Ann and H.J. Smead
Aerospace Engineering Sciences
UNIVERSITY OF COLORADO **BOULDER**

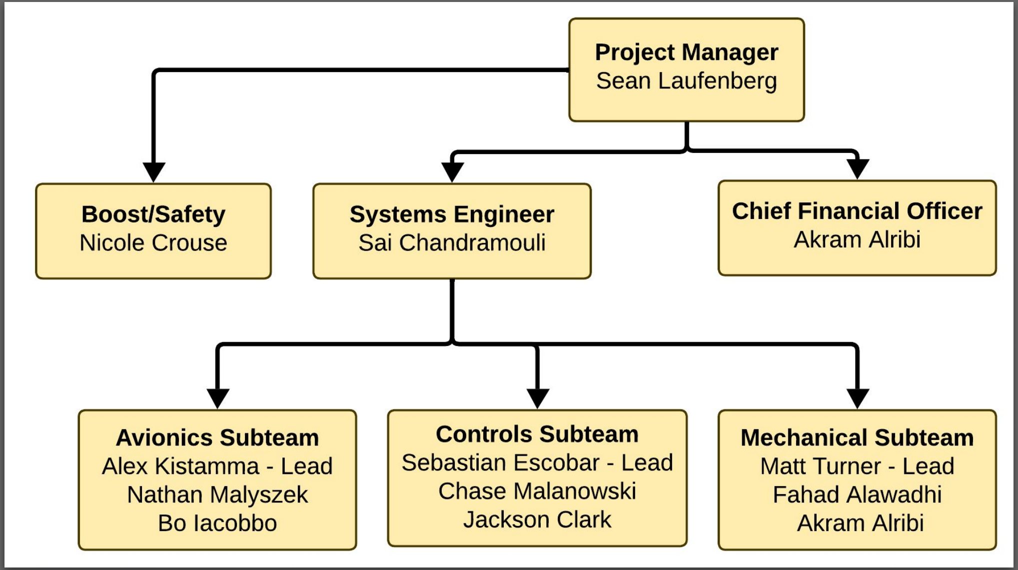
Humanitarian Aid Winged Kit

Concept Design Review: 12/11/24

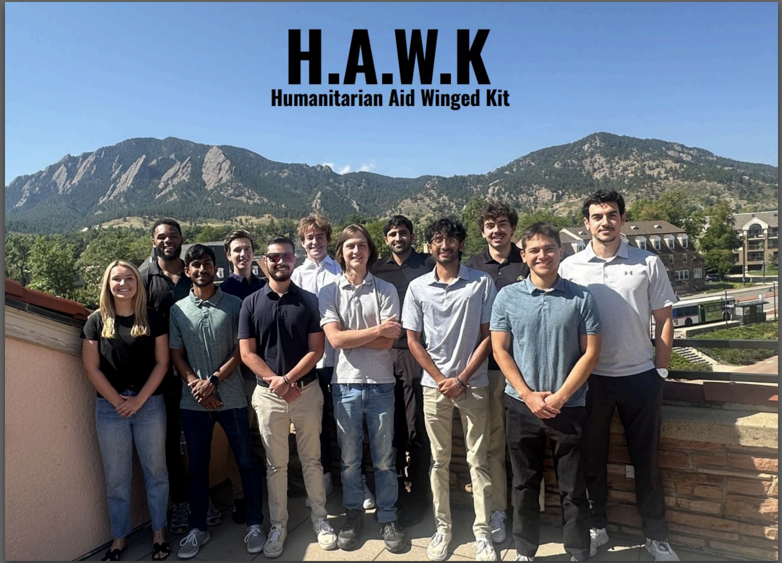
Team Members: Akram Alribi, Sai Chandramouli, Nicole Crouse, Sebastian Escobar, Sean Laufenberg, Alex Kistamma, Matt Turner, Fahad Alawadhi, Bo Iacobbo, Nathan Malyszek, Jackson Clark, Chase Malanowski

H.A.W.K.

Meet The Team



Team Structure



Team Photo

Project Description

Mission Motivation

- Delivering aid to people in need is **time consuming** and **logistically challenging**
- **Terrain can hinde**r delivery efforts

Stuck hiker needs help on a mountain

Mission Statement

"Accurately deliver an **emergency rescue kit** via **rocket-glider** to a **stranded individual** in a remote, hard-to-reach location. Dedicated to providing survival items in a time sensitive situation."

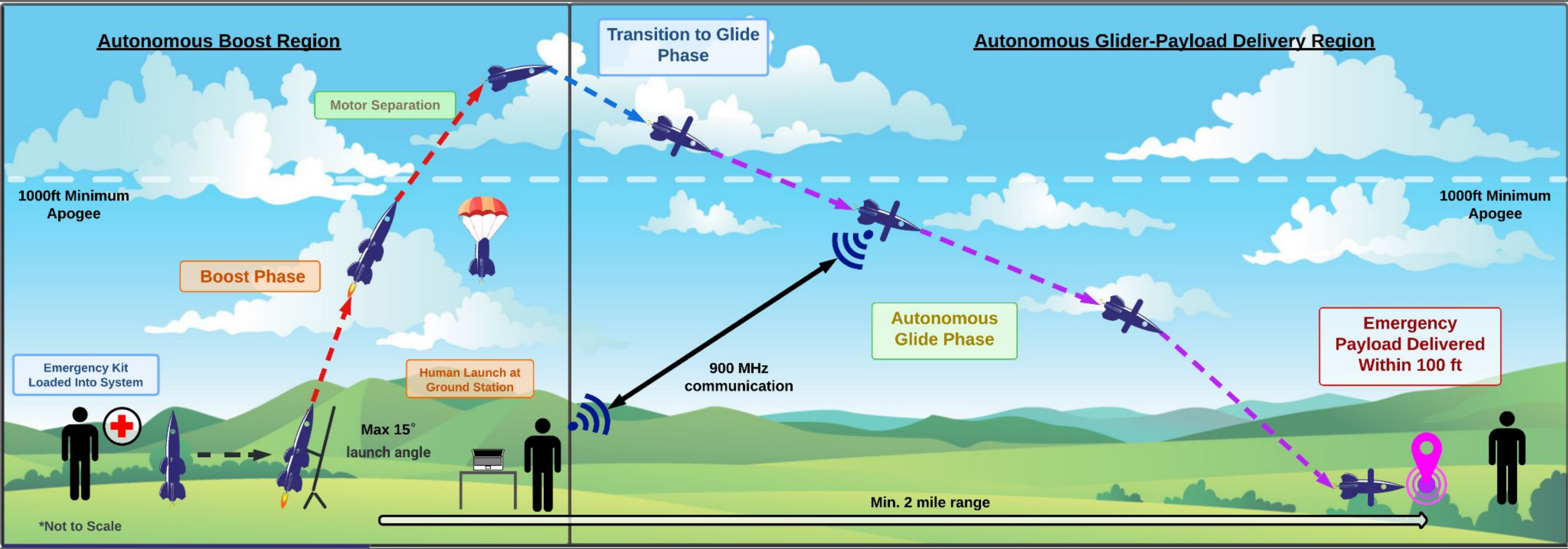
Mission Statement

Emergency Survival Kit Payload

Rocket that can hold emergency payload

[Item and weight breakdown]

Concept of Operations

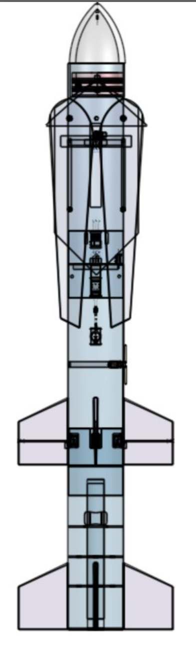


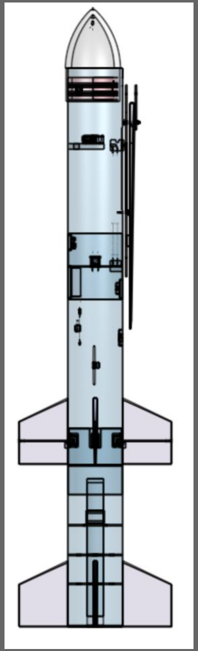
Key Driving Requirements

Req. ID	Requirement	Parent	Child	Verification
☆ **FR 3.0**	**The system must deliver the payload via glider post rocket motor powered boost phase**	-	DR 3.1-3.4	D
☆ **FR 4.0**	**The system must glide & land to a predetermined location within 100 ft accuracy of target**	-	DR 4.1- 4.2	D
DR 3.1	**The system must utilize an impulse class J, K, or L rocket motor**	FR 3.0	DR 3.1.1	I
DR 3.2	**The system structure and components necessary for glider payload delivery must remain intact post boost phase**	FR 3.0	DR 3.2.1-3.2.3	T/A
DR 4.2	**The rocket-glider system shall be able to reach the target destination from a minimum of 2 miles away**	FR 4.0	DR 4.2.1	T/A
DR 3.4.1	**The glider controls system shall land the body in an orientation such that the payload remains undamaged and intact**	DR 3.4	-	D

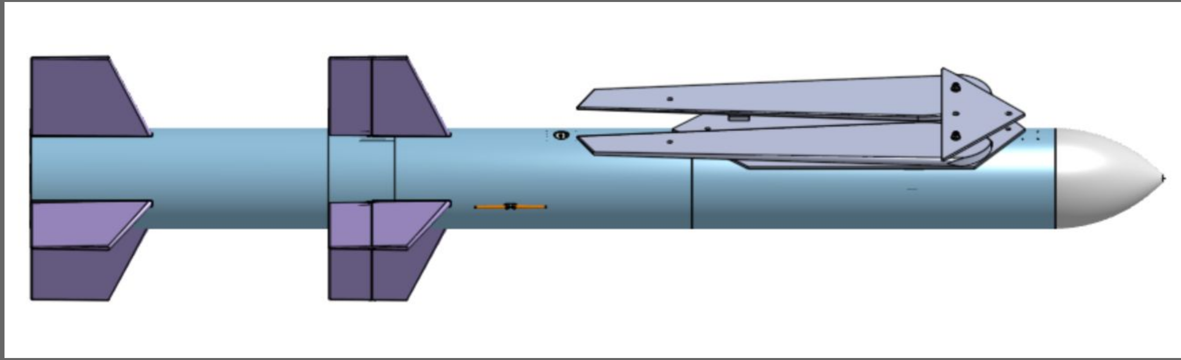
Design Solutions

Design Overview: Boost Phase





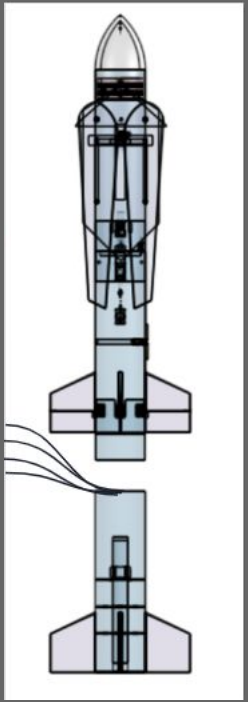
WEIGHT: 41 lbs
HEIGHT: 106 in. (8 ft. 10 in.)
FUSELAGE DIAMETER: 10 in.



Boost Flight Specs

Stability proof

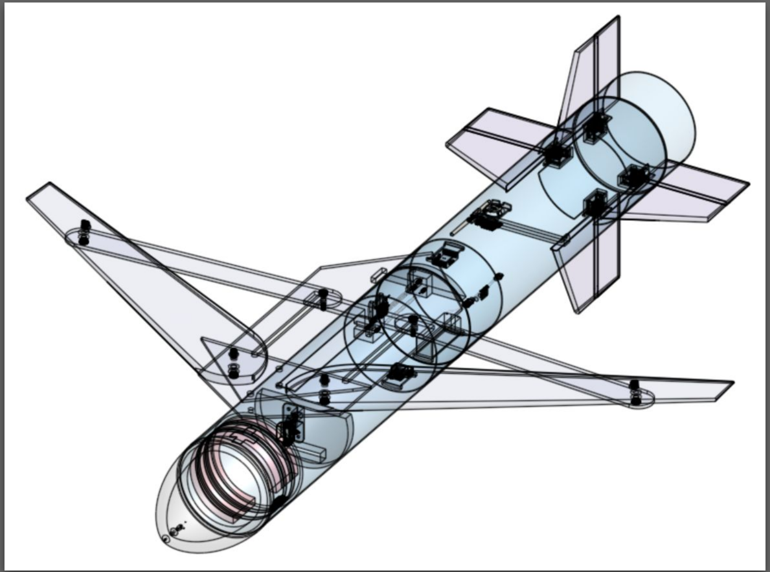
Design Overview: Transition Phase

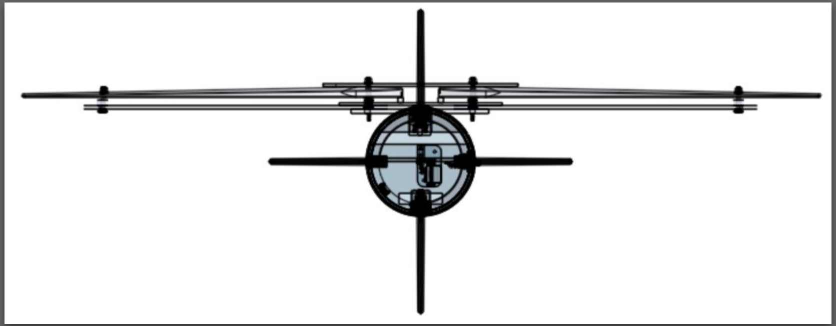


WINGSPAN: 72 in.
WEIGHT: 29.9 lbs
HEIGHT: 88 in. (7 ft. 4 in.)

Separation Calculations

Design Overview: Glide Phase

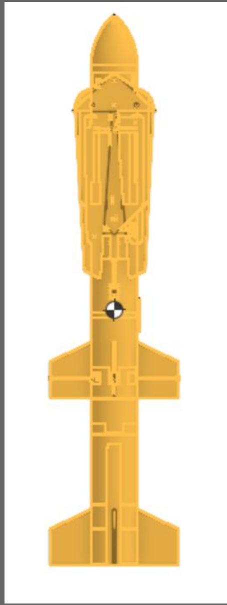


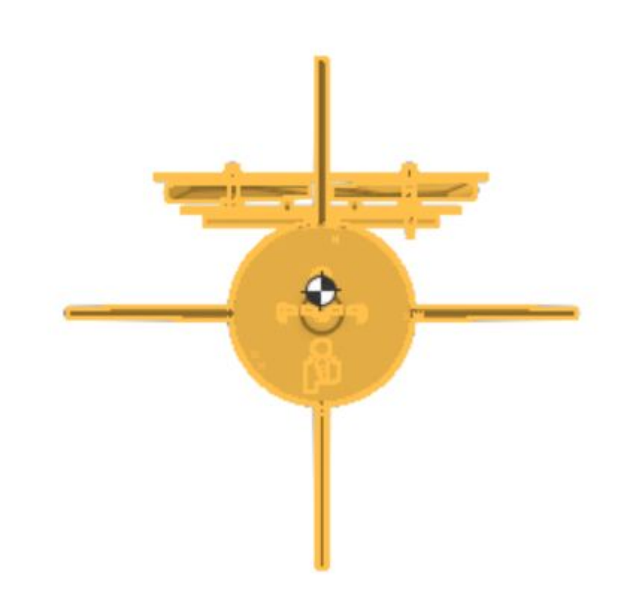


WINGSPAN: 72 in. (6 ft.)
WEIGHT: 29.9 lbs
HEIGHT: 88 in. (7 ft. 4 in.)

