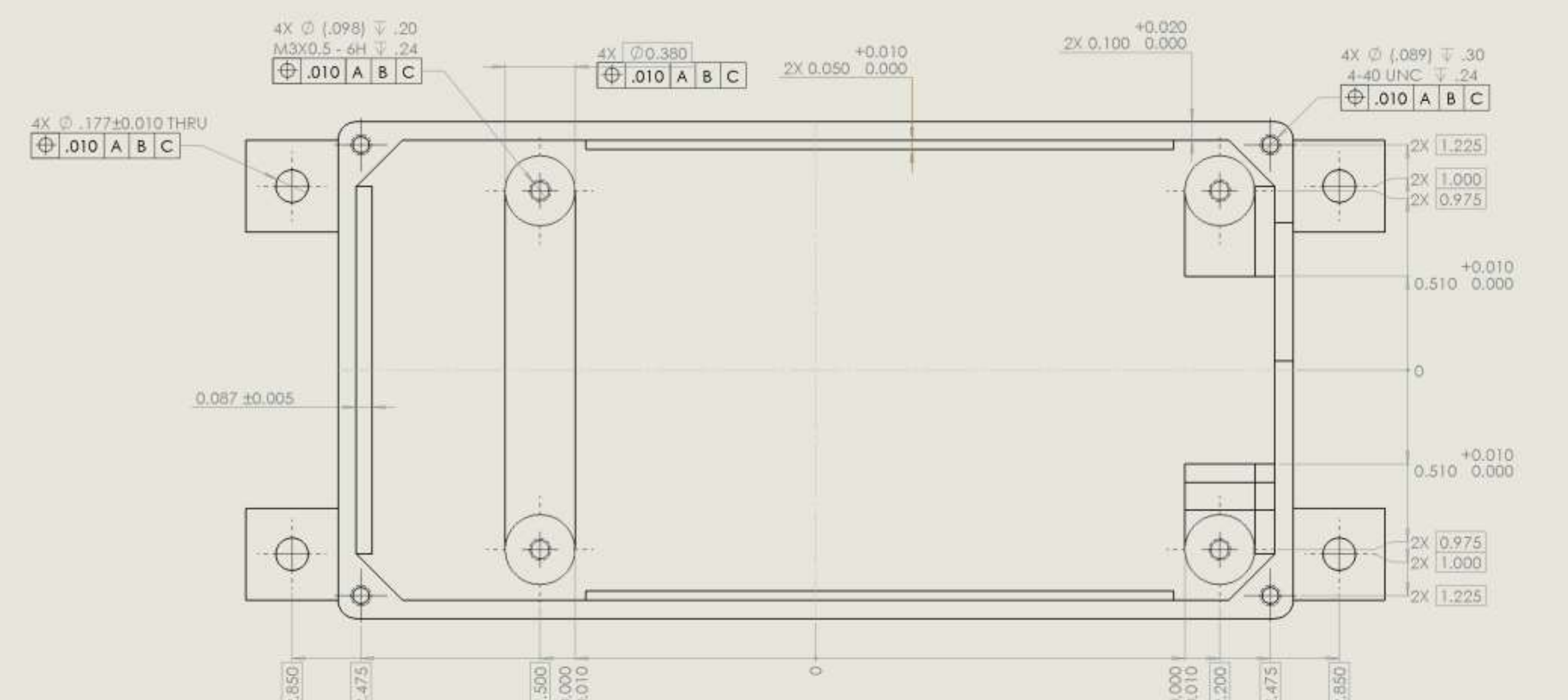
Max time: 0.33s + Max time: Negligible + Max time: 0.2s + Max time: 0.2s = Max total time: 0.73s

Requirement	Satisfaction
FR 8.0: The system shall have the ability to switch between the GPS and GPS-denied flight modes within 1 second of RFI detection	The switch will happen with a maximum time of 0.73s

FUNCTIONAL REQUIREMENTS

FR	
FR1	The UAS shall have a flight time of 60 minutes.
FR2	The UAS shall fly in maximum winds of 30 km/hr.
FR3	The UAS shall fly in GPS denied environment for a linear distance of up to 2 km and a time of 200 seconds.
FR4	The UAS shall support all flight hardware and instrumentation.
FR5	The UAS and its testing shall adhere to FAA and CU Boulder regulations.
FR6	The UAS shall be capable of flying the operational payload.
FR7	The system shall fly autonomously given a pre-programmed flight plan.
FR8	The system shall have the ability to seamlessly switch between GPS and GPS-denied flight.
FR9	The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.
FR10	The system shall create a profile of RF signal power.
FR11	The payload components shall be fully functional in a self-contained structure.
FR12	The payload shall have the ability to measure and localize an RFI source in GPS-denied environments.

PAYLOAD STRUCTURE DESIGN

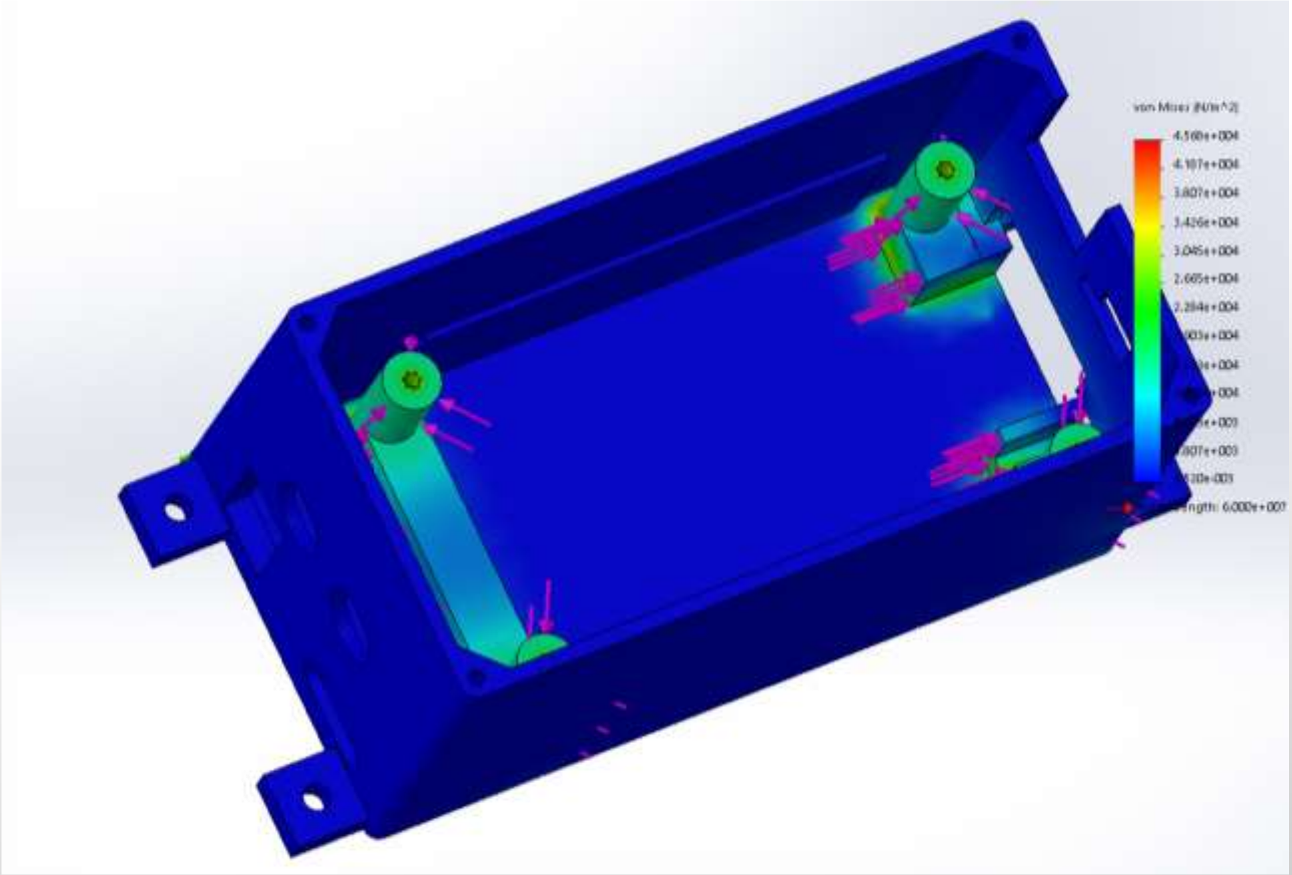


Top View

STRUCTURAL ANALYSIS

Model name:Payload Box
Study name:Static 2(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 1.3e+003

Structural Test	Yield Stress (N/m^2)	Factor of Safely
Static 1	6.00e7	3.562e3
Static 2	6.00e7	1.313e3
Static 3	6.00e7	2.751e3
4g Drop Test	6.00e7	N/A



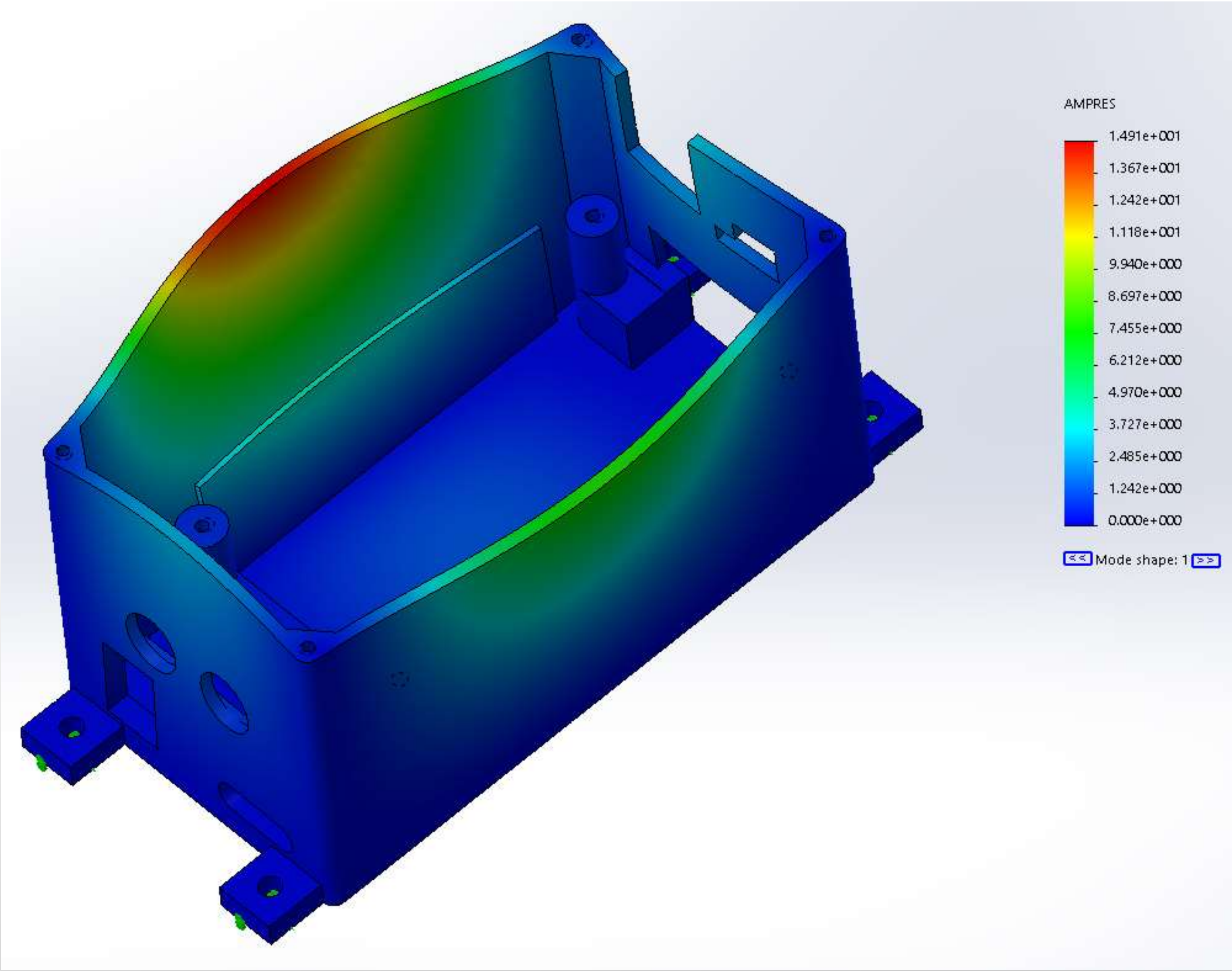
STRUCTURAL REQUIREMENTS SUMMARY

Requirement	Satisfaction
DR 6.1: The operational payload must be small enough to fit within the UAS payload bay.	With dimensions of 3"X3"X5" the payload easily fits in the Talon payload bay as shown in the UAS CAD Model
DR 11.2: The operational payload structure shall have a mechanical interface to allow for attachment to a baseplate structure.	There are four clearance holes for #8-32 screws located on flanges that will be used to mount the structure inside the payload bay
DR 12.5: The operational payload shall have an exterior interface for power and data post processing.	There are interfaces for a clip-in power switch, wires to the MicroZed, wires to the antenna, and wires to the LTE modem
DR 12.6: The operational payload shall have an access panel on the exterior structure.	The lid of the structure can easily be removed by removing the four #4-40 screws located on the top

MODAL FREQUENCY

Model name:Payload Box
Study name:Frequency 1(-Default-)
Plot type: Frequency Amplitude1
Mode Shape : 1 Value = 186.19 Hz
Deformation scale: 0.00105701

Requirements	Satisfaction
DR 11.1: Each structural component of the operational payload shall have a first modal frequency of above 100 Hz.	First modal frequency of the structure is 186 Hz.



OPERATIONAL PAYLOAD BATTERY

Capacity:
2200 mAh

Voltage Output:
5V

Payload draws at a maximum of 5W

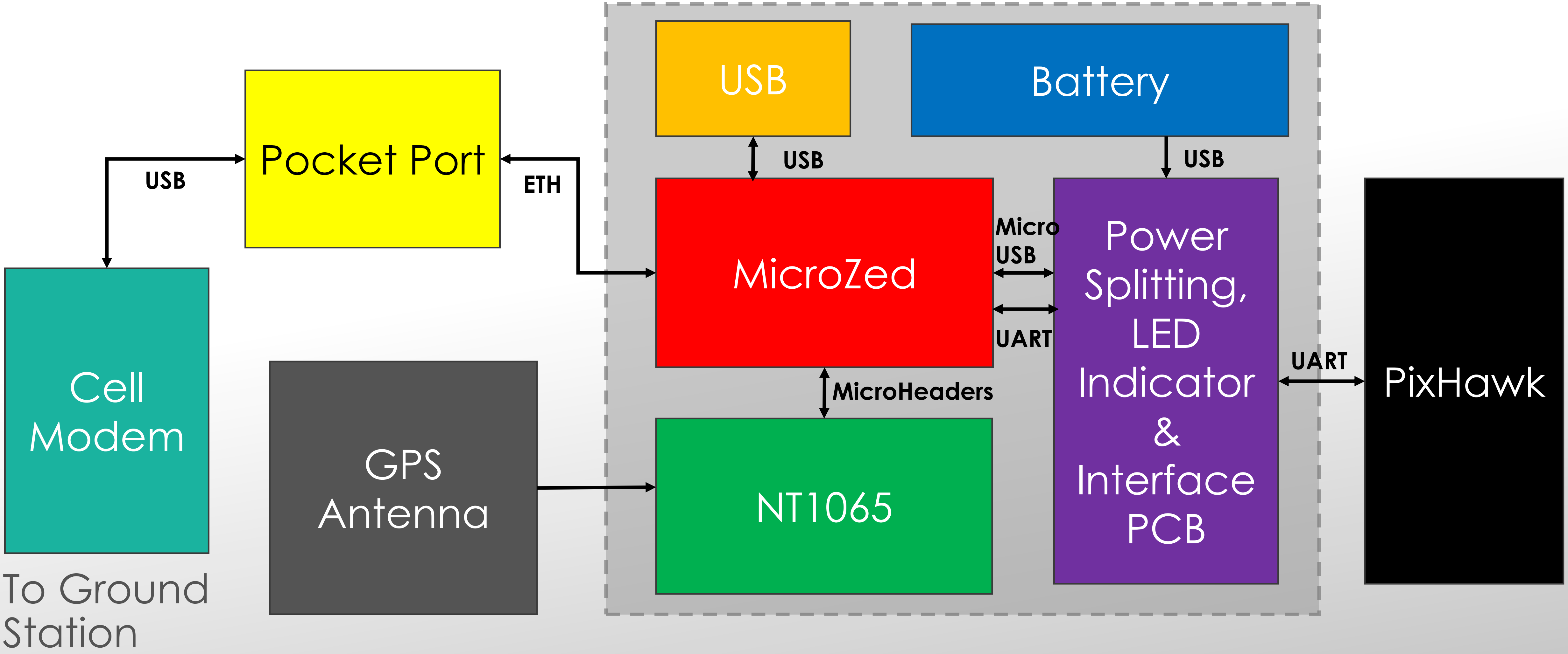
Battery Discharge Duration:

$$\frac{2200\text{mAh} * 5\text{V}}{1000} = 11\text{ Wh}$$

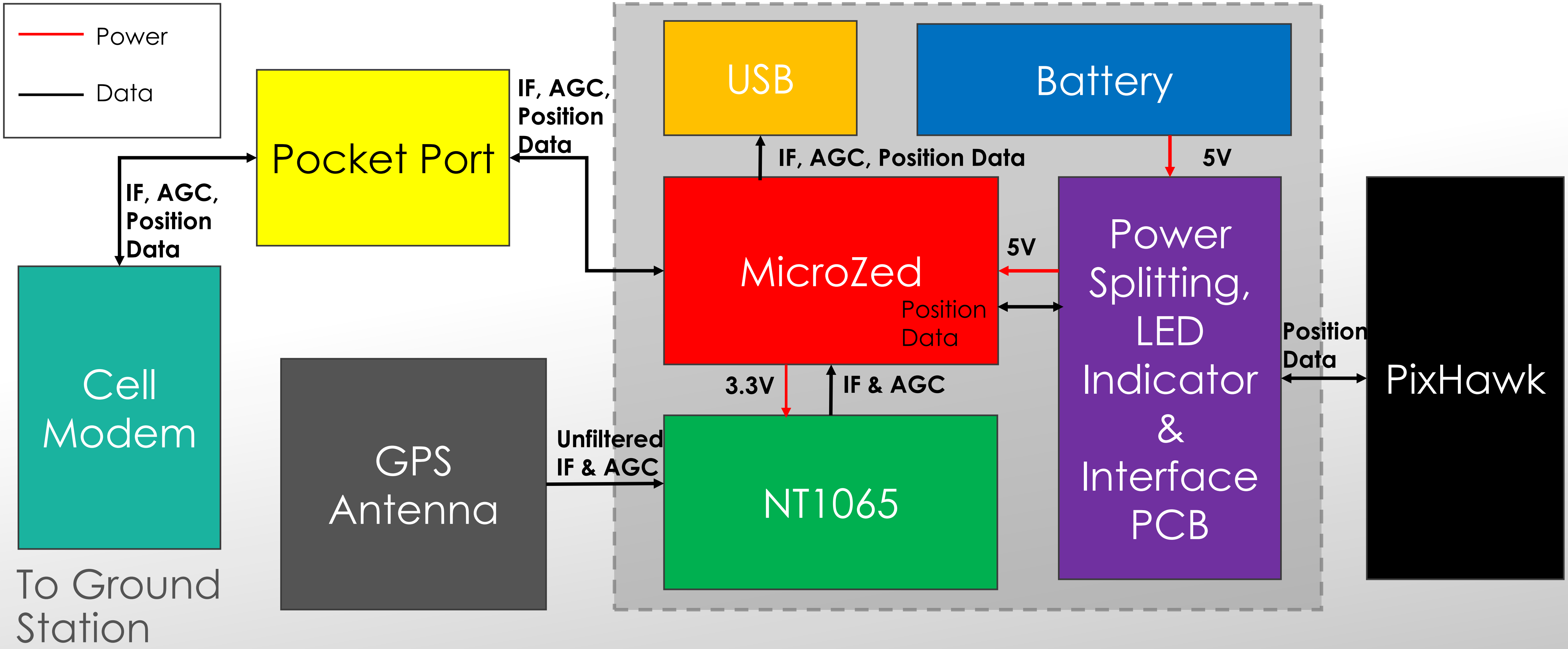
$$\frac{11\text{Wh}}{5\text{W}} = 2.2\text{ hours}$$

Requirement	Satisfaction
FR 12.2: The operational payload shall have its own power source	The battery selected will power the operational payload
FR 12.2.1: The operational payload shall operate for at least 1 hour	The payload should be able to operate for 2.2 hours

