FLAME Test Readiness Review

The Fire Limiting Aerial Management Ensemble:

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Project Overview

Mission Objective

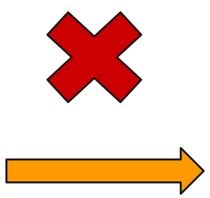
- Autonomously fly to and from locations of interest through an Unmanned Aerial System (UAS)
- Drop payloads of mock fire retardant in targets at locations of interest to show proof of concept of a fire prevention UAS

Mission Challenges

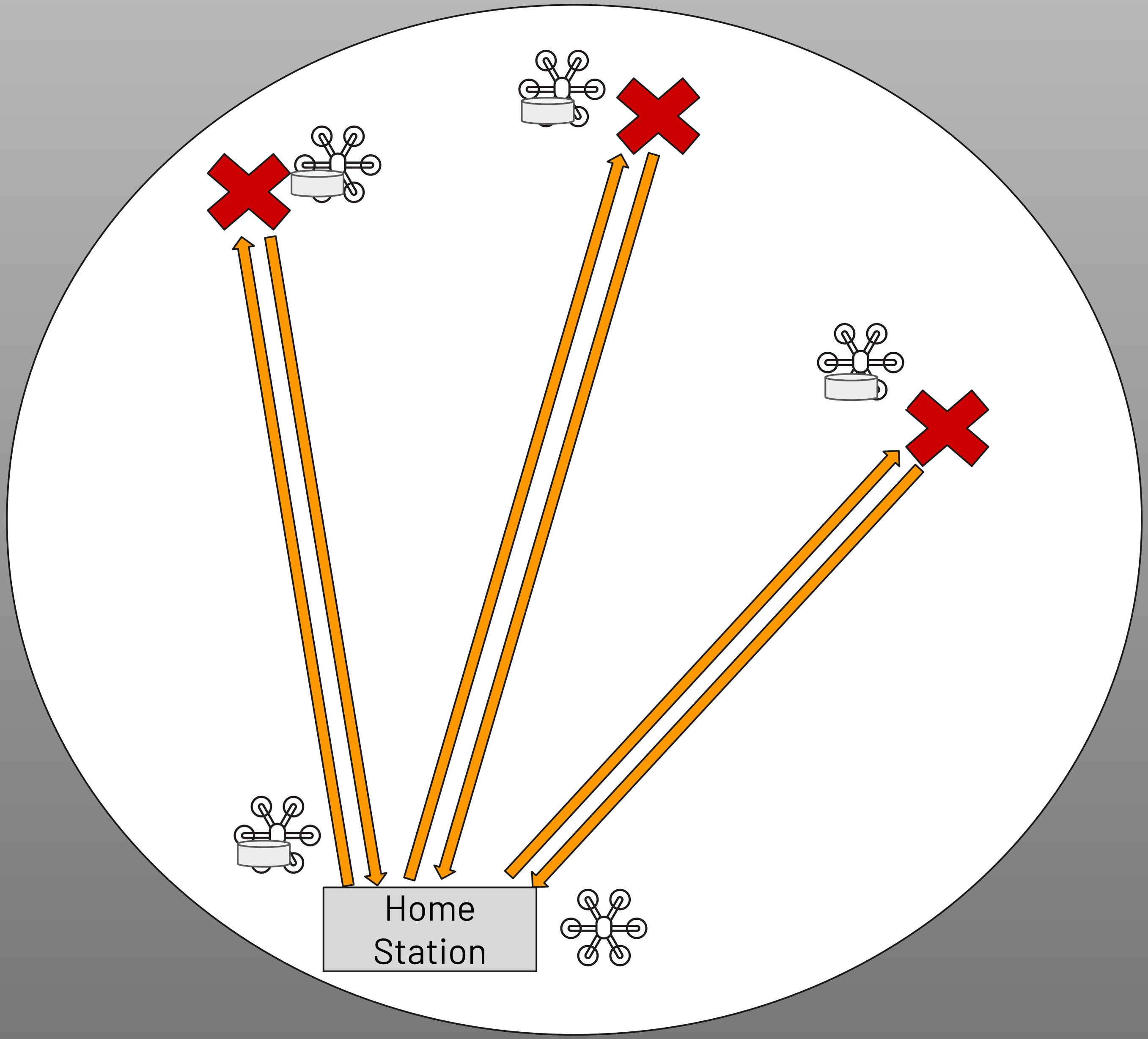
- Deploy water payload within 1 meter accuracy of 3 given target locations in 20 minutes
- Autonomous takeoff, flight, and landing capabilities, with ability for human-in-the-loop takeover
- Support at least 5 pounds of payload through takeoff and flight

FLAME Autonomous Firefighting UAS High Level ConOps

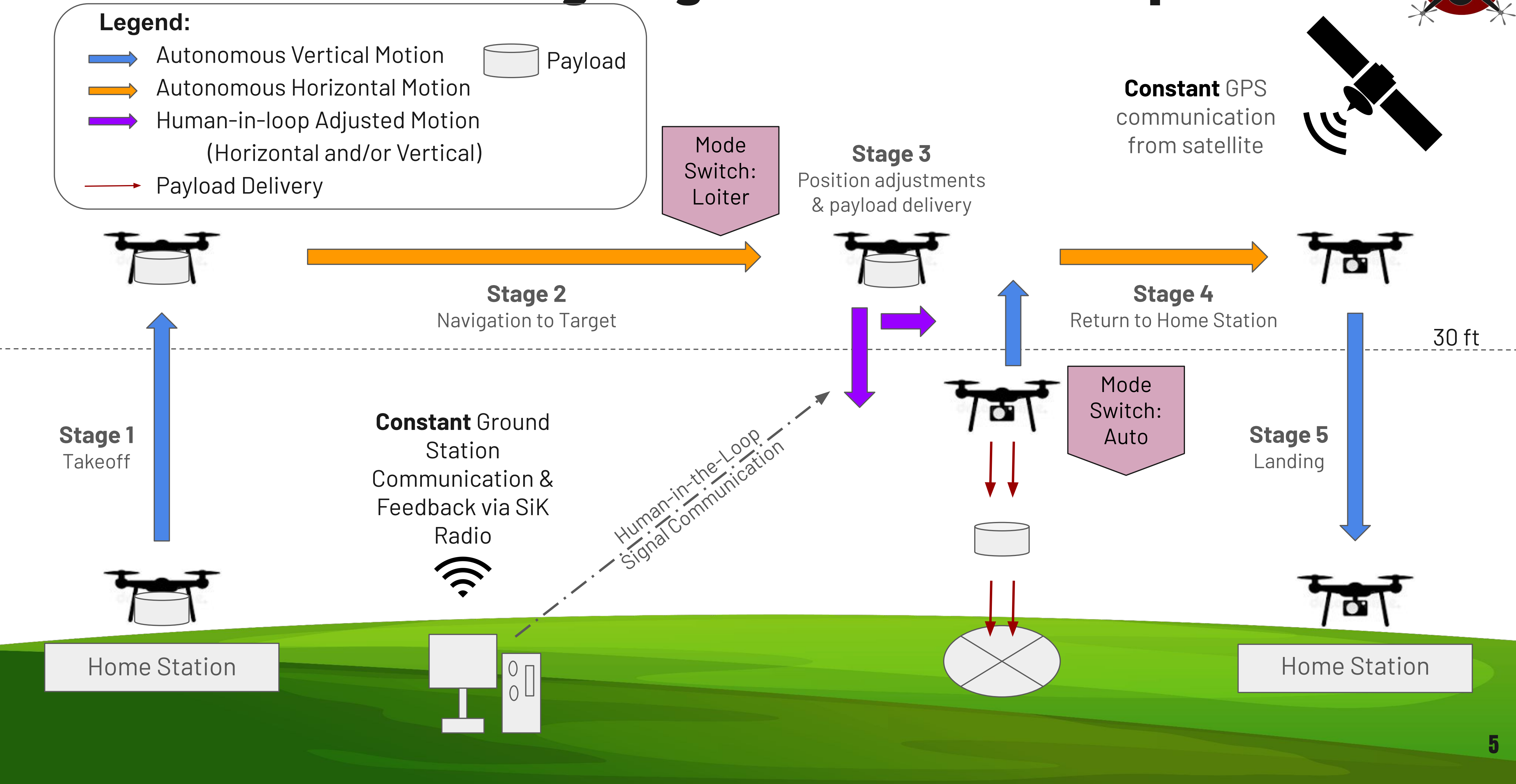
Legend:



- 100 meter diameter mission zone
- Given a home base location within mission zone
- Given GPS coordinates of three target locations
- Travel to target location
- Deploy payload
- Return to home station
- Ground team reloads a new 5 pound payload
- Repeat for 2 additional target locations



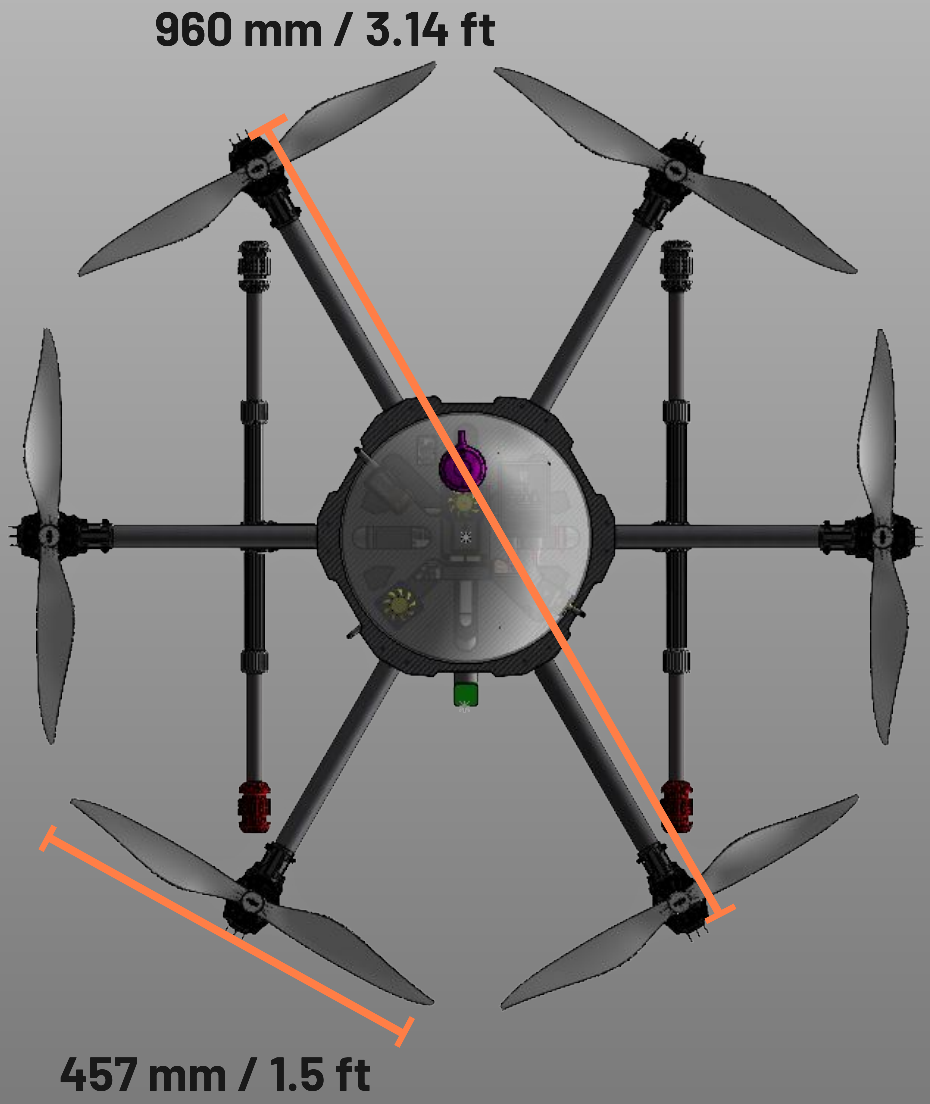
FLAME Autonomous Firefighting UAS Low-Level ConOps



Design Review

Changes since CDR/IDR

Design Overview

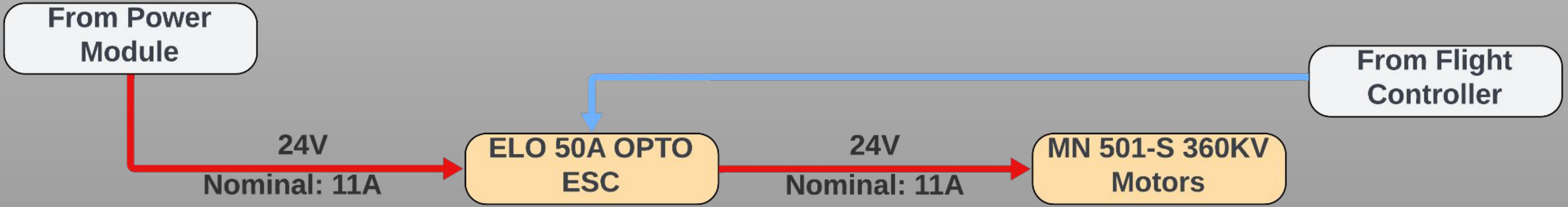


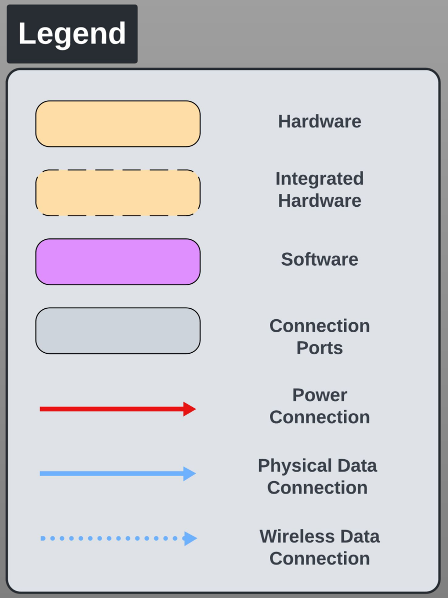
Software Selections

- **ArduPilot and Mission Planner**
  - Compatible
  - Documentation
- **Capabilities**
  - Save and load mission profiles
  - Simulation-In-The-Loop
  - Data logging
- **Mission Planner Commands**
  - Takeoff
  - Waypoint travel
  - Altitude Hold
  - Return to launch
  - Land

Software Selections	
Use	**Software**
Autopilot	ArduPilot
Mission Planning	Mission Planner

Design Changes





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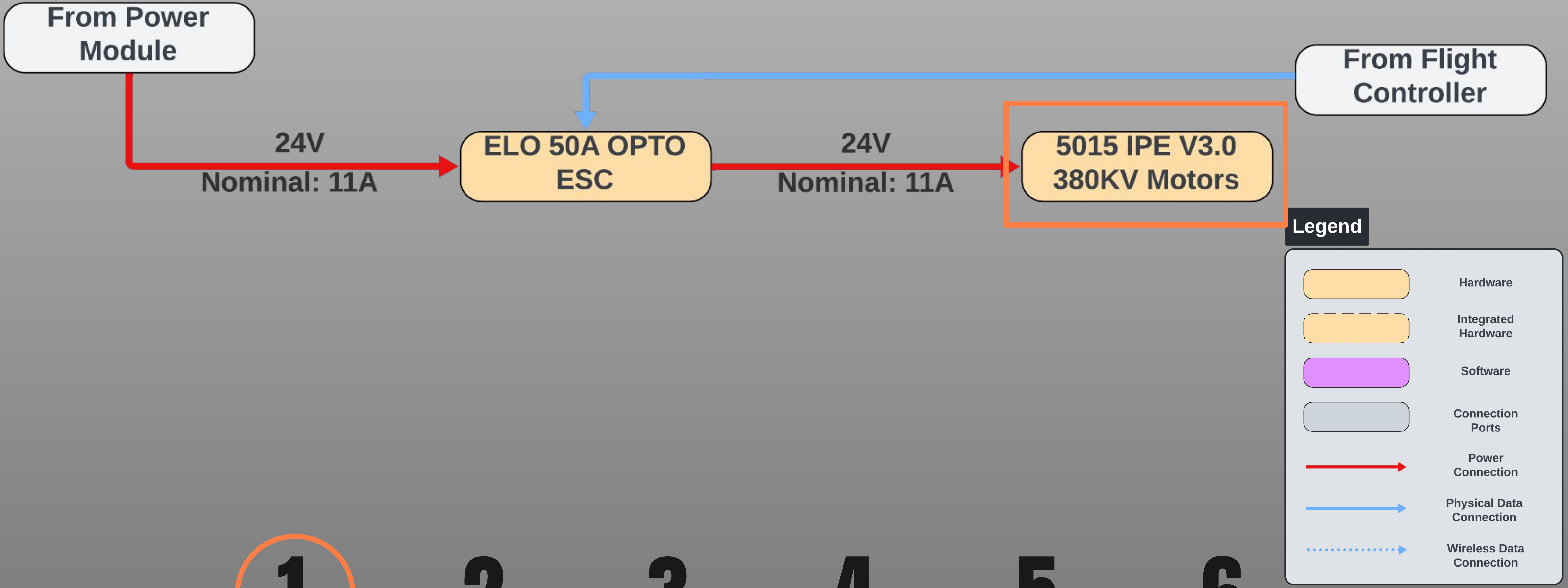
Design Changes



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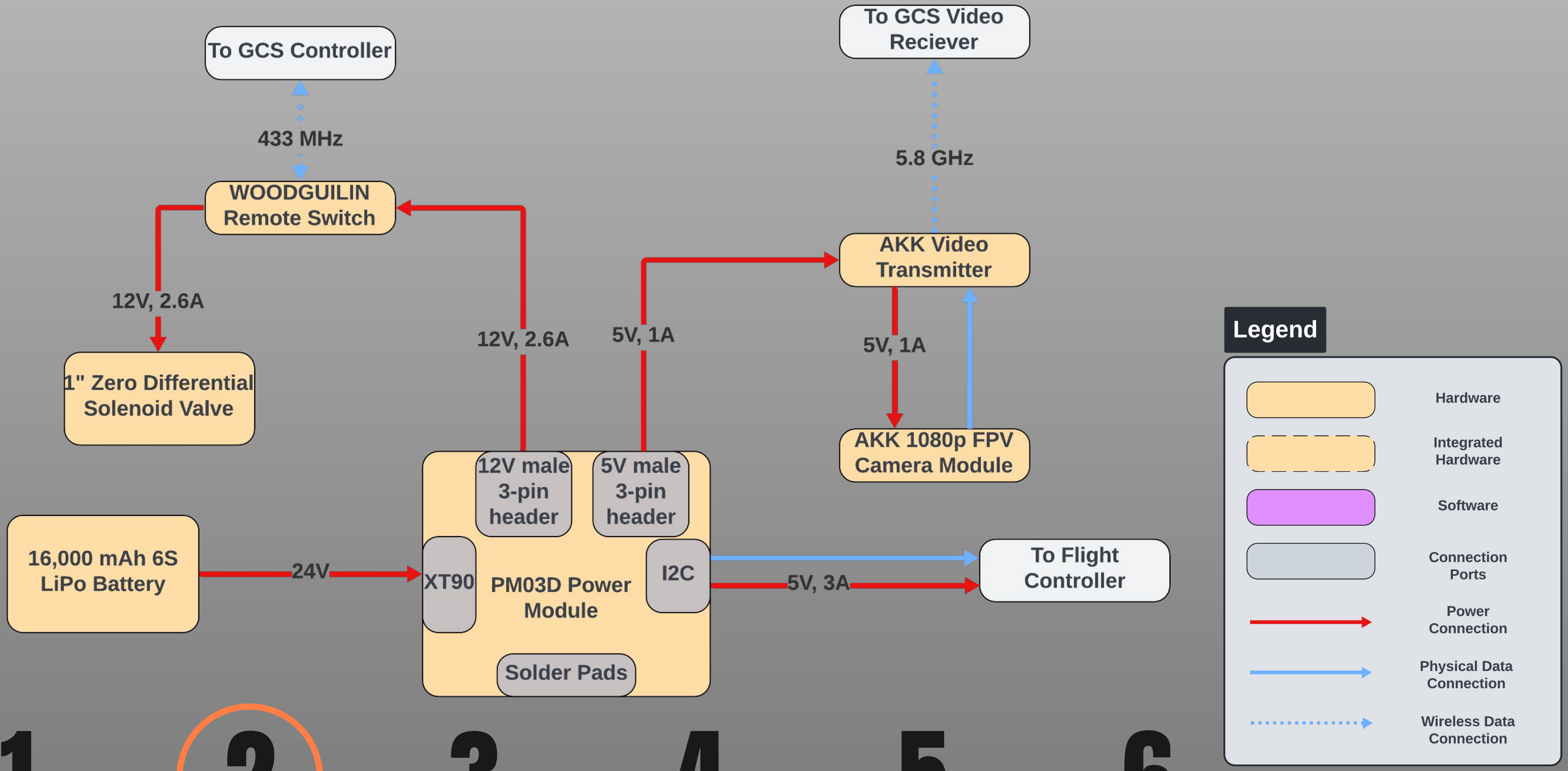

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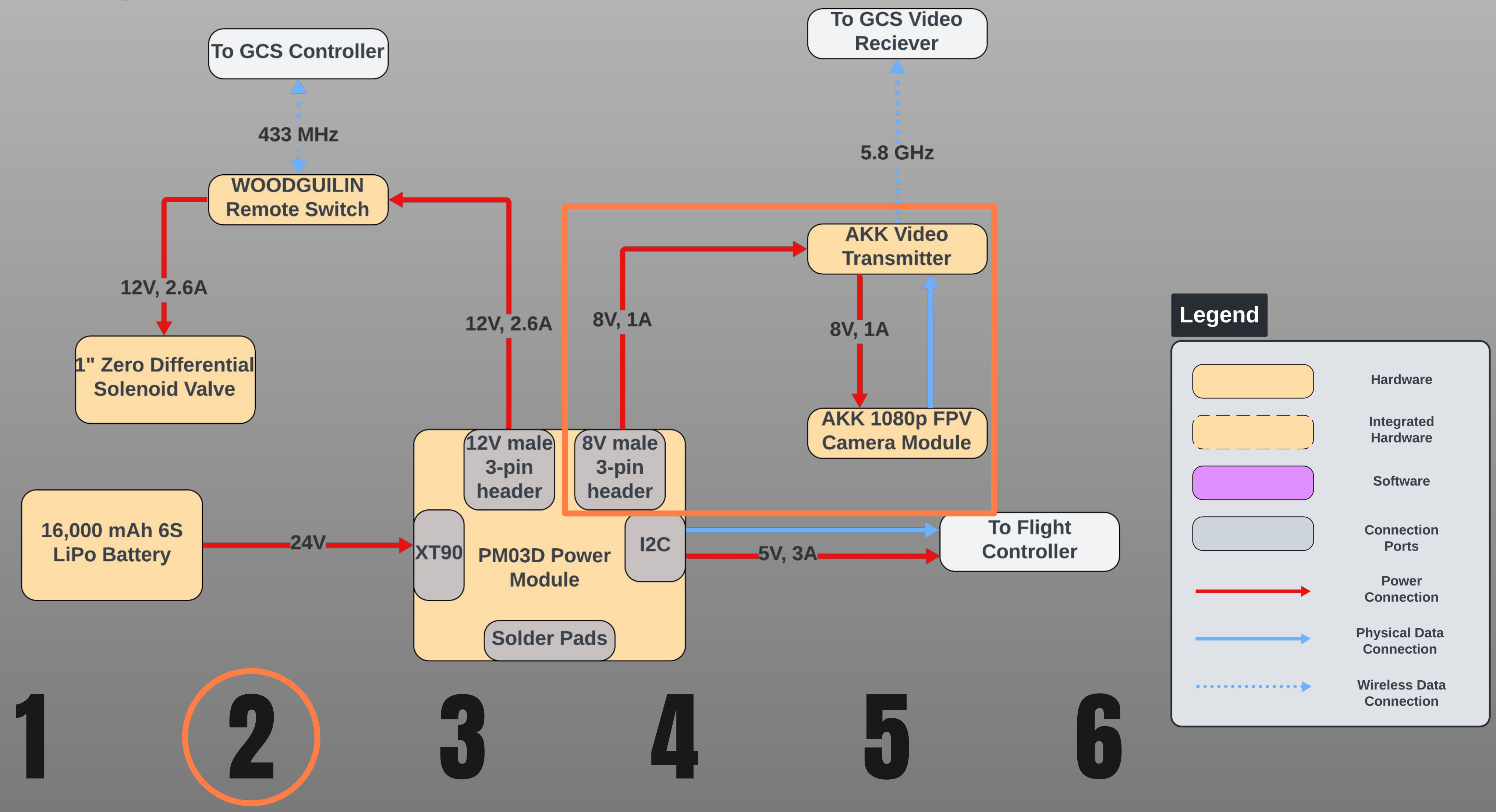