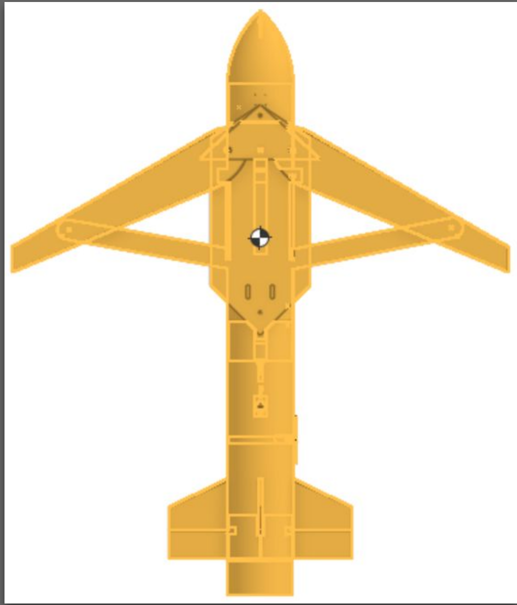
Design Overview: Centers of Gravity

BOOST



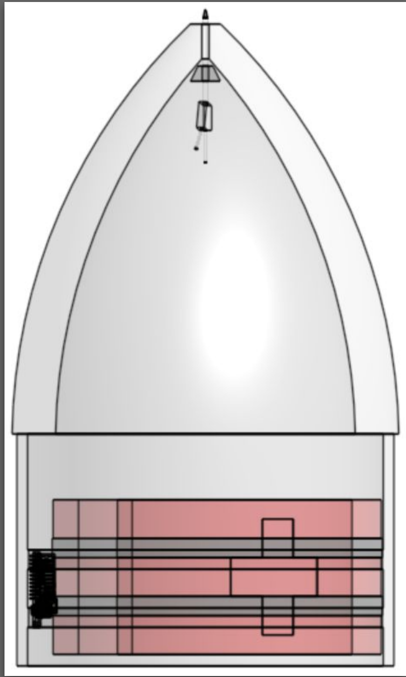


GLIDE

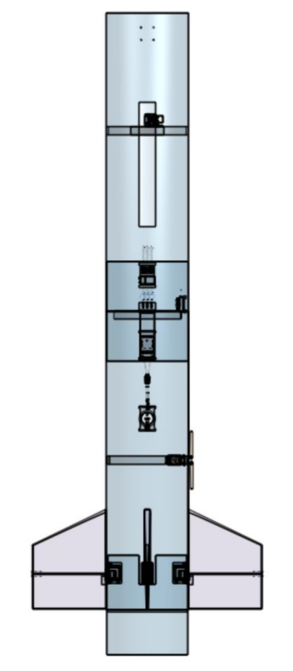


Design Overview: System

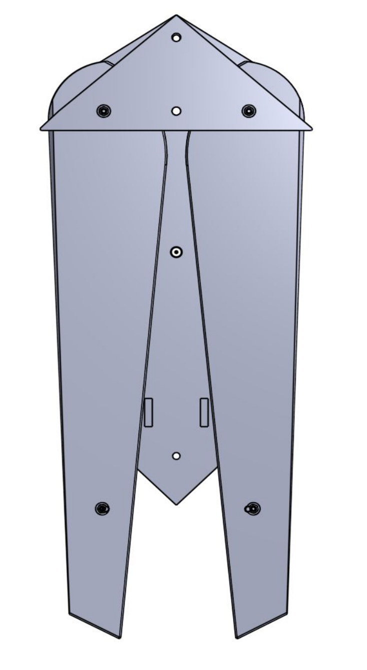
NOSE CONE



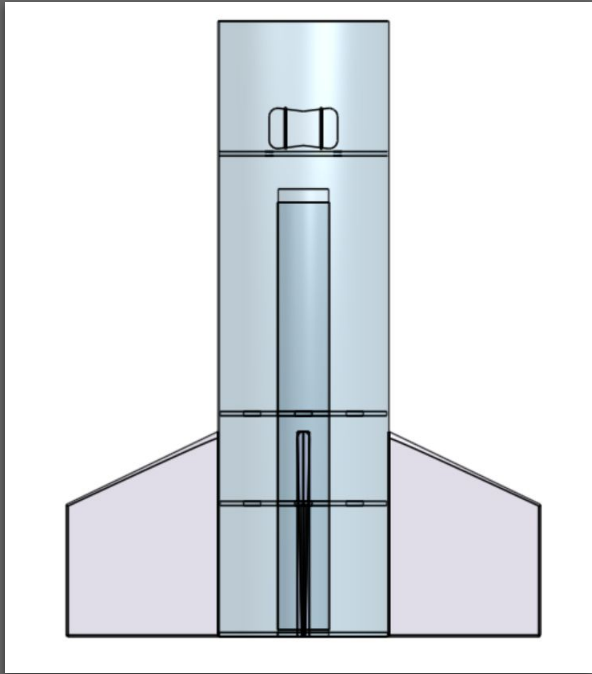
FUSELAGE



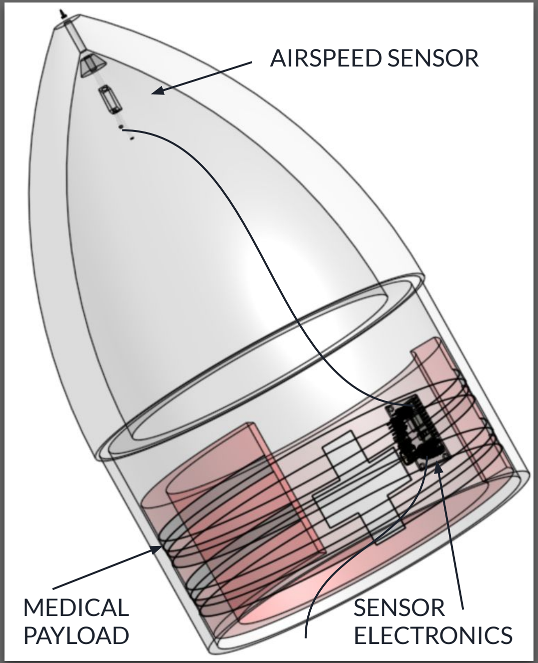
WINGS/DEPLOYMENT MECHANISM

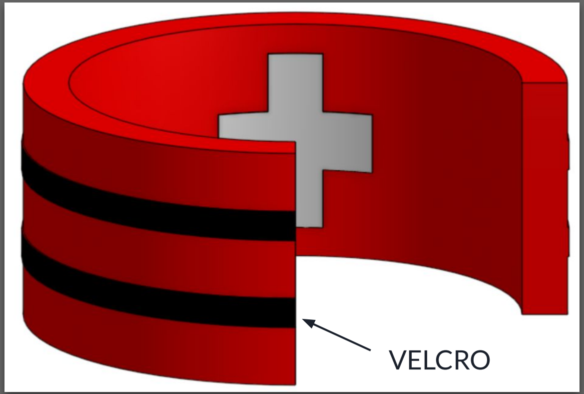


EJECTING AFT

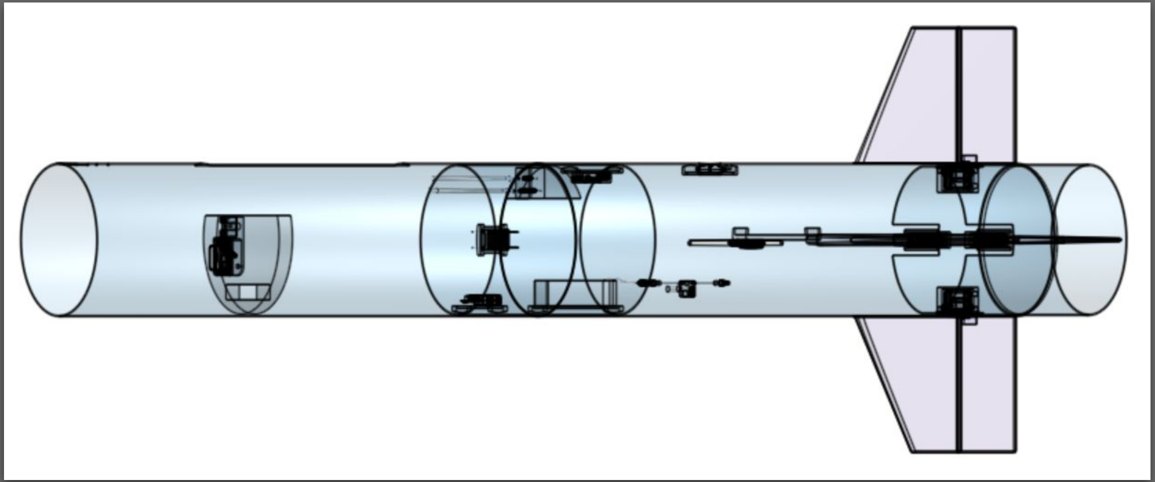


Design Overview: Sub-system - Nosecone





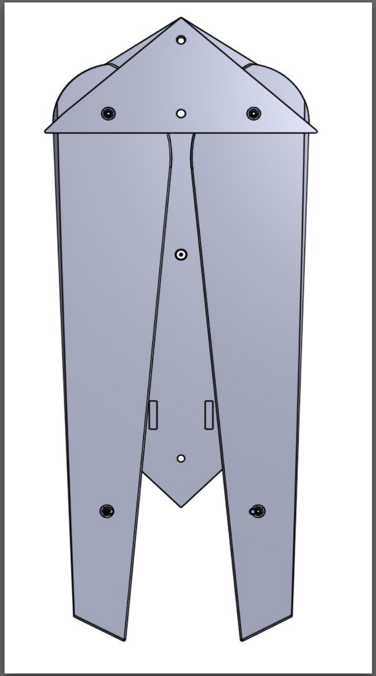
Design Overview: Sub-system - Fuselage



Fiberglass Composition

- Wider than conventional fuselages
- Manufactured in house
- Modular, piece together with couplers
- ⅛ inches thick

Design Overview: Sub-system - Deployable Wings

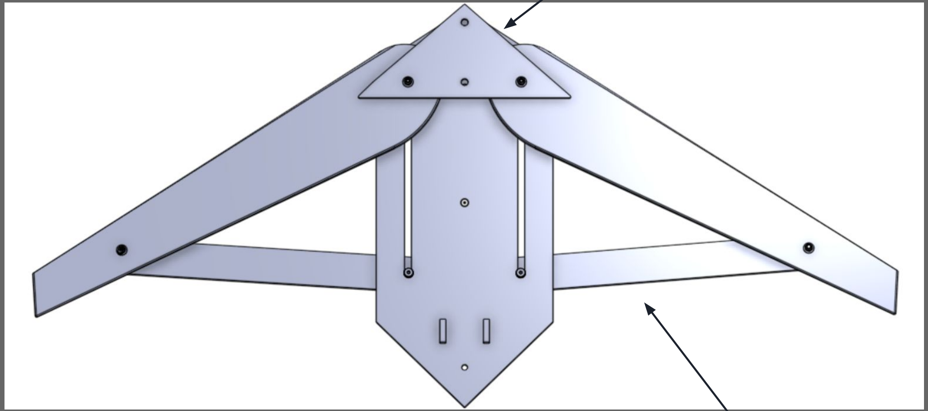


Top Down View Stowed

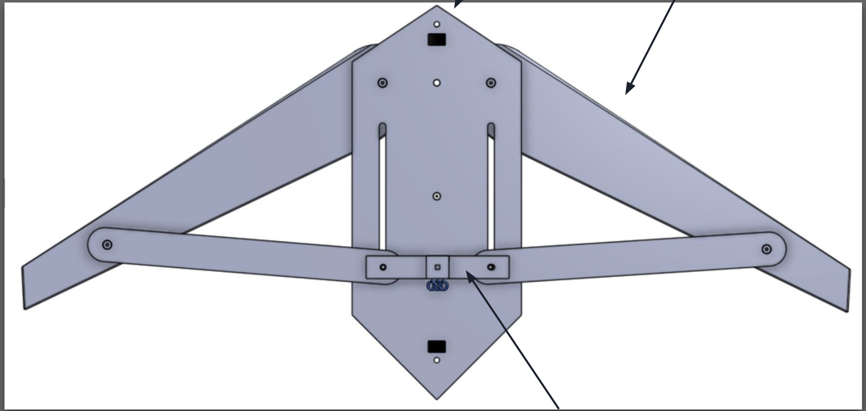
Bottom Up View Stowed

- Deploys at apogee
- Spring loaded

Design Overview: Sub-system - Deployable Wings

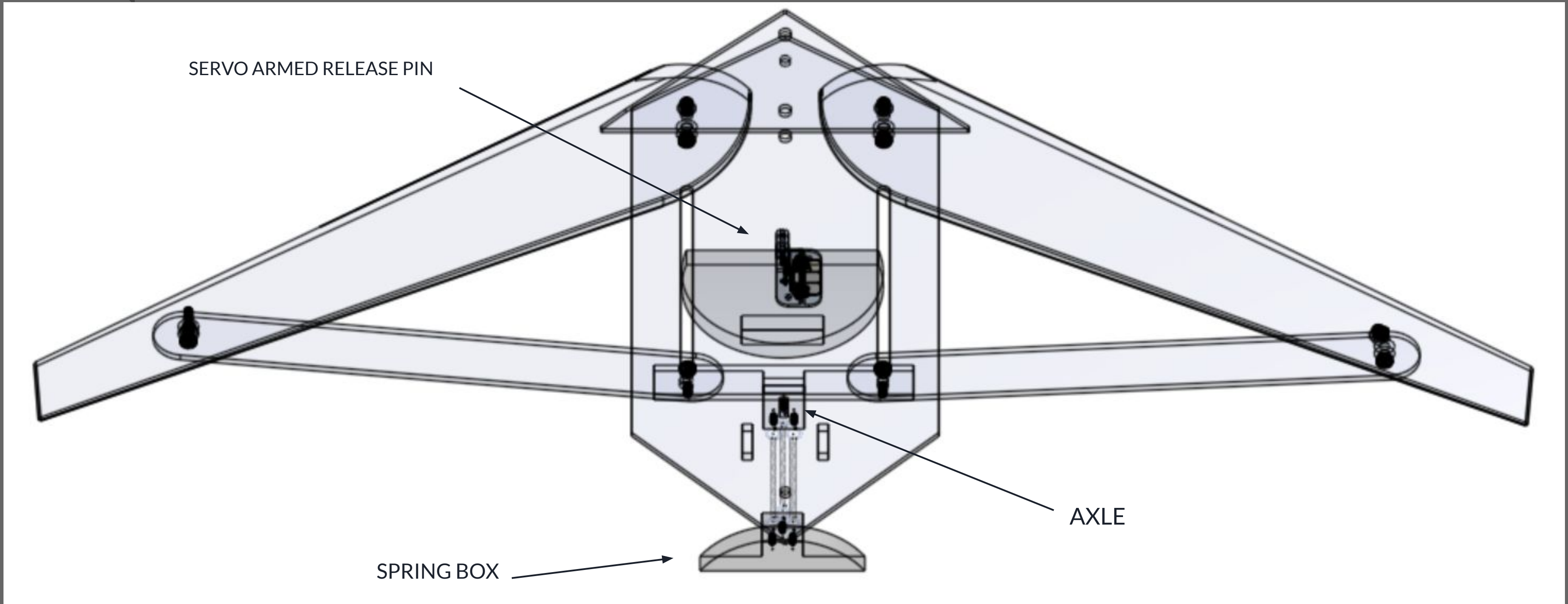


Top-Down Deployed

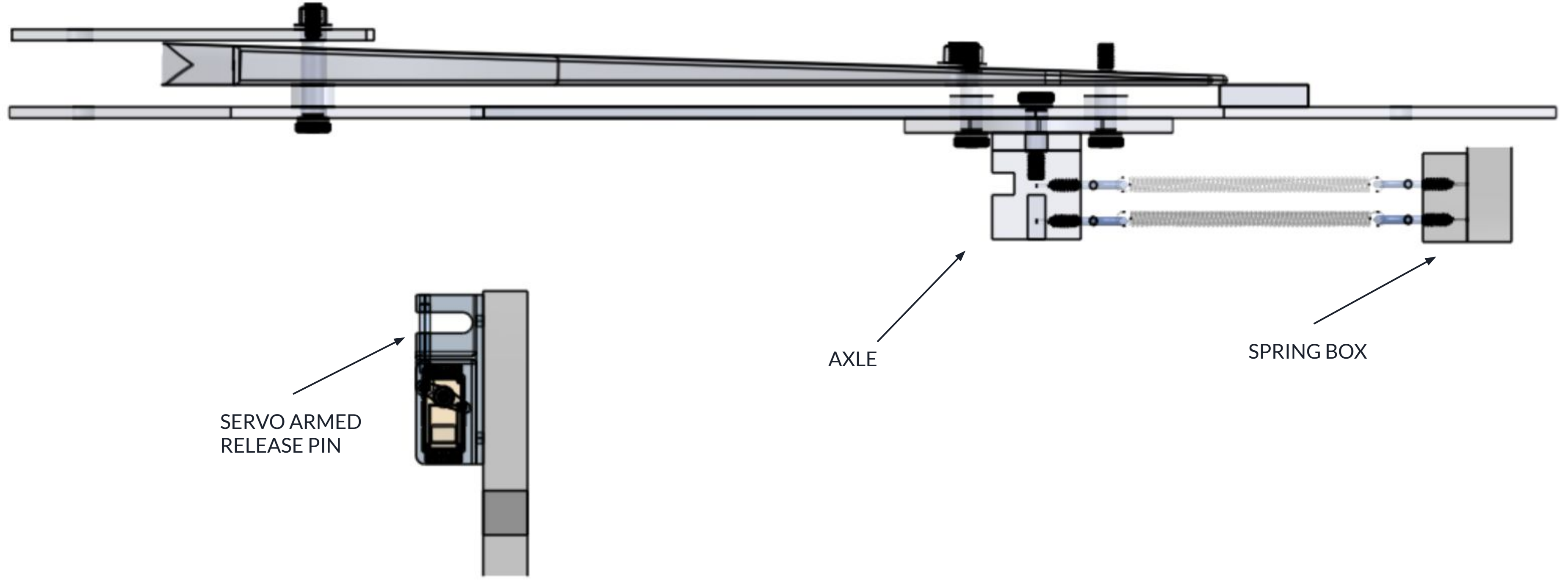


Bottom-Up Deployed

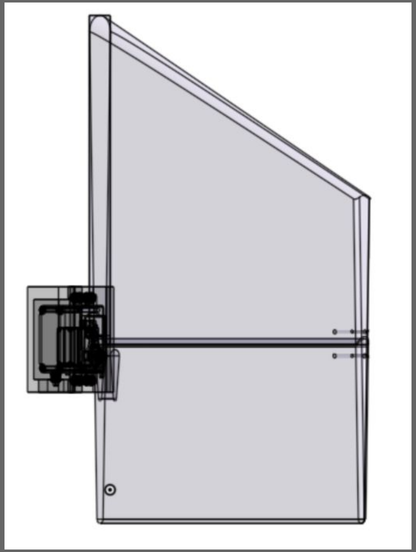
Design Overview: Sub-system - Deployable Wings

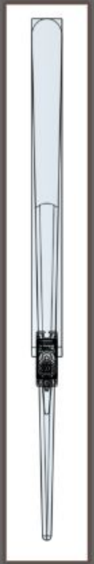


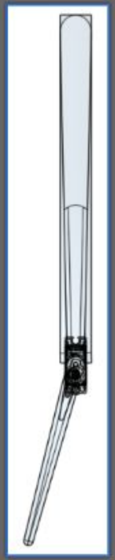
Design Overview: Sub-system - Deployable Wings

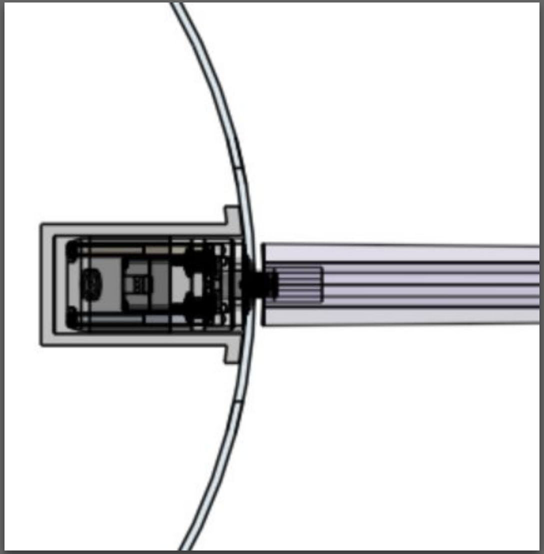


Design Overview: Sub-system - Control Surfaces (Fins)





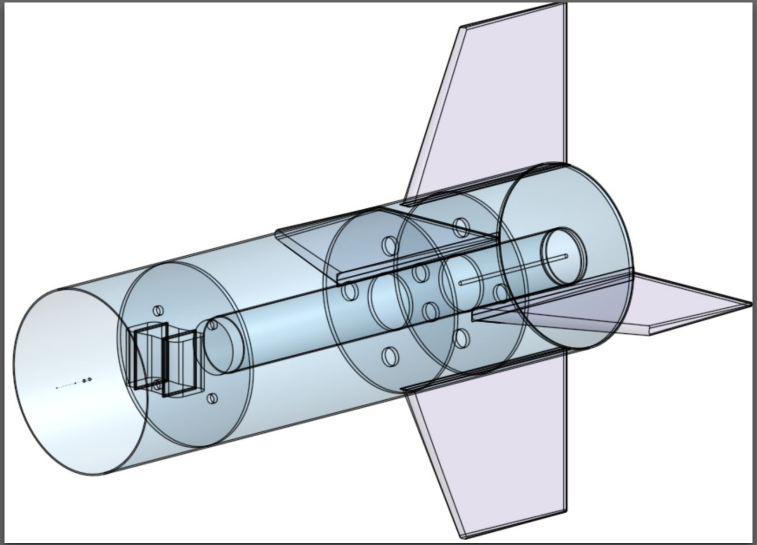




Design Overview: Sub-system - Ejecting Aft (Motor and Parachute)

60” Parachute

[Parachute Specs]



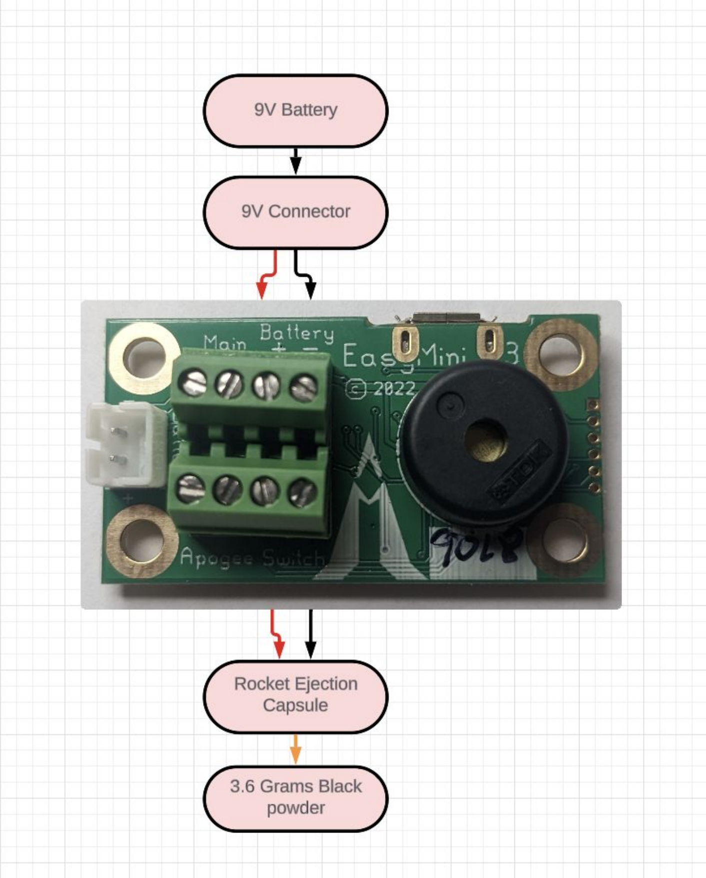
L1420R-PS

Apogee: ~2200 ft

[Boost Flight Specs]
[Motor Specs]

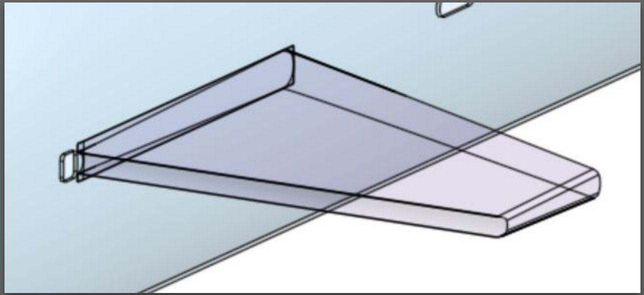
Design Overview: Sub-system - Separation

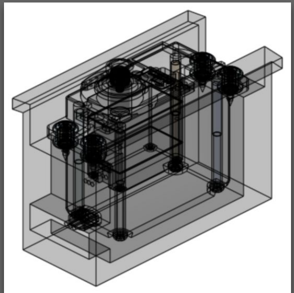
Power: 9V battery
Black Powered required: 3.6 g
Force Required: 628 lbs

