FLAME Critical Design 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

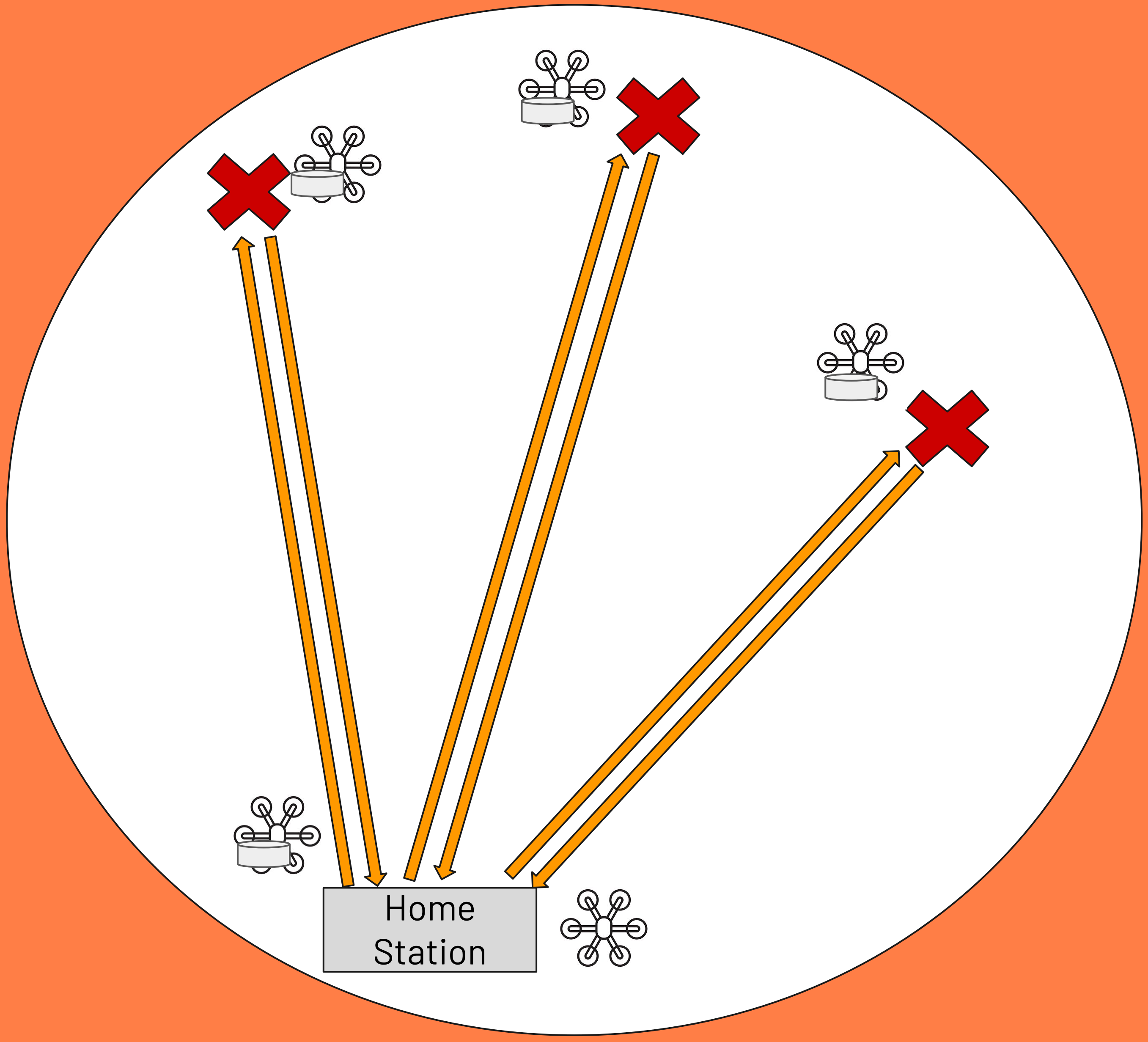
FLAME Autonomous Firefighting UAS High Level ConOps

Legend:

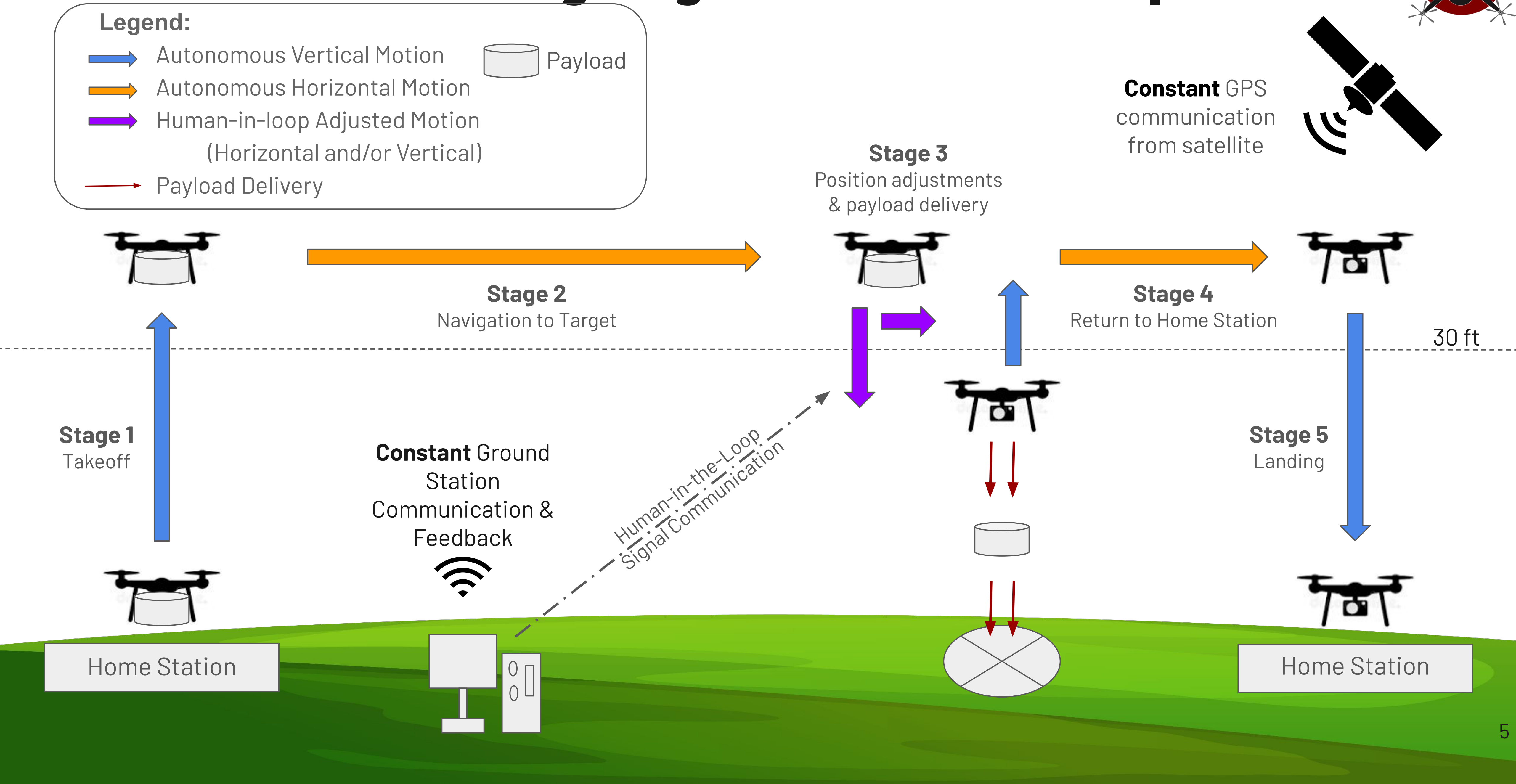
Target Location

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

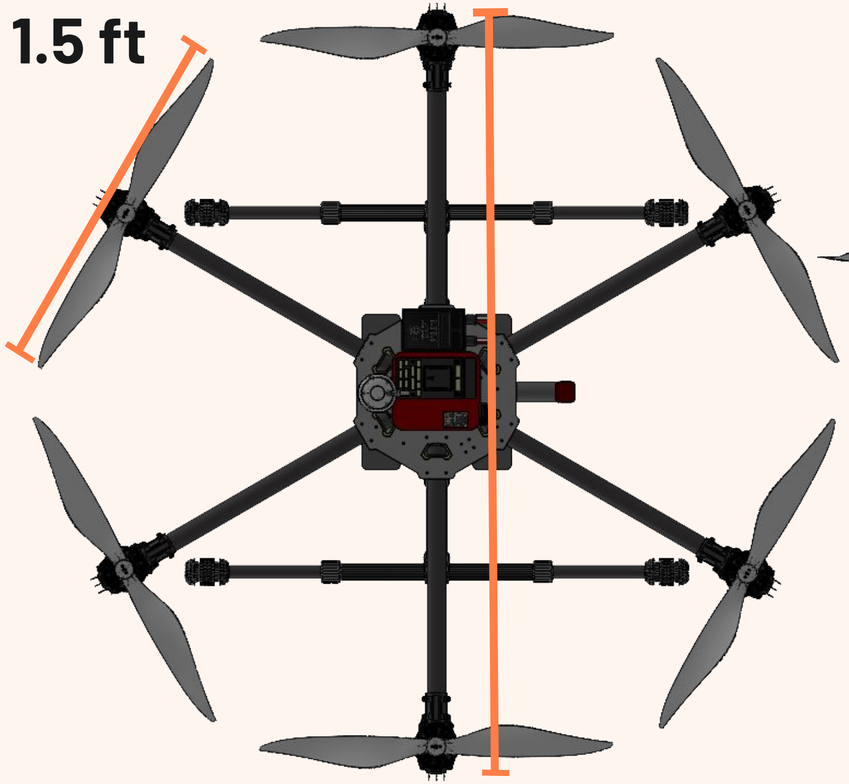


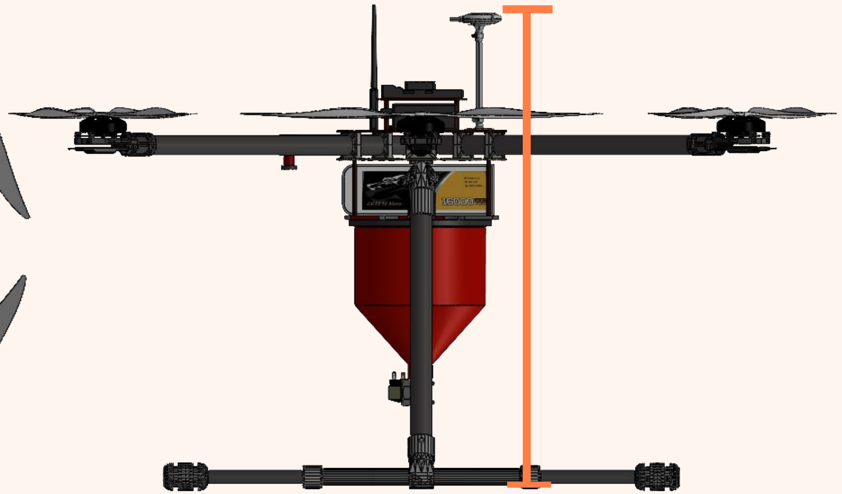
Key Driving Requirements

Key Requirement Number	Key Requirement Description
FR 1.2	The UAS shall be able to take off autonomously
FR 1.3	The UAS shall be able to land autonomously
FR 1.4	The UAS shall be capable of making 3 drops in a 20 minute span
FR 2.1	The UAS shall be able to carry and deploy 5 pounds of payload per target location
FR 3.1	The system shall utilize human-in-the-loop to navigate from 10 meters RMS accuracy to 1 meter from target location
FR 3.5	The system shall deploy the payload and have it land within +/- 1 meter accuracy of target location