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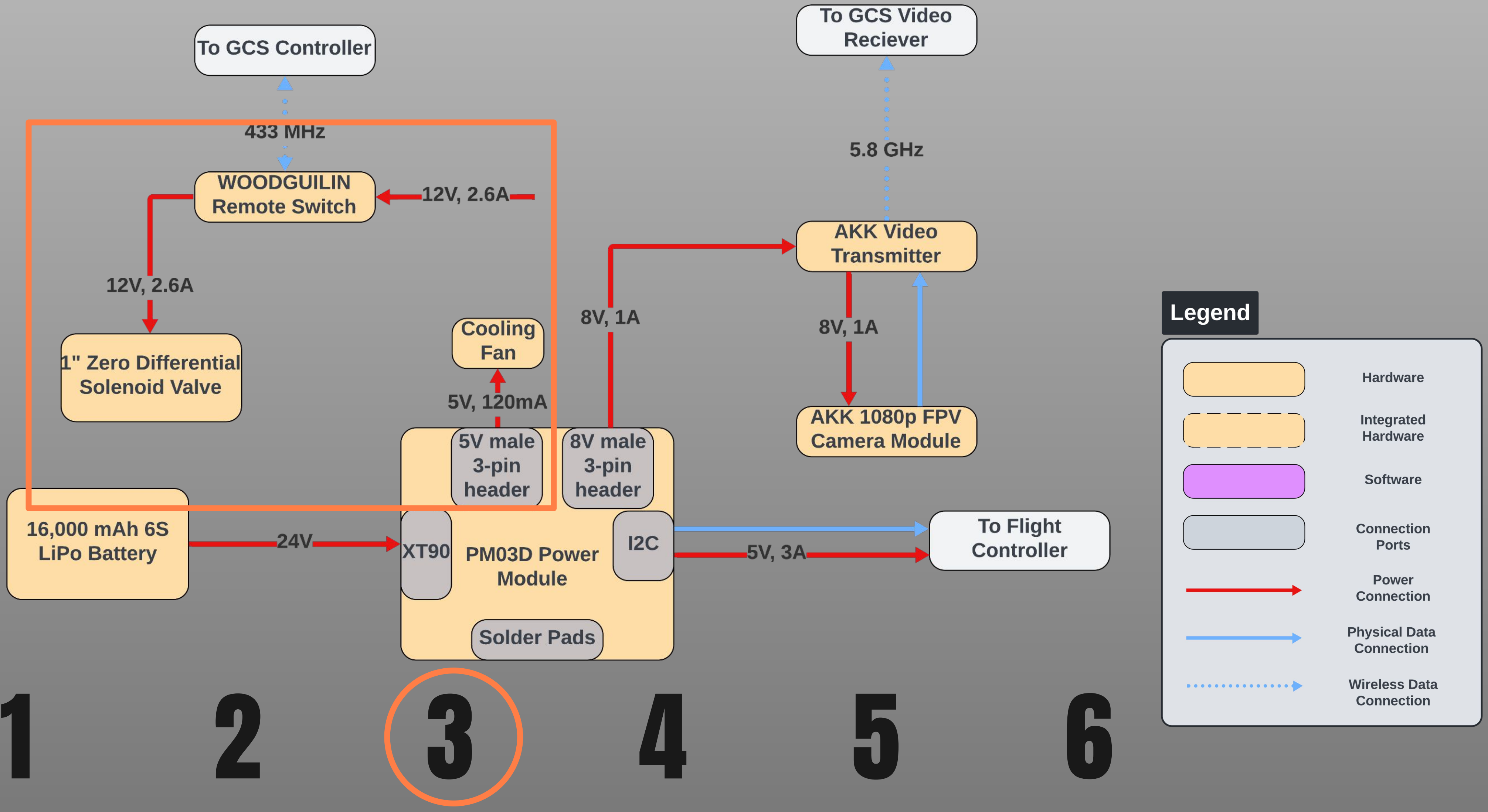

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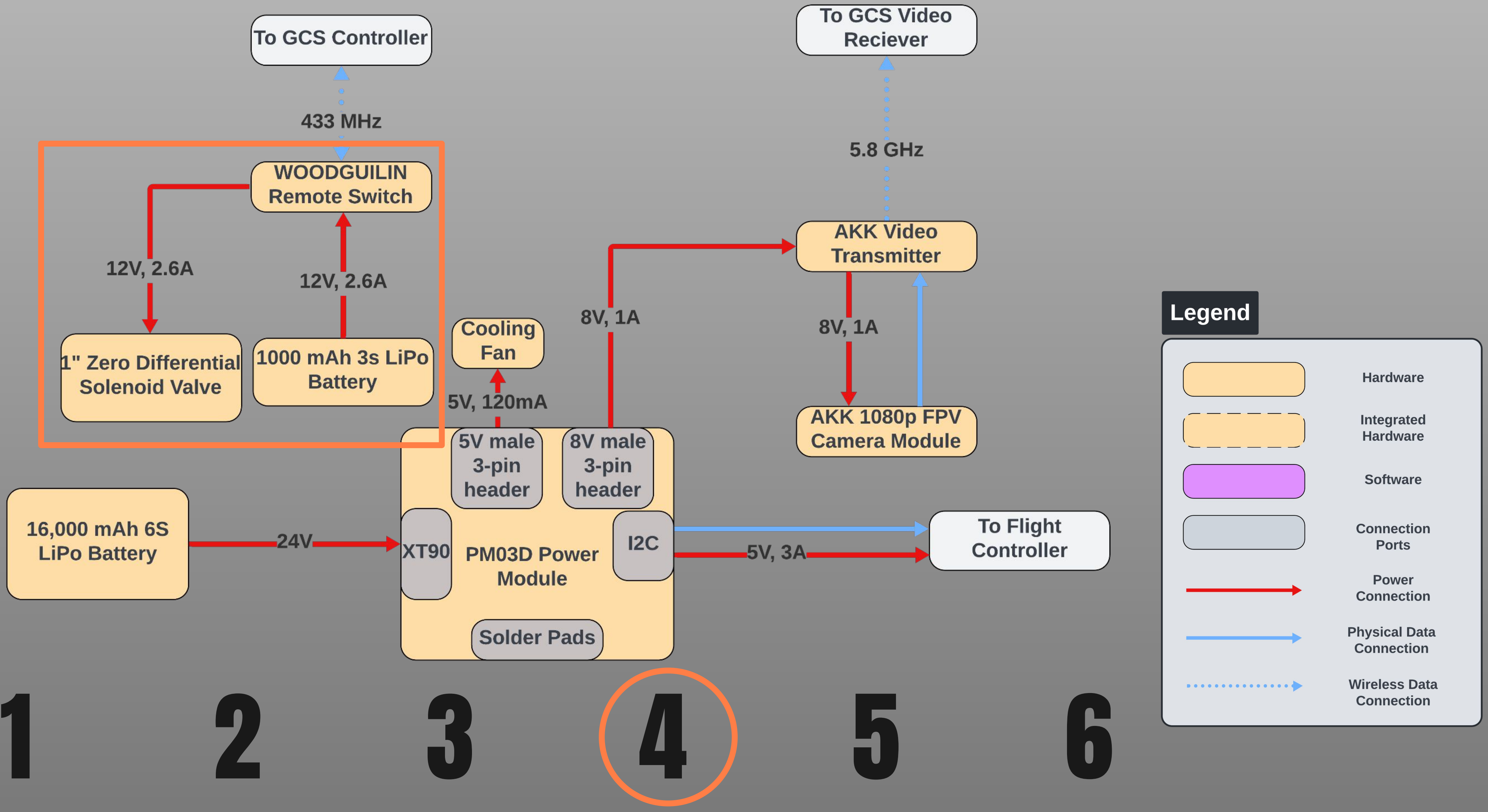

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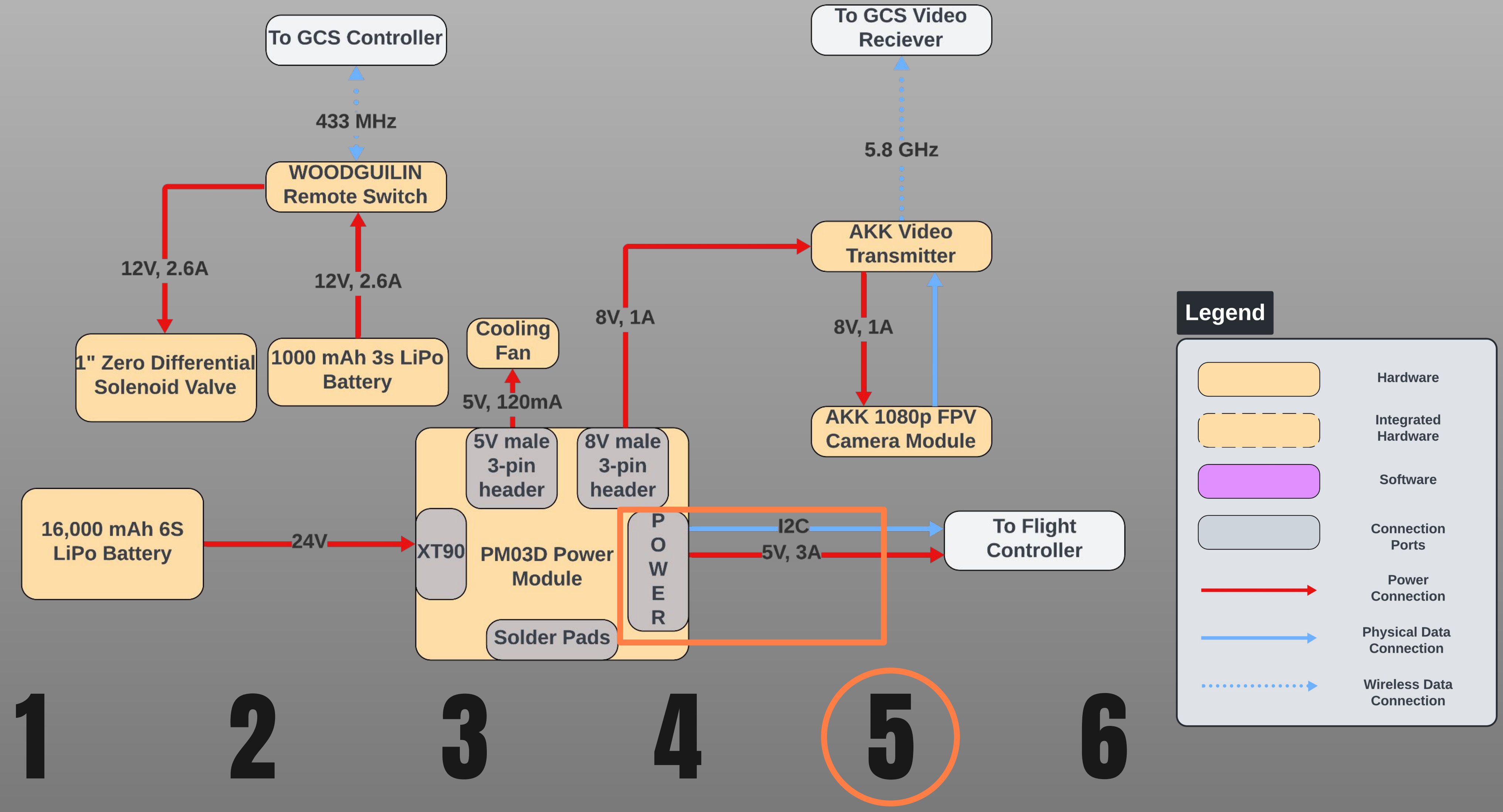

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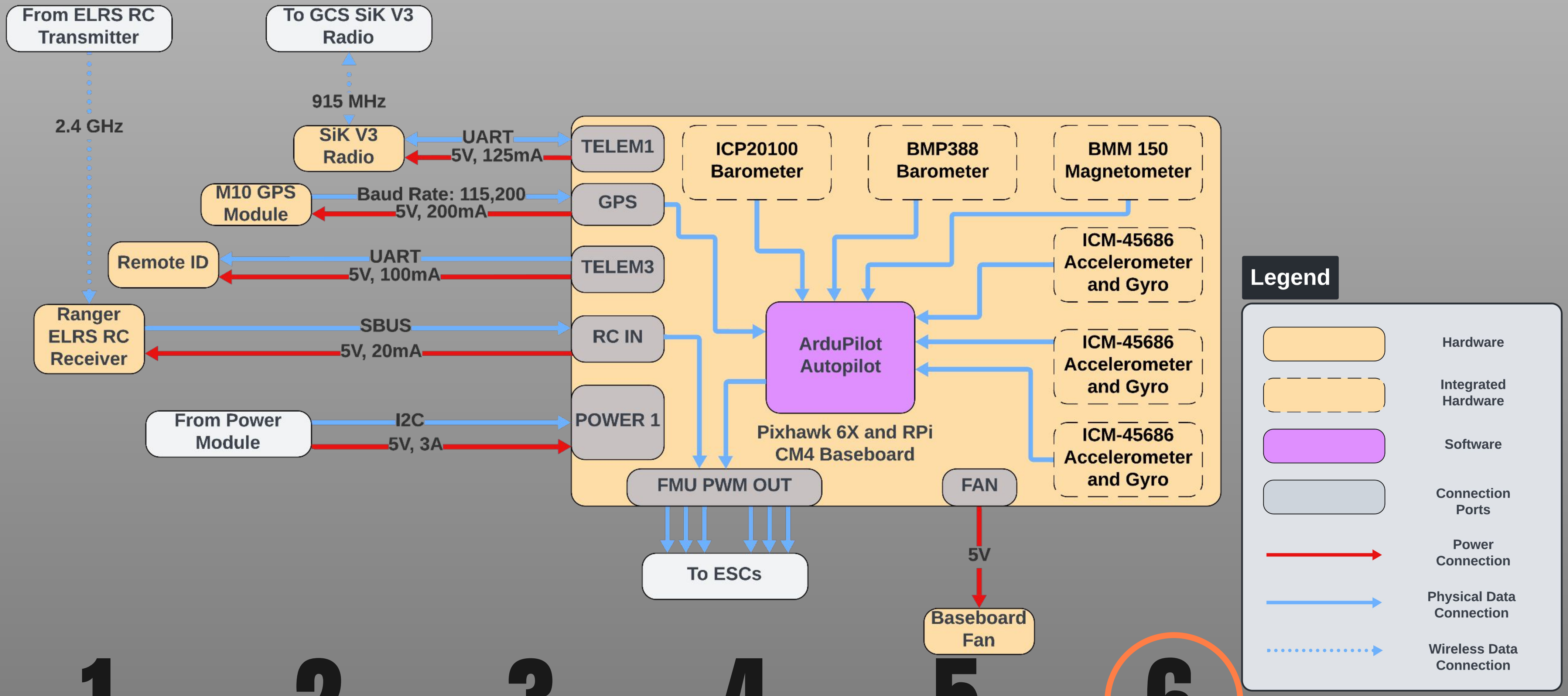

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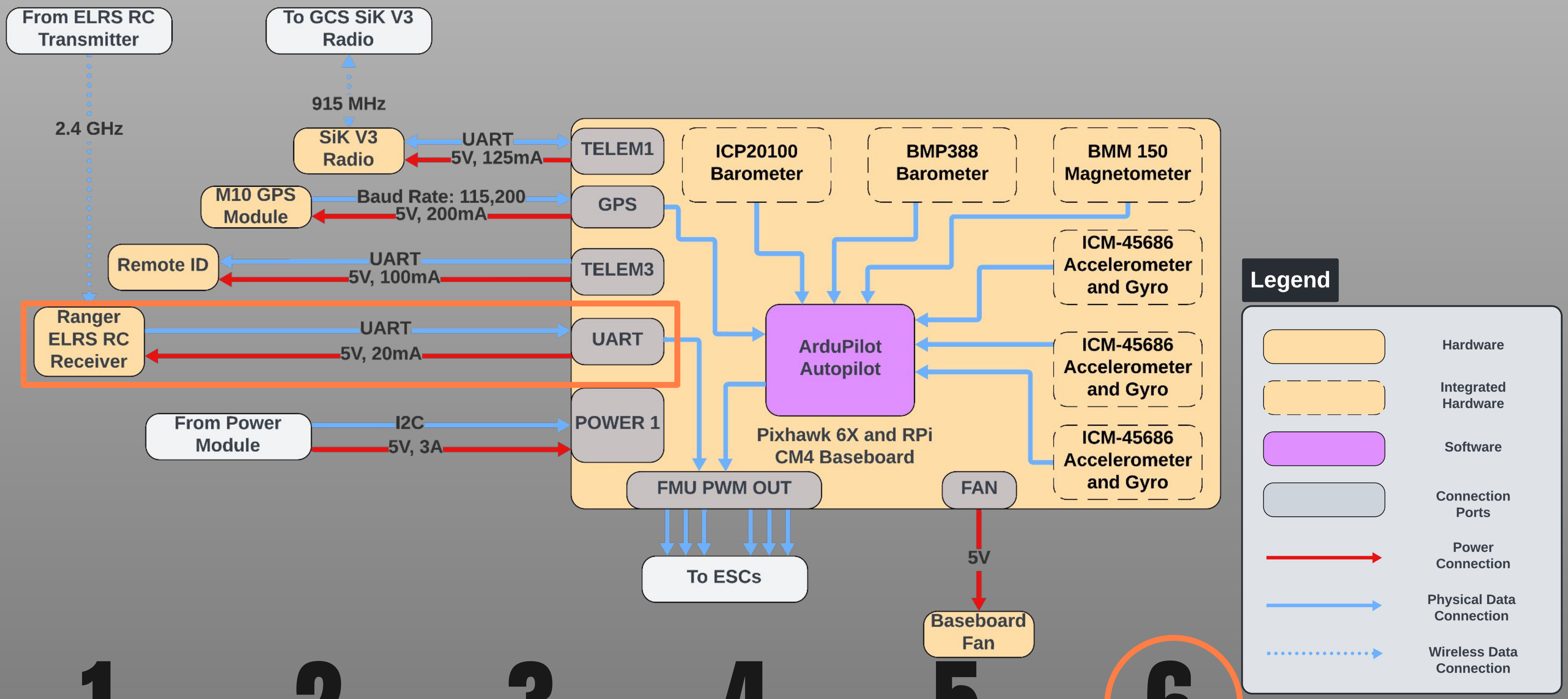
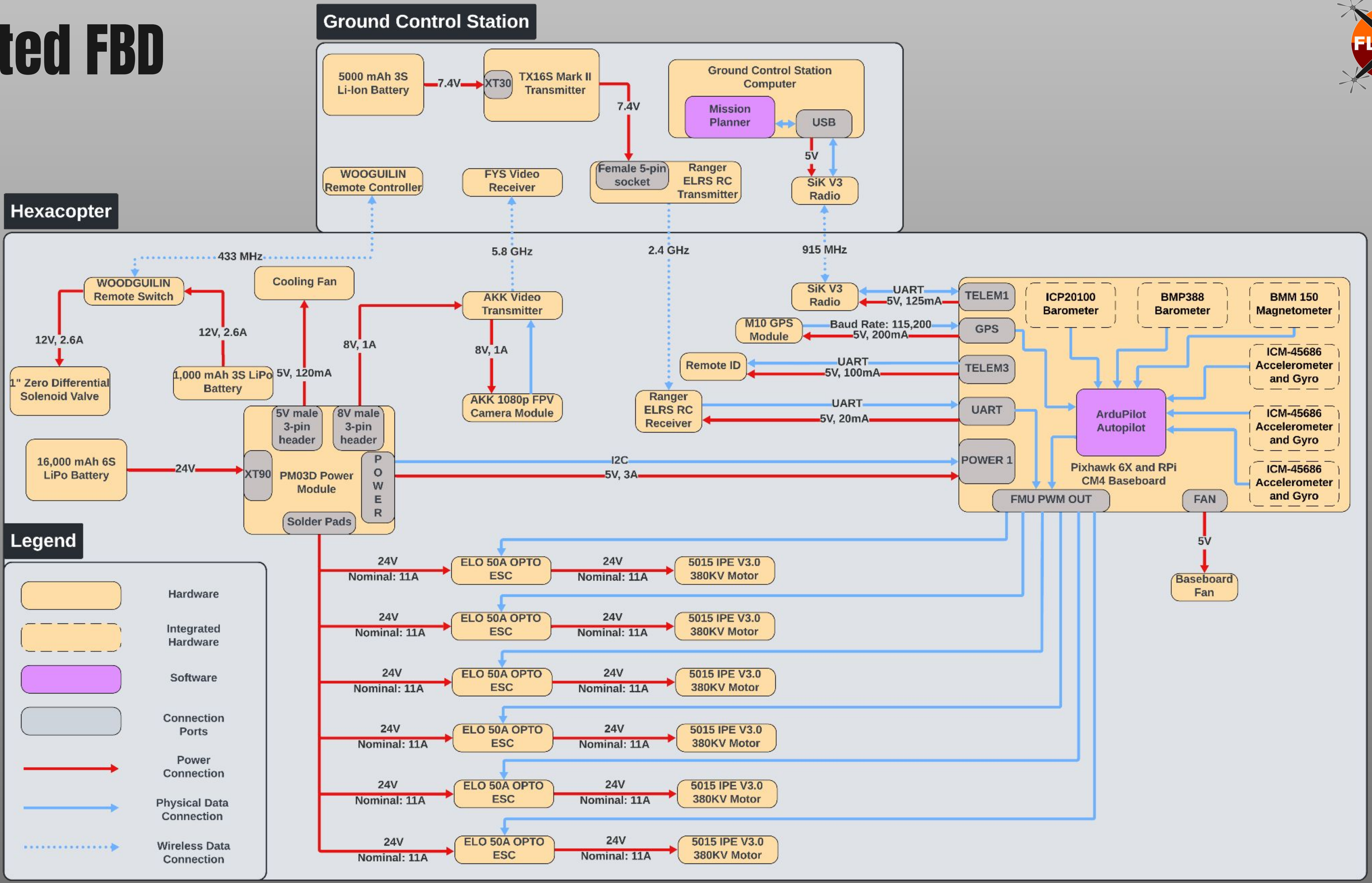


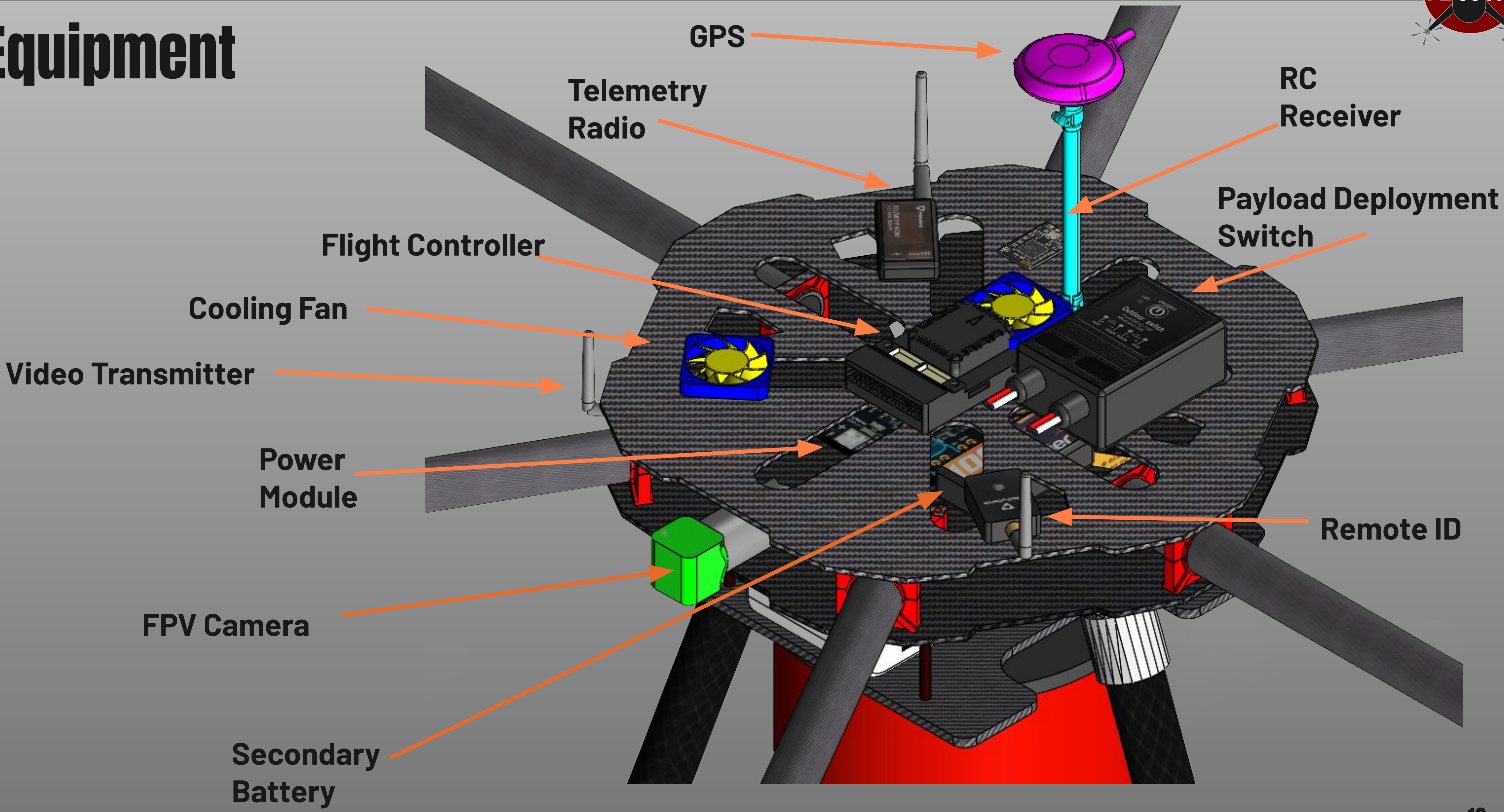
1 2 3 4 5 6

Updated FBD



Ground Control Station
5000 mAh 3S Li-Ion Battery
7.4V
XT30
TX16S Mark II Transmitter
7.4V
Ground Control Station Computer
Mission Planner
USB
5V
WOOGUILIN Remote Controller
FYS Video Receiver
Female 5-pin socket
Ranger ELRS RC Transmitter
SiK V3 Radio
Hexacopter
433 MHz
5.8 GHz
2.4 GHz
915 MHz
WOODGUILIN Remote Switch
Cooling Fan
AKK Video Transmitter
SiK V3 Radio
UART
5V, 125mA
TELEM1
ICP20100 Barometer
BMP388 Barometer
BMM 150 Magnetometer
M10 GPS Module
Baud Rate: 115,200
5V, 200mA
GPS
12V, 2.6A
12V, 2.6A
8V, 1A
8V, 1A
ICM-45686 Accelerometer and Gyro
Remote ID
UART
5V, 100mA
TELEM3
1" Zero Differential Solenoid Valve
1,000 mAh 3S LiPo Battery
5V, 120mA
AKK 1080p FPV Camera Module
Ranger ELRS RC Receiver
UART
5V, 20mA
UART
ArduPilot Autopilot
ICM-45686 Accelerometer and Gyro
5V male 3-pin header
8V male 3-pin header
16,000 mAh 6S LiPo Battery
24V
XT90
PM03D Power Module
POWER
I2C
5V, 3A
POWER 1
Pixhawk 6X and RPi CM4 Baseboard
ICM-45686 Accelerometer and Gyro
Solder Pads
FMU PWM OUT
FAN
5V
Baseboard Fan
24V
Nominal: 11A
ELO 50A OPTO ESC
5015 IPE V3.0 380KV Motor
Legend
Hardware
Integrated Hardware
Software
Connection Ports
Power Connection
Physical Data Connection
Wireless Data Connection