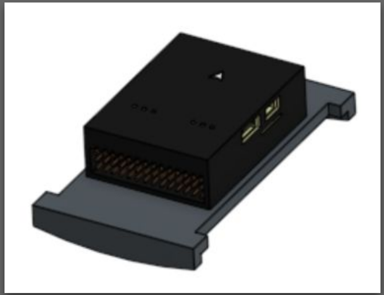


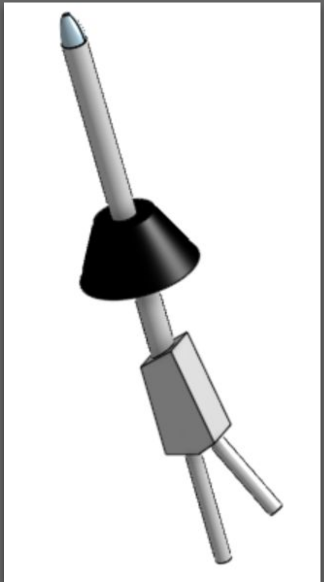
Separation Specs

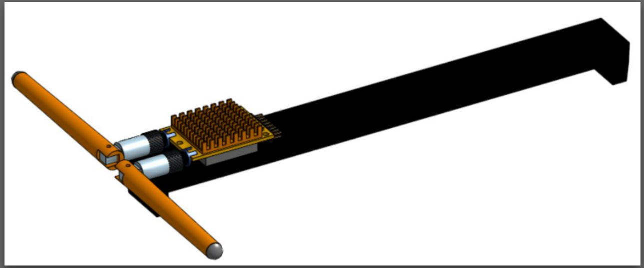
Design Overview: Mounting and Fastening

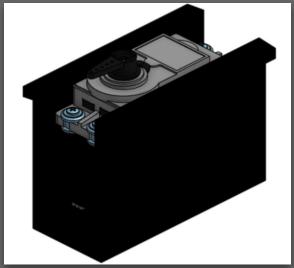


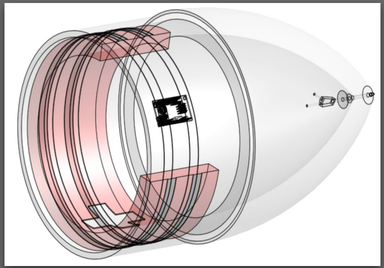




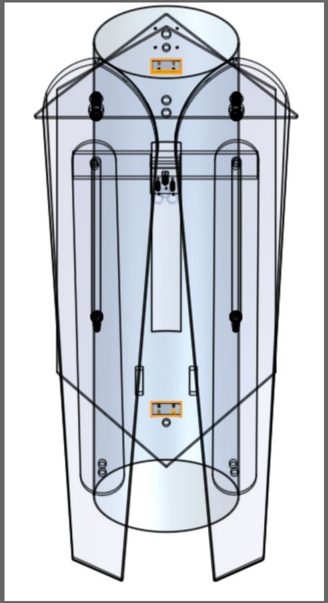


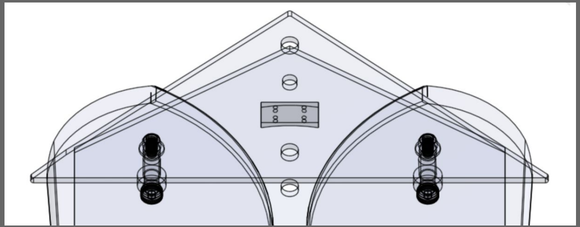


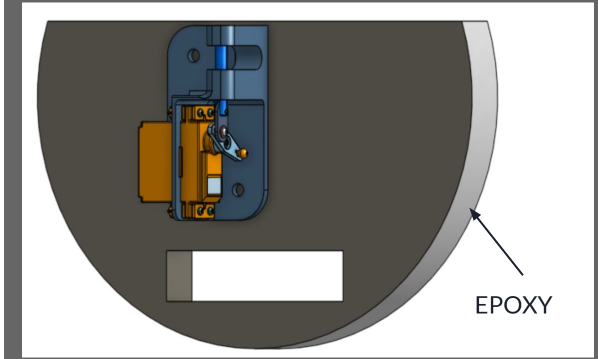


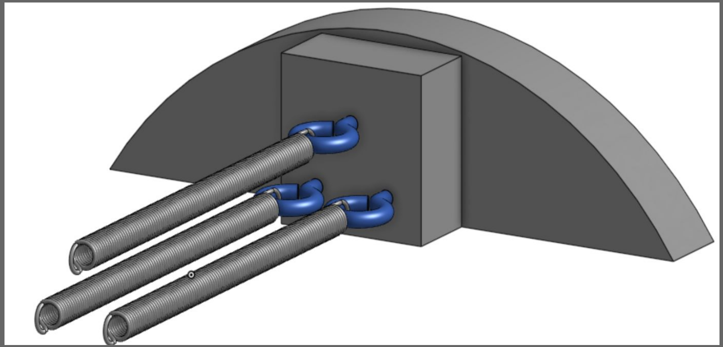


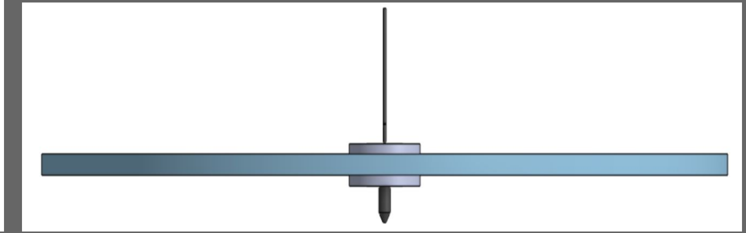
Design Overview: Mounting and Fastening



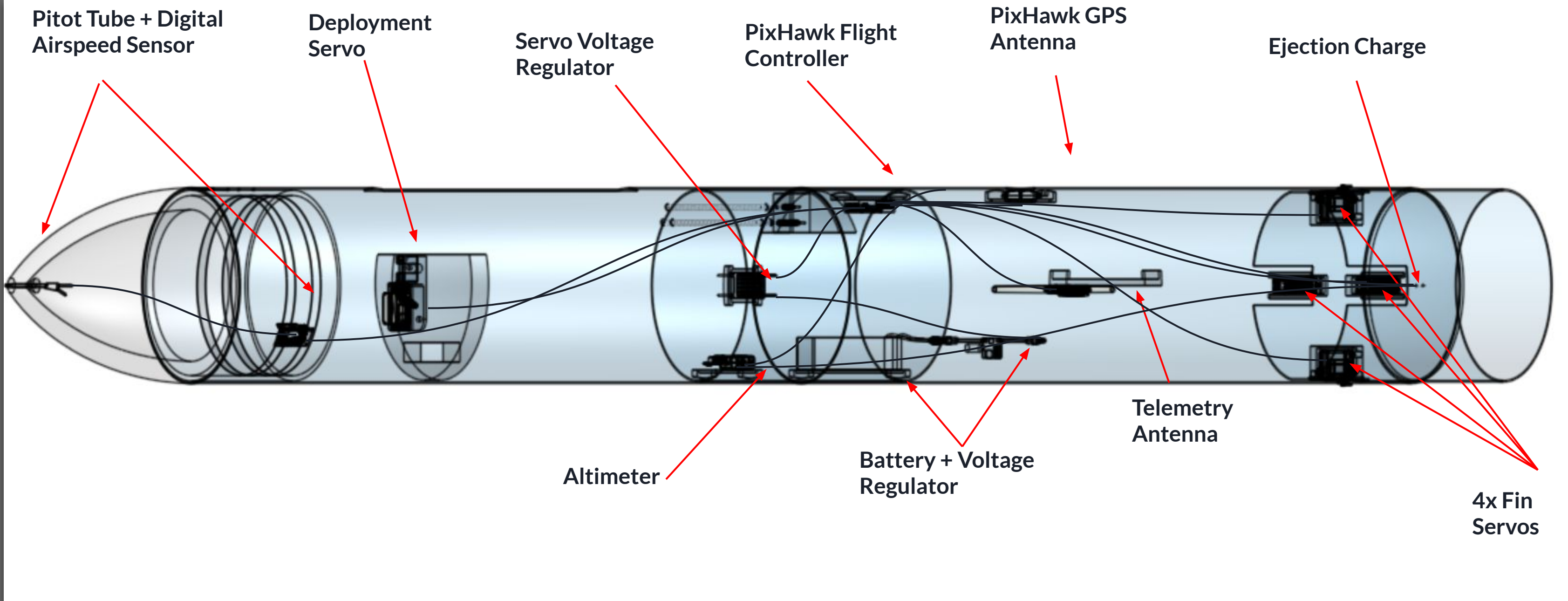








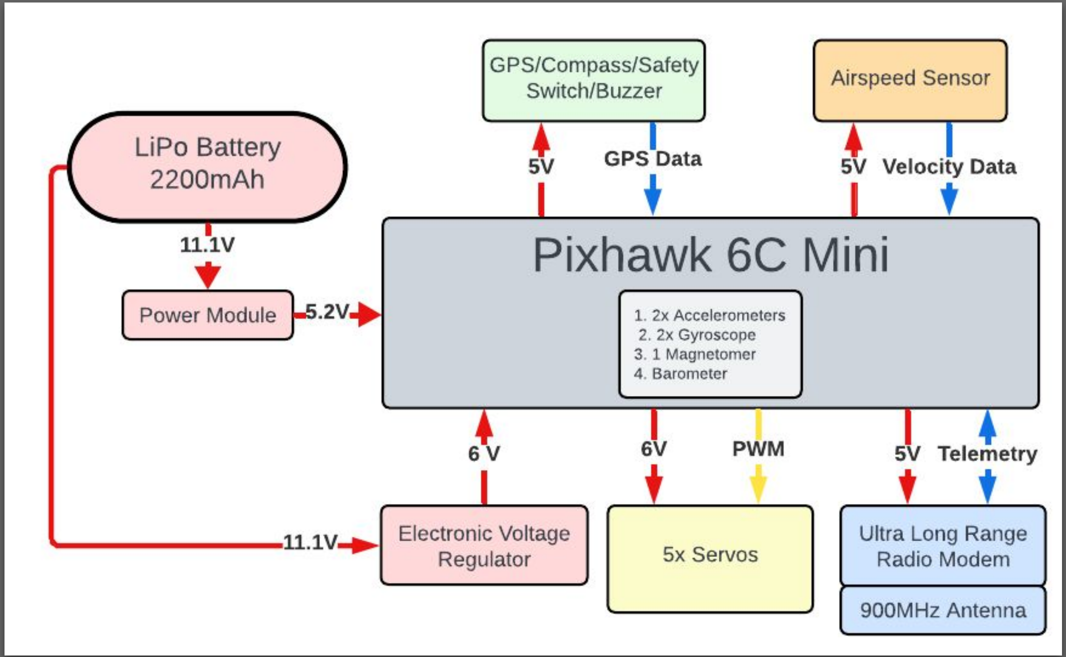
Design Overview: Sub-system Avionics



Design Overview: Avionics System Level Objectives

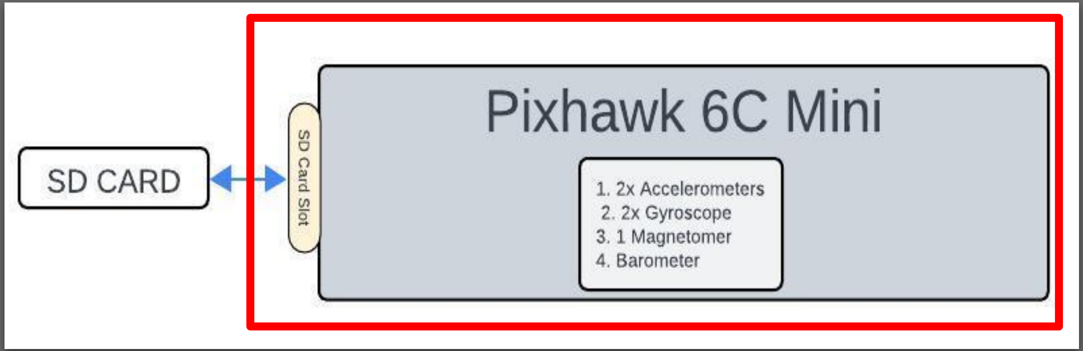
High Level Objectives

1. Measure **acceleration**, **velocity**, **position**, and **orientation**
2. Provide sufficient **power** to all subsystems
3. Wireless **communication** with ground station
4. Actuate **control surfaces**
5. **Deploy** wings



Design Overview: Avionics Subsystem

Flight Controller

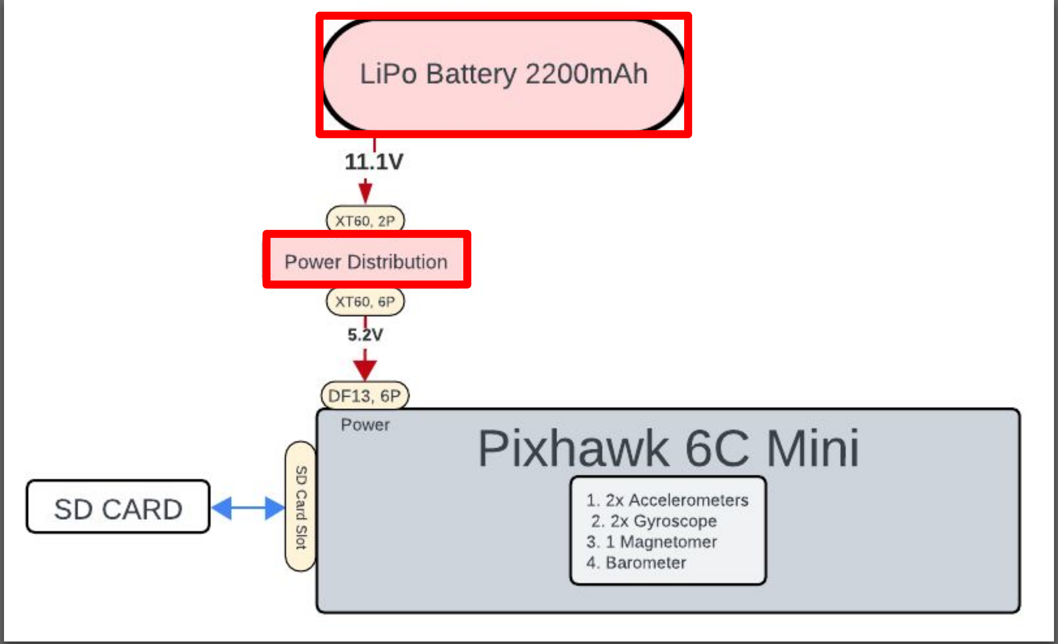


- Flight computer for glider system
- Multiple onboard sensors for collecting vehicle state
- Ability to add additional external sensors
- Multiple servo outputs
- Native ArduPilot Support

Source: Holybro

Design Overview: Avionics Subsystem

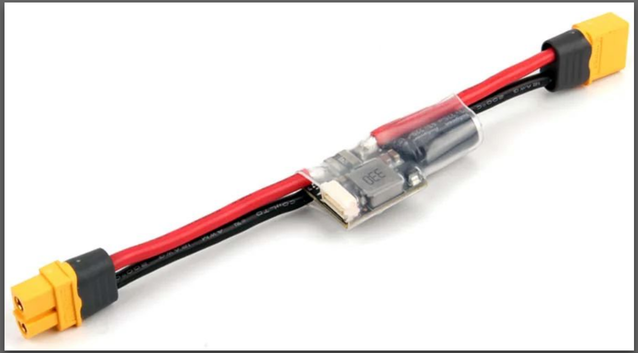
Battery + Power Distribution



LiPo 2200mAh

Source: HobbyKing

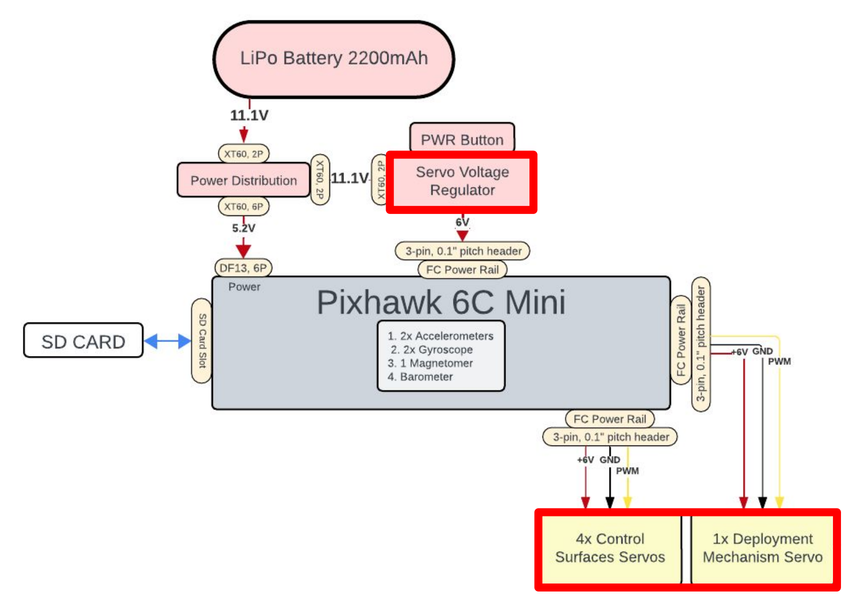
Voltage



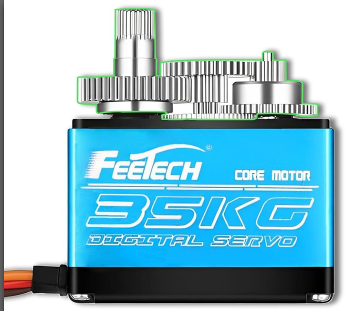
Source: Holybro

Design Overview: Avionics Subsystem

Servo Voltage Regulator + Servos

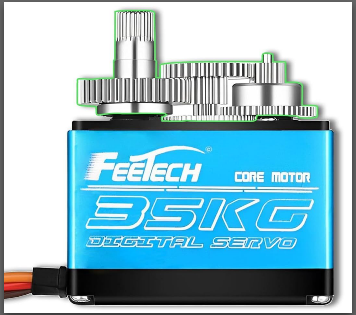


4x Control Surface Servos



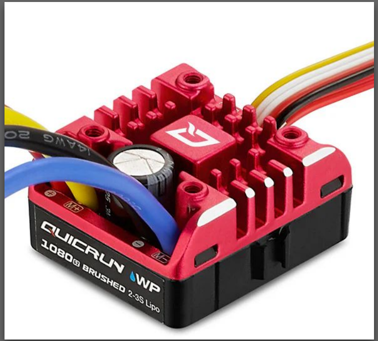
[Source: Geekstory Store]

1x Deployment Servo



[Source: Geekstory Store]

Servo Voltage Regulator

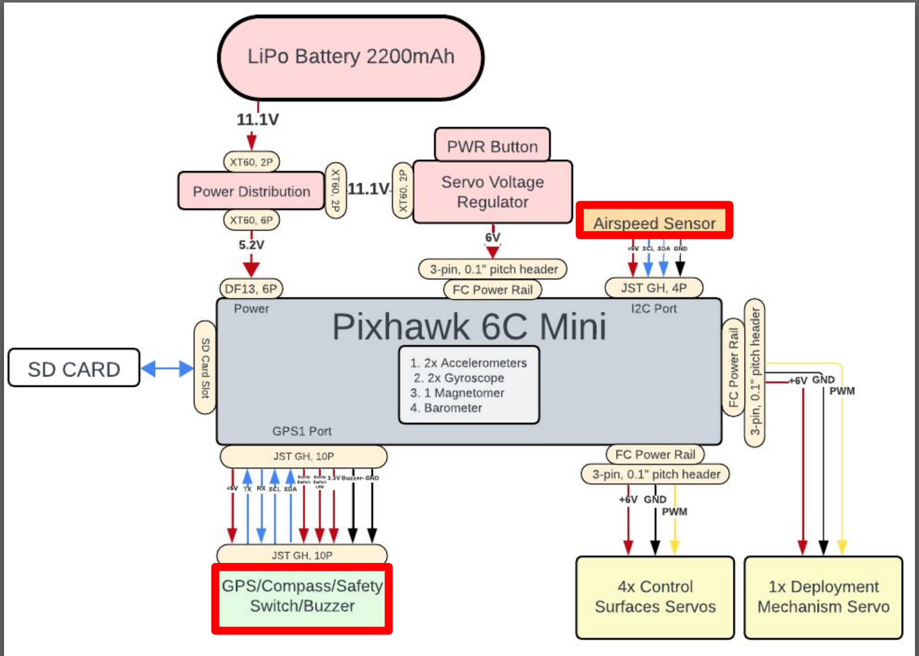


[Source: Hobby Wing]

[Servo Specs]