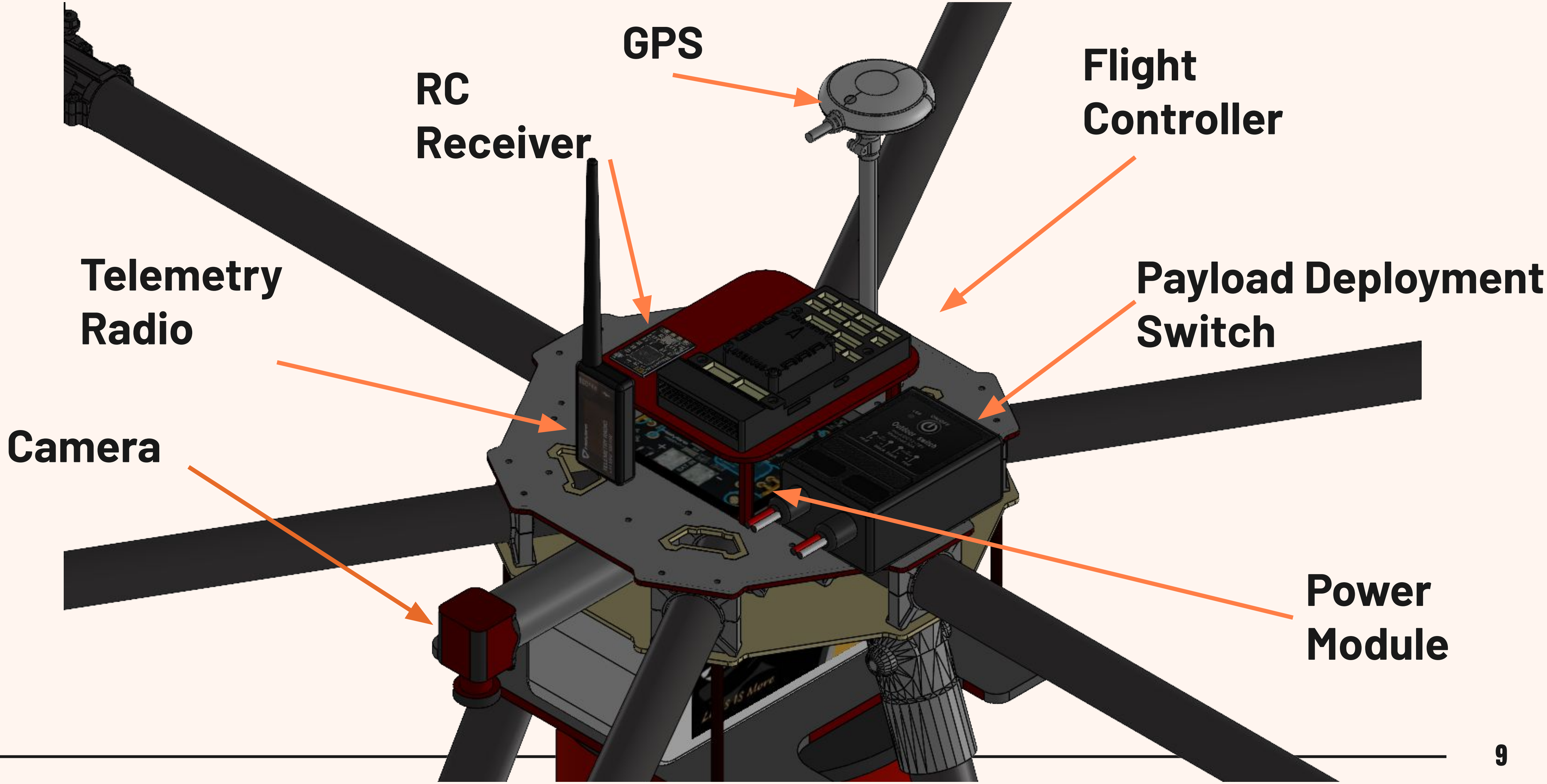
Design Solution

Multirotor Drone Assembly

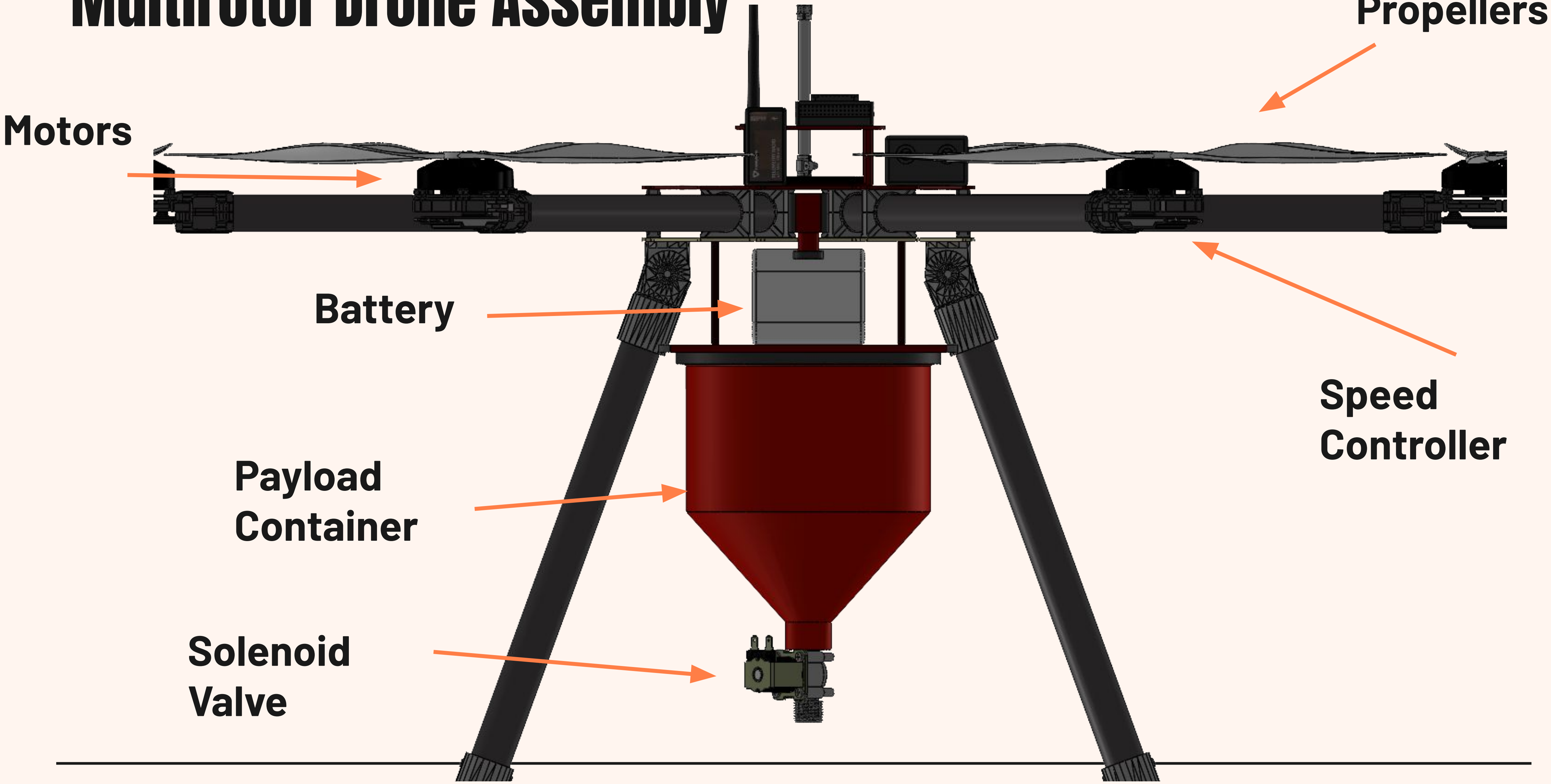




Multirotor Drone Assembly



Multirotor Drone Assembly



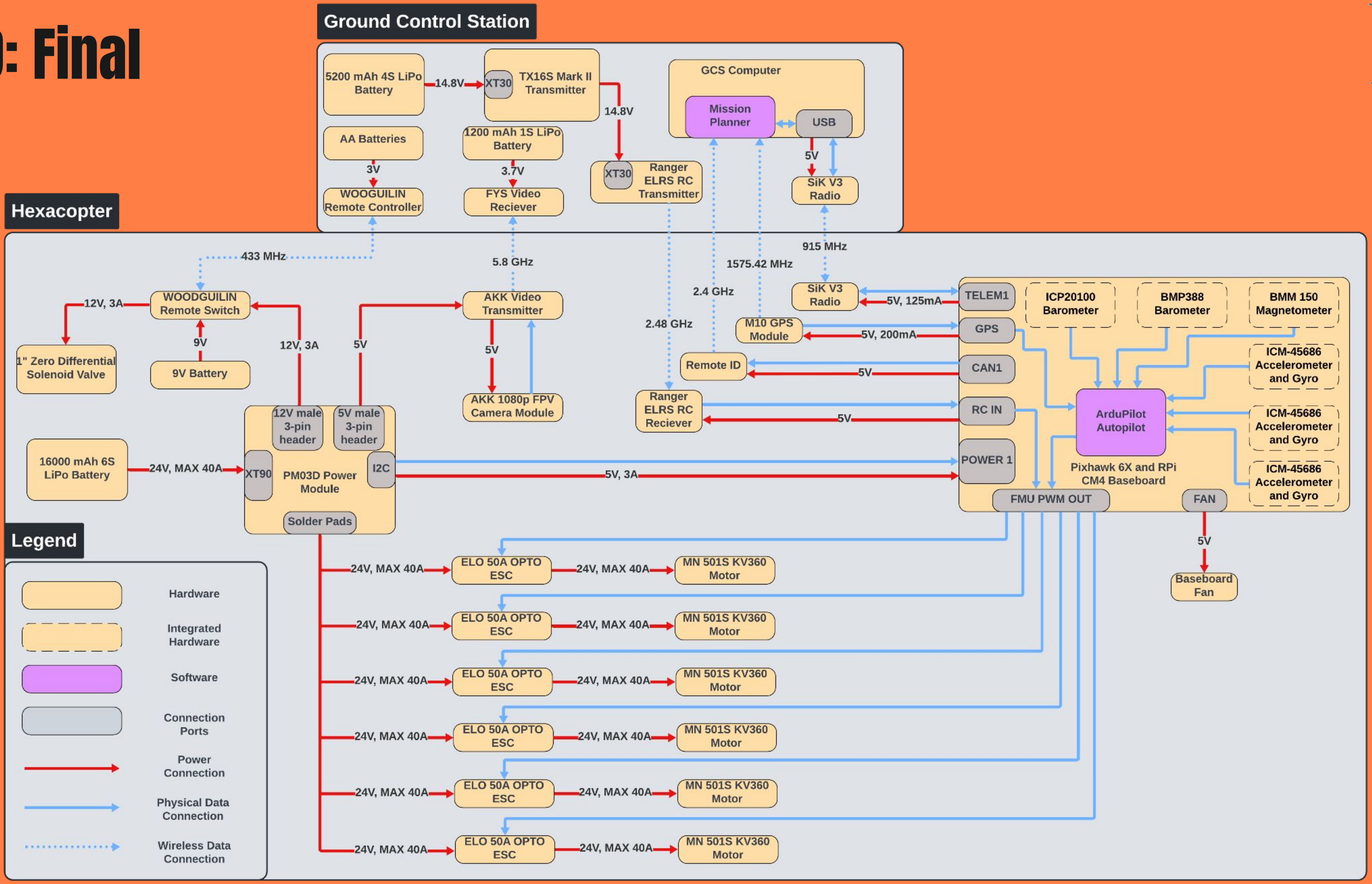
System Overview: Mass Budget

- **Max Mass**
  - 22.67 kg **(50 lbs)** requirement
- **Modeling Section Assumptions**
  - **10.5 kg** to leave room for additional 3D printed components and wiring
  - **0.75 kg (1.65 lbs)** deemed to be enough buffer
  - Will take ~10% extra payload

Subsystem	Mass (kg)
Power	2.05
Communications	0.03
Control	0.46
Propulsion	1.54
Payload Deployment	1.37
Airframe/Structure	1.8
Sensing	0.1
Total	**7.35**
Total with Payload	**~9.75**

*Component level mass breakdown can be found in backup slides

FBD: Final



Ground Control Station
5200 mAh 4S LiPo Battery
14.8V
XT30
TX16S Mark II Transmitter
14.8V
GCS Computer
Mission Planner
USB
AA Batteries
3V
WOOGUILIN Remote Controller
1200 mAh 1S LiPo Battery
3.7V
FYS Video Reciever
XT30
Ranger ELRS RC Transmitter
5V
SiK V3 Radio
Hexacopter
433 MHz
5.8 GHz
915 MHz
1575.42 MHz
2.4 GHz
2.48 GHz
12V, 3A
WOODGUILIN Remote Switch
9V
1" Zero Differential Solenoid Valve
9V Battery
12V, 3A
5V
AKK Video Transmitter
5V
AKK 1080p FPV Camera Module
SiK V3 Radio
5V, 125mA
M10 GPS Module
5V, 200mA
Remote ID
5V
Ranger ELRS RC Reciever
5V
TELEM1
GPS
CAN1
RC IN
POWER 1
ICP20100 Barometer
BMP388 Barometer
BMM 150 Magnetometer
ICM-45686 Accelerometer and Gyro
ArduPilot Autopilot
ICM-45686 Accelerometer and Gyro
ICM-45686 Accelerometer and Gyro
Pixhawk 6X and RPi CM4 Baseboard
FMU PWM OUT
FAN
5V
Baseboard Fan
12V male 3-pin header
5V male 3-pin header
16000 mAh 6S LiPo Battery
24V, MAX 40A
XT90
PM03D Power Module
I2C
5V, 3A
Solder Pads
24V, MAX 40A
ELO 50A OPTO ESC
24V, MAX 40A
MN 501S KV360 Motor
24V, MAX 40A
ELO 50A OPTO ESC
24V, MAX 40A
MN 501S KV360 Motor
24V, MAX 40A
ELO 50A OPTO ESC
24V, MAX 40A
MN 501S KV360 Motor
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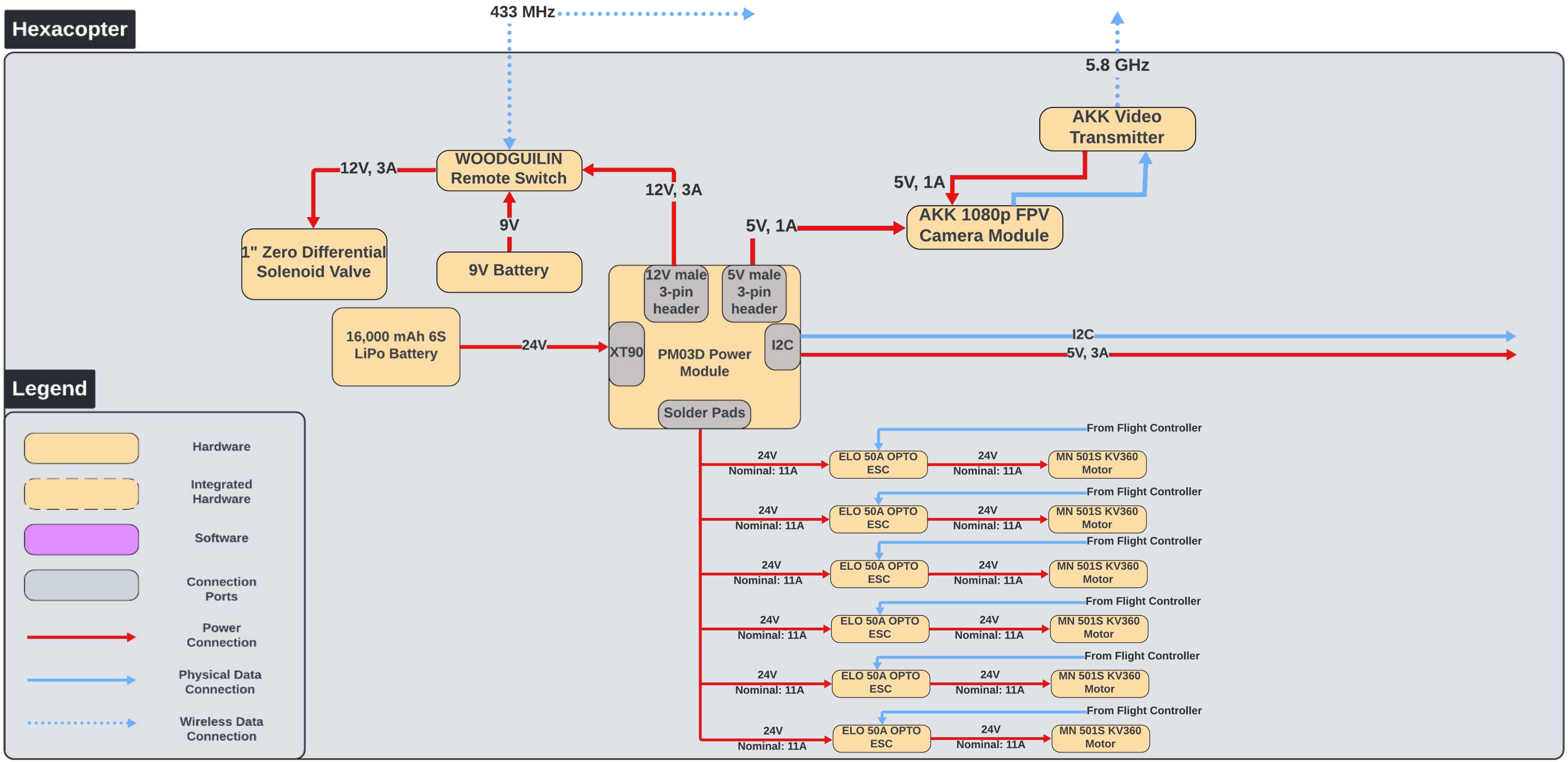
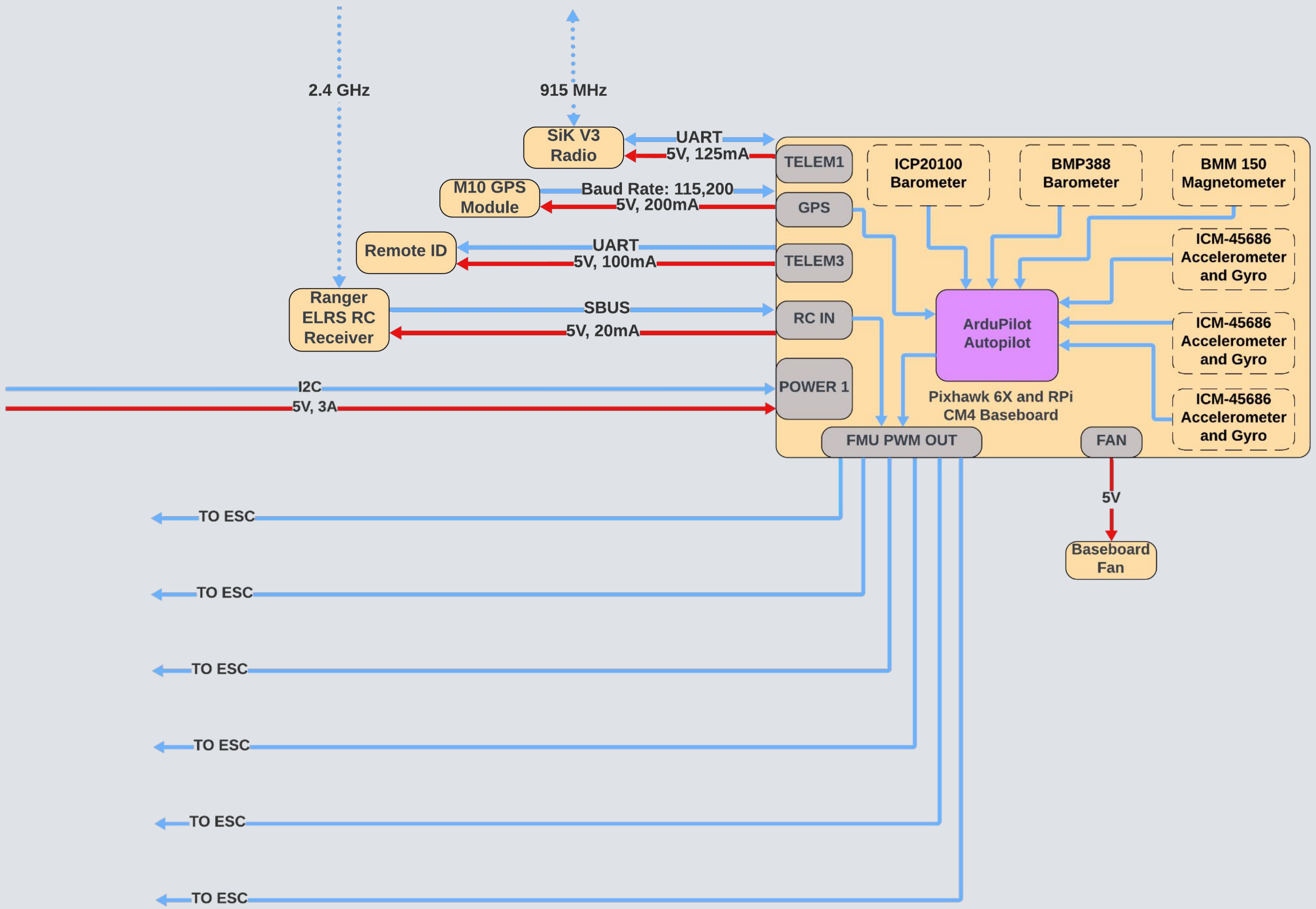
ELO 50A OPTO ESC
24V, MAX 40A
MN 501S KV360 Motor
24V, MAX 40A
ELO 50A OPTO ESC
24V, MAX 40A
MN 501S KV360 Motor
Legend
Hardware
Integrated Hardware
Software
Connection Ports
Power Connection
Physical Data Connection
Wireless Data Connection