Equipment



GPS
Telemetry Radio
RC Receiver
Payload Deployment Switch
Flight Controller
Cooling Fan
Video Transmitter
Power Module
Remote ID
FPV Camera
Secondary Battery

Equipment

GPS

Payload Deployment Switch

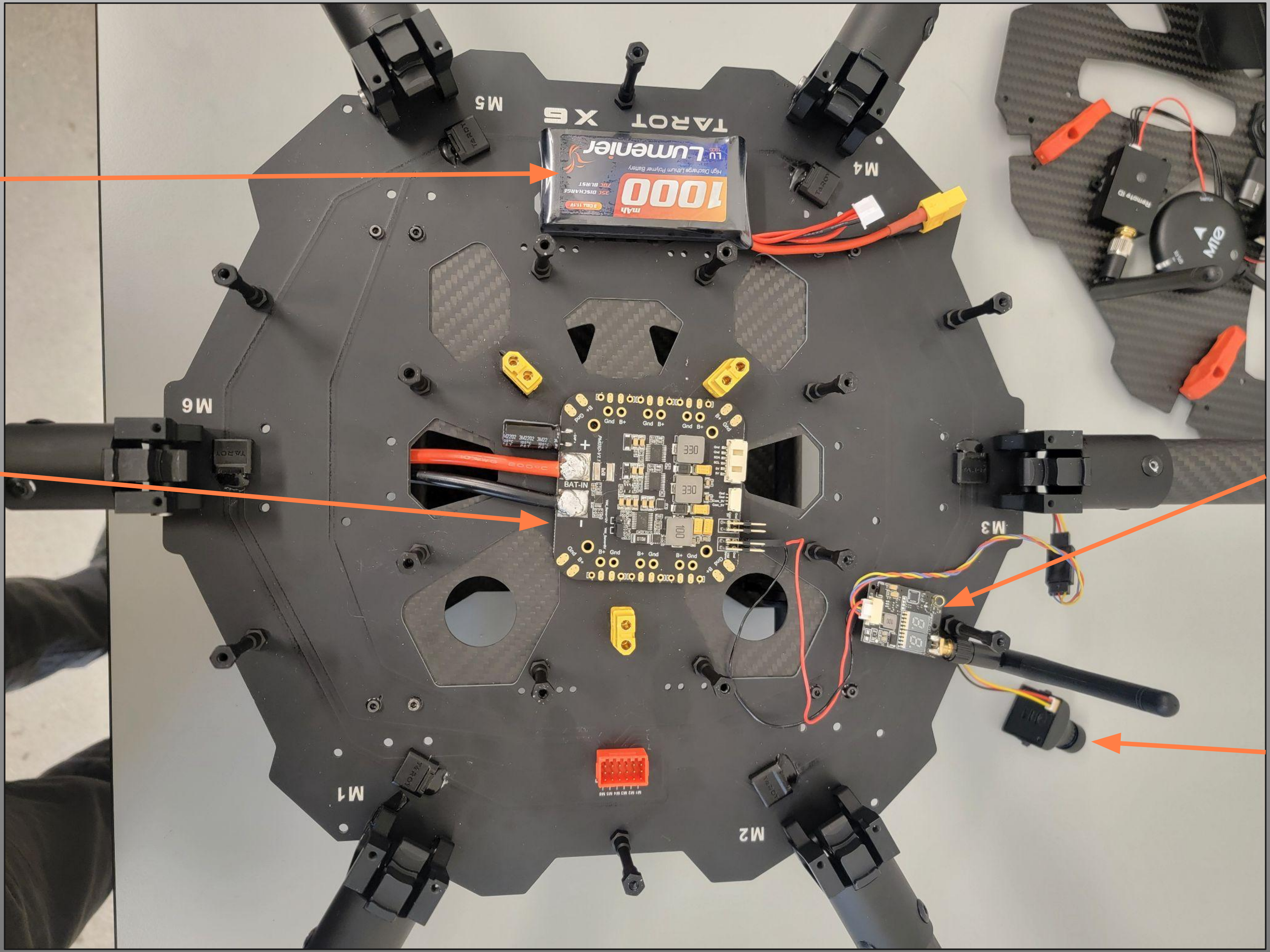
Remote ID

Flight Controller

Secondary Fan

Telemetry Radio

Equipment



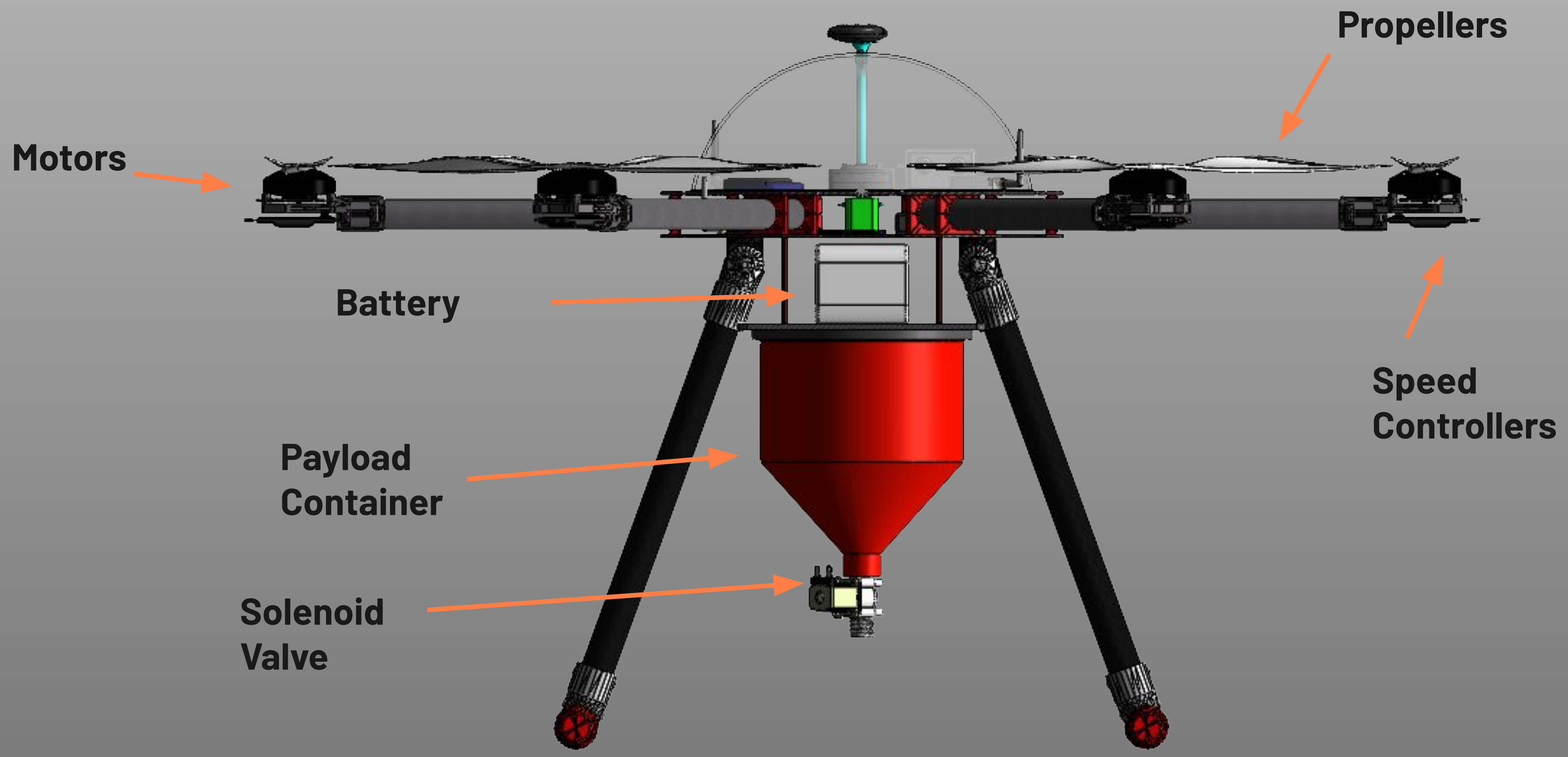
Secondary Battery

Power Module

Video Transmitter

FPV Camera

Equipment



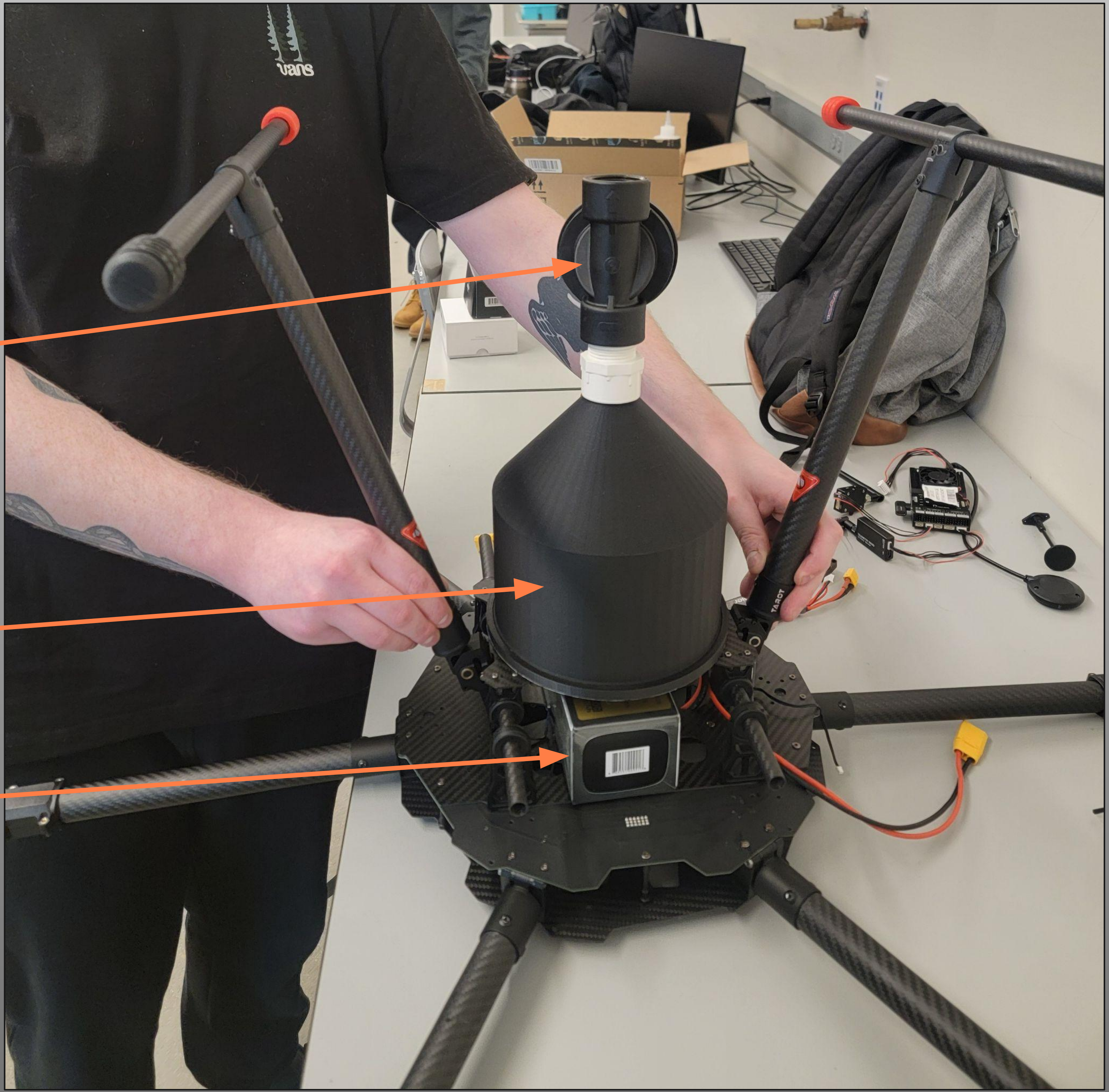
Propellers
Motors
Battery
Speed Controllers
Payload Container
Solenoid Valve

Equipment

Solenoid Valve

Payload Container

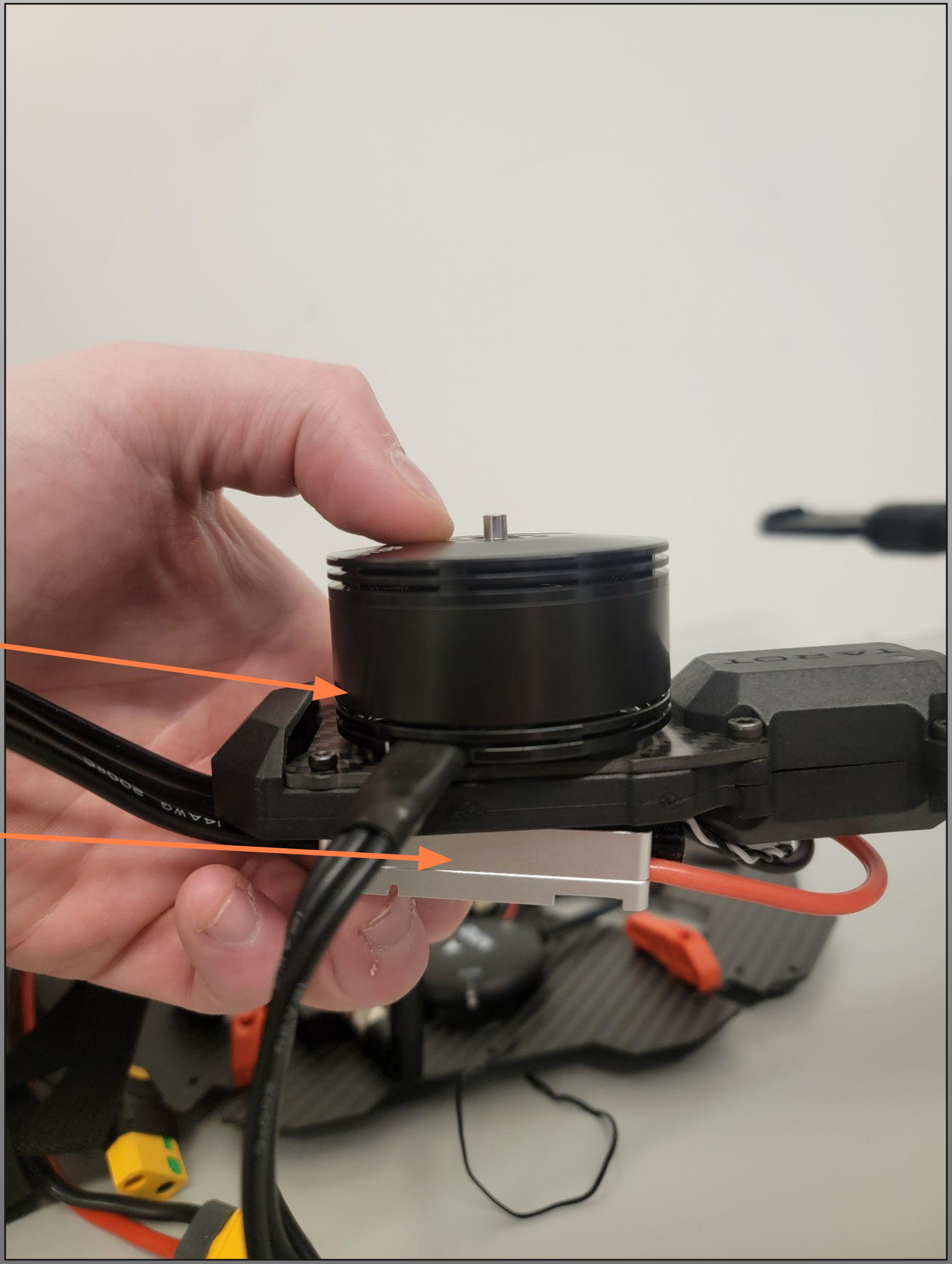
Battery



Equipment

Motor

ESC



Schedule

Remaining Tests

Tests	Requirements Fulfilled	Status
Payload Deployment Time	FR 1.5, DR 1.7	In Progress
Rotor Thrust Evaluation*	FR 1.1, 1.4, 1.5, 2.2,	Not Started
Payload Deployment Accuracy	FR 2.1, 3.5	Not Started
GPS Accuracy	FR 3.1, DR 1.2	In Progress
Battery Health	FR 1.1, 1.4	Completed
Mass Flow Rate	FR 2.1, 3.4, DR 5.1.1	Not Started
RC Control (Initial Flight)	FR 3.1, DR 1.5	Not Started
Autonomous Flight	FR 1.2, 1.3, DR 1.2	Not Started
Premature Payload Deployment	FR 2.1, 3.4, DR 5.1.1	Not Started
Single Mission Leg*	FR 1.1, 1.2, 1.3, 1.5, 1.6, 1.7, 2.1, 2.2, 3.1	Not Started
Payload Reload	FR 1.4, 2.1	Not Started
Final Mission	FR 1.1-6, 2.1, 2.2, 3.1, 3.5	Not Started

*Will be discussed later in the presentation

FLAME

Spring Semester Progress Tracking

Project start: **Thu, 1/16/2025**

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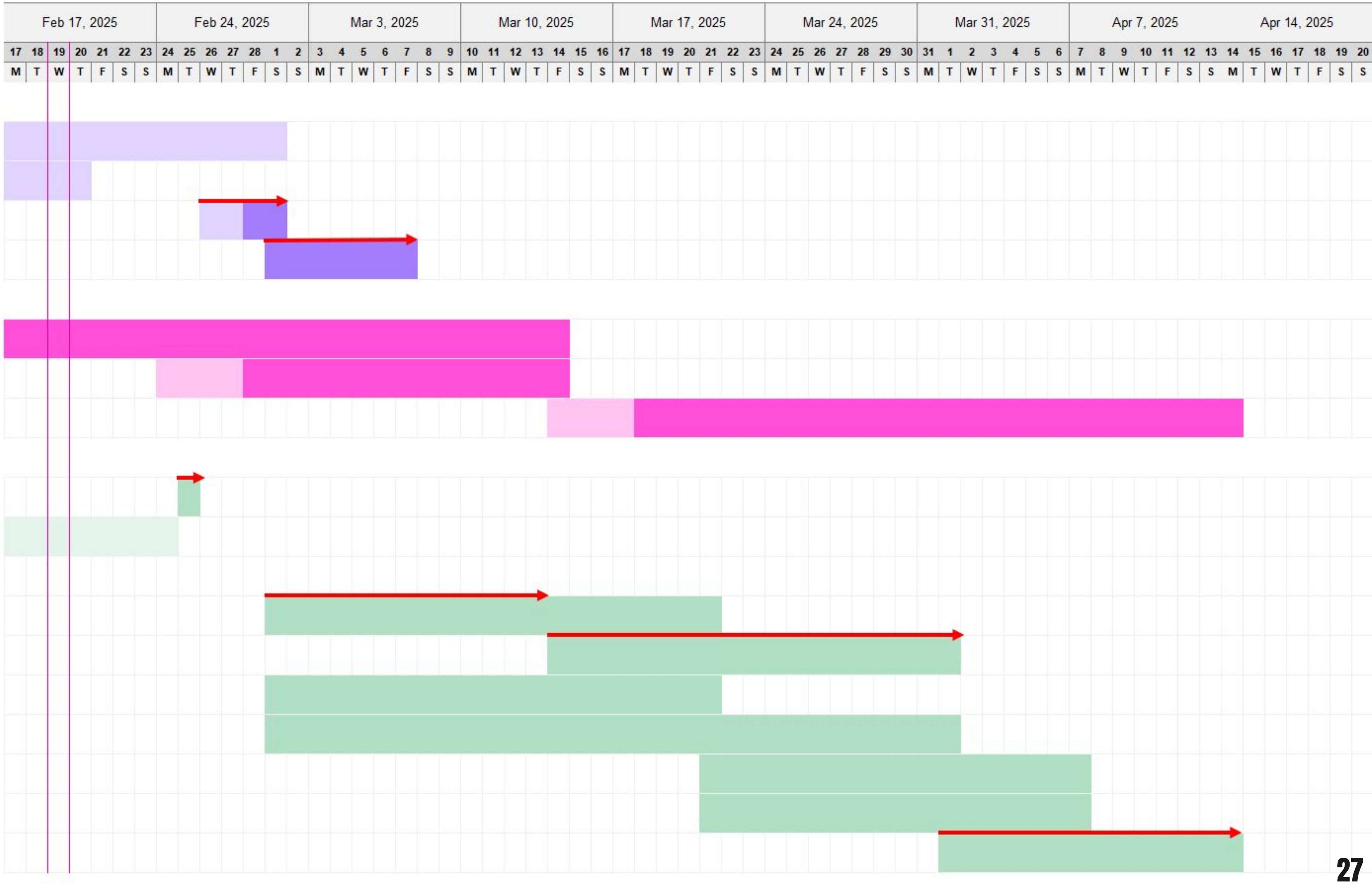
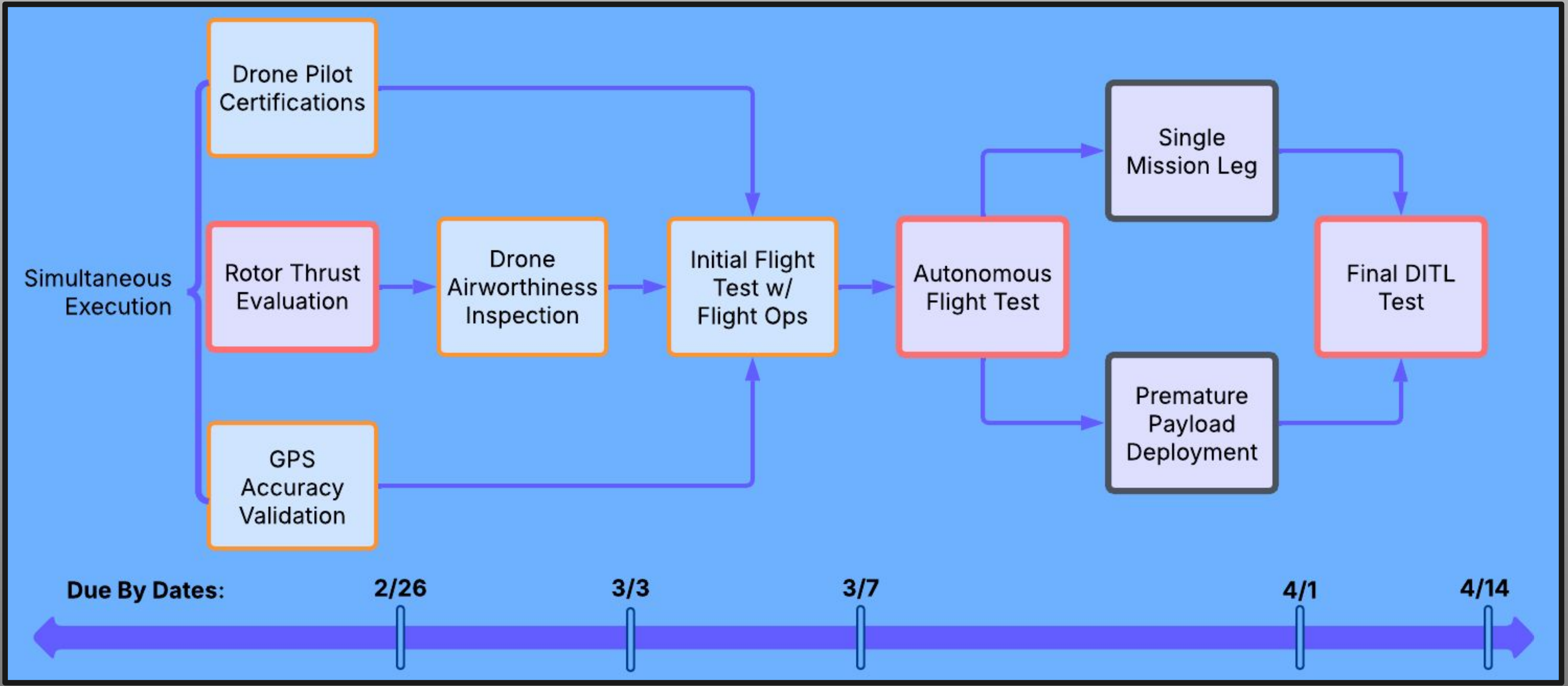
TASK	PROGRESS	START	END
Flight Ops Milestones			
Drone Pilot Canvas Course	100%	1/16/25	3/1/25
Drone Pilot Flight Certification	100%	2/7/25	2/20/25
Drone Airworthiness Inspection	50%	2/26/25	3/1/25
Initial Flight	0%	3/1/25	3/7/25
Integration			
Software Avionics	50%	1/16/25	3/14/25
Avionics Structure	25%	2/24/25	3/14/25
Final System	13%	3/14/25	4/14/25
Testing			
Thrust Eval	0%	2/25/25	2/25/25
Payload Deployment Time	100%	1/23/25	2/24/25
Battery	100%	1/23/25	2/12/25
Remote Controlled Flight	0%	3/1/25	3/21/25
Autonomous Flight	0%	3/14/25	4/1/25
GPS	0%	3/1/25	3/21/25
Payload Deployment Accuracy	0%	3/1/25	4/1/25
Single Mission Leg	0%	3/21/25	4/7/25
Premature Payload Deployment	0%	3/21/25	4/7/25
Final System	0%	4/1/25	4/14/25