PAYLOAD WIRING DIAGRAM



PAYLOAD WIRING DIAGRAM



FILE TRANSFER

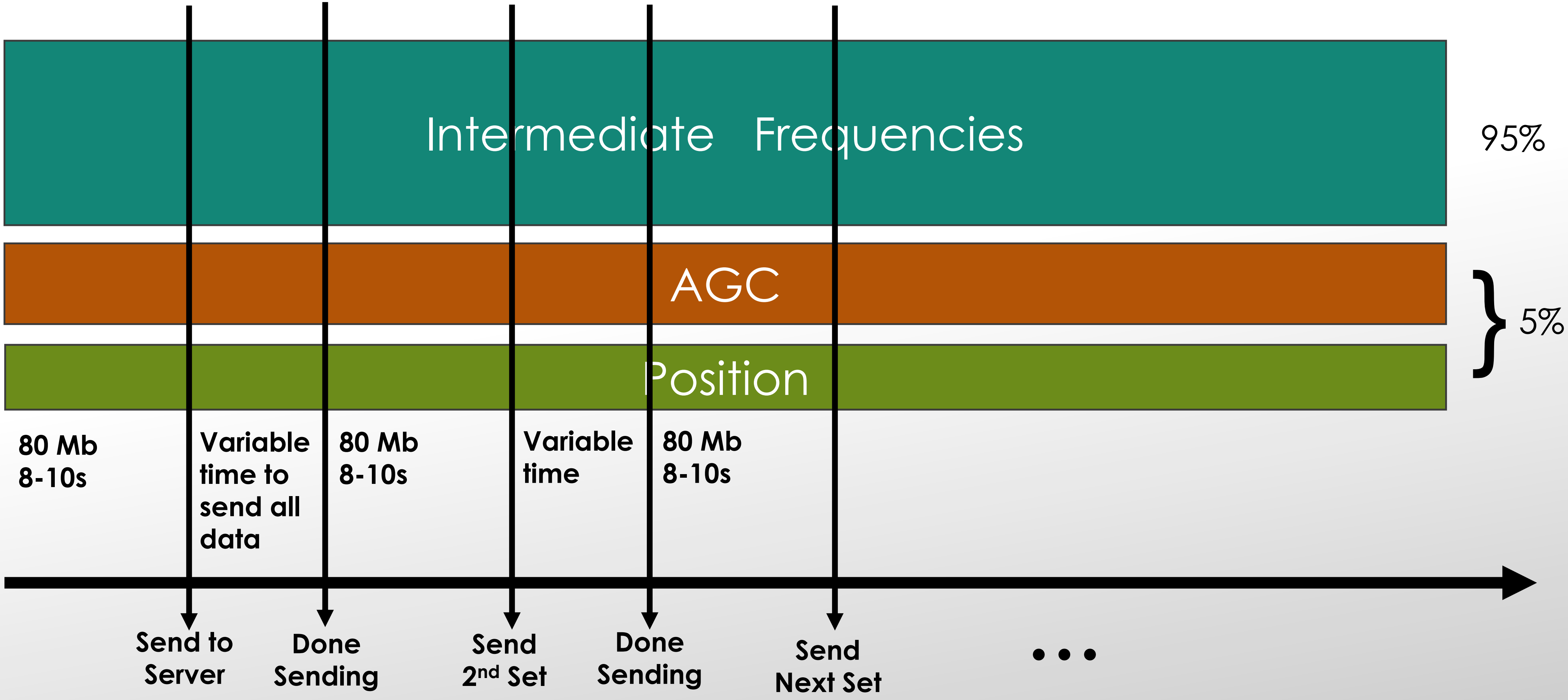
SSH/SCP File Transfer Service

Cellular enabled Linux Machine

Cellular Network Access

Linux Machine with Public IP and open port

DATA TRANSFER



REQUIREMENTS & SATISFACTION

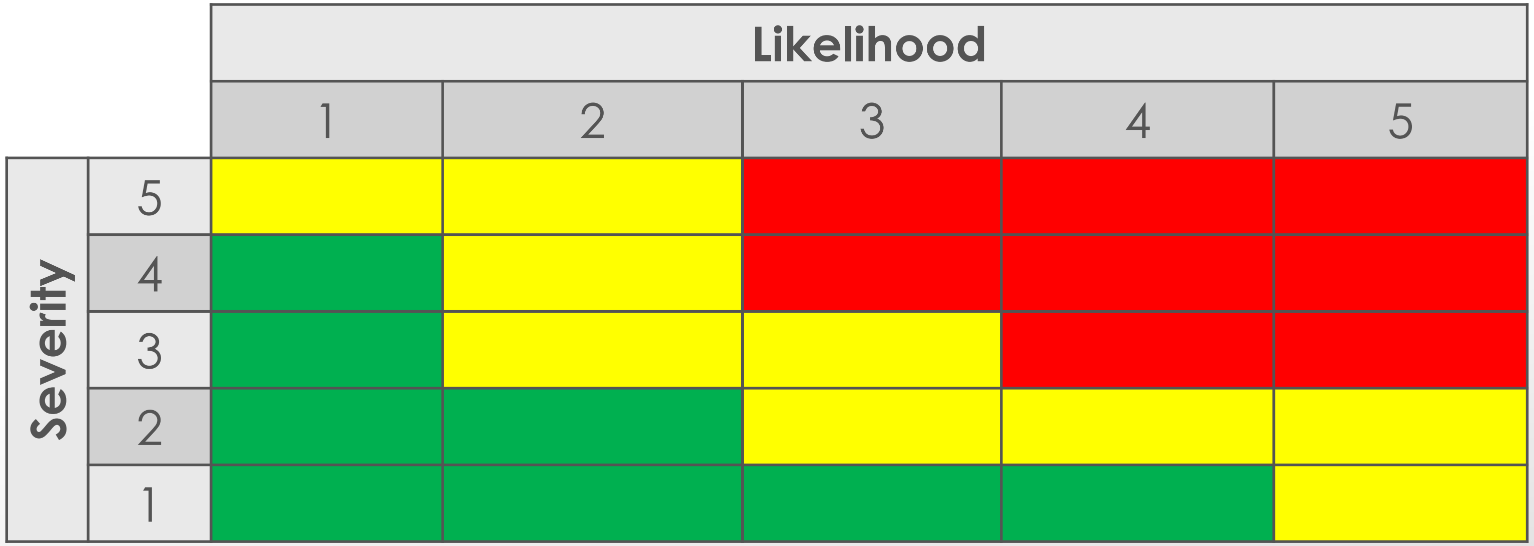
Requirements	Satisfaction
DR9.1: The UAS flight algorithm shall output GPS data which will be compared with the estimated flight generated by inertial sensors.	The PixHawk sends the position data from both the inertial sensor package (IMU) and the GPS data of the UAS.
DR 10.1: The localization algorithm used with the operational payload shall function using payload hardware only.	The data is taken with the payload and sent to a ground station.
DR 10.4: The localization algorithm shall interface with the flight algorithm during flight to receive positional data.	The connection between the PixHawk and the Microzed sends the position data.
DR 10.5: The algorithm shall store data for post-processing.	All of the data is saved to the USB drive connected to the Microzed.
DR 12.1: The operational payload shall have its own processing unit.	The Microzed is the processing unit of the operational payload.
DR 12.3: The operational payload shall have a board capable of measuring RFI power in the GPS band using AGC circuitry.	The NT1065 redesign and antenna.
DR 12.4: The payload shall have a transmitter to relay the data, in real time, back to the ground station.	Transmission to ground station through LTE Modem and MicroZed.

FUNCTIONAL REQUIREMENTS

FR	
FR1	The UAS shall have a flight time of 60 minutes.
FR2	The UAS shall fly in maximum winds of 30 km/hr.
FR3	The UAS shall fly in GPS denied environment for a linear distance of up to 2 km and a time of 200 seconds.
FR4	The UAS shall support all flight hardware and instrumentation.
FR5	The UAS and its testing shall adhere to FAA and CU Boulder regulations.
FR6	The UAS shall be capable of flying the operational payload.
FR7	The system shall fly autonomously given a pre-programmed flight plan.
FR8	The system shall have the ability to seamlessly switch between GPS and GPS-denied flight.
FR9	The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.
FR10	The system shall create a profile of RF signal power.
FR11	The payload components shall be fully functional in a self-contained structure.
FR12	The payload shall have the ability to measure and localize an RFI source in GPS-denied environments.

RISK ANALYSIS

RISK ANALYSIS - INTRODUCTION



Likelihood	Severity
1 = 0-20%	1 = Insignificant
2 = 20-40%	2 = Minimal
3 = 40-60%	3 = Manageable but not ideal
4 = 60-80%	4 = Damage to physical components
5 = 80-100%	5 = Project cannot be completed

RISK ANALYSIS - RISKS

R1	There is too much noise in the AGC data which leads to the UAS not knowing when to switch flight modes
R2	The time taken to switch between flight modes is over 1 second and it causes the UAS to crash
R3	There is structural damage to the airframe while taking off/landing
R4	Landing using the barometer data causes a small error in vertical location. The UAS does not land where it should or crashes
R5	Line of sight of the UAS is lost
R6	Operating conditions differ from simulated conditions causing a higher rate of error
R7	There is not enough bandwidth to downlink the AGC data

		Likelihood				
		1	2	3	4	5
Severity	5		R5	R2		
	4		R3	R1	R4	
	3			R6/R7		
	2					
	1					

RISK ANALYSIS - MITIGATION

R1	Coat payload structure in RFI paint to reduce noise in AGC data
R2	Ground tests will done to ensure that flight mode switches in time. If it does not, improvements will be made to the algorithm
R3	Skid plates have been added to the nose and underbelly of the UAS to ensure a more safe landing
R4	LIDAR and Optical Flow devices were mounted on the UAS to improve accuracy
R5	A "Return to Home" function will be set on the UAS that allows it to fly back to the takeoff location
R6	Simulations have been run with data from real flights to ensure that the UAS can still achieve the necessary levels of success
R7	Tests will be run during varying times of the day to ensure that the AGC downlink will be possible

		Likelihood				
		1	2	3	4	5
Severity	5	**R2**	**R5**	**R2**		
	4	**R4**	**R3**	**R1**	**R4**	
	3	**R7**		**R6/R7**		
	2	**R6**	**R3/R1**			
	1		**R5**			

RISK ANALYSIS - RISK 2

Severity: 5 **Likelihood: 3** **Total: 15**

Description: Once the UAS realizes that it is in GPS denied flight, it needs to switch flight modes. If this process takes longer than 1 second, the UAS could crash

Mitigation Options:

- Before the UAS flies, feed in simulated data on the ground to monitor time taken to switch flight modes
- In the event of failure during flight testing, manual control will be taken over the UAS to fly back to the ground and troubleshoot

Post Mitigation Risk Analysis

Severity: 5 **Likelihood: 1** **Total: 5**

RISK ANALYSIS - RISK 4

Severity: 4 **Likelihood: 4** **Total: 16**

Description: Trusting only the barometer data could lead to an inaccurate reading of altitude. This could cause the UAS to think that is above the ground and crash into it on landing

Mitigation Options:

- LIDAR and Optical Flow have been added to the airframe so that the accuracy of positioning, especially closer to the ground, would be increased

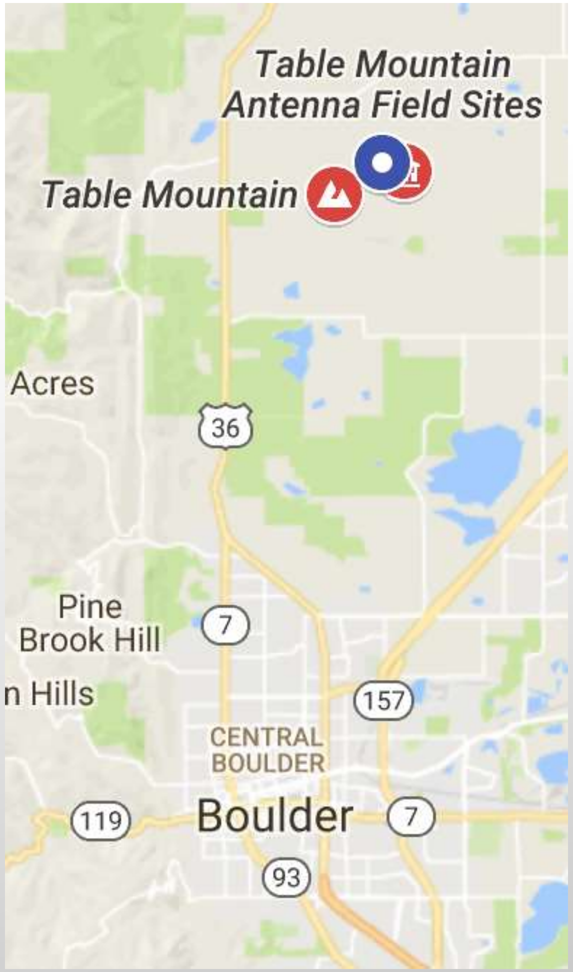
Post Mitigation Risk Analysis

Severity: 4 **Likelihood: 1** **Total: 4**

VERIFICATION AND VALIDATION

TEST LOCATION: TABLE MOUNTAIN

- Full flight test will be performed at Table Mountain, CO
- CU RECUV can give access with two week notice
- Test environment is flat grassland free of large obstructions



TEST PLAN

Ground Level

Test	Date (2018)
❑ Talon Hardware Calibration	February 9-12
❑ Payload Functional Ground and Downlink Testing	February 17-24
❑ GPS Denied Algorithm Ground Testing	February 20-24
❑ System Integration	February 9-26

Preliminary Flight Test

Test	Date (2018)
❑ Talon EKF Calibration and Functionality Test	February 12-28
❑ GPS Guided Flight Test, Endurance test	February 24-28
❑ INS Guided Flight (Straight and Level)	March 1-17
❑ Localization & Power Profile	March 1-17

Mission Level Test

Test	Date (2018)
❑ Maneuvers in GPS Denied Environment	March 19-30
❑ Mission Level Flight Test and Localization	March 19-30
❑ Redundant Tests	March 20-30

GROUND TESTING

Test	Goals	Requirements Verified
Talon Hardware Calibration	• Verify that Talon UAV hardware (servos, PixHawk) is ready for flight • Tune EKF/Kalman filter	• **FR 4**: UAS shall support all flight hardware and instrumentation
Payload Functional Ground and Downlink Testing	• Verify data collection • Thermal Analysis • Verify downlink capability	• **FR 11**: Payload shall be self contained • **DR 11.5**: The temperature of the payload shall remain below the operating temperatures of all components • **FR 9**: The UAS flight algorithm shall record and transmit data for all 6 degrees of freedom to assess flight performance.
GPS Denied Algorithm Testing	• Verify navigation mode switch time • Verify autopilot is ready for flight	• **FR 8**: The UAS software shall seamlessly switch from GPS guided flight to inertial guided flight • **DR 8.2**: UAS software shall utilize and RF power threshold in order to trigger a switch in flight modes
System Integration	• Verify components interface	• **All functional requirements**

PRELIMINARY FLIGHT TEST

Test	Goals	Requirements Verified
Talon EKF Calibration and Functionality Test	• Tune EKF based on flight performance • Verify threshold drift during INS flight	• **DR 3.2**: The drift of the UAS in the Z direction (altitude) shall remain under 10 m • **DR 3.3**: The drift of the UAS in the x and y direction shall be less than 40m from 100 seconds of GPS denied flight.
GPS Guided Flight Test, Endurance test	• Verify autonomous flight and successful flight plan • Verify basic flight capabilities	• **FR 1**: UAS shall have a flight time of 60 minutes • **FR 2**: UAS shall fly in maximum winds of 30 km/hr • **DR 2.1**: UAS shall fly at a maximum speed of 45km/hr • **FR 7**: UAS shall fly autonomously on a pre-programmed flight plan
INS Guided Flight (Straight and Level)	• Verify INS flight for 2km linear distance	• **FR 3**: UAS shall fly in GPS denied conditions for a linear distance of 2km • **DR 7.2.2:** The UAS shall fly straight and level until GPS signal is regained.
Localization& Power Profile	• Verify AGC & GPS data is obtained	• **FR 12:** Payload shall measure RF & localize and RF source • **FR 10:** The system shall create a profile of RF signal power.

MISSION LEVEL TEST

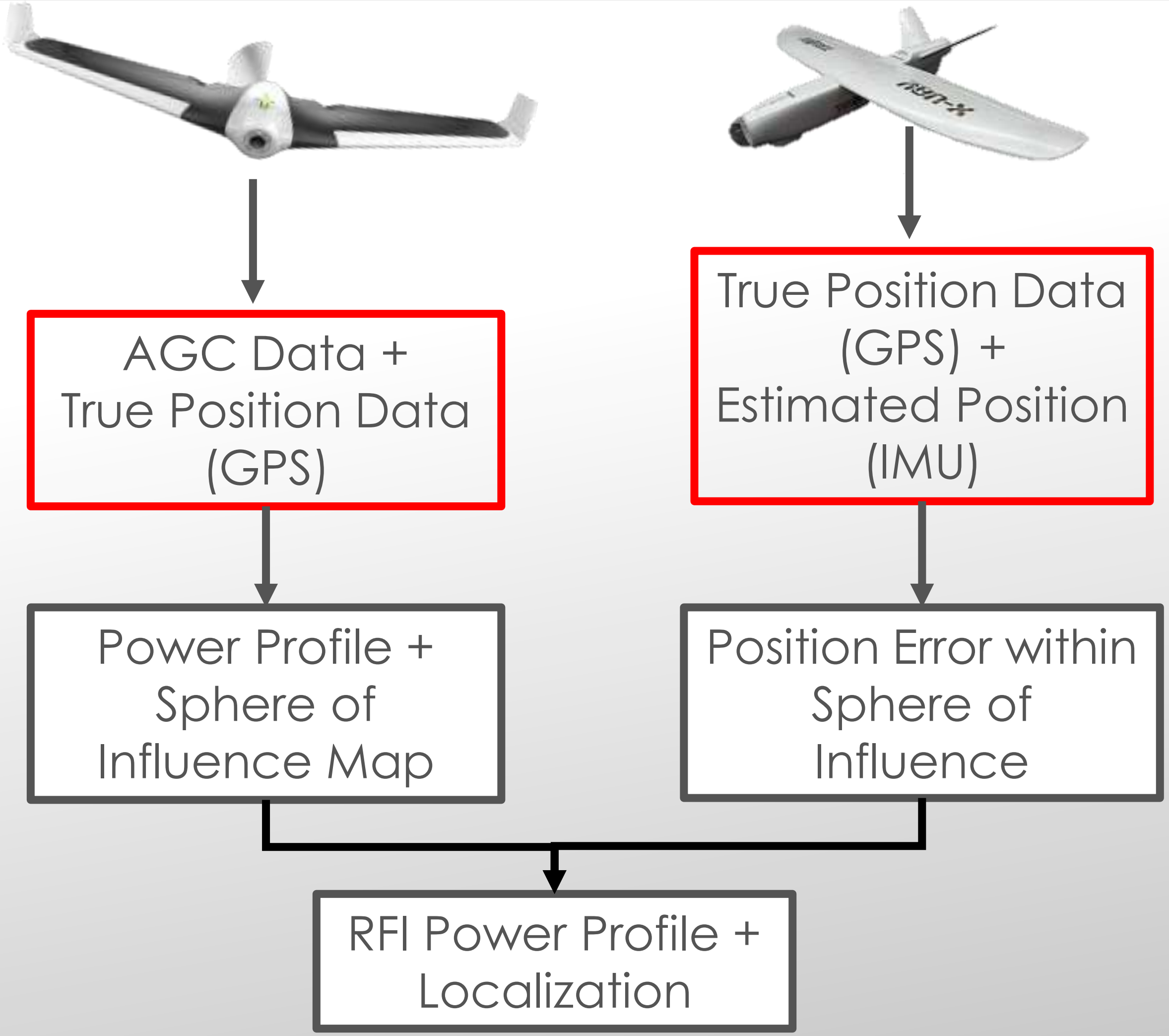
Test	Goals	Requirements Verified
Maneuvers in GPS Denied Environment	• Verify autopilot functions using INS data • Verify UAS executes flight plan in GPS denied area	• **FR 8**: The system shall have the ability to seamlessly switch between GPS and GPS-denied flight. • **DR 8.2.1**: The flight algorithm shall switch back to GPS flight when power level drops below power threshold. • **DR 8.2.2**: The UAS flight algorithm shall correct path and recalibrate inertial sensors once access to GPS is regained. • **DR 7.1.2:** The UAS flight system shall be able to withstand high winds as defined in FR2 while using a pre-programmed flight plan.
Mission Level Flight Test and Localization	• Verify autonomous flight and successful flight plan • Verify basic flight capabilities	• **DR 10.2**: System shall localize within a circular area with a 40 meter radius. • **Ensuring requirements met for Preliminary flight test are met simultaneously**
Redundant Tests	• Verify data collected is optimized and system error is minimal	

LOCALIZATION METHOD

Sphere of influence of a standard 2.4GHz Wi-Fi router mapped using Parrot Disco UAV:

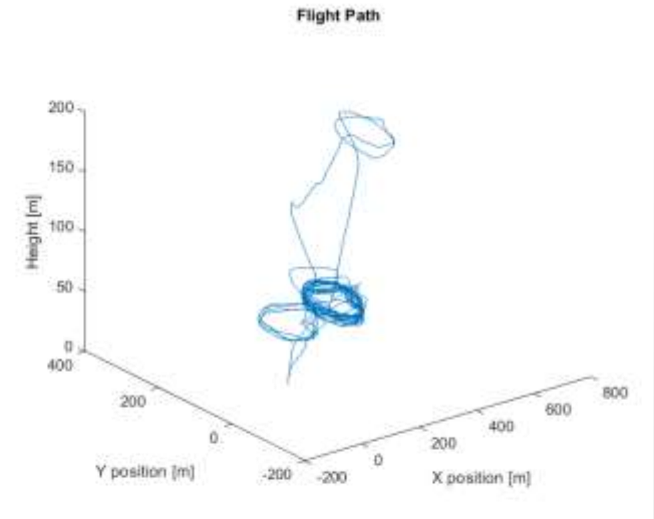
- Supports autonomous flight
- Built-in Wi-Fi receiver
- Built-in GPS receiver

The power map will be used in conjunction with the Talon flight in order to perform localization that incorporates the position error generated by the IMU



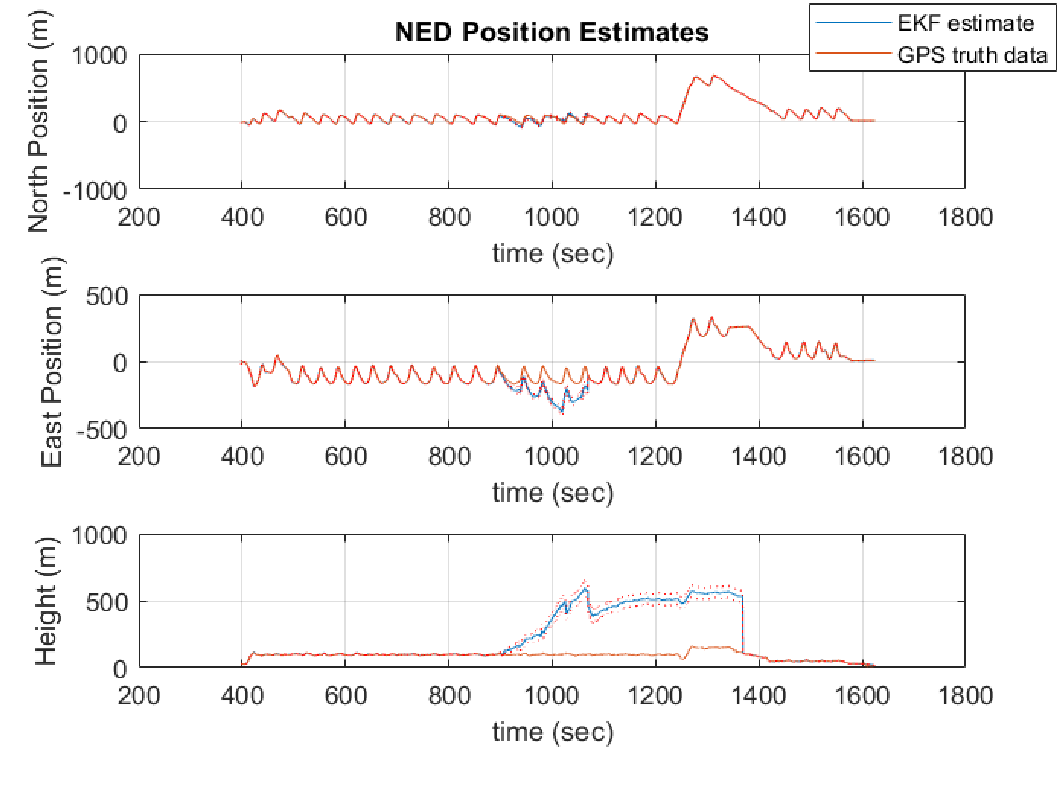
MODIFIED ARDUPILOT
SIMULATIONS – SOFTWARE IN THE LOOP

InertialNav
- Simulink/C model used to test state estimation
- Uses actual flight data to test EKF performance
- Useful for tuning EKF