FBD: Hexacopter Breakdown Part 1



FBD: Hexacopter Breakdown Part 2

Hexacopter

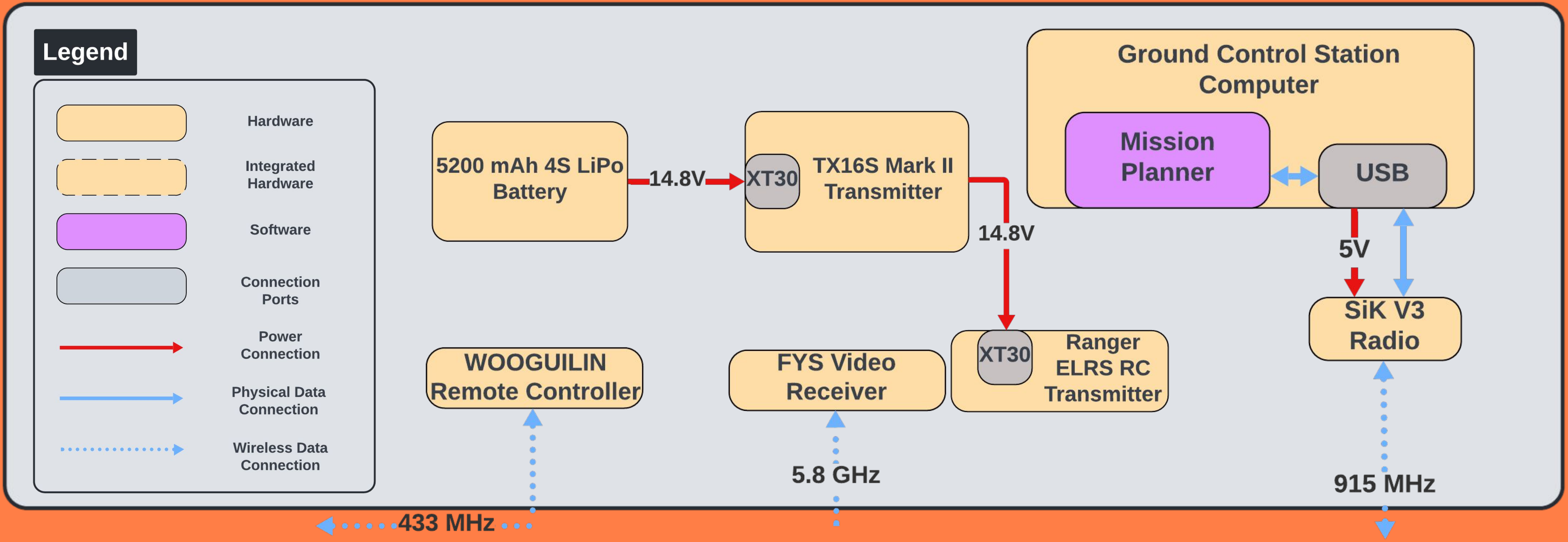


Legend

	Hardware
	Integrated Hardware
	Software
	Connection Ports
	Power Connection
	Physical Data Connection
	Wireless Data Connection

FBD: Ground Control Station Breakdown

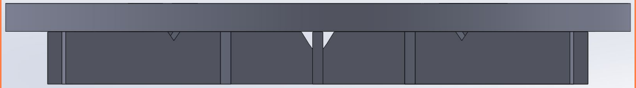
Ground Control Station

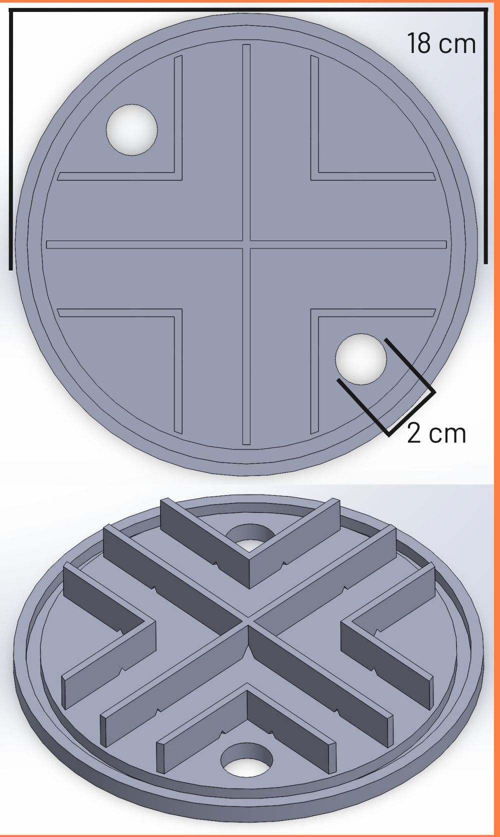


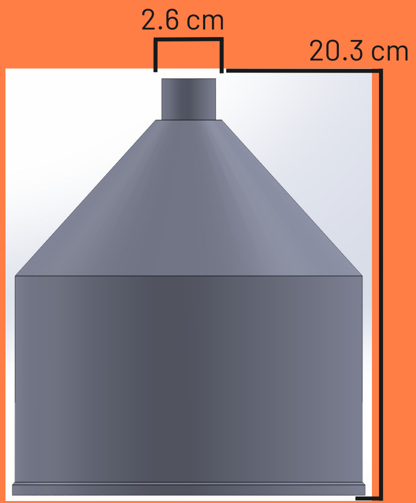
Payload Deployment Subsystem: Container

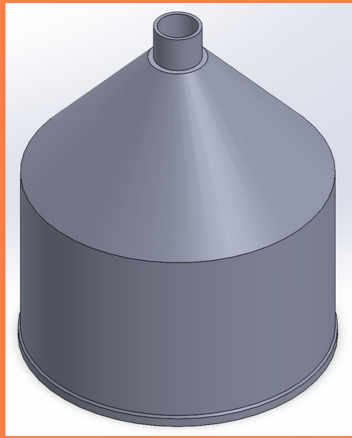
- **~10 % Payload Margin**

- **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

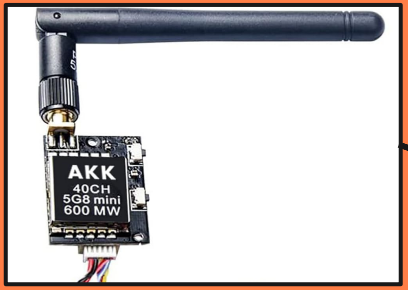
Control Subsystem: Software Selections

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

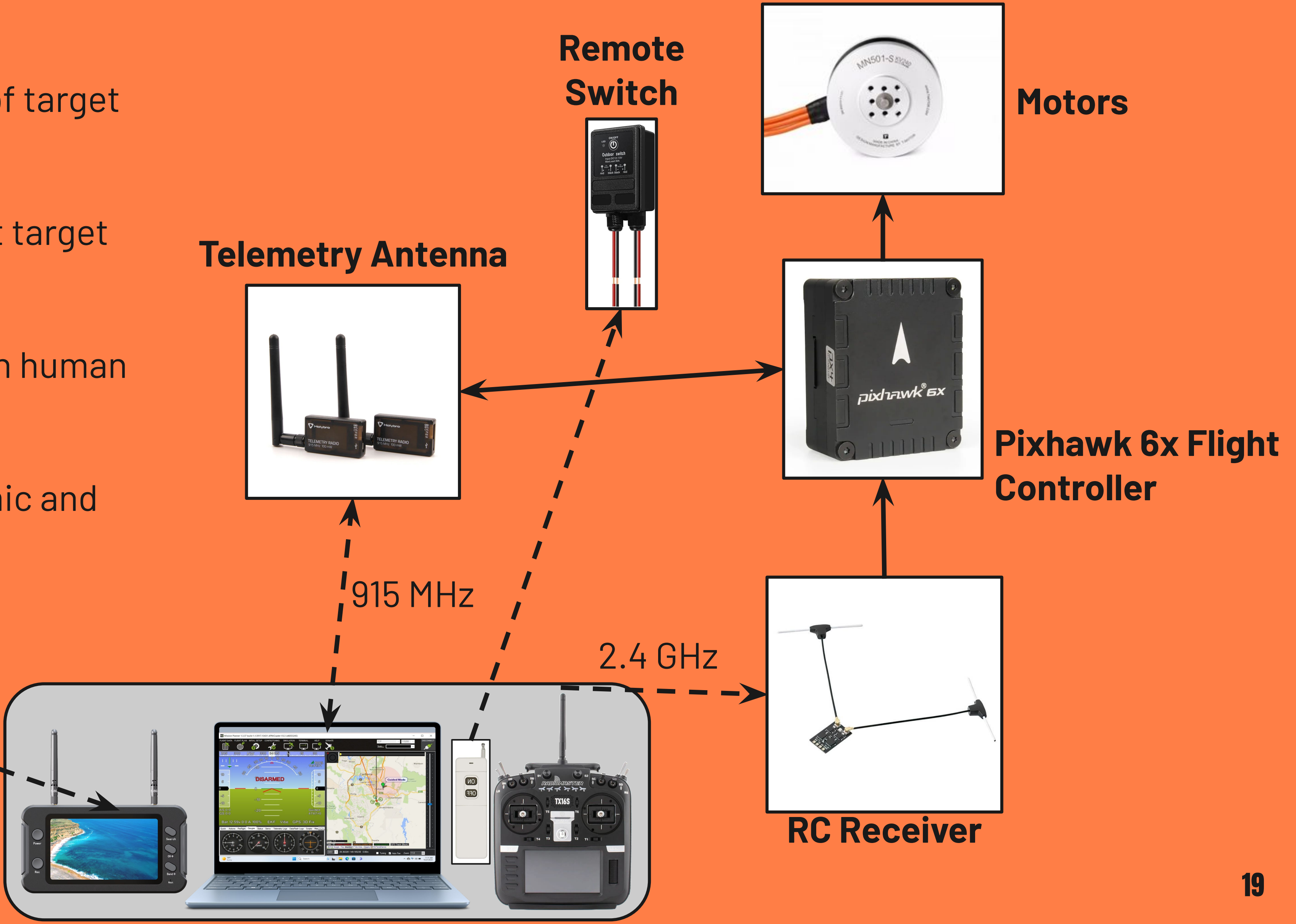
Software Selections	
Use	**Software**
Autopilot	ArduPilot
Mission Planning	Mission Planner

Control Subsystem: Human Control

- **Human-in-the-Loop (HITL)**
  - Human control within 10m of target
  - Human takeover
- **PixHawk 6X**
  - Automatic switch to HITL at target
  - Automatic control gains
- **Video Receiver**
  - Allow visual connection with human and target
- **Telemetry**
  - Concurrent position, dynamic and mission data



Video Transmitter



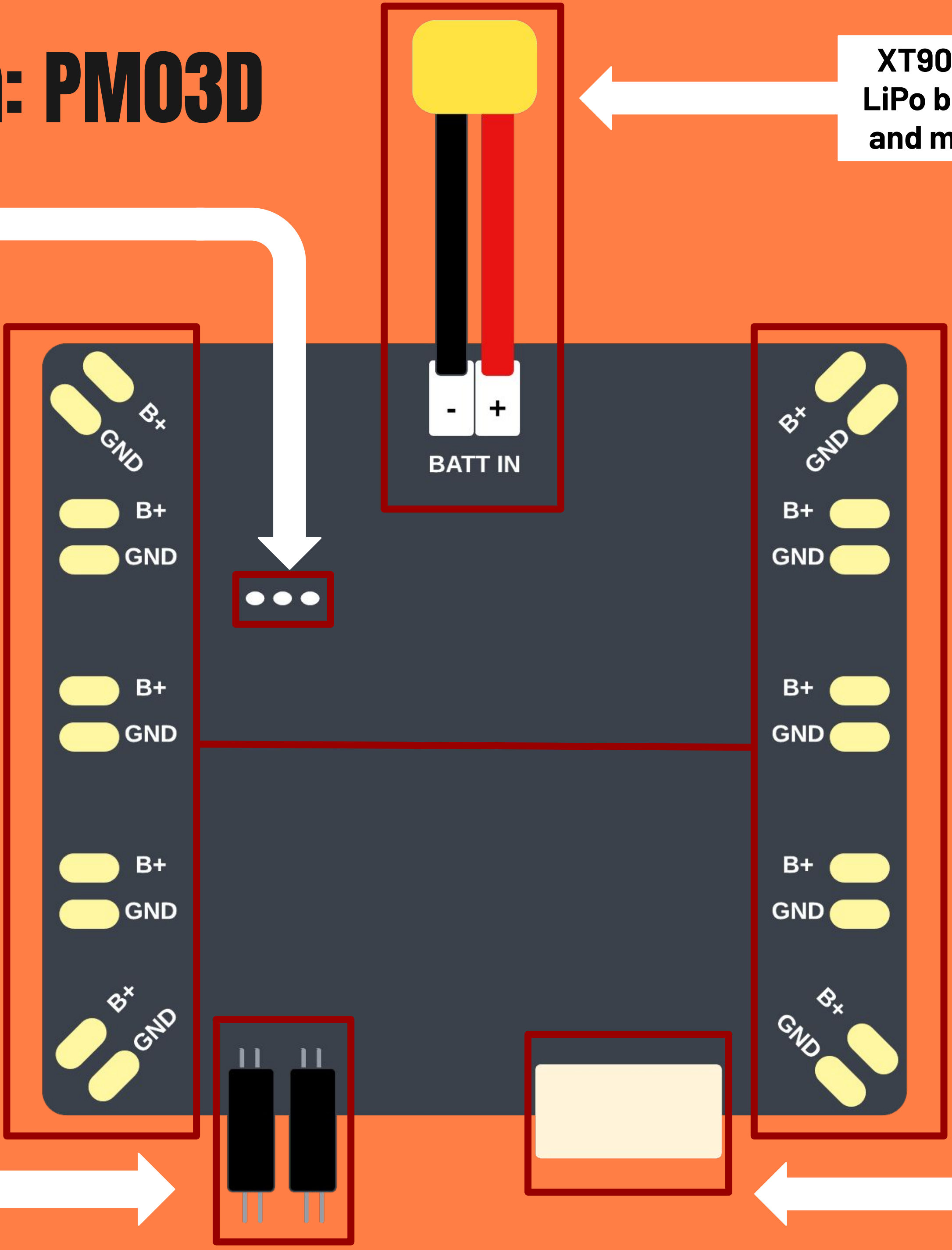
Power Subsystem: Onboard Batteries

- **Main power supply**
  - LiPo 6S (24V), 16000 mAh, max 40A, 30C discharge rate
  - XT90 Connector
  - Powers entire drone
  - 1988 g / 4.3 lbs

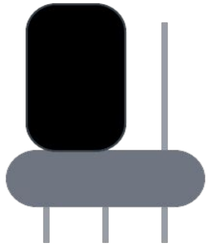
- **Remote switch power supply**
  - Standard 9V battery
  - Powers solenoid switch

Power Subsystem: PM03D

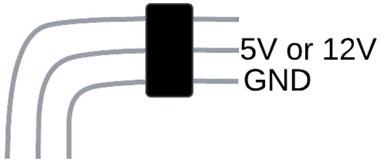
XT90 Connector to 6S (24V) LiPo battery with 10 AWG wire and max peak current of 40A



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

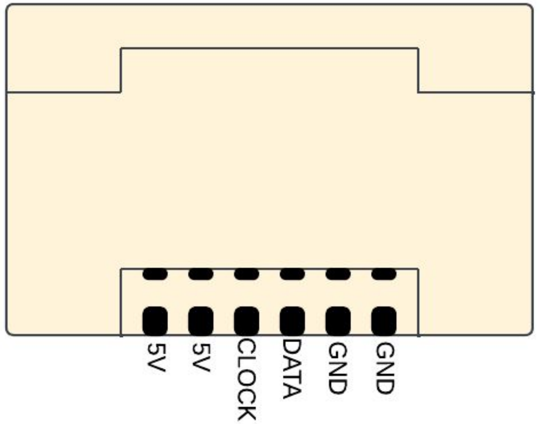


Solder pads to ESCs and motors, outputs battery voltage of 24V and max peak current of 40A



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

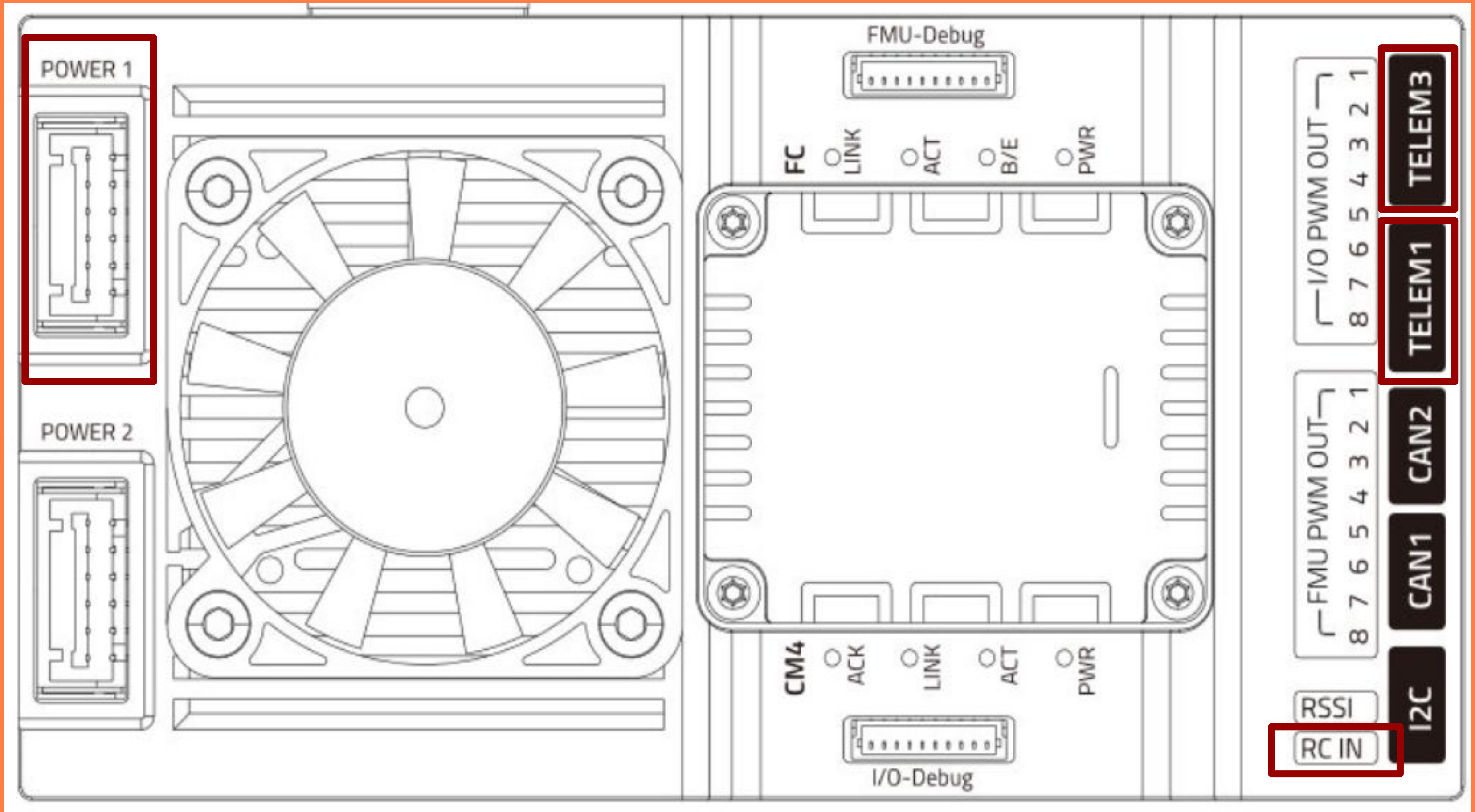
12V 3-pin male header to remote switch & Solenoid valve (right)