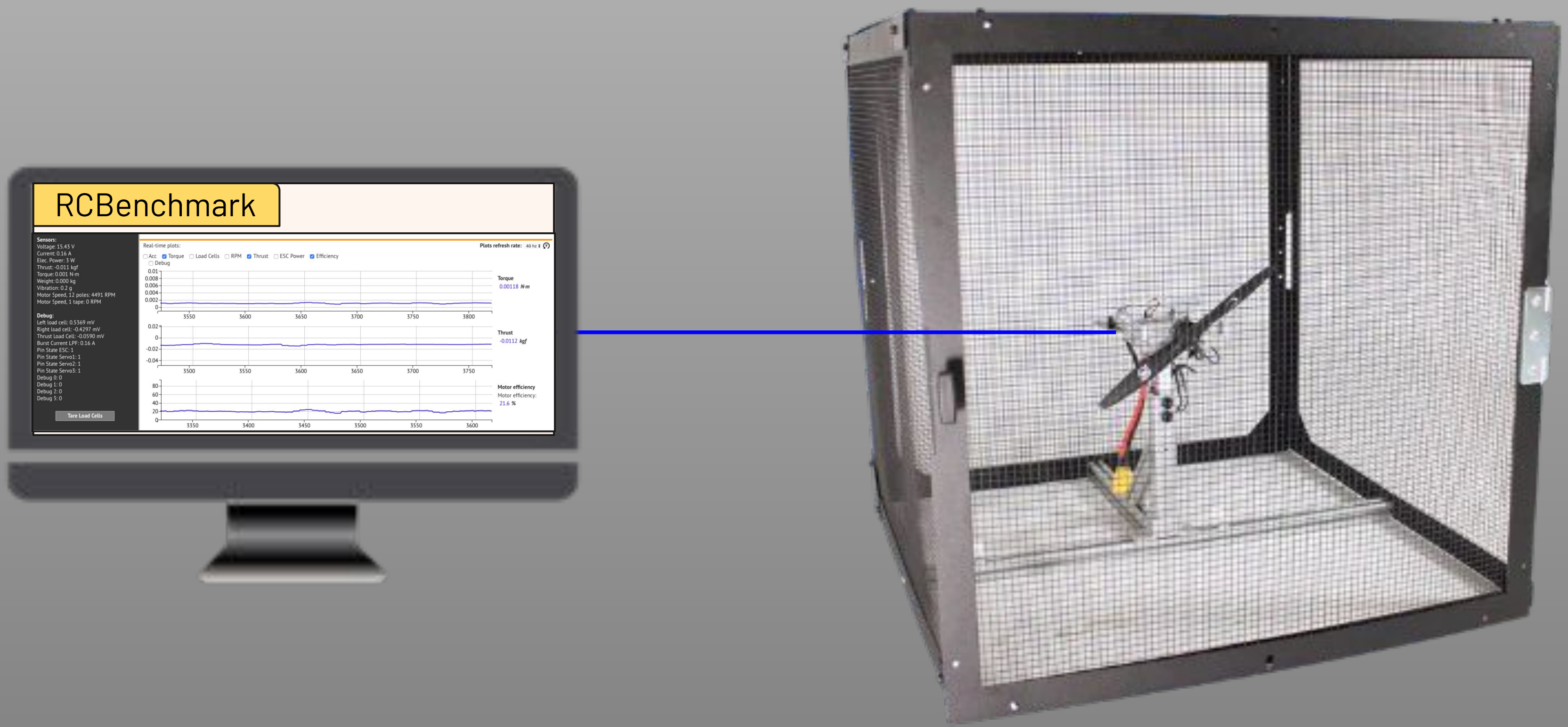


Critical Path



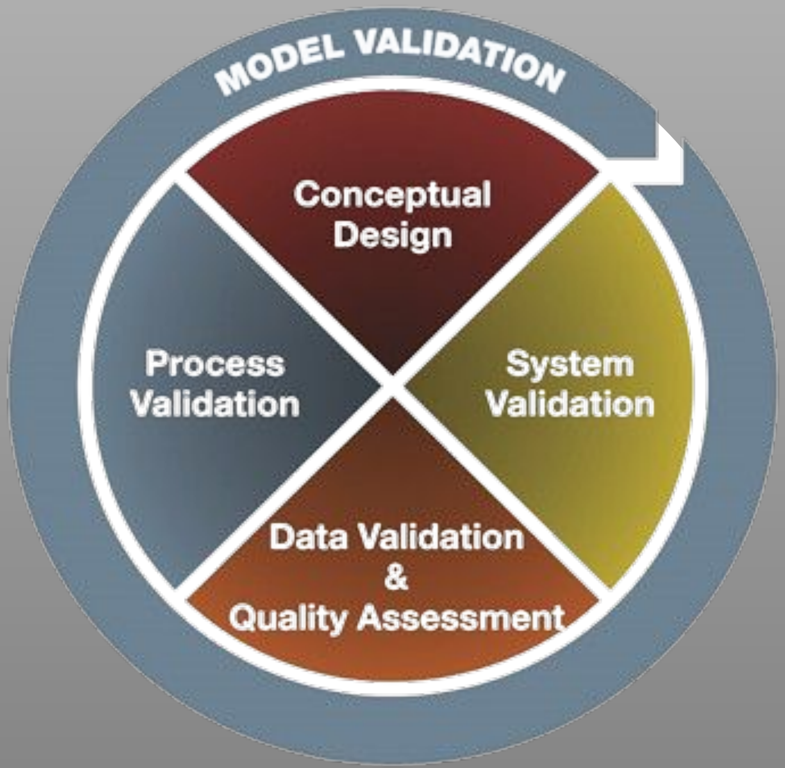
Static Thrust Test

Brief Overview



Reasons for Test

- **Model Validation**
  - Thrust profile results:
    - Thrust does not match model: Change model
    - Thrust matches model: First stage of validation
    - Second stage of validation is with DiTL test
- **Thrust Profile Expectations**
  Gain a better understanding of the thrust profile of our motors
    - Allows using experiential data rather than rely on data sheets
    - Allows us to understand the power draw of our motors, can edit the energy model based on results

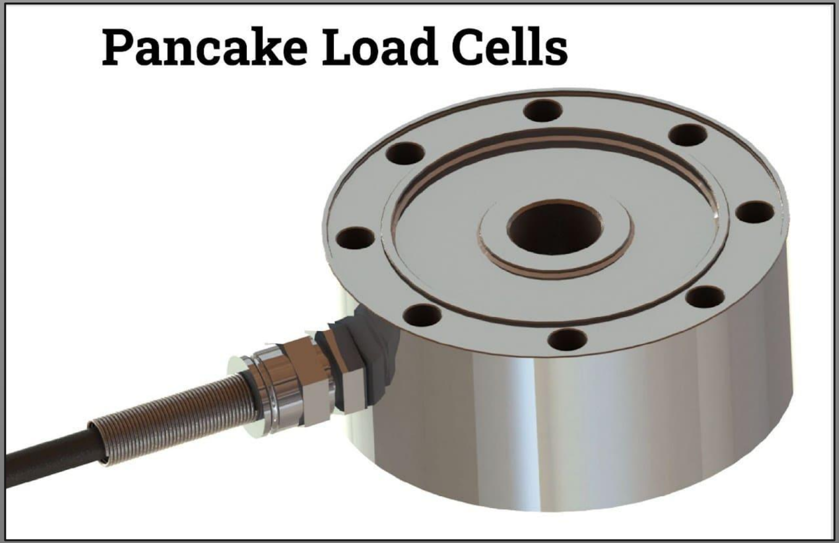


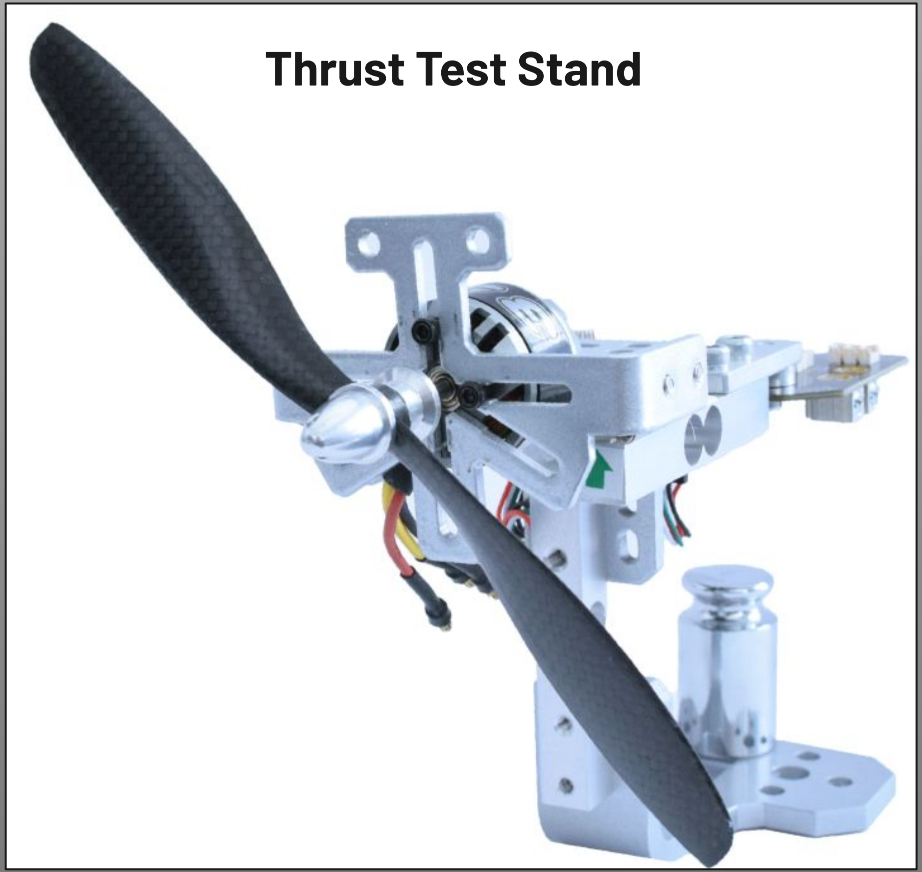
Driving Requirements

- **FR 2.2** The system shall be able to take off, fly, and land with a minimum fire retardant weight of 5 pounds
- **DR 3.1.1** The propulsion subsystem shall provide thrust sufficient to lift the aircraft and its payload during take off and landing
- **DR 3.1.4** The propulsion subsystem shall provide sufficient thrust to reach the 30 foot hard deck

Sensors, Basics, and Test Organization

- **Facility:** Design/Build/Fly, Engineering Center
- **Sensor:** Series 1580 Test Stand
  - Sensor type: Load cell
  - Sampling rate: up to 50 Hz
- **Calibration plans**
  - Software calibration was completed with DBF using RCBenchmark Calibration wizard on 1/22
  - Stand hardware calibrated on 2/21





Sensor Specs

	Range	Tolerance	Requirements	Meet Requirements?
Voltage Supplied	0-50 V	0.5% ± 0.05 V	24 V	✅
Current Supplied	0-55 A	1.0% ± 0.1 A	45 A (max)	✅
Force	-5 to +5 kgf	0.5% ± 0.005 kgf	1.67 kgf per motor	✅
Sampling	Up to 50 Hz	N/A	> 0.02s per thrust increase	✅

Safety Equipment

- Tools for adjusting motor and test stand
- Fire Blanket
- ABC Fire Extinguisher
- Class D Fire Extinguisher
- First Aid Kit
- Communication Devices - cell phone
- Safety Glasses - For all Flight personnel in zone
- Safety Gloves

Pre-Thrust Test Checks

Activities that must be performed prior to starting motor thrust testing:

1. Team evacuation and safety briefing
2. Mounting and component inspection
3. Software and Hardware calibration check
4. Safety equipment check and verification
5. Identify hazardous areas
    a. Propeller rotation plane
    b. Open side of the testing chamber
6. Verify motor is properly secured in test stand

Pre-Thrust Test Checks - Motor Mounting

Attaching motor to test stand steps:

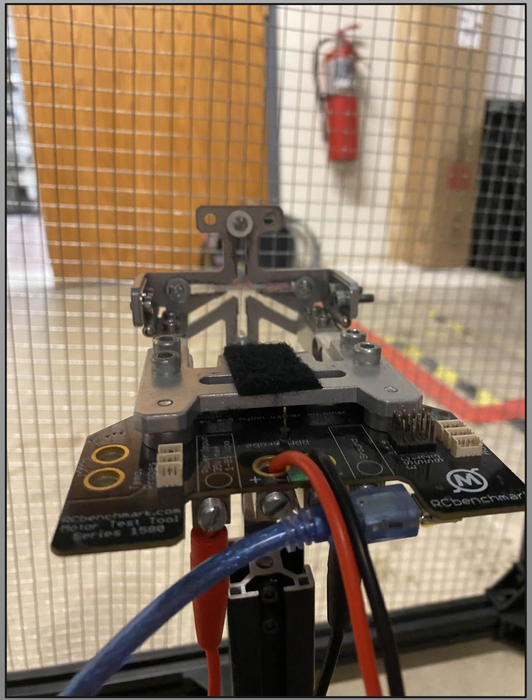
- Secure motor into testing cell
- Connect data cables
  - ESC to motor
  - Computer to ESC

If testing with no propellers:

- Connect battery to ESC
  - Avoid throttling to high speeds

If testing with propellers:

- Ensure battery is disconnected from ESC
- Attach propellers to motor
- Connect battery to ESC



Test Procedure

- **Motor Thrust Testing:**
    - Clear area
    - Begin thrust test with a verbal countdown from 5
    - Spool up motors in increments of 5% power
        - Wait 5 seconds between each increment
        - Go until 100% power – do not exceed
    - Begin spooling down motors in increments of 20% power
    - Once motor is stationary, give call that the test is finished
    - Disconnect battery
    - Save / Download the available data from throughout the test
    - Dismount motor from test stand to complete test

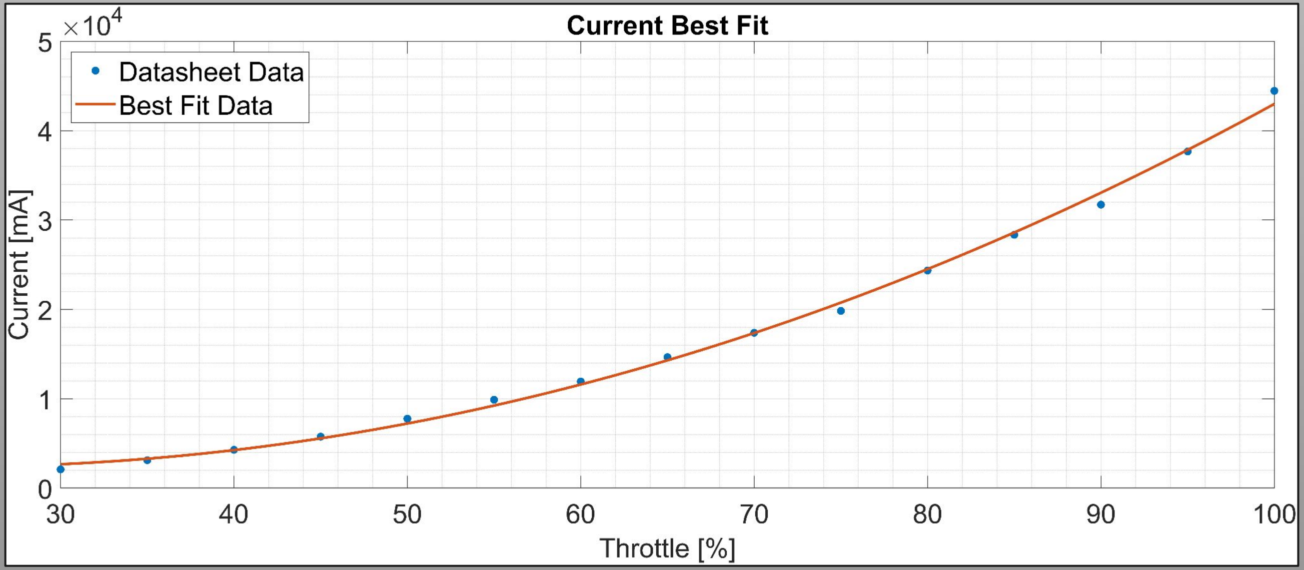
Data Acquisition

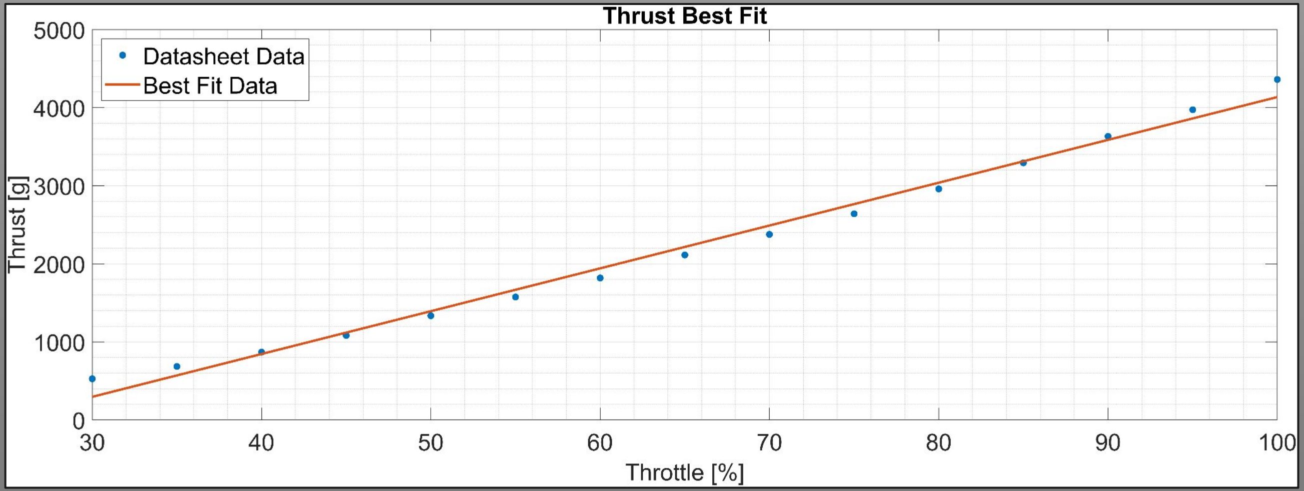
- **Thrust Values**
  - Varying power levels
  - 0.005 kgf accuracy
- **Power Draw Values**
  - Continuous data at various motor speeds
  - 0.05 V accuracy
- **Outputs as .csv file**
  - Easy MATLAB integration

Test Data Analysis

Using test data the Energy Consumption Model can be improved

- Analyze test data:
  - Compare empirical results with data sheet values
  - Test data vs Throttle %
- Use in Energy Model:
  - Replace data sheet values with test data in model
  - Air-density ratio adjustment can be removed



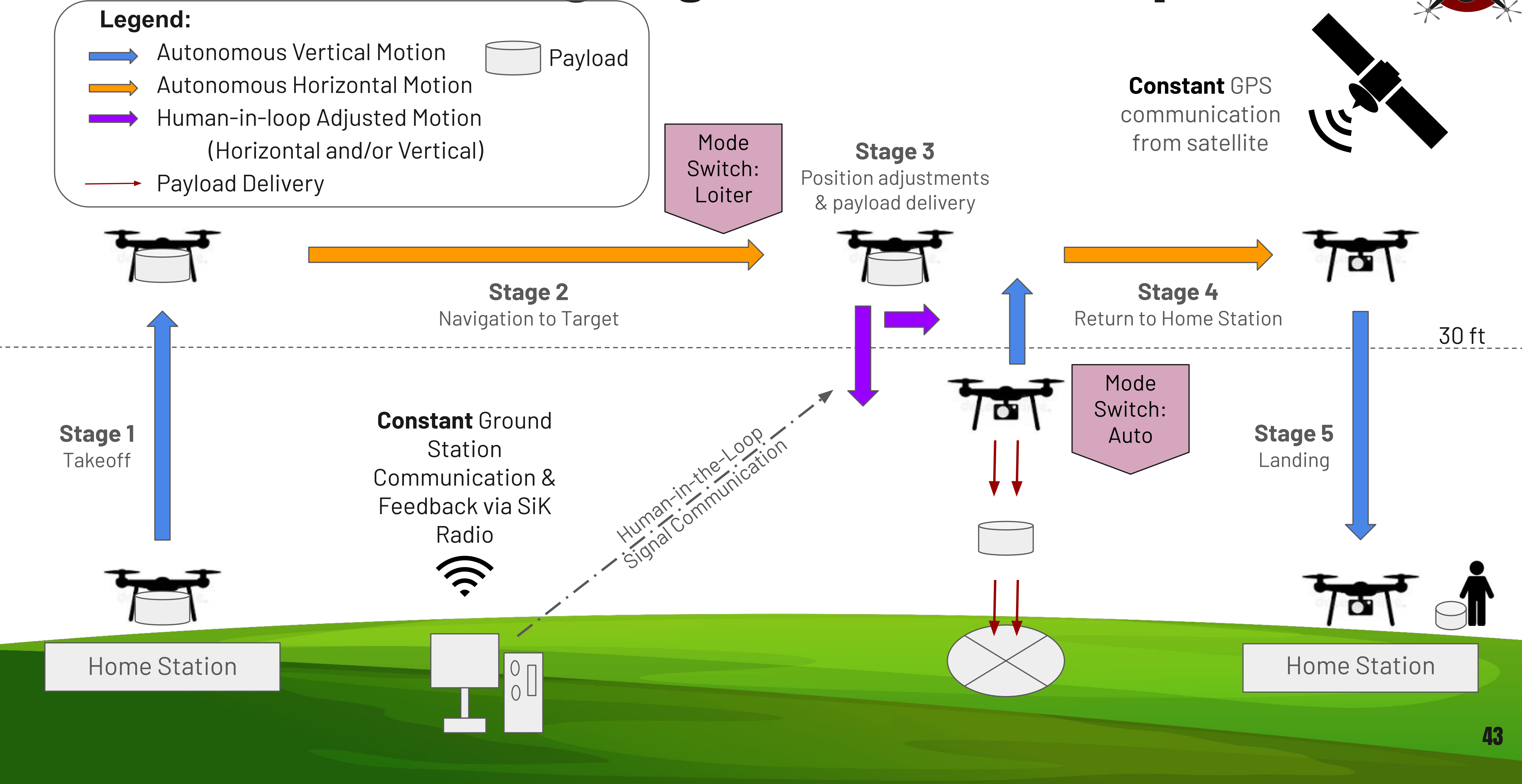


Pass / Fail Criteria

- **Test Pass**
    - Accurate data is collected on the motors
        - Thrust
        - ESC Power
        - Motor efficiency
- **Motor Pass / Fail**
    - Test values meet data sheet performance / test values significantly differ from data sheet
        - Output 5 kgf thrust at maximum
    - Smooth thrust outputs for all power levels
- **Expected Performance**
    - Test data can output necessary thrust at a given level for the mission's success

Single Leg Test

FLAME Autonomous Firefighting UAS Low-Level ConOps



Reasoning Behind Test

- **Validate Dynamics Model**
  - Behavior during deployment
  - If model and results do not match, fix model accordingly
- **Validate Energy Consumption Model**
  - If model does not match test-data, update model
  - Ensure drone has sufficient energy capacity / endurance to complete full mission
- **Verify High Level Functional Requirements**
  - Most driving requirements are verified by this single leg test
    - 100m range
    - 5 lbs of payload
    - 20 minute time limit (test should be less than a third)

Driving Requirements

- **FR 1.1** The system shall have a minimum range of 100 meters
- **FR 1.2** The system shall be able to take off autonomously
- **FR 1.3** The system shall be able to land autonomously
- **FR 1.7** The system shall be operable in mild weather conditions
- **FR 2.1** The system shall carry and deploy 5 pounds
- **FR 3.1** The system shall utilize human-in-the-loop to navigate from 10 meters RMS accuracy to 1 meter from location of interest

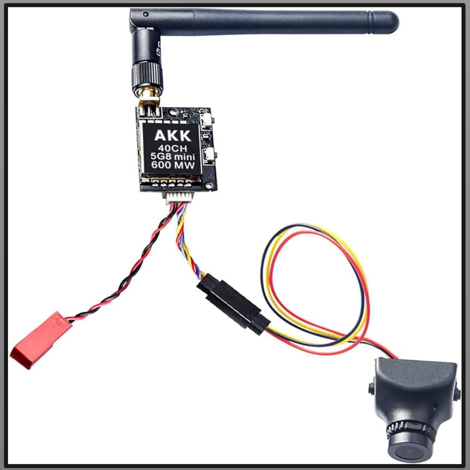
Prerequisite Tests

- Motor Thrust Stand Evaluation
- Payload Deployment Accuracy/Time
- Autonomous Flight Test
- GPS Accuracy
- Payload Reload
- Battery Health
- Mass Flow Rate
- RC Control (Initial Flight)
- Premature Payload Deployment

Sensor Specs

- **PixHawk 6X**
  - Onboard sensors
    - **3** Accelerometers/Gyroscopes
    - **2** Barometers
    - Magnetometer
  - Uses ArduPilot
    - Tested multiple times
    - Provides data logging for flight analysis
  - 5V, 3 A input / Max 5V, 1.5 A output