Design Overview: Avionics Subsystem

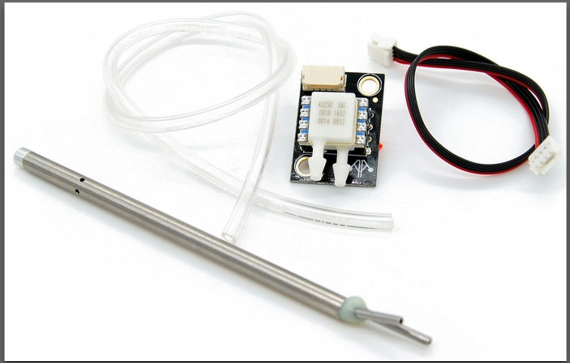
Sensors Overview



GPS /Compass Module

Source: Holybro

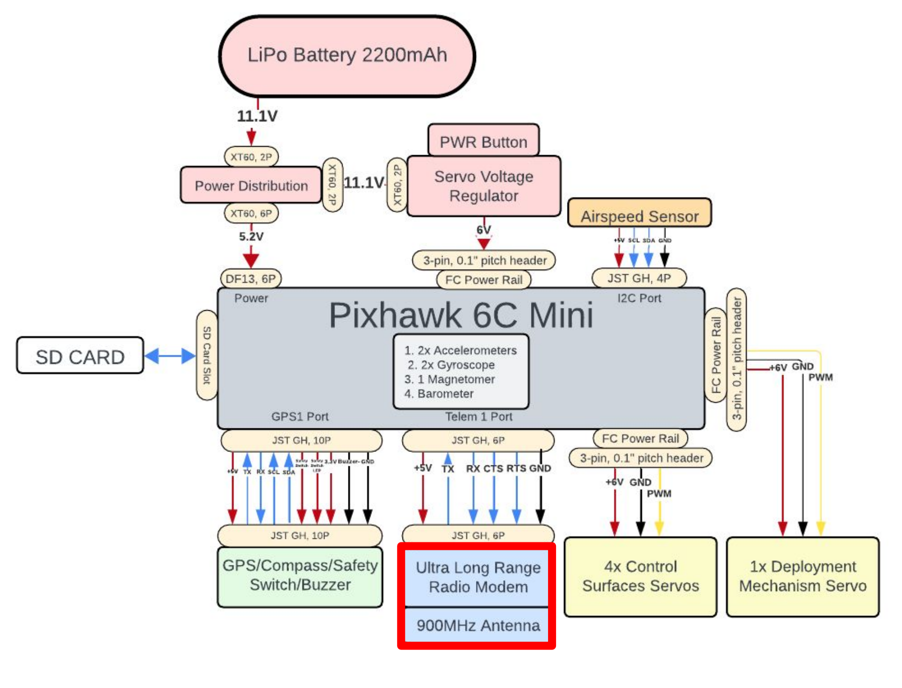
Airspeed Sensor



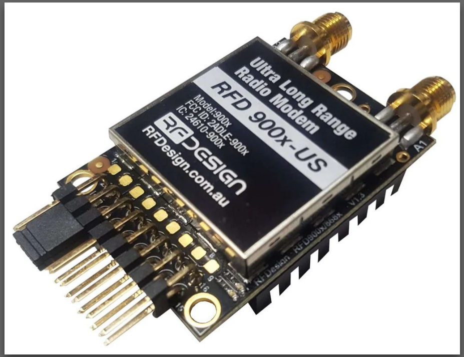
Source: Holybro

Design Overview: Avionics Subsystem

Telemetry



Ultra Long Range Radio Modem

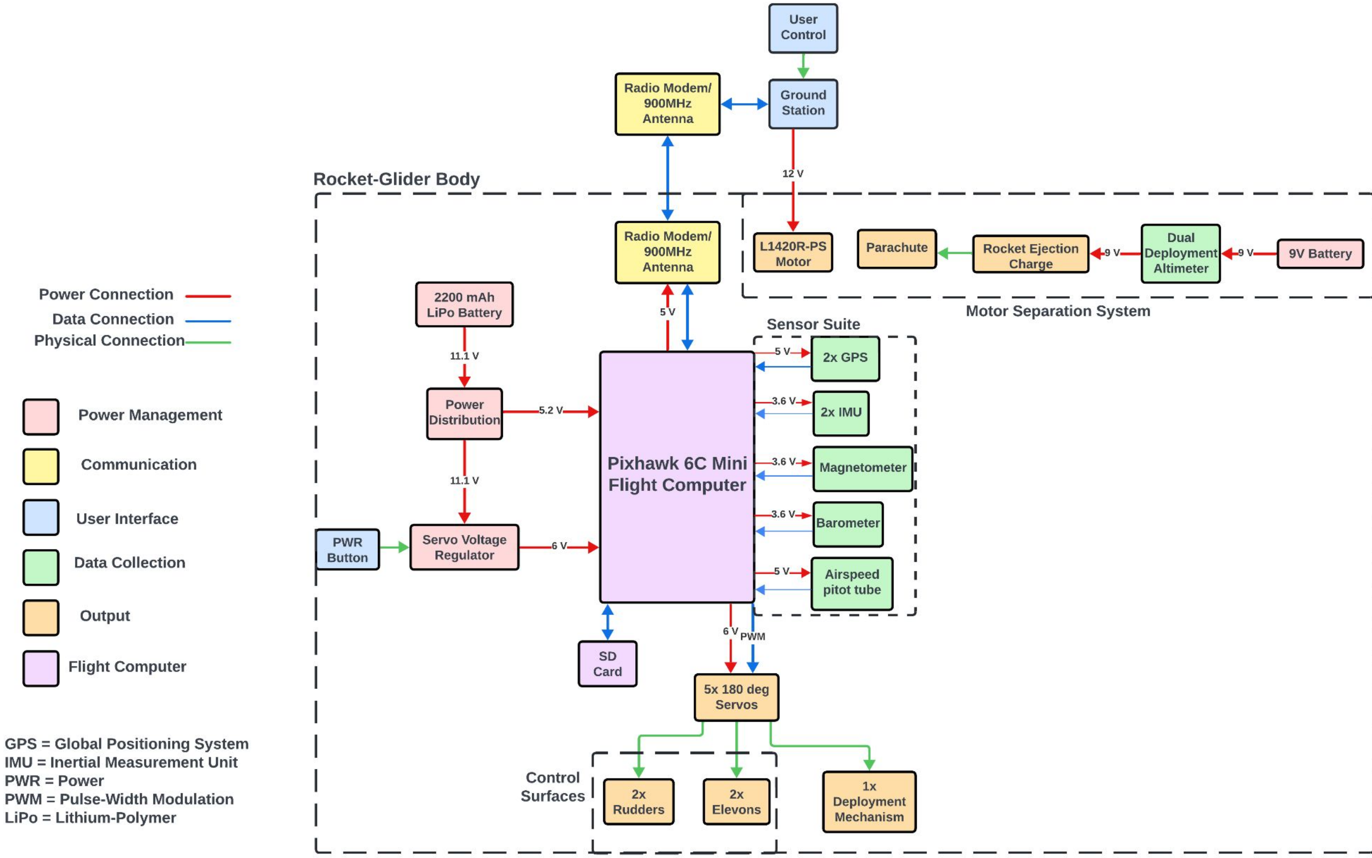


Source: IR-LOCK

900MHz 3dBi Dipole Antenna

Source: IR-LOCK

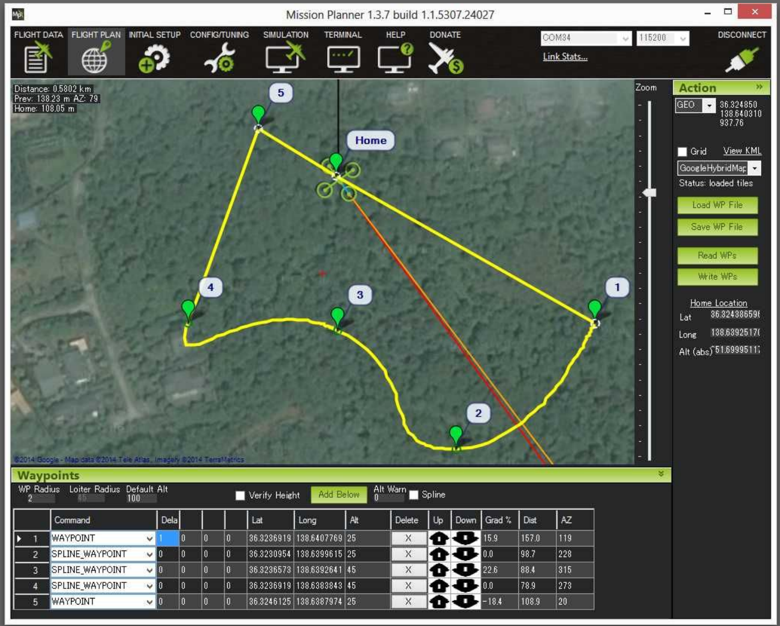
Functional Block Diagram



ArduPilot

ArduPlane

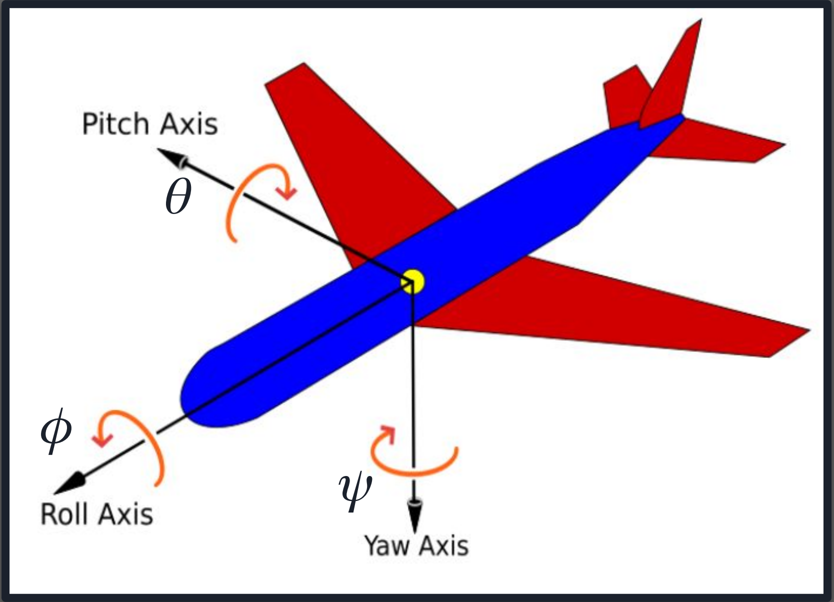
- Open source software that runs natively on the **PixHawk**
- Allows us to input aircraft geometry, fin locations, trim conditions, etc
- Allows for guidance **waypoints** to be set before flight
- Multiple flight "modes" with support for fixed wing aircraft (i.e. gliders)



ARDUPILOT

https://ardupilot.org

Design Overview: Sub-system - Control Axes

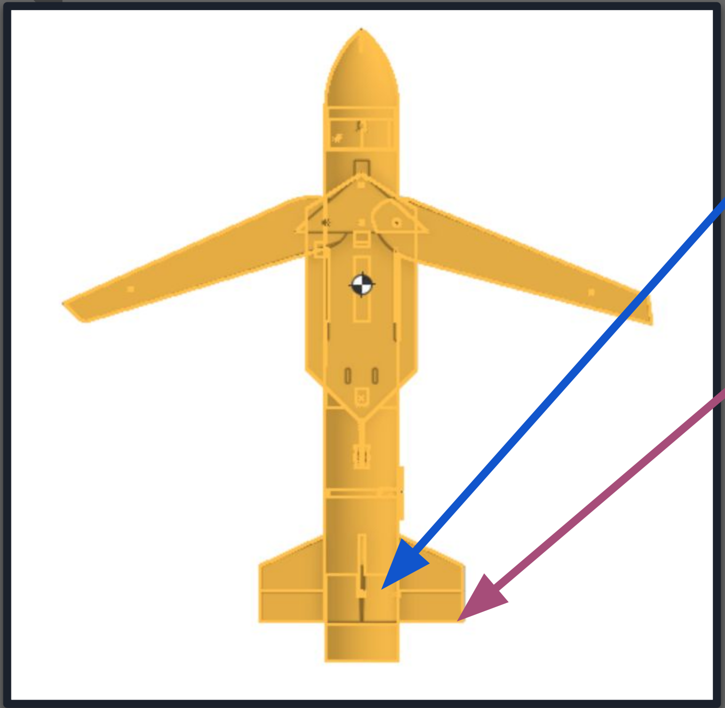


Control Yaw = Actuate Rudder

Control Pitch = Actuate Elevator

Control Roll = Actuate Ailerons

Design Overview: Sub-system - Control Surfaces



Vertical Fins

- Used together = act as rudder

Lateral Fins

- Used together = act as elevators

All Four Fins = act as ailerons

Design Overview: Sub-system - Controls

What is being controlled?

★ Active ϕ, θ, ψ control throughout flight to reach destination

Why?

★ Controlling for wind perturbations, glide configuration, and heading

Why PID as a solution?

- Proportional Control: Nominal trim configuration & fixed destination
- Integral: Reducing steady-state settling error (necessary for "long" periods of control authority)
- Derivative: Incorporating damping required to quicken settle-time

Engineering Models

Controls Design: ArduPilot

- ArduPilot (ArduPlane) is typically used for conventional fixed wing aircraft
- Custom control configurations can be implemented, but not guaranteed to work
- Native simulation in ArduPilot software is not sufficient for analysis

Controls Design: The Chosen Software

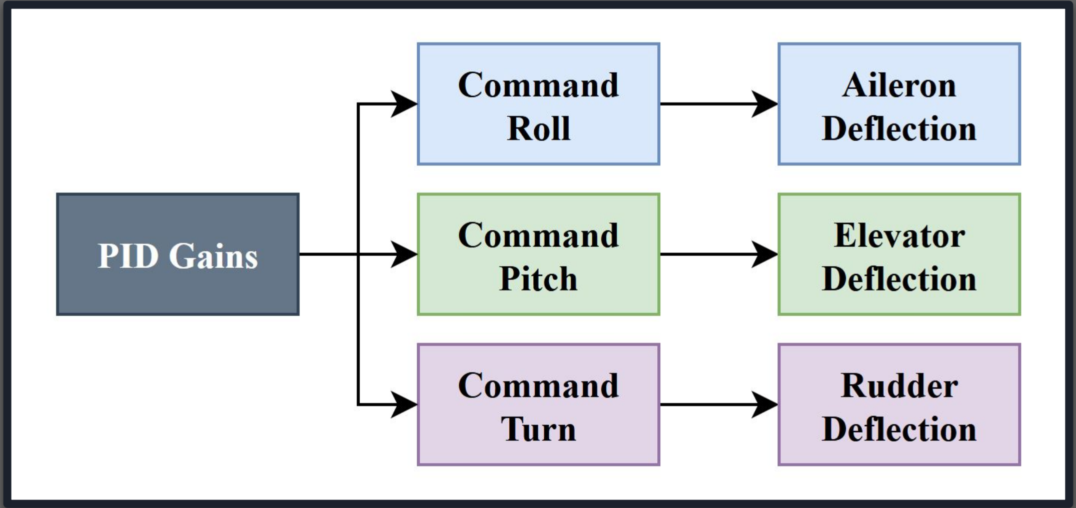
Why Simulink: Reputable simulation & computational tool used by industry (ex. SNC)
MATLAB compatibility (familiarity, built-in functions)
Block programming language (ease of use)

We verified Simulink results with our own 6DOF dynamics adapted model from ASEN 3801

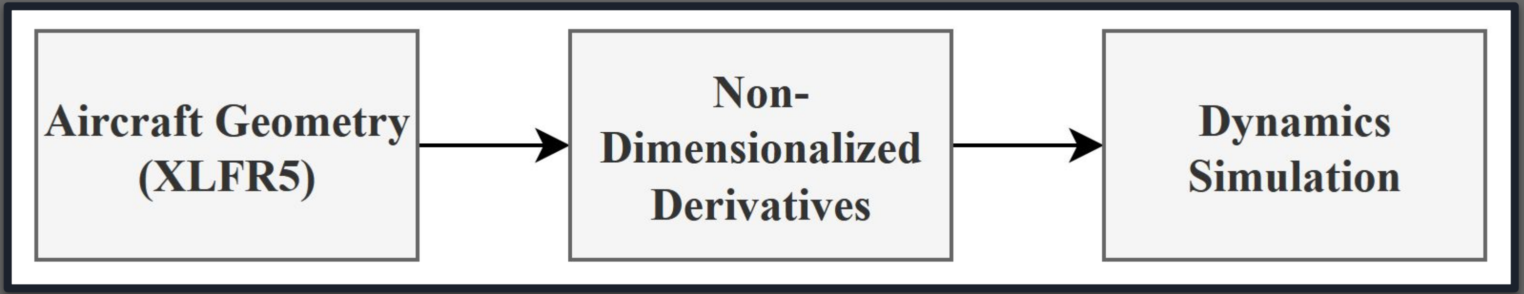
Controls Design: Ardupilot Dynamics and Control Laws

- Open source control law
  - Allows us to control all 6 DOF of the aircraft

Control Laws



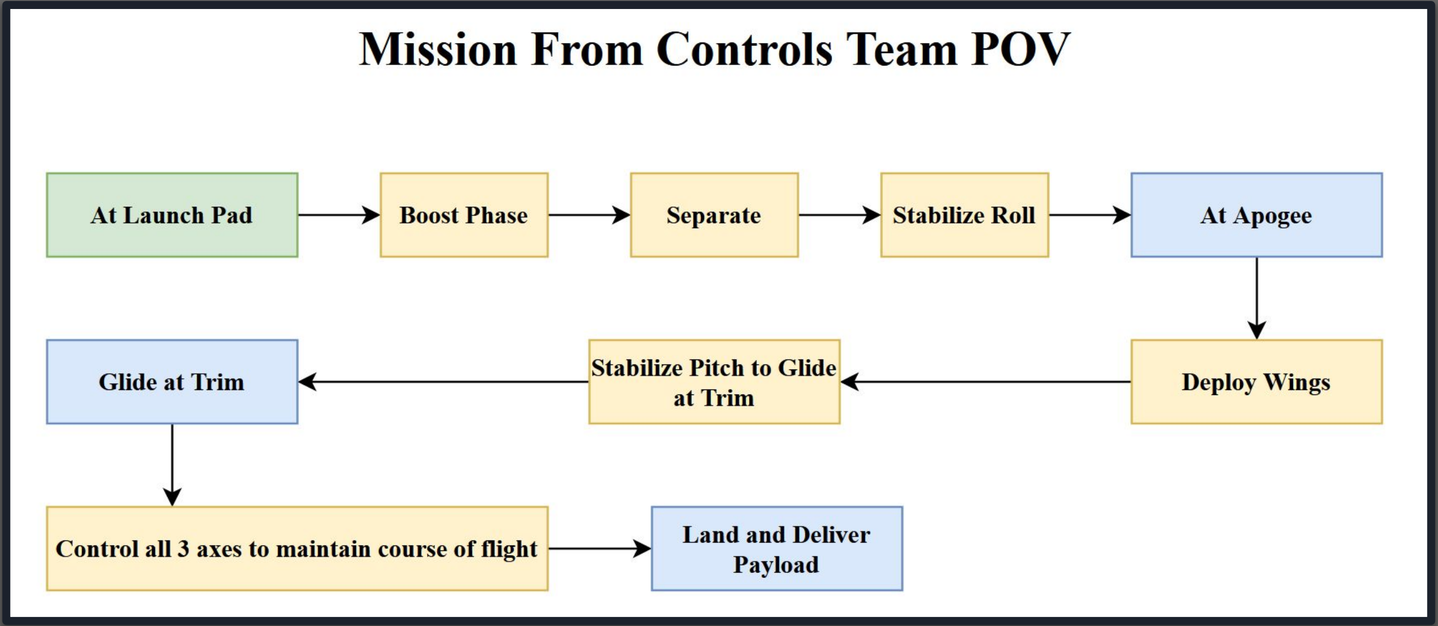
Controls Design: Ardupilot with Our Plane



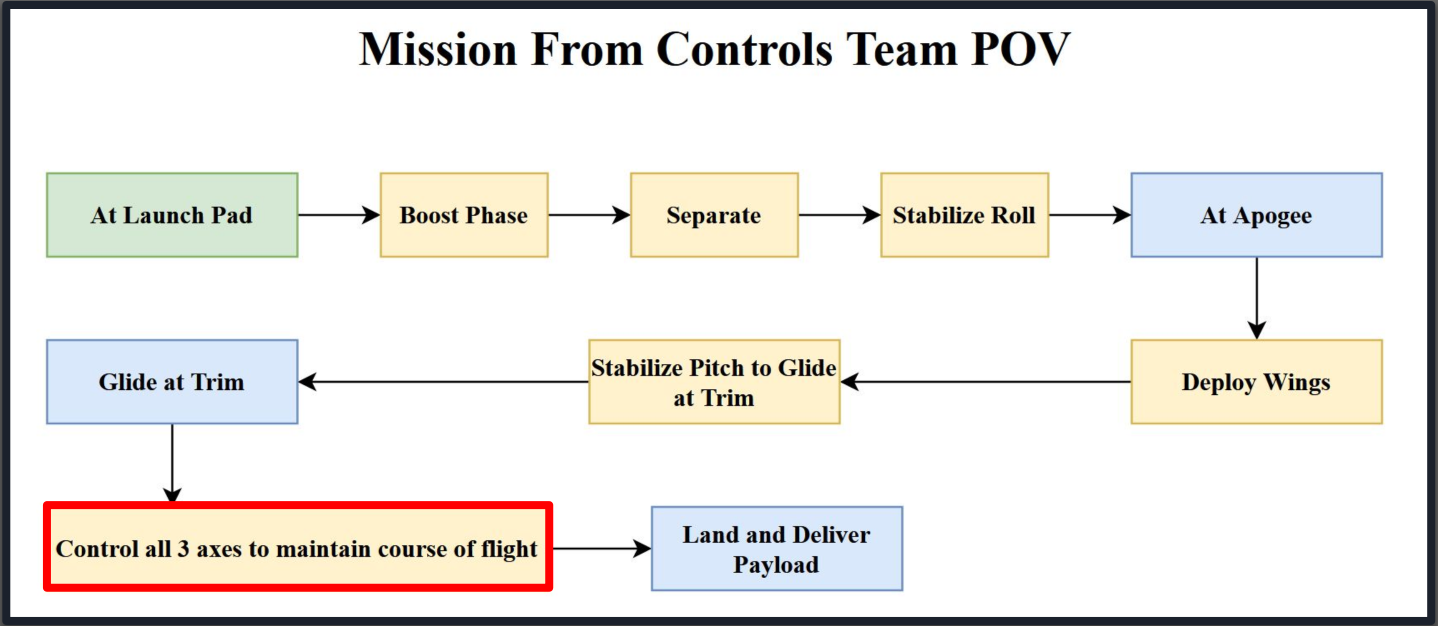
XFLR SD/NP Validation: Slide 97, Slide 98, Slide 99