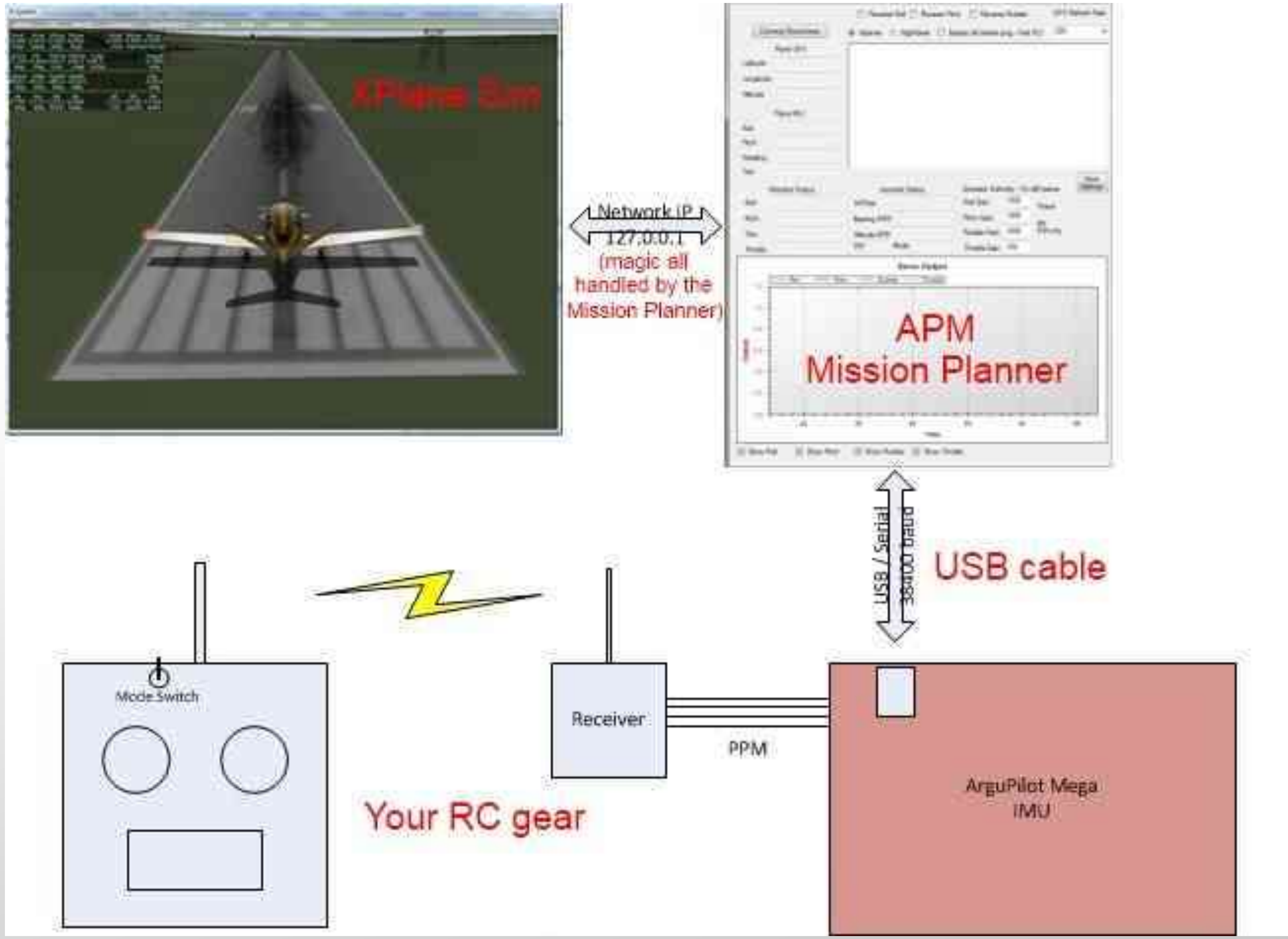
Flight path from test data

- EKF state estimation of test data without GPS for 200s
- Height error ~500m
  - Will be improved with barometer + chosen IMU
- Y-position error ~200m
  - Will be improved with chosen IMU
- RAMROD flightpath is simpler than test data used



MODIFIED ARDUPILOT
SIMULATIONS – HARDWARE IN THE LOOP

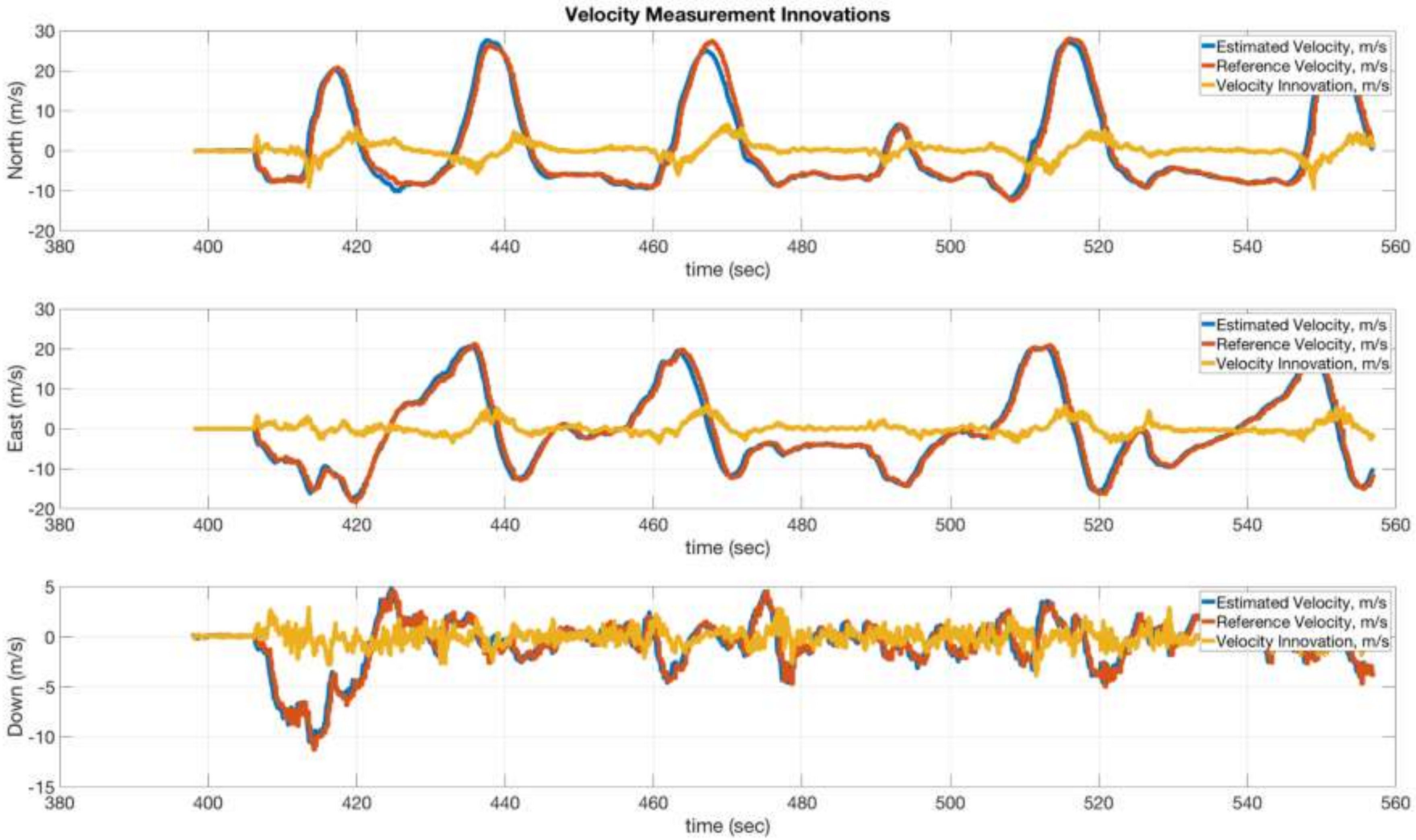
X-Plane
- Runs ArduPilot directly on PixHawk
- Interfaces with computer as a physics simulator
- Will be used as final verification of modified ArduPilot before flight/ground tests



EKF2 TUNING

- Default tune built around stock PixHawk sensors. A higher quality IMU, as well as a pitot tube, and optical flow sensor are to be added.
- Tuning for new IMU
  - Static baseline test
  - Utilize Mission Planner to analyze telemetry logs, view filter innovations
  - Update Parameters
  - Repeat
- Flight testing to follow static ground tests
  - Allow for pitot tube and optical flow tuning

EKF2 TUNING



Velocity Measurement Innovations
North (m/s)
East (m/s)
Down (m/s)
time (sec)
Estimated Velocity, m/s
Reference Velocity, m/s
Velocity Innovation, m/s

PROJECT SUMMARY

ORGANIZATIONAL CHART

- Dennis Akos — Customer
- Jade Morton — Advisor

- Selby Stout — Project Manager
- Jorgen Baertsch — Financial Lead
- Justin Williams — Systems Engineer
- Mary Landis — Test Engineer
- Kennedy Harrmann — Safety Officer

Technical Leads

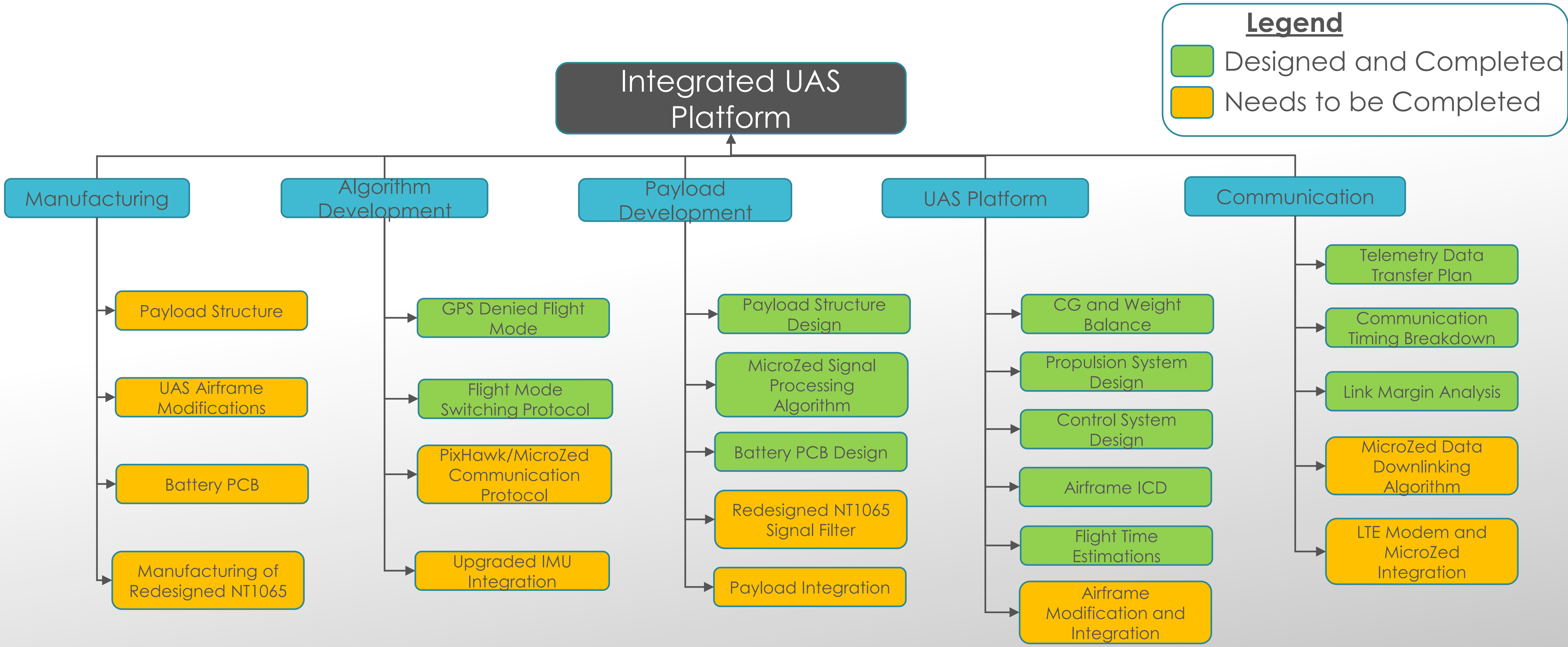
- Jake Ursetta — Electrical/Pilot
- Ian Cooke — Manufacturing
- Sarah Larson — Mechanical
- Ethan Morgan — Software
- Harrison Mast — Controls
- Samantha Williams — Communications

WORK BREAKDOWN STRUCTURE

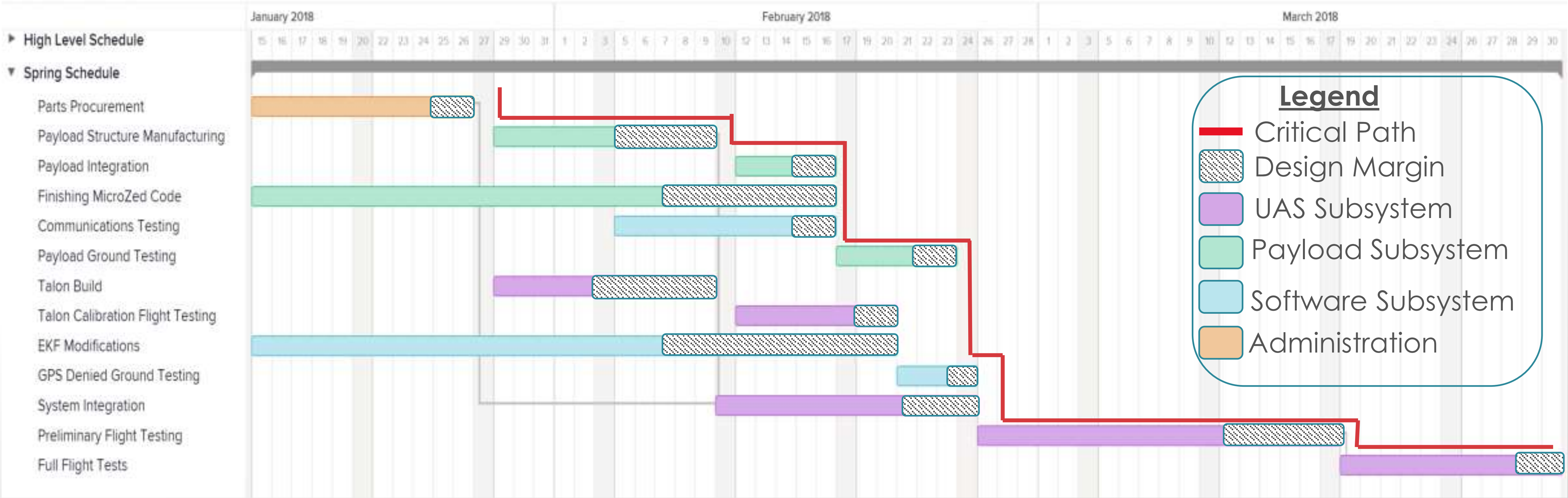
Legend
- Designed and Completed
- Needs to be Completed

- Integrated UAS Platform
  - Course Deliverables
    - PDD
    - CDD
    - PDR
    - CDR
    - FFR
    - MSR
    - TSR
    - AIAA
    - SFR
    - PFR
    - PTS
    - SPS
  - Project Management
    - Schedule/ Gantt Chart
    - Work Breakdown Structure
  - Financial
    - PDR Budget
    - Cost Plan
    - Spring EEF Application
    - Spring Financial Reports
  - Safety
    - Risk Analysis
    - Manufacturing Safety Plan
    - Testing Safety Plan
  - Testing and Integration
    - Payload Ground Testing
    - Aircraft ground Testing
    - Aircraft Calibration Flight Testing
    - Algorithm Verification Flight Testing
    - Full System Integration
    - Full System Flight Testing

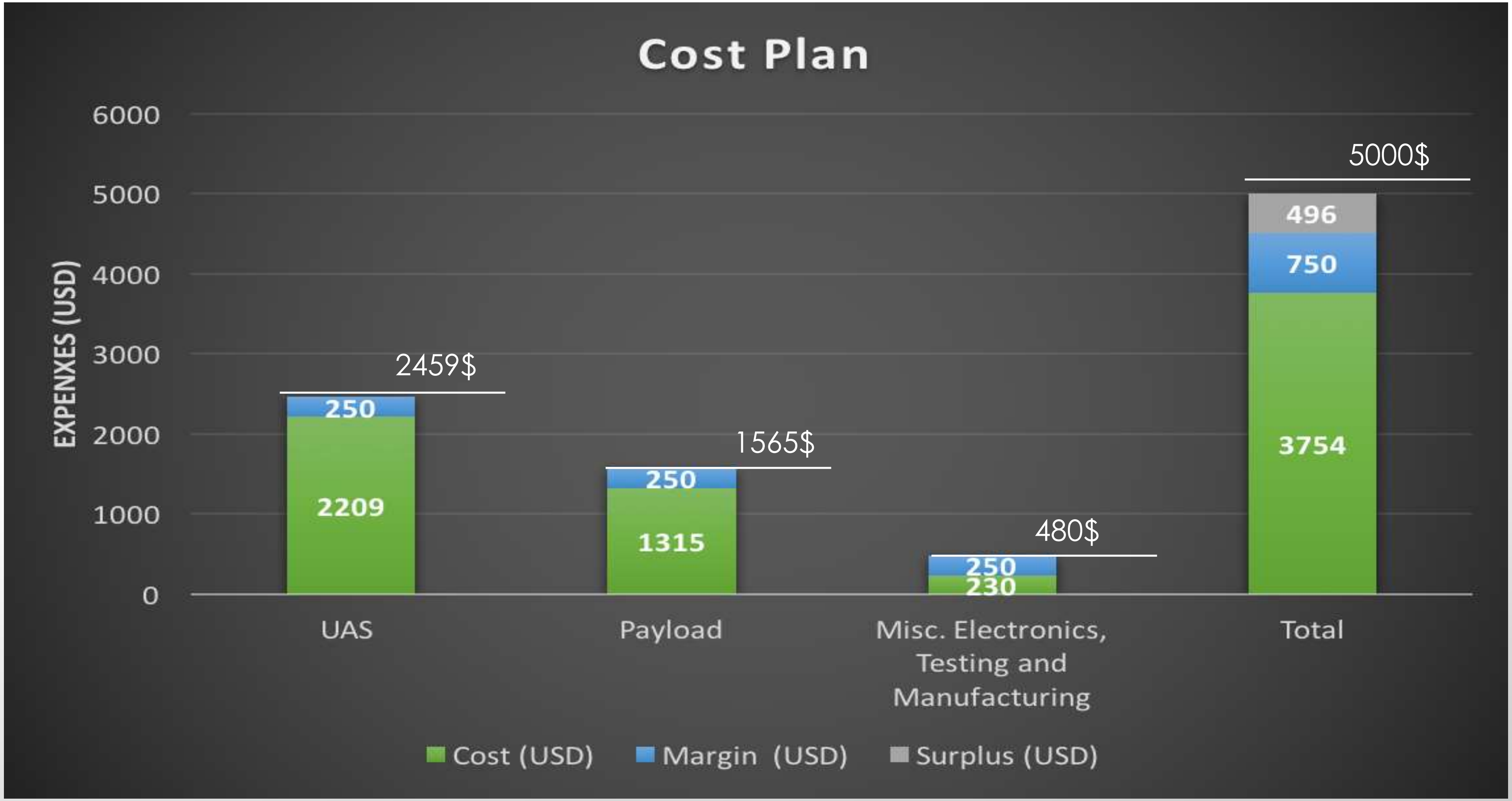
WORK BREAKDOWN STRUCTURE



SPRING SCHEDULE



BUDGET BREAKDOWN



ACKNOWLEDGEMENTS

Advisor: **Jade Morton**

Customer: Dennis Akos

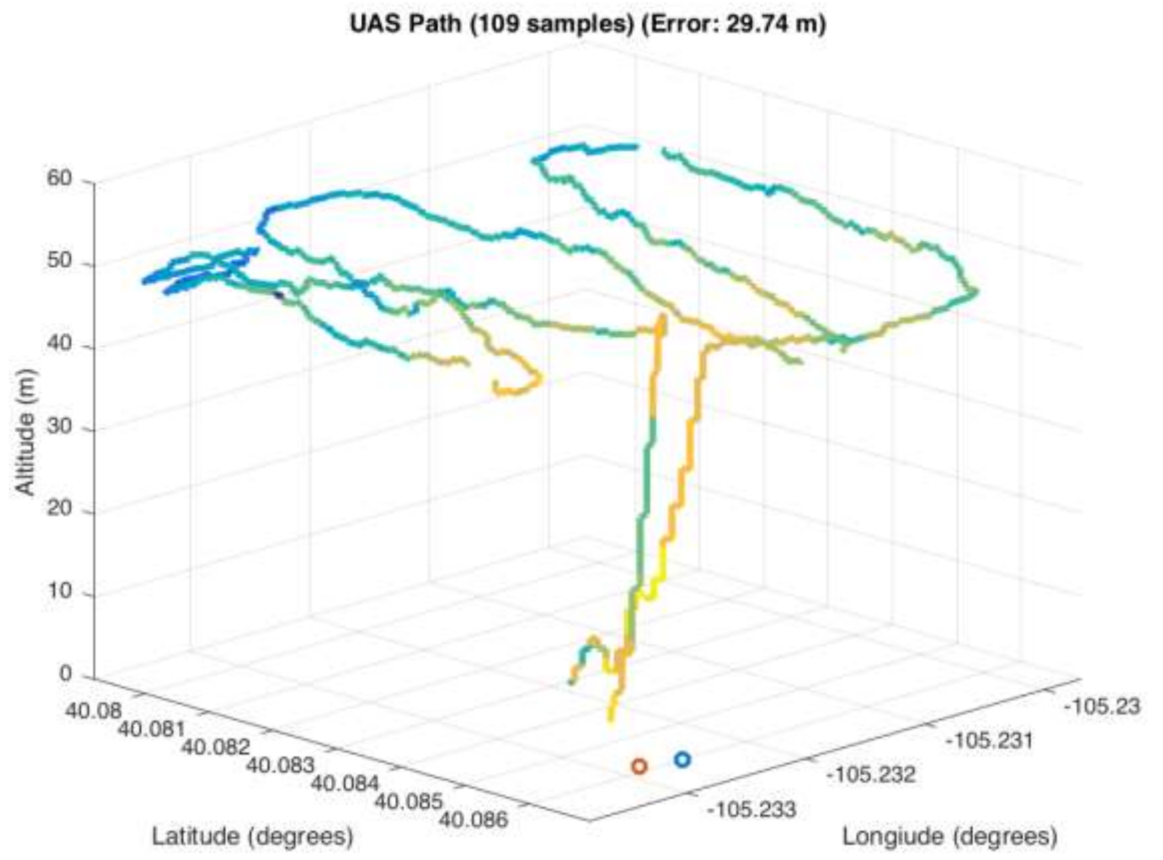
PAB: Donna Gerren, Bobby Hodgkison, Trudy Schwartz, Matt Rhode, Jelliffe Jackson, Torin Clark, Zoltan Sternovsky, Francsico Lopez-Jimenez, Dale Lawrence

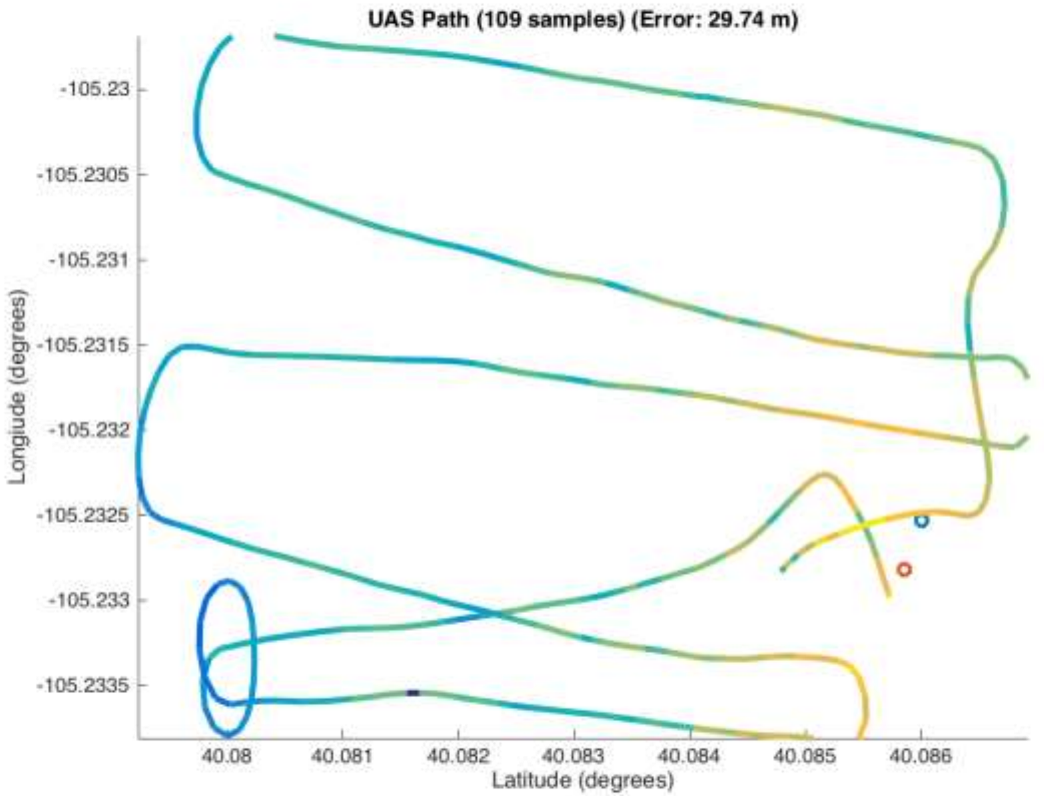
IRISS/RECUV: Daniel Liebert, Cory Dixon

QUESTIONS?

