FLAME
FINAL REVIEW

The Fire Limiting Aerial Management Ensemble:

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Project Purpose

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

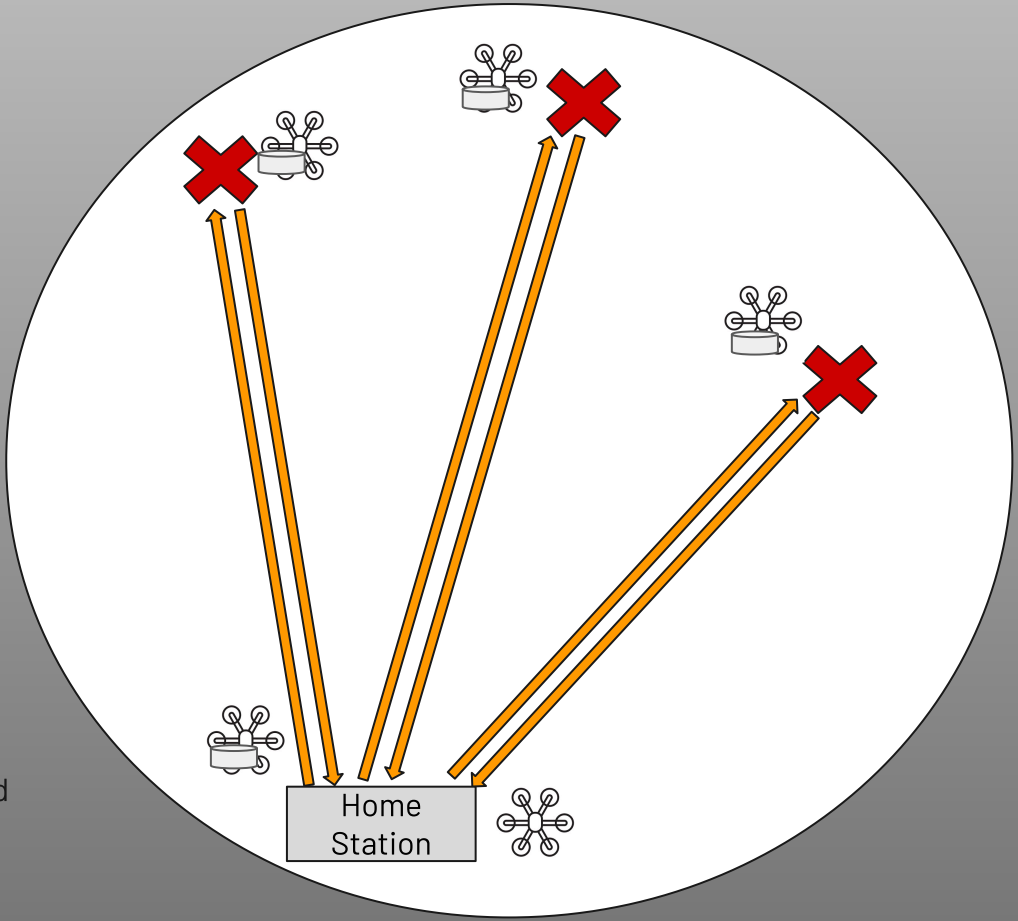
FLAME Autonomous Firefighting UAS High Level ConOps

Legend:

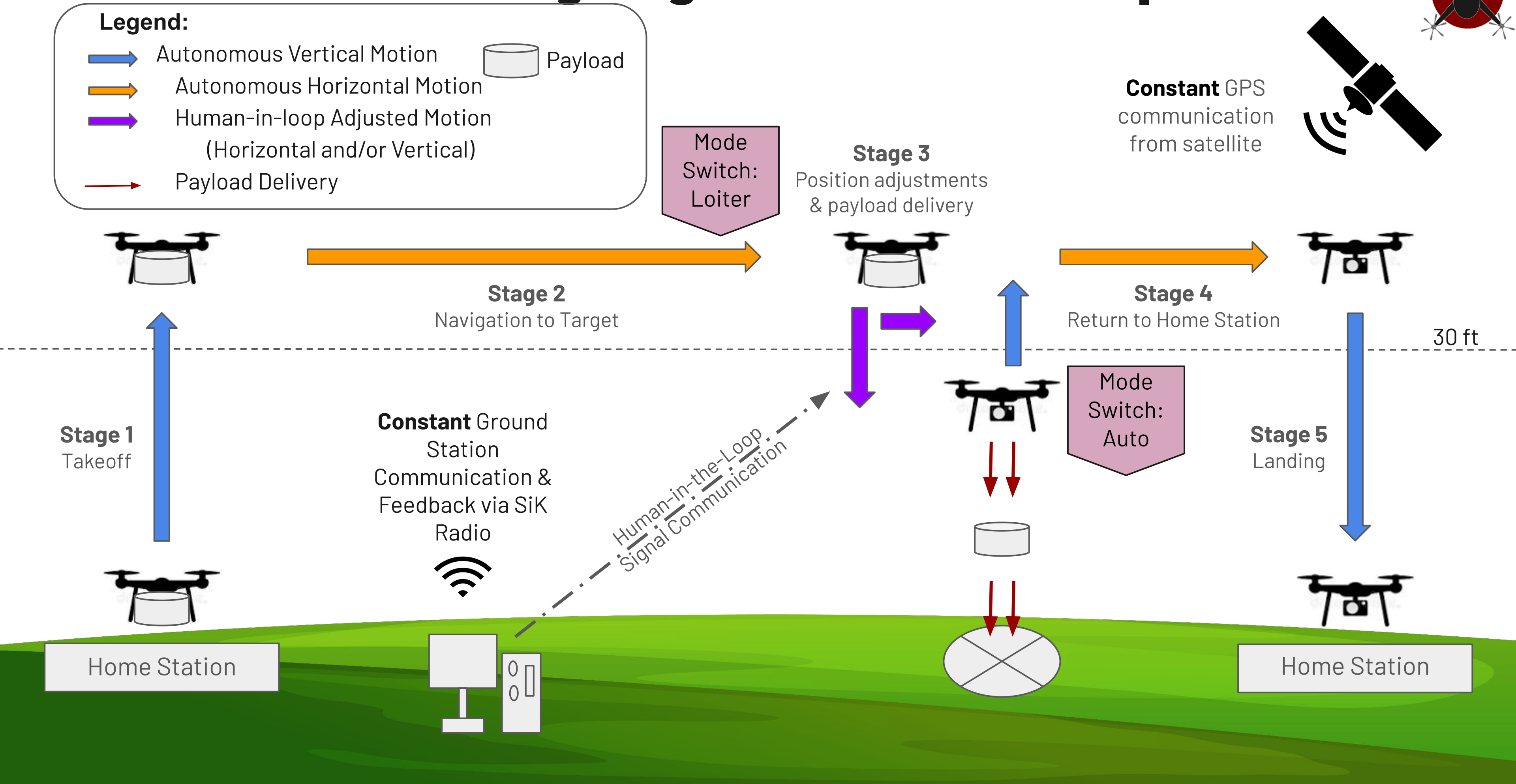
Target Location

Autonomous Travel

- 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



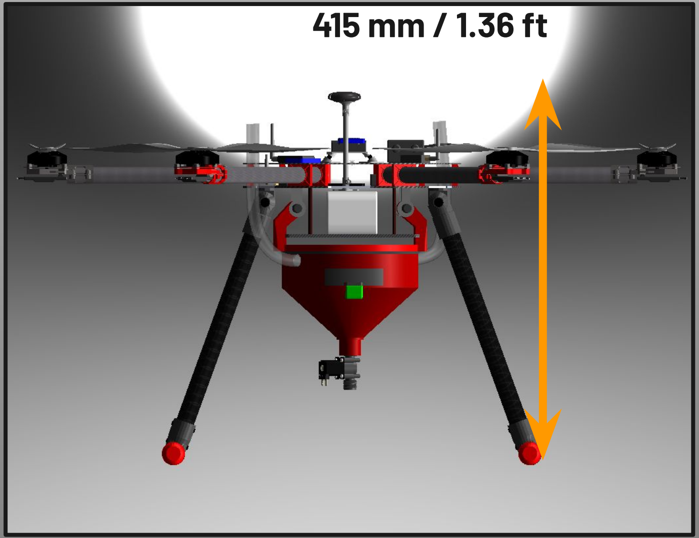
Key Driving Requirements

- **FR 1.4:** The system shall be capable of making **3 drops** in a **20-minute span.**
- **FR 2.1:** The system shall carry and deploy **5 pounds** of fire retardant per target location.
- **FR 1.2:** The system shall be able to takeoff autonomously.
- **FR 1.3:** The system shall be able to land autonomously.
- **FR 1.1:** The system shall have a minimum range of **100 meters.**
- **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

Design Review

Project Purpose | Design Review | Test Overview & Results | Program Management & Systems Engineering

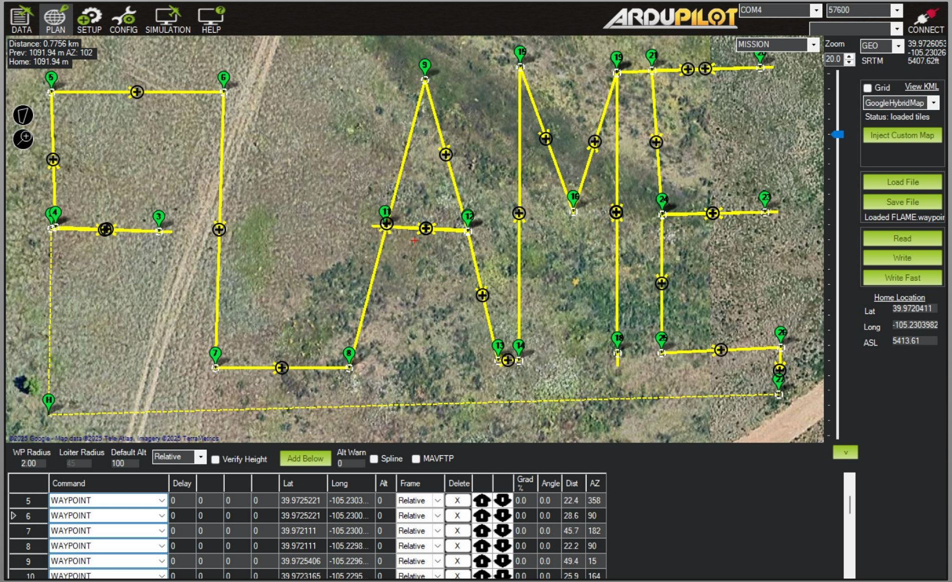
Design Overview



Software Selections

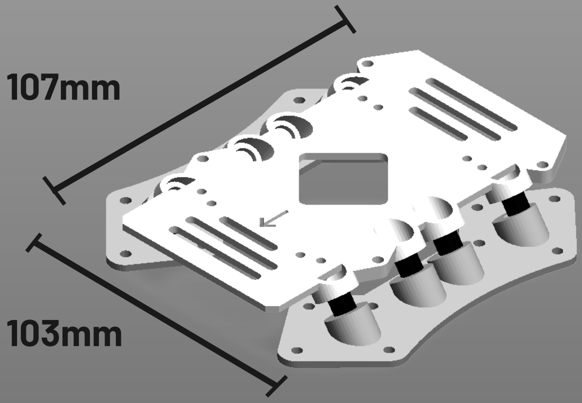
- **ArduPilot and Mission Planner**
  - Compatible
  - Documentation
- **Capabilities**
  - Save and load mission profiles and geofences
  - Simulation-In-The-Loop
  - Data logging
- **Mission Planner Commands**
  - Takeoff
  - Waypoint Travel
  - Altitude Hold
  - Return to launch
  - Land

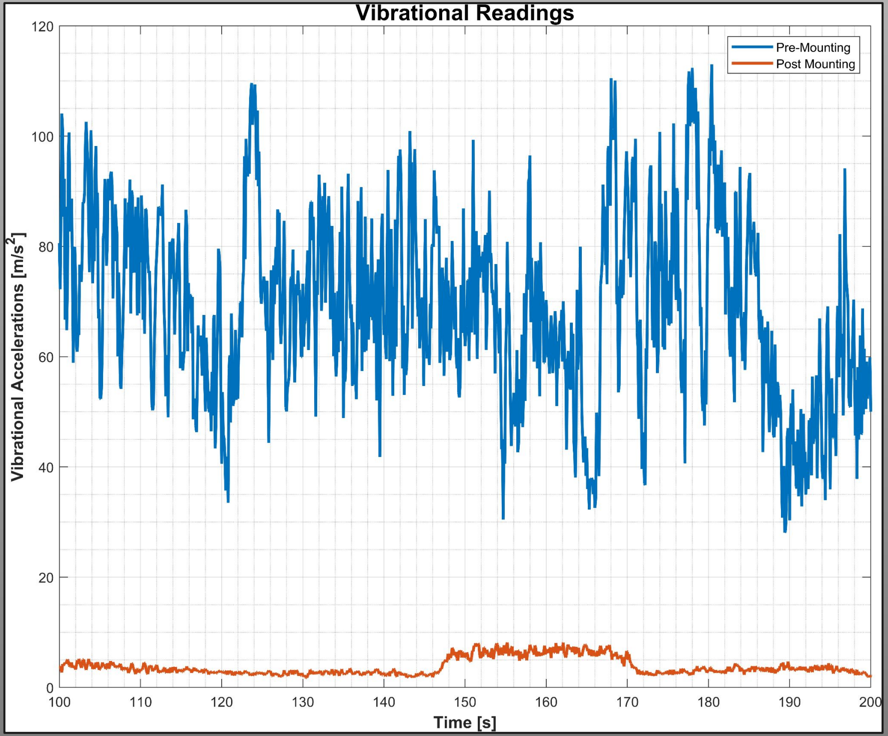
Software Selections	
Use	**Software**
Autopilot	ArduPilot
Mission Planning	Mission Planner



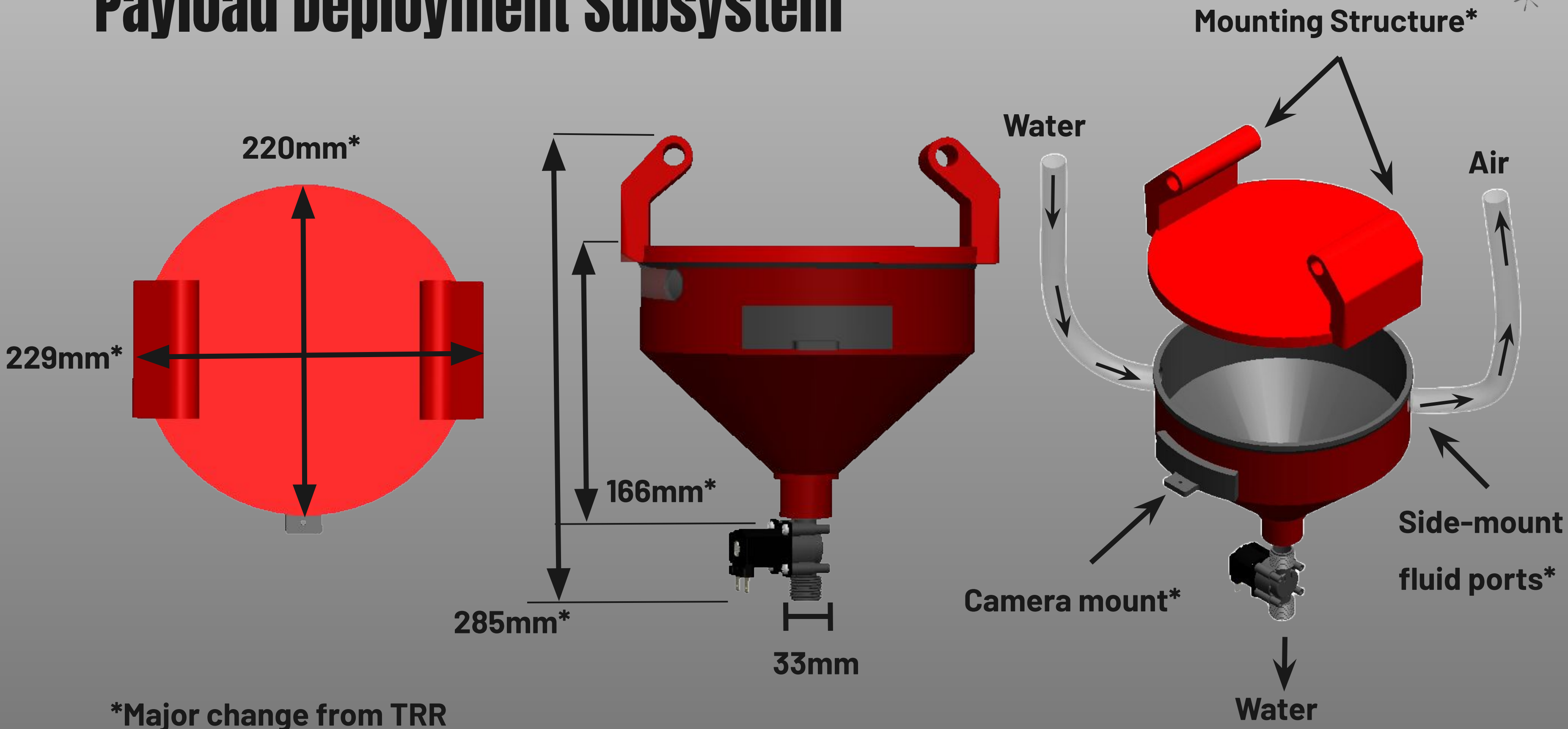
Changes Since TRR: Anti-vibration Mount

- **Vibrational Issues**
  - Flight controller mounted with sticky tape
  - Accelerometer clipping
- **Fix**
  - Mount to isolate flight controller from frame
  - Rubber grommets to damp vibrations