Breakdown: Slide 89, Slide 90, Slide 91

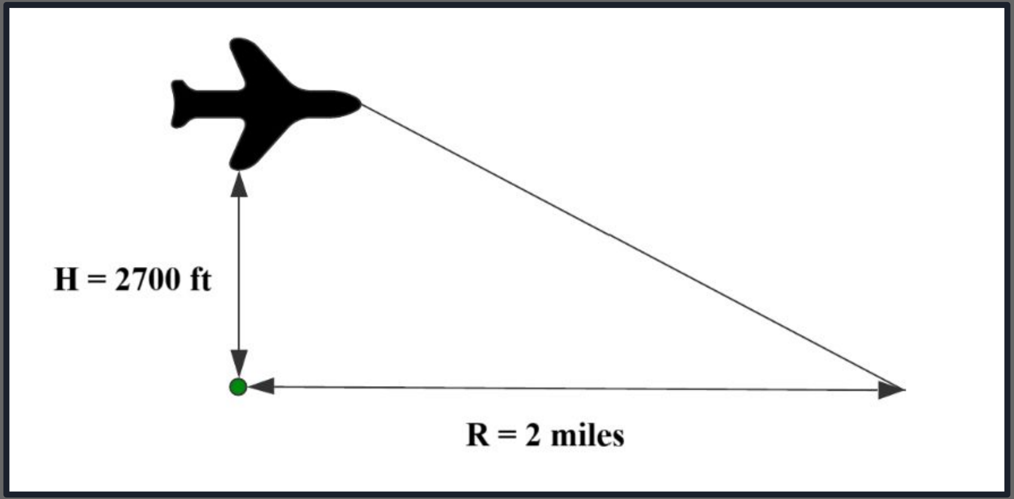
Controls Design: The Sequence of Events



Controls Design: The Sequence of Events



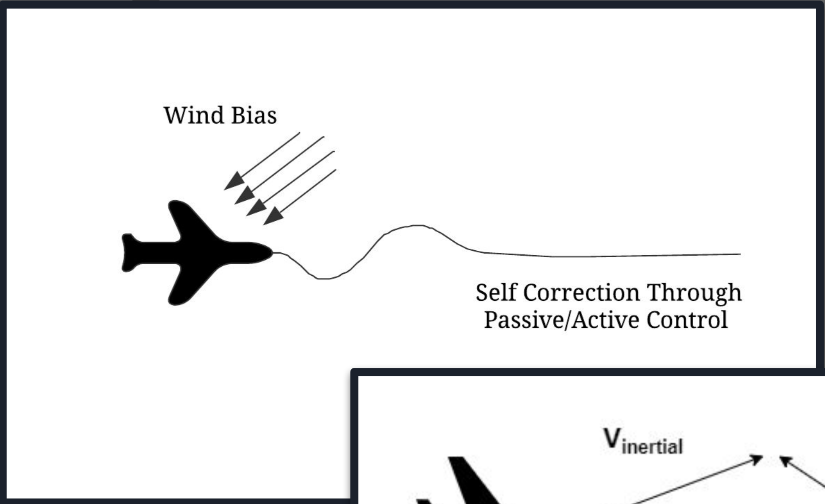
Glide Range Requirement

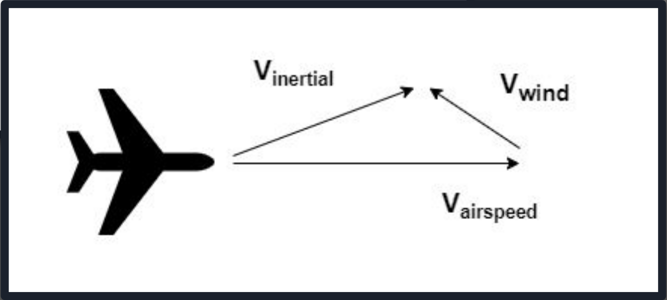


- Assuming an apogee of 2400 ft
- Need to achieve a horizontal range of 2 miles
- Assuming constant L/D max
- Models show we need L/D >= 4.4 (wing geometry)
    - **Current L/D max = 4.71**

Slide 95: Glide Model

Wind Disturbance Correction Requirement



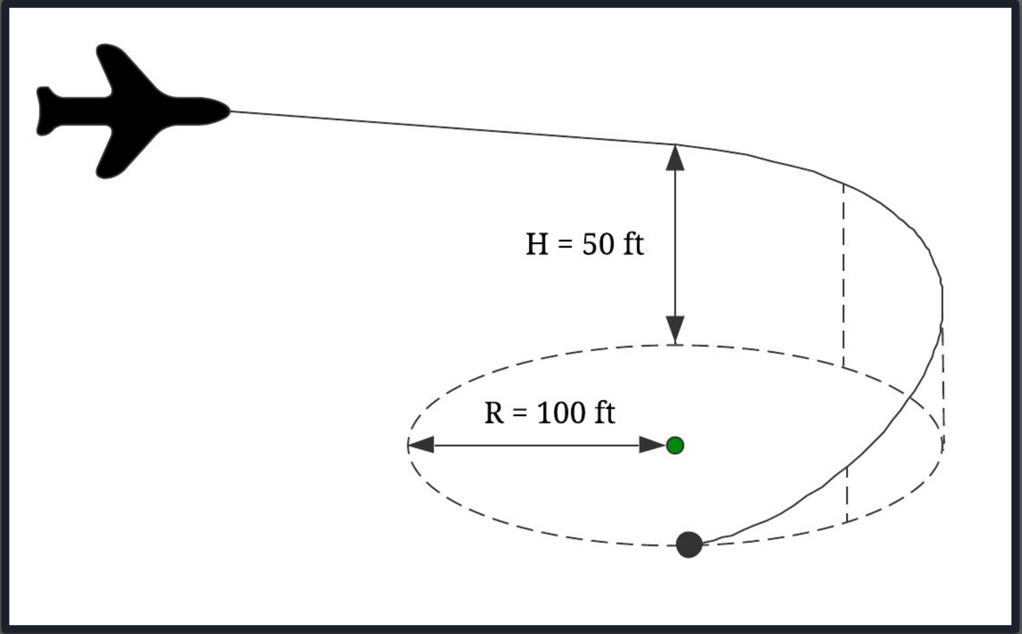


Slide 88: Wind Perturbation Analysis

- Wind artificially included in model via 2 implementations
  - Constant/uniform wind gust
  - Irregular gusts of wind greater than nominal value
    - Acting for 20 seconds

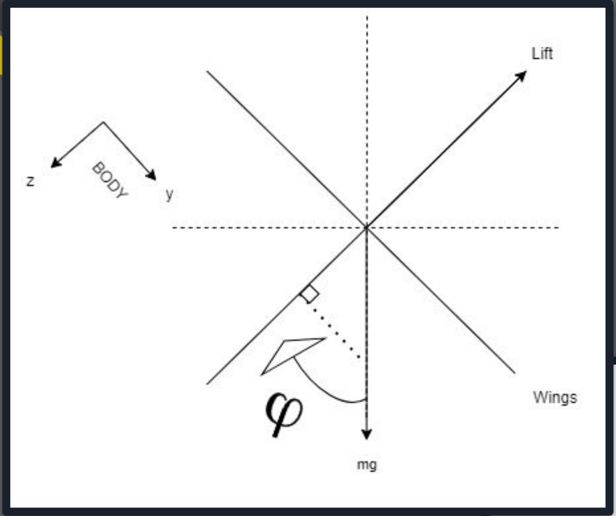
- PID axis control surfaces tuned to account for these disturbances

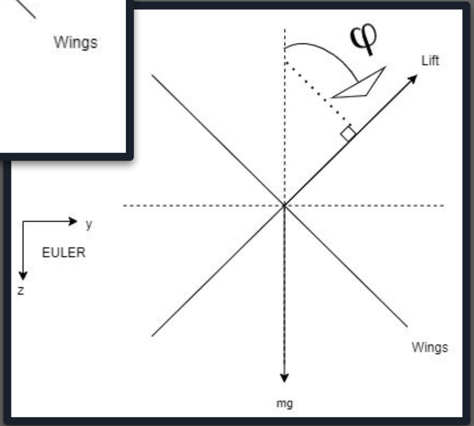
Turn / Descent Radius Requirement



- Margin of error for landing location = 100ft (requirement)
- Expected visible range for our glider in the sky = 50 ft
- Must be able to commit a coordinated 100ft turn radius maneuver to spiral down within destination margin of error

Coordinated Turn Lat/Long Rate Derivations





Body Coordinates: (r ~ PQR) (R = Radius)

$$\mathrm{V} = \omega R = rR \rightarrow R = \frac{V}{r}$$
$$\sum F_{Lat} = ma_c = mg\sin\phi = m\frac{V^2}{R}$$
$$g\sin\phi = \frac{V^2}{R}$$
$$r = \frac{g\sin\phi}{V}$$

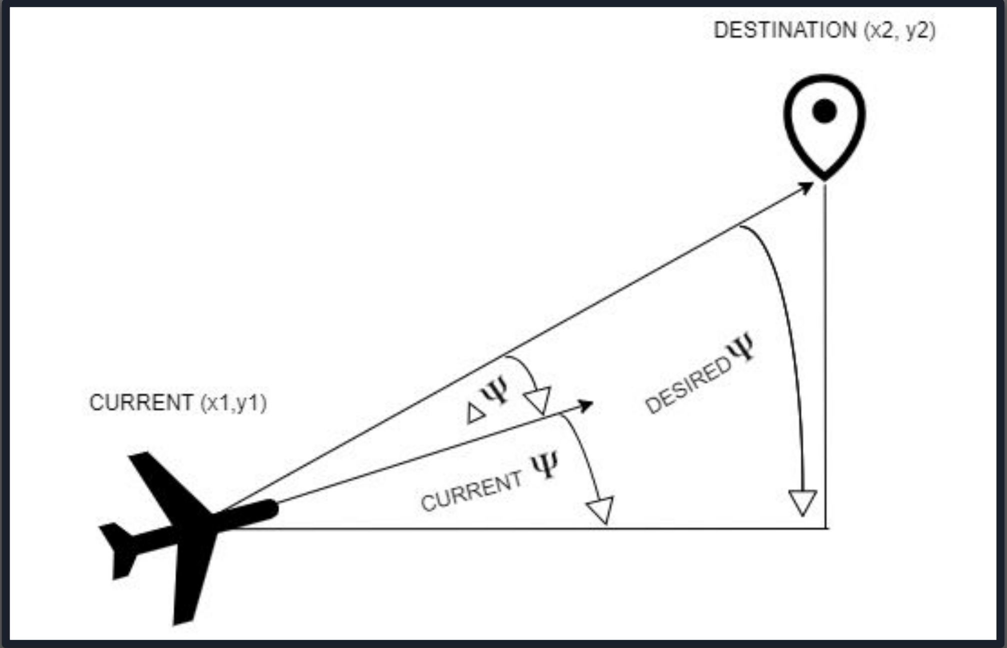
Euler Coordinates:

$$\sum F_y = 0 = L\cos\phi - mg$$
$$L = \frac{mg}{\cos\phi}$$

Body Coordinates: (q ~ PQR) (R = Radius)

$$\mathrm{V} = \omega R = qR \rightarrow R = \frac{V}{q}$$
$$\sum F_{Lon} = ma_c = L - mg\cos\phi = m\frac{V^2}{R}$$
$$\frac{mg}{\cos\phi} - mg\cos\phi = mVq$$
$$q = \frac{g}{V}(\sin\phi\tan\phi)$$

Waypoint Finding Calculations



Calculate Desired ψ

$$\Delta y = y_2 - y_1$$
$$\Delta x = x_2 - x_1$$
$$\psi_{Desired} = \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right)$$

Calculate Delta ψ

$$\Delta\psi = \psi_{Current} - \psi_{Desired}$$

Gain Desired Aileron Deflection

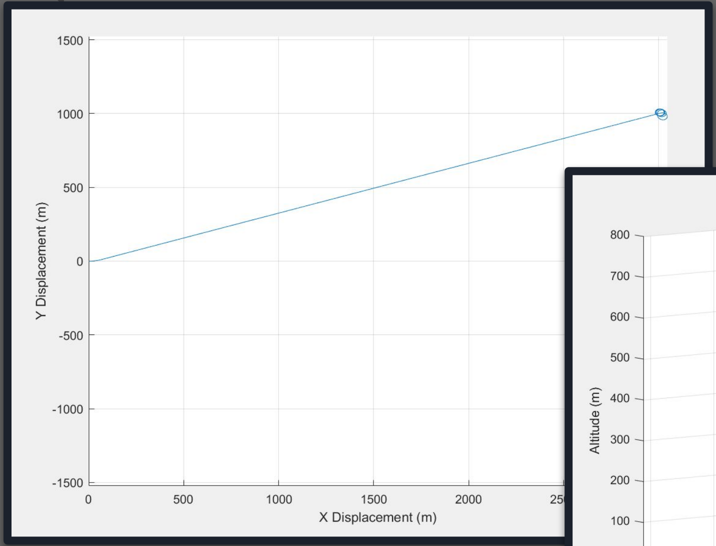
$\Delta\psi$ -> δ_{Alieron}

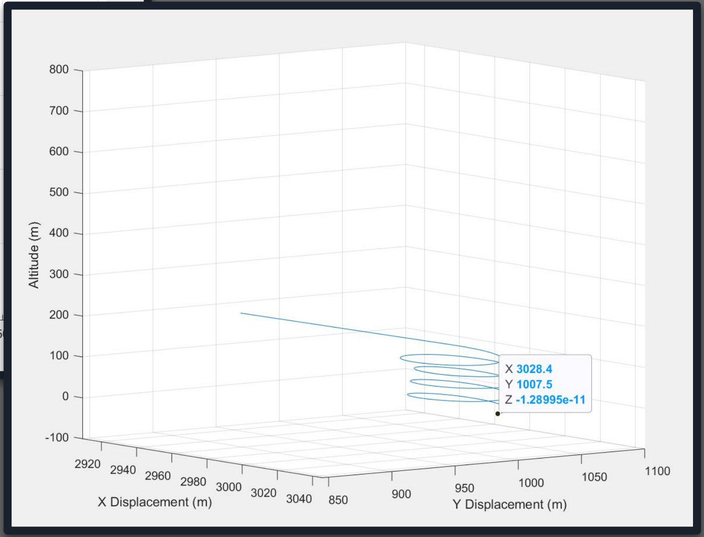
Forward Induced ϕ Angle

δ_{Alieron} creates non-zero ϕ angle

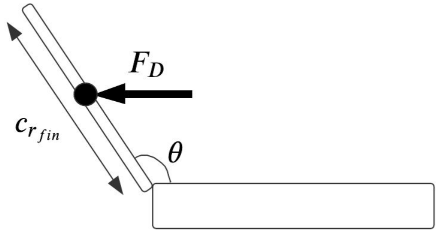
Coordinated Turn to Waypoint Full Implementation

- Initially travelling in the positive X direction
- Changes course and spirals down within 100 feet of target





Servo-Actuator Torque and Angle of Deflection Requirement

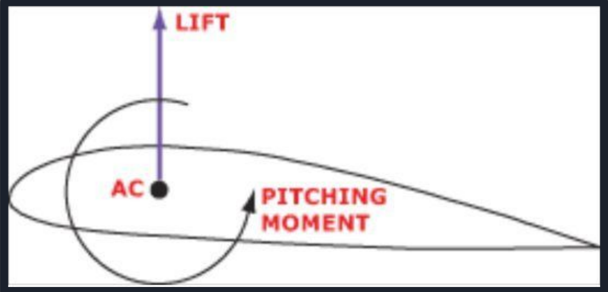


$$F_D = \frac{1}{2} * \rho * V^2 * C_D * A_c$$

$$T = F_D * \frac{c_{r_{fin}}}{2} * cos(\theta - 90)$$

- Max Deflection Angle Required = 0.5 rad
- Max Deflection from Servo Chosen = 3.14 rad

- Torque Required = 59.77 oz-in
- Torque From Servo Chosen = 400.65 oz-in



Models Takeaways

We can physically reach our target and know how Ardupilot will do it

- Proved through our wind disturbance, glide, and turn models

We can mechanically endure the flight

- Proved through the servo actuator angle and torque requirements, and the structural wing analysis

Model	Significance
Boost Stability	• 1000 ft minimum apogee
Glide Model	• 2 mile minimum glide range
Structural Analysis	• Withstand flight conditions throughout mission • Transitioning from boost to glide
Power Budget	• Power supply through entire mission profile
★ Glide Stability	• Payload deliver within 100 ft accuracy

Spring Plan

Spring Testing Table

Test	Requirements Verified	Method
Payload Survivability	DR 3.4	Visual
Telemetry	DR 1.1	Data Acquisition
Avionics Integration	DR 1.1.1	Integration Test
Avionics Survivability	DR 4.1	Visual/Data Acquisition
☆ Wing Deployment	DR 3.5	Visual
Power	DR 4.1.1	Visual/Data Acquisition
Wing Deployment Structure	DR 3.2	Visual
☆ Glide	DR 3.4.1	Visual, Data Acquisition
☆ Ascent Stability	DR 4.2.1	Visual, Data Acquisition
☆ Transition Phase	DR 3.5	Data Acquisition
Wing Structure	DR 3.2	Visual

Most Critical Tests

Test	Location	Equipment
Glide	AERO Building	Small Scale Glide Phase Prototype
Ascent Stability	Launch Site	Avionics, Small Scale Ascent Prototype
Transition Phase	Launch Site	Wing Deployment System, Avionics, Small Scale Ascent Prototype
Deployment	AERO Building	Wing Deployment System
Power System Test	AERO Building	Avionics

Ascent Stability

Objective

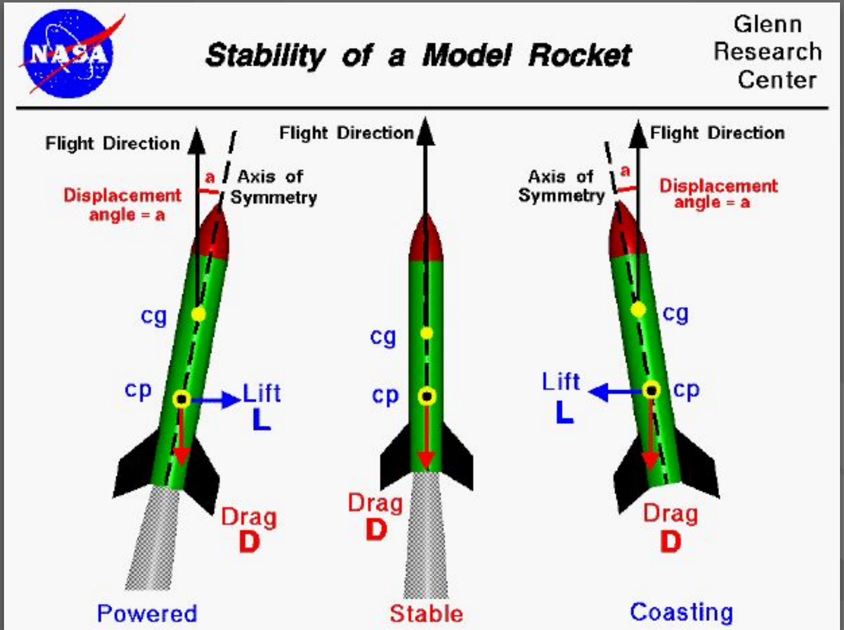
- Verify stability of boost stage.

Procedure

- Build small scale boost configuration.
- Launch at regulated site.

Metrics for Success

- Fins properly stabilize ascent.
- Flight controller data verifies our model.



Ascent Stability

Preliminary Testing

- Initial tests showed stability in small scale estes model.
- Will test stability with separation next.

Transition Phase

Objective

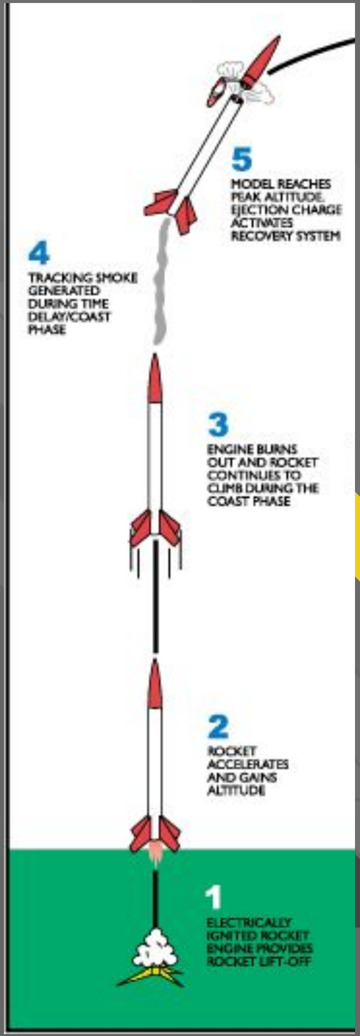
- Verify ability to correct orientation prior to wing deployment.

Procedure

- Build small scale boost configuration with control surfaces.
- Launch at regulated site.
- Correct roll prior to apogee.

Metrics for Success

- System is able to properly correct orientation.
- Flight controller data reflects control predictions.



Wing Deployment

Objective

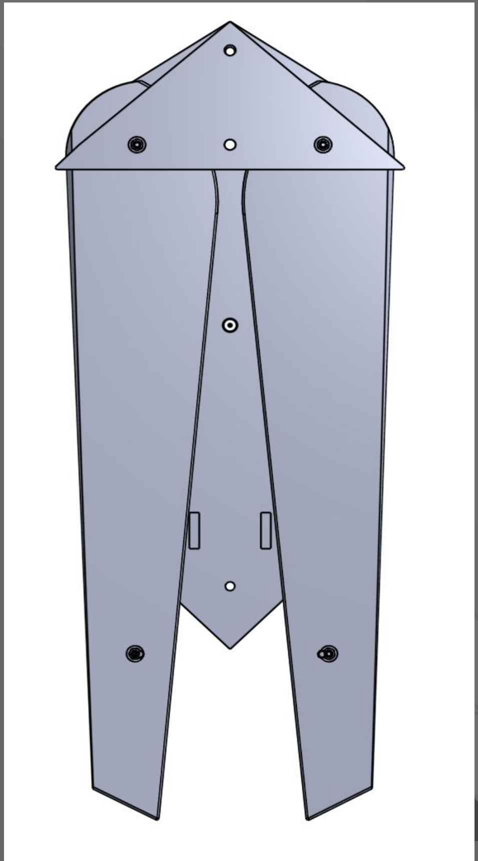
- Verify ability to deploy.

Procedure

- Build full scale deployment system.
- Ensure success of chosen spring and servo.

Metrics for Success

- Spring is able to counteract drag force.
- Servo is able to withstand torque due to spring.



Glide

Objective

- Verify ability to correct flight path and hit target.

Procedure

- Build small scale glider configuration.
- Throw off balcony with varying orientation.