BACKUP SLIDES

LOCALIZATION MODEL





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NONLINEAR LEAST-SQUARES
CURVE-FITTING

- The distance to the receiver can be estimated using nonlinear least-squares curve fitting. If we assume an unknown transmitter location at position (x,y) on a finite search grid, we can use the free space loss principle from the previous slide. The space loss coefficient $\boldsymbol{\alpha}$ is determined by obstructions and ground reflections in the environment.

$$P_{12} = P_1 - P_2 = 10\alpha \log_{10}\left(\frac{d_2}{d_1}\right) \Rightarrow P_{12} = 5\alpha \log_{10}\left[\frac{(x-x_2)^2+(y-y_2)^2}{(x-x_1)^2+(y-y_1)^2}\right]$$

- The objective function Q measures the difference between the actual measured power between two grid points and the predicted power difference between two grid points.

$$Q(x,y) = \sum_{k<l}\left[\bar{P}_{kl} - 5\alpha \log_{10}\left[\frac{(x-x_l)^2+(y-y_l)^2}{(x-x_k)^2+(y-y_k)^2}\right]\right]^2,$$

- The (x,y) grid point where the objective function Q is minimized is the estimated transmitter location

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SIGNAL ATTENUATION IN FREE SPACE

- The path-loss for a given environment can be approximated by:

$$D^{-\alpha}$$

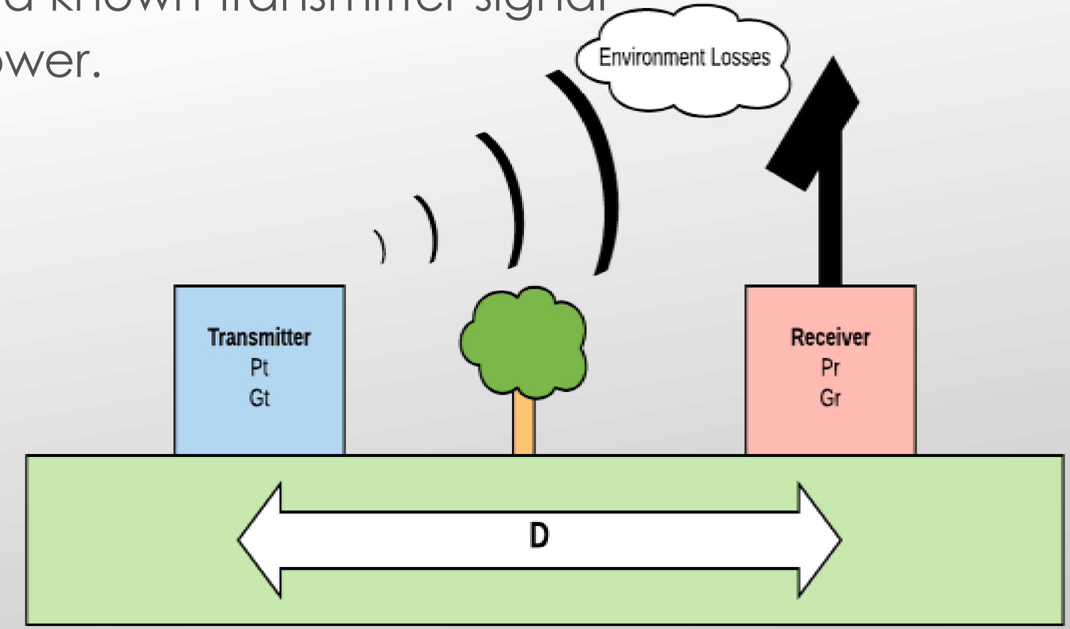
Where **α** is the path-loss exponent.

- Ideally, signal intensity decreases proportional to the inverse square of distance between transmitter and receiver in three-dimensional space. (**α** = -2)

- Factors such as noise interference, ground reflection, obstacles, and imperfect antenna gains can increase signal attenuation.

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi)^2 D^{-\alpha} L}$$

α can be determined by measuring actual signal attenuation in the test environment with known transmitter/ receiver locations and known transmitter signal power.



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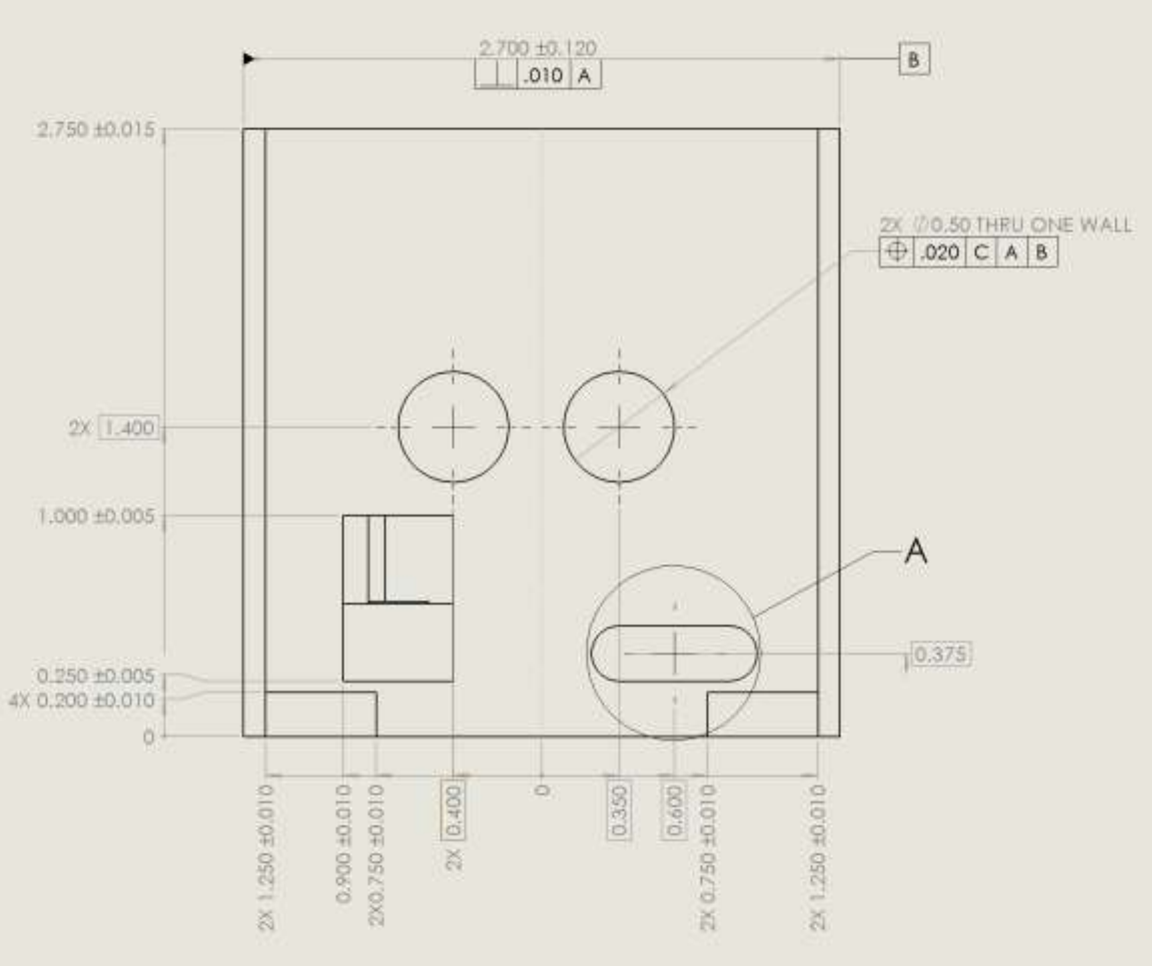
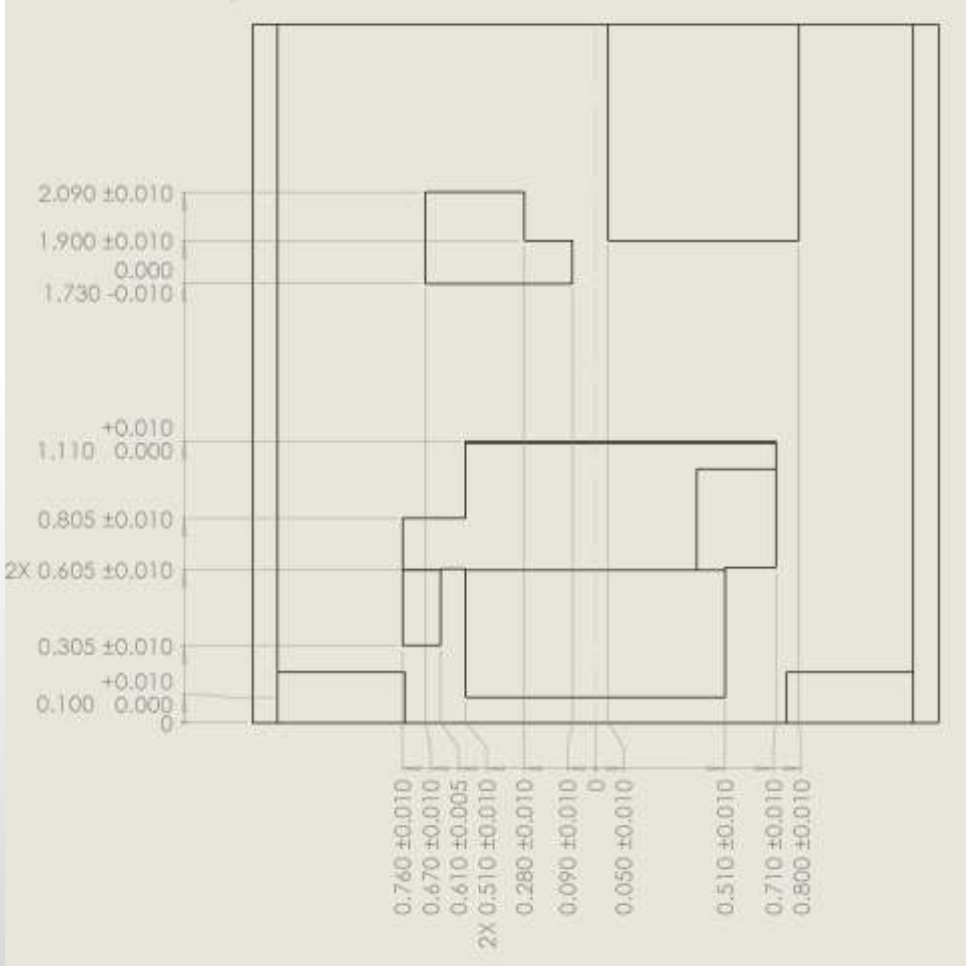
PAYLOAD STRUCTURE BOX DIMENSIONS



Left View



Right View

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PAYLOAD STRUCTURE BOX DIMENSIONS

Front View

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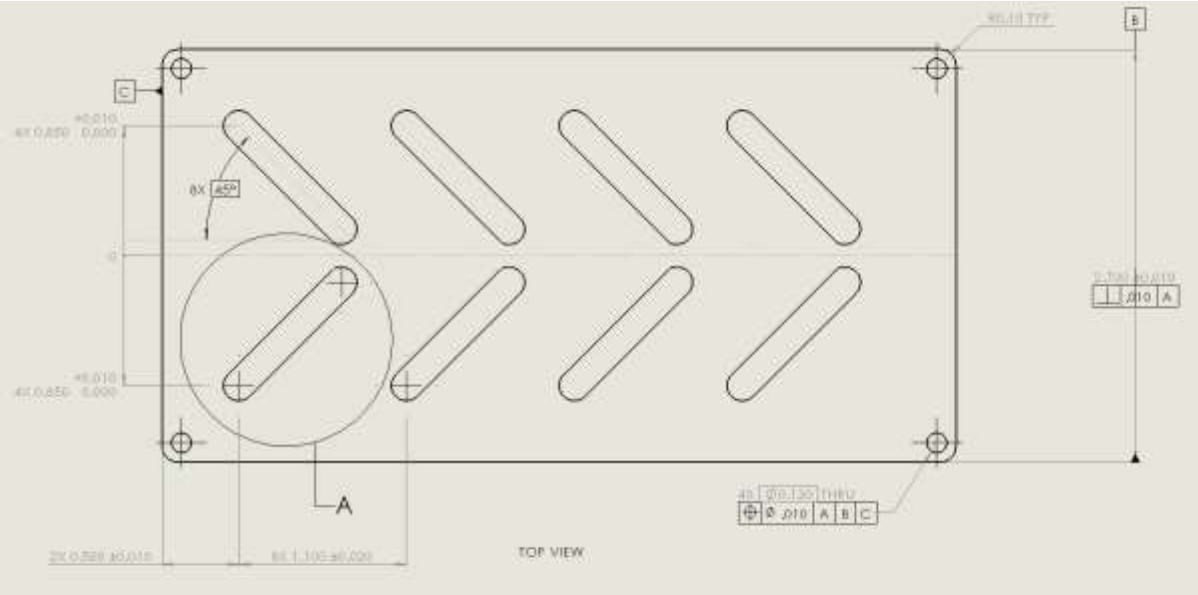
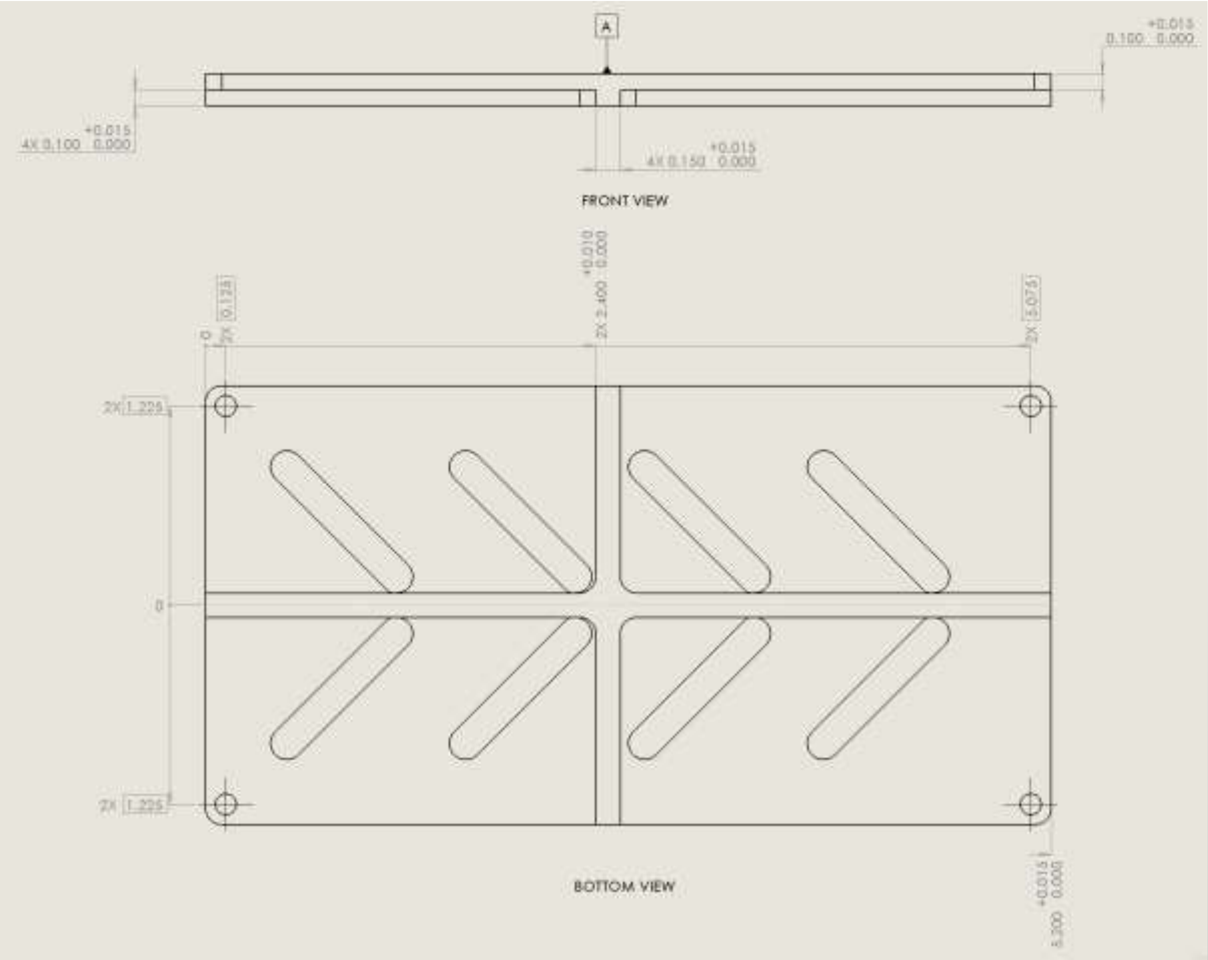
PAYLOAD STRUCTURE TOP DIMENSIONS





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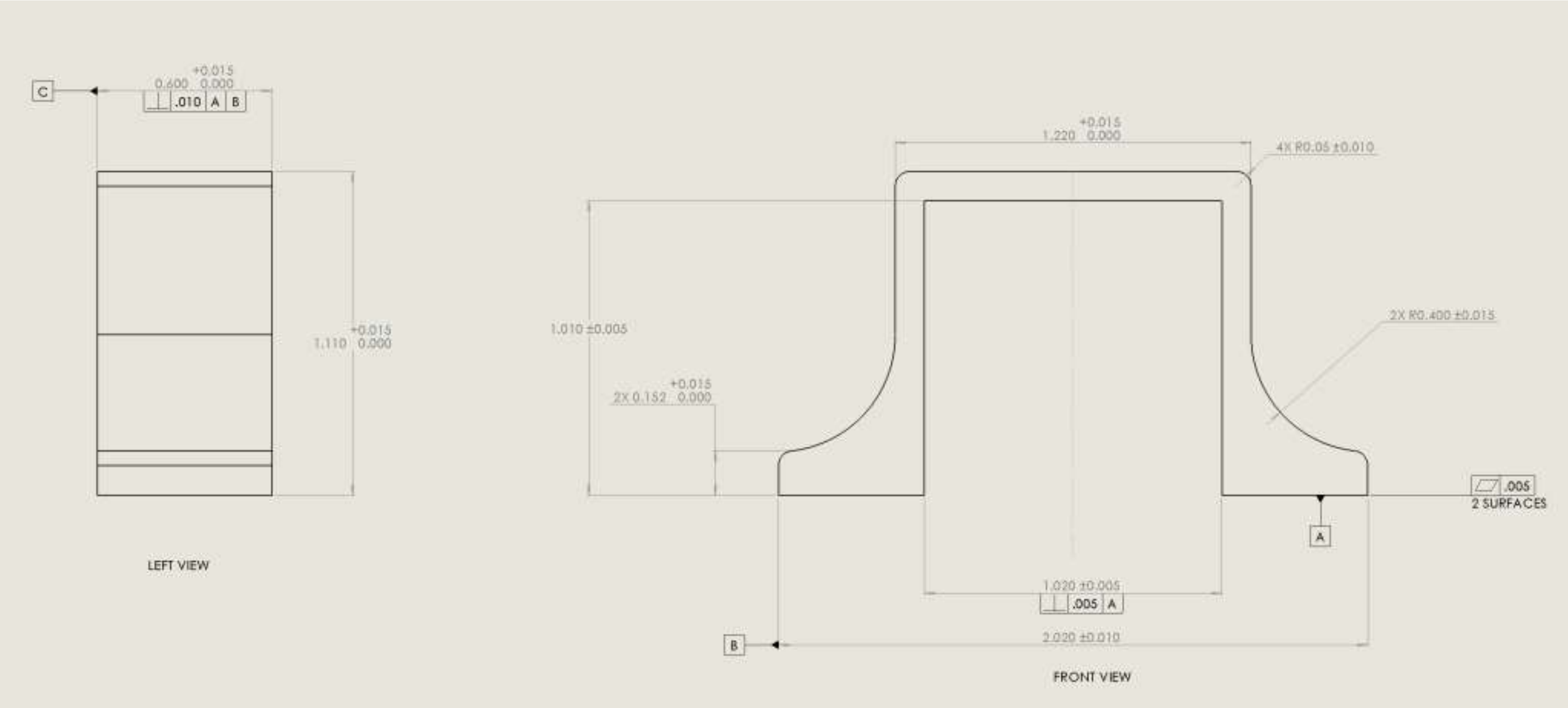
BATTERY BRACKET DIMENSIONS