Sensor Specs



- **M10 GPS**
  - Connects directly to flight controller
  - 2.0m CEP accuracy (50% Circular Error Probable)
  - < 200 mA at 5 V
  - GPS L1 Frequency Band (1575.42 MHz)

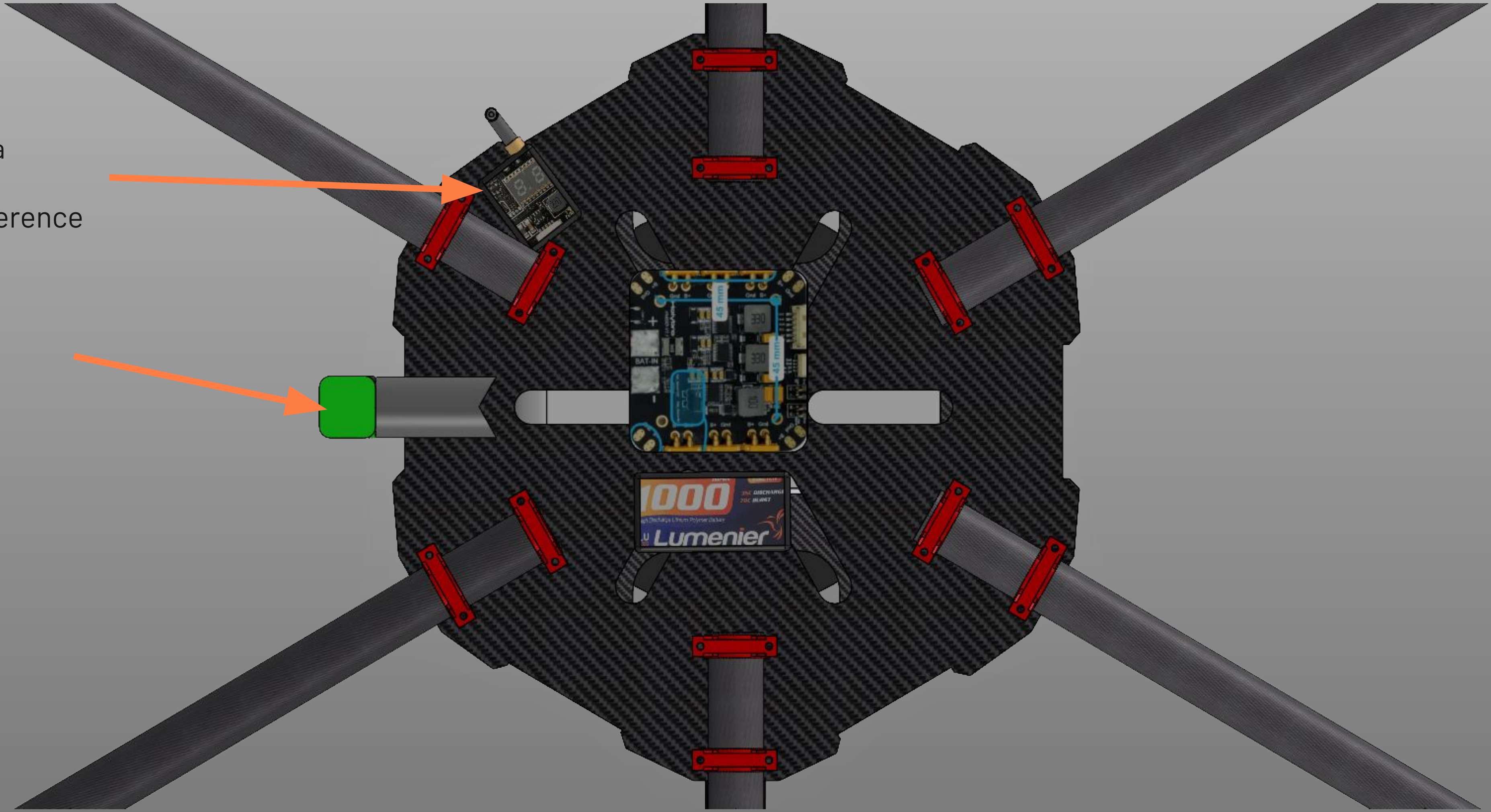
- **700TVL 2.8mm 120 Degree FPV Camera**
  - Horizontal resolution: 1080p
  - Connected directly to power module for 8V

- **AKK KC04 5.8G 600mW FPV Transmitter**
  - Transmitting distance > 3000m
  - Video band width: 0-8.0 MHz
  - 280mA at 5V
  - 5.8 GHz signal transmitted directly to 5.8GHz FPV monitor

Placement of Sensors

- **Video Transmitter**
  - Placed on edge for antenna
  - Fan for circulation
  - Away from battery interference

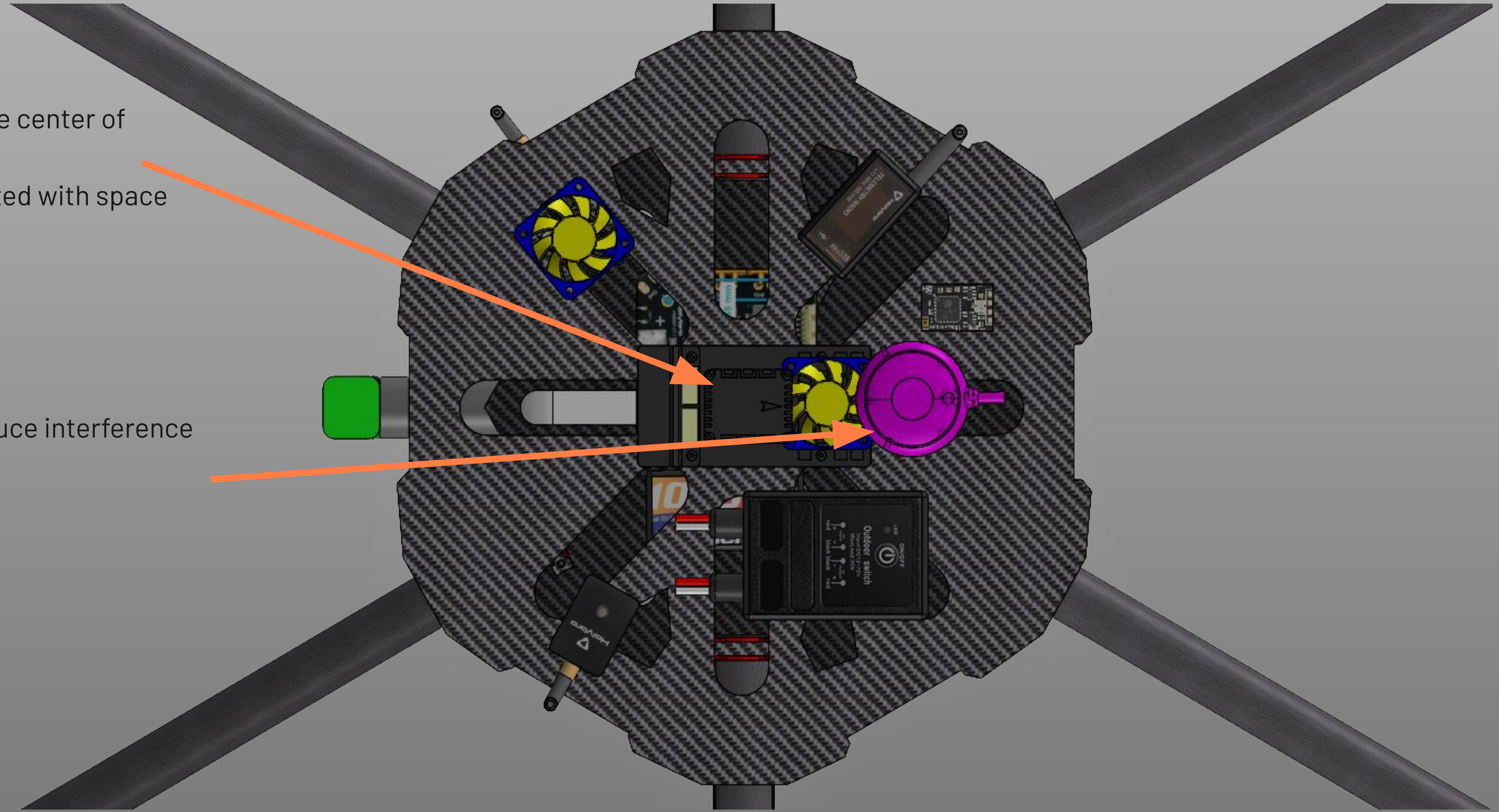
- **Camera**
  - Mounted with offset from the center



Placement of Sensors

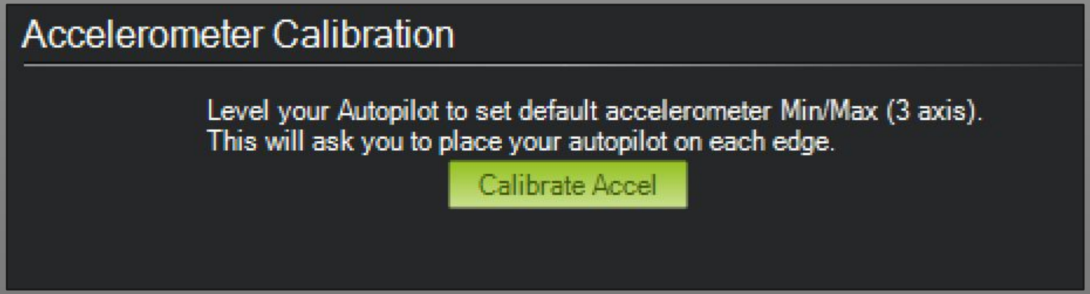
- **Flight Controller**
  - Placed near/directly above center of gravity
  - Allow wires to be distributed with space

- **GPS**
  - Placed near center to reduce interference from motors
  - Mounted on a stand



Calibration Plans

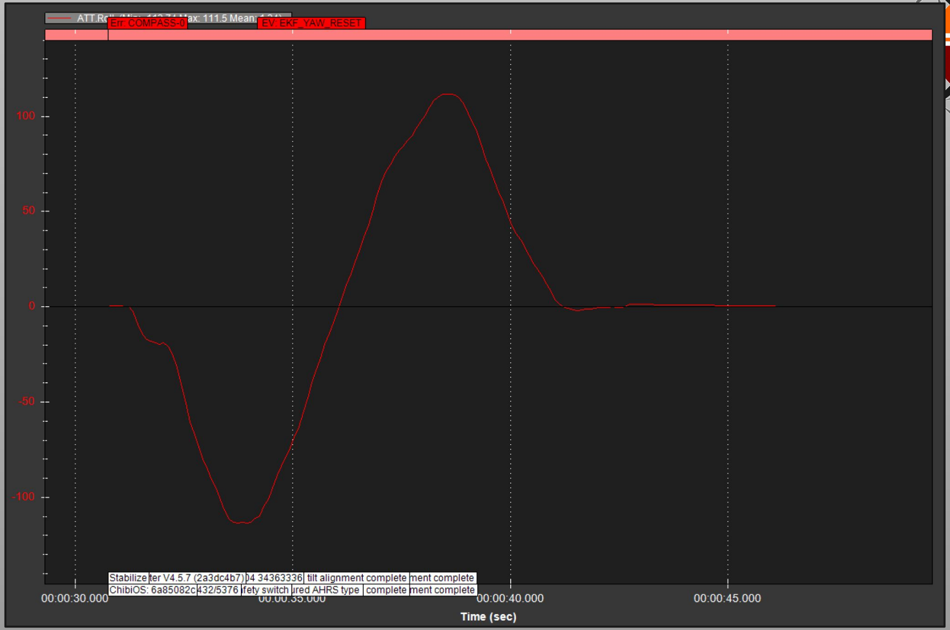
- **Pixhawk 6X Flight Controller**
  - Use Mission Planner Software
  - Follow steps in the Accelerometer Calibration tab
  - Set on flat surface and rotate the flight controller on different slides
- **RC Controller**
  - Set Minimum and Maximum Values for Joysticks and AUX inputs
- **Electronic Speed Controllers**
  - Calibrate the thrust inputs with the RC controller
- **FPV Camera**
  - Calibrate the focus of the FPV camera to our pilot’s desired liking

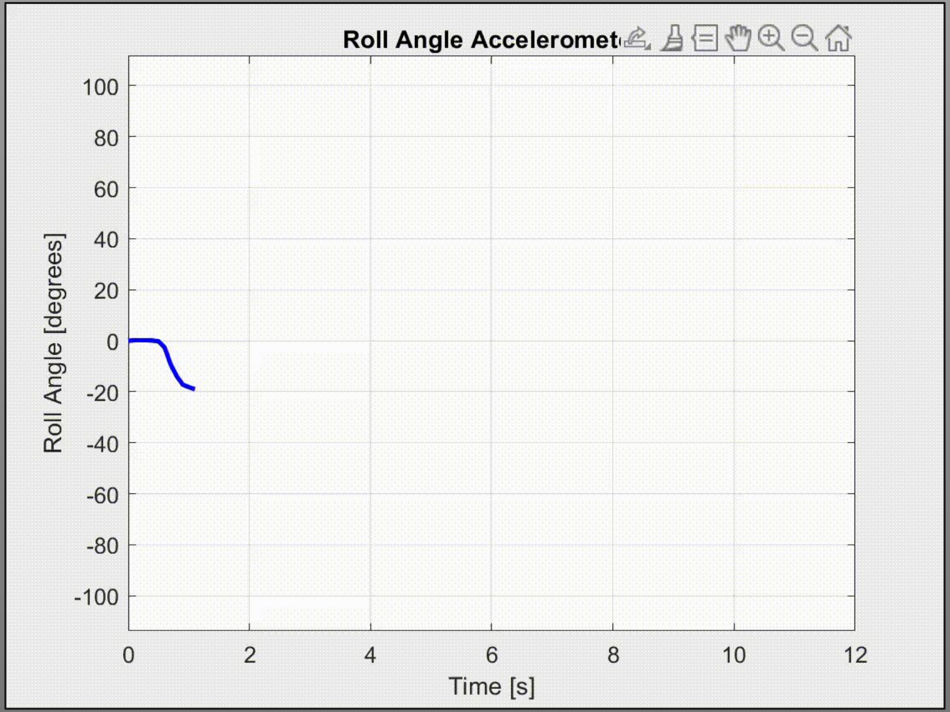


Data Acquisition/Analysis

- Utilize onboard sensors to verify expected mission performance
  - Position (lat, long, alt)
  - Attitude
  - Battery current draw
  - Battery voltage
  - Throttle

- CPU Onboard Flight Controller collects data, writes to SD Card
  - MAVLink download
- Plot collected data and compared to model
  - Mission Planner
  - MATLAB





Equipment and Facilities

- **Ground Station**
  - Laptop with Mission Planner
  - Transmitter
  - Video Receiver Screen
  - Remote Switch Controller
  - Communication Devices
  - Landing Pad
  - Target
- **Safety equipment**
  - Tools to repair and adjust drone
  - Extra set of batteries
  - Fire Blanket
  - First Aid Kit
  - Safety Glasses, hard hats, high visibility vests
  - Long pants/sleeves
  - Class ABC & D Fire Extinguishers
  - Any additional equipment

- **Test facilities**
  - CU South
  - AERO backyard (potentially)

Pre-Flight Checks

Check	Responsibility
1. Pre-Flight Check: Ground Station	• Open mission planner on laptop and load mission • Plug in telemetry radio • Power on video receiver
2. Pre-Flight Check: Hexacopter	• Unfold hexacopter in a clear, open area free of obstruction • Inspect Frame thoroughly for fractures, splintering or deformation • Inspect that the propellers are installed correctly • Address issues that can be restored on site or abort mission
3. Pre-Flight Check: Systems Check	• Ensure telemetry radios are paired and communicating • Check the GPS coordinates by comparison to google maps coordinates • Arm hexacopter and test control systems to ensure motor response and flight controller calibration
4. Pre-Flight Check: Ground Team	• Once drone is ready, mission leader checks ground station and supporting crew before takeoff • Allow teams to do training and preparation before flight day
5. Perimeter	• Launch area is 10 meters from ground station • Area of flight is 100 meters in diameter • VOs ensure hexacopter stays in perimeter

Flight Day Procedure

Safety Step	Responsibility
1. Safety Team Preparations	● Mission Leader checks roles and responsibilities of every team member ● Establish authority of PIC ● Every team member must understand their role and gather necessary resources to be successful ● Notify Mission Leader if resources or understanding is not available
2. Pre-Flight Checks	● See previous slide for relevant pre-flight checks
3. Perimeter	● Ensure negligible change of testing environment ● Follow all CU South policies
4. Go/No-Go	● In order for the flight to proceed, each team member must independently determine that conditions are sufficient for the flight to proceed ● The decision to "Go" must be unanimous
5. Flight	● Ensure that everyone has cleared the drone area and remains cleared during flight ● PIC establishes flight countdown ● Once countdown is finished, execute mission ● Once mission is complete, PIC and Mission Leader ensure safe retrieval parameters

Go/No-Go

- **Go**
  - Wind: 0-10 miles per hour
  - Visibility: > 3 statute miles
  - Clouds: Floor > 1,000 ft AGL
  - Ground Station: receives telemetry and GPS data
- **No-Go**
  - Wind: over 10 miles per hour
  - Visibility: < 3 statute miles
  - Weather: rain, snow, fog
  - Ground station: unable to receive telemetry data and/or GPS data
  - Airspace restrictions and/or Temporary Flight Restrictions (TFR)

Key

Evac Route

Geo Fence [200m]

Operating Zone [150m]

Visual Observer

Ground Station & Safety Equipment

Zone Clearance Personnel

Pass/Fail Criteria

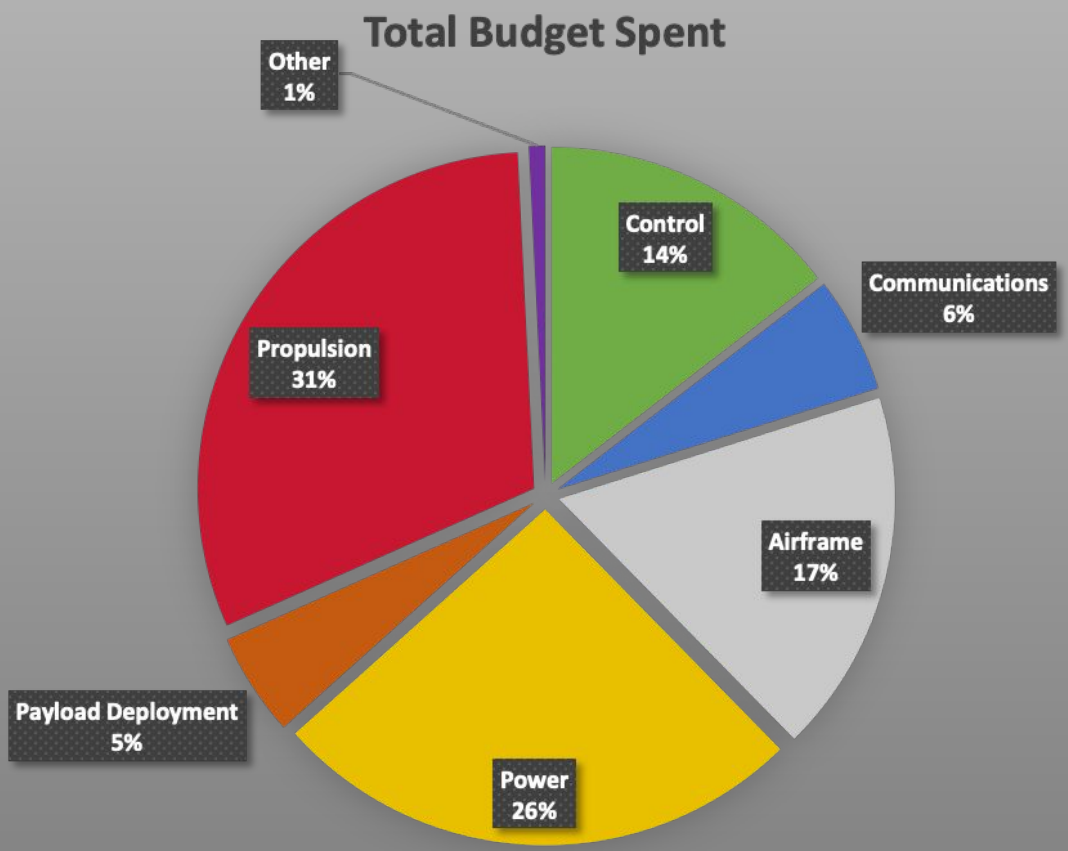
- **Pass**
  - Drone reaches target zone autonomously
  - Payload deployed on target
  - Drone returns to base and lands autonomously
  - Drone is reloaded with no issues

Completed within ⅓ of full mission time (20 minutes)

- **Fail**
  - Drone loses control in flight and has to switch to human operation before target range
  - Payload doesn't hit target
  - Drone needs human operation to land or system loses control during landing
  - Payload deploys early
  - Unrecoverable communication error occurs
  - Drone goes below 30 foot hard deck during autonomous flight
  - Unable to complete in ⅓ of full mission time
  - Reloading complications occur
- **Expected Performance**
  - UAS successfully completes mission laid out in ConOps within ⅓ of a full mission time

Budget

Budget Details



Subsystem	Total Spent
Propulsion	$1027.07
Power	$855.34
Airframe	$588.13
Control	$483.97
Communications	$185.55
Payload Deployment	$164.80
Other	$31.98

- Overall Spent
  - **$3336.84**
- Total Remaining
  - **$663.16**
- All major components have been purchased and received

Additional Budget Details

Phase	Amount Spent	Allocated Budget	Margin
Phase 1: Testing	$185.40	$250 ~~$500~~	25.9% Under Budget
Phase 2: Manufacturing	$3113.78	$3650 ~~$3000~~	14.7% Under Budget
Phase 3: Expo/Other	$31.98	$100 ~~$500~~	68.0% Under Budget
Total	$3325.17	$4000	16.9% Under Budget

Critical Budget Items

Component	Amount Needed	Spares	Expected Cost	Expected Lead Time	Failure Risk	Failure Impact	Failure Preparations
Airframe	1	0	$499.99 per Airframe	7-14 days	Medium	Medium	• Super glue/flex tape • Budget margins for Individual Parts
Propellers	6	6	$56.11 per 8 Propellers	14-28 days	High	Low	• Always have spares to prepare for long lead times
Motors	6	0	$102.60 per Motor	3-10 days	Low	Medium	• Safe handling • Safe flying • Budget Margins
Battery	1	1	$335.99 per Battery	3-10 days	Low	High	• Safe handling • Safe flying • Budget margins

Questions?