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

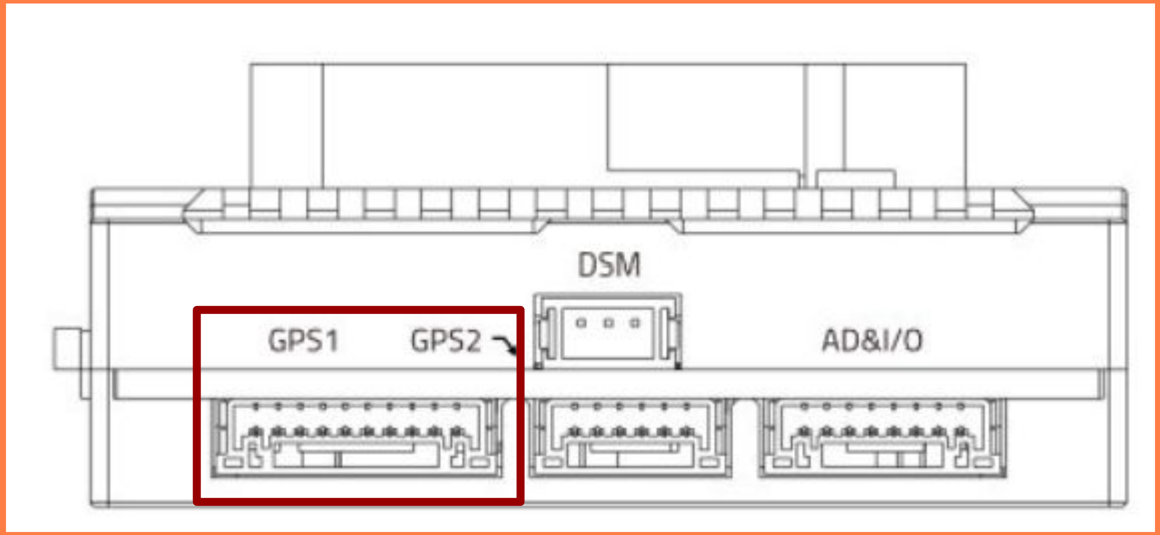
Power Subsystem: Pixhawk 6X and RPi CM4 Baseboard

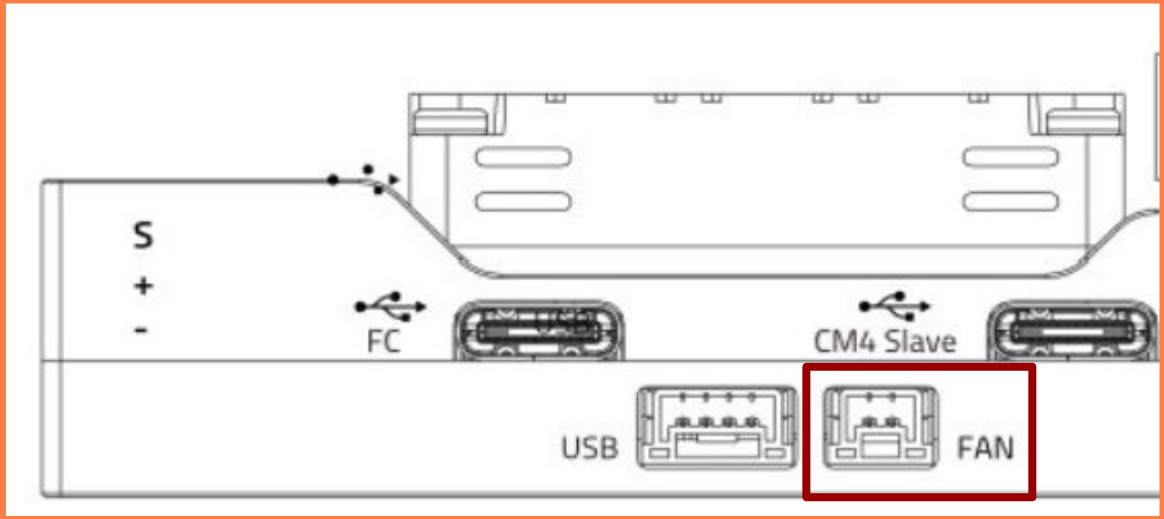
- **POWER 1**
  - Input power from PM03D
- **RC IN**
  - Powers RC receiver with 5V pin
- **TELEM1**
  - Powers SiK V3 Radio with 5V pin
- **TELEM3**
  - Powers Remote ID with 5V pin



Power Subsystem: Pixhawk 6X and RPi CM4 Baseboard

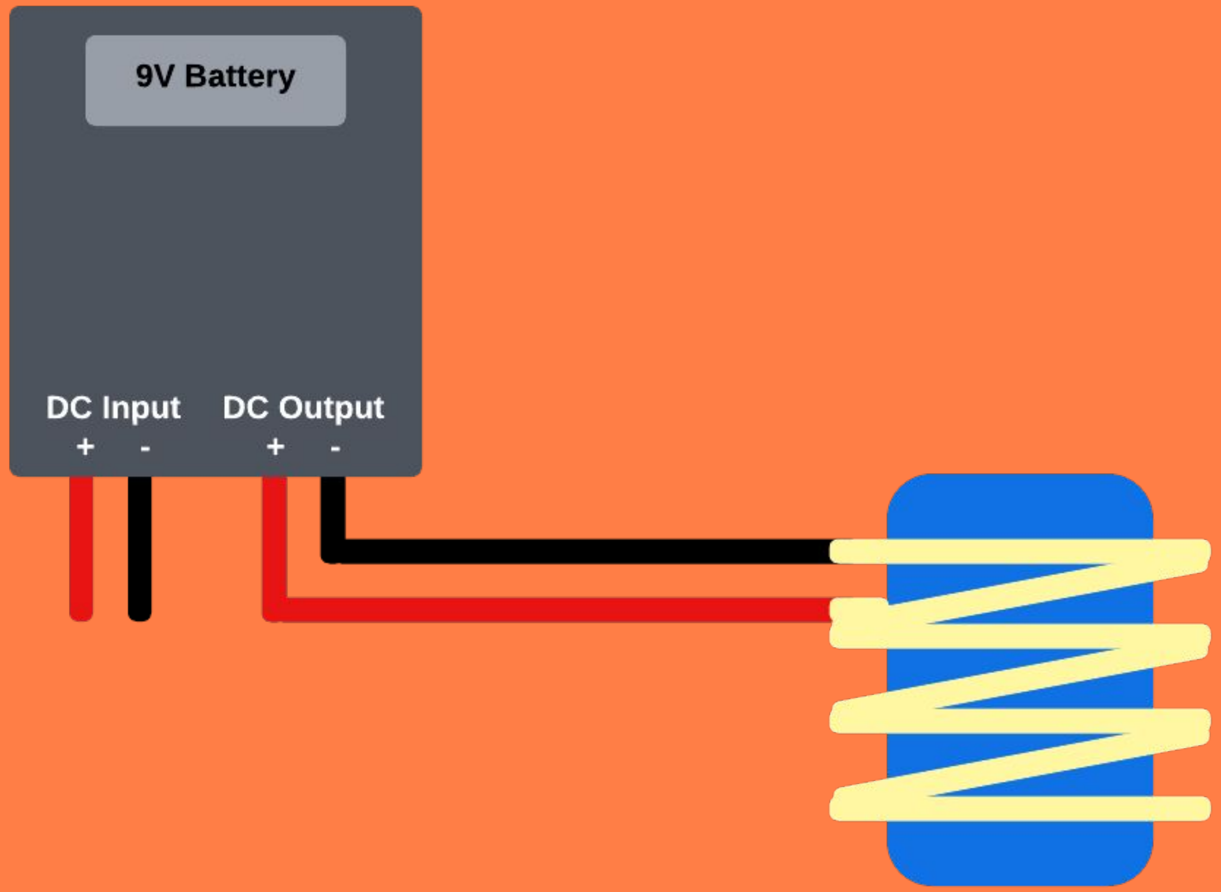
- **GPS1**
  - Powers M10 GPS module with 5V pin
- **FAN**
  - Powers baseboard cooling fan with 5V pin
- **Connections**
  - All connections are JST GH receptacle connectors





Power Subsystem: Remote Switch and Solenoid Valve

- **Remote Switch Power**
  - 9V battery
- **How it works**
  - 12V input to switch from PM03D male 3-pin header
  - Normally closed valve
  - Ground operator closes the switch, the connection is made to solenoid valve, retracting the plunger



Engineering Modeling

Engineering Models

Model	Impacts	Requirements
Energy Consumption Analysis	**Rotor count, battery selection, motor selection, propeller selection**	**FR 1.4, FR 2.1, DR 2.1.1, DR 3.1.1, DR 3.2.1**
Flight Dynamics/Stability	Mission leg times for mission performance model	FR 1.2, FR 1.3, FR 1.5, DR 5.1.1, DR 5.3.1
Payload Deployment Time	Payload deployment times for mission performance model	FR 1.4, DR 1.7
Payload Container Size	Container dimensions, container material, attachment method	DR 1.1.3, DR 6.2.2, DR 7.2.3

Key Requirements

Key Requirement Number	Key Requirement Description
FR 1.4	The UAS shall be capable of making three drops in a 20-minute span
FR 2.1	The UAS shall be able to carry and deploy a 5-pound payload per target location
DR 2.1.1	The power subsystem shall provide sufficient power to support operation of all components during entire mission duration
DR 3.1.1	The propulsion subsystem shall provide sufficient thrust to lift the aircraft and payload during all mission segments
DR 3.2.1	The propulsion subsystem shall deliver thrust within an operational range of a 100-meter diameter

Critical Risks Reduced

- **Mission Feasibility**
  - Energy consumption for mission segments
  - Battery capacity
  - Battery power

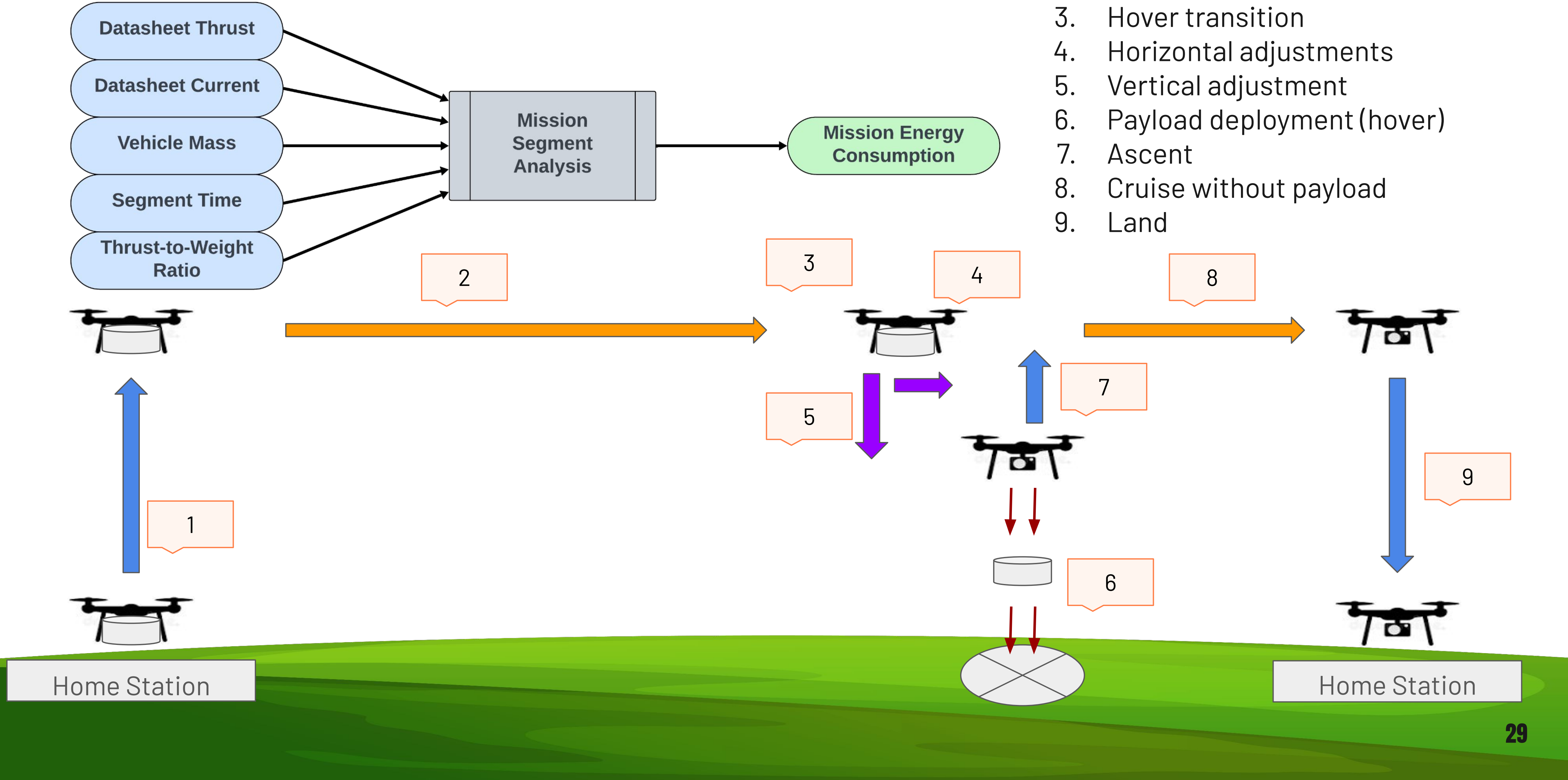
- **Known Dimensions and Values**
  - Battery size and weight

- **Risks Reduced**
  - Know the dimensions of aircraft
  - Know the energy consumed during mission legs
  - Weight criteria hit

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

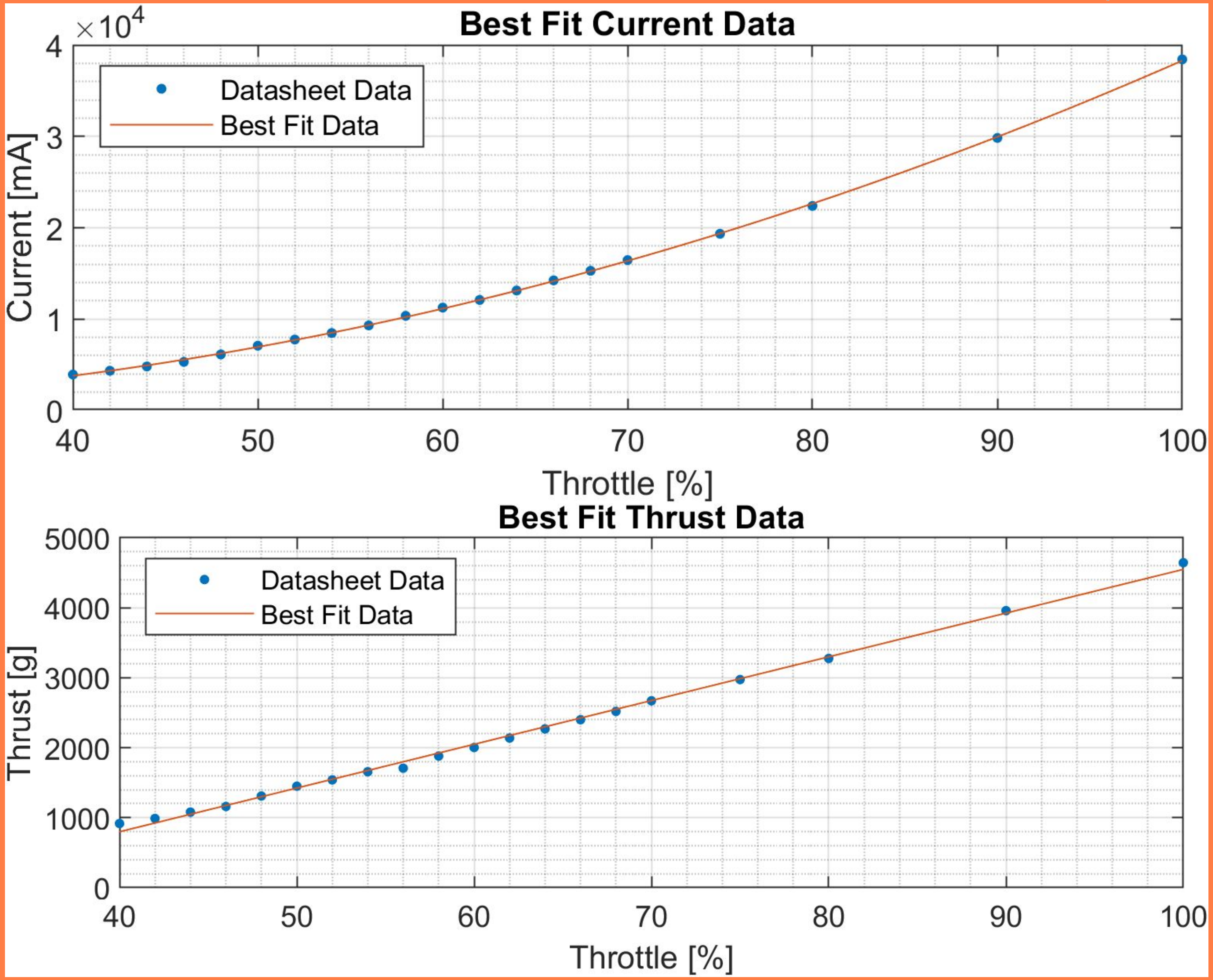
$$T_{alt} = T_{data} \frac{\rho_{alt}}{\rho_{s.l.}} = 0.85 T_{data}$$