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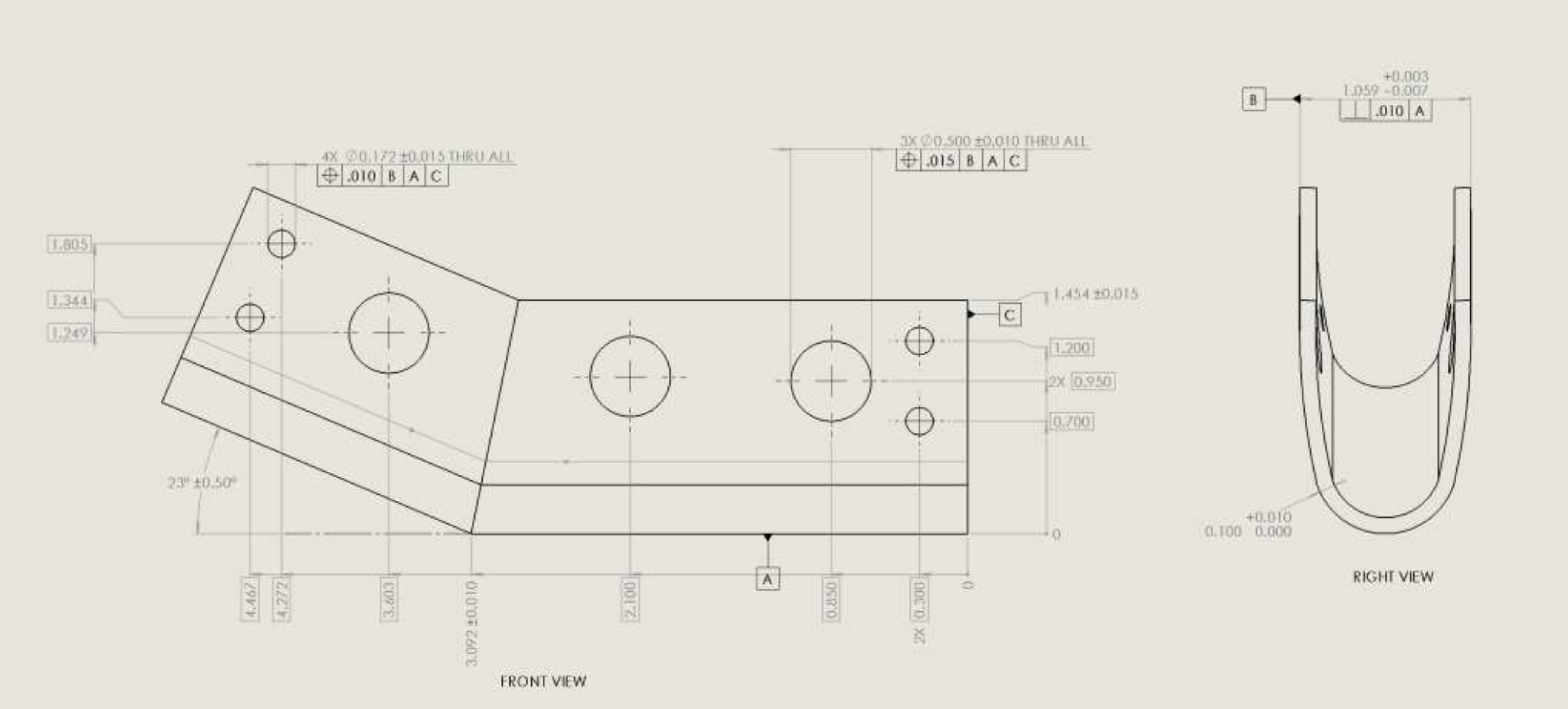
TAIL SKID DIMENSIONS



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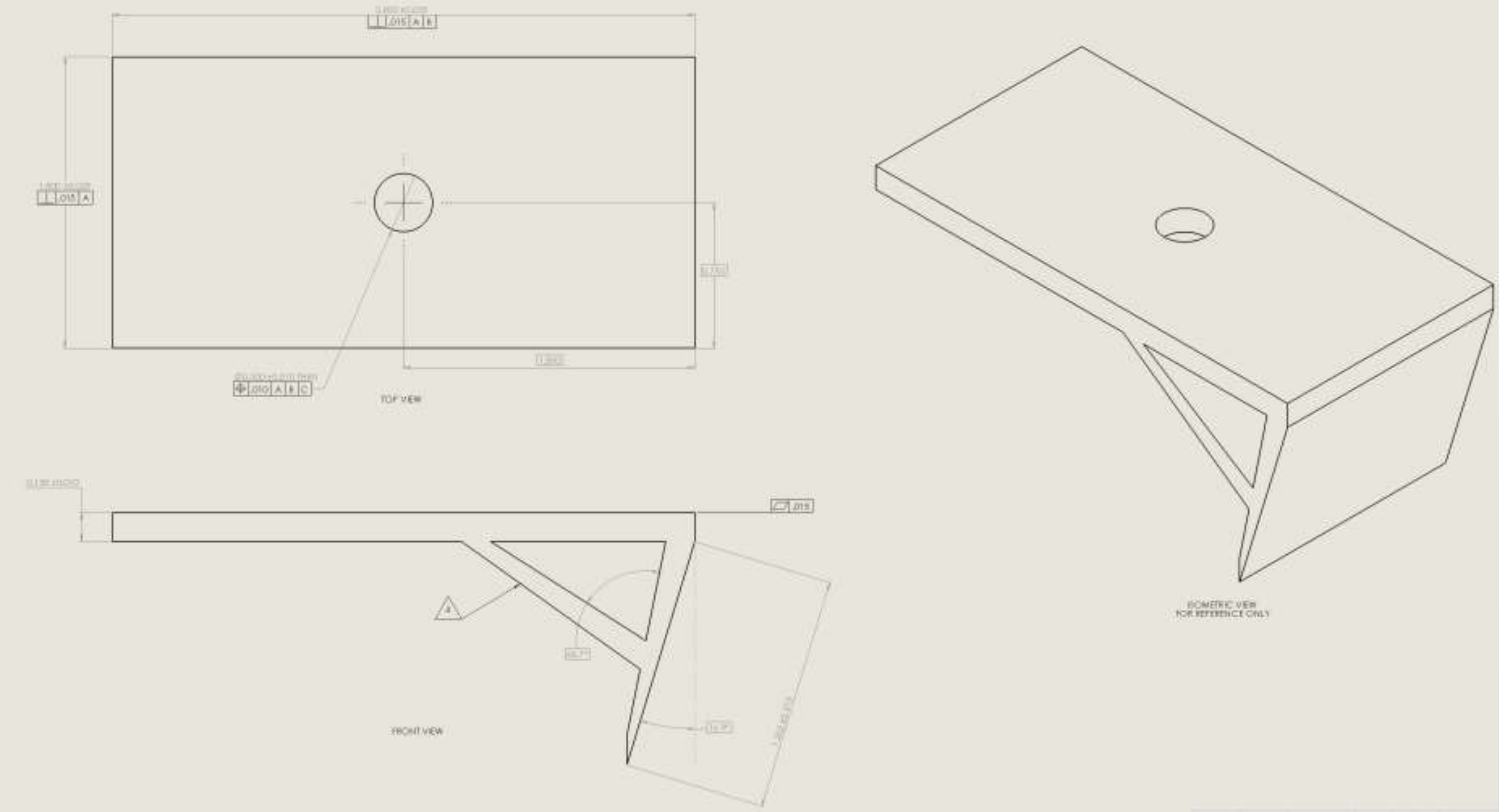
HD CAMERA MOUNT DIMENSIONS



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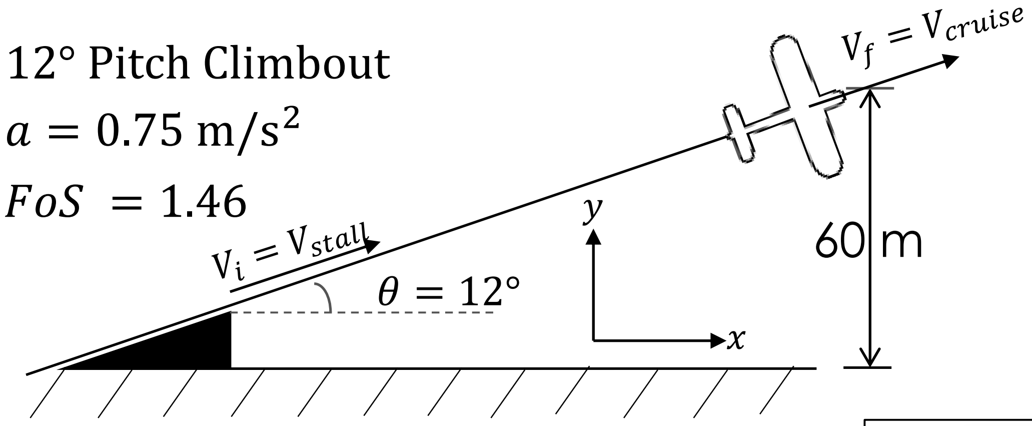
MAXIMUM POWER REQUIRED

12° Pitch Climbout

$a = 0.75 \text{ m/s}^2$

$FoS = 1.46$

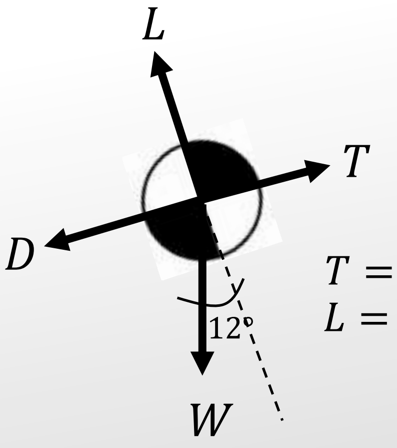


$$PR_{max} = TV_f = V_f(D + ma + mg\sin\theta)$$

$$PR_{max} = V_f\left(\frac{1}{2}\rho V_f^2 S\left(C_{D,0} + \frac{C_L^2}{\pi e AR}\right) + m(a + g\sin\theta)\right)$$

$$\boxed{PR_{max} = \left[\underbrace{\frac{1}{2}\rho V_f^3 S C_{D,0}}_{\text{Parasitic Drag}} + \underbrace{\frac{(mg\cos\theta)^2}{\frac{1}{2}\rho V_f S}\left(\frac{1}{\pi e AR}\right)}_{\text{Induced Drag}} + \underbrace{mV_f(a + g\sin\theta)}_{\text{Climb-out}}\right]\underbrace{\frac{1}{\eta_{overall}}(FoS)}_{\text{Efficiency and Safety Factor}}}$$

PR Due To: Parasitic Drag, Induced Drag, Climb-out, Efficiency and Safety Factor



$T = D + ma + mg\sin\theta$

$L = mg\cos\theta$

$\rho = 1.047 \text{ kg/m}^3$ $V_f = 14.4 \text{ m/s}$ $S = 0.545 \text{ ft}^2$ $m = 3.467 \text{ kg}$

$AR = 5.42$ $C_{D,0} = 0.027$ $crud = 0.29$ $e = 0.8$ $\eta_{overall} = 85\ \%$

$$\boxed{PR_{max} = 671 \text{ W}}$$

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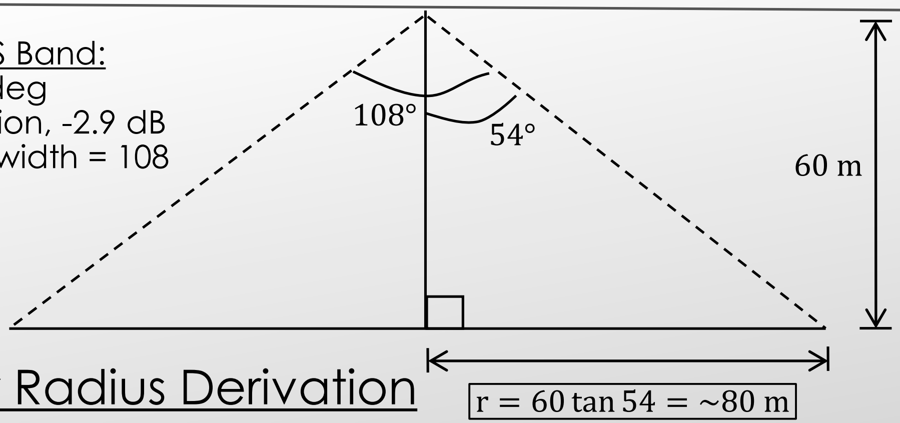
TIME AND DISTANCE COVERED IN GPS-DENIED ENVIRONMENT

$R = 500\ \mathrm{m}$	Radius of GPS-Denied Area
$r = 80\ \mathrm{m}$	Sensor Range
$R/r = 6.2$	Ratio
$L = 3000\ \mathrm{m}$	Length of Side of Search Area

Total flight Path Length:

$$S = 4L - 8R\left(\frac{1}{R/r}\right) + \frac{\left(L - 3R\left(\frac{1}{R/r}\right)\right)\left(L - 4R\left(\frac{1}{R/r}\right)\right)}{2R\left(\frac{1}{R/r}\right)} = 57.14\ \text{km}$$

L1 GPS Band:
@ 10 deg Elevation, -2.9 dB Beamwidth = 108 deg



Sensor Radius Derivation

Distance Covered in GPS-Denied (D):

Even Terms of R/r:

$$D(R/r) = 2R + 4R\sum_{n=1}^{\frac{1}{2}R/r - 1}\sqrt{1 - 4n^2\left(\frac{1}{R/r}\right)^2}$$

Odd Terms of R/r:

$$D(R/r) = 4R\sqrt{1 - \left(\frac{1}{R/r}\right)^2} + 4R\sum_{n=1}^{\frac{1}{2}(R/r - 3)}\sqrt{1 - (2n+1)^2\left(\frac{1}{R/r}\right)^2}$$

$$\boxed{D(R/r) \approx 787.7\,R/r - 264.2 = 4.5\ \text{km}}$$

With $S = 57.14$ km, $R/r = 6.2$, and desired FT of 63 + minutes,

$$\boxed{V_{cruise} = 14.4\ \mathrm{m/s},\ FT = 66.13\ \text{min}}$$

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UAS WEIGHT BREAKDOWN

Flight System (FS)		
Component	Quantity	Weight [g]
Motor w/ Prop	1	221
Battery	2	423
Pixhawk Power Module	1	22
ESC	1	133
Receiver	1	14
Aileron Servo	2	22
Ruddervator Servo	2	10
Wet Noodle	3 ft	16 g/ft*3 ft = **48**
Airframe	1	1050
Total		**2398**

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UAS WEIGHT BREAKDOWN

Autopilot (AP)		
Component	Quantity	Weight [g]
Pixhawk 2	1	74
IMU	1	24
Telemetry Antenna	1	45
GPS Module	1	47
Airspeed Sensor/Pitot Tube	1	9/3
LiDAR	1	22
Optical Flow	1	18
Total		**242**

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UAS WEIGHT BREAKDOWN

Operational Payload (OP)		
Component	Quantity	Weight [g]
Main Structure	1	135
Top Structure	1	26
Battery bracket	1	5.2
Hardware	1	2.9
Battery	1	73
Wires	1	30
Battery PCB	1	30
MicroZed	1	43.6
NT1065 V. RAMROD	1	25
Power Monitoring Antenna	1	180
TOTAL		**536.1**

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UAS WEIGHT BREAKDOWN

Miscellaneous (MS)		
Component	Quantity	Weight [g]
Wires	-	50
Connectors	-	50
HD Camera	1	40
Total		**140**

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UAS WEIGHT BREAKDOWN

Structural Components (SC)		
Component	Quantity	Weight [g]
Forward Mounting Plate	1	68
Aft Mounting Plate	1	55
Forward Skidplate	1	15
Rear Skidplate	1	17
Total		**155**

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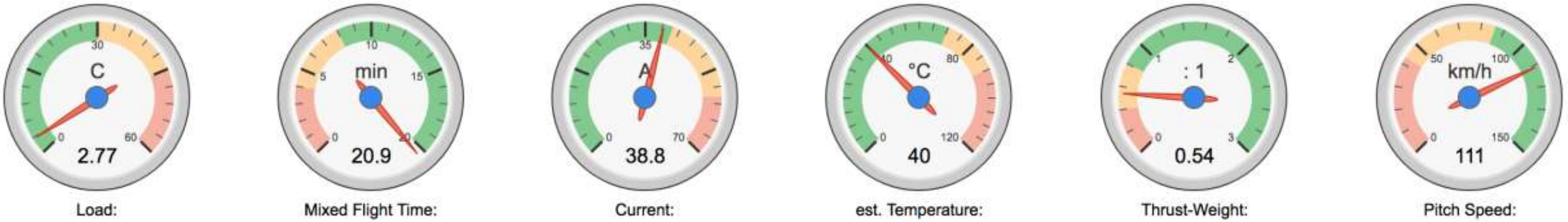
FLIGHT TIME

General	Model Weight: 3500 g incl. Drive; 123.5 oz	# of Motors: 1 (on same Battery)	Wing Area: 54.5 dm²; 844.8 in²	Drag: coeffcient; 0.027 Cd	Cross Section: 8.1 dm²; 125.6 in²	Field Elevation: 1609 m ASL; 5280 ft ASL	Air Temperature: 21 °C; 70 °F	Pressure (QNH): 900 hPa; 26.58 inHg
Battery Cell	Type (Cont. / max. C) - charge state: LiPo 14000mAh - 30/45C - normal	Configuration: 3 S 1 P	Cell Capacity: 1400(mAh; 1400(mAh total	max. discharge: 85%	Resistance: 0.001 Ohm	Voltage: 3.7 V	C-Rate: 30 C cont.; 45 C max	Weight: 844 g; 29.8 oz
Controller	Type: CC Phoenix Edge HV 80	Current: 80 A cont.; 80 A max	Resistance: 0.001 Ohm	Weight: 125 g; 4.4 oz	Wire extension battery: AWG10=5.27mm²	Length: 0 mm; 0 inch	Wire extension motor: AWG10=5.27mm²	Length: 0 mm; 0 inch
Motor	Manufacturer - Type (Kv) - Cooling: E-flite - Power 25B (1250); medium; search...	KV (w/o torque): 1250 rpm/V; Prop-Kv-Wizard	no-load Current: 2 A @ 10 V	Limit (up to 15s): 58 A	Resistance: 0.02 Ohm	Case Length: 54 mm; 2.13 inch	# mag. Poles: 14	Weight: 183 g; 6.5 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 10 inch; 254 mm	Pitch: 6 inch; 152.4 mm	# Blades: 2	PConst / TConst: 1.08 / 1.0	Gear Ratio: 1 : 1	Flight Speed: 0 km/h; 0 mph	calculate



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FLIGHT TIME

Remarks:

Battery

Load:	2.77	C
Voltage:	10.96	V
Rated Voltage:	11.10	V
Energy:	155.4	Wh
Total Capacity:	14000	mAh
Used Capacity:	11900	mAh
min. Flight Time:	18.4	min
Mixed Flight Time:	20.9	min
Weight:	2532	g
	89.3	oz

Motor @ Optimum Efficiency

Current:	31.49	A
Voltage:	10.96	V
Revolutions*:	12418	rpm
electric Power:	345.0	W
mech. Power:	301.5	W
Efficiency:	87.4	%

Motor @ Maximum

Current:	38.80	A
Voltage:	10.92	V
Revolutions*:	12176	rpm
electric Power:	423.8	W
mech. Power:	369.4	W
Efficiency:	87.2	%
est. Temperature:	40	°C
	104	°F

Wattmeter readings

Current:	38.8	A
Voltage:	10.96	V
Power:	425.2	W

Propeller

Static Thrust:	1884	g
	66.5	oz
Revolutions*:	12176	rpm
Stall Thrust:	1216	g
	42.9	oz
avail.Thrust @ 0 km/h:	1884	g
avail.Thrust @ 0 mph:	66.5	oz
Pitch Speed:	111	km/h
	69	mph
Tip Speed:	583	km/h
	362	mph
specific Thrust:	4.45	g/W
	0.16	oz/W

Total Drive

Drive Weight:	3124	g
	110.2	oz
Power-Weight:	123	W/kg
	56	W/lb
Thrust-Weight:	0.54	: 1
Current @ max:	38.80	A
P(in) @ max:	430.7	W
P(out) @ max:	369.4	W
Efficiency @ max:	85.8	%
Torque:	0.29	Nm
	0.21	lbf.ft

Airplane

All-up Weight:	3500	g
	123.5	oz
Wing Load:	64	g/dm²
	21	oz/ft²
Cubic Wing Load:	8.7	
est. Stall Speed:	43	km/h
	27	mph
est. Speed (level):	102	km/h
	63	mph
est. Speed (vertical):	-	km/h
	-	mph
est. rate of climb:	5.8	m/s
	1135	ft/min

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Motor Partial Load

Propeller	Throttle	Current (DC)	Volage (DC)	el. Power	Efficiency	Thrust		Spec. Thrust		Pitch Speed		Speed (level)		Motor Run Time
rpm	%	A	V	W	%	g	oz	g/W	oz/W	km/h	mph	km/h	mph	(85%) min
1800	14	0.3	11.1	3.1	38.4	41	1.5	13.3	0.47	16	10	-	-	2549.5
2700	21	0.6	11.1	7.0	57.5	93	3.3	13.2	0.47	25	15	-	-	1130.9
3600	28	1.2	11.1	13.7	69.4	165	5.8	12.0	0.42	33	20	-	-	575.7
4500	35	2.2	11.1	24.3	76.6	257	9.1	10.6	0.37	41	26	-	-	325.0
5400	42	3.6	11.1	39.8	80.9	371	13.1	9.3	0.33	49	31	-	-	198.7
6300	49	5.5	11.1	61.1	83.6	504	17.8	8.3	0.29	58	36	-	-	129.2
7200	57	8.1	11.1	89.4	85.3	659	23.2	7.4	0.26	66	41	55	34	88.2
8100	64	11.4	11.1	125.8	86.4	834	29.4	6.6	0.23	74	46	68	42	62.6
9000	72	15.6	11.0	171.3	87.0	1029	36.3	6.0	0.21	82	51	75	47	45.9
9900	**80**	**20.7**	**11.0**	**227.0**	**87.4**	**1245**	**43.9**	**5.5**	**0.19**	**91**	**56**	**83**	**52**	**34.6**
10800	**88**	**26.8**	**11.0**	**294.2**	**87.5**	**1482**	**52.3**	**5.0**	**0.18**	**99**	**61**	**91**	**56**	**26.6**
11700	96	34.2	11.0	374.0	87.5	1739	61.4	4.7	0.16	107	66	98	61	20.9
12176	100	38.8	11.0	423.8	87.2	1884	66.4	4.4	0.16	111	69	102	63	18.4