Metrics for Success

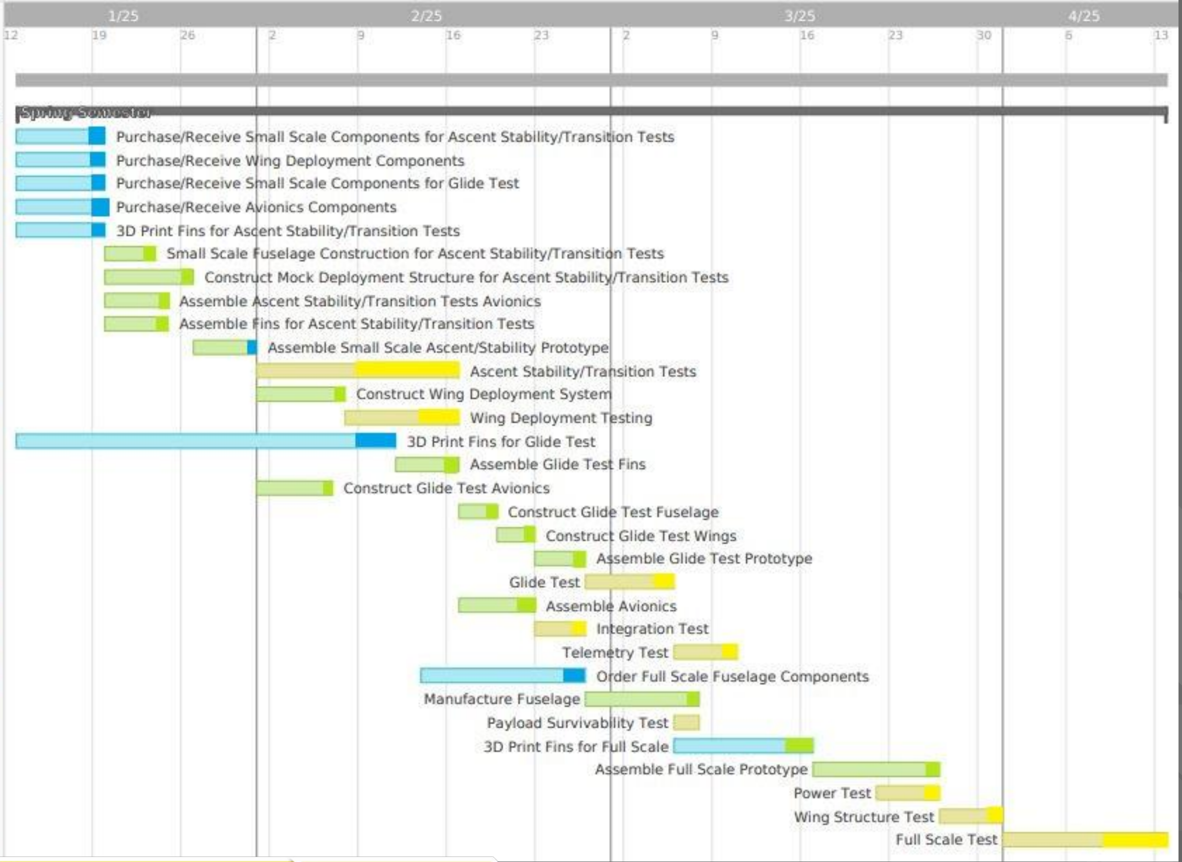
- Glider stabilizes properly.
- Glider lands within zone scaled to requirements.
- Flight controller data verifies model.

Safety Risks

Test	Risk	Solution
Full Scale Glide	Injury	Safety vests, hard hats, communication
Ascent Stability	Injury, Fire	Adhering to rules/regulations
Transition Phase	Injury, Fire	Adhering to rules/regulations

Spring Schedule

H.A.W.K.	start	end
Spring Semester	**01/13/25**	**04/13/25**
Purchase/Receive Small Scale Comp...	01/13	01/19
Purchase/Receive Wing Deployment ...	01/13	01/19
Purchase/Receive Small Scale Comp...	01/13	01/19
Purchase/Receive Avionics Compone...	01/13	01/19
3D Print Fins for Ascent Stability/Tra...	01/13	01/19
Small Scale Fuselage Construction fo...	01/20	01/23
Construct Mock Deployment Structur...	01/20	01/26
Assemble Ascent Stability/Transition ...	01/20	01/24
Assemble Fins for Ascent Stability/Tr...	01/20	01/24
Assemble Small Scale Ascent/Stabilit...	01/27	01/31
Ascent Stability/Transition Tests	02/01	02/16
Construct Wing Deployment System	02/01	02/07
Wing Deployment Testing	02/08	02/16
3D Print Fins for Glide Test	01/13	02/11
Assemble Glide Test Fins	02/12	02/16
Construct Glide Test Avionics	02/01	02/06
Construct Glide Test Fuselage	02/17	02/19
Construct Glide Test Wings	02/20	02/22
Assemble Glide Test Prototype	02/23	02/26
Glide Test	02/27	03/05
Assemble Avionics	02/17	02/22
Integration Test	02/23	02/26
Telemetry Test	03/06	03/10
Order Full Scale Fuselage Componen...	02/14	02/26
Manufacture Fuselage	02/27	03/07
Payload Survivability Test	03/06	03/07
3D Print Fins for Full Scale	03/06	03/16
Assemble Full Scale Prototype	03/17	03/26
Power Test	03/22	03/26
Wing Structure Test	03/27	03/31
Full Scale Test	04/01	04/13



Cost Plan

- Budgeting of H.A.W.K project is unique due to large configuration changes throughout mission requirements which requires heavy testing.
- Current margin accounts for failures during boost and glide tests.
- HAWK has unique and substantial control and boost requirements that require specific budgeting for frequent testing and expensive prototyping.

Cost Plan

Expenses	Expected Cost	Left-over amount
Electronics Equipment*	$723	$3277
Rocket Motor	$1300	$1977
Boost Test	$100	$1877
Transition Test	$723	$1154
Glide Test	$100	$1054
Mechanical Equipment	$600	$454
Separation Equipment	$150	$304

*= https://docs.google.com/spreadsheets/d/1Gx3rv07oDmRVMQRW_LsqOOiyiLERkYhJmVIEBli3Zv0/edit?gid=0#gid=0

- Mechanical equipment includes: body material, nose cone, ejection charge, and deployment mechanism servos.

References

- *Introduction to flight, John D. Andersen et. al.*
- Anderson, J. B., Mary, *Introduction to flight*, S.l.: Mcgraw-Hill Education, 2021.
- Raymer, D. P., *Aircraft Design: A Conceptual Approach*, Washington, D.C.: American Institute of Aeronautics and Astronautics Inc. , 1992.

Thank you!

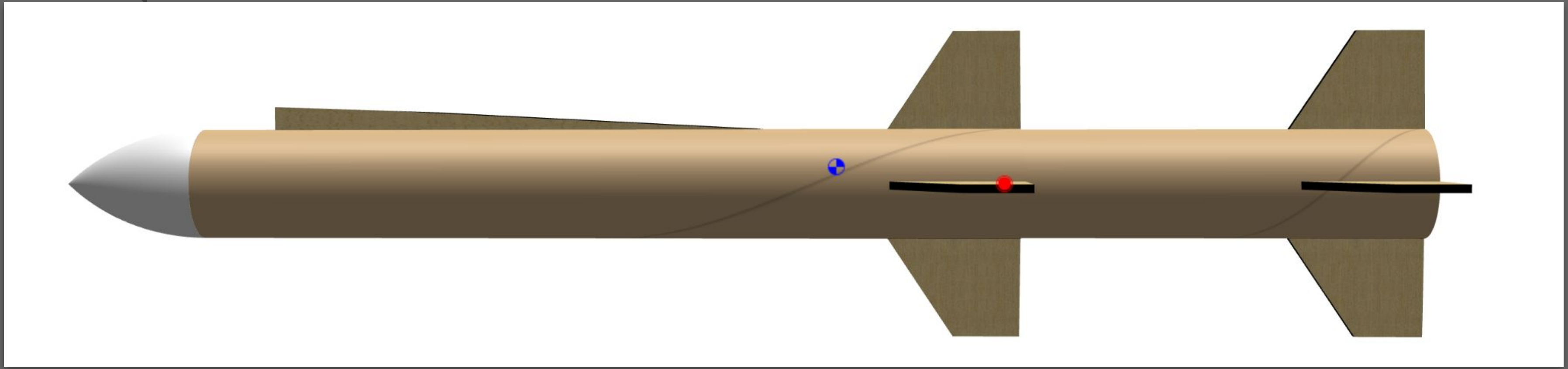
Questions?

Backup Slides

What’s in our rescue kit payload?

Part Name	mass (g)	Quantity	Total Weight (g)	Category Weight (g)
Bandage pack	36.22	1	36.22	367.32
small wound compress	0.7	4	2.8	
large wound compress	2.05	4	8.2	
alcohol pad	1.425	8	11.4	
dry burn dressing	7.5	1	7.5	
elastic bandage	10	1	10	
burn gel	3.5	1	3.5	
emergency blanket	62.8	1	62.8	
flashlight	84.6	1	84.6	
compass	28.6	1	28.6	
flint and steel	43.3	1	43.3	
knife	47.8	1	47.8	
whistle	2.6	1	2.6	
wire saw	17	1	17	
zip ties	0.2	5	1	

Boost Stability



Stability: 1.52 cal / 12.3 %

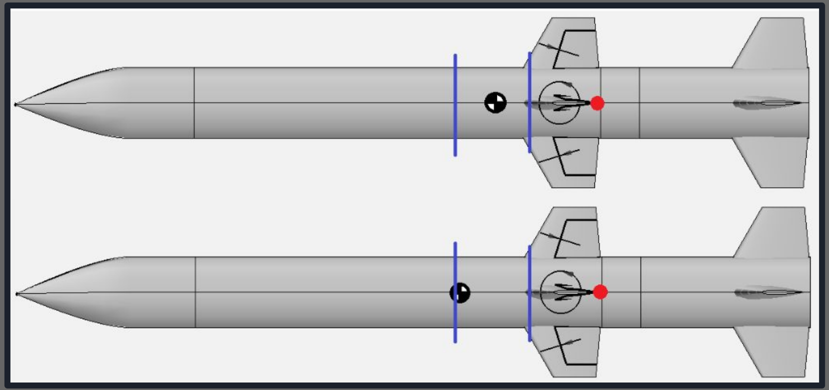
CG: 181 cm

CP: 220 cm

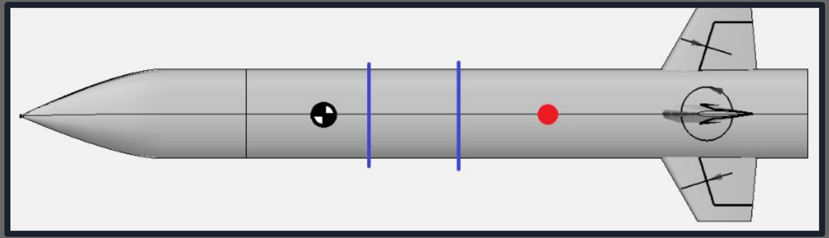
at M=0.300

Stability (Cont.)

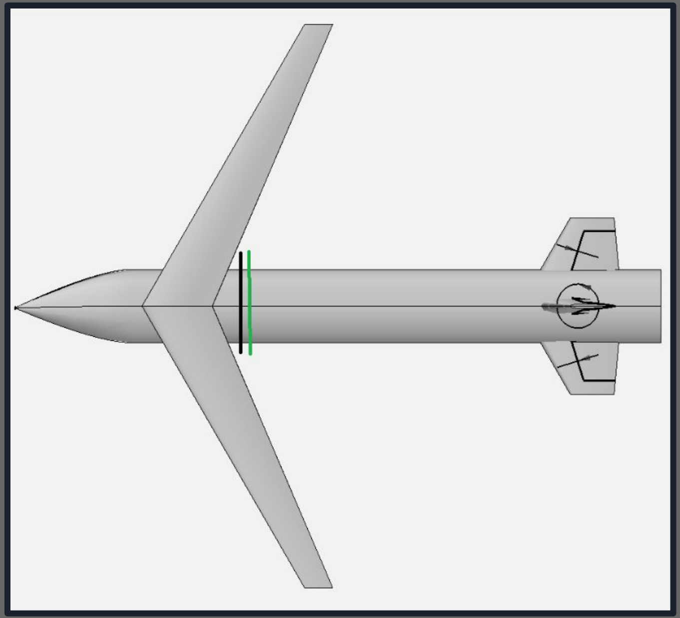
Center of Gravity | Center of Pressure | Neutral Point



Before and After Motor Burn



After Seperation



After Deployment (Static Margin of 13%)

Motor Specifications

L1420R-PS

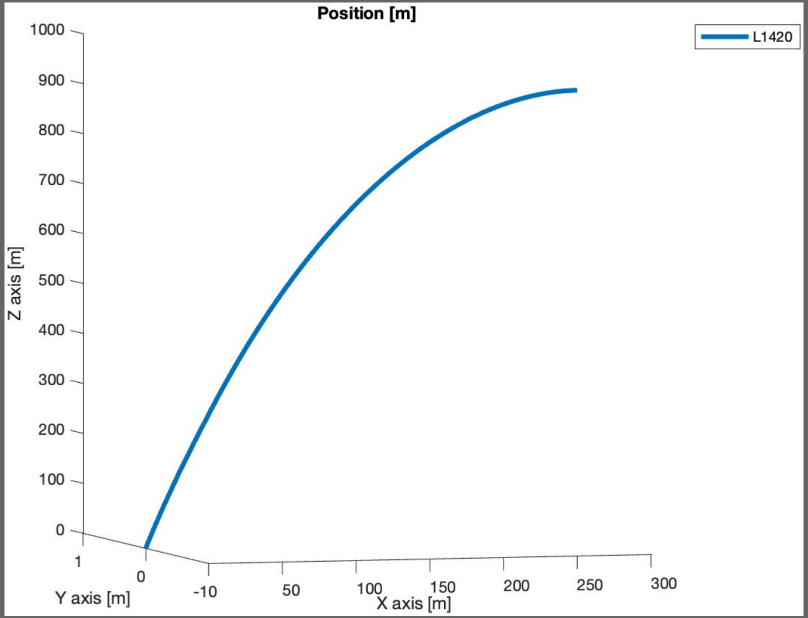
Total Mass: 4562 g

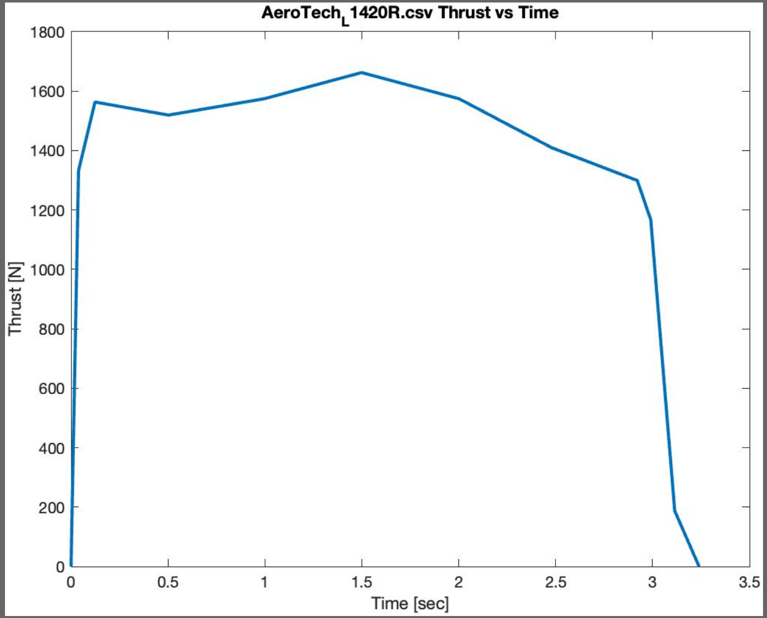
Motor Specifications

Total impulse:	4,603 N-sec (1,035 lb-sec)
Burn time:	3.2 sec
Peak thrust:	370 lbs (1,646 N)

Boost Flight Specifications: L1420R-PS

Level 2 Rocket Motor
Max Height: 2375.33 feet
Max speed: 333.304 mph





Rocket Calculations

Boost Model

Calculates:

- **Max Height**
- Time to Apogee
- Max Velocity
- Digitizes thrust curves

Assumptions:

- 41 lb
- 10 inch diameter
- reasonable approximation for air density

$F_{Net} = ma$

$F_{Net} = F_{Thrust} - F_{Gravity} - F_{Drag}$

$a = (F_{Thrust} - F_{Gravity} - F_{Drag}) / m$

$F_{Thrust} =$ Motor Force

$F_{Drag} = 0.5*\rho*Cd* V^2$

$m = 41 lbs$

Separation Calculations

$$Pressure(psi) = \frac{Force(lbs)}{Area(inch^2)}$$

For 10 inch diameter and 12 inch length

$$volume(inches^3) = \frac{\pi \times (diameter(inches))^2 \times Length(inches)}{4}$$

$$Grams(BP) = \frac{454grams}{1lbf} \times \frac{Pressure(psi) \times Volume(inches^3)}{266\frac{inches\bullet lbf}{lbm} \times 3307 \circ R}$$

Parachute

60" Elliptical Parachute

Weight Rating: 13 lbs

Weight of separation: 12.41513

Epoxy Strength

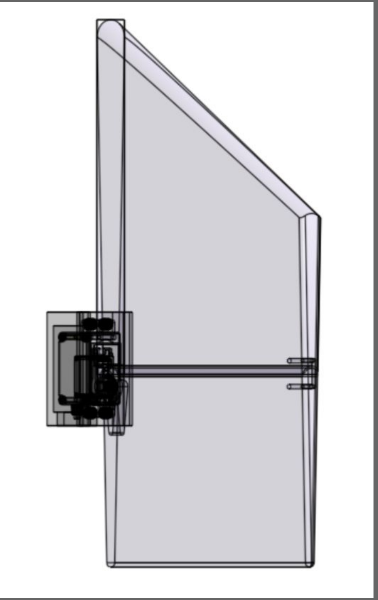
West System epoxy products are widely used because of the convenience and easy availability. If you buy into the system, pumps and all, you have a versatile and easy to use system. Unlike hobby shop epoxy, West System is very thin, perfect for fiberglassing. To thicken it, you can use a variety of powdered additives, each of which has its own uses.

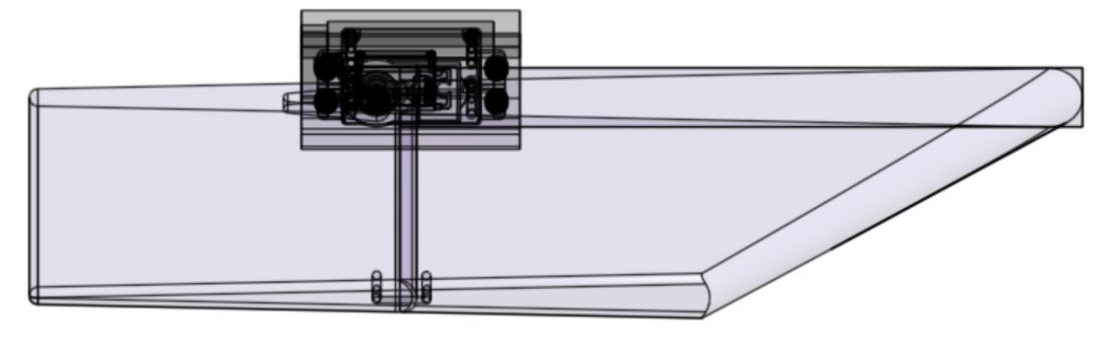
Sample	Material	Epoxy	Strength #	Average
1-2A	G-10	West System	2379.331	2346.5 (SD 24)
1-2B	G-10	West System	2337.961	
1-2C	G-10	West System	2322.104	

- Researched multiple commonly used epoxy solutions
- Shear strength of several thousand lbs is widely accessible

Control Fin Stake

- Stake to support control fin lever arm
- High-strength epoxy at servo-fin interface





Design Overview: Avionics Subsystem

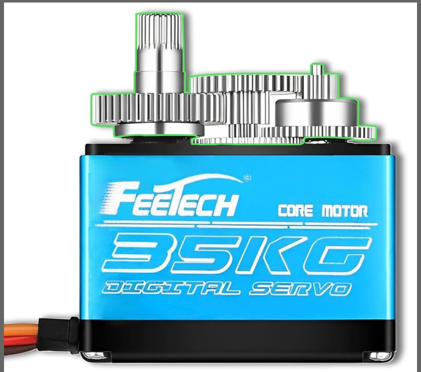
Power Module Specifications

Source: Holybro

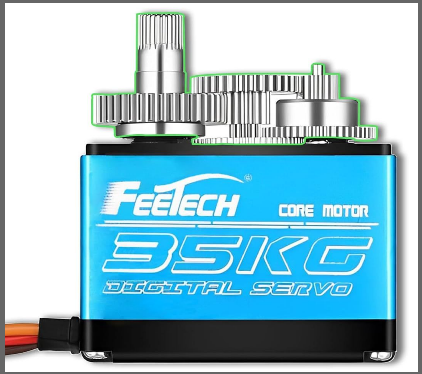
Input Voltage	Max Input Current	Output Voltage	Max Output Current
11.1VDC (3S)	60A	5.2VDC	3A

Design Overview: Avionics Subsystem

4x Control Surface Servos

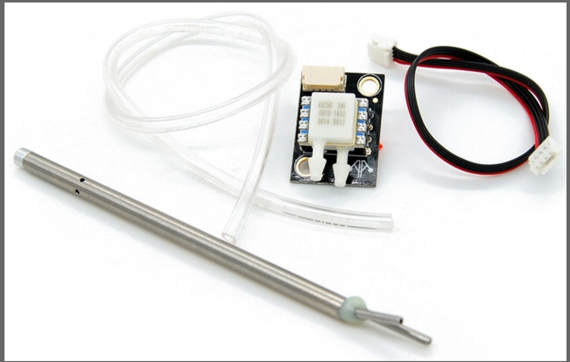


1x Deployment Servo



Item	Quantity	Required Torque [oz-in]	Actual Torque [oz-in]	FOS
Control Surface Servo	4	59.77	400.65	6.71
Deployment Servo	1	308.30	400.65	1.30