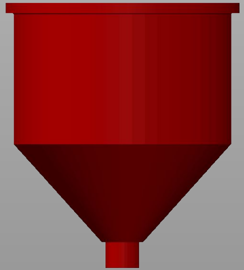
Payload Deployment Subsystem

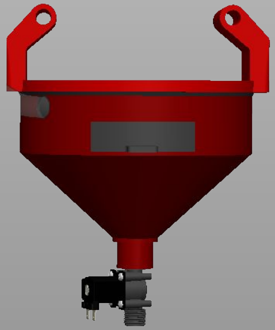


*Major change from TRR

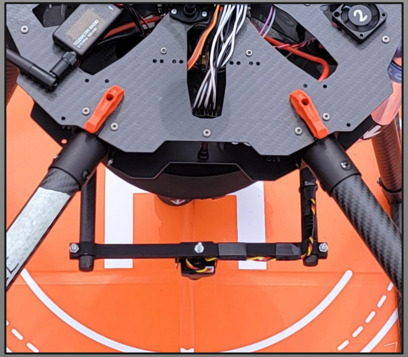
Changes Since TRR

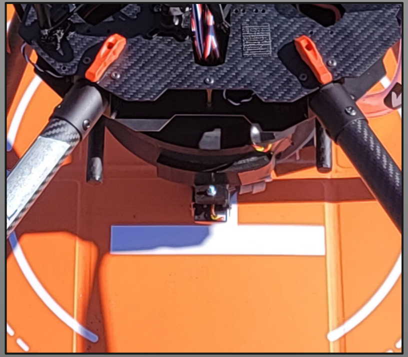
- Payload Container





- Camera Location





Payload Deployment Subsystem

WOOGUILIN Remote Controller

433 MHz

WOODGUILIN Remote Switch

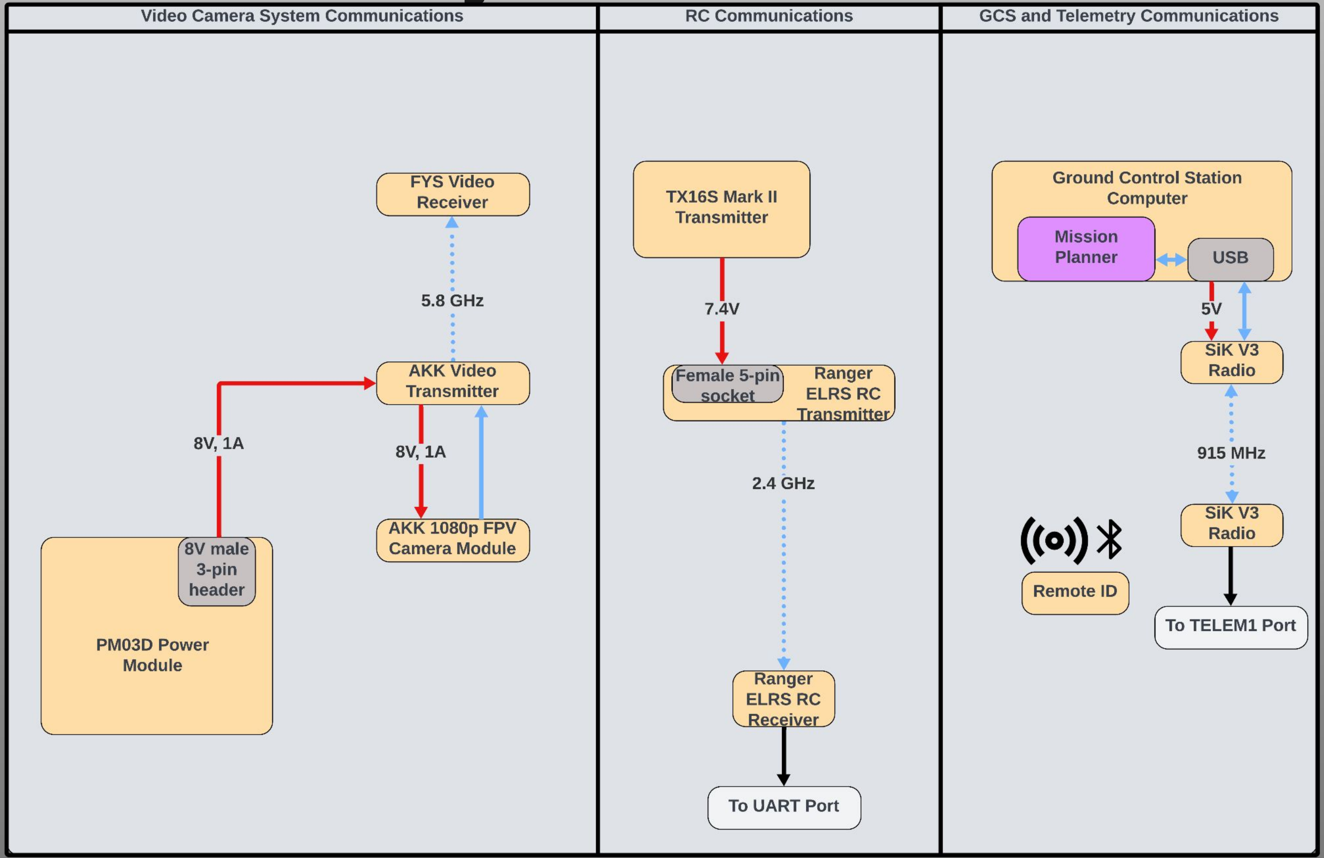
12V, 2.6A

12V, 2.6A

1" Zero Differential Solenoid Valve

1,000 mAh 3S LiPo Battery

Communications Subsystem



Test Overview and Results

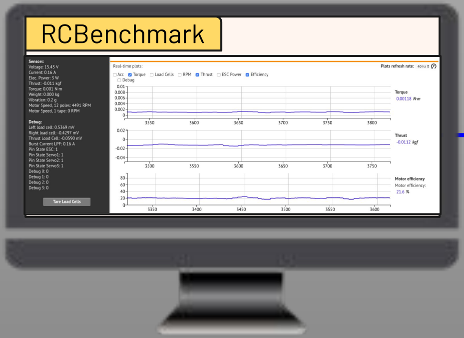
Completed Tests

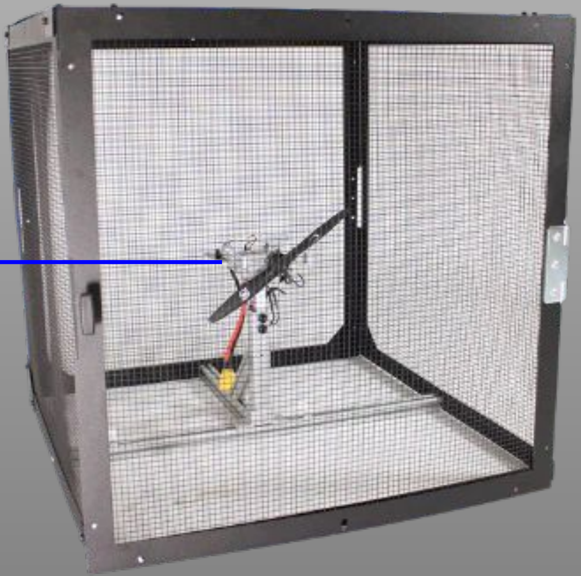
Tests	Requirements Fulfilled	Status
Payload Deployment Time	FR 1.5, DR 1.7	Completed
Rotor Thrust Evaluation*	FR 1.1, 1.4, 1.5, 2.2,	Completed
Payload Deployment Accuracy	FR 2.1, 3.5	Completed
GPS Accuracy	FR 3.1, DR 1.2	Completed
Battery Health	FR 1.1, 1.4	Completed
RC Control (Initial Flight)	FR 3.1, DR 1.5	Completed
Autonomous Flight	FR 1.2, 1.3, DR 1.2	Completed
Premature Payload Deployment	FR 2.1, 3.4, DR 5.1.1	Completed
Single Mission Leg*	FR 1.1, 1.2, 1.3, 1.5, 1.6, 1.7, 2.1, 2.2, 3.1	Completed
Payload Reload	FR 1.4, 2.1	Completed
Final Mission	FR 1.1-6, 2.1, 2.2, 3.1, 3.5	Completed

*Will be discussed later in the presentation

Test 1:
Static Thrust Test

Brief Overview/Setup





Reasons for Test

- **Model Validation**
  - Thrust profile results:
    - 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
    - ArduPilot thrust fitting parameters for non-linear thrust profiles

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 2.1.1** The power subsystem shall provide power to support operation of all systems for the mission duration
- **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

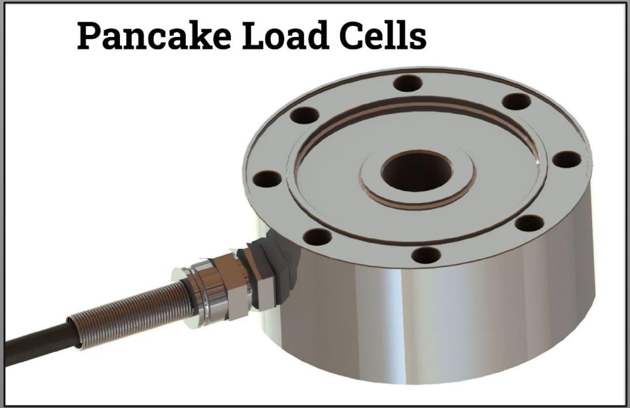
Sensor Specs

	Range	Tolerance	Requirements	Meet Requirements?
Voltage	0-50 V	0.5% ± 0.05 V	24 V	✅
Current	0-55 A	1.0% ± 0.1 A	≤ 50A*	✅
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	✅

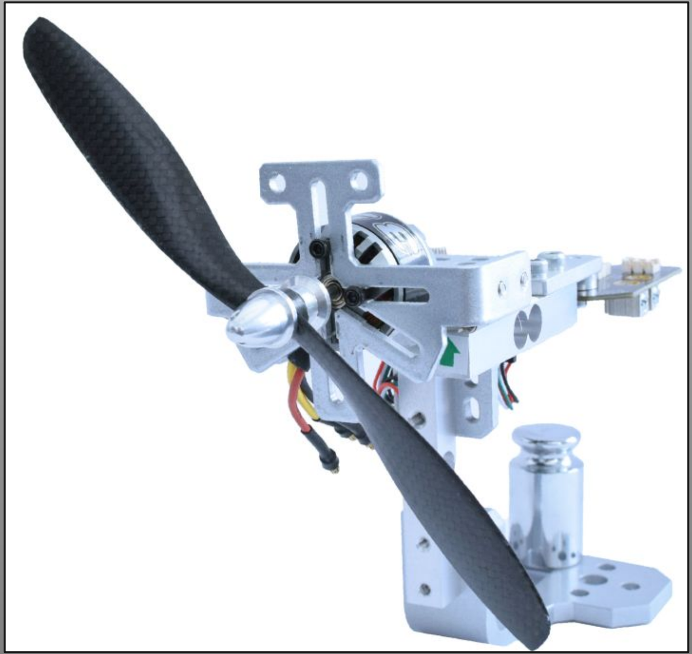
***Hit current cutoff of 50A at 90% throttle. No operation occurs at this throttle, so deemed acceptable**

Test Setup

- **Facility:** Design/Build/Fly, Engineering Center
- **Sensor:** Series 1580 Test Stand
    - Sensor type: Load cell
    - Sensor type: Voltage and current sensor
    - Sampling rate: up to 50 Hz

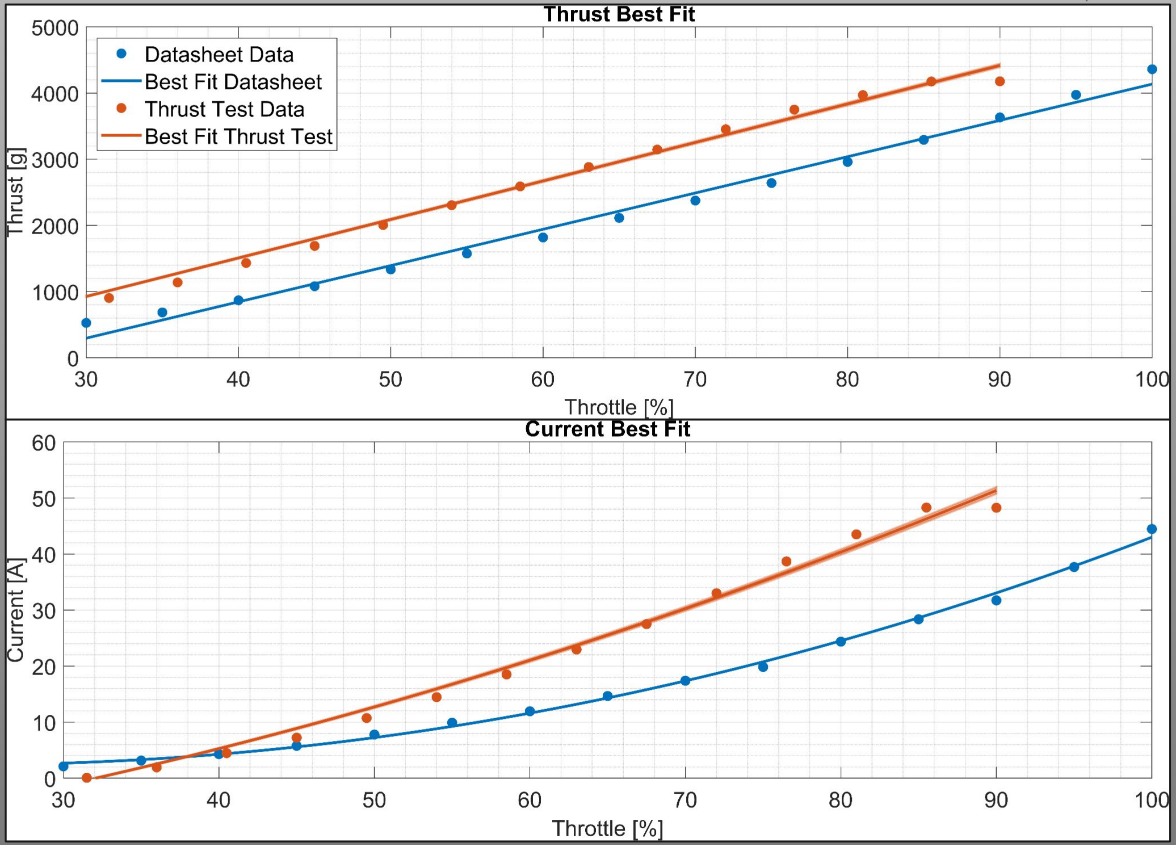


Thrust Test Stand



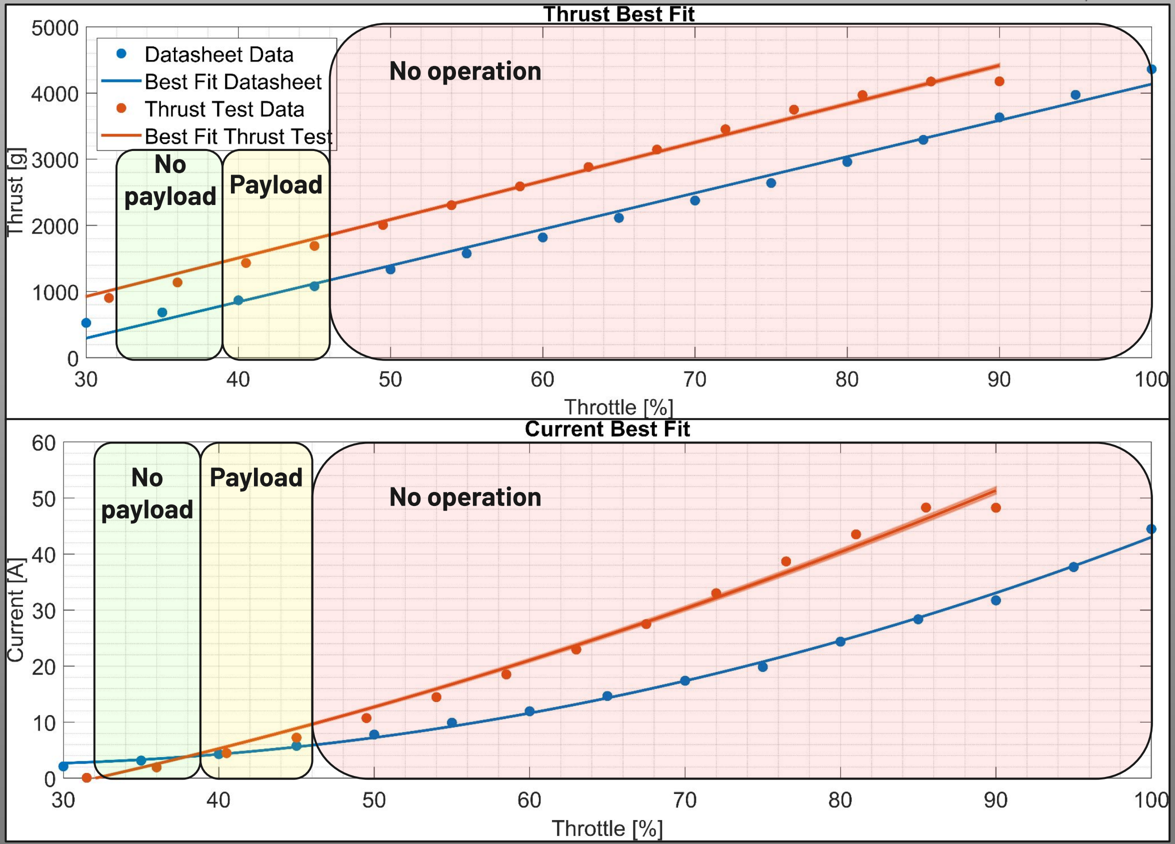
Test Data Analysis

- **Results**
  - Average of 20 samples at each throttle per test, 3 tests
  - Higher thrust profile than expected
  - Much higher current draw at higher throttles
  - Linear thrust profile
    - No need to adjust in ArduPilot