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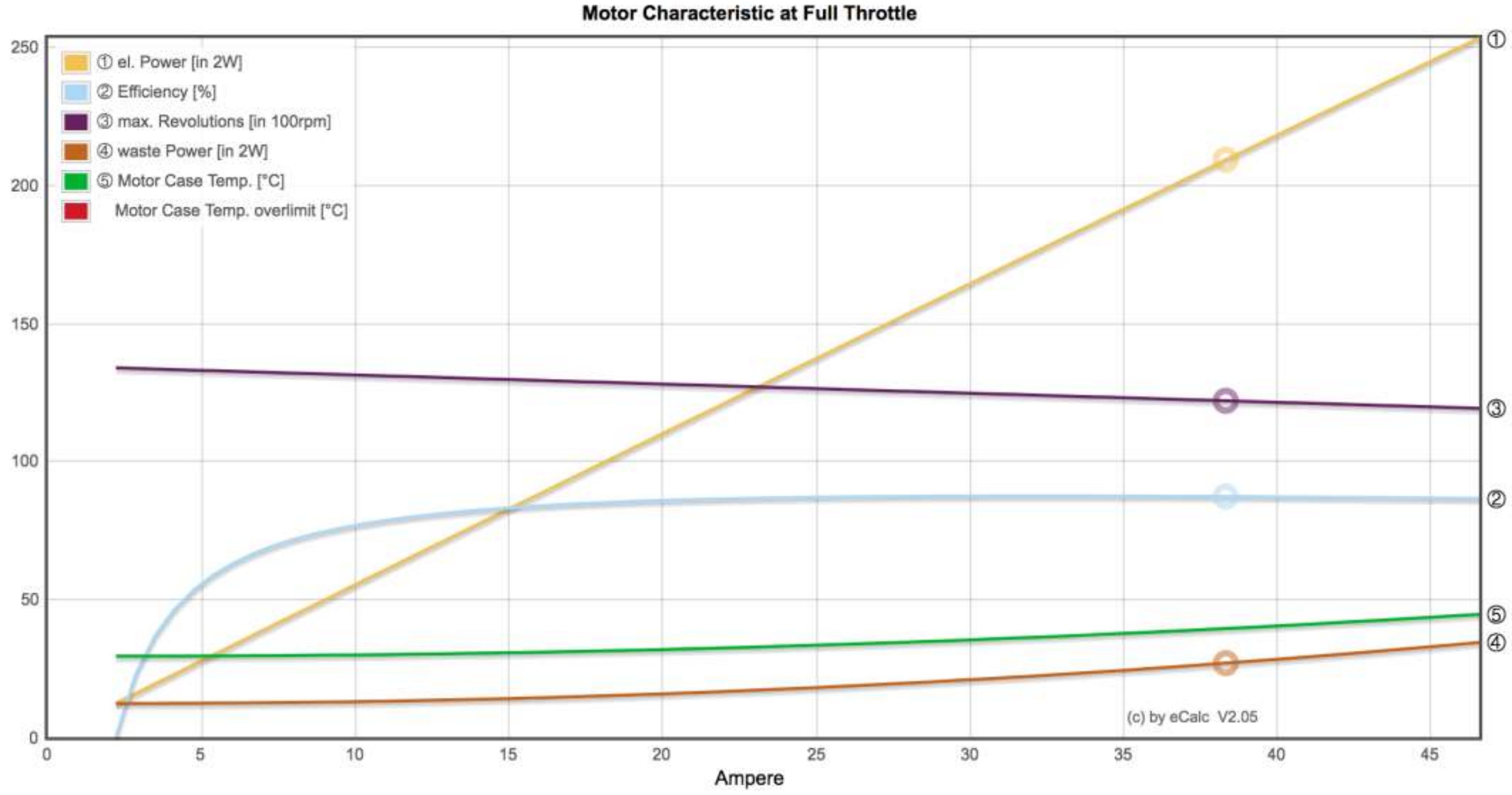
FLIGHT TIME



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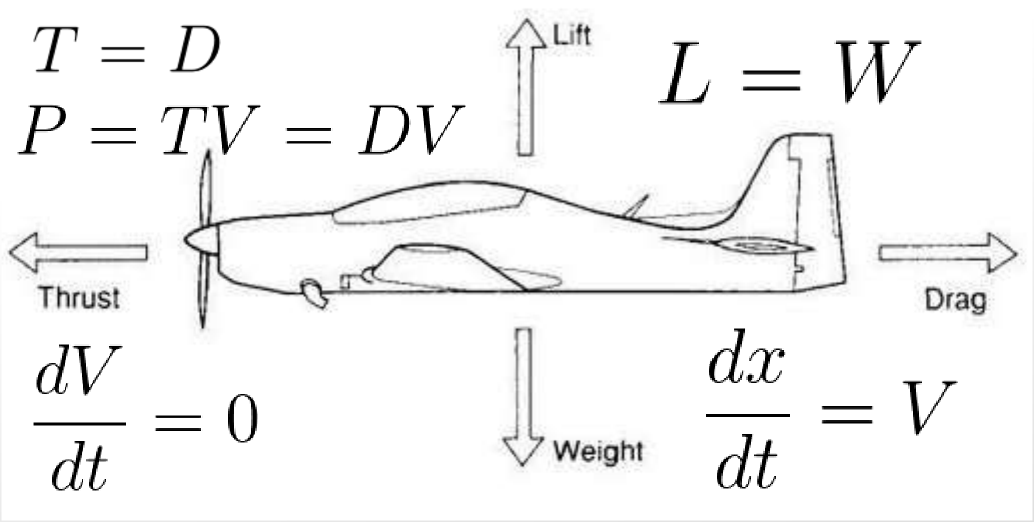
UAS MODEL

Foundational Questions

1. Can the selected UAS platform achieve a 60-minute flight time? Which airframes can/can't?
2. What is the upper limit of endurance for our UAS platform?
3. How can we optimize for minimum power consumption onboard the UAS?
4. How much will the UAS weigh given airframe and electronics? How heavy does the battery need to be? How much power is required?



Assumptions
E = 63 min (inc. 5% buffer)
Worst-case headwind is 10 m/s
Steady, level flight throughout
Battery discharge depth is 85%
Overall system efficiency is 85%

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UAS MODEL

Equations	Quantity [Units]
$m_b = \frac{C_b}{\sigma}$	Battery Mass [kg]
$W = g(m_e + m_{elec} + m_{fp} + m_b)$	Total Weight [N]
$C_{D,0} = \sum_{i=1}^{N} k_i c_{f_i} S_{wet_i}/S_{ref}$	Parasite Drag Coefficient [none]
$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V}\left(\frac{1}{\pi e b^2}\right)$	Power Required For Steady, Level Flight [W]
$P_{true} = \frac{P_{flight}}{\eta_{overall}}$	Propulsion System Power Required for Steady, Level Flight [W]
$E = 3600\eta_{overall}\frac{V_b D_b C_b}{P_{flight}}$	Endurance [s]

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UAS MODEL

Name	Variable	Value
Density	ρ [kg/m^3]	1.047
Wing Area	S [m^2]	0.545
Wingspan	*b [m]*	1.718
Efficiency Factor	e [%]	80
Propulsive Efficiency	$\eta_{overall}$ [%]	85
Battery Discharge Depth	D_b [%]	85
Endurance	E [min]	63
Capacity Density	σ [mAh/kg]	16600
Battery Voltage	V_b [V]	11.1

Name	Variable
Velocity	V [m/s]
True Power Req'd	P_{true} [W]
Parasite Drag Coeff.	$C_{D,0}$ *[none]*
Battery Weight	W_b [N]
Total Weight	W [N]
Total Drag	D [N]

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UAS MODEL

$$P_{flight} = TV = DV$$

$$P_{flight} = V(\frac{1}{2}\rho V^2 S)(C_{D,0} + \frac{C_L^2}{\pi e AR})$$

$$C_L = \frac{W}{\frac{1}{2}\rho V^2 S}$$

$$P_{flight} = \frac{1}{2}\rho V^3 S\left(C_{D,0} + \frac{W^2}{(\frac{1}{2}\rho V^2 S)^2}\left(\frac{1}{\pi e AR}\right)\right)$$

$$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)$$

$$P_{flight} = \frac{1}{2}\rho V^3 S C_{D,0} + \frac{W^2}{\frac{1}{2}\rho V}\left(\frac{1}{\pi e b^2}\right)$$

$$P_{true} = \frac{P_{flight}}{\eta_{overall}}$$

Can find $V_{min,PR}$ by setting $\frac{\partial P_{flight}}{\partial V} = 0$

$$\frac{\partial P_{flight}}{\partial V} = 0 = \frac{3}{2}\rho V^2 S C_{D,0} - \frac{W^2}{\frac{1}{2}\rho V^2}\left(\frac{1}{\pi e AR}\right)$$

$$V_{min,PR} = \left[\frac{4}{3}\left(\frac{W}{S}\right)^2\left(\frac{1}{\rho^2 C_{D,0}}\right)\left(\frac{1}{\pi e AR}\right)\right]^{\frac{1}{4}}$$

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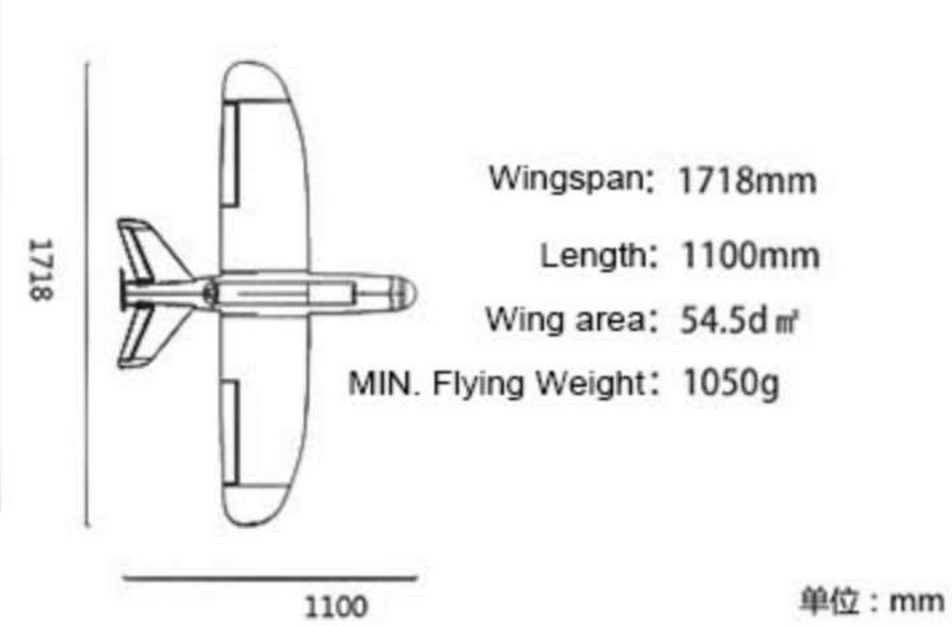
UAS MODEL

Parameters

<u>Well-Known Parameters</u>
- S - Wing Area (given by manufacturer, easy to measure)
- AR - Wing Aspect Ratio (easy to measure b (wing span) and then calculate)
- W - Total Weight (easy to measure on a scale)
- E - Endurance (easy to measure with a timer)

<u>Unknown Parameters, Fairly Easy to Measure</u>
- ρ - Air Density (Take temp + pres measurements)
- V - Airspeed (use total + static pressure from pitot tube measurement)

<u>Unknown Parameters, Difficult to Measure</u>
- CD,0 - Parasitic Drag Coefficient (difficult to estimate and measure)
- e - wing efficiency factor (difficult to measure/estimate)



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UAS MODEL

Most Impactful Parameters

Which parameters will have the largest impact upon the Power Required (and hence endurance?)

- $V \rightarrow V^3$ in first term, $1/V$ in second term (Which terms will dominate for given airframes? How much effect does a given velocity increase have on required power?)
- $W \rightarrow W^2$ in second term (how much of a power increase is required for a given weight increase?)
- $b \rightarrow 1/b^2$ in second term (does increasing wingspan (also increases weight) produce an appreciable decrease in required power?)
- η - Overall efficiency of the propulsion system could be extremely low

Less important parameters

- $C_{D,0}$ - wide range of values, could significantly impact power required

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UAS MODEL

Drag Buildup

$$C_{D,0} = \sum_{i=1}^{N} k_i c_{f_i} S_{wet_i} / S_{ref}$$

k is form factor
c_f is skin friction coefficient
S_{wet} is wetted area
N = 3 (wing, fuselage, tail)
$S_{ref} = S_{wing}$

$$c_f = \frac{0.455}{(\log_{10}(Re_L))^{2.58}}$$

$$Re_L = \frac{\rho V L}{\mu}$$

$k = 1 + 2(t/c) + 60(t/c)^4$ Wing and Tail

$k = 1 + 1.5(d/l)^{1.5} + 7(d/l)^3$ Fuselage

$S_{wet} = 2(1 + 0.2(t/c))S_{ref}$ Wing and Tail

$S_{wet} = 2\pi(d/2)^2 + \pi d l$ Fuselage

$$C_{D,0} = C_{D,0,wing} + C_{D,0,fuselage} + C_{D,0,tail}$$

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UAS MODEL

RECUV Talon Drive System

Component	Type
Motor	E-Flite Power 25BL (1250 Kv)
Battery	Thunder Power RC TP7000-3SH (14000 mAh)
ESC	Phoenix Edge HV 80A
Propeller	APC 9x7 10x7

- RECUV operates XUAV Talon in long-endurance configuration with suite of sensors and antennas
- Serves as excellent point of reference for RAMROD Talon-based UAS

60 min+ Flight time is feasible on this airframe

RECUV Talon Overview

Component	Weight [g]
Battery Weight [g]	**422 (x2)**
Total Weight [g]	**3343**
Motor Power Rating [W]	**700 (1250 Kv)**
Motor Power Rating [W]	**700 (1250 Kv)**
Battery Capacity [mAh]	**7000 3S 11.4 V (x2)**
Optimal Cruise Speed [m/s]	**14-17**
Endurance [min]	**60-90**

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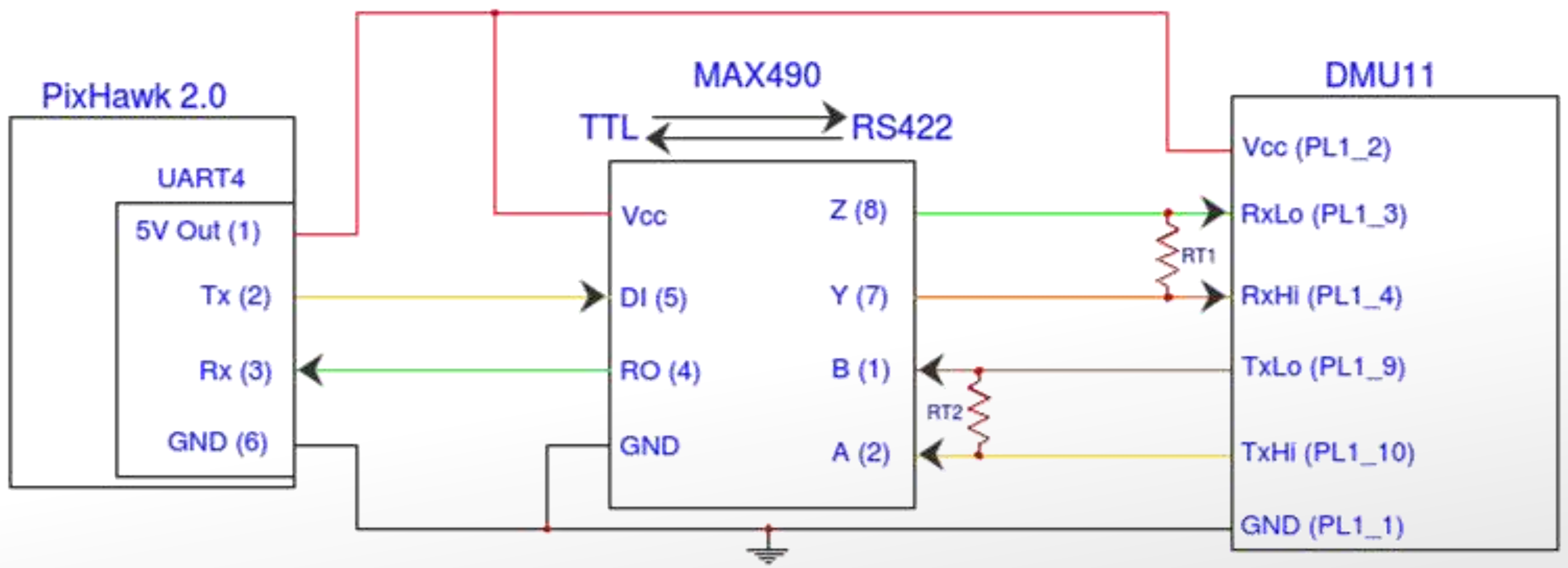
DMU11 INTERFACE



PIN GUIDE: PixHawk

PixHawk 2.0:
- 5V Out = 5V supply to sensor
- Tx = UART transmit output
- Rx = UART receive input
- GND = Ground

PIN GUIDE: MAX490

MAX490:
- A = Non-inverting receiver input
- B = Inverting receiver input
- Y = Non-inverting driver output
- Z = Inverting driver output
- DI = Driver input
- RO = Receiver output
- Vcc = Supply voltage
- GND = Ground

PIN GUIDE: DMU11

DMU11:
- RxLo = Negative receive
- RxHi = Positive receive connection
- TxLo = Negative transmit connect
- TxHi = Positive transmit connection
- Vcc = Supply voltage
- GND = Ground
- RT = Termination resistor (120Ω)

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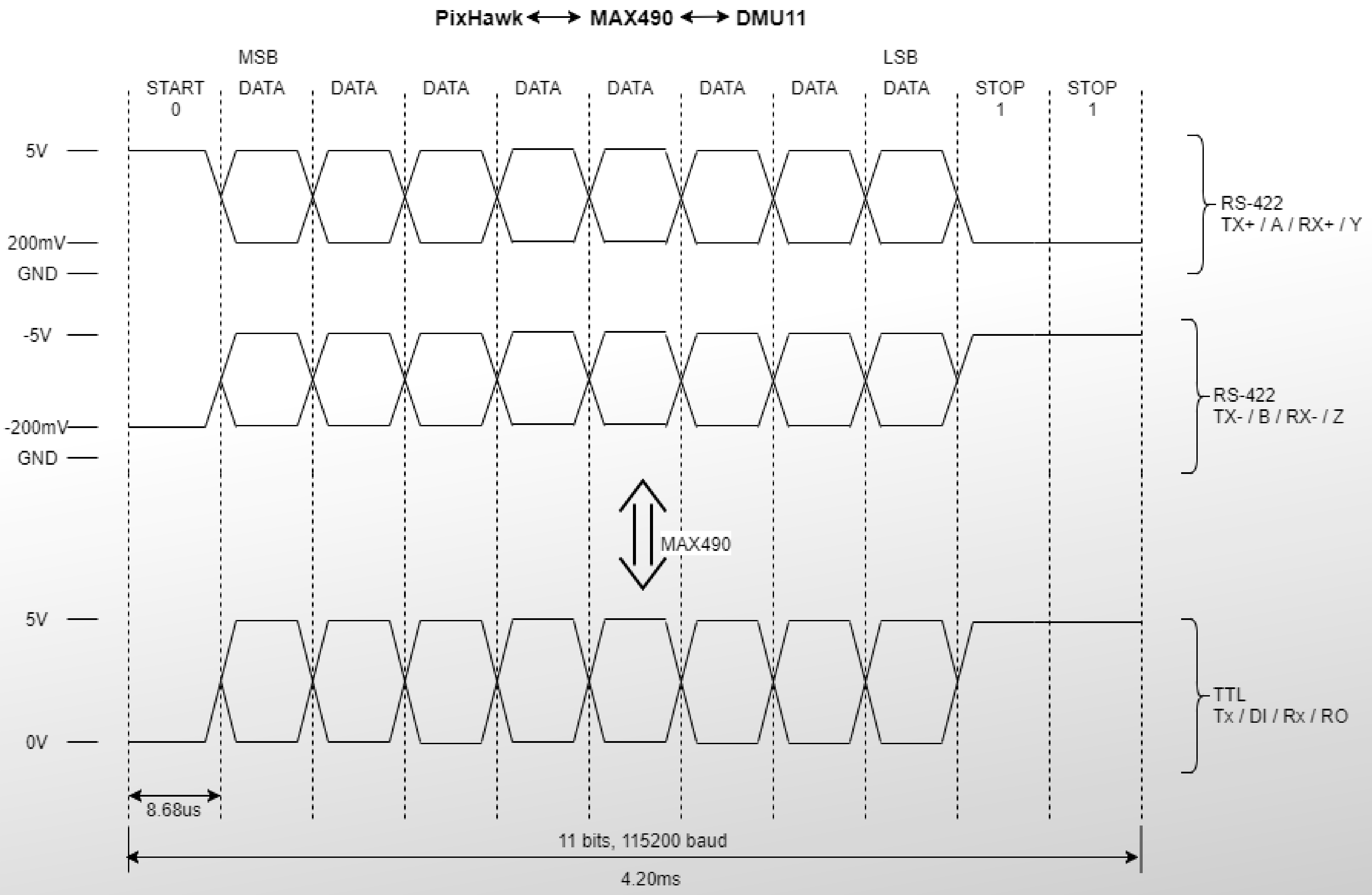
DMU11 INTERFACE



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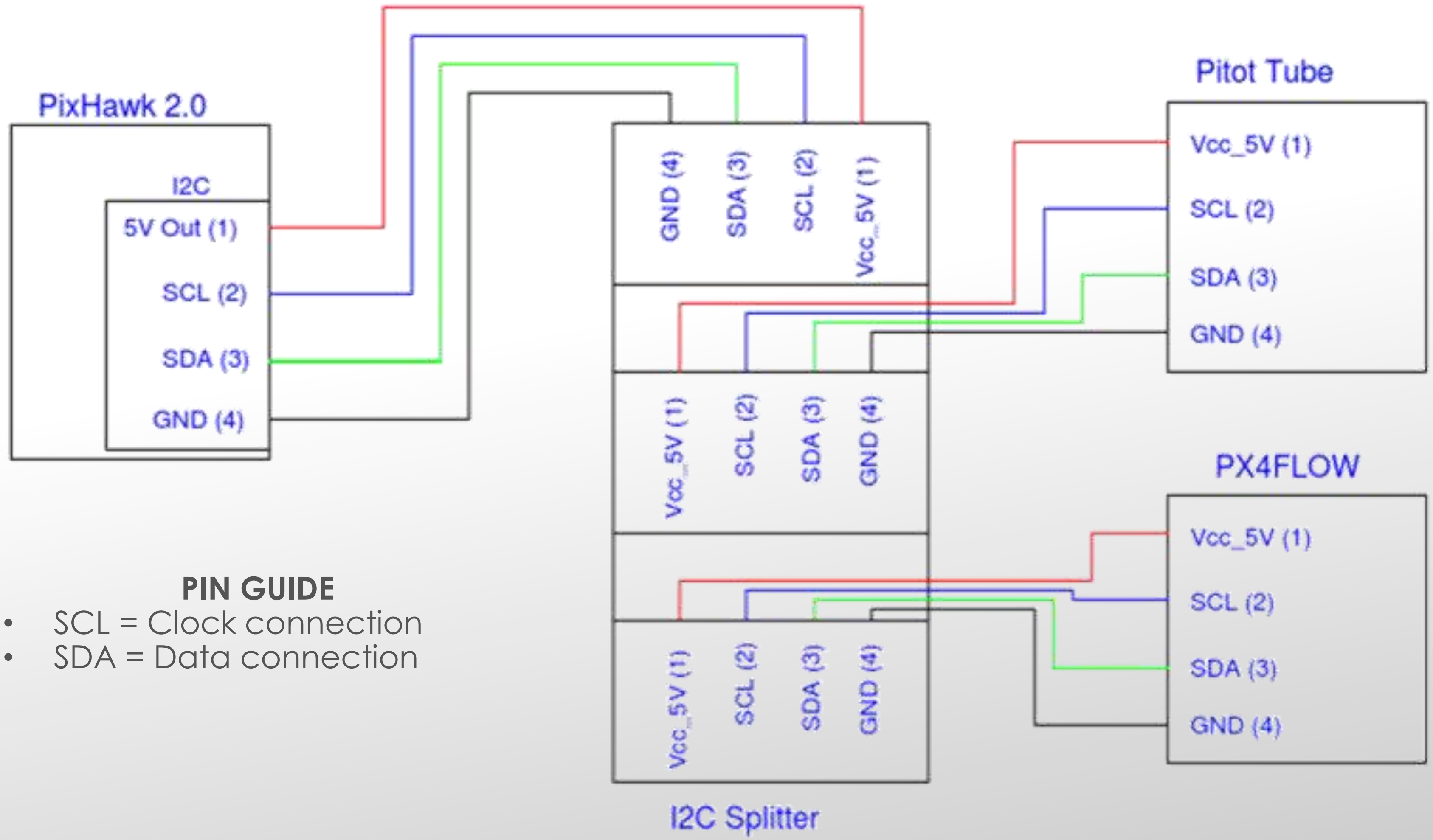
PX4FLOW / PITOT TUBE INTERFACE



PIN GUIDE

- SCL = Clock connection
- SDA = Data connection

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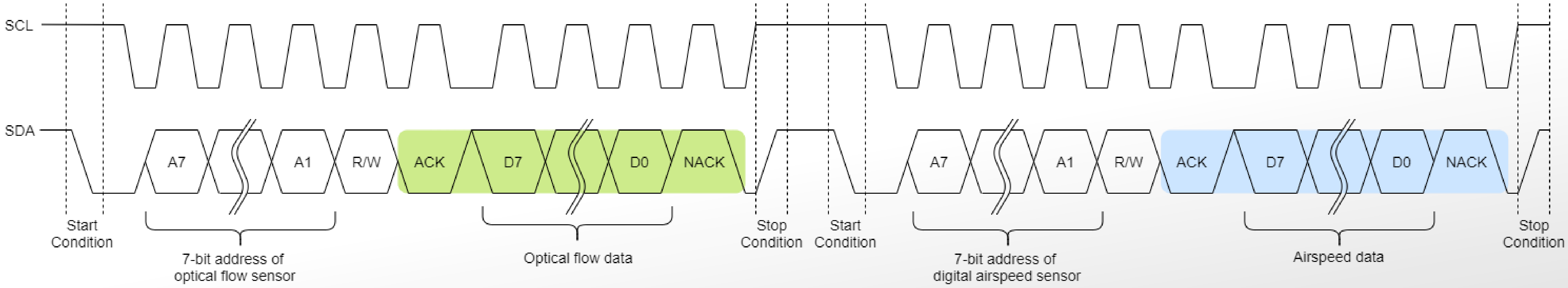
PX4FLOW / PITOT TUBE INTERFACE

PixHawk I2C Master Receive Operation



Example data transmission, switching between the flow sensor and airspeed sensor through the I2C splitter

No color: Sent by PixHawk
Sent by flow sensor
Sent by airspeed sensor

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RISK ANALYSIS - RISK 1

Severity: 4 **Likelihood: 3** **Total: 12**

Description: The noise in the downlink of the AGC data makes the UAS appear as if it has not yet entered the sphere of influence of the PPD and it will continue to trust it's GPS even if it shouldn't. It will also tell the UAS not to trust its GPS if it can

Mitigation Options:

- Downlink the data during different times of the day to try and find the time of day that downlinking the data is the most difficult to ensure that the UAS can downlink in the worst case scenario

Post Mitigation Risk Analysis

Severity: 2 **Likelihood: 2** **Total: 4**

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RISK ANALYSIS - RISK 3

Severity: 4 **Likelihood: 2** **Total: 8**

Description: The UAS could have structural damage when it lands. This damage could be severe enough to force the team to buy a replacement part.