Design Overview: Avionics Subsystem



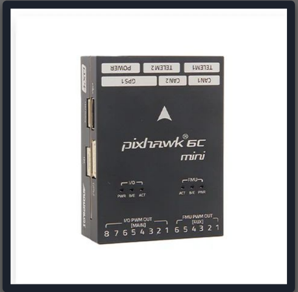
- External GPS module
- Gives real time position, velocity, heading, and altitude
- Seamless integration into PixHawk system, same manufacturer

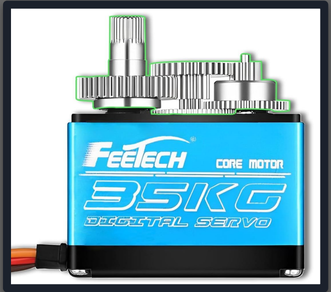
- External pitot tube at nose
- Uses static and dynamic pressures to estimate airspeed
- Gives system air relative velocity in addition to ground speed

PixHawk Sensors

Sensor	Range	Accuracy	Data Rate
Accel/Gyro: ICM-42688-P	±16 g/2000 dps	0.0005 g/0.06 dps	2 KHz
Accel/Gyro: BMI055	±16 g/2000 dps	0.008 g/0.06 dps	2 KHz
Mag: IST8310	±1600uT (x-y), ±2500uT (z)	0.3 uT	1 KHz
Barometer: MS5611	10-1200 mbar	1.5 mbar	10 Hz
Airspeed: MS4525DO	0-100 m/s	0.84 Pa	10 Hz
GPS: M9N	N/A	1.5 m CEP	5 Hz

Power Budget





Item	QTY	Current Consumption (mA)	Voltage (V)	Total Power Consumption [W]
Pixhawk 6C Mini	1	2500	5.2	13
GPS Module	1	200	5	1
Servos	5	750	6	5.4
Telemetry Radio	1	1000	5	5
Total		**4450**		**23.5**

LiPo Battery Model

Battery Specifications

Source: getfpv

Battery Type	Voltage	Capacity	Number of Cells	Max Continuous Discharge
LiPo	11.1VDC	2200 mAh	3S	25C

LiPo Battery Model

Major Assumptions

1. Constant Current Draw = 4.45A
2. Linear End Voltage = 10.05V
3. Battery Internal Resistance = 9Ohm per cell
4. Nonlinear Region 1 is the first 20% of runtime
5. Nonlinear Region 2 is the last 20% of runtime
6. Decaying constant k = 5
7. Efficiency of 90%

Improvements

1. Non constant current draw - Determine varying currents at different times
2. Adjust decay constant with experimental data
3. Measure real battery internal resistance
4. Adjust time of nonlinear regions to experimental data
5. Calculate inefficiencies
6. Calculate runtime with a 5-10% safety factor to cutoff voltage

LiPo Battery Model: Equations

Solving for Total Runtime

$$Runtime = \frac{Capacity \cdot 60}{I_{total}}$$

Solving for linear range of operation

$$m = \frac{(NominalVoltage - LinearEndVoltage)}{\Delta t}$$

Solving for nonlinear ranges of operation

$$V(t) = V_{inital} + (V_{final} - V_{inital}) \cdot e^{-k \cdot \frac{t}{T}}$$

Solving for actual voltage

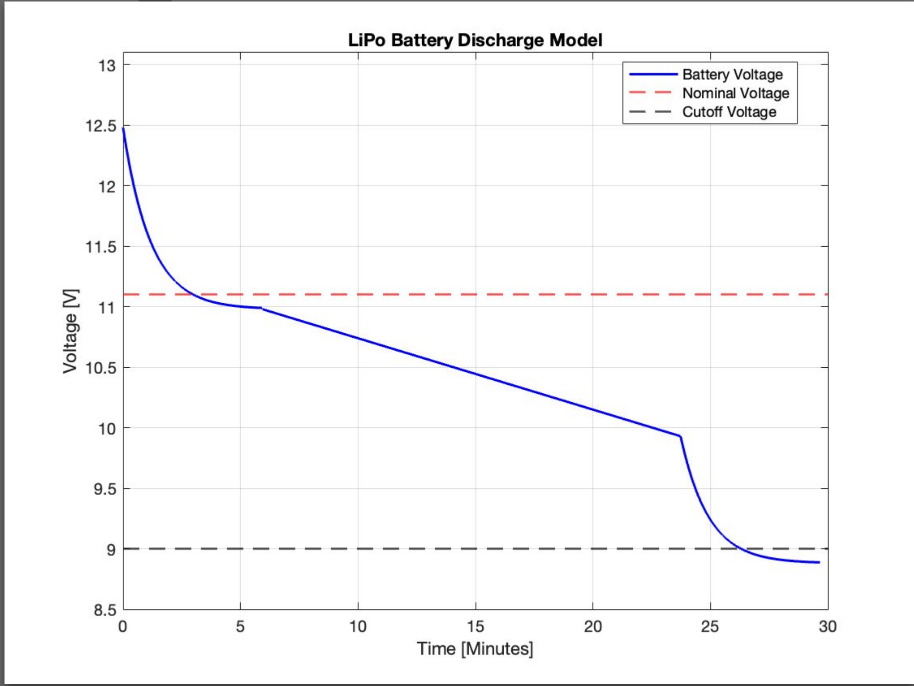
$$V_{actual}(t) = Voltage(t) - V_{drop}$$

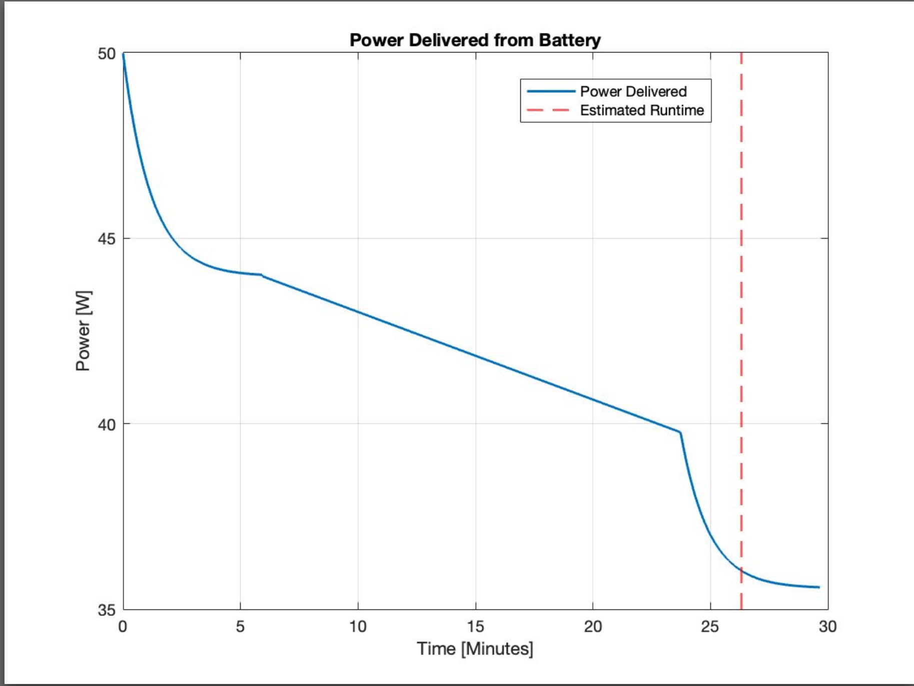
Solving for Power Delivered

$$P(t) = V_{actual}(t) \cdot I_{total} \cdot efficiency$$

LiPo Battery Model

Estimated Runtime 26.31 minutes -> *Assuming constant current the entire time which isn't true*





Why PID?

Proportional Derivative Control (PD Control)

- Decreases steady state error and increases damping

Proportional Integral Control (PI Control)

- Increases system type and might lead to increased overshoot (harder to tune gains)

Proportional Derivative Integral Control (PID Control)

- Increases system type and allows for **easier gain tuning to achieve desired closed loop response**

How are we tuning our gains?

Useful techniques

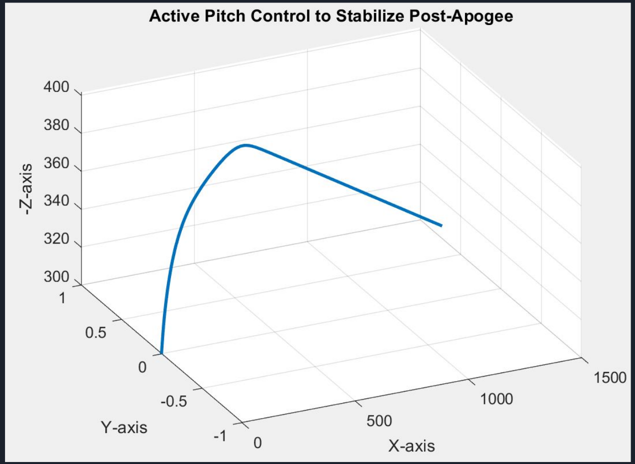
- Ziegler-Nichols Method (numerical-based)
- Root Locus (plot-based)
- Frequency Response Analysis (plot-based)

MATLAB Simulink PID Controller Auto-tuner employs all three for SISO systems!

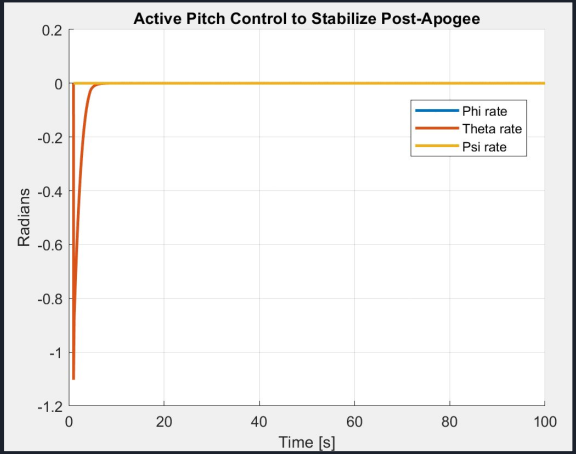
Ardupilot will take care of all the control integration for us!

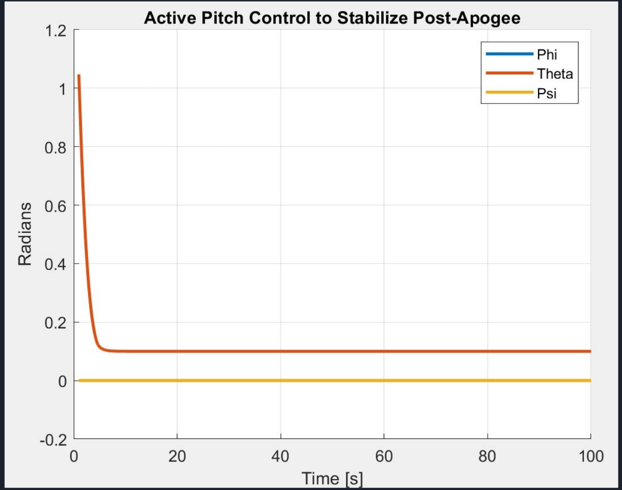
We will test the gains and adjust according to our desired closed loop response

Stabilize Pitch to Glide at Trim

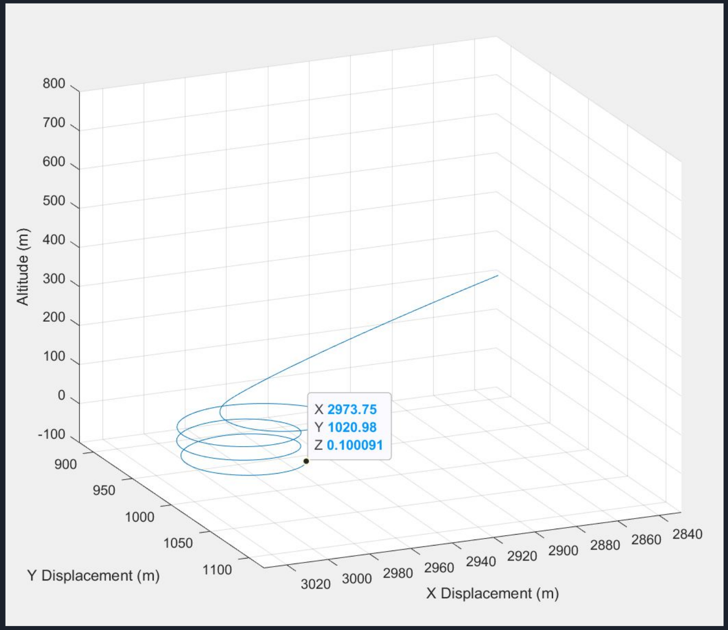


Controlling and eliminating pitch rate while aiming for a specific trim angle.

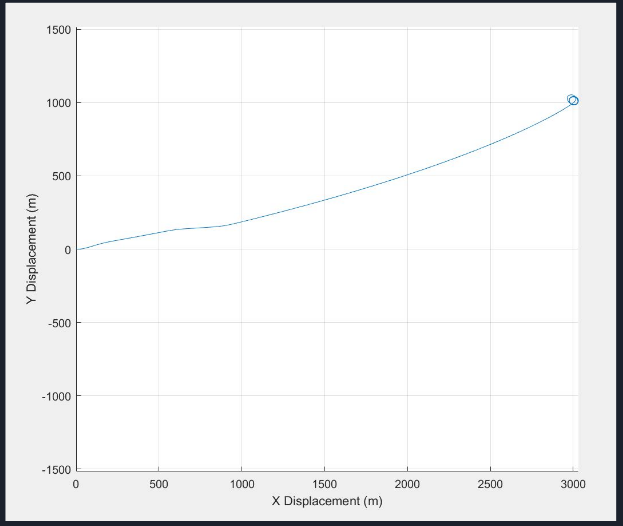




Wind Perturbation Analysis



- Modelled wind effects on the accuracy of control system
- Maximum speed to maintain 100ft accuracy
  - 10 mph constant wind with gusts up to 20mph



Controls Design: The Beginnings of an Aircraft Dynamics Model (6DOF)

Nonlinear equations of motion are linearized to allow for linear control systems.

Assumptions:

- Knowledge of full state with no sensor noise
- Rigid body, symmetric-aircraft about the x-z plane
- Flat Earth, constant mass and constant gravitational acceleration
- Small disturbance theory

Force equations

$$
\begin{aligned}
X - mgS_\theta &= m(\dot{u} + qw - rv) \\
Y + mgC_\theta S_\Phi &= m(\dot{v} + ru - pw) \\
Z + mgC_\theta C_\Phi &= m(\dot{w} + pv - qu)
\end{aligned}
$$

Moment equations

$$
\begin{aligned}
L &= I_x\dot{p} - I_{xz}\dot{r} + qr(I_z - I_y) - I_{xz}pq \\
M &= I_y\dot{q} + rp(I_x - I_z) + I_{xz}(p^2 - r^2) \\
N &= -I_{xz}\dot{p} + I_z\dot{r} + pq(I_y - I_x) + I_{xz}qr
\end{aligned}
$$

Body angular velocities in terms of Euler angles and Euler rates

$$
\begin{aligned}
p &= \dot{\Phi} - \dot{\psi}S_\theta \\
q &= \dot{\theta}C_\Phi + \dot{\psi}C_\theta S_\Phi \\
r &= \dot{\psi}C_\theta C_\Phi - \dot{\theta}S_\Phi
\end{aligned}
$$

Euler rates in terms of Euler angles and body angular velocities

$$
\begin{aligned}
\dot{\theta} &= qC_\Phi - rS_\Phi \\
\dot{\Phi} &= p + qS_\Phi T_\theta + rC_\Phi T_\theta \\
\dot{\psi} &= (qS_\Phi + rC_\Phi)\sec\theta
\end{aligned}
$$

Velocity of aircraft in the fixed frame in terms of Euler angles and body velocity components

$$
\begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \\ \frac{dz}{dt} \end{bmatrix} = \begin{bmatrix} C_\theta C_\psi & S_\Phi S_\theta C_\psi - C_\Phi S_\psi & C_\Phi S_\theta C_\psi + S_\Phi S_\psi \\ C_\theta S_\psi & S_\Phi S_\theta S_\psi + C_\Phi C_\psi & C_\Phi S_\theta S_\psi - S_\Phi C_\psi \\ -S_\theta & S_\Phi C_\theta & C_\Phi C_\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}
$$

Source: Illinois Institute of Technology https://control.asu.edu/Classes/MMAE441/Aircraft/441Lecture9.pdf

Controls Design: The Beginnings of an Aircraft Dynamics Model

Nondimensionalized Force & Moment Coefficients (Stability Frame)

- Geometric Parameters: Stability & Control Derivatives (from XFLR5 CAD)
- Dynamic Parameters: Alpha, Beta, Velocity, Rotation Rates, Deflections

General Coefficient Build-Up Example:

$$C_L = C_{L,0} + C_{L,\alpha}\alpha + C_{L,q}q + C_{L,\delta_e}\delta_e$$

Lift Coefficient Example note: q nondimensionalized by c/(2V)

Rotate Coefficients into Body Frame (DCM Matrix)

Controls Design: The Beginnings of an Aircraft Dynamics Model

<u>Dimensionalized Force & Moments in Body Frame</u>

- Nondimensional Variables: Force & Moment Coefficients
- Dimensionalization Variables: rho, V, S, b, c, etc. (flight conditions & geometry)

Force Dimensionalization Example:

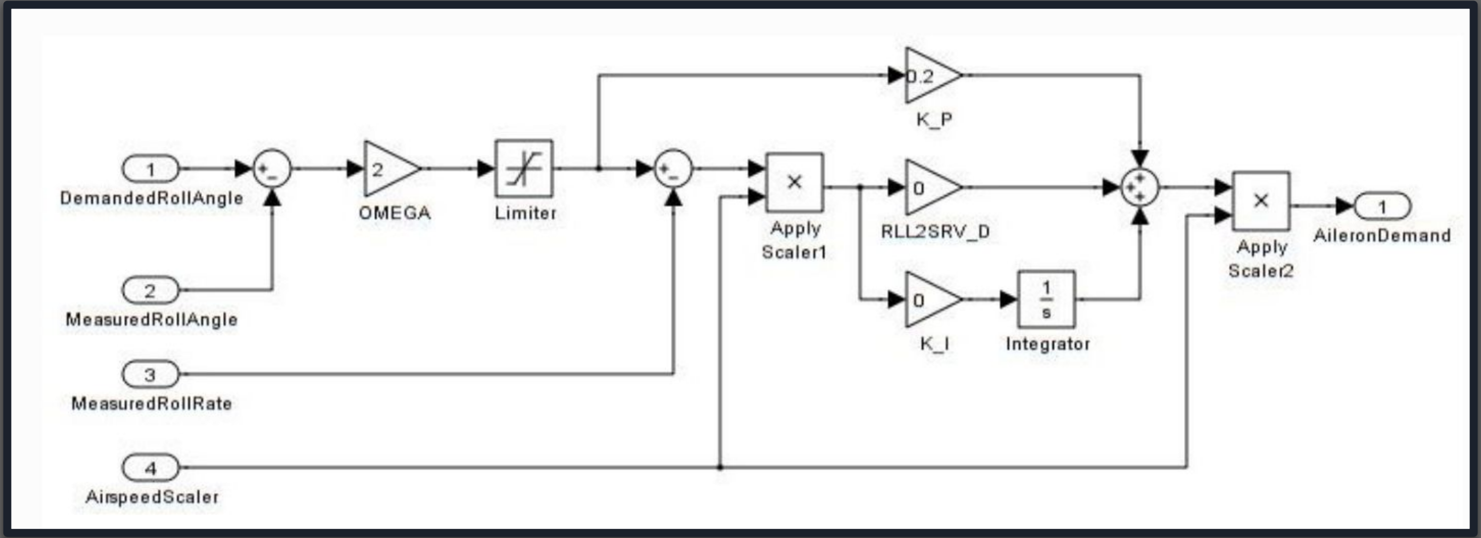
$$L = \frac{1}{2}\rho u_0^2 S C_L$$

Specific to Lift Use NP & CG (Static Margin) to find inherent Moments due to Lift

Rotate Forces & Moments into Inertial frame & pass into General 6DOF Dynamics System including Gravity