Backup Slides

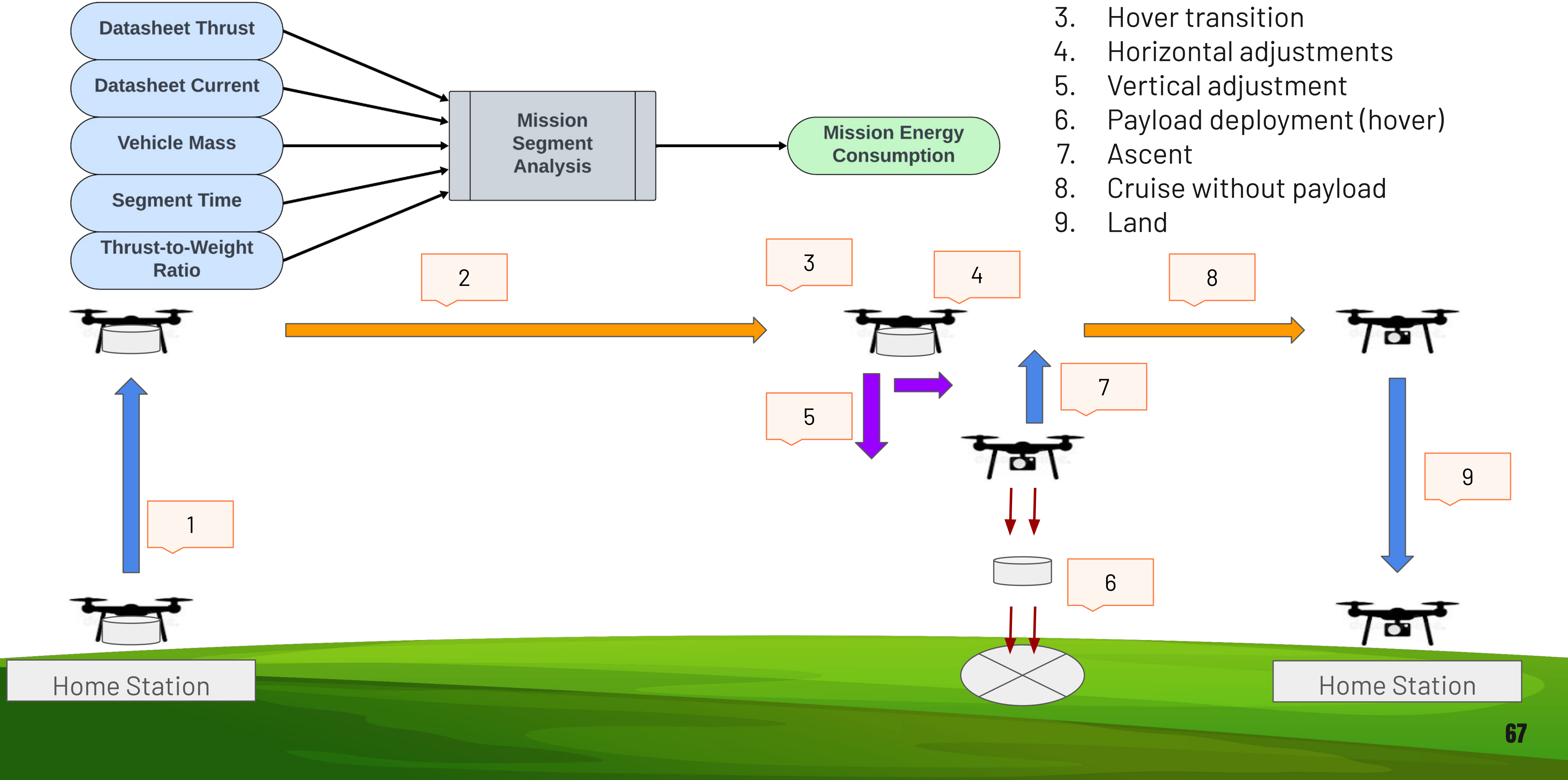
Table of Contents

CDR Modeling

Energy Consumption Analysis Model

Mission Segments:

1. Takeoff
2. Cruise with Payload
3. Hover transition
4. Horizontal adjustments
5. Vertical adjustment
6. Payload deployment (hover)
7. Ascent
8. Cruise without payload
9. Land



Model Uncertainty

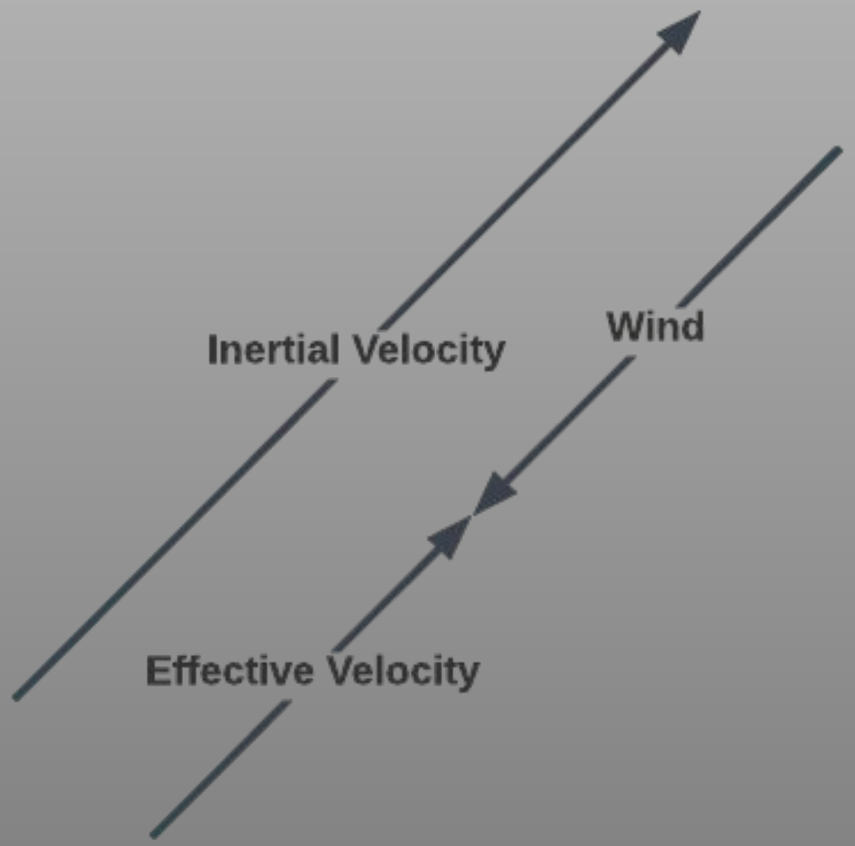
- **Motor thrust values**
  - Unknown test altitude of motor datasheet data
  - Multiply datasheet thrust values by ratio of air densities of Boulder and sea-level

$$T_{alt} = T_{data}\frac{\rho_{alt}}{\rho_{s.l.}} = 0.85T_{data}$$

- **Human-in-the-loop (HITL) segment times**
  - Dynamics model cannot account for time lengths of the HITL segments
  - Allowed for 60 seconds for HITL segments

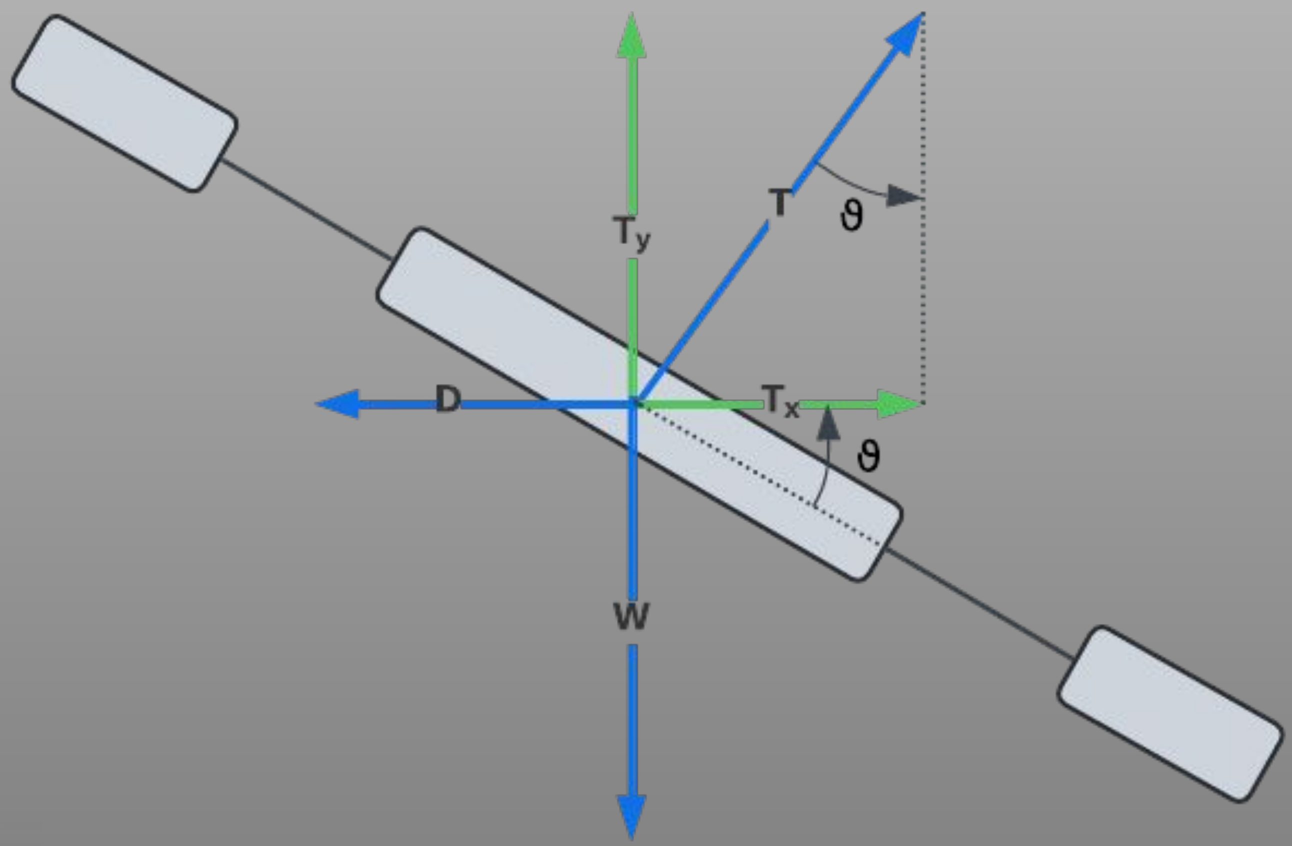
Modeling Wind

- **Assumed worst case scenario**
  - A headwind directly opposing vehicle velocity vector
- **Boulder average wind conditions**
  - Max of 10 mph from January-April
- **To account for wind**
  - Lowered desired velocity by 10 mph (4.47 m/s) in model



Modeling Drag

- **Assumed: Steady, level, unaccelerated flight**
  - Horizontal thrust equal to drag
  - Horizontal thrust dependent on tilt angle
  - Simplify drag equation for aerodynamic force coefficient, ν
- **Accounting for drag**
  - Within dynamics model
  - Nu: ν
    - Very small (approximately 0.005)
    - Drag considered negligible



At maximum velocity:

$$T_x = D = \frac{1}{2}\rho C_D A V^2 = \nu V^2$$

Thrust-to-Weight and Velocity

- **Thrust to Weight Ratio**
  - Not an input parameter for ArduPilot
- **Maximum Tilt Angle**
  - Set to 10 degrees
    - This is the smallest maximum tilt angle for ArduPilot
- **Modeled Equations:**
  - Assuming negligible drag, no wind, symmetrical thrust, steady and level flight, and no shift in center of mass

Tilt angle Required to maintain constant T/W ratio:

$$\frac{T}{W} = \sec\theta$$

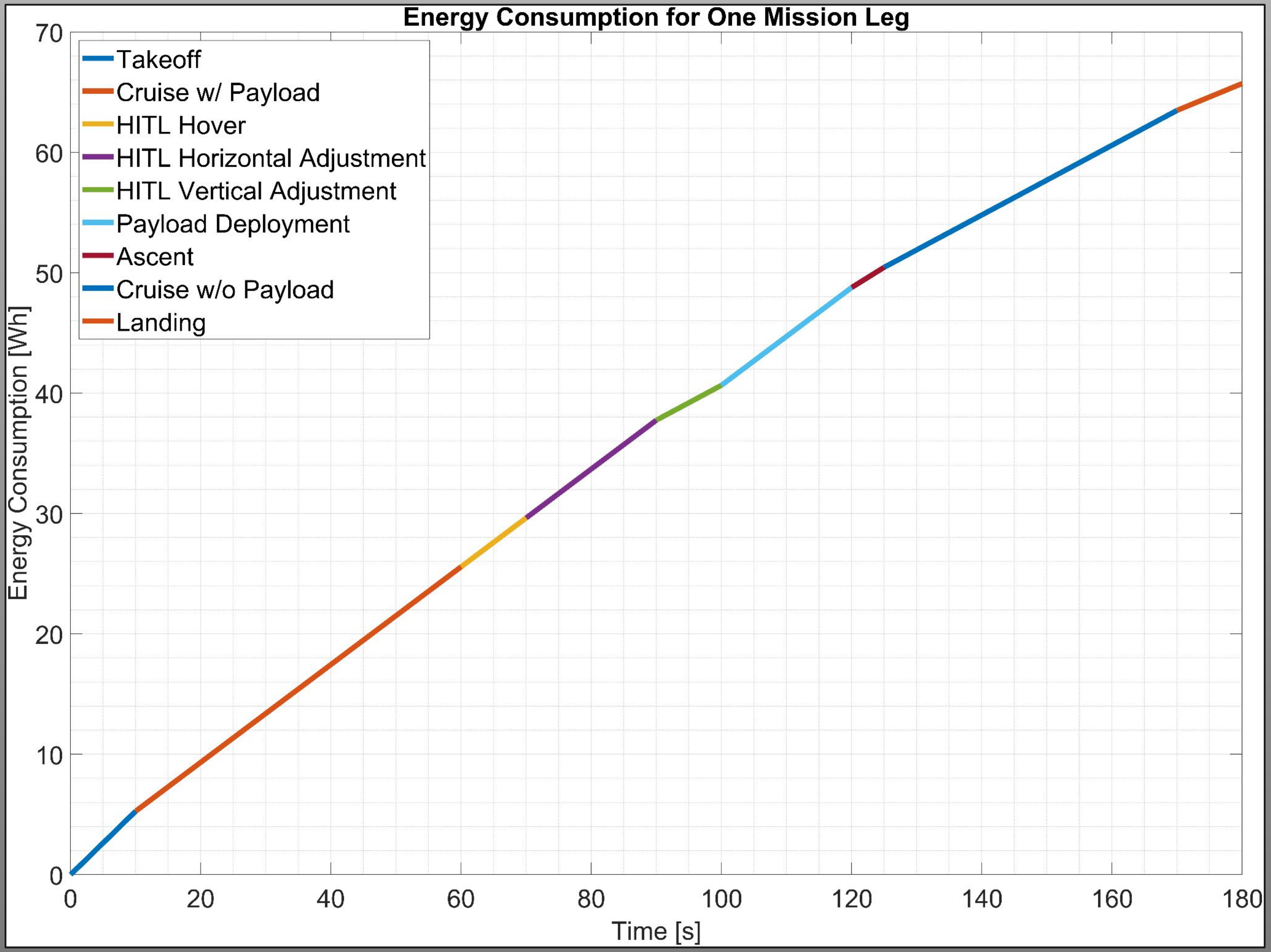
Velocity as a function of time for given tilt angle and T/W ratio:

$$v(t) = \frac{T}{W} * t\sin\theta$$

Model Results: Mission Performance of Hexacopter

- **One mission leg results (100 m)**
  - 65.7 Wh per mission leg
    - Multiply total by four to represent the total number mission legs with an extra for a buffer
  - 180 seconds per mission leg
    - 12 minutes for entire mission
    - 8 minutes of reloading
      - <1 minute of reloading per mission leg is expected
- **Account for battery Depth of Discharge (DoD)**
  - Typically ~85%
  - Gives us battery energy capacity of 309.2 Wh
  - 16,000 mAh 6S LiPo = 355.2 Wh

$$E_{batt} = \frac{E_{mission}}{DoD}$$



Dynamics Model: Governing Equations

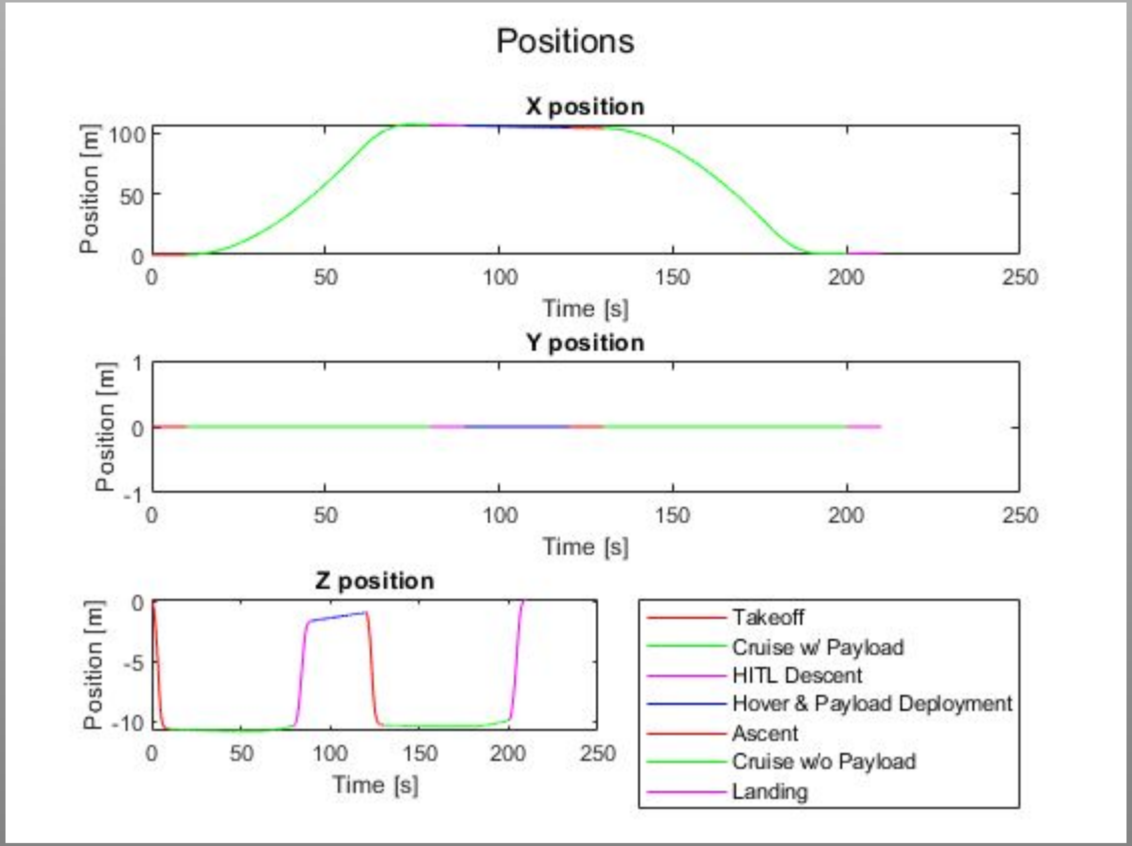
$$\begin{pmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix} \begin{pmatrix} u^E \\ v^E \\ w^E \end{pmatrix}$$

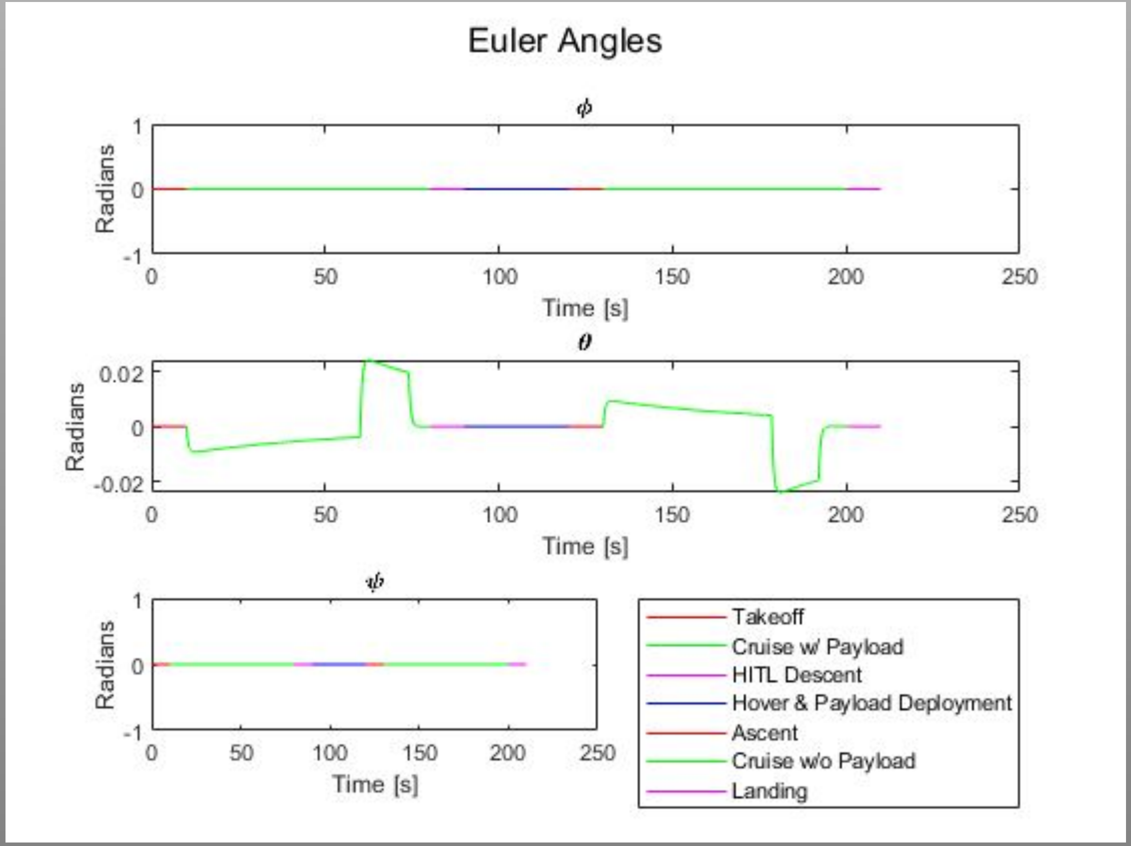
$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & \sin\phi \tan\theta & \cos\phi \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi \sec\theta & \cos\phi \sec\theta \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$\begin{pmatrix} \dot{u}^E \\ \dot{v}^E \\ \dot{w}^E \end{pmatrix} = \begin{pmatrix} rv^E - qw^E \\ pw^E - ru^E \\ qu^E - pv^E \end{pmatrix} + g \begin{pmatrix} -\sin\theta \\ \cos\theta \sin\phi \\ \cos\theta \cos\phi \end{pmatrix} + \frac{1}{m} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \frac{1}{m} \begin{pmatrix} 0 \\ 0 \\ Z_c \end{pmatrix}$$

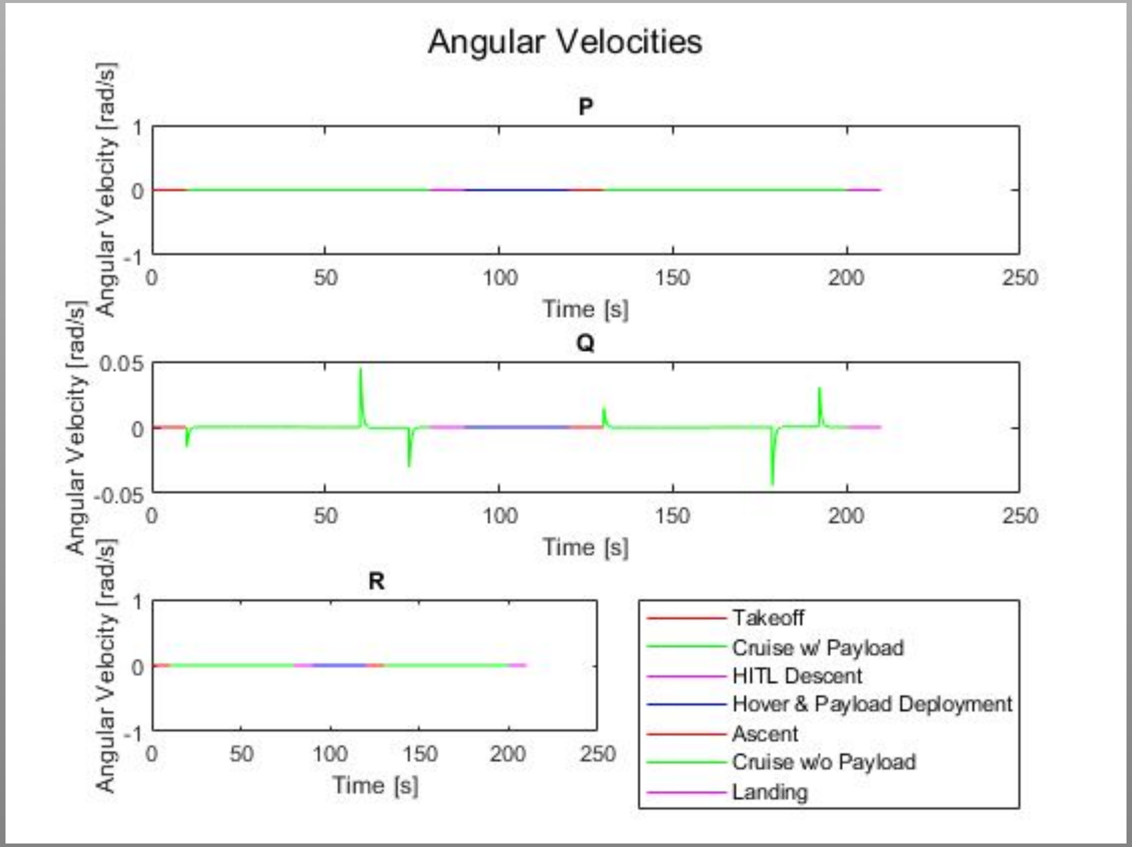
$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{I_y - I_z}{I_x} qr \\ \frac{I_z - I_x}{I_y} pr \\ \frac{I_x - I_y}{I_z} pq \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L \\ \frac{1}{I_y} M \\ \frac{1}{I_z} N \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L_c \\ \frac{1}{I_y} M_c \\ \frac{1}{I_z} N_c \end{pmatrix}$$