Mitigation Options:

- Skid plates have been added to the bottom of the UAS so when the UAS lands, the fuselage will not hit the ground
- Structural analysis of the airframe has been conducted to ensure that the structure can handle a significant load

Post Mitigation Risk Analysis

Severity: 2 **Likelihood: 2** **Total: 4**

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RISK ANALYSIS - RISK 5

Severity: 5 **Likelihood: 2** **Total: 10**

Description: While testing the UAS, it flies out the line of sight and the team is unsure about where it is

Mitigation Options:

- A "Return Home" function will be implemented so that this problem doesn't happen
- An HD camera has been added to the front of the UAS and the pilot of the UAS will be able to see what the UAS sees if they take manual control

Post Mitigation Risk Analysis

Severity: 1 **Likelihood: 2** **Total: 2**

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RISK ANALYSIS - RISK 6

Severity: 3 **Likelihood: 3** **Total: 9**

Description: The simulations the team uses with simulated data don't behave the same as real life and some of the items the team bought will no longer be adequate for the project

Mitigation Options:

- Simulations have been run using data from real flights to show that the parts selected should be adequate
- Margins have been built into the budget along with duplicate parts being ordered in order to avoid this. The biggest concern is if the IMU gets destroyed

Post Mitigation Risk Analysis

Severity: 2 **Likelihood: 1** **Total: 2**

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RISK ANALYSIS - RISK 7

Severity: 3 **Likelihood: 3** **Total: 9**

Description: If the AGC can't downlink then a power profile of the signal source will not be able to be replicated at the ground station and the localization will not be possible

Mitigation Options:

- Test during different times of the day with varying bandwidth traffic to ensure that our downlink will work during the busiest time of the day
- Ensure that the AGC data and positional data get sent down before the IF data in order to generate the power profile

Post Mitigation Risk Analysis

Severity: 3 **Likelihood: 1** **Total: 3**

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FAA POLICY

1. Pilot must have eyes on the UAS at all times.
2. Manual controls must be ready and available at all times.
3. Flight paths may not be within a 5 mile radius of an airport unless the airport has been notified and has approved of the flight path.
4. Flight must be under 400 ft. altitude.
5. The Aircraft must remain under 55 lbs.

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EKF2 TUNING

- Pitot Tube
  - EK2_EAS_NOISE
  - EK2_EAS_GATE
- Optical Flow
  - EK2_MAX_FLOW
  - EK2_FLOW_NOISE
  - EK2_FLOW_GATE
  - EK2_FLOW_DELAY
- IMU
  - EK2_GYRO_PNOISE
  - EK2_ACC_PNOISE
  - EK2_GBIAS_PNOISE
  - EKF2_GSCL_PNOISE
  - EK2_ABIAS_PNOISE

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EKF2 STATES

- Attitude (Quaternions)
- Velocity (North, East, Down)
- Position (North, East, Down)
- Gyro bias offsets (X,Y,Z)
- Gyro bias factors (X,Y,Z)
- Z acceleration bias
- Earth magnetic field (X,Y,Z)
- Body magnetic field (X,Y,Z)
- Wind velocity (North, East)

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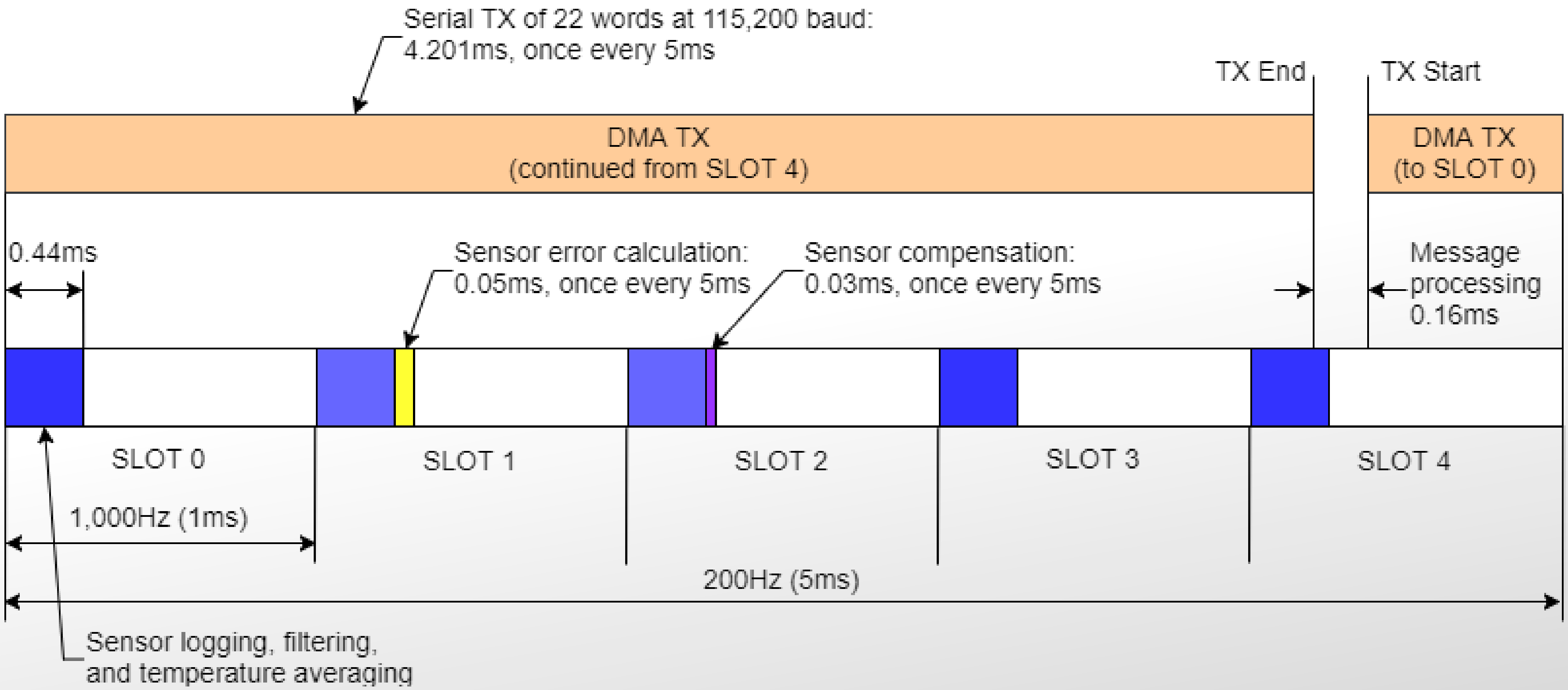
DMU11 DATA TRANSMISSION



Message Contents

Word	Data Item
0	Header
1	Message Count
2-3	X-Axis Angular Rate
4-5	X-Axis Acceleration
6-7	Y-Axis Angular Rate
8-9	Y-Axis Acceleration
10-11	Z-Axis Angular Rate
12-13	Z-Axis Acceleration
14-15	Reserved
16-17	Average IMU Temperature
18	System Start-up BIT Flags
19	System Operation BIT Flags
20	Reserved
21	Checksum

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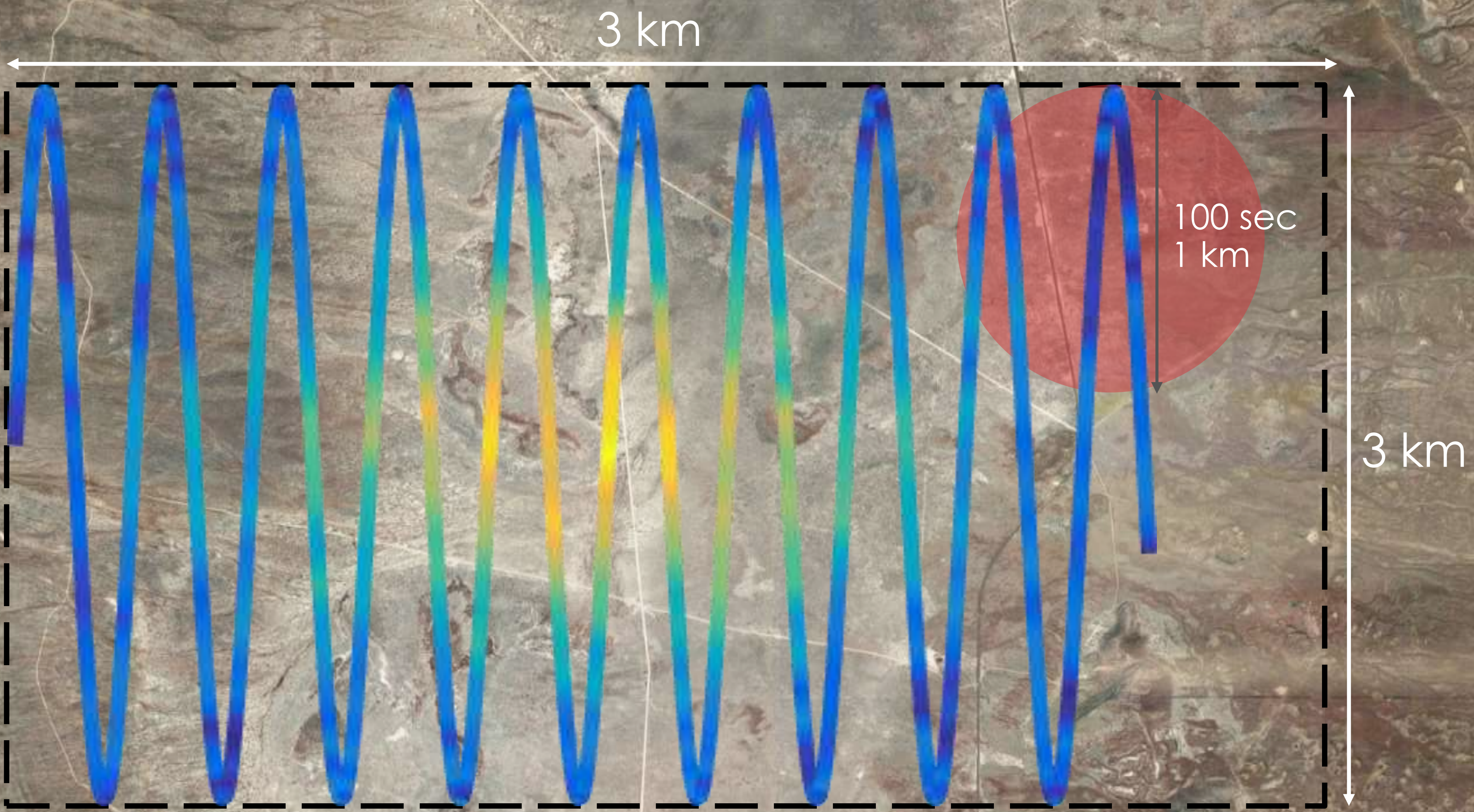
Maximum Time in GPS Denied Conditions



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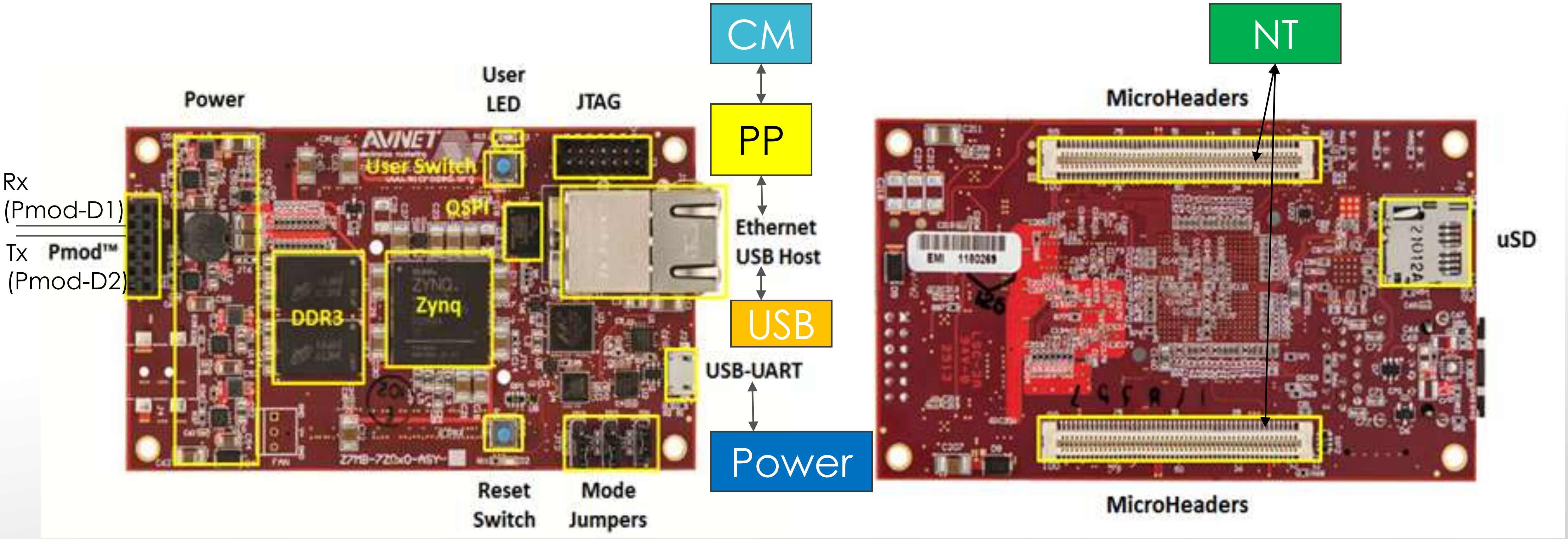
MICROZED WIRING AND CONNECTIONS



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BUDGET BREAKDOWN

Item	Quantity	Cost per Unit (USD)	**Total Cost (USD)**
UAS Components			
XUAV Talon Airframe	2	125	250
Pixhawk 2.1 w/cube	1	200	200
E-Flight Power 25 BL Motor	1	70	70
E-Flight 60-Amp Pro Switch-Mode	1	85	85
TP7000-3SHV Battery	2	100	200
Garmin LiDAR Lite	1	150	150
Eagle Tree Prandtl Pitot Tube Kit	2	9	18
Pixhawk Digital Airspeed Sensor	1	52	52
Pixhawk PX4Flow	1	100	125
APC10x7 Propeller	3	3	9
AR7700 Serial Receiver	1	60	60
Spectrum Dx6i Transmitter	1	200	200
TTL 3DR Radio Telemetry kit	1	36	36
Mobius HD ActionCam	1	65	65
Here GPS Reciever	1	48	58
HS-5065MG Wing Servos	4	31	124

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BUDGET BREAKDOWN

Item	Quantity	Cost per Unit (USD)	**Total Cost (USD)**
HS-5055MG Tail Servos	4	18	72
DMU11 INS	1	360	360
Battery Charger and Case	1	113	113
UAS Total			**2247**
Payload Components			
MicroZed	1	220	220
Nt1065	1	500	500
PCB	1	30	30
2200mAh USB Battery Pack	1	15	15
TW7872 GPS Antenna	1	400	400
Nylonx Carbon Fiber Filament	2	75	150
Payload Total			**1315**
Materials			
Misc. Electronics			200
Testing			30
Project Total			**3792**
Margin			**1208**

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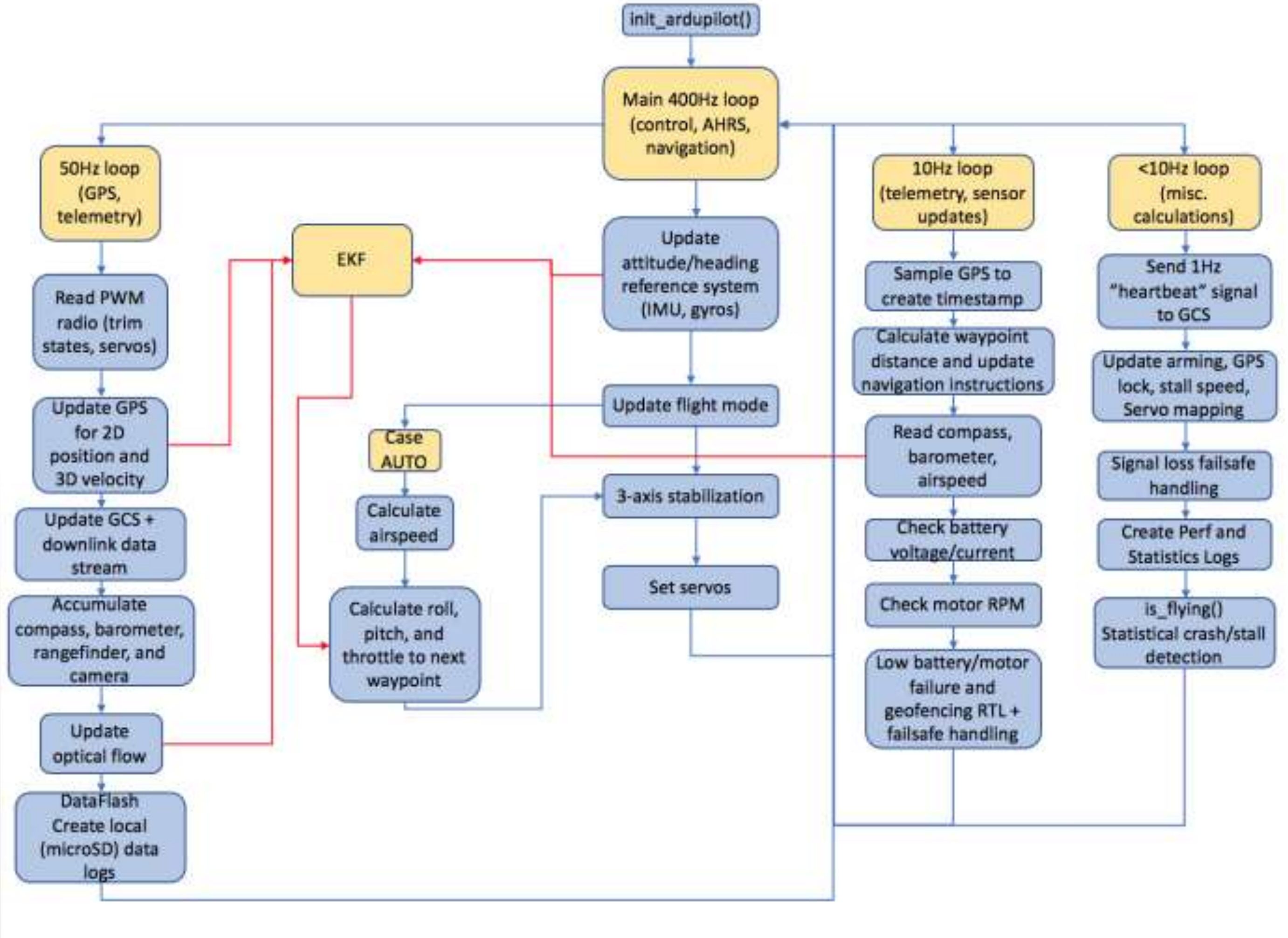
ARDUPILOT - AUTO