- **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

Motor Datasheet

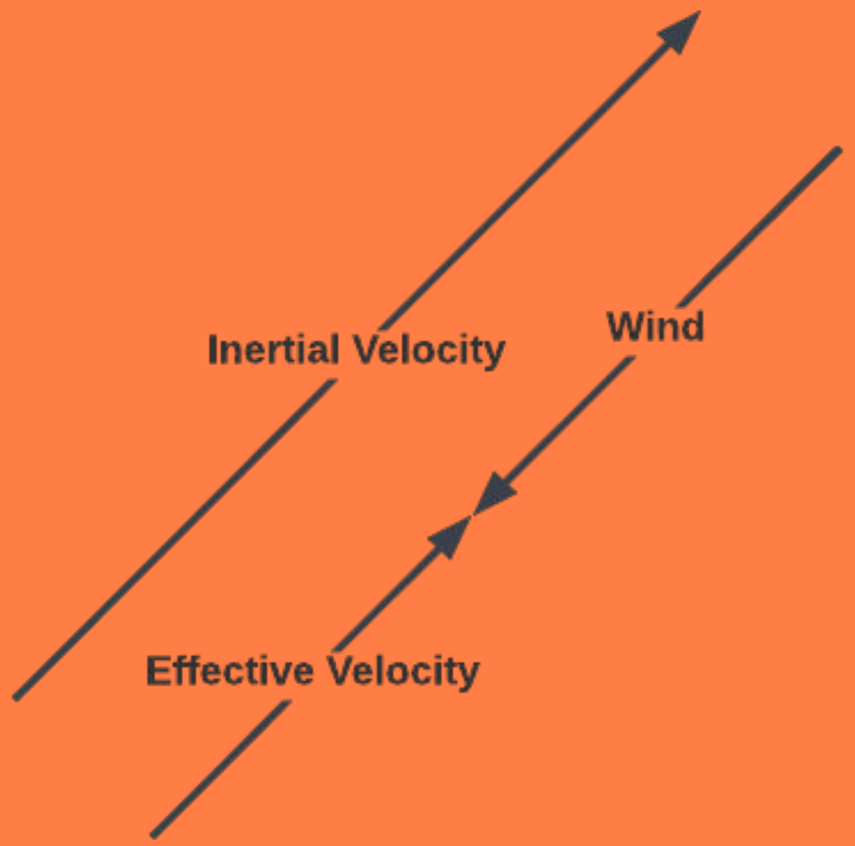
- **Datasheet data**
  - Current draw and thrust values for discrete throttle percentages
- **Least Squares Fitting**
  - Allows us to pull data point between given throttle percents
- **Tested Different Motors**
  - Final selection largely affected by availability

Motor	Energy Consumption (4/6/8 rotors) [Wh]	Cost (per motor)
MN4110 KV 340	379/279/242	$86.99
MN501-S KV 380	**356/291/272**	**$99.90**
MN505-S KV 360	358/306/295	$109.90



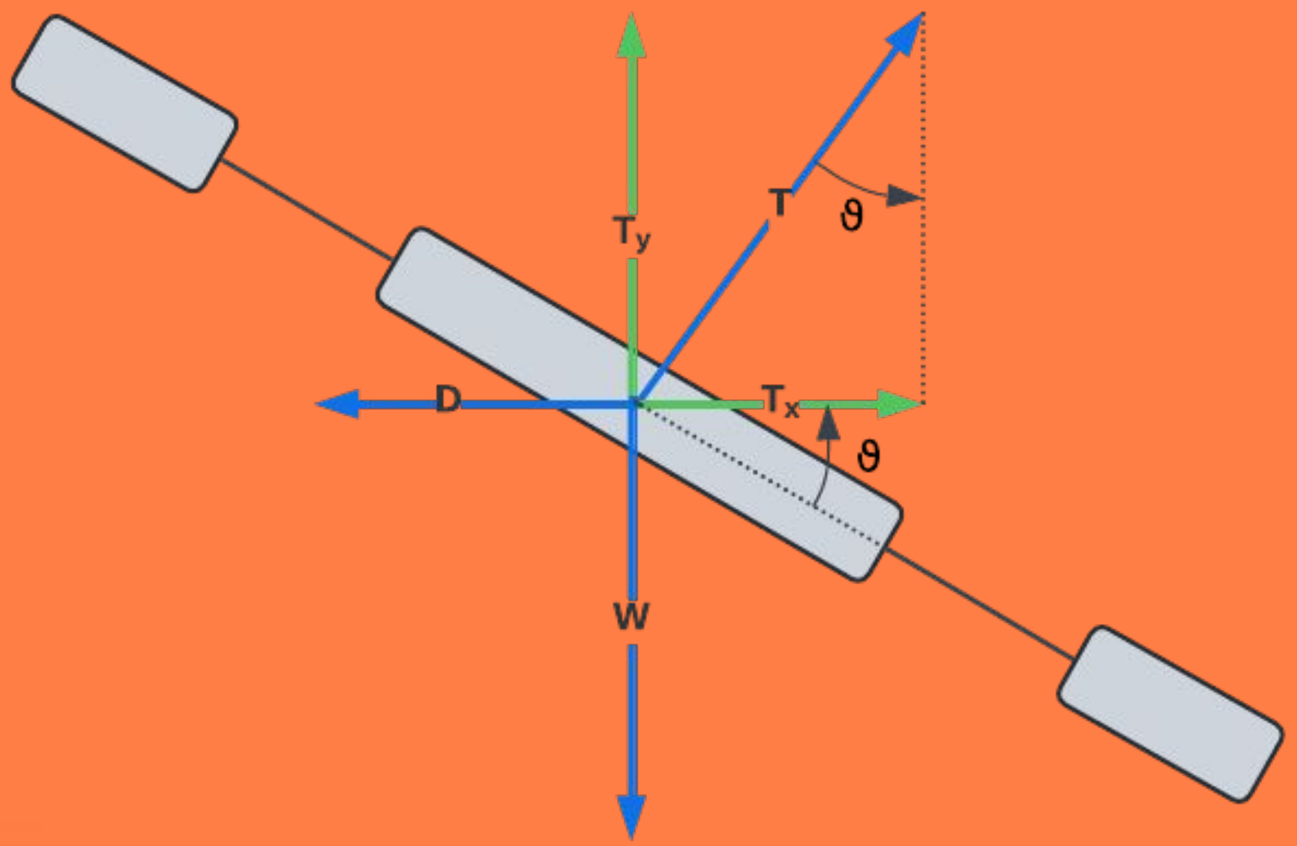
Modeling Wind

- **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:

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

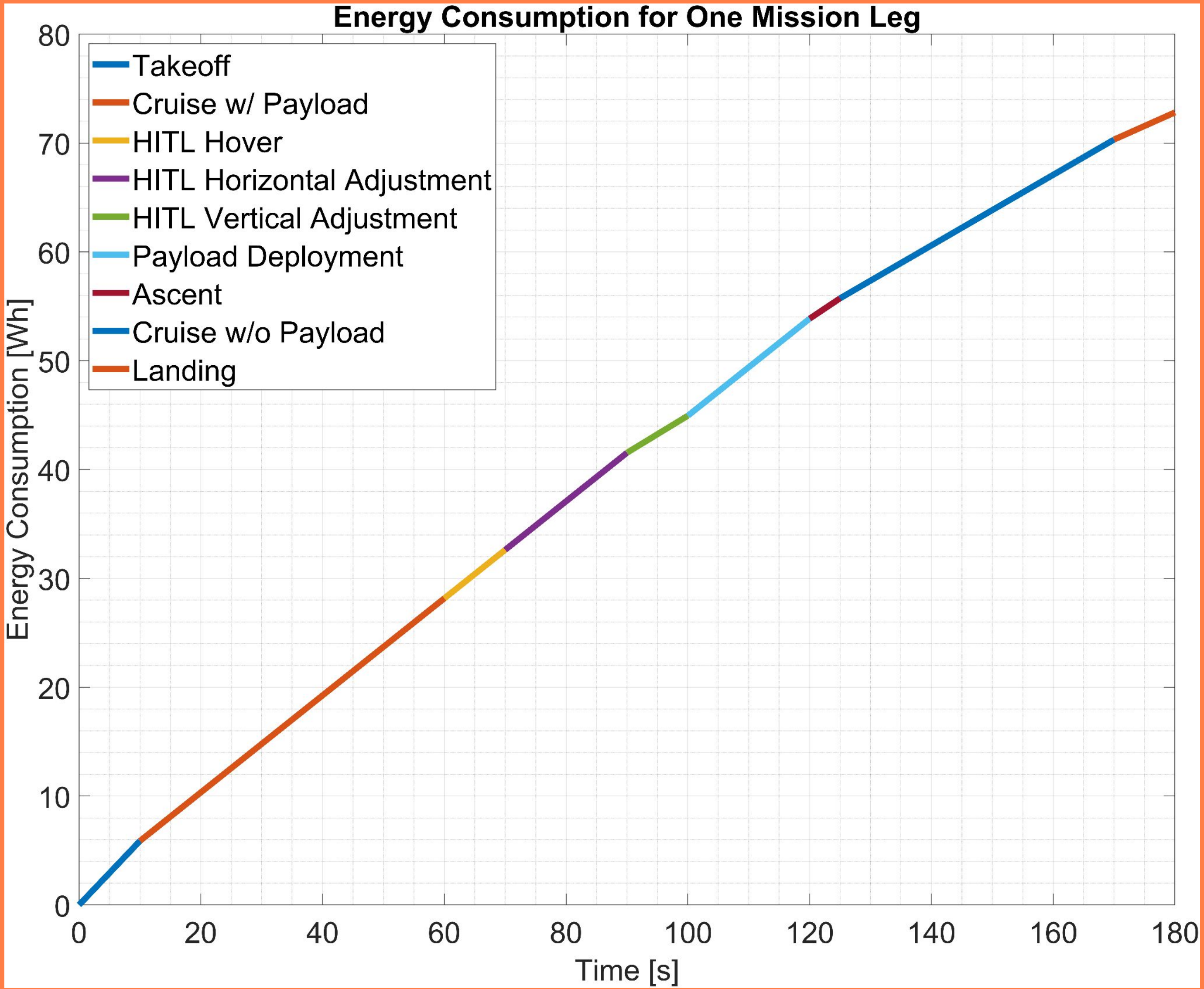
Velocity as a function of time for given tilt angle and T/W ratio:

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

Model Results: Mission Performance of Hexacopter

- **One mission leg results (100 m)**
  - 72.8 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 342.6 Wh
  - 16,000 mAh 6S LiPo = 355.2 Wh

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



Back to Key Requirements

- **Model Results**
  - 16,000 mAh battery can support entire mission with buffer
  - Within time limit
  - Motor/propeller pair selection can deliver sufficient thrust within range

Key Requirement Number	Key Requirement Description
FR 1.4	The UAS shall be capable of making three drops in a 20-minute span
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DR 3.2.1	The propulsion subsystem shall deliver thrust within an operational range of a 100-meter diameter

Spring Plans

Remaining Tests

Tests	Requirements Fulfilled
Rotor Thrust Evaluation	FR 1.1, 1.4, 1.5, 2.2,
Payload Deployment	FR 2.1, 3.5
GPS Accuracy	FR 3.1, DR 1.2
Battery Capacity/Flight Time	FR 1.1, 1.4
RC Control	FR 3.1, DR 1.5
Autonomous Flight	FR 1.2, 1.3, DR 1.2

Spring Schedule

TASK	ASSIGNED TO	PROGRESS	START	END
Component Procurement/Fabrication				
Airframe		0%	1/16/25	2/1/25
Battery		0%	1/16/25	2/1/25
Payload Container		0%	1/16/25	2/16/25
Rotors		0%	1/16/25	2/1/25
Propellers		0%	1/16/25	2/1/25
GPS Sensor		0%	1/23/25	2/20/25
Telemetry Receiver/Transmitter		0%	1/23/25	2/20/25
Visual Feedback Sensor		0%	1/23/25	2/20/25
Payload Deployment System		0%	1/23/25	2/20/25

TASK	ASSIGNED TO	PROGRESS	START	END
Testing				
Rotors		0%	1/23/25	2/26/25
Battery		0%	1/23/25	2/26/25
Remote Controller		0%	1/23/25	3/5/25
Autonomous Flight		0%	2/20/25	4/1/25
GPS		0%	1/30/25	3/5/25
Payload Deployment System		0%	2/20/25	4/1/25
Final System		0%	2/27/25	4/14/25
Integration				
Software Avionics		0%	2/1/25	3/14/25
Avionics Structure		0%	2/20/25	3/14/25
Final System		0%	3/14/25	4/14/25

Spring Schedule

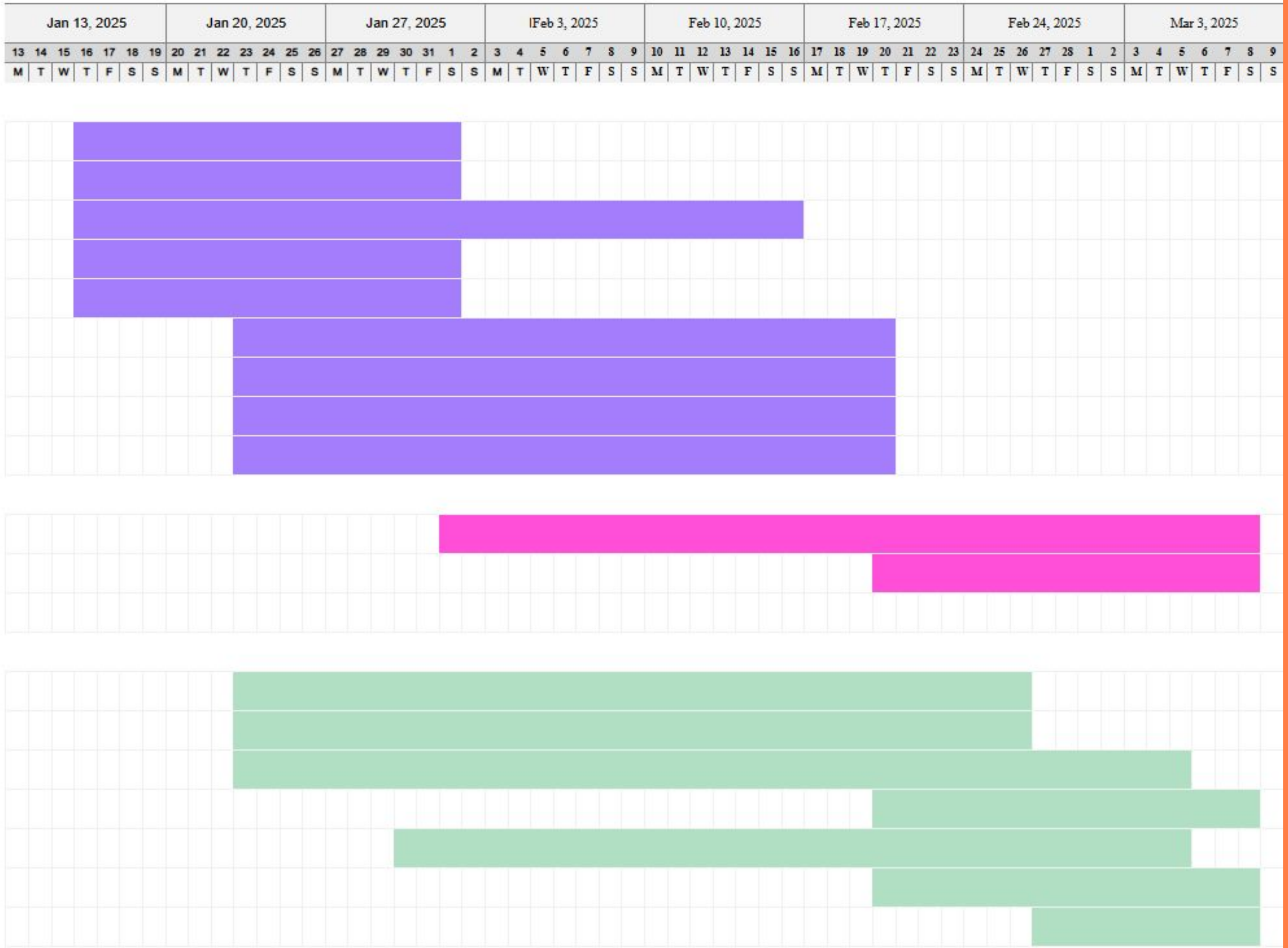
FLAME

Spring Semester Progress Tracking

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

1

TASK	ASSIGNED TO	PROGRESS	START	END
Component Procurement/Fabrication				
Airframe		0%	1/16/25	2/1/25
Battery		0%	1/16/25	2/1/25
Payload Container		0%	1/16/25	2/16/25
Rotors		0%	1/16/25	2/1/25
Propellors		0%	1/16/25	2/1/25
GPS Sensor		0%	1/23/25	2/20/25
Telemetry Reciever/Transmitter		0%	1/23/25	2/20/25
Visual Feedback Sensor		0%	1/23/25	2/20/25
Payload Deployment System		0%	1/23/25	2/20/25
Integration				
Software Avionics		0%	2/1/25	3/14/25
Avionics Structure		0%	2/20/25	3/14/25
Final System		0%	3/14/25	4/14/25
Testing				
Rotors		0%	1/23/25	2/26/25
Battery		0%	1/23/25	2/26/25
Remote Controller		0%	1/23/25	3/5/25
Autonomous Flight		0%	2/20/25	4/1/25
GPS		0%	1/30/25	3/5/25
Payload Deployment System		0%	2/20/25	4/1/25
Final System		0%	2/27/25	4/14/25