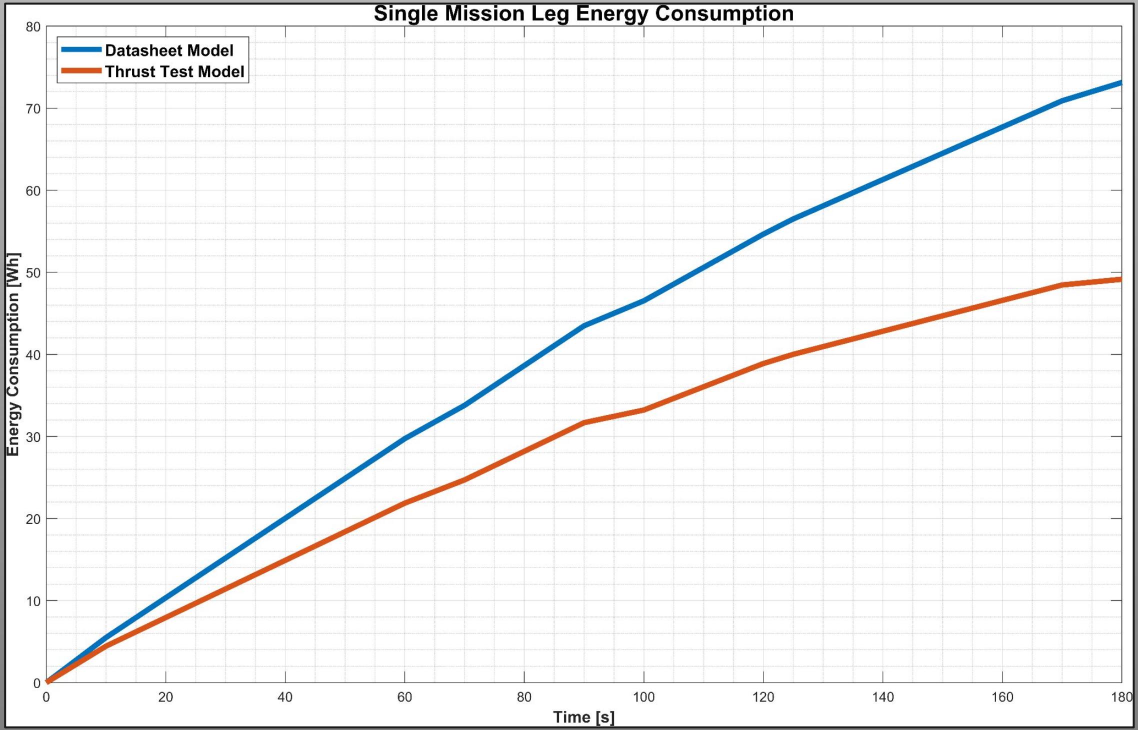
Test Data Analysis

- **Impact**
  - 18.2 lbs (8.25 kg) without payload
    - Average of **1.375 kgf/motor**
    - Higher for takeoff, lower for landing
  - 23.7 lbs (10.75 kg) with payload
    - Average of **1.792 kgf/motor**
    - Higher for takeoff, lower for landing
  - Mission is roughly split 50-50 between these 2 states



Test Data Analysis

- **Impact to Energy Consumption Model**
  - Better performance
    - Higher thrust profile
    - Allowed for more than 4 mission legs (if necessary)



Requirements

Requirement	Description	Verified?	Notes
FR 2.2	The system shall be able to take off, fly, and land with a minimum fire retardant weight of 5 pounds	Not via this test	Verifying vehicle propulsion capabilities is an important step
DR 2.1.1	The power subsystem shall provide power to support operation of all systems for the mission duration	Not via this test	Propulsion subsystem accounts for majority of power consumption
DR 3.1.1	The propulsion subsystem shall provide thrust sufficient to lift the aircraft and its payload during take off and landing	Yes	Need a **T/W ratio > 1** to achieve this. Can achieve **~2.33**
DR 3.1.4	The propulsion subsystem shall provide sufficient thrust to reach the 30 foot hard deck	Yes	Need a **T/W ratio > 1** to achieve this. Can achieve **~2.33**

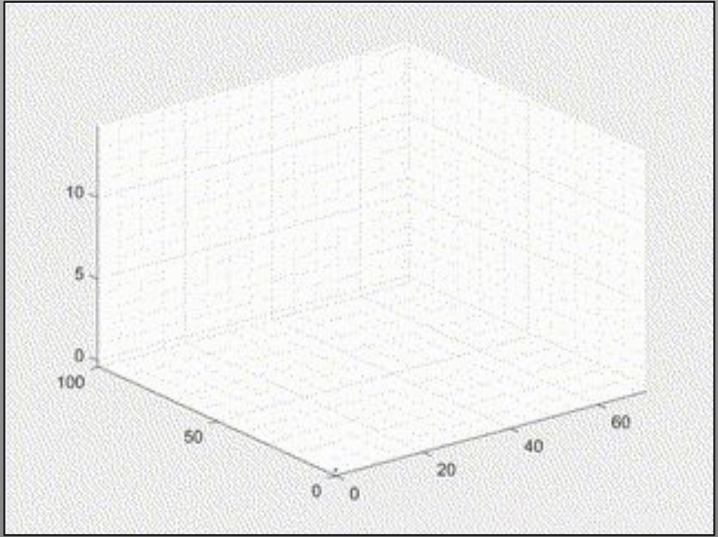
Test 2: Single Leg Test

Test Setup

- **Ground Station**
  - Computer with Mission Planner
  - SiK Radio
  - Video receiver
  - Payload switch controller
  - RC Transmitter
- **Drone**
- **Reload Equipment**
  - Payloads
  - Funnel
- **Safety Equipment**
  - Fire extinguisher
  - Bucket of sand
- **Flight Crew**

Reasoning Behind Test - Validation:

- **Dynamics Model**
  - Behavior during payload deployment
  - Estimate for flight time
  - Overall flight path
- **Energy Consumption Model**
  - If model does not match test-data, update model
  - Ensure drone has sufficient energy capacity / endurance to complete full mission
- **Requirements**

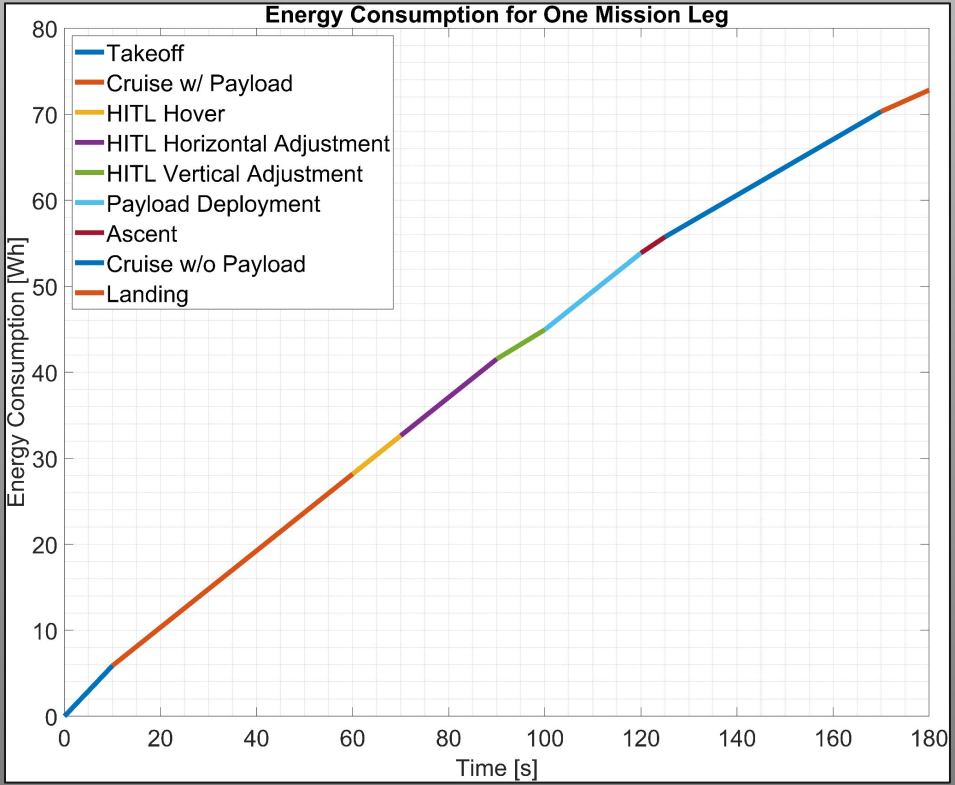


Driving Requirements

- **FR 1.1** The system shall have a minimum range of **100 meters**
- **FR 1.2[1.3]** The system shall be able to take off [land] autonomously
- **FR 1.4** The system shall be capable of making **3 drops** in a **20-minute span**
- **FR 1.6** The system shall only vertically translate below the **30 foot hard deck**, at the location of interest and take-off/landing position
- **FR 3.5** The system shall deploy the payload and have it land within a **+/- 1 meter accuracy** of target location

CDR Energy Model Recap

- **Assumptions**
  - Constant speeds
  - No vertical adjustments during cruise
  - Target is 100 meters away
    - Data being presented will be for 100 meter mission legs
  - Constant T/W ratio for each segment
  - Current and voltage originally from motor datasheet



CDR Energy Model Recap

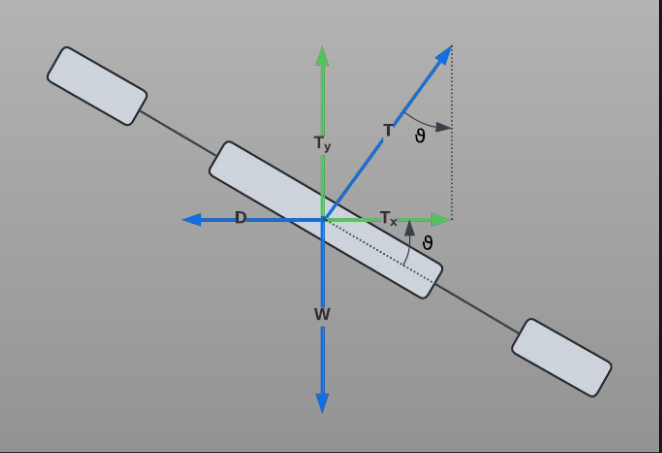
- **Governing Equations**

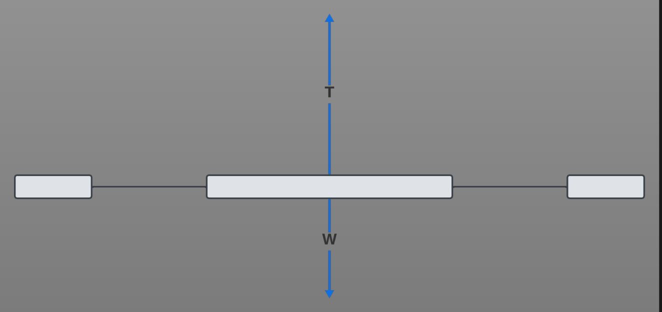
$$\frac{T}{W}\Big|_{horz} = sec(\theta)$$

$$\frac{T}{W}\Big|_{vert} = 1 + \frac{a_z}{g}$$

$$P = IV$$

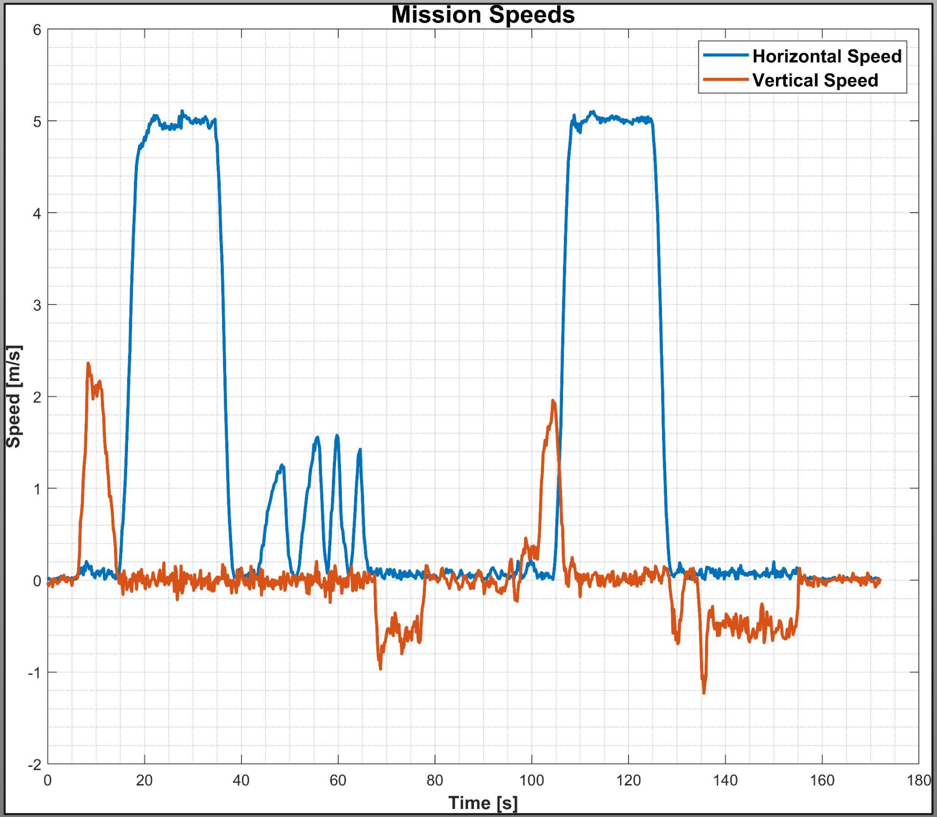
$$E = Pt$$





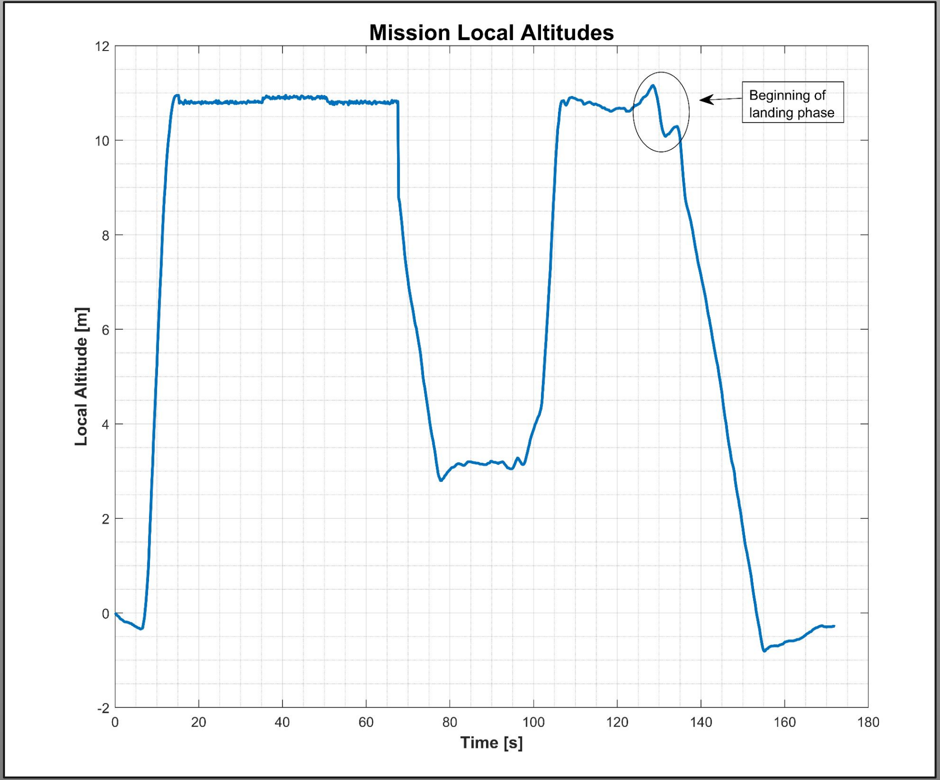
Addressing Assumptions: Constant Speed

- **Horizontal Speeds**
  - Accelerates/decelerates in ~4 seconds for cruise legs, near constant for rest
  - Horizontal adjustment phase is oscillating while pilot adjusts
    - Not a good assumption here
- **Vertical Speeds**
  - Accelerates/decelerates in ~2-3 seconds
  - Much shorter leg durations
    - Not a good assumption here