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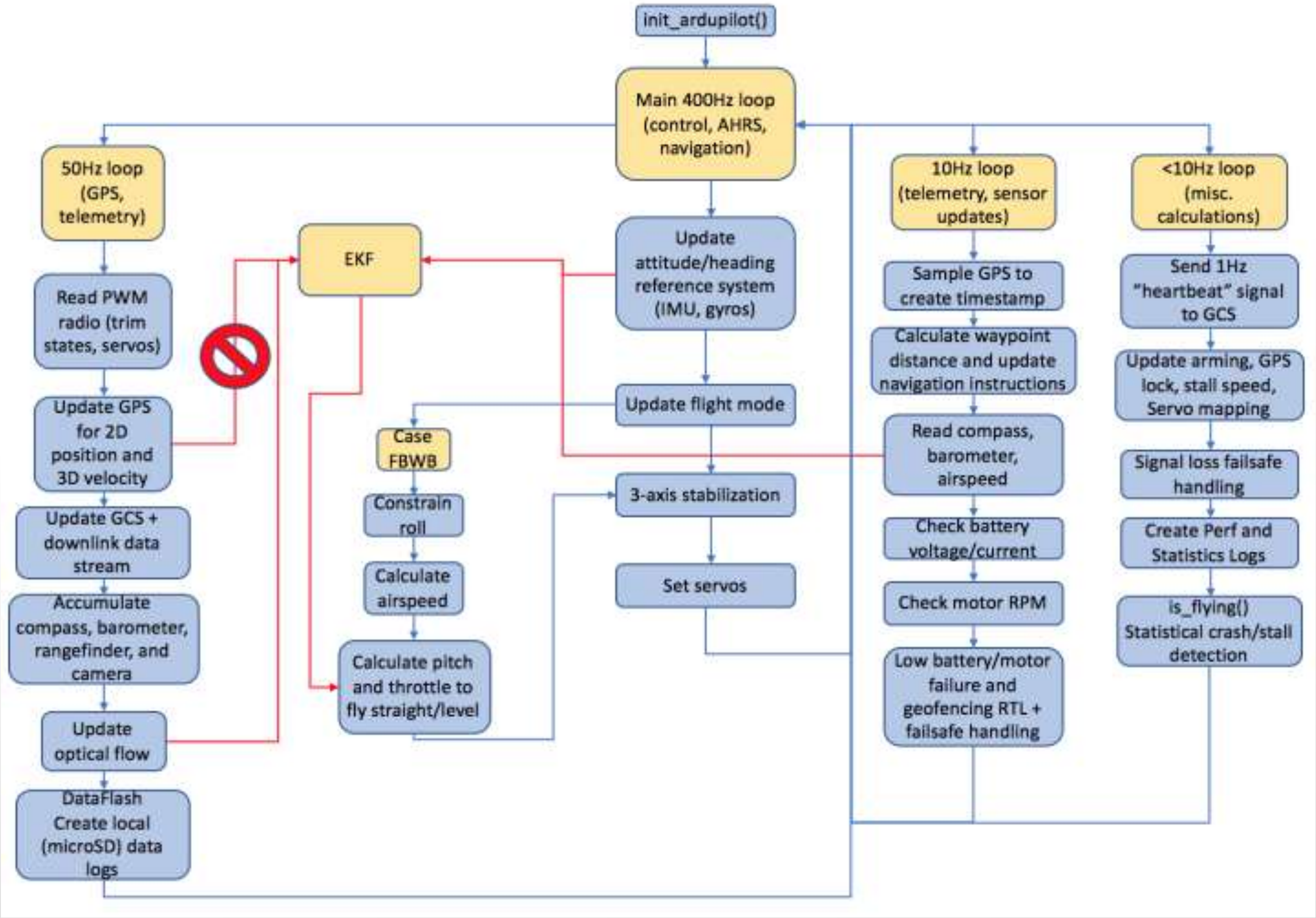
ARDUPILOT -FBWB



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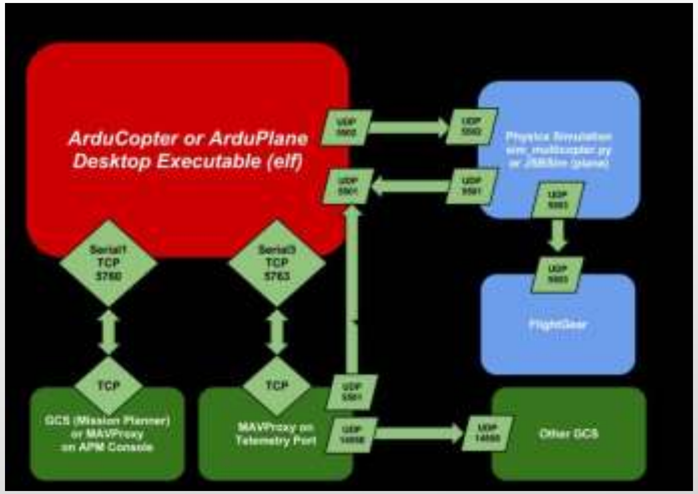
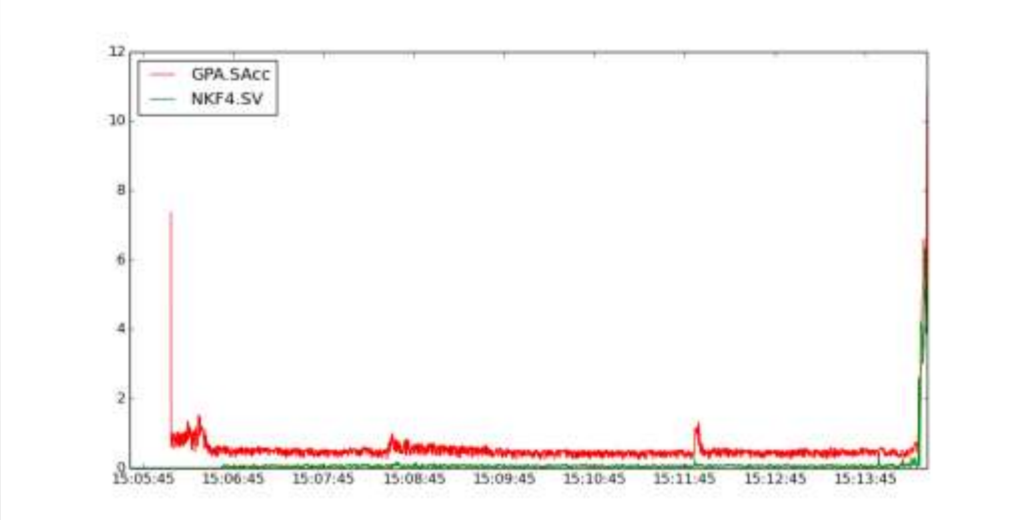
MODIFIED ARDUPILOT
SIMULATIONS – SOFTWARE IN THE LOOP

MavProxy
- Runs autopilot code in real time natively on Windows/Linux
- Sensor data estimated based on predictive modeling
- Useful to test/debug code changes
- Access to full range of C++ debuggers
- Can test physical sensors using serial connections



Replay
- Use DataFlash to simulate flight using actual flight data, with changed parameters
- Useful for testing flight-mode switch with actual data
- EKF tuning



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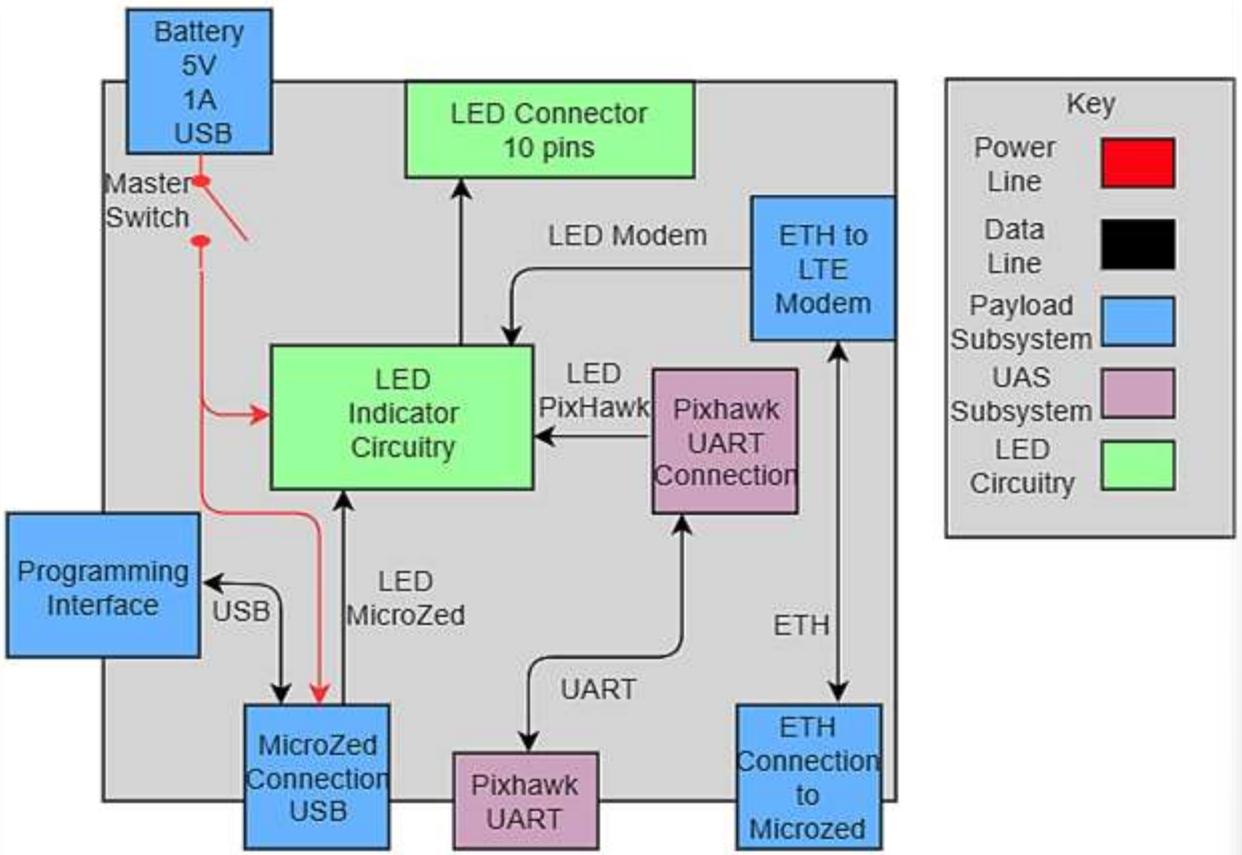
BACK UP - OPERATIONAL PAYLOAD
INTERFACE BOARD



Interface Board – PCB Design

Splits power between different systems in payload

Connection between MicroZed and PixHawk

LED Indicators to verify connections

Programming access to MicroZed

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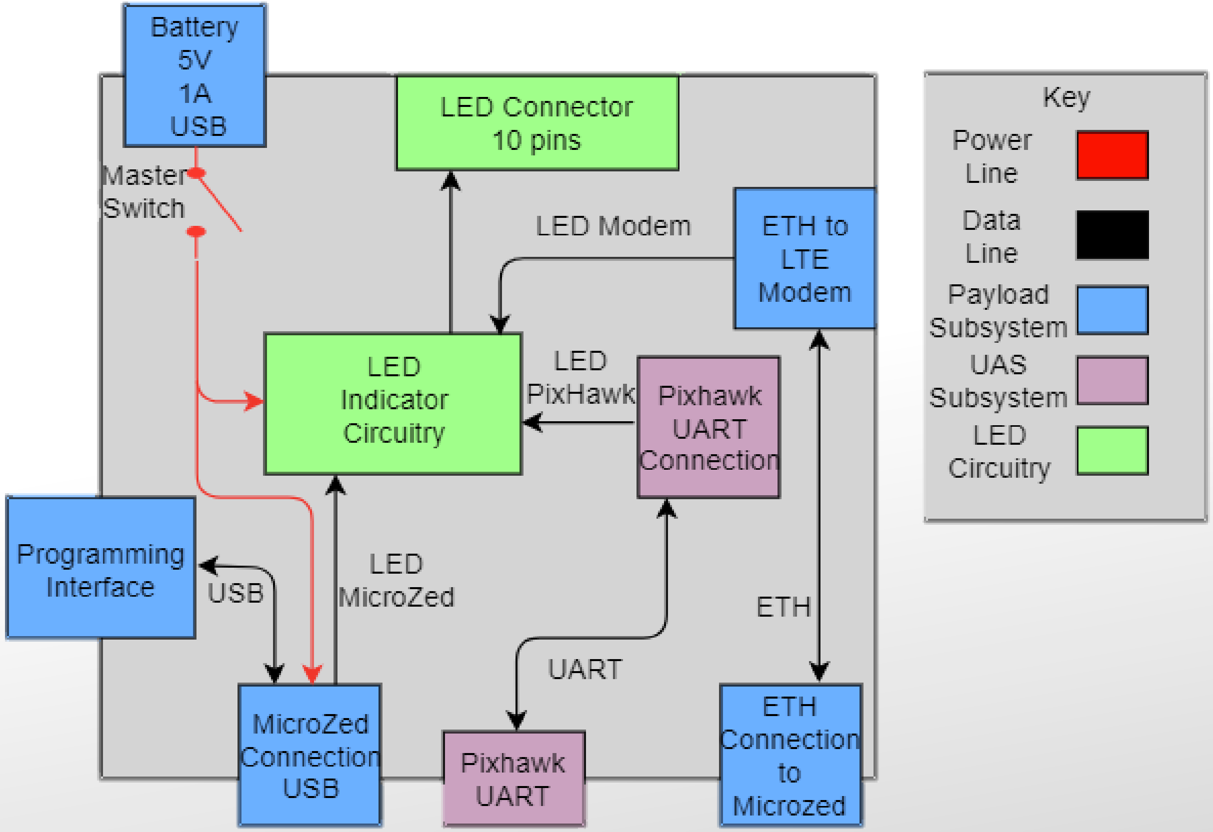
BACK UP – INTERFACE BOARD CONNECTIONS



Interface Board – PCB Design

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Programming access to MicroZed

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OPTICAL FLOW CALCULATIONS

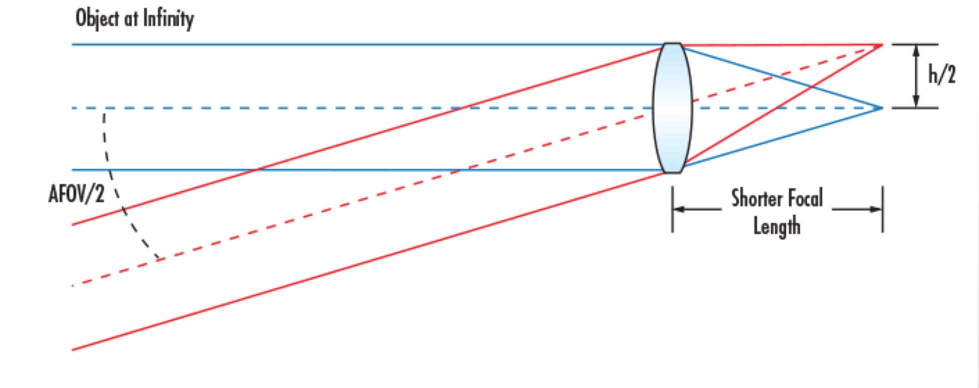
Pixel Size $p = 6.0 \text{ x } 6.0\ \mu\text{m}$

Focal length $f = 16$ mm

Resolution = 480 x 752 pixels

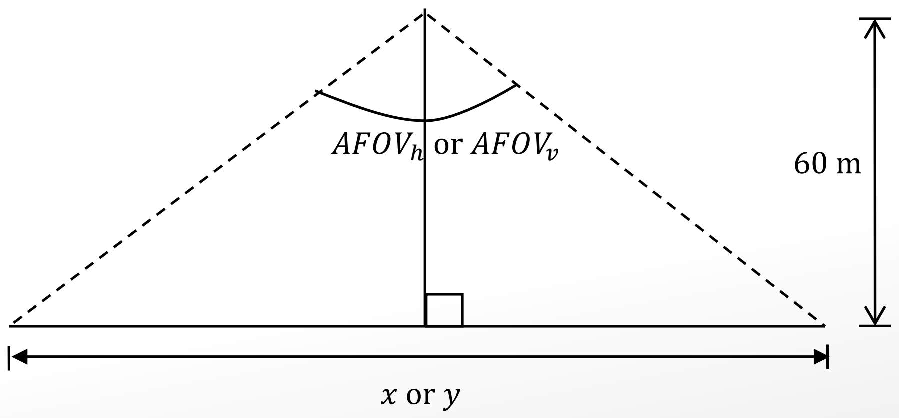
$w = (480 \text{ pixels})(6.0\ \mu\text{m}) = 2.88 \text{ mm}$

$h = (752 \text{ pixels})(6.0\ \mu\text{m}) = 4.512 \text{ mm}$



$$AFOV_h = 2\tan^{-1}\left(\frac{w}{2f}\right) = 10.26°$$

$$AFOV_v = 2\tan^{-1}\left(\frac{h}{2f}\right) = 16.05°$$



$$\boxed{x = 2(60 \text{ m})\tan\left({}^{AFOV_h}/_2\right) = 10.8 \text{ m}}$$ Horizontal distance seen

$$\boxed{y = 2(60 \text{ m})\tan\left({}^{AFOV_v}/_2\right) = 16.9 \text{ m}}$$ Vertical distance seen

$$\boxed{x_{res} = y_{res} = \frac{x}{w} = \frac{y}{h} = 0.0225 \text{ m/pixel}}$$ Resolution

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IMU HARDWARE

DMU11 From Silicon Sensing

- Gyro bias = +/- 0.25 deg/s
- Gyro bias drift = +/- 0.025 deg/s
- Gyro bias instability < 10 deg/hr
- ARW < 0.4 deg/sqrt(hr)
- Acc. bias = +/- 3.0 mg
- Acc. bias drift = +/- 1.0 mg
- Acc. bias instability < 0.05 mg
- VRW < 0.05 m/s/sqrt(hr)
- Size: 22 x 22 x 10.6 mm
- Mass: 24 g
- Cost: $359.00 (including evaluation kit)

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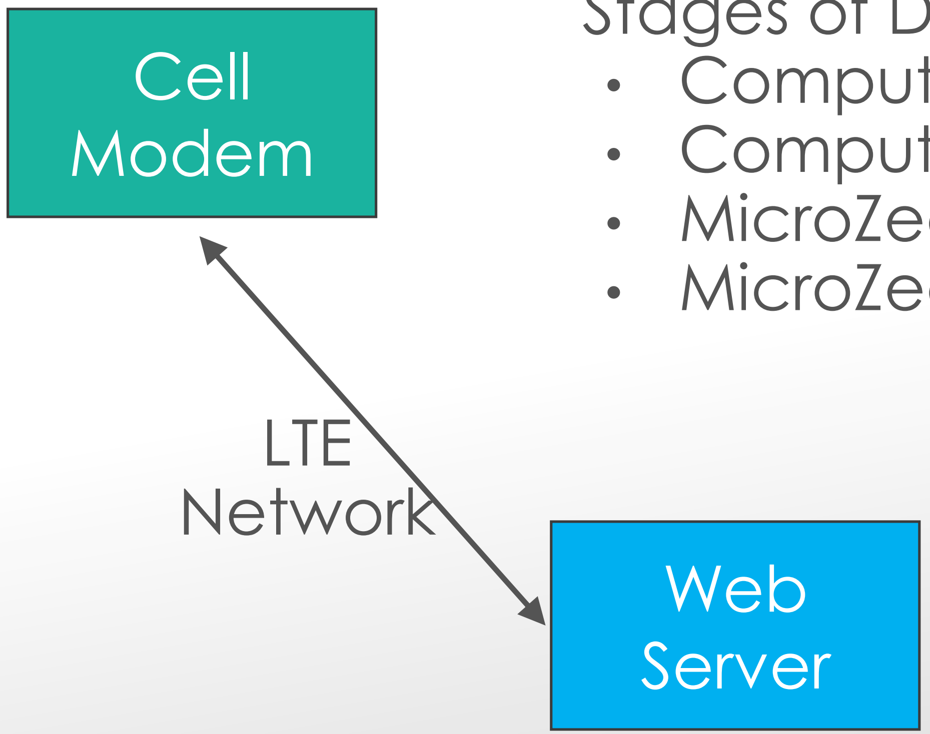
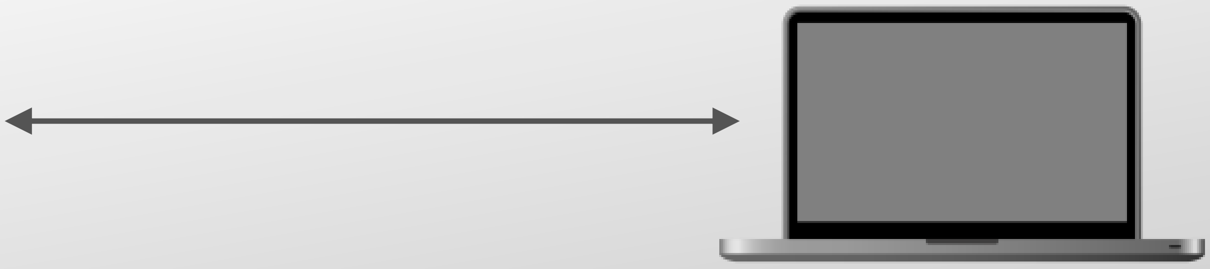
V&V DATA TRANSFER TESTING METHOD

Stages of Data Transfer testing

- Computer to Computer with Wifi (sine wave)
- Computer to Computer with 64 bit counter
- MicroZed to Computer
- MicroZed to Server to Computer via cell network





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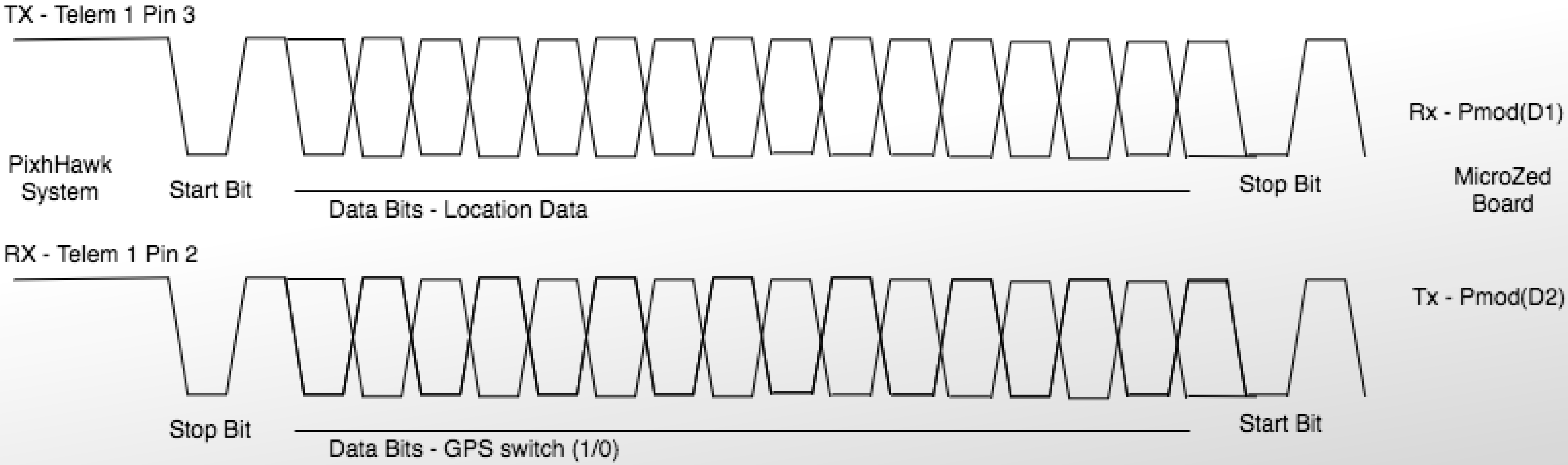
TIMING DIAGRAM



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DESIGN SOLUTION

Parameter	Value
Takeoff Weight	3471 g
Wing Span	1.718 m
Battery Capacity	14000 mAh
Maximum Flight Endurance	92 min
RFI Sampling Rate	3 Hz
GPS Sample Rate (location)	10 Hz
Max Data Transfer Rate to Ground	10 Mbps
Cruise Speed	14.4 m/s
Cruise Altitude	60 m

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TAKE OFF & LANDING

Take Off

Manual
- Initial testing
- Hand launch w/ transmitter

Autonomous
- Deliverable
- Bungee or hand launch

Landing

Manual
- Testing/Emergency
- Controlled using transmitter

Autonomous
- Deliverable
- Controlled using PixHawk

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OPERATIONAL TEMPERATURES

Component	Minimum Temperature (C)	Maximum Temperature (C)
MicroZed	-40	80
NT1065	-40	85
Battery	-20	60

The openings in the box will allow for heat dissipation and keep the components within the operating temperatures.

Requirements	Satisfaction
DR 11.3: The temperature inside the operational payload shall stay within the operating temperature of all electronic components contained	The operational temperatures of the components will not go outside their operating temperature.

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