Critical Remaining Tests

Test	Description	Purpose	Test Location	Required Equipment
Rotor Thrust Evaluation	Measure specific thrust values of individual motor and propellor pairs	• Validate flight models and mission feasibility • Provide exact values for ArduPilot	Aero Building	Thrust test stand, calibration tools, RCBenchmark GUI
Payload Deployment	Drop payload from drone in flight onto targets	• Determine accuracy of deployment method • Validate complete payload deployment	Flight site	Target(s) and measurement equipment
GPS Accuracy	Compare GPS data with Google Earth coordinates	• Validate GPS accuracy	CU South	Ground Station

Risks Associated

- **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

Cost Plan

Phase	Duration	Expected Cost	Allocated Budget	Margin
Phase 1: Testing	11/24 - 12/24	$160.41	$500	67.9% Under Budget
Phase 2: Manufacturing	01/25 - 04/25	$2759.29	$3000	8.0% Under Budget
Phase 3: Expo	04/25 - 05/25	**TBD**	**TBD**	**TBD**
Other	-	**TBD**	$500	**TBD**
Total	-	$2919.70	$4000	27.0% Under Budget

- **Remaining Cost Uncertainties**
  - Phase 3
  - Manufacturing and testing
  - Target and other unestablished costs
  - Shipping Fees
- **Lead Time Uncertainties**
  - Phase 2
    - Lead times mainly fall within 3-10 days
  - Shipping

Questions?

References

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3. “Drkstore 5803 5.8g FPV monitor with DVR 40ch 4.3 inch LCD display 16:9 NTSC/PAL,” *The FPV Store you Deserve* Available: https://www.drkstore.in/drkstore-5803-5-8g-fpv-monitor-with-dvr-40ch-4-3-inch-lcd-display-169-ntsc-pal/.
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6. *1" Plastic Zero Differential Solenoid Valve* (no date) *Electricsolenoidvalves.com*. Available at https://www.electricsolenoidvalves.com/1-inch-plastic-zero-differential-solenoid-valve/?utm_source=bing&utm_medium=cpc&utm_campaign=Electric+Solenoid+Valves+Product+Listings&utm_term=4579603368674790&utm_content=Ad+group+%231 (Accessed: 13 October 2024).
7. “Mission planner home¶,” *Mission Planner Home - Mission Planner documentation* Available: https://ardupilot.org/planner/.
8. “Canada’s One stop FPV shop,” *EpicFPV* Available: https://epicfpv.ca/.

Backup Slides

Mass Budget Breakdown

Power		
Component	**Quantity**	**Mass [kg]**
16,000 mAh 6S LiPo Battery	1	1.988
Elo 50A OPTO ESC	6	0.288
PM03D Power Module	1	0.059
Communications		
Component	**Quantity**	**Mass [kg]**
AKK 5.8 G Transmitter	1	0.005
SiK Telemetry Radio V3	1	0.024
RC Receiver	1	0.005
Control		
Component	**Quantity**	**Mass [kg]**
Pixhawk 6X Flight Controller	1	TBD (measure actual one)

Mass Budget Breakdown

Propulsion		
Component	**Quantity**	**Mass [kg]**
MN501-S IP45 KV360 Motors	6	1.050
P18*6.1 Propellers	6	0.2

Payload Deployment		
Component	**Quantity**	**Mass [kg]**
Payload	1	2.4
Payload Container	1	.39
12V 1" Solenoid Valve	1	0.71
Wireless Remote Switch	1	0.23
PVC Pipe Adapter	1	0.04

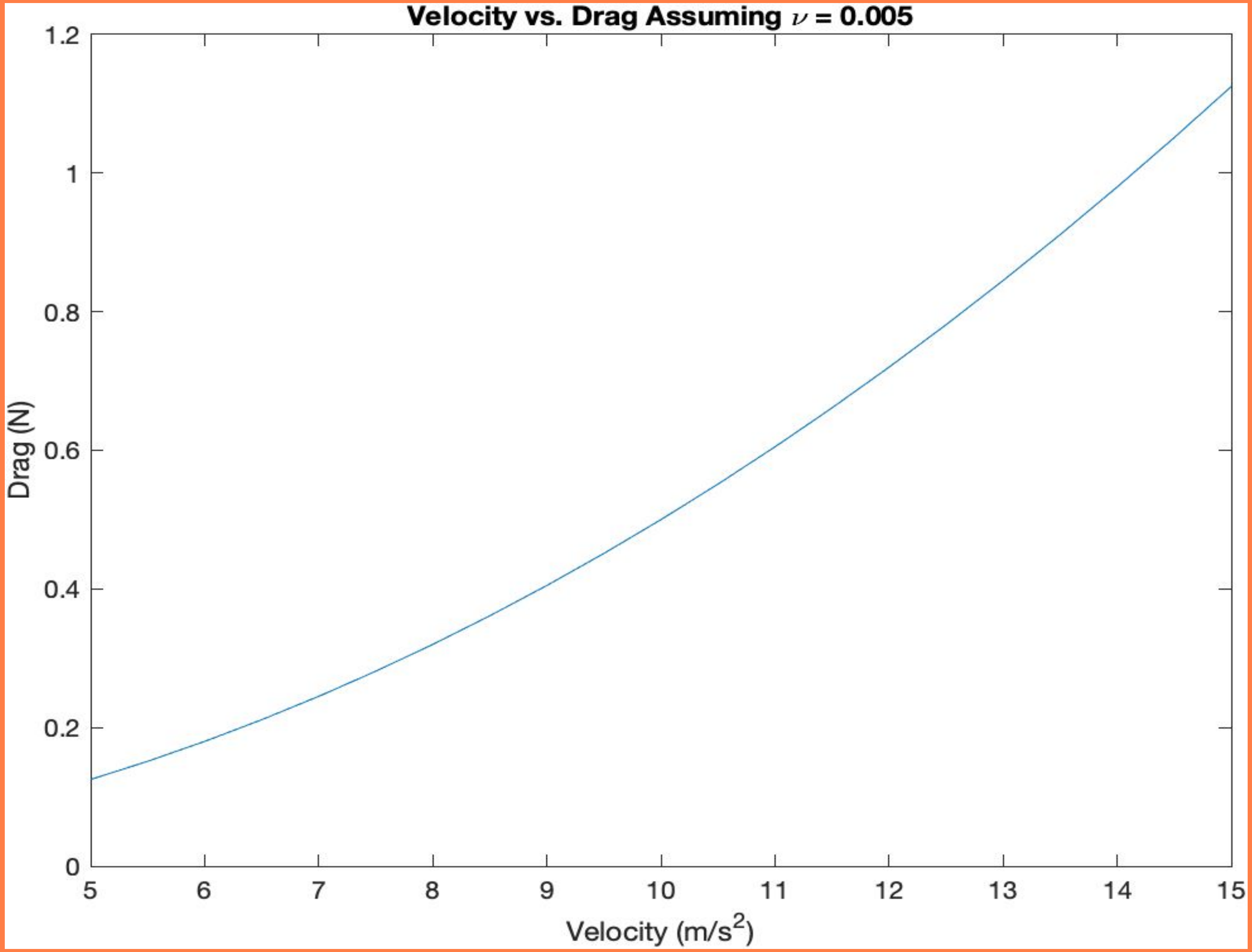
Airframe/Structure		
Component	**Quantity**	**Mass [kg]**
Tarot 960 X6 Airframe	1	1.8

Mass Budget Breakdown

Sensing		
Component	**Quantity**	**Mass [kg]**
AKK 5.8 G FPV Camera	1	0.005
M10 GPS	1	0.032

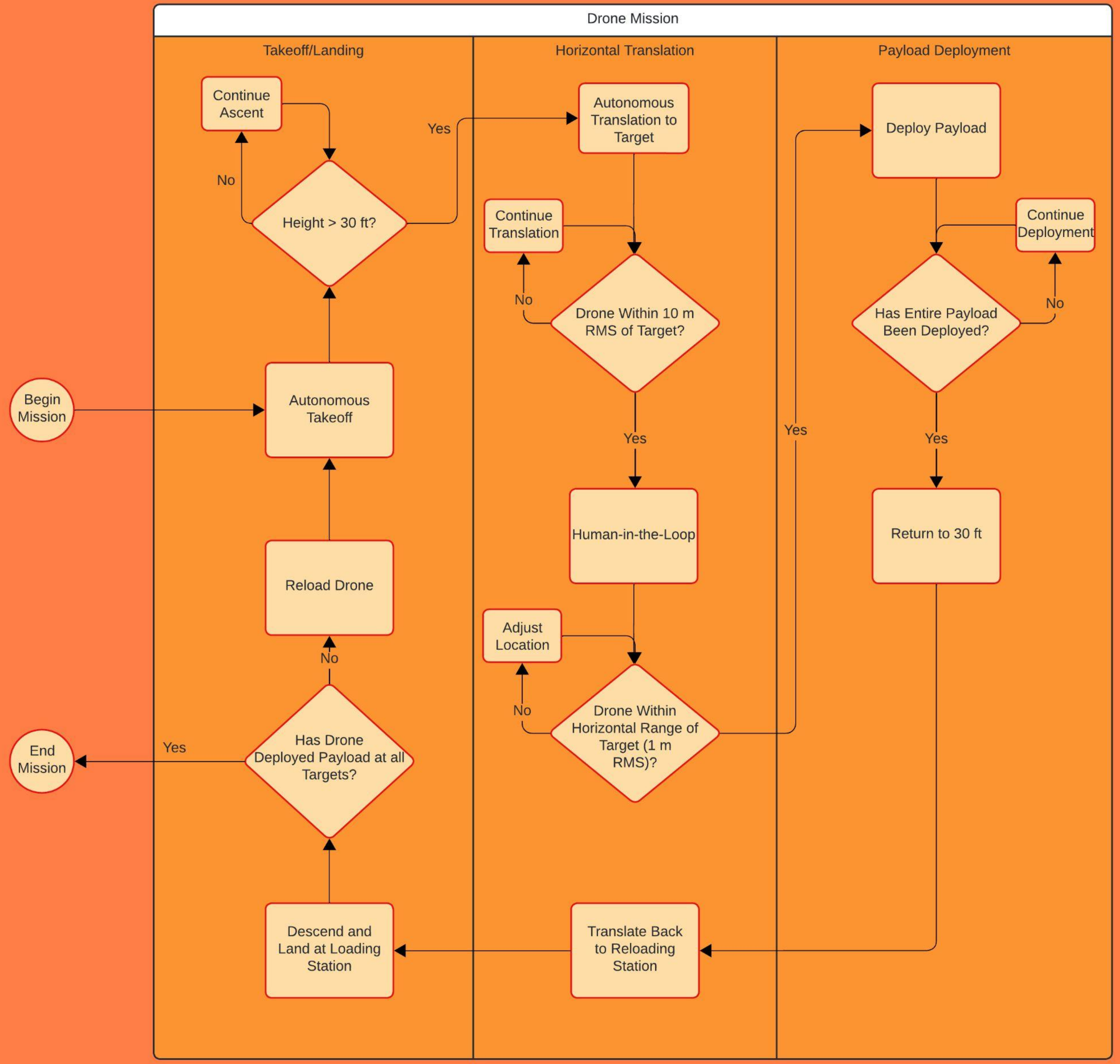
Velocity vs. Drag Graphs

- **Maximum Velocity**
  - Approximately 1 N of drag
    - 101 grams
- **Horizontal Thrust**
  - 10,000+ grams of thrust
    - 101 grams of drag is negligible

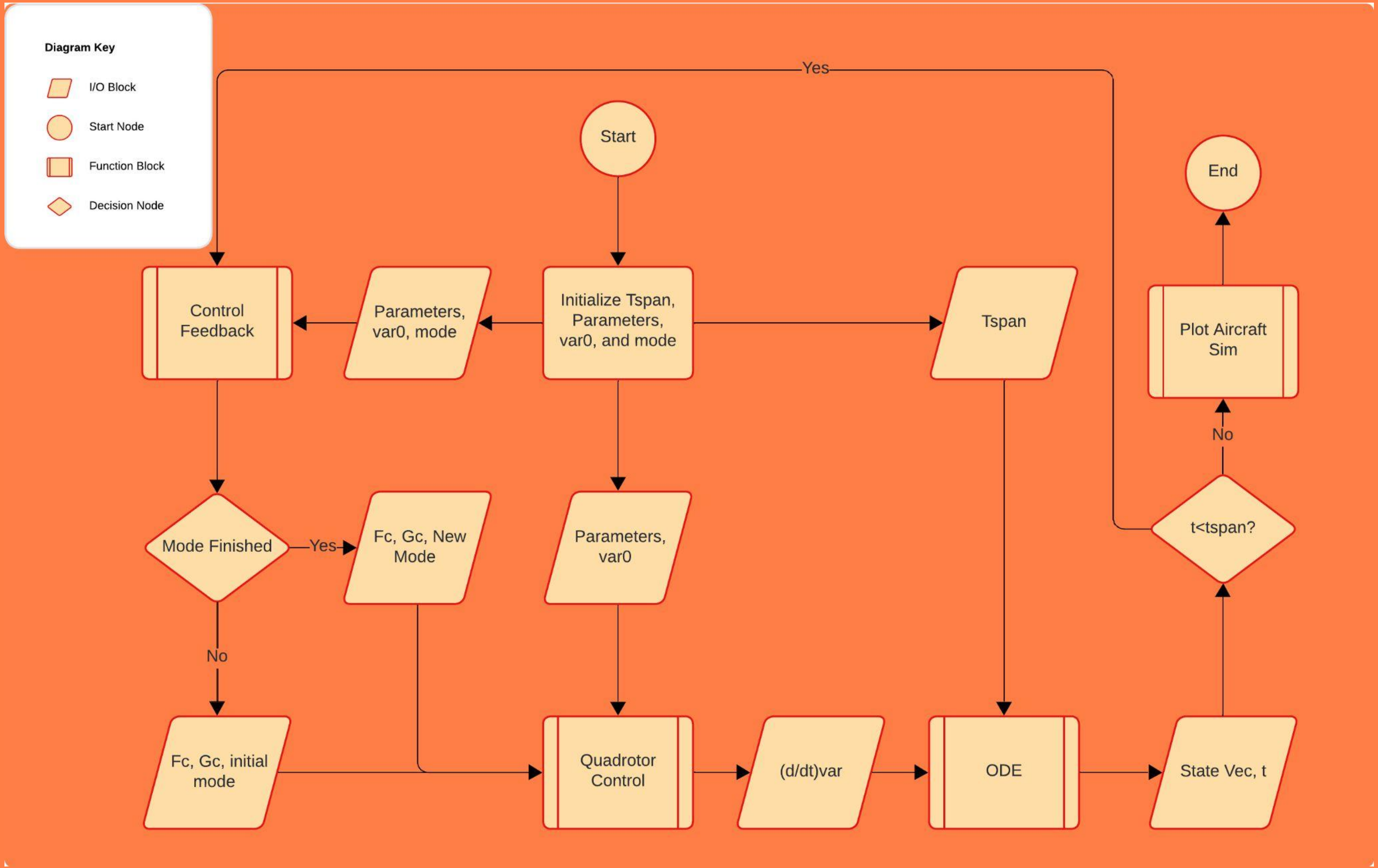


Control Subsystem: Software State Machine/Flowchart

- **State Machine/Flowchart**
  - Used to show the modes and flow of our mission
- **Control Software**
  - High level representation of our controls software: **ArduPilot**