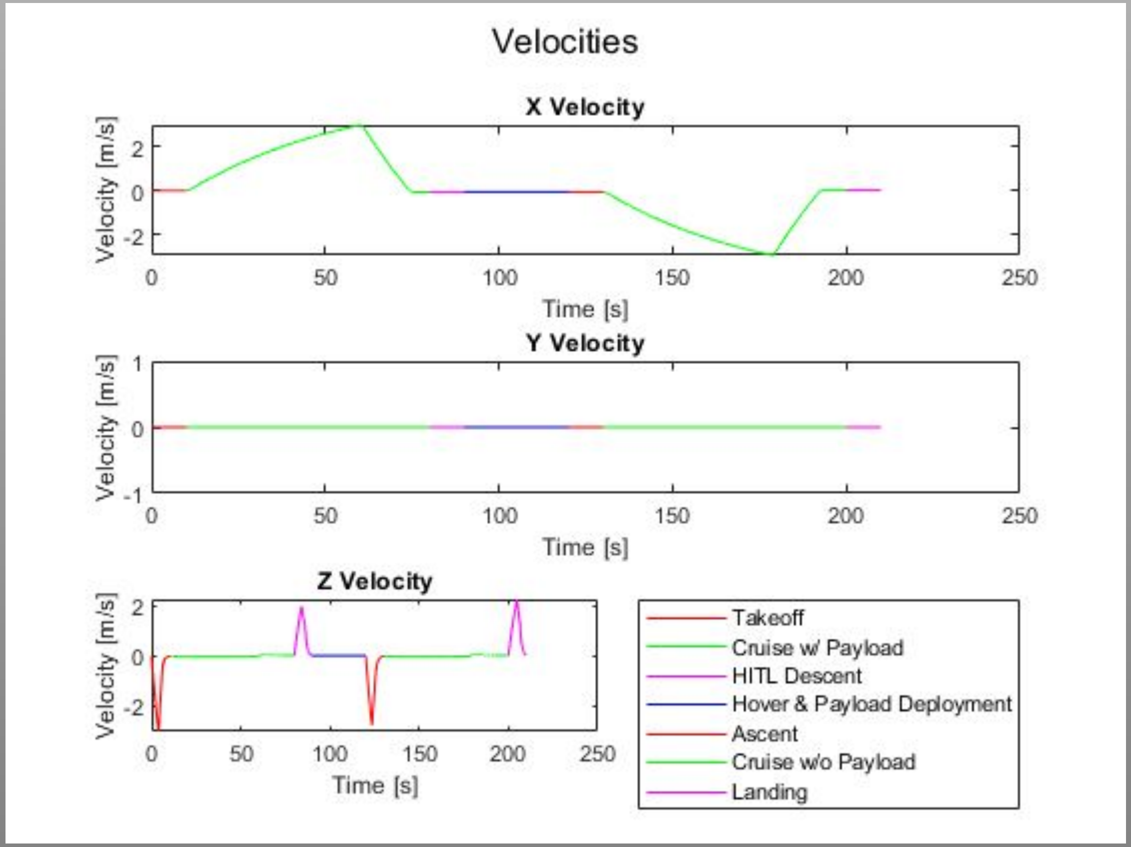
Dynamics Model: Plots



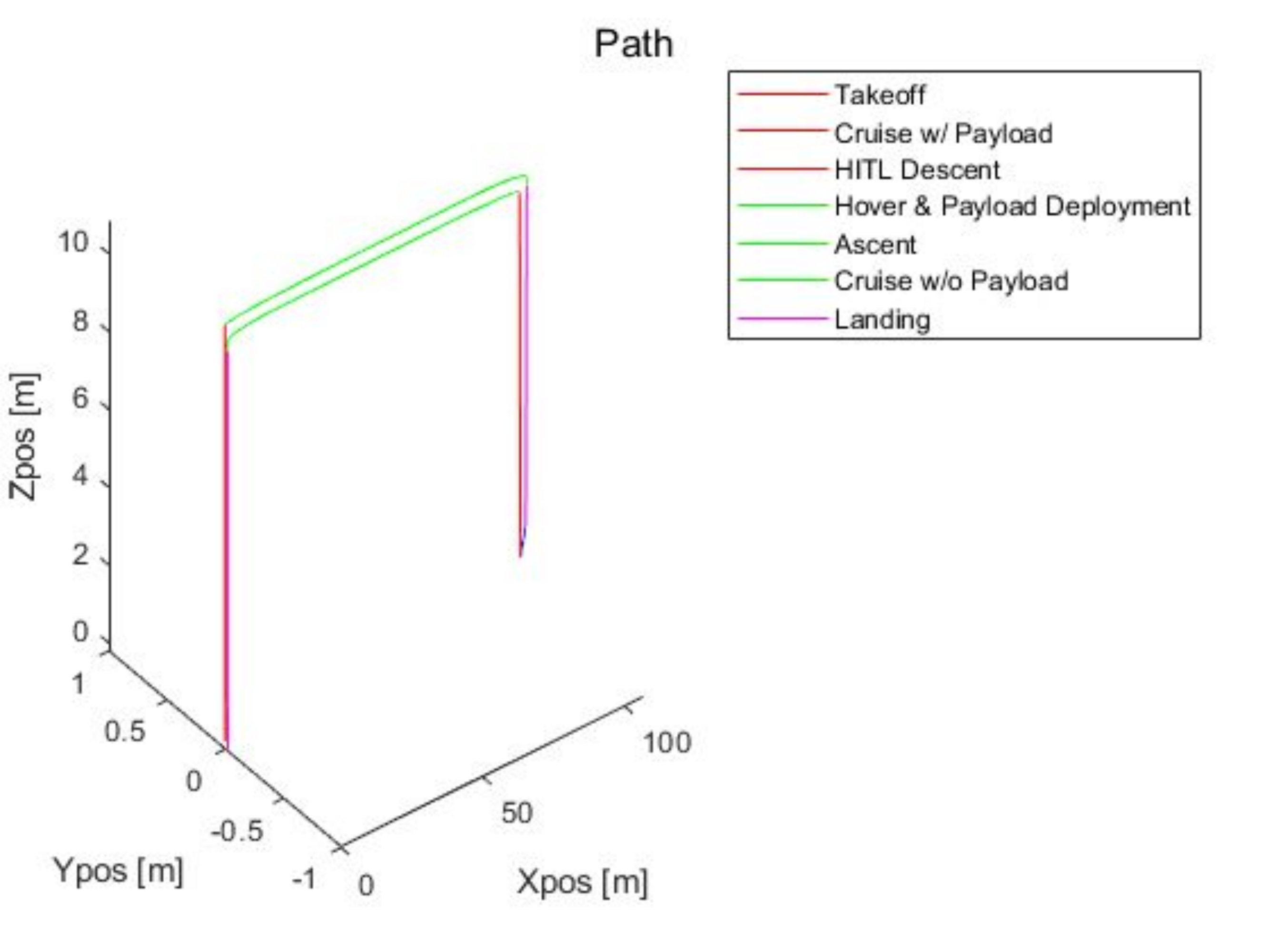


Dynamics Model: Plots (Continued)

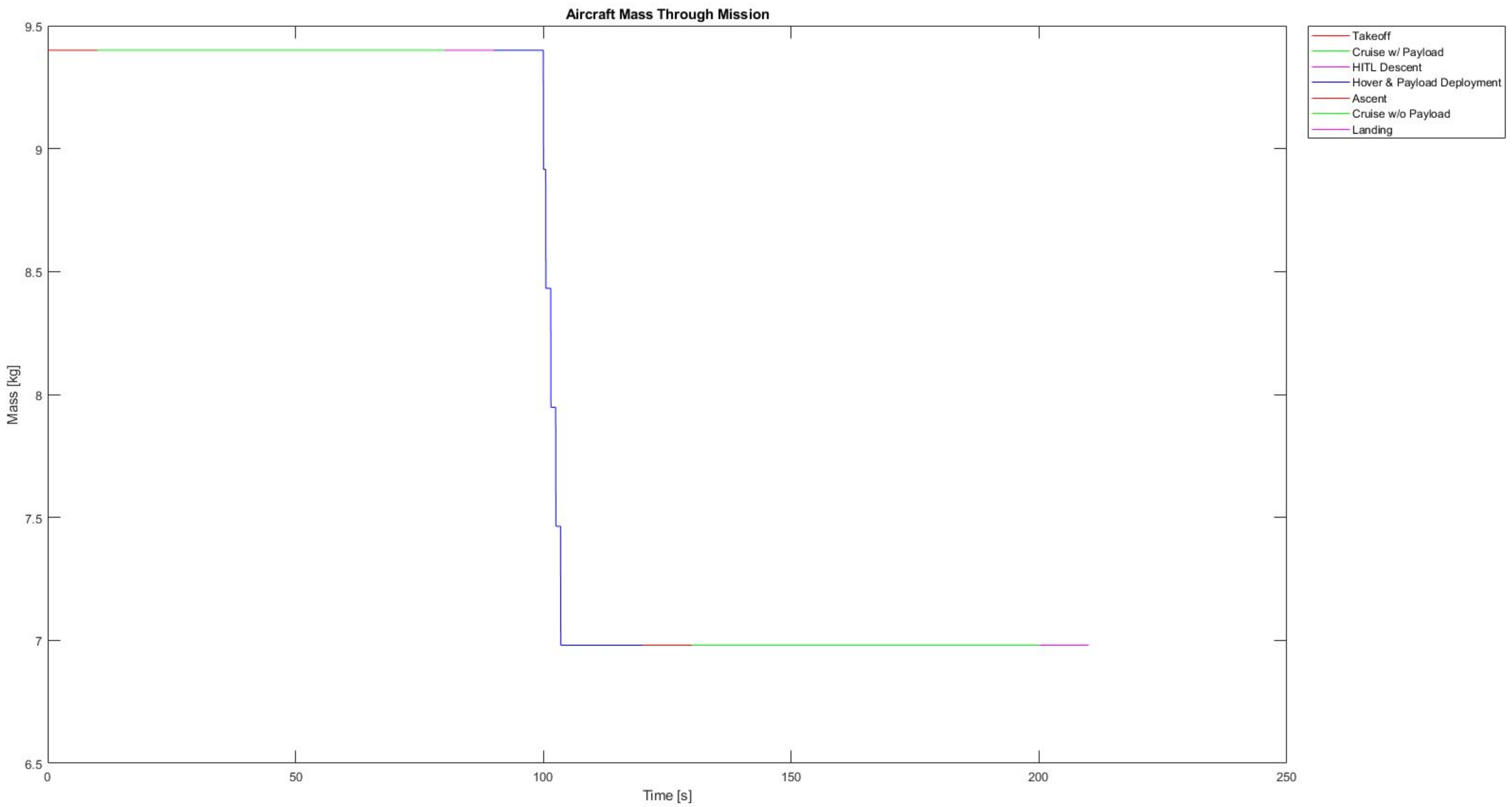




Dynamics Model: Plots (Continued)

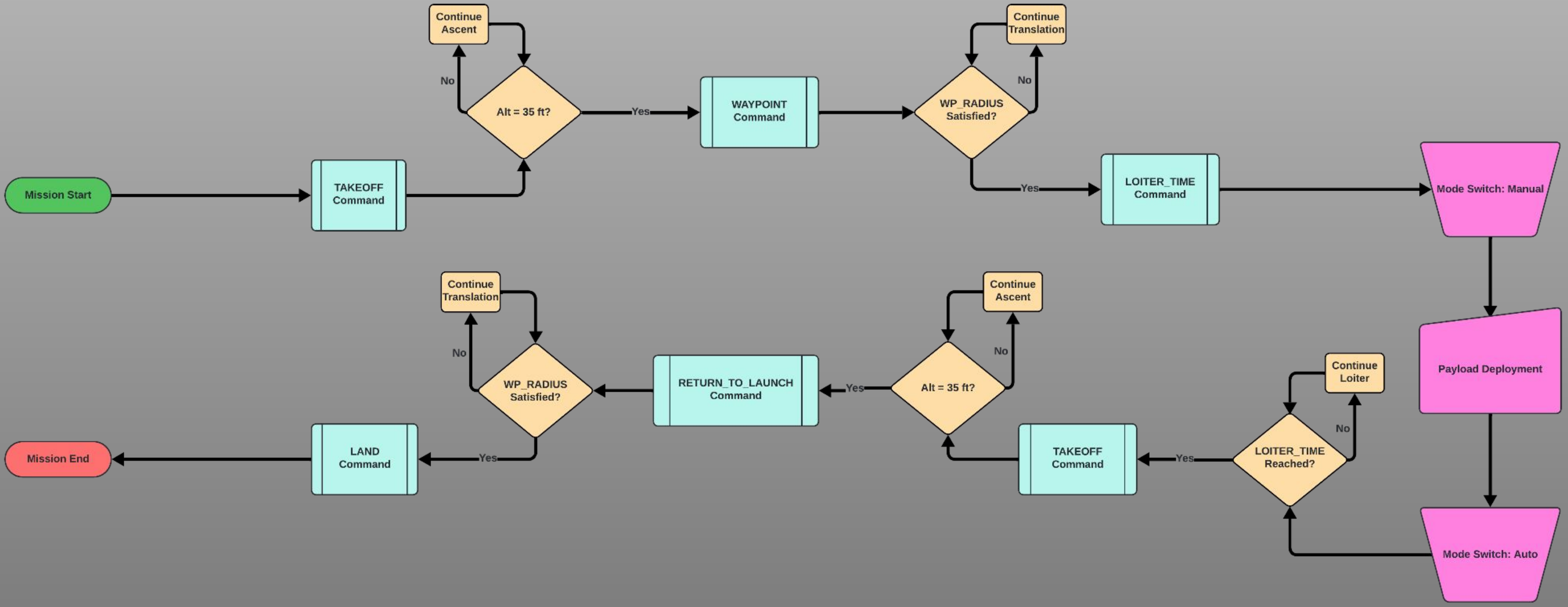


Dynamics Model: Plots (Continued)



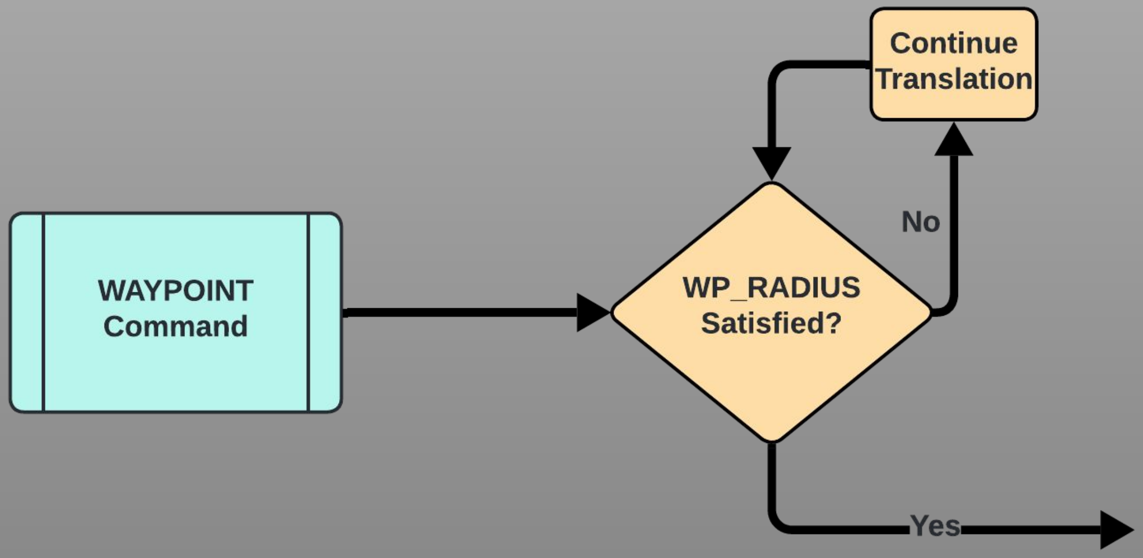
Software/Electrical

ArduPilot Mission Architecture



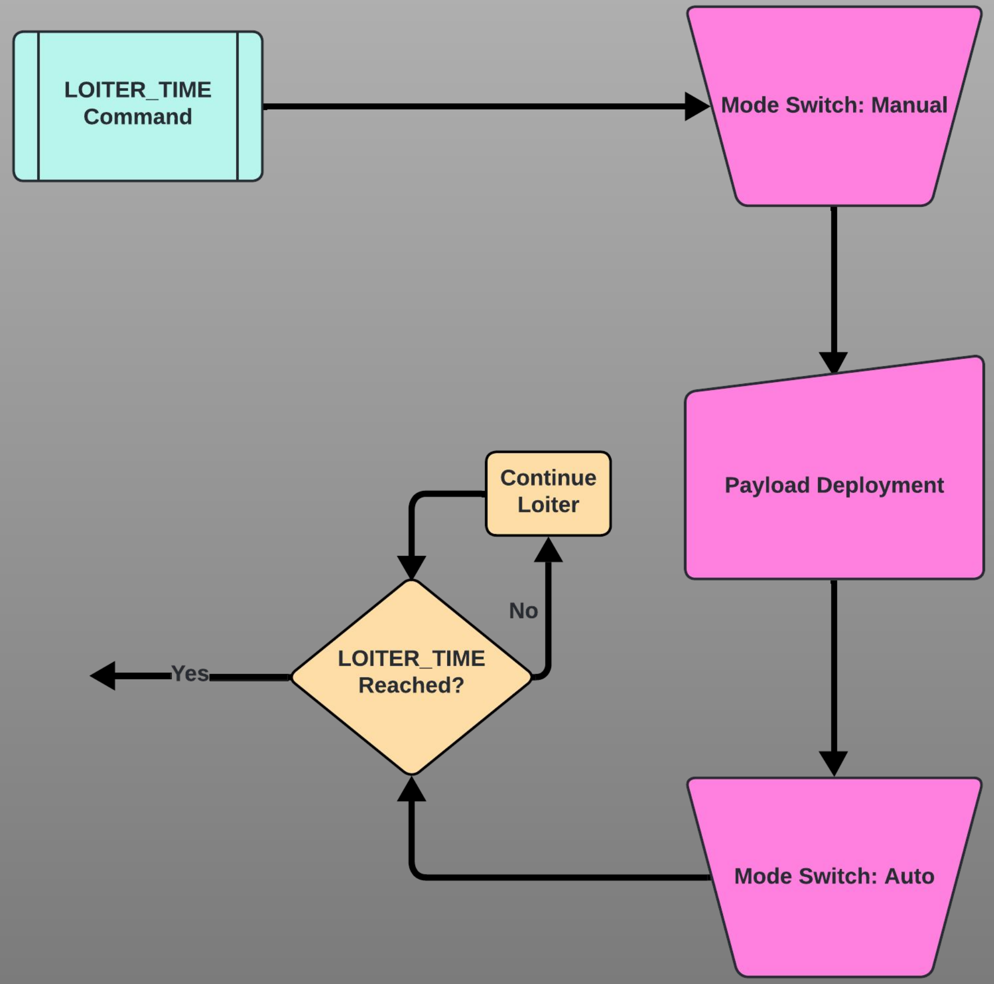
ArduPilot Mission Architecture

- WAYPOINT
  - Entered through latitude and longitude
- WP_RADIUS
  - Configurable parameter prior to mission start
  - Have a 10m requirement
    - Extended Kalman Filter 3 (EKF3)
      - Estimated position and attitude
      - 3 IMUs -> 3 EKF3 “calculations” in parallel
      - Will use the EKF3 output with the best health
      - Based on consistency of sensor data
      - Extended Kalman Filter Navigation Overview and Tuning — Dev documentation



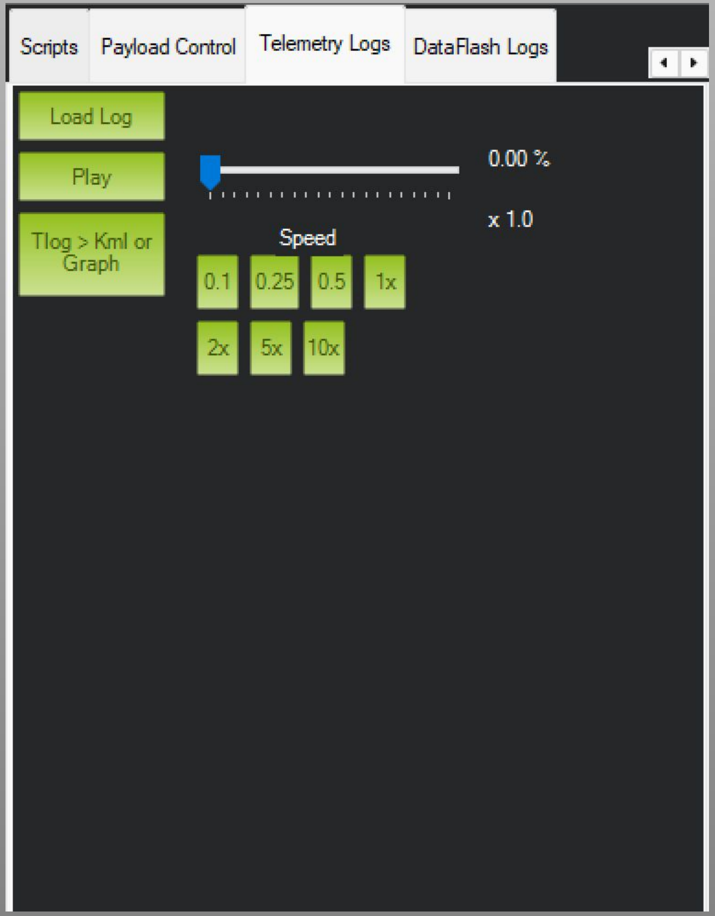
ArduPilot Mission Architecture

- LOITER_TIME
  - Configurable within mission setup
- Mode Switch: Manual
  - On RC Controller
  - Will pause mission commands
  - Will be done once drone has stopped translation
    - Telemetry data/visual observation
- Mode Switch: Auto
  - On RC Controller
  - Will resume mission commands
  - Will be done once payload deployed
    - Visual inspection on camera
- PID Gains
  - Tune for lighter weight
  - Adjust acceleration parameters by ratio of min_TOW/max_TOW
    - Units of centidegrees per second squared
    - Per ArduPilot "Tuning Instructions"

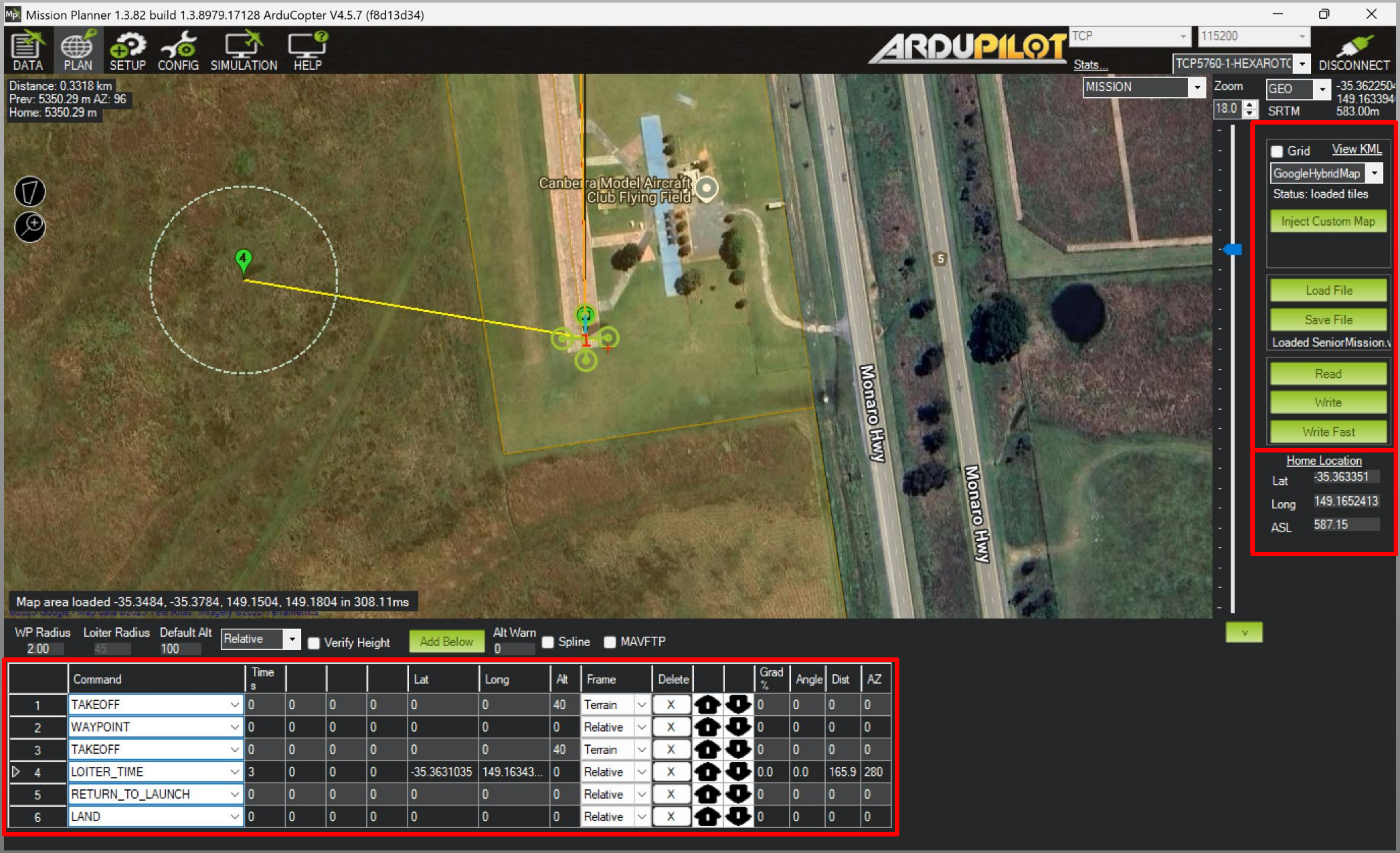


Data Management

- Log Types
  - DataFlash
    - Logs are stored on an SD card
    - Downloadable via Mavlink
    - Export MATLAB file
  - Telemetry
    - Recorded by ground station
    - Information sent via SiK Radio
    - Graph within Mission Planner
  - Redundancy
    - Data loss prevention



Mission Planner GUI: Mission Planning



- **Mission Commands**
  - Load pre-saved mission commands
  - Manually set home location via coordinates
  - Manually type altitude and latitude/longitude