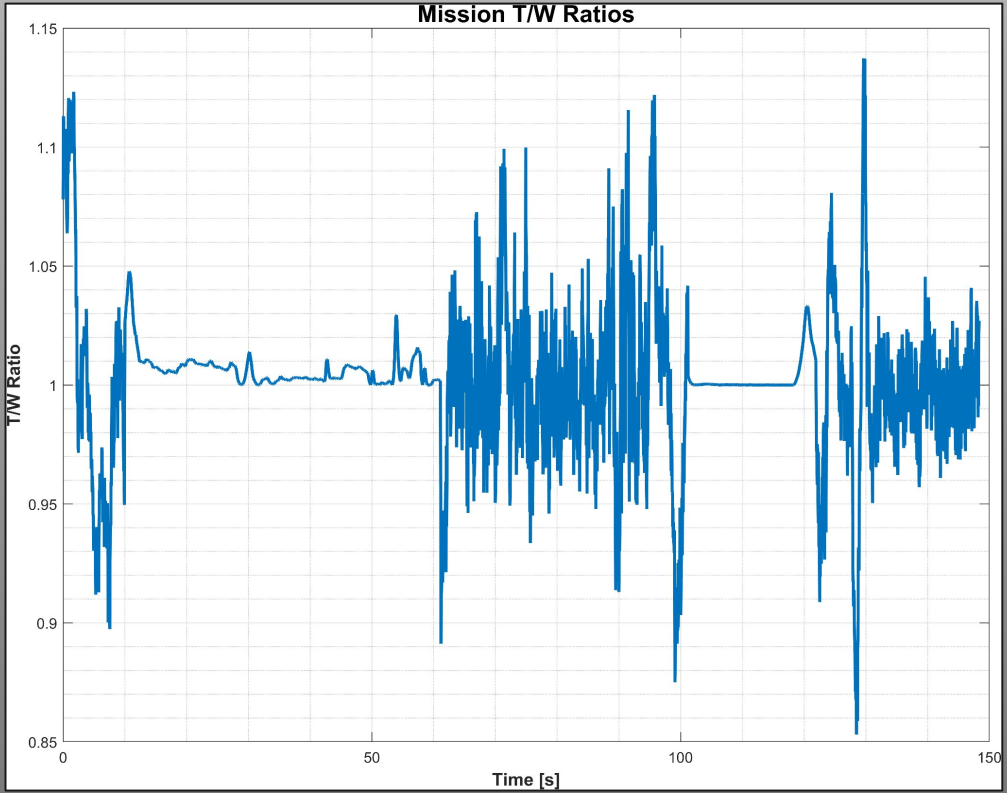
Addressing Assumptions: No Vertical Adjustments (Cruise)

- **Cruise Altitudes**
  - < 0.5 meters of variance while cruising over flat ground
  - Based on barometer readings
    - Change in terrain led to changes in vehicle altitude
    - Possible fixes:
      - Lidar
      - Uploading terrain data
  - Autopilot began landing towards end of return cruise leg



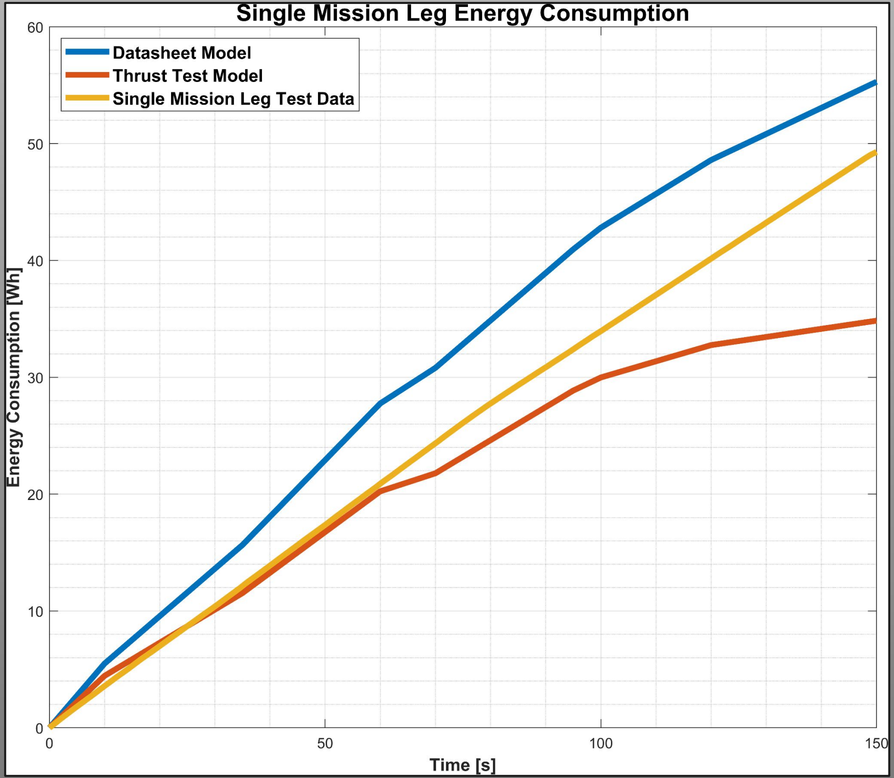
Addressing Assumptions: Constant T/W Ratio For Each Segment

- **Vertical Translation**
  - Peaks for acceleration, dips for deceleration
- **Human-In-The-Loop**
  - Largest variance in T/W ratios
    - Due to stop/go movement for aligning
    - Could be improved upon through pilot practice
    - Varies during payload deployment due to autopilot “learning” new hover throttle
- **Horizontal Translation**
  - Near constant for both bog cruise legs



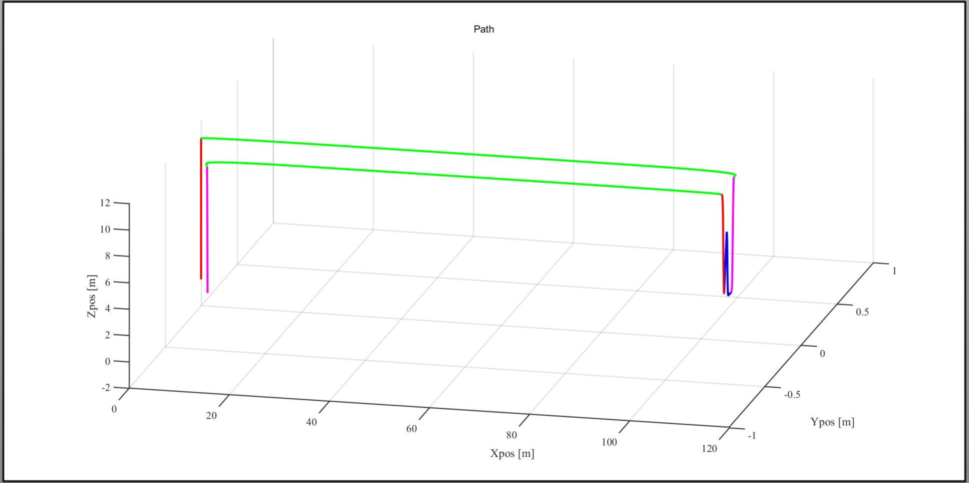
Test Results vs Modeled Results

- **Comparison**
  - Test results lie between datasheet model and thrust test stand model
    - Adjusted model time segments to match those of the data
  - Pilot adjustments had a large influence on energy used
- **Discrepancies**
  - Thrust test stand model only account for voltage sag of a singular motor
    - For same power, higher current necessary
  - Small offset of test data vs model due to current draw of components **(Roughly 2-4 A)**
  - Energy spent on trimming to fight any wind and wind gusts
  - Constant T/W assumption is the most incorrect assumption
    - T/W didn't vary as heavily as expected for mission segments

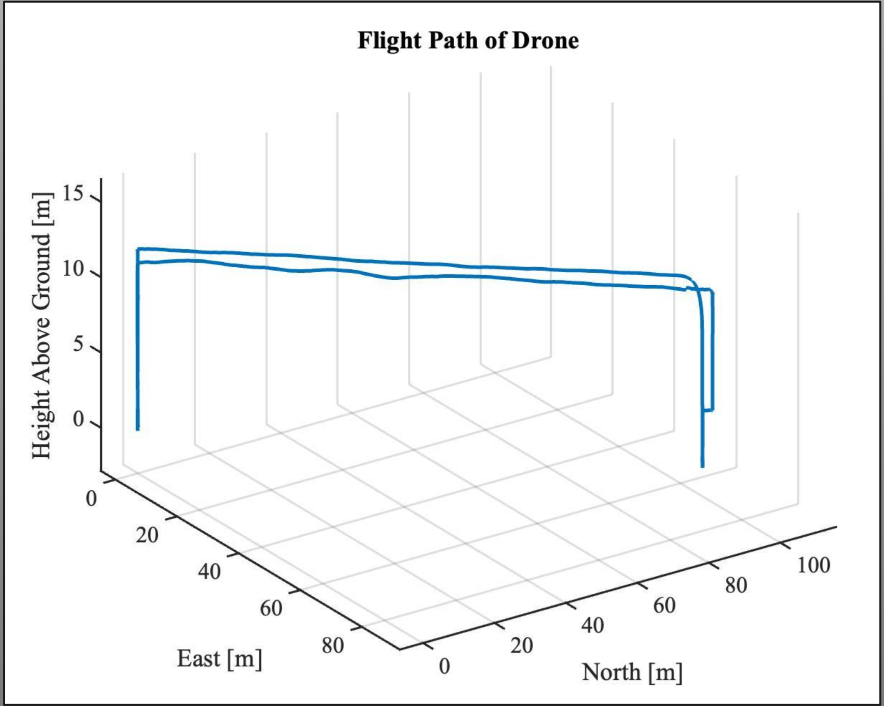


Test Data Analysis: Dynamics

- **Flight Path**

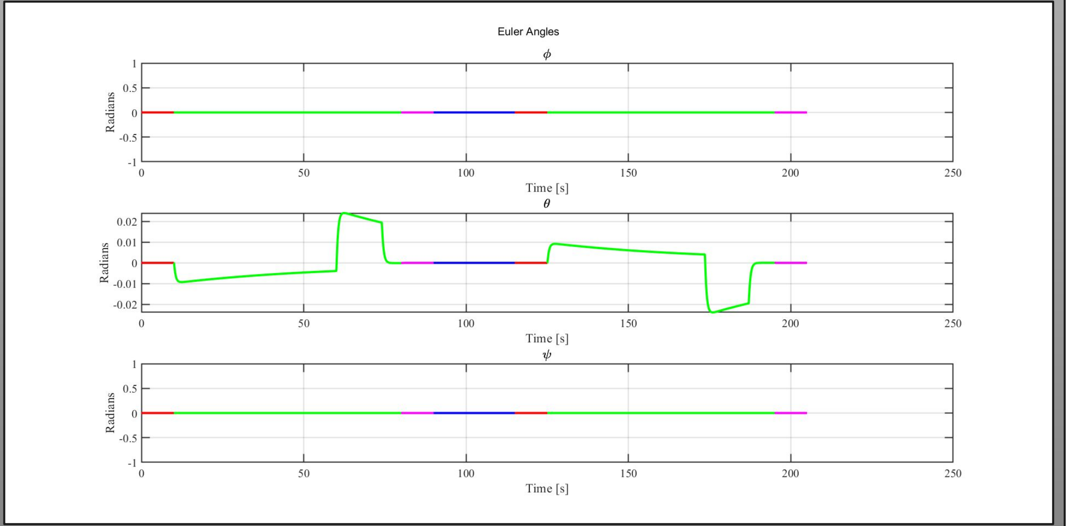


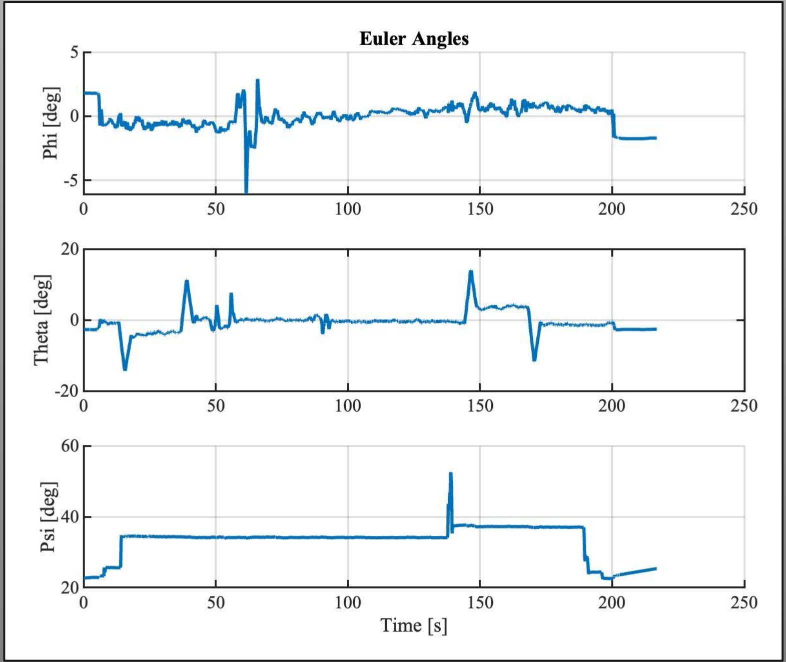
	Model	Test
Time of Flight	204.5 sec	216.1 sec
Distance	101.1 m	106.8 m



Test Data Analysis: Dynamics

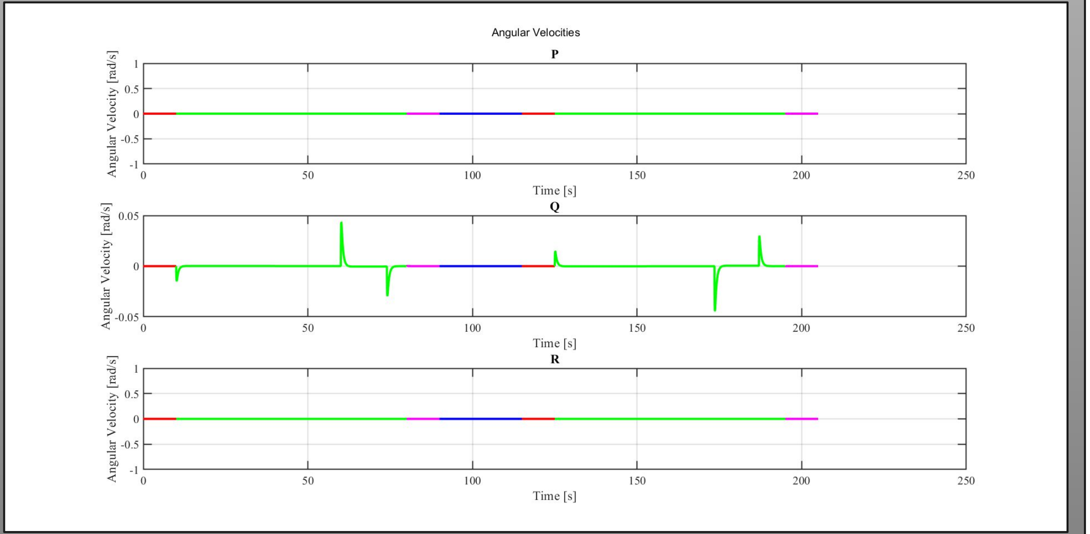
- **Euler angles**

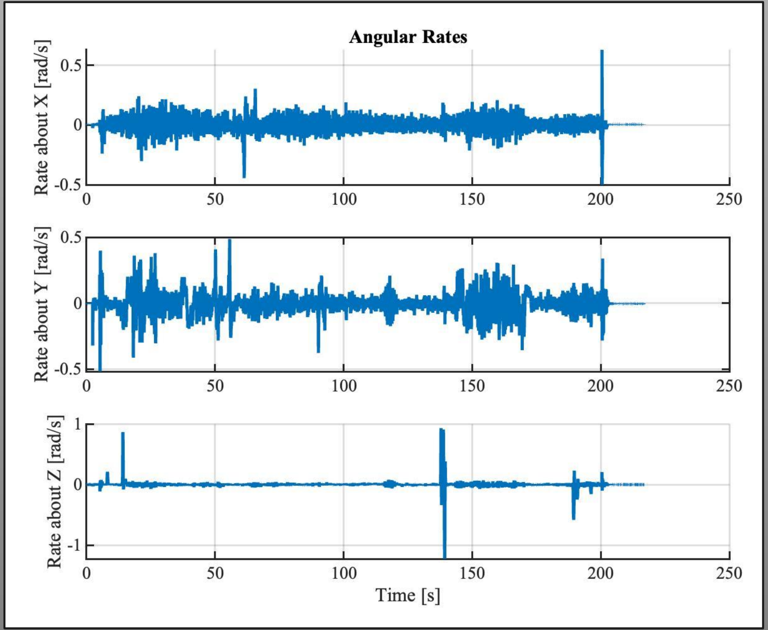




Test Data Analysis: Dynamics

- **Angular Rates**





Was the model a success?