Dynamics Model: Development Flow Chart



Dynamics Model: Governing Equations

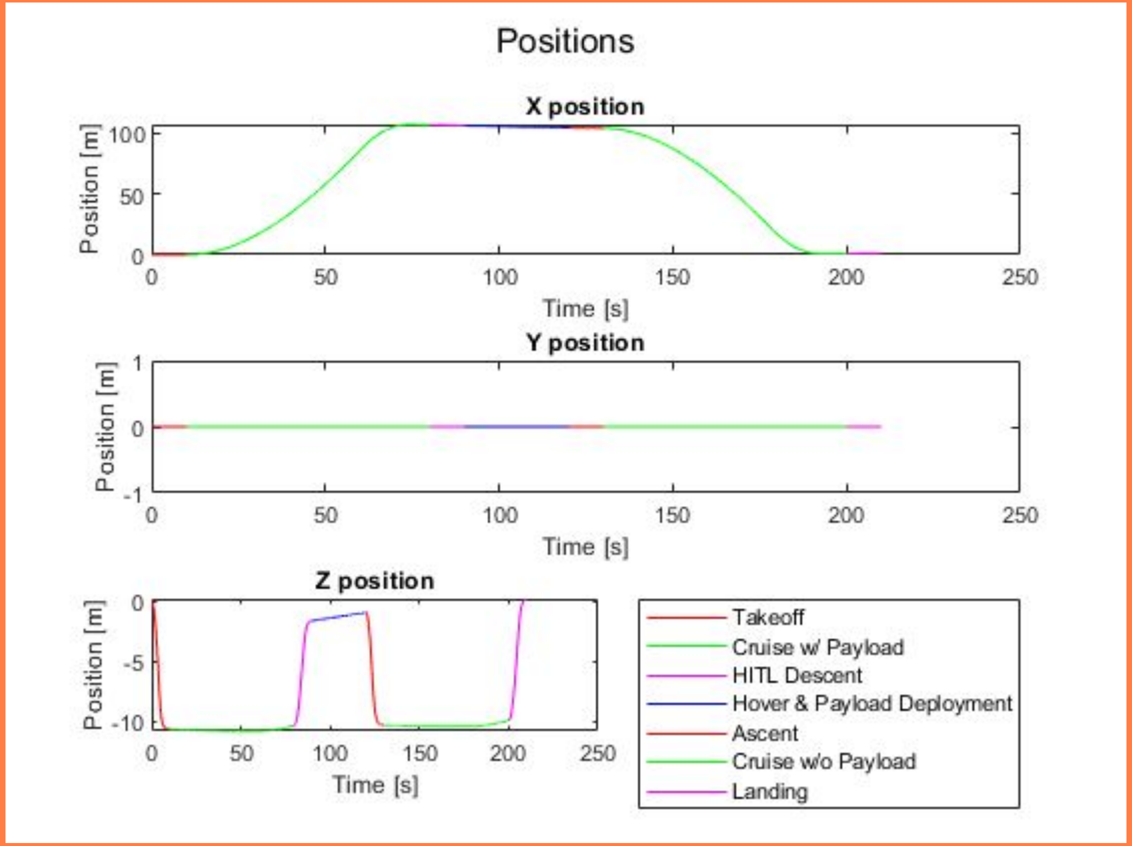
$$\begin{pmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi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

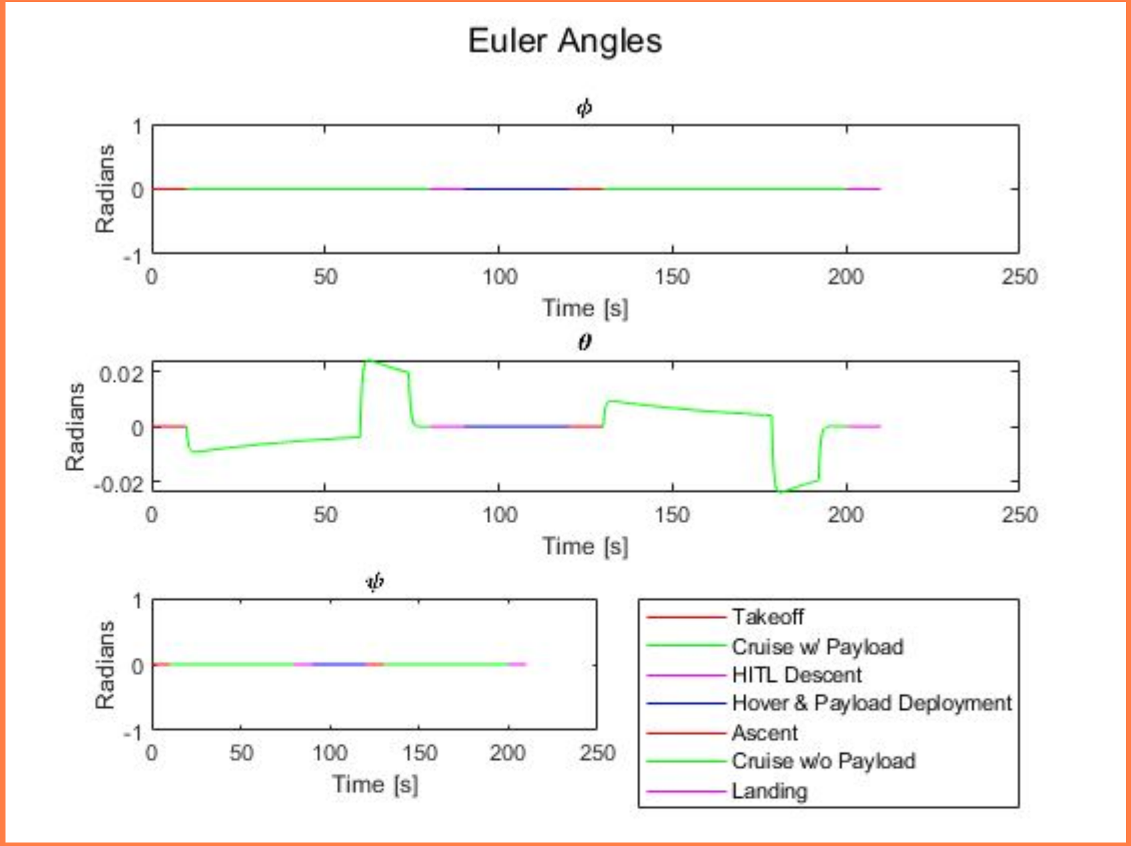
$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

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

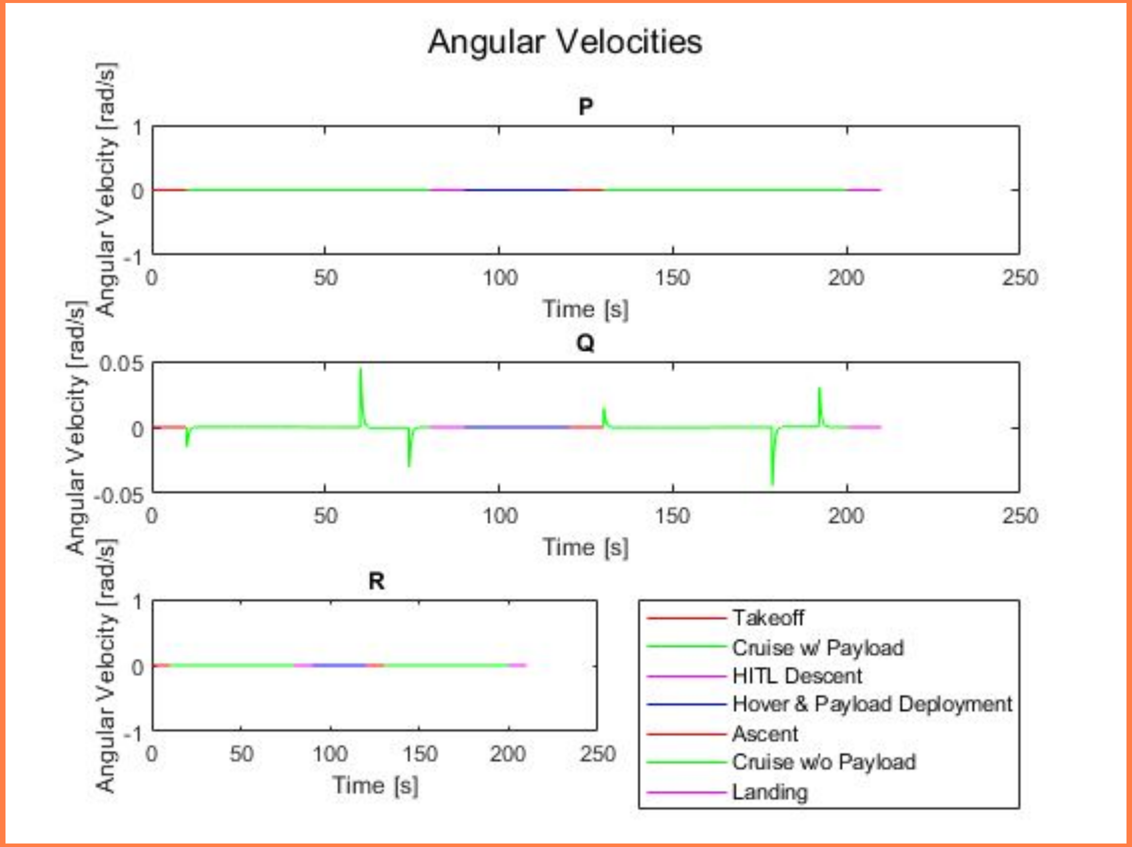
$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{I_y - I_z}{I_x} qr \\ \frac{I_z - I_x}{I_y} pr \\ \frac{I_x - I_y}{I_z} pq \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L \\ \frac{1}{I_y} M \\ \frac{1}{I_z} N \end{pmatrix} + \begin{pmatrix} \frac{1}{I_x} L_c \\ \frac{1}{I_y}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

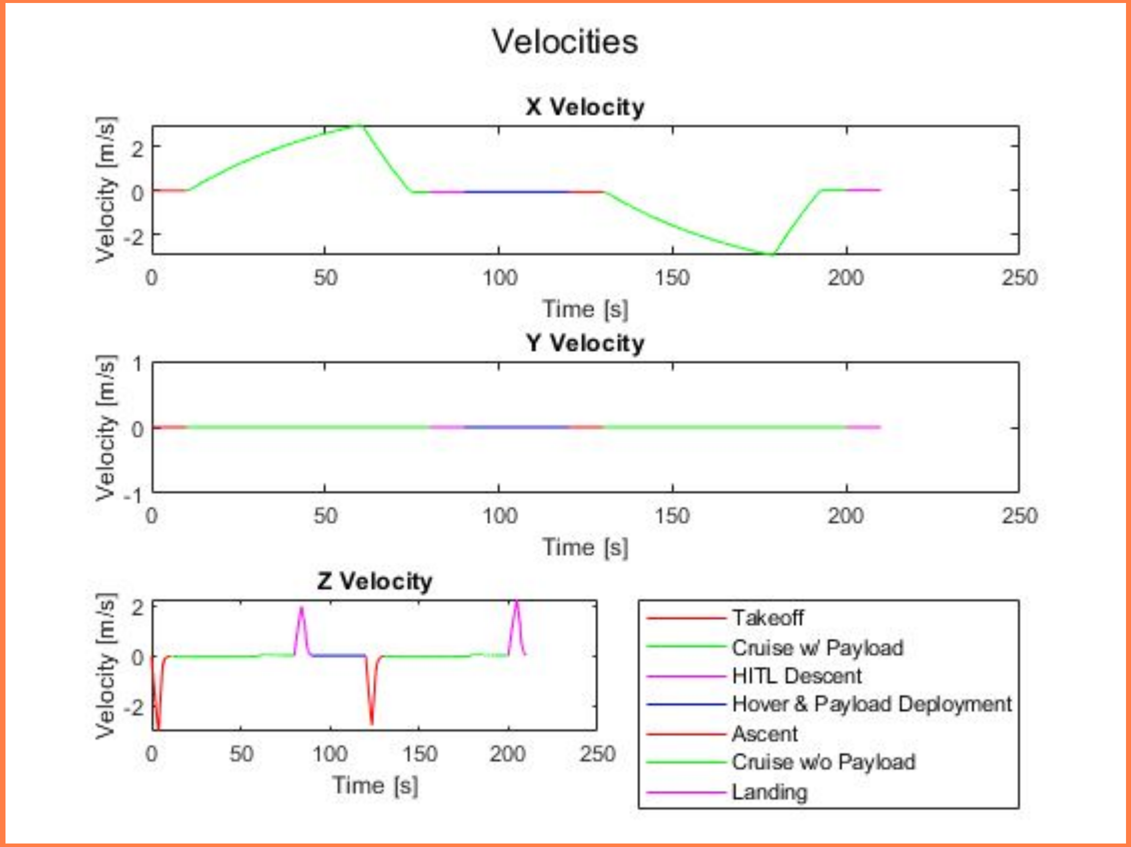
Dynamics Model: Plots



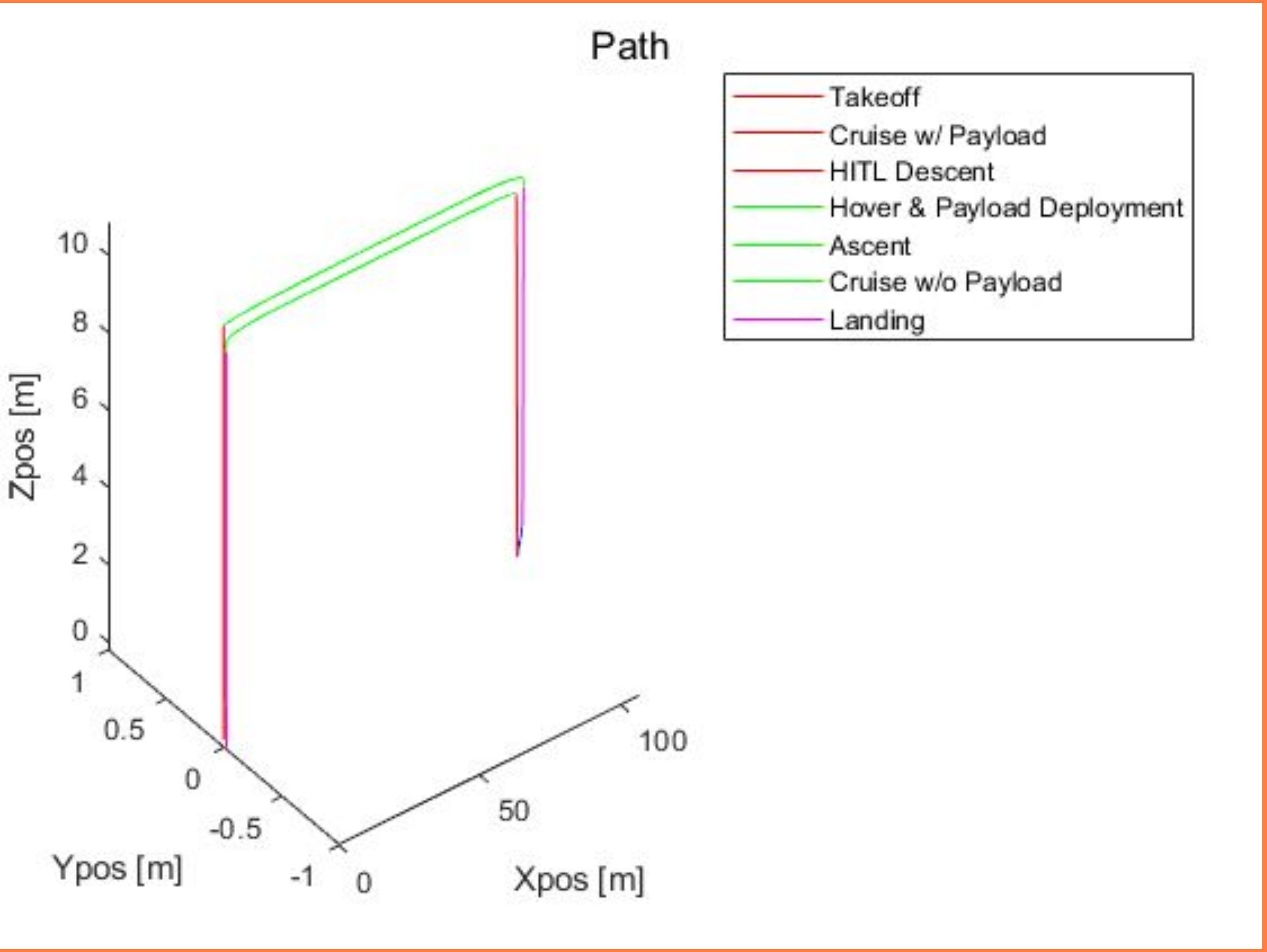


Dynamics Model: Plots (Continued)