Mission Planner GUI: Mission Status

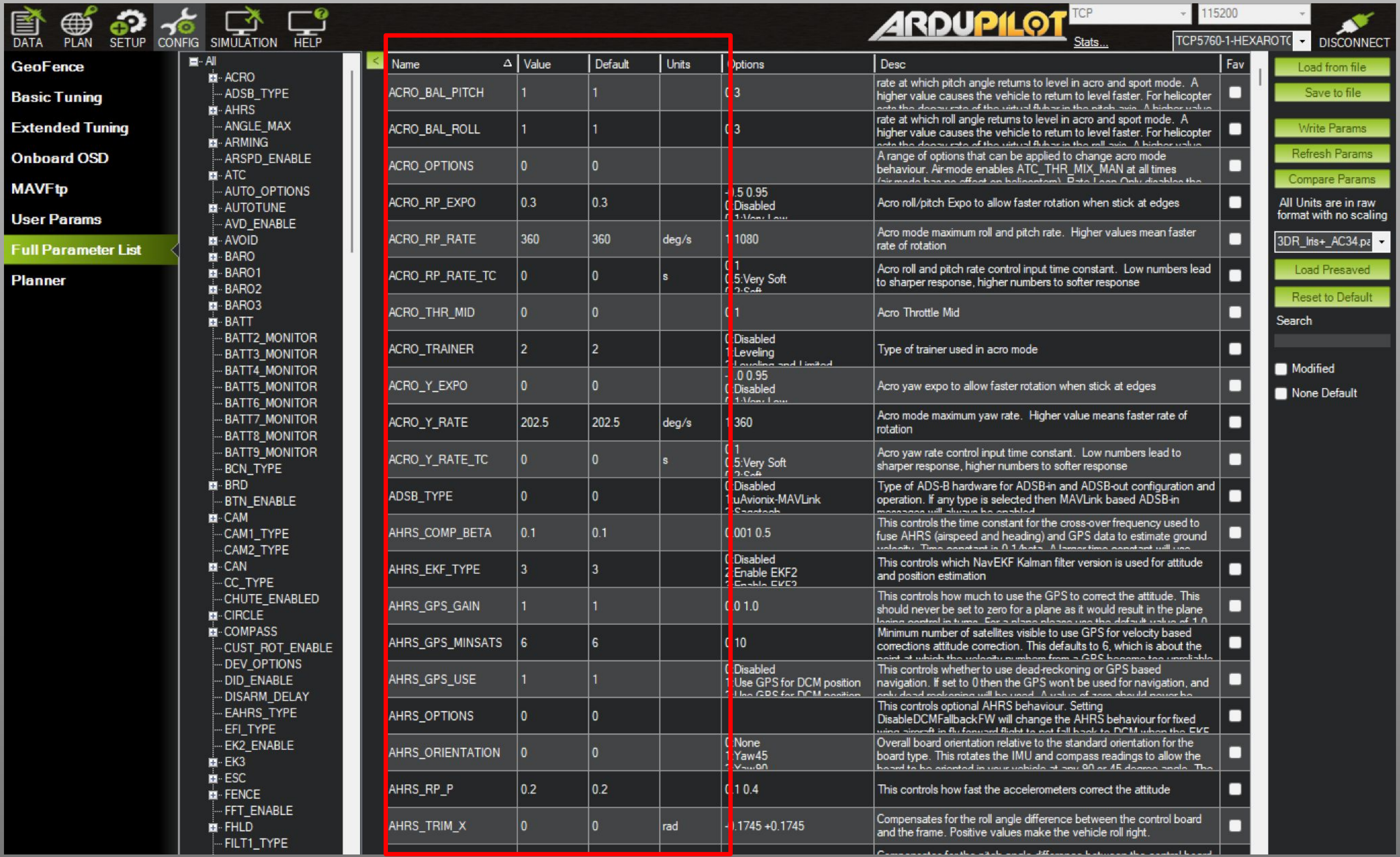
- **Mission Status**
  - Armed/disarmed (safety)
  - Mission timer
  - Battery info
  - Airspeed/ground speed
  - Attitude
  - Asses mission progress
  - Let pilot know when to take control

Mission Planner GUI: Tuning

- **Tuning**
  - Follow ArduPilot "Tuning Instructions" for min_TOW

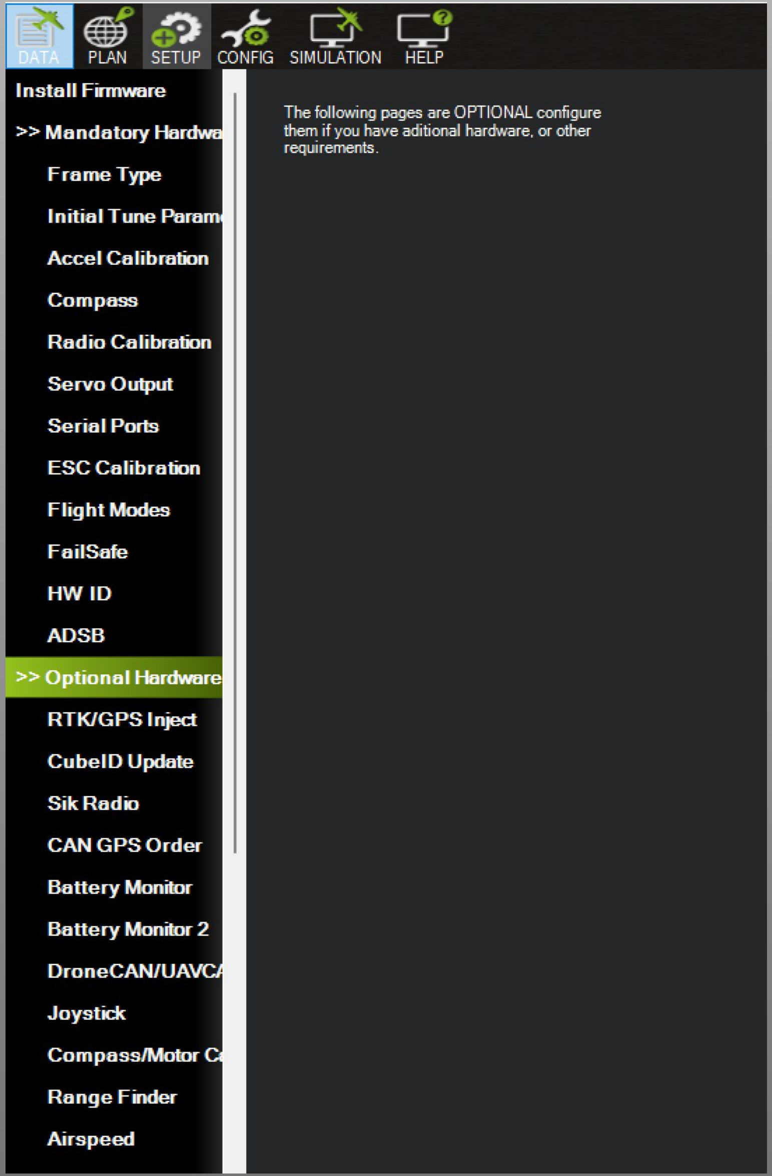
85

Mission Planner GUI: Parameters



- **Parameters**
  - Manually adjust parameters as needed
    - Payload deployment

Mission Planner GUI: Setup



- **Hardware**
  - Mandatory
    - Frame type
    - ESC Calibration
    - Set Flight Modes
    - Calibrate PixHawk sensors
  - Optional
    - GPS
    - SiK Radio
    - Battery Monitor (PM03D Power Module)

Specifications

SiK Telemetry Radio V3

- Over 300 meters in range
- Error correction up to 25% of bit errors
- Easy Plug-in to Flight controller.
- 915 MHz Radio Signal
- 125mA at 5V
- Compatible with Ardupilot and Mission Planner

Specifications

RadioMaster ExpressLRS 2.48 GHz Receiver

- 2.48 GHz Signal
- Plug Directly into Flight Controller
- Receives directly from 2.48 GHz Transmitter
- Dual Channel for signal sensitivity
- UART communication protocol

Specifications

12V Remote Control Switch

- Range of 1500 meters
- 433MHz Operation Frequency
- Attached to power module
- 9 V battery

Specification

Remote ID

- Range: > 5km detection range
- 2.4GHz (ERP) Wifi broadcast
- Directly into flight controller
- FAA Guidelines
- 5 Volts

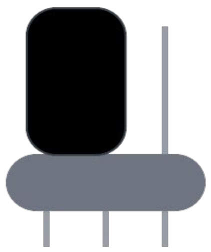
Specifications

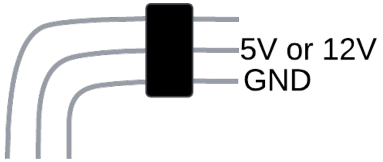
Tattu Lipo Battery

- 16000mAh
- 22.2 V 6S
- 30 Discharge Rate Capacity
- Power Model to prove its success

PM03D Power Module

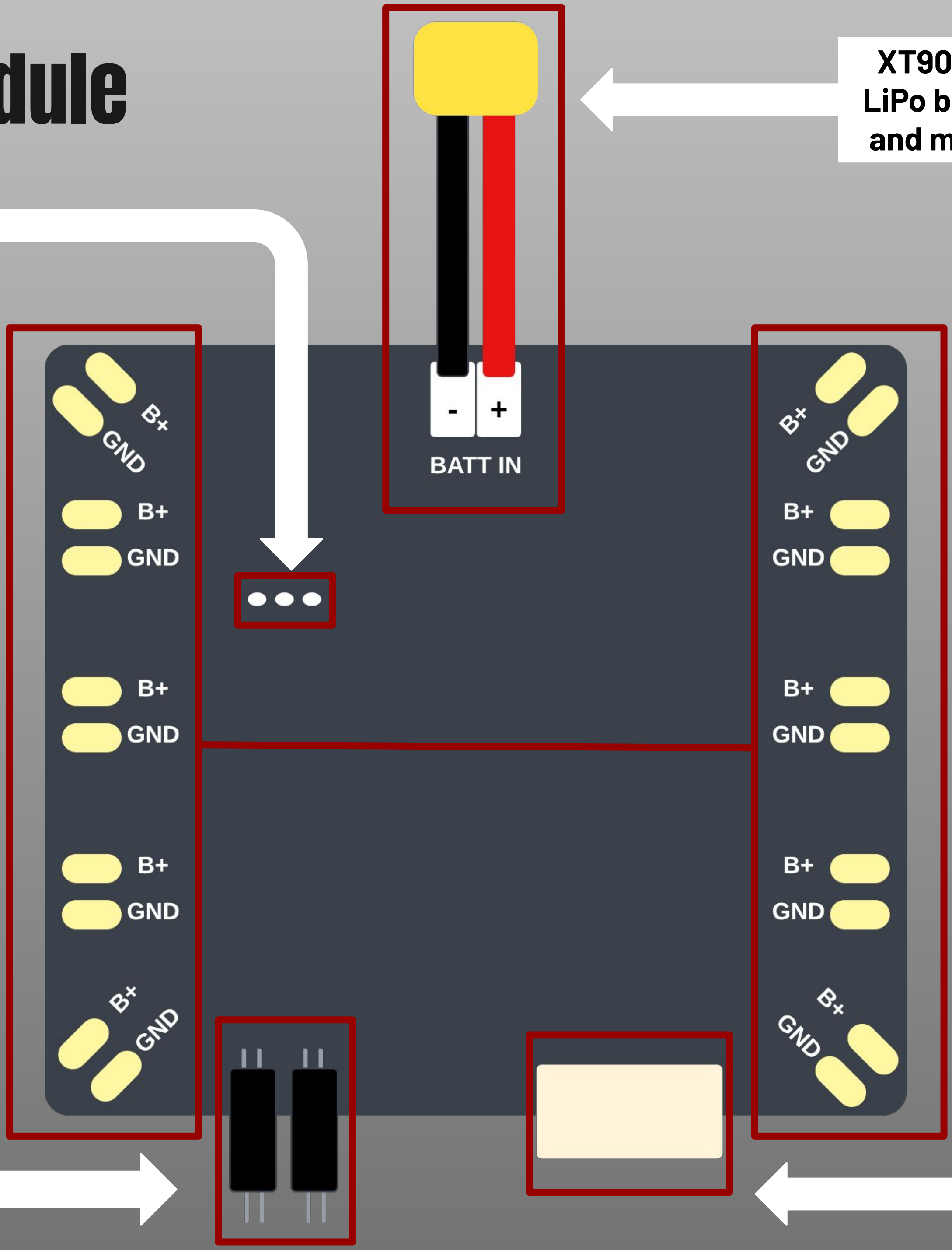
Configure male 3-pin header to 12V with header jumper





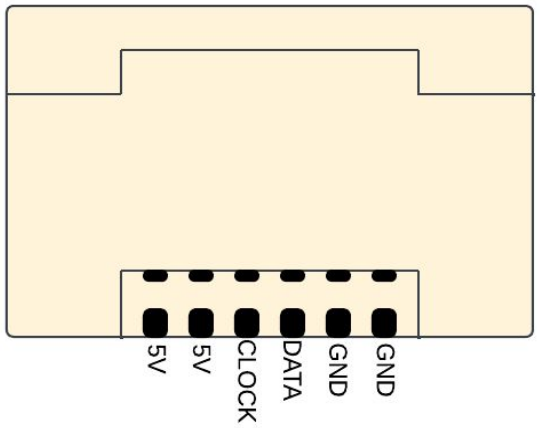
5V 3-pin male header to camera and video transmitter (left)

12V 3-pin male header to remote switch & Solenoid valve (right)



XT90 Connector to 6S (24V) LiPo battery with 10 AWG wire and max peak current of 40A

Solder pads to ESCs and motors, outputs battery voltage of 24V and max peak current of 40A



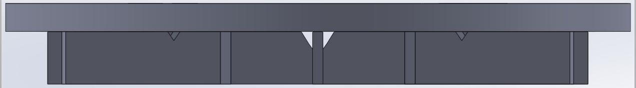
I2C digital signal data output and Pixhawk 6X power (5V) with JST GH receptacle connector

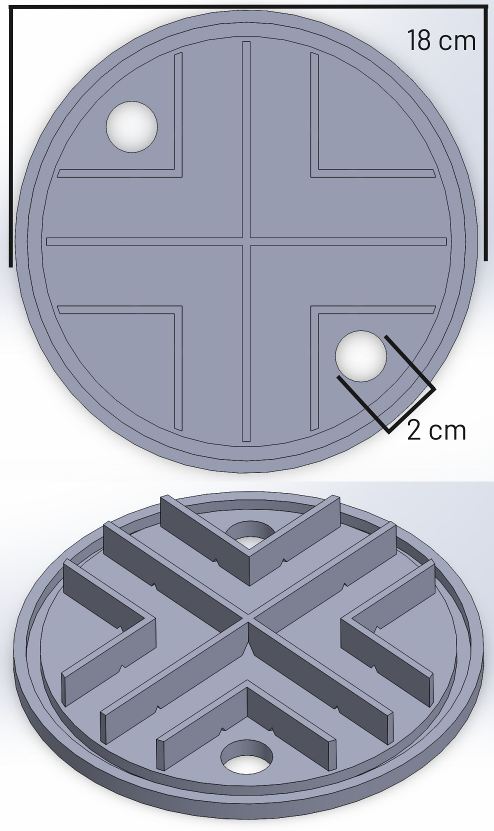
Hardware

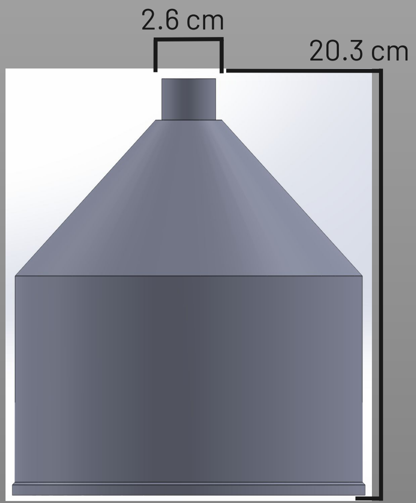
Payload Deployment Subsystem: Container

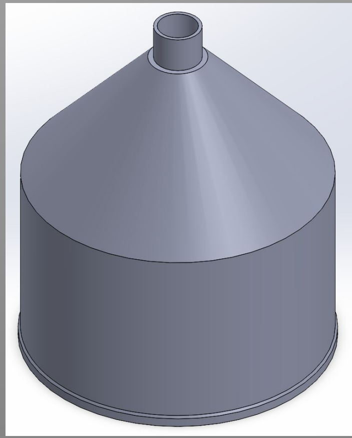
- **~10 % Payload Margin**

- **Payload Stability / Fluid Flow**
  - Baffles
  - Angled walls to promote outflow
  - Airflow/Fill Ports
- **Manufacturing Constraints - 3D Printing**
  - Overhang <50 degrees
  - Minimize support material
- **Structural Analysis - Design Space Optimization**
  - Minimize surface area (container mass)
  - Minimize moment of inertia
- **Airframe Integration**
  - To be completed after airframe delivery









Cylinder Height	Total Height	Slant Angle	Top Radius	Bottom Radius	Contained Payload Volume	PLA Volume	Estimated PLA Density	Estimated PLA Mass	Estimated Total Mass
9.94 cm	16 cm	48 deg	8 cm	1.27 cm	2,479 cm^3	255 cm^3	1.24 g/cm^3	316 g	2,735 g

Payload Deployment Subsystem: Deployment Mechanism

Remote Switch

Solenoid Valve

1" NPT - Schedule 40 Slip Coupling

Vinyl Tubing

Airframe Subsystem

Frame Selected: Tarot T960 Hexacopter

- Carbon fiber arms, legs, motor mounts
- Aluminum arm locking mechanisms
- Adjustable battery Mounting Plate

Total Mass	Tip to Tip Length	Landing Gear Clearance	Standard Propeller Size
2.12 kg	960 mm	320 mm	18”

Safety

Personnel: Safety Teams

- **Flight team**
  - Aircraft Inspection lead (AIL)
    - Ethan Davis
    - Facilitate pre/post-flight safety checks
  - Software Inspection Lead (SIL)
    - Jared Steffen
    - Ensure all electronics are primed with up-to-date software and amply charged for testing/mission
- **Fire Safety Team**
  - Fire Extinguisher Handler (FEH)
    - Alex Putnam
    - Responsible handling of a fire extinguisher in event of combustion
- **Injury Team**
  - Designated Driver (DD)
    - Ian McCarty
    - Responsible for transportation to nearest hospital if injury occurs
  - Boulder Fire Department Contactor (FD Contactor)
    - Jack Pearse
    - Responsible for contacting Boulder FD if necessary

★ **FAA required position**

☆ **91-57C certified Pilot**

Personnel: Nominal Flight Ops Team

- **Mission Leader (ML)**
  - Drew Kane
  - Responsible for overall direction of the mission in coordination with PIC
    - Cannot override PIC regarding operation of aircraft
- **Flight Operations Coordinator (FOC)**
  - Brady Sivey
  - Responsible for all ground-based operations, delegates tasks as necessary
- **Flight Crew Lead (FCL)**
  - Braden Nelson
  - Must oversee operations and ensure airworthiness

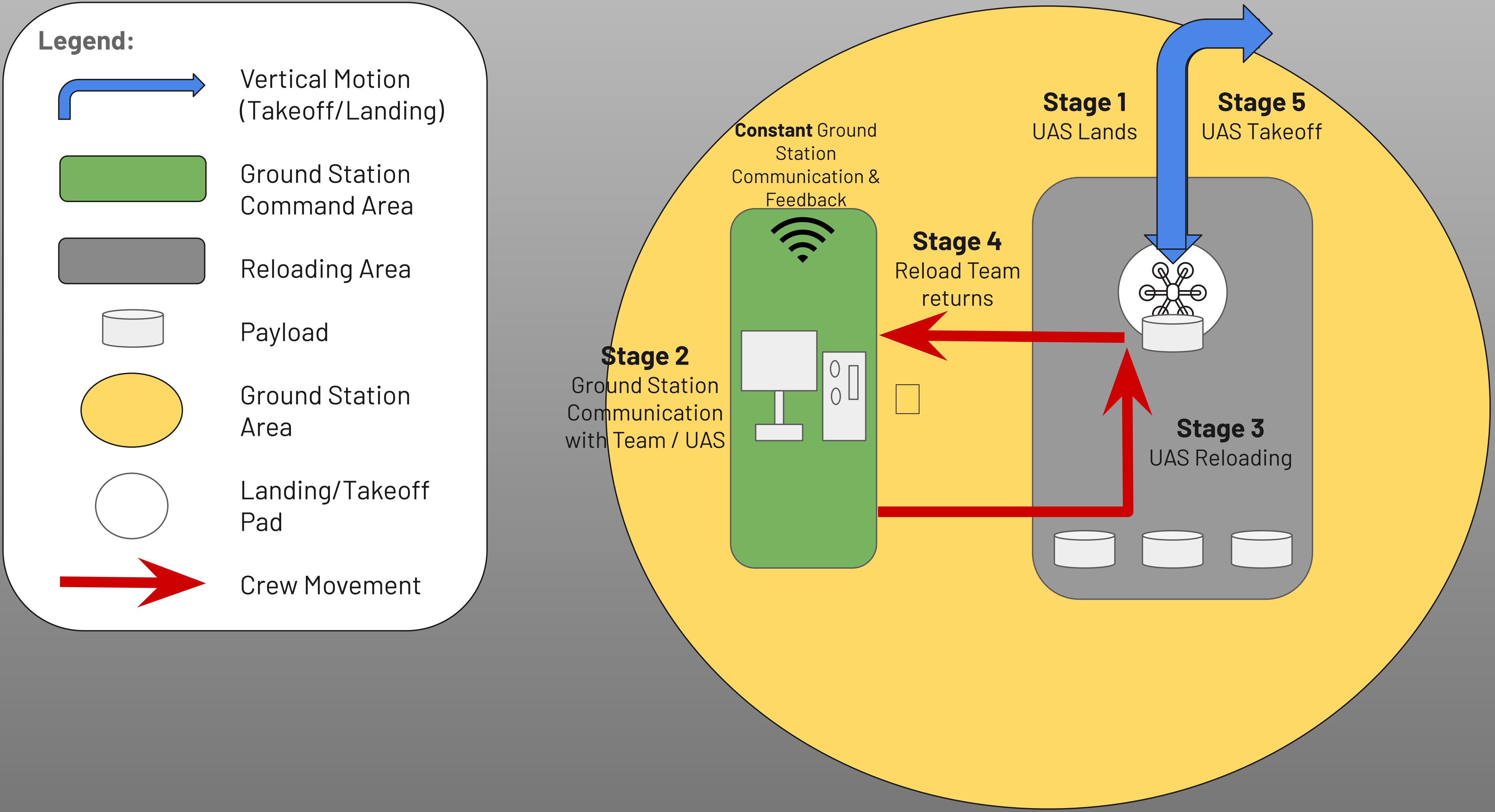
★ FAA required position
☆ 91-57C certified Pilot

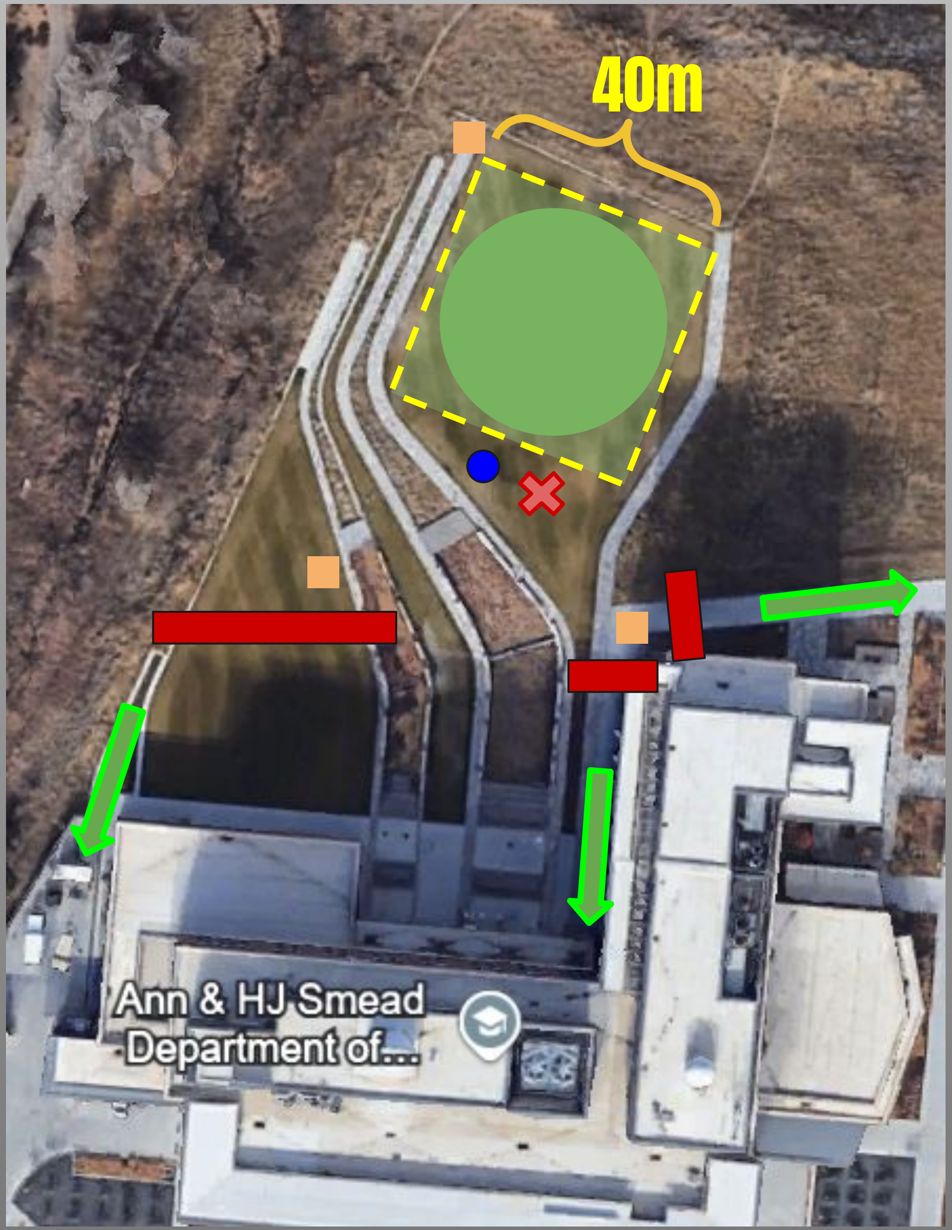
Personnel: Nominal Flight Ops Team

- **Pilot In Control (PIC) ★ / Pilot at Controls (PAC-M)**
  - Donovan Gavito ☆
  - Pilot the drone and responsible for all Flight Operations and Safety
- **Pilot At Control Of Ground Station (PAC-O)**
  - Maximillian Brown ☆
  - Pilot at Controls for the Ground Station
- **Visual Observer (VO) ★**
  - Braden Nelson, Christian Bowman ☆, Jared Steffen
  - Primary visual observer responsible to mention issues that are noticeable
- **Reloading Unit (RU)**
  - Josh Geeting, Ethan Davis
  - Responsible for safely reloading the aircraft with the new payload in between mission legs

★ FAA required position
☆ 91-57C certified Pilot

FLAME Autonomous Firefighting UAS Reloading ConOps





Key

- Evac Routes
- Zone Restriction
- Geo Fence
- Operating Zone
- Visual Observer
- Ground Station & Safety Equipment
- Zone Clearance Personnel