- **Flight path shape is accurate**
  - Distance travelled correlates with time flown - Model accurately represented flight
  - **Overall: Success**
- **Euler angles are accurate**
  - Phi discrepancy based on drone wobbles due to GPS
  - Theta nearly mapped out drone behavior
  - Yaw discrepancy due to optimal motion depicted in model due to realistic drone movements in certain modes
  - **Overall: Success**
- **Angular Velocities have discrepancies**
  - Likely due to realistic drone movements
  - Hard to justify results
  - **Overall: Uncertain**

Reasonably Accurate model with understandable discrepancies

Requirements

Requirement	Description	Verified?	Notes
FR 1.1	The system shall have a minimum range of **100 meters**	Yes	Performed majority of mission legs at 100 meters. Could perform **<300 meters**
FR 1.2 [1.3]	The system shall be able to take off [land] autonomously	Yes	Autopilot was able to takeoff/land autonomously, including when hitting battery/communication failsafes
FR 1.6	The system shall be capable of making **3 drops** in a **20-minute** span	Yes	Single mission leg performed in **150 seconds**. Reloading time averaged at **60-90 seconds**. Up to **4 mission legs** performed on a single battery
FR 3.5	The system shall deploy the payload and have it land within a **+/- 1 meter accuracy** of target location	No	Best test was **4.6/5 lbs**. This could heavily be improved upon by pilot practice and adding a convergent nozzle on end of solenoid (we did not have room)

Program Management & Systems Engineering

Challenges and Successes

Challenges

- **Modeling**
  - Odd results below 30% throttle from motor thrust evaluation
  - Unreliable datasheets (RID and motors)
- **Assembly**
  - Motor spin direction
  - Payload container attachment
  - Stripping bolts
  - Leaks
  - Bad instructions / Packaging
- **Testing**
  - Vibration
    - Gain tuning
  - Cracked landing gear
  - Aiming payload
    - 4.6 out of 5 lbs

Successes

- **Modeling**
  - Allowed confidence in design and testing
  - Models accurately represented data obtained
- **Assembly**
  - Electronic successes
  - 3D printing
  - Vehicle satisfied all requirements
  - Payload container size restraints
- **Testing**
  - Autonomous translocation
  - Battery failsafe landings
  - Completion of mission

Predicted Risks vs. Reality

From CDR:

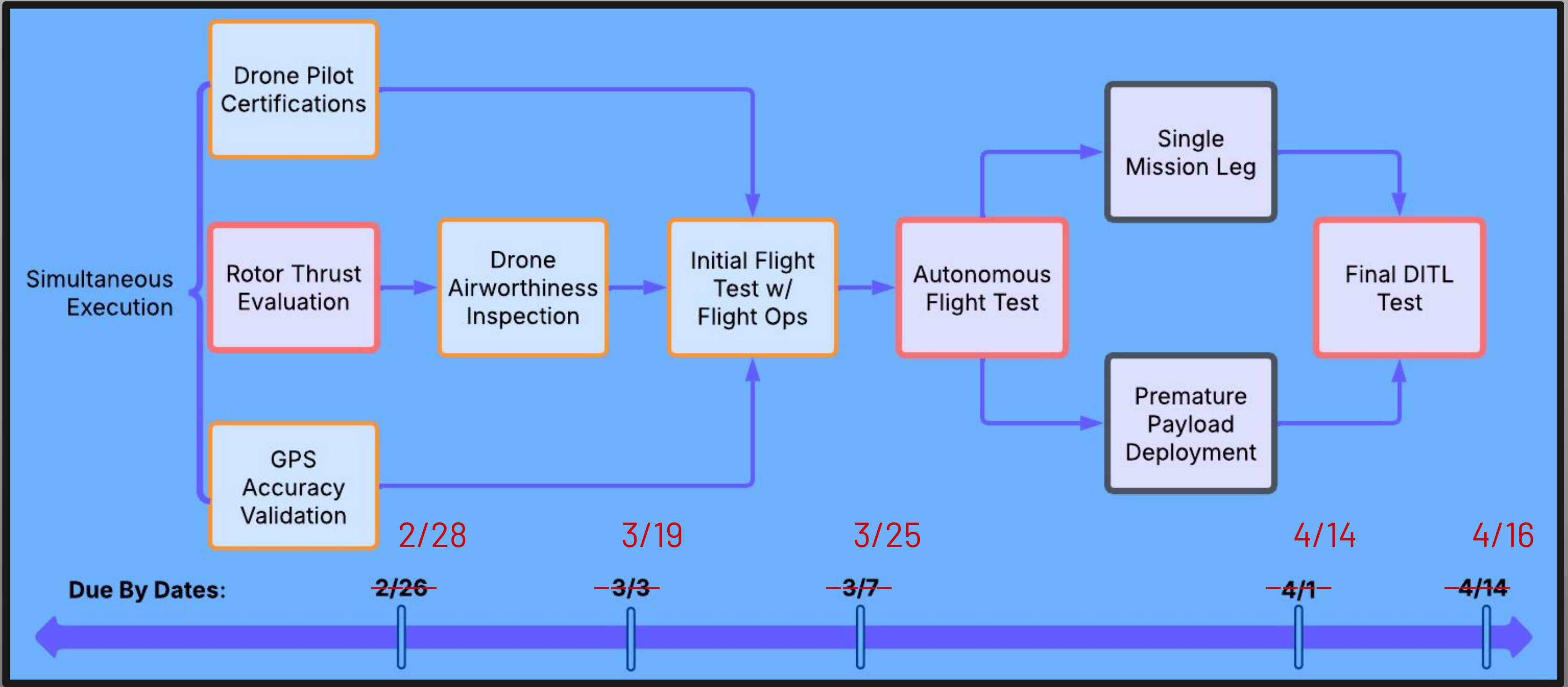
- **Human Safety due to moving propellers**
    - Follow CU Flight Ops to prevent accidents and take extreme precautions during testing
    - Internal Safety Review before testing

- **Environmental Impacts**
    - Contain all payload deployments
    - Retrieve any used components during testing

Actual:

- **Human Safety:**
    - 0 incidents
    - Preflight checklist, flight procedure, and flight location schematics integral
- **Environmental Impacts:**
    - 0 incidents
    - Required extra care and attention

Planned vs. Actual Executed Schedule



Management Lessons Learned

- **Scheduling**
  - Allocate extra time for testing
  - Allow for flexibility
  - Effectively communicate the schedule with team
- **Risk Reduction**
  - Take extra care before, during and after tests
  - Make sure all members of the team are on the same page
- **Team Cohesiveness**
  - Requires time and effort
  - Constant communication
  - Internalize constructive criticism and use it
- **Scope Creep**
  - Work with team to assess what is and isn't feasible
  - Prepare options to off-ramp

Budget Details

Phase	Amount Spent	Allocated Budget	Margin
Phase 1: Testing	$193.39	$250 ~~$500~~	22.6% Under Budget
Phase 2: Manufacturing	$3250.98	$3650 ~~$3000~~	10.9% Under Budget
Phase 3: Expo/Other	$149.93	$100 ~~$500~~	49.9% Over Budget
Total	$3594.30	$4000	10.1% Under Budget

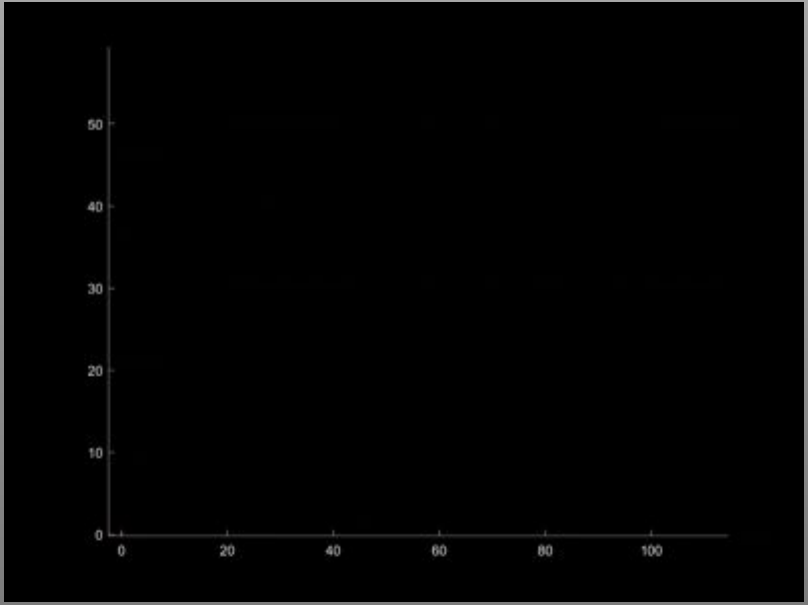
Budget Reflection

- **No overall budget issues**
  - Items procured ahead of time
  - Finances tracked and managed well
    - Unestablished costs
    - Manufacturing/testing mishaps
- **Proper management of parts**
  - Safe handling and manufacturing
    - Minimal need to re-procure parts
- **Successful planning**
  - Budget planning during CDR
    - Minimized impact of lead times
    - Allowed for minor alterations of budget plan

Industry Cost Calculation

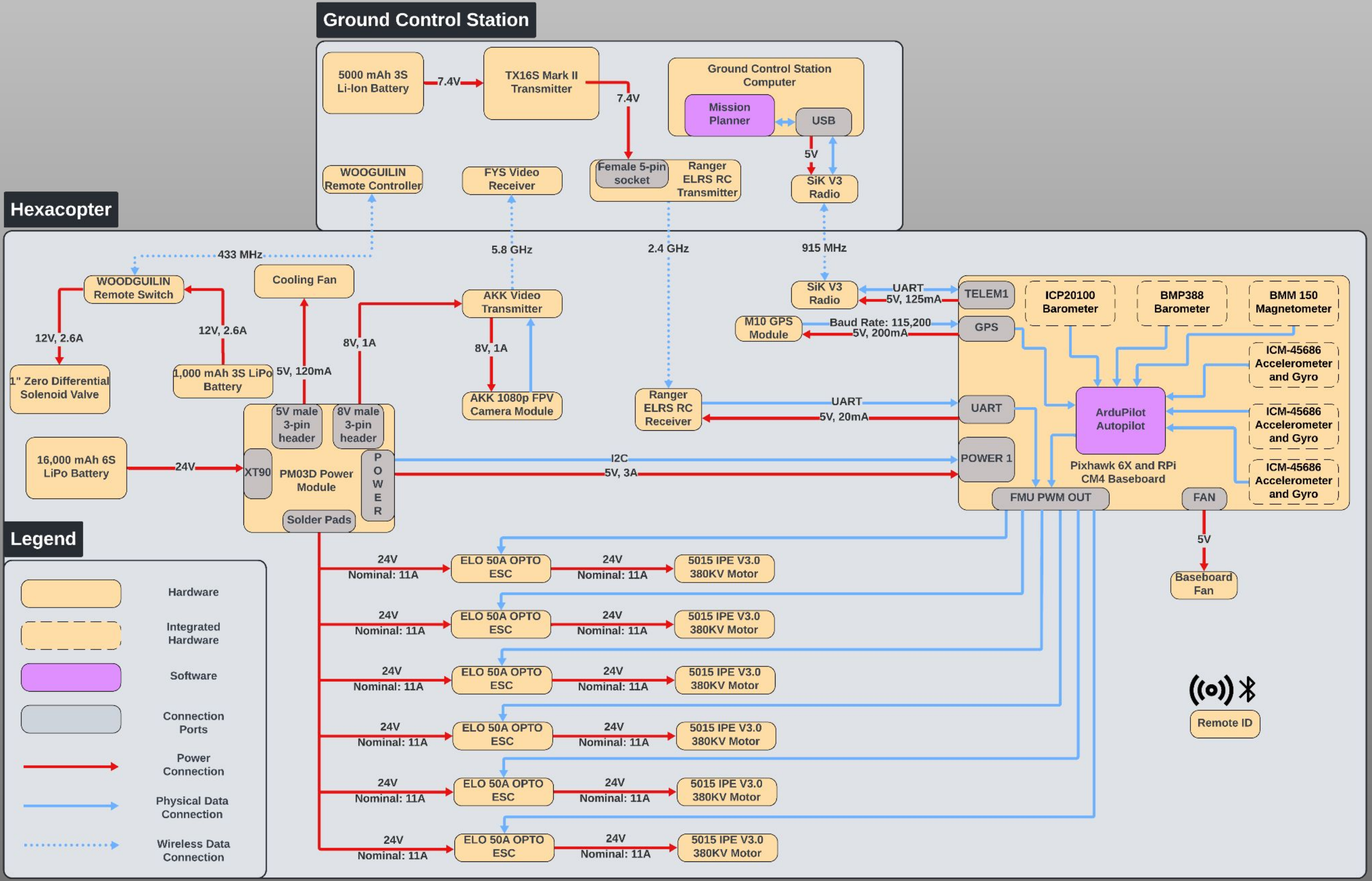
	Quantity
Total hours worked per week (all members)	96 Hours
Total weeks worked (all members)	32 Weeks
Total Hours worked (all members)	3072 Hours
Total Cost of Materials	$3594.30
Total Cost of Wages (No Overhead)	$110,769.23
Total Cost of Wages (With Overhead)	$188,307.69
Overall Total Industry Cost	$191,901.99

Questions?



Backup Slides

Functional Block Diagram

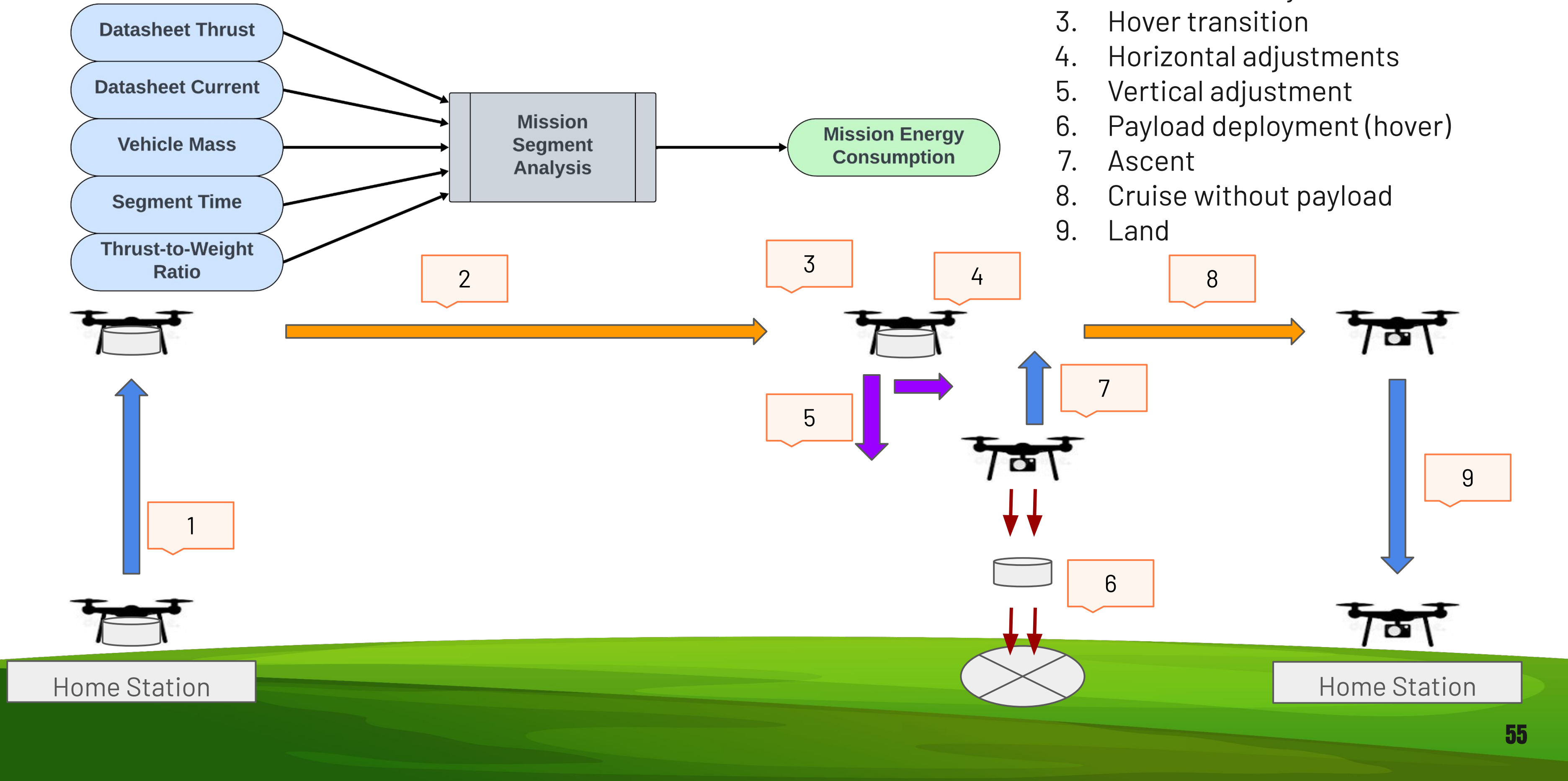

Ground Control Station
5000 mAh 3S Li-Ion Battery
7.4V
TX16S Mark II Transmitter
7.4V
Ground Control Station Computer
Mission Planner
USB
5V
SiK V3 Radio
WOOGUILIN Remote Controller
FYS Video Receiver
Female 5-pin socket
Ranger ELRS RC Transmitter
Hexacopter
433 MHz
5.8 GHz
2.4 GHz
915 MHz
WOODGUILIN Remote Switch
Cooling Fan
AKK Video Transmitter
SiK V3 Radio
UART
5V, 125mA
TELEM1
ICP20100 Barometer
BMP388 Barometer
BMM 150 Magnetometer
12V, 2.6A
12V, 2.6A
8V, 1A
8V, 1A
M10 GPS Module
Baud Rate: 115,200
5V, 200mA
GPS
ICM-45686 Accelerometer and Gyro
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
24V
Nominal: 11A
5015 IPE V3.0 380KV Motor
Remote ID
Legend
Hardware
Integrated Hardware
Software
Connection Ports
Power Connection
Physical Data Connection
Wireless Data Connection