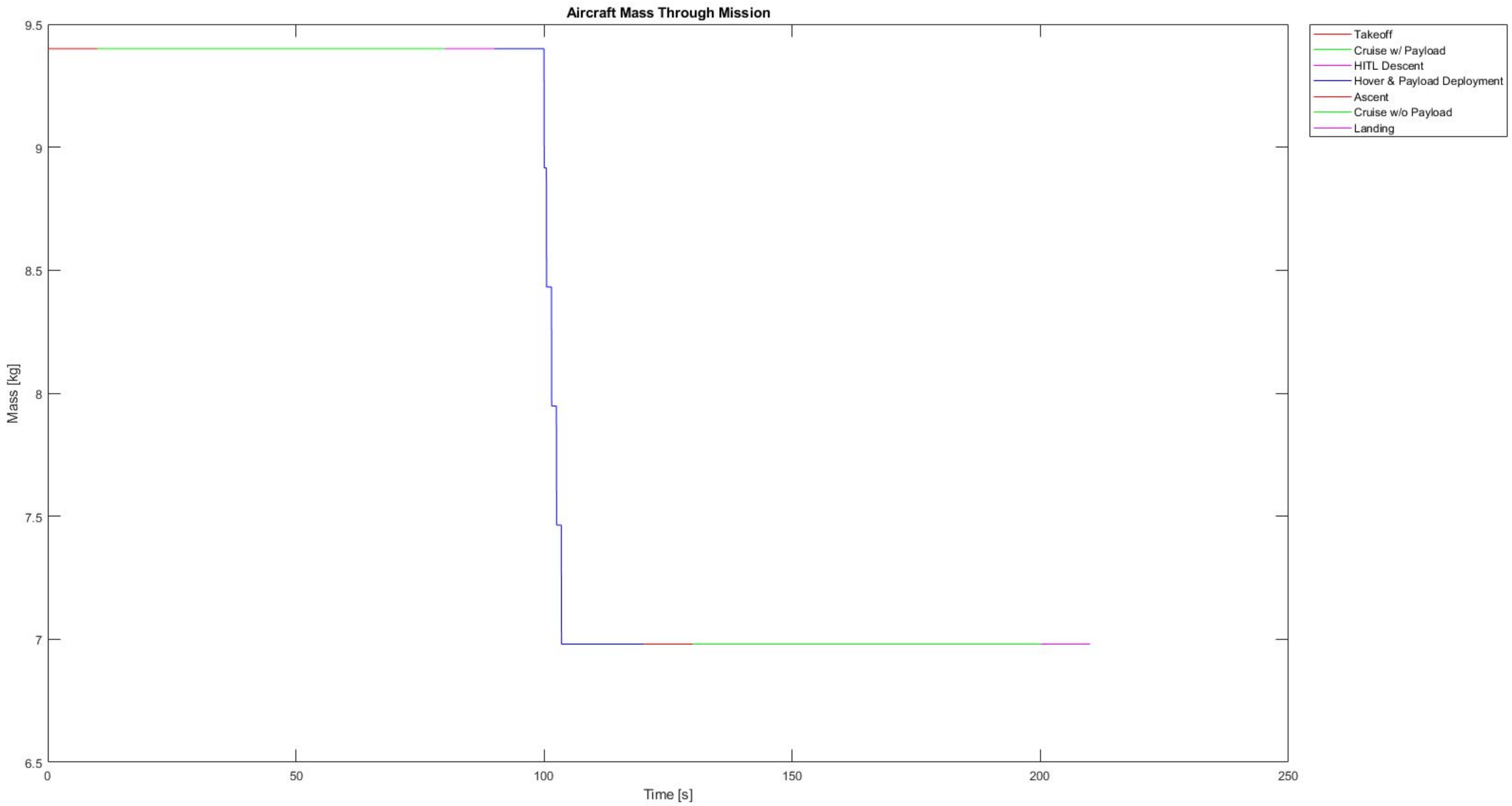




Dynamics Model: Plots (Continued)



Dynamics Model: Plots (Continued)



Historical Data

- **Tarot X6 Drone Kit**
  - Includes Power Kit
  - Lifts a total weight of 12kg
  - Uses Tarot 5008-340KV Brushless Motors
  - 1855 Carbon Fiber Propellers

Airframe Subsystem

Frame Selected: Tarot T960 Hexacopter

- Carbon fiber arms, legs, motor mounts
- Aluminum arm locking mechanisms
- Adjustable battery Mounting Plate
- Total Dimensions:
    - 22 x 10 x 4 in

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

Communications Subsystem: Components

BETAFPV SuperD ELRS

On-board

5VDC Input Voltage

20dBm Telemetry Power

2.4Ghz Frequency

1.1g weight

SIK Telemetry Radio

On-board

5VDC input voltage

100 mW max output power at 915 MHz

433-915 MHz frequency options

9.4 g weight

RadioMaster Ranger Micro ELRS

Ground system

6-16 VDC voltage range

2.4GHz Frequency

Up to 1W power output

1000 Hz packet rate

25 Hz refresh rate

Remote ID

On-board

5VDC input voltage

2.4GHz Frequency

5km range

27.5g weight

AKK KC04 FPV Transmitter

On-board

5 VDC input

6.5MHz audio frequency

0-8.0 MHz video bandwidth

3Km range

Propulsion Subsystem

Motor: T-Motor MN501-S IP

- Waterproof
- Dust resistant
- High temperature resistant

Propellor: QWinOut 1855

- Carbon Fiber

Speed Controller: Eolo 50A Light Version V2

- Low Noise
- Fast Response

Motor Max Thrust	Max Power	Idle Current/ Peak Current	Propellor Size and Pitch	Max Allowable Voltage	Max Allowable Continuous Current	Max Allowable Peak Current
5.2 kg	1000 W	1.4 A/40 A	18″ with 5.5″ pitch	26.1 V	50 A	60 A

Sensing Subsystem

Accelerometer: ICM-45686 Motion Sensor

- 3x included in Pixhawk 6x
- Accelerometer & Gyroscope
- 6 axis motion sensing

Barometer: ICP 20100 & BMP 388

- 2x included in Pixhawk 6x
- Low Power, high accuracy

Magnetometer: BMM150

- Absolute spatial orientation and motion vectors

Accel. Power Draw	Barometer Power Draws	Absolute Pressure Accuracy	Relative Pressure Accuracy	Pressure Range	Magno. Power Draw	Magno. Resolution
640 µA	1 & 3.4 µA	±0.05 kPa	±0.008 kPa	30-110 kPa	500 µA	0.3µT

Sensing Subsystem

FPV Camera

1280X720 Resolution

1 V peak to peak/75 Ohms

HolyBro M10 GPS

5VDC Input Voltage

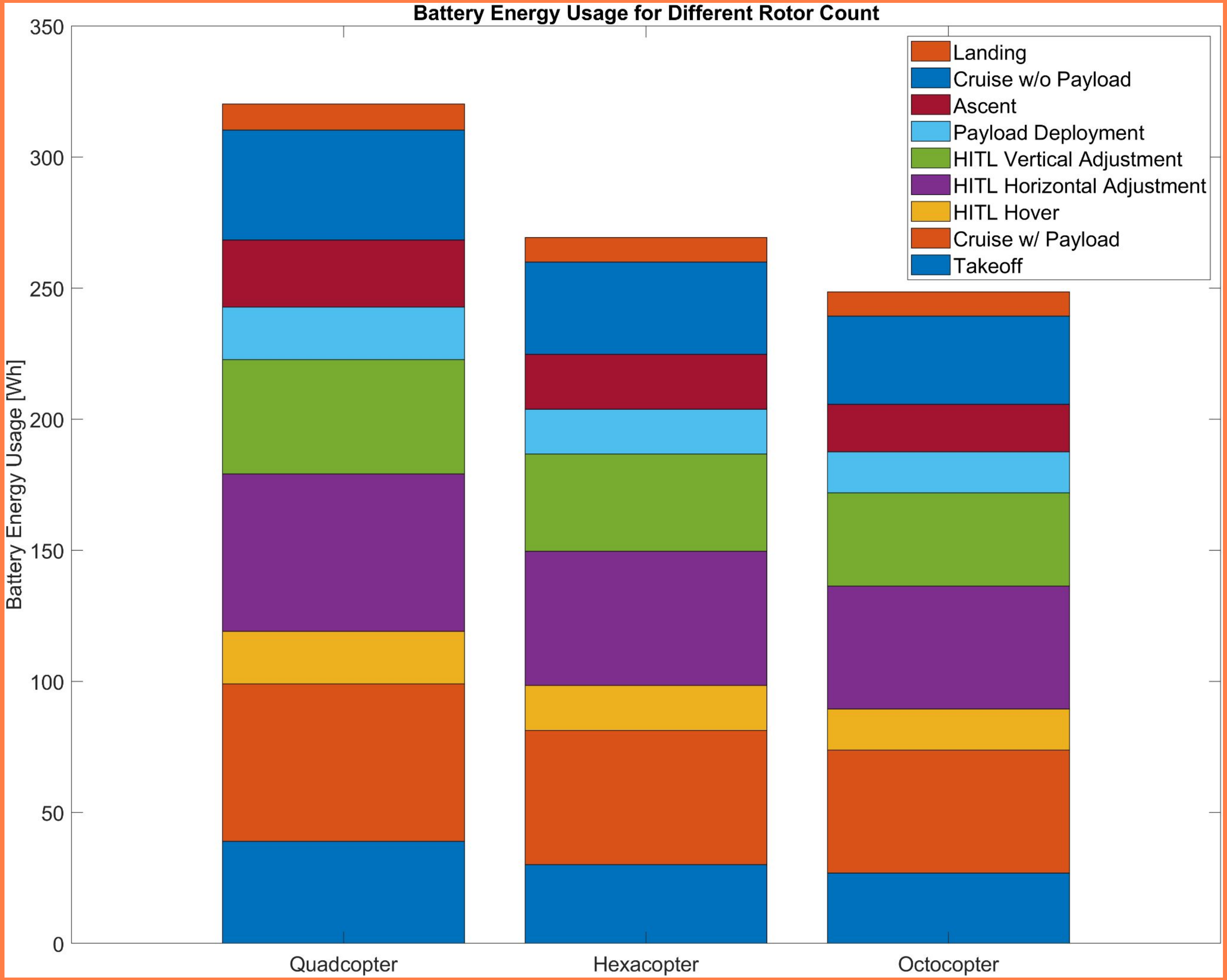
25-10Hz update rate

2m accuracy

32g weight

Model Results: Rotor Count Energy Use

- **Rotor count trade study metric**
  - Energy consumption over mission
- **Trends**
  - More rotors = more energy efficient
  - Less current draw per motor for same total vehicle thrust
    - Current draw has quadratic growth
  - Diminishing returns as rotor count increased

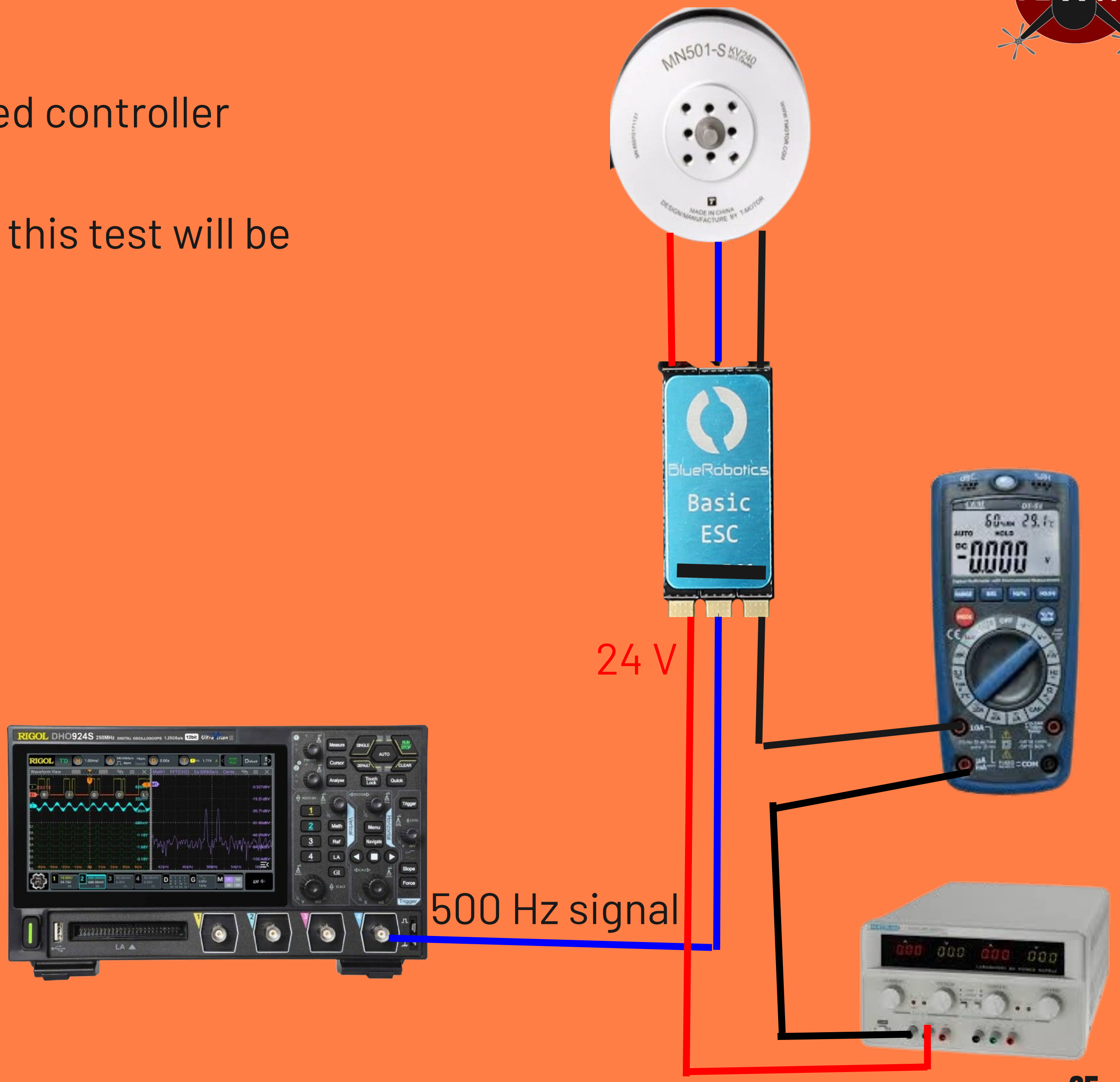


Motor Current Draw Validity

- Simulate throttle with a single motor and speed controller

- Due to time frame and equipment limitations, this test will be conducted in the spring

- **Equipment that will be used**
  - MN501-S IP45 T-Motor
  - Eolo 50A Light Version V2 ESC 4-6S ESC
  - Oscilloscope
  - Multi-meter
- **Inputs**
  - 24V
  - 500 Hz
  - Vary signal duty cycle
  - Vary input current
- **Output**
  - Current Draw



Motor Current Draw Validity

Datasheet for MN501-S IP45 T-Motor

Throttle %	Current (A)
40%	3.93
50%	7.09
60%	11.26
70%	16.46
75%	19.34
80%	22.39
90%	29.83
100%	38.43

Test results for MN501-S IP45 T-Motor

Throttle %	Current (A)
40%	TBD
50%	TBD
60%	TBD
70%	TBD
75%	TBD
80%	TBD
90%	TBD
100%	TBD

User Defined ArduPilot Parameters

- FRAME_TYPE
  - Select vehicle configuration/rotor count
- ANGLE_MAX
  - Select maximum tilt angle
- WP_NAV_SPEED
  - Select maximum horizontal velocity
- WP_NAV_SPEED_UP
  - Select maximum takeoff velocity
- WP_NAV_SPEED_DOWN
  - Select maximum landing velocity
- WP_NAV_RADIUS
  - Select acceptable radius from waypoint to be considered complete
- WP_NAV_ACCEL
  - Select maximum horizontal acceleration
- WP_NAV_ACCEL_Z
  - Select maximum vertical acceleration

Budget Tracker: Phase 1

Component	Quantity	Total Price
T-Motor MN501-S	1	$94.46*
Eolo 50A Light Version V2 ESC 4-6S	1	$40.96*
Polymaker PLA PRO Filament 1.75mm Color Black	1	$24.99*

Note - These items have already been received with shipping factored into the total price

Budget Tracker: Phase 2

Component	Quantity	Total Price
4.3" DVR 5.8GHz 40CH FPV Monitor	1	$59.99
RadioMaster Ranger Micro 2.4Ghz ELRS Module	1	$39.99
BETAFPV SuperD ELRS 2.4GHz Diversity Receiver	1	$24.99
AKK KC04 5.8G 600mW FPV Transmitter 700TVL 2.8mm 120 Degree FPV Camera for Racing Quadcopter	1	$32.99
SiK Telemetry Radio V3	1	$58.99
Tarot X6 Drone Kit	1	$499.99

Budget Tracker: Phase 2

Component	Quantity	Total Price
PM03D Power Module	1	$45.99
Eolo 50A Light Version V2 ESC 4-6S	5	$184.92
T-Motor MN501-S	5	$454.10
WOODGUILIN Remote Switch	1	$36.99
Pixhawk 6X	1	$144.00
TX16s mk2	1	$210.00

Budget Tracker: Phase 2

Component	Quantity	Total Price
M10 GPS	1	$43.99
Remote ID	1	$29.59
Tattu 16000mAh 22.2V 6S 30C Lipo Battery Pack w/ XT90-S Plug	2	$671.98
1" Plastic Zero Differential Solenoid Valve	1	$72.60
1" PVC Pipe Fitting Adapter	1	$20.98
QWinOut 1855 propellers	1	$56.68

Budget Tracker: Phase 2

Component	Quantity	Total Price
Flex Tape	1	$20.00
Pipe Cement	1	$4.00
XT90 to XT60 plugs	2	$9.96
Yeah Racing RC XT60 1-6S Smoke Stopper	1	$6.99
Pixhawk 6X Cable Set	1	$22.59
Zeee Fireproof Explosionproof Large Capacity Battery Storage Guard Pouch for Lipo Charge & Storage	1	$11.99