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

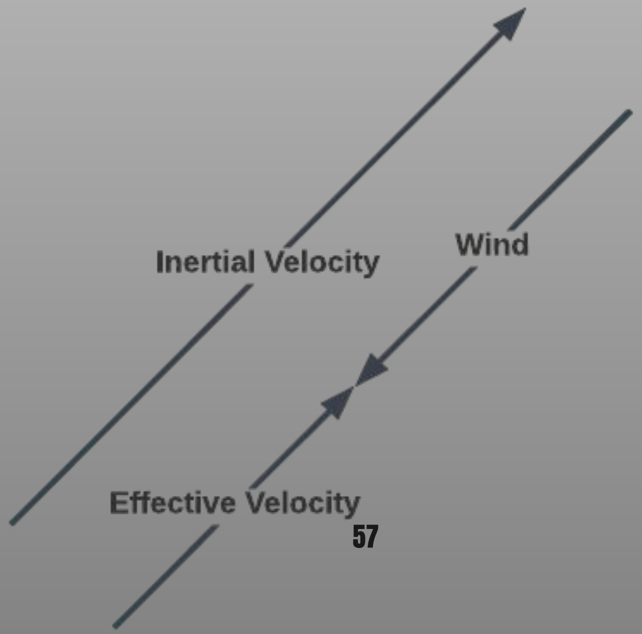
- **Motor thrust values**
  - Unknown test altitude of motor datasheet data
  - Multiply datasheet thrust values by ratio of air densities of Boulder and sea-level

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

- **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

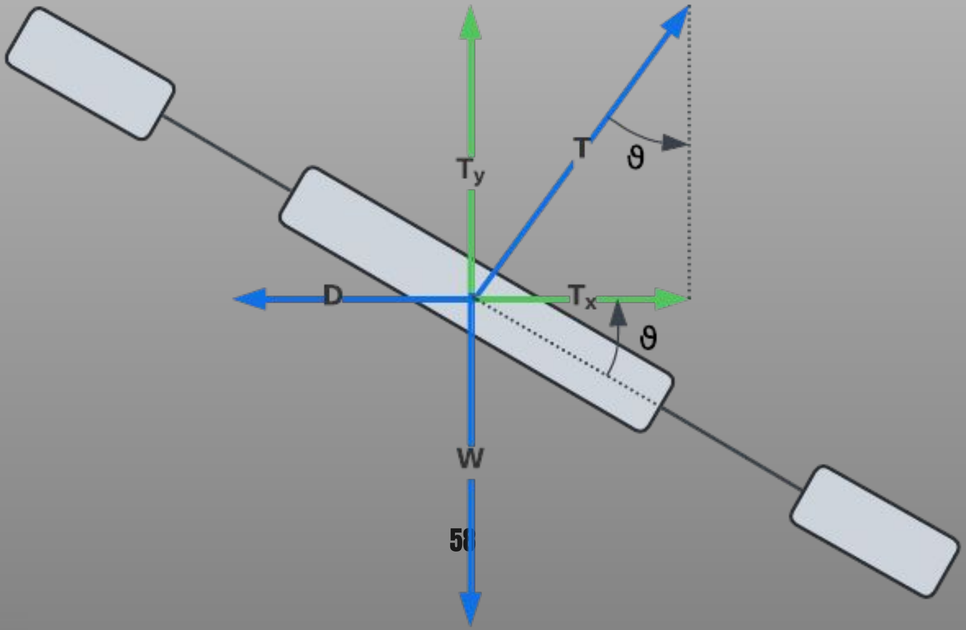
Modeling Wind

- **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:

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

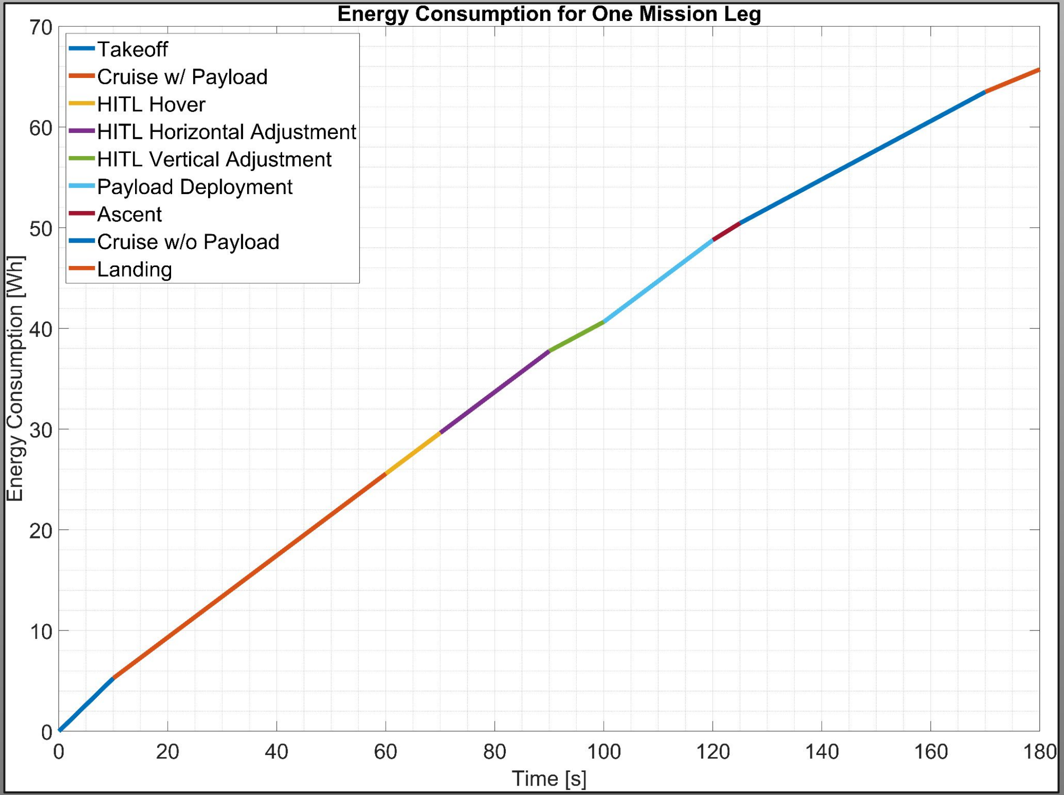
Velocity as a function of time for given tilt angle and T/W ratio:

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

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

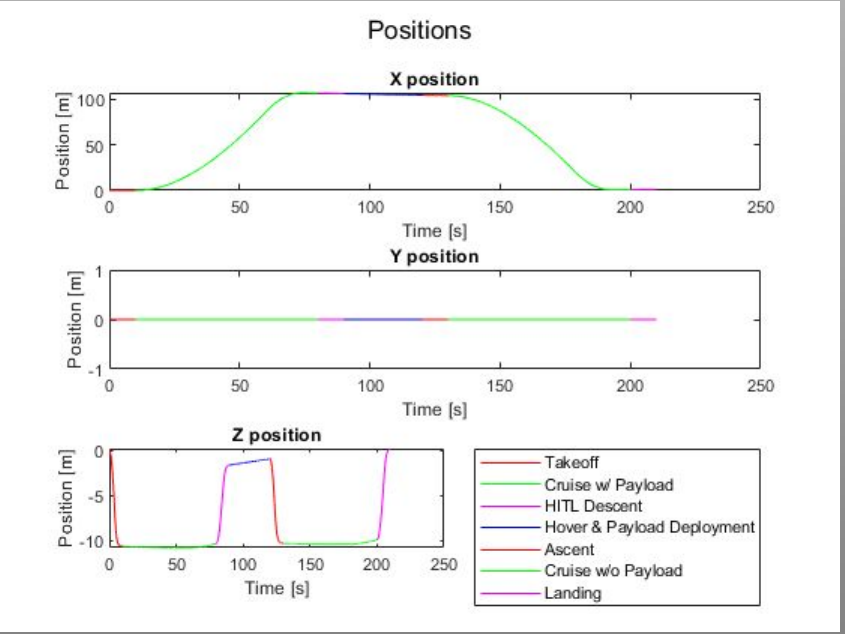
$$\begin{pmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi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

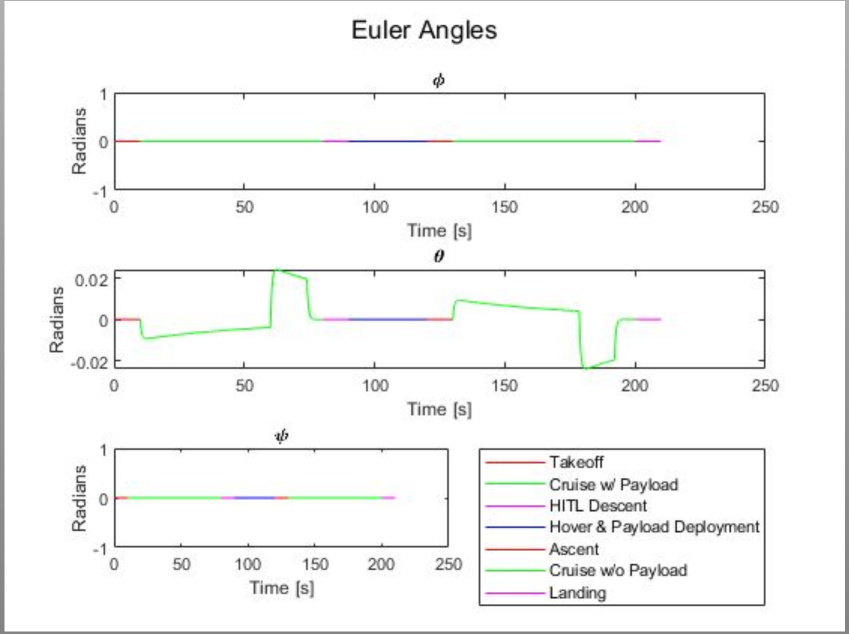
$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

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

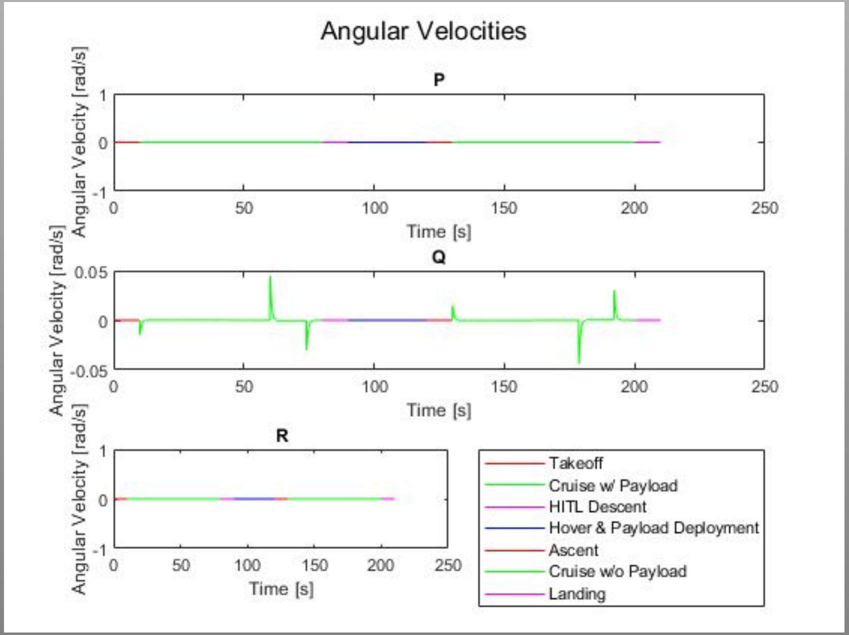
$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{I_y - I_z}{I_x} qr \\ \frac{I_z - I_x}{I_y} pr \\ \frac{I_x - I_y}{I_z} pq \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L \\ \frac{1}{I_y} M \\ \frac{1}{I_z} N \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L_c \\ \frac{1}{I_y}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

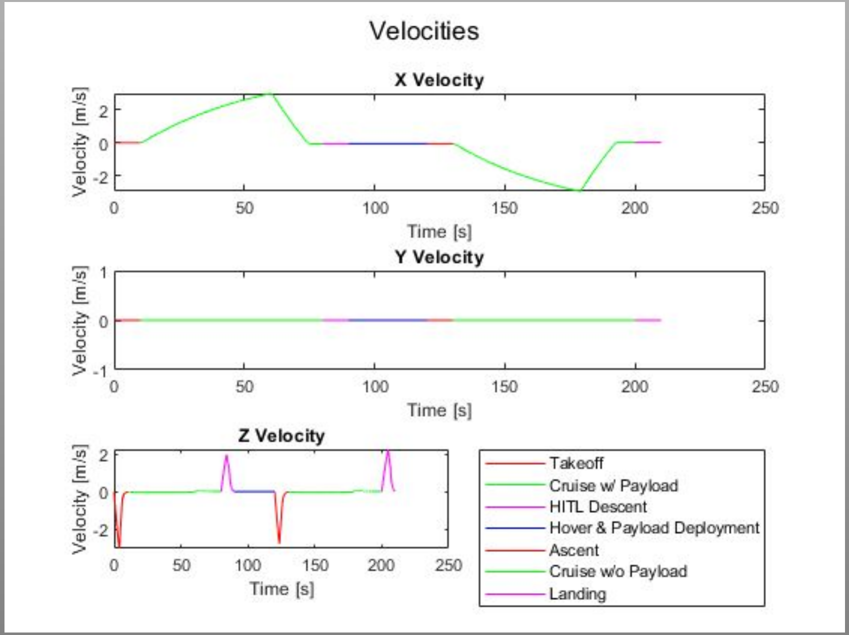
Dynamics Model: Plots



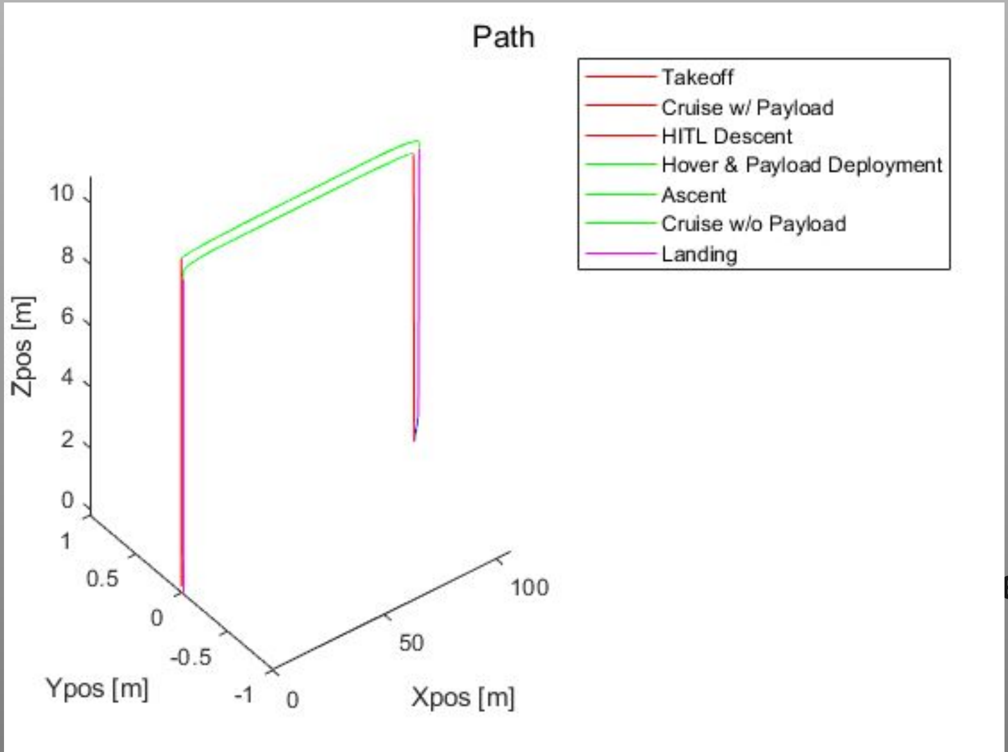


Dynamics Model: Plots (Continued)

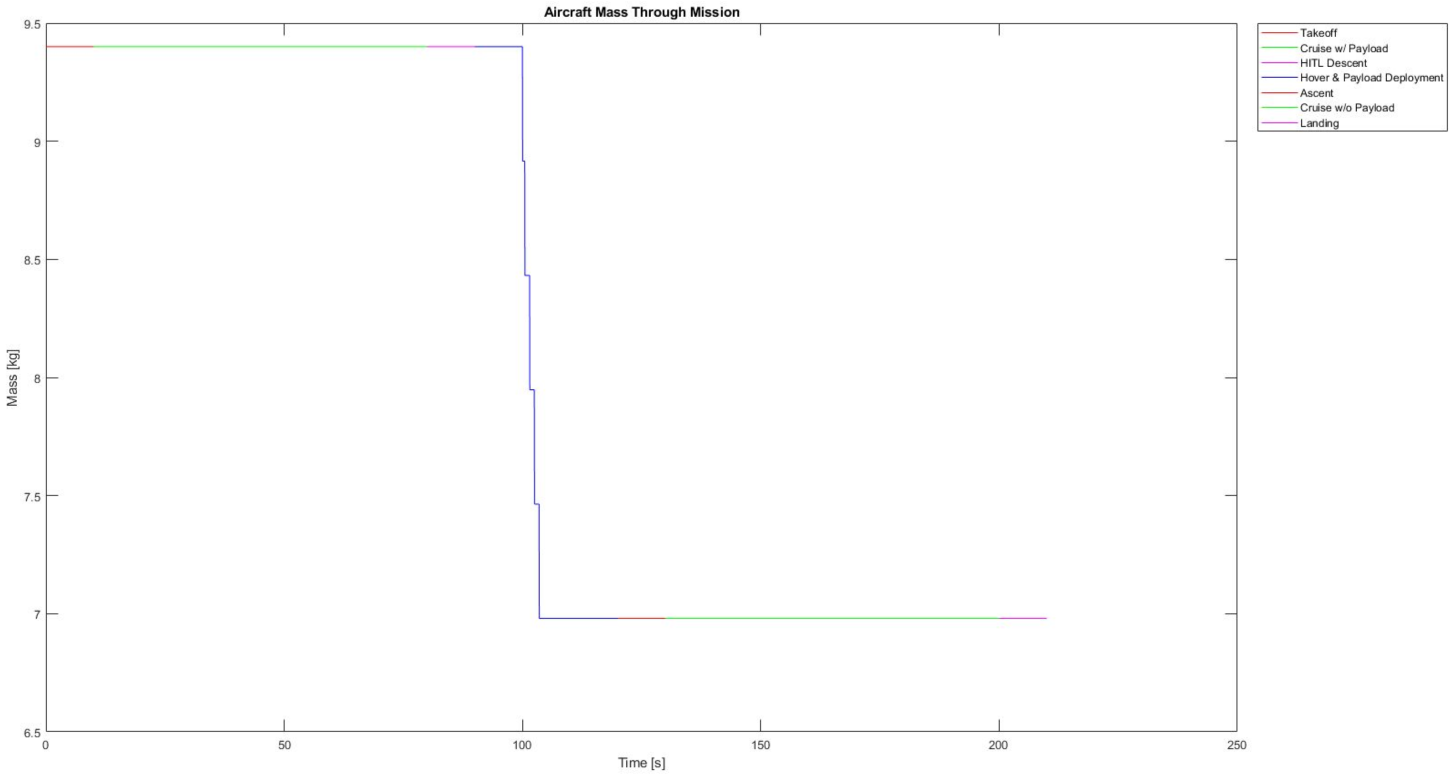




Dynamics Model: Plots (Continued)

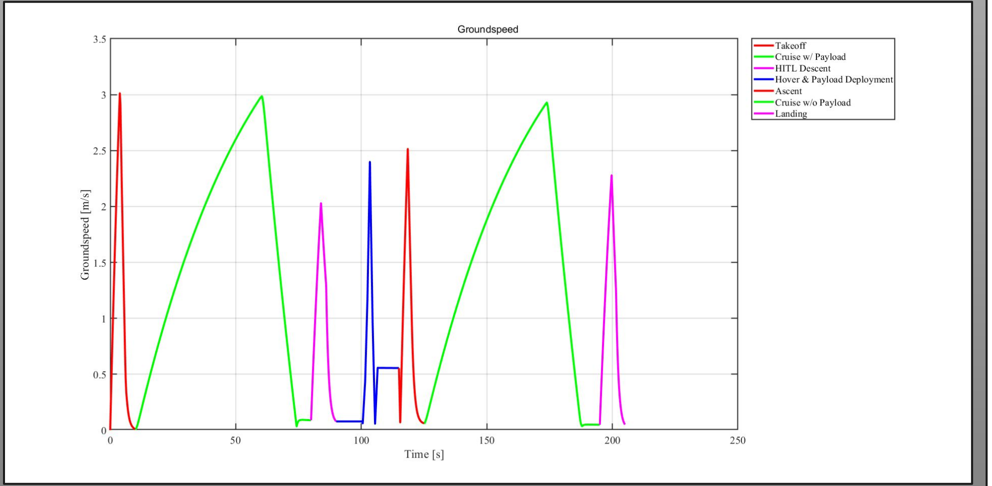


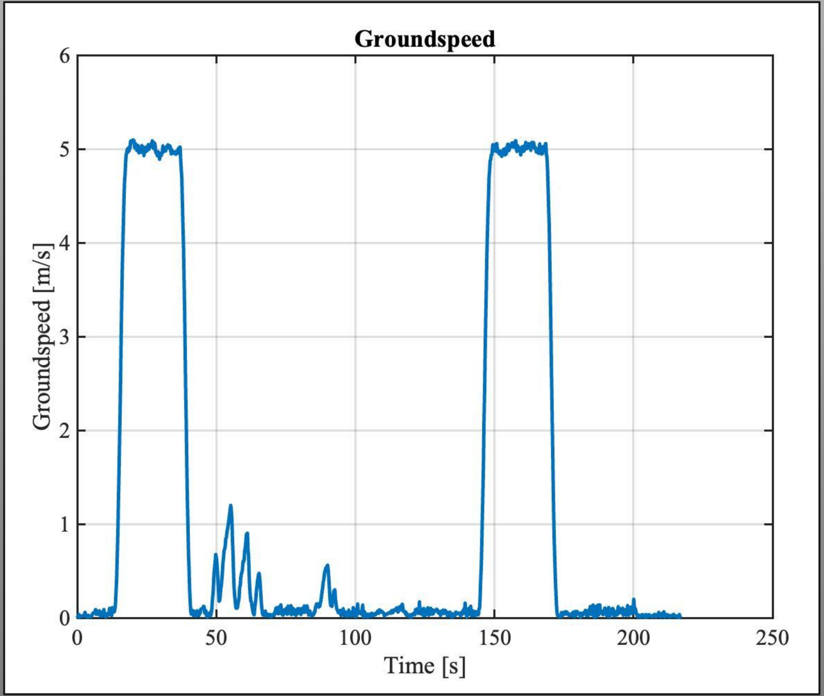
Dynamics Model: Plots (Continued)



Test Data Analysis: Dynamics

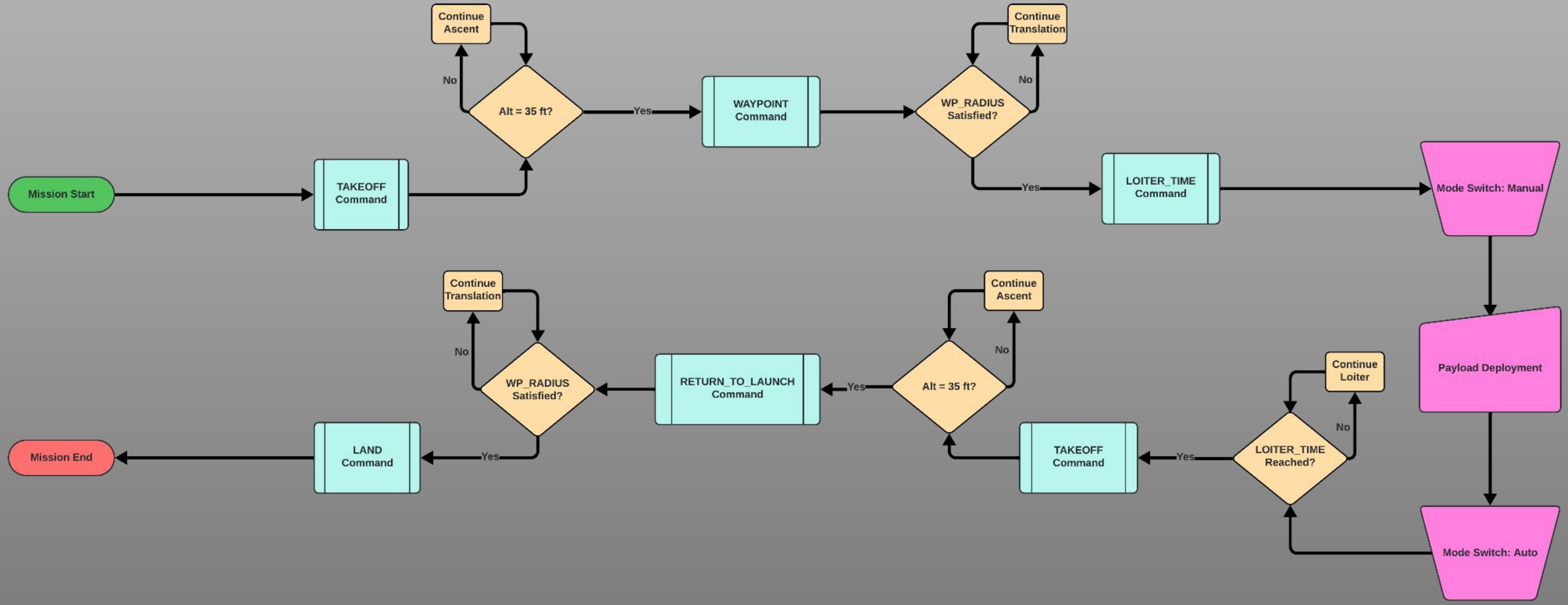
- **Groundspeed**





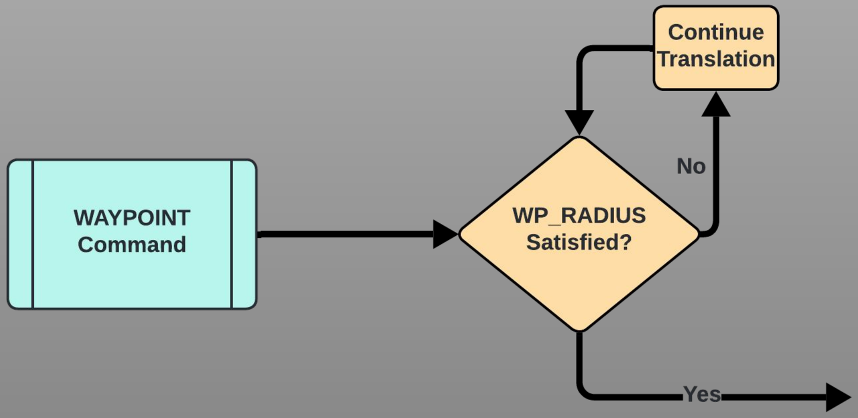
Software/Electrical

ArduPilot Mission Architecture



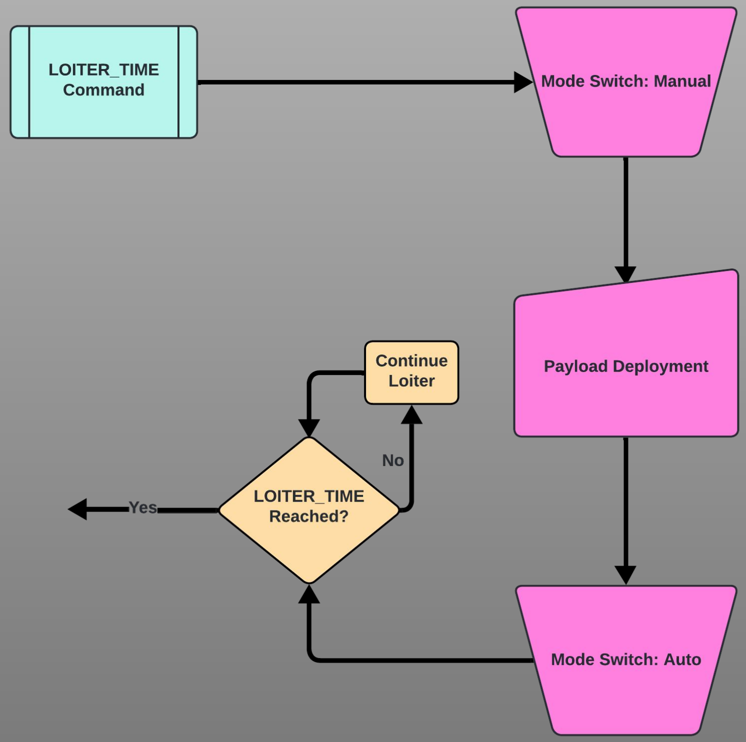
ArduPilot Mission Architecture

- 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



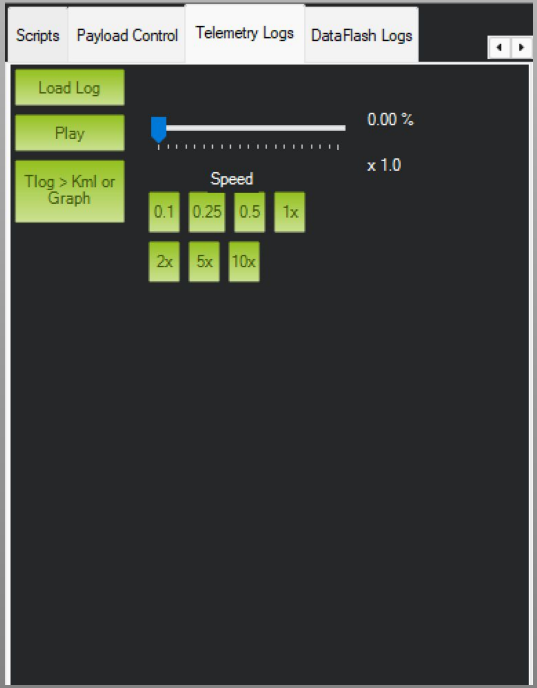
ArduPilot Mission Architecture

- 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"

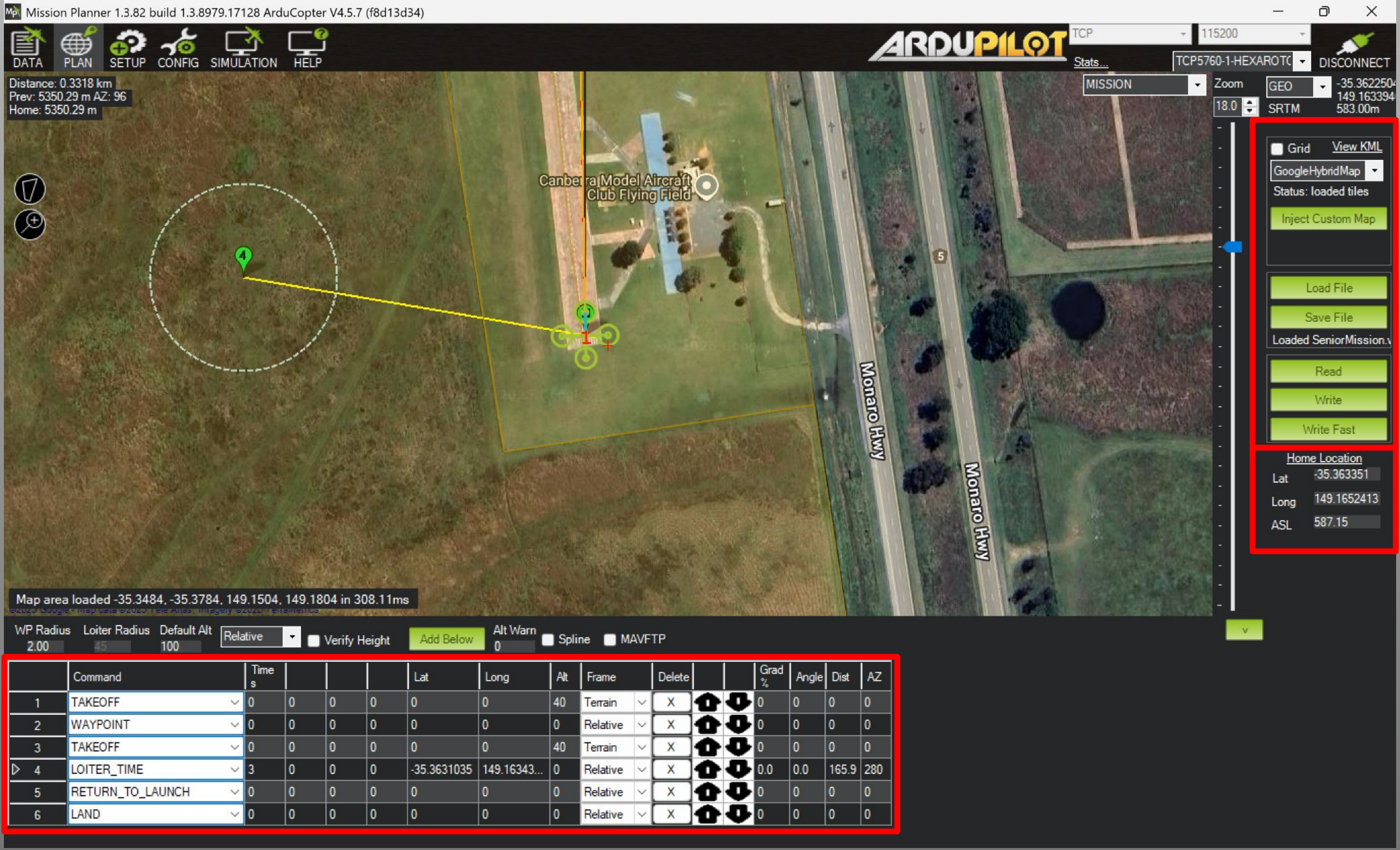


Data Management

- 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

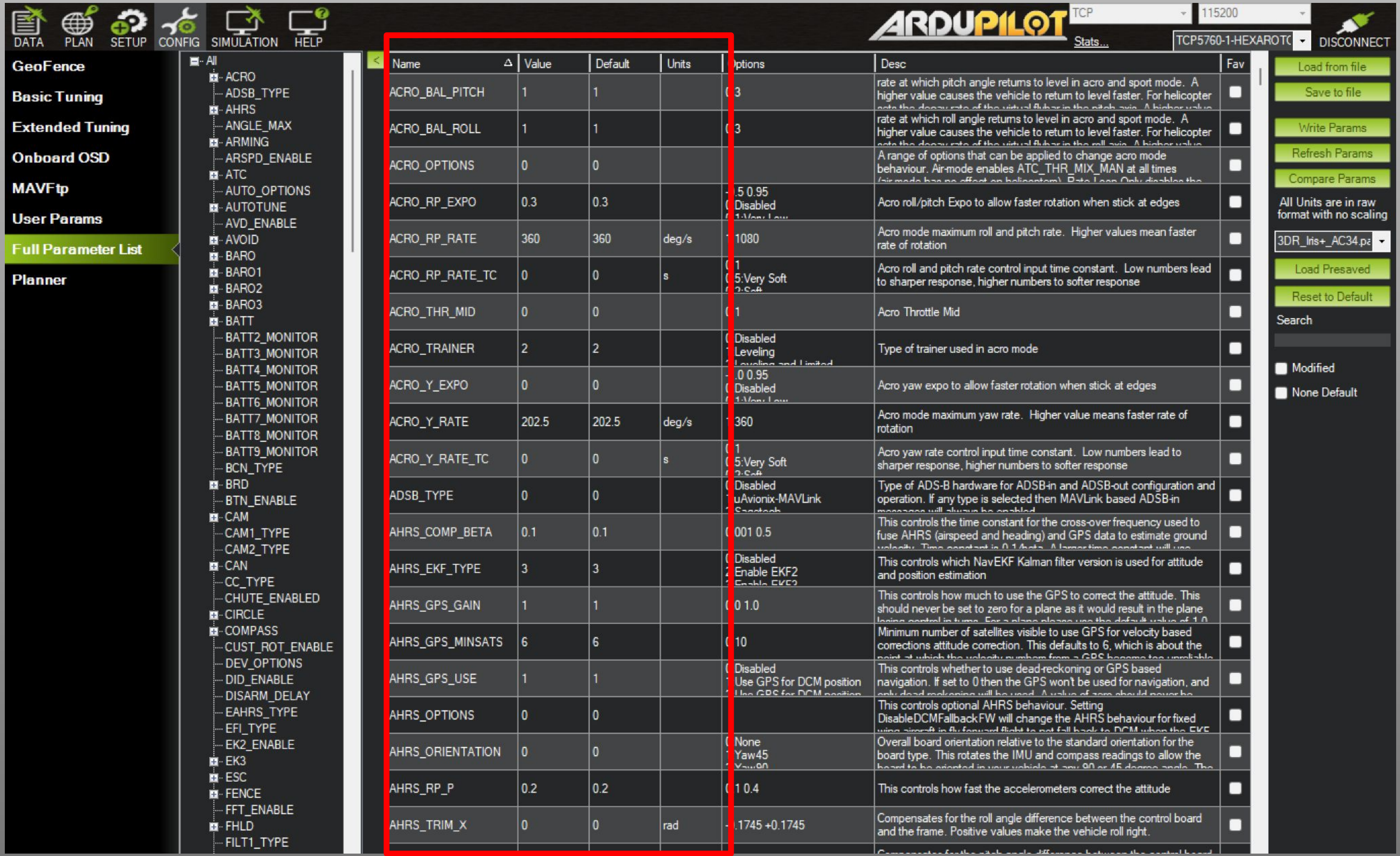
Mission Planner GUI: Mission Status

- **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

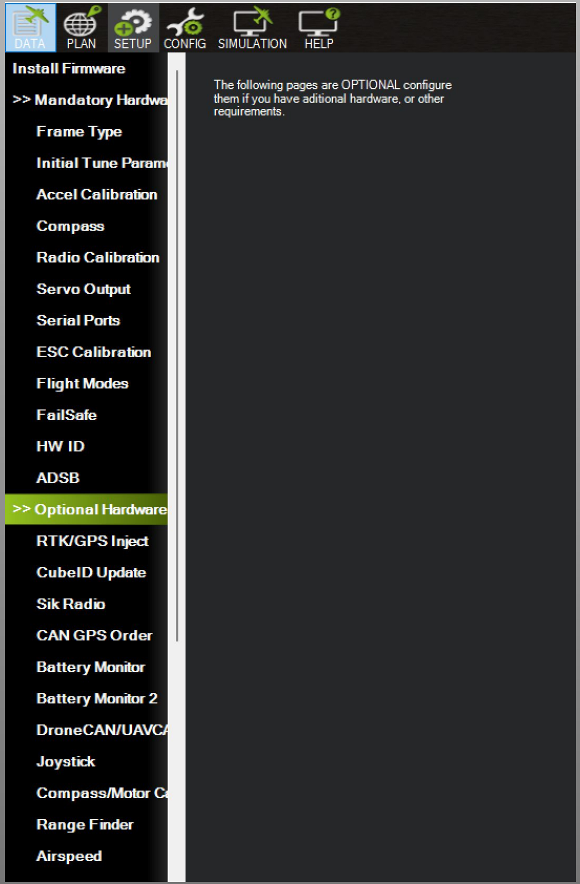
- **Tuning**
  - Follow ArduPilot “Tuning Instructions” for min_TOW

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

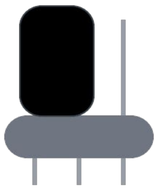
Tattu Lipo Battery

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

PM03D Power Module

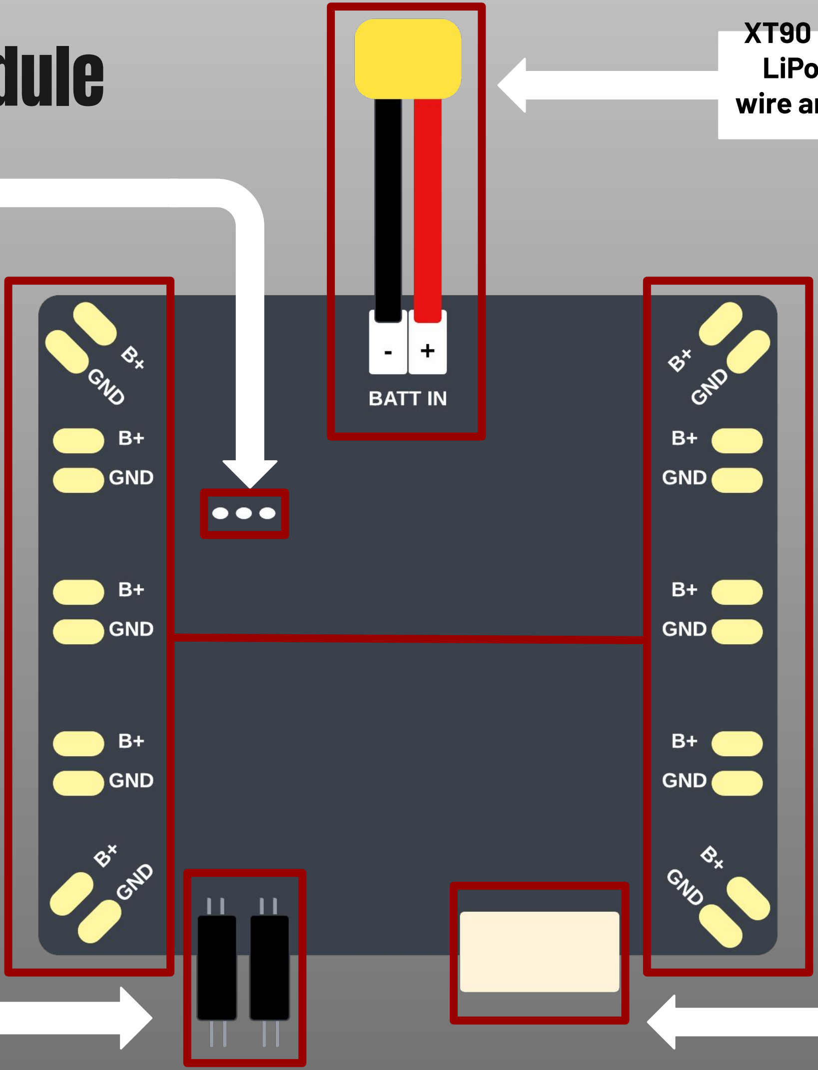
XT90 Connector to 6S (24V) LiPo battery with 10 AWG wire and max peak current of 40A

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

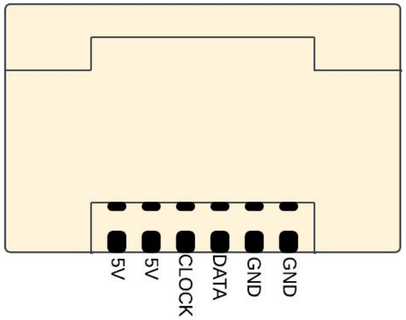


5V 3-pin male header to camera and video transmitter (left)

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



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: 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

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★ **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

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★ **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

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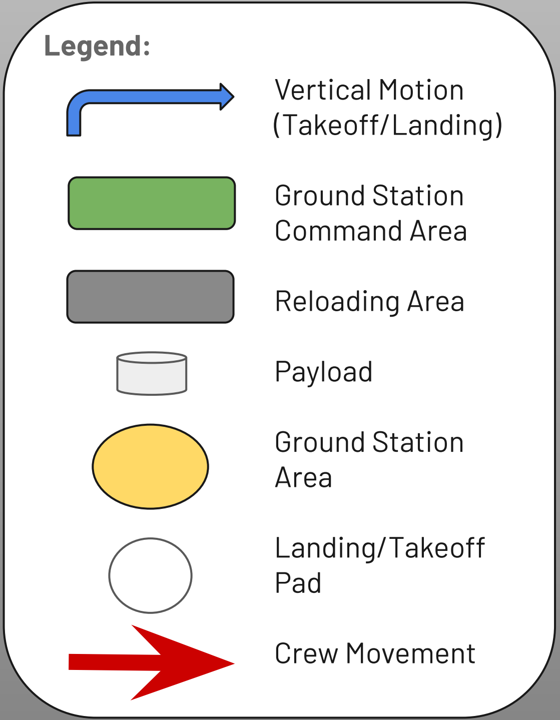
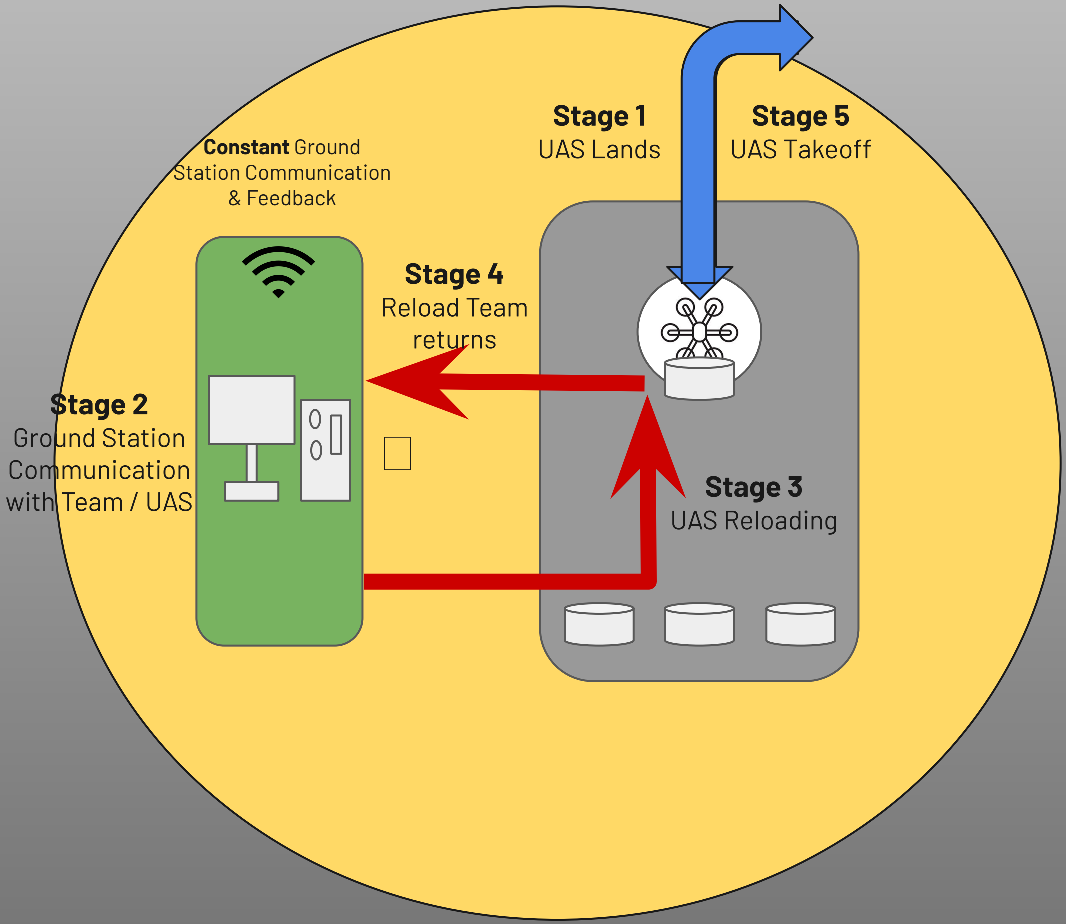
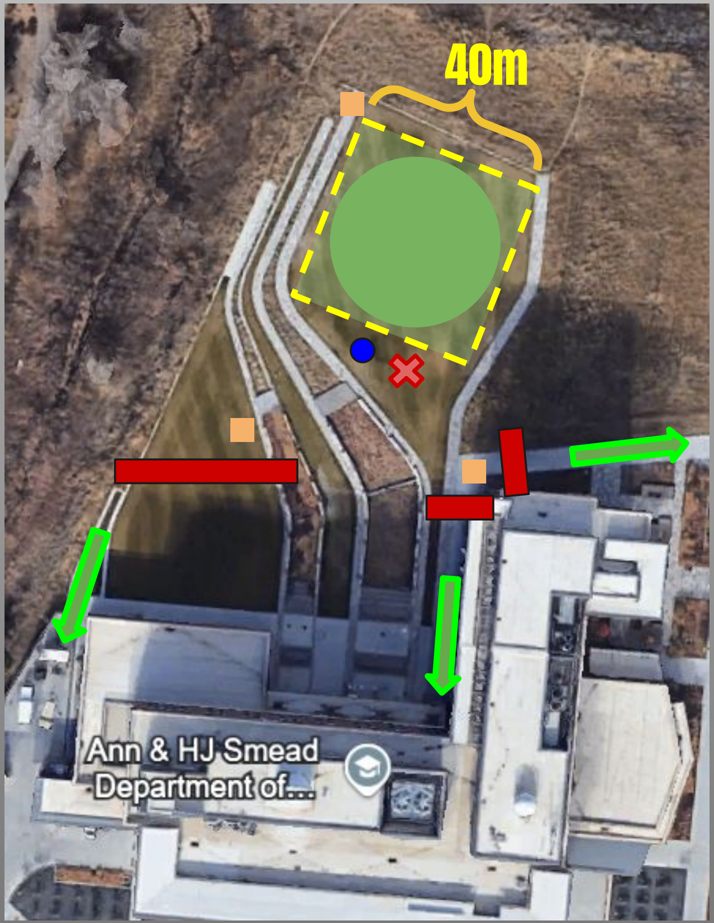
★ FAA required position
☆ 91-57C certified Pilot

FLAME Autonomous Firefighting UAS Reloading ConOps







Key

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