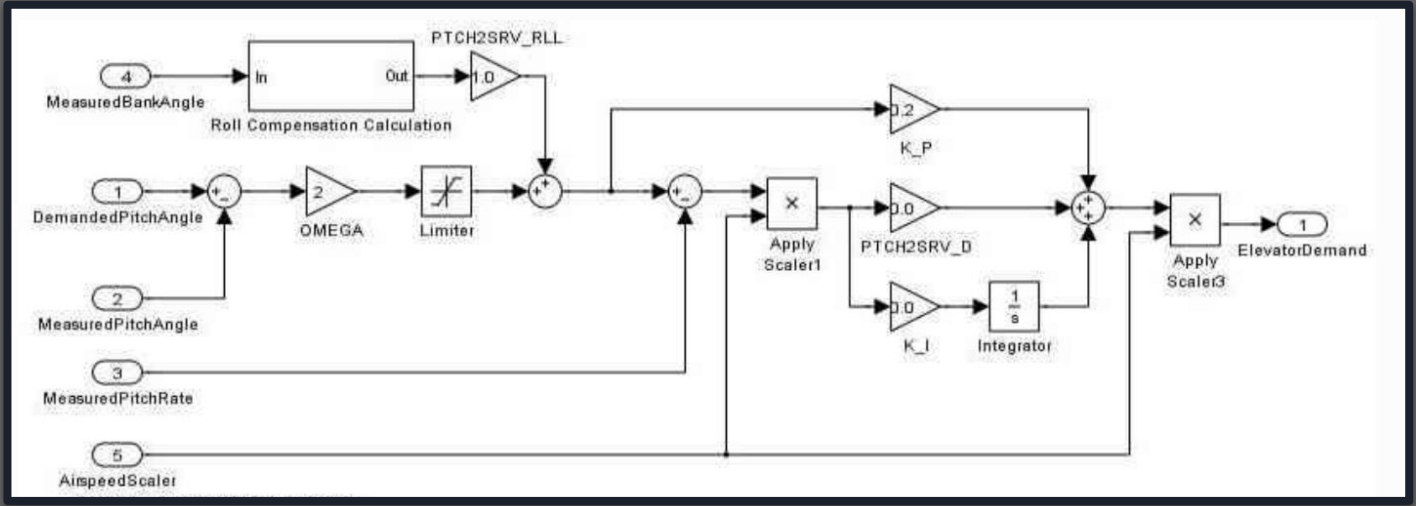
Controls Design: Ardupilot Control Laws

Roll Controller



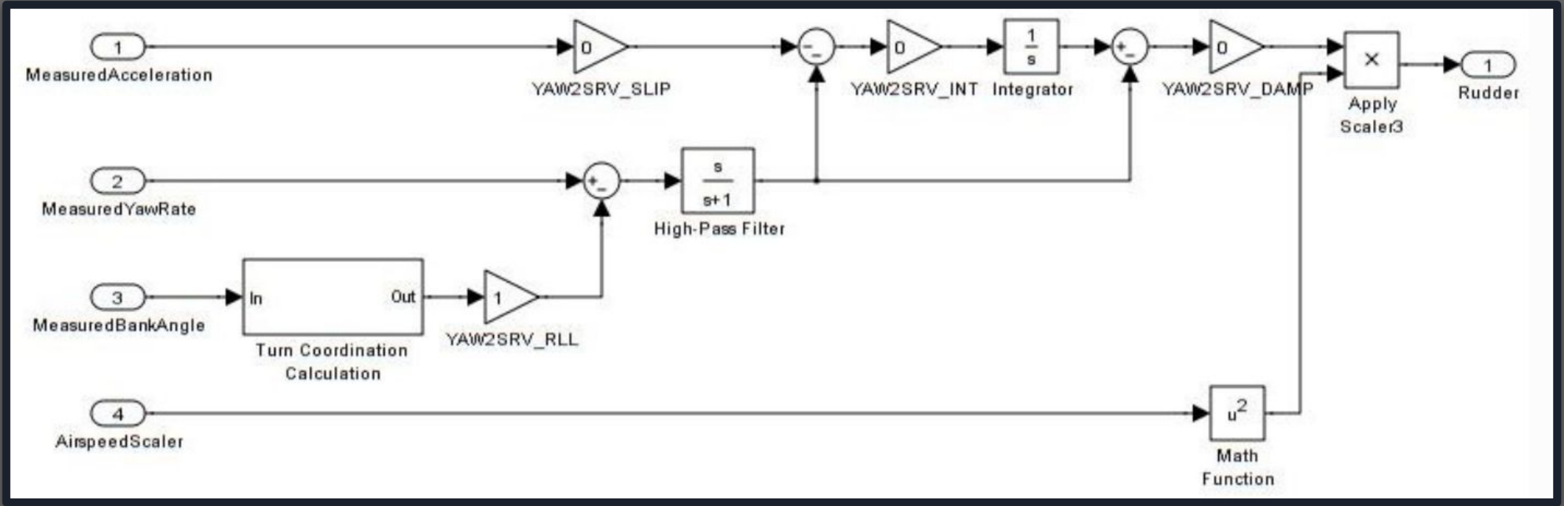
Controls Design: Ardupilot Control Laws

Pitch Controller

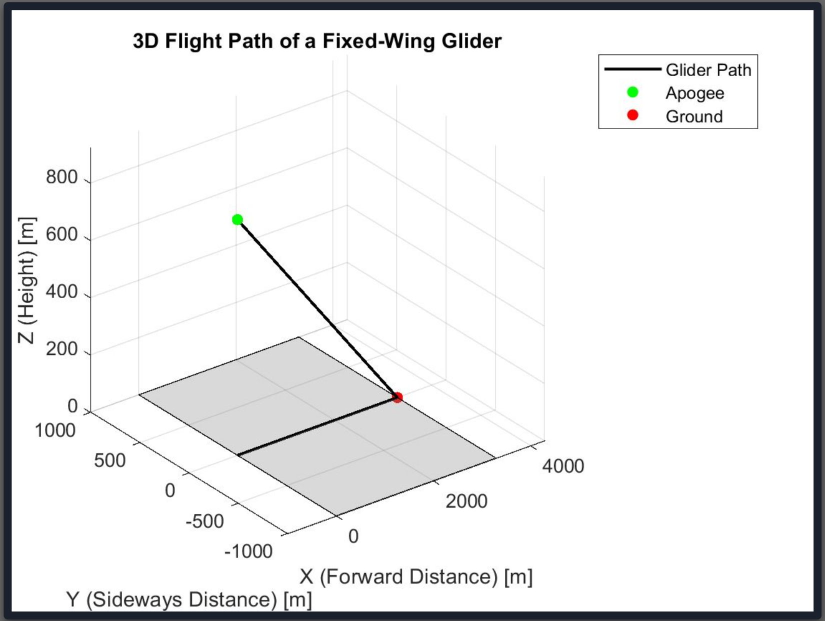


Controls Design: Ardupilot Control Laws

Yaw Controller



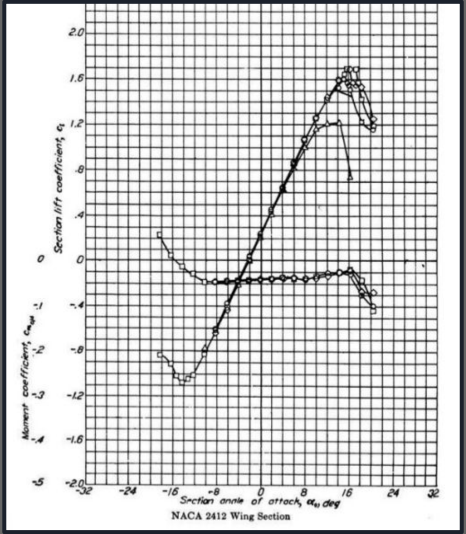
Simplified Glide Model



- L/D needed to achieve a range of 2 miles from 2200 ft ~= 4.
- Assumptions:
  - L/D ~= glide ratio
  - Constant descent rate
  - Glide angle ~= atan(1,glide ratio)
  - Raymer’s e equation for swept wings
  - L/D = L/D max (depends on AR and parasite drag)

CR Refresher Aerodynamics Model (Old/Original)

1. Empirical Airfoil Data



/ -> a_0 -> a

2. Anderson Coefficient Lift Formulas

$C_L = a * (\alpha - \alpha_{L=0})$

$k1 = 1/(\pi * e_0 * AR)$

$k2 = -2 * k1 * C_{L,minDrag}$

$C_{Di} = k1 * C_L^{\,2} + k2 * C_L$

3. Steady Unaccelerated Flight (SUF)

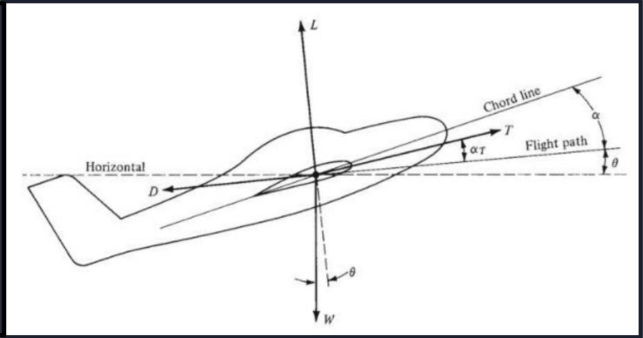
$T = D + W*\sin(\alpha)$

$L = W*\cos(\alpha)$

$W= m*g$

$V = \sqrt{(2*L)/(\varrho*C_L*S_{ref})}$

$Re = \varrho*V*c/\mu$



CR Refresher Aerodynamics Model (Old + New)

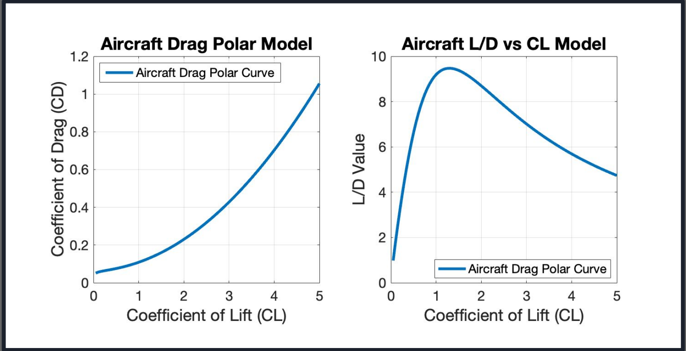
4. Raymer Component Build-up Model

AR & TR -> Chord -> Re -> C_f

SA -> FF

Sref -> S_{wet} & S_{Ref}

$C_{D0} = \sum(C_f * FF * Q * S_{wet})/S_{ref} + C_{D,L\&P}$

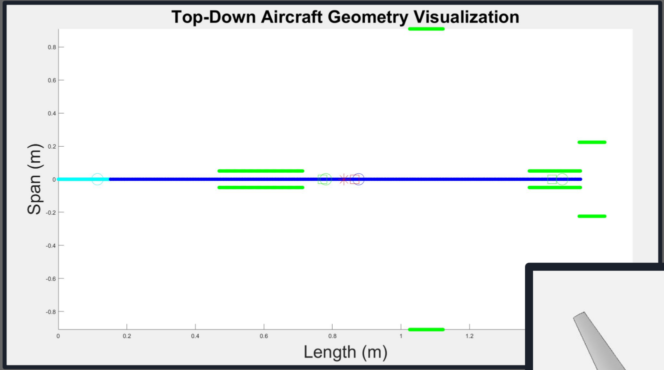


5. CG/NP Models (New)

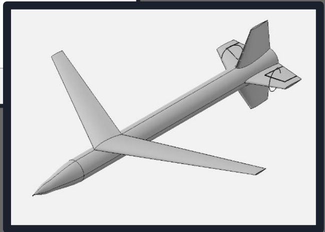
Assume xz plane symmetry (y)

CG_x: $\sum(m_{part} * x_{part}) / \sum(m_{parts})$

NP: $h_n = h_0 + \eta_s V_s (a_s / a_w)(1 - (d\varepsilon / d\alpha))$



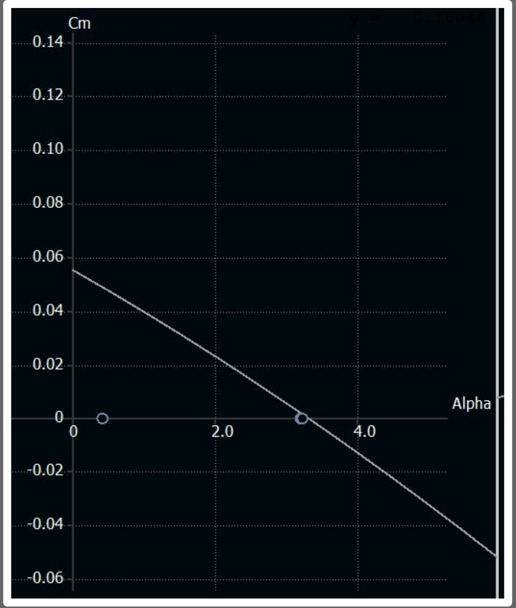
MATLAB 2D Top-Down Geometry



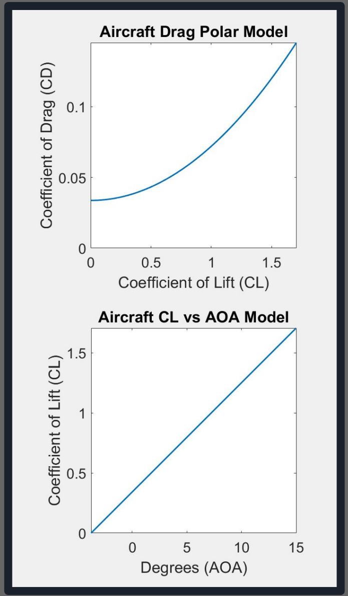
XFLR 3D Geometry

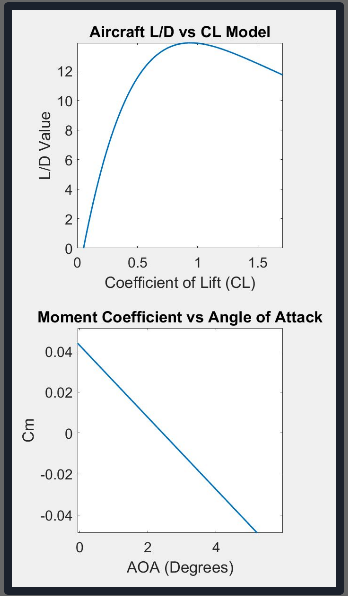
XFLR MATLAB Representation/Validation

XFLR Cm vs Alpha



Updated MATLAB Figures





MATLAB Cm vs Alpha

XFLR Cm vs Alpha y-intercept:

~ 0.58

MATLAB Cm vs Alpha y-intercept:

= 0.43 (-25% margin) (acceptable)

XFLR Cm vs Alpha slope:

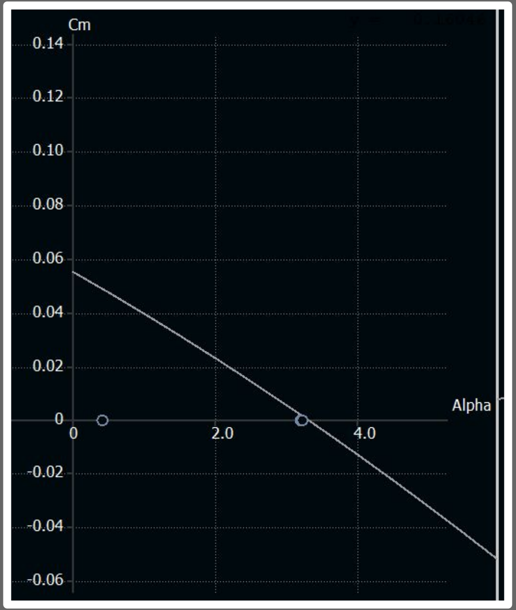
~ -0.0183

MATLAB Cm vs Alpha slope:

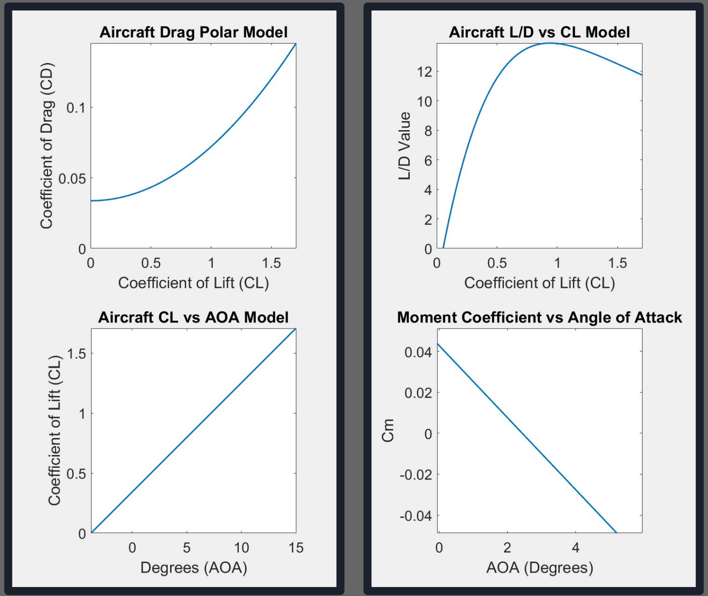
= -0.0176 (4% margin) (great✅)

XFLR MATLAB Representation/Validation

XFLR Cm vs Alpha



Updated MATLAB Figures



MATLAB Cm vs Alpha

XFLR NP Position:

14.96 inches aft of leading edge

MATLAB NP Position:

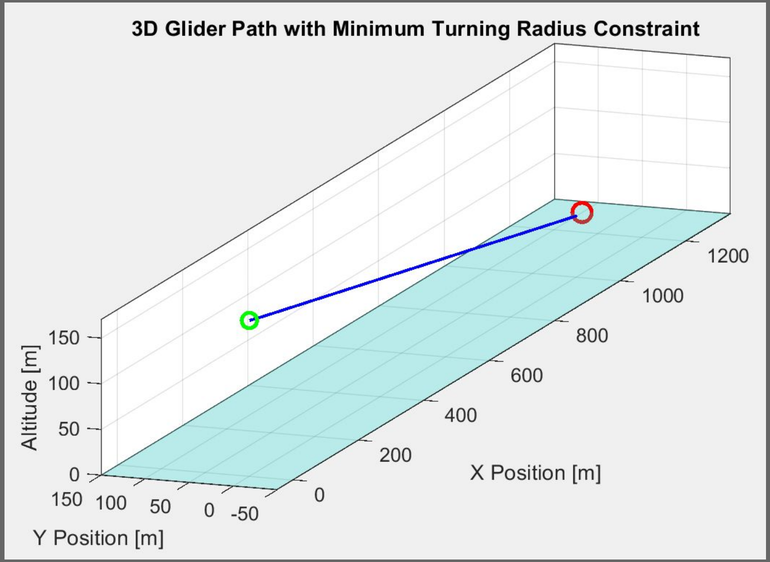
15.56 inches aft of leading edge

(4% margin) (great✅)

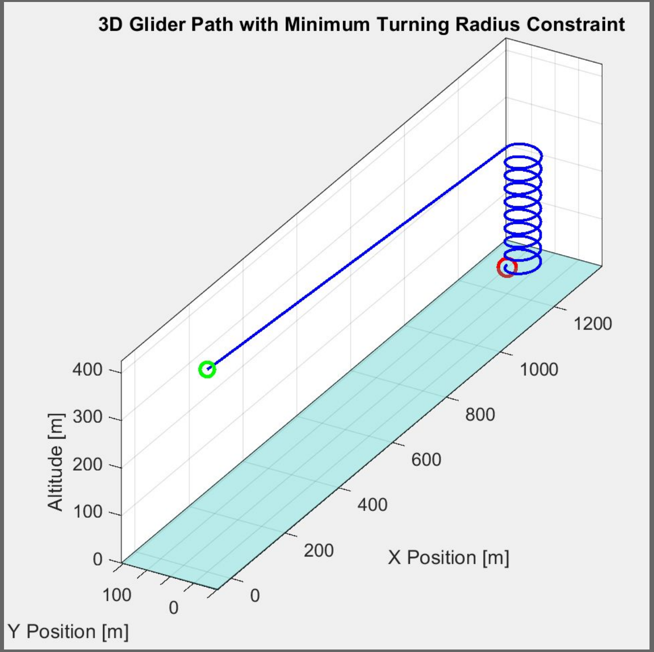
*Assumes constant L/D and descent rate for turns

How will we get there?

Pure Pursuit Algorithm* For Single Waypoint



Ideal Case



Overshoot Case

Error Estimates

- Varied output of XFLR stability derivatives
  - Ensure robustness of control gains

- Effects on waypoint guidance accuracy
  - Landed within 100 feet of target if error is below 15%

- Conclusions
  - XFLR is accurate enough for our application
  - Widely used for small scale aircraft control systems
  - Above 15% error, still reaches target but outside of 100 feet range
    - Safe to launch

Fin Structural Analysis

- NACA 0006 Airfoil
- Used V_{max} ≅300 ft/s (during boost)
- $C_D = C_d + C_{d,i}$ (from Airfoiltools and OpenVSP)

Ideal 0 deg angle of attack:

- **M = 2.676 lbf*in**
- **σ_b = 5.35 psi**

Account for perturbations incase, max 5 deg angle of attack:

- **M = 31 lbf*in**
- **σ_b = 62 psi**

Types of metals	Yield strength (PSI)	Ultimate tensile strength (PSI)
Stainless Steel 304	40,000	90,000
Aluminum 3003	21,000	22,000
Steel grade 50	50,000	65,000
Aluminum 6061-T6	40,000	45,000
Titanium Ti-6Al-4V (Grade 5)	160,000	170,000
Steel A36	36,000	58,000
AISI 1065 Carbon steel	71,000	92,100

Gensun Precision Machining www.china-machining.com

Deployment System Structural Analysis

- ¼ in. diameter Aluminum 6061 retention pin
- For 70 lb normal force in single shear, stress is 1,429 psi
- Aluminum 6061 shear is 30,000 psi
- Therefore, pin can hold spring force without bending or breaking

- Estimated friction force on pin: 22.2 kg
- With 1cm moment arm, torque is 22.2 kg cm
- Therefore, servo with 28.8 kg cm of torque can reliably pull the pin out

Fuselage Structural Analysis

- Compressive Force on Fuselage

$$F_{aerodynamic} = \frac{1}{2}\rho V^2 C_{drag} A_{csc} = 582.51\ (N)$$

$$F_{inertial} = F_{max\ thrust} = 1646\ (N)$$

$$F_c = F_{aerodynamic} + F_{inertial} = 2228.51\ (N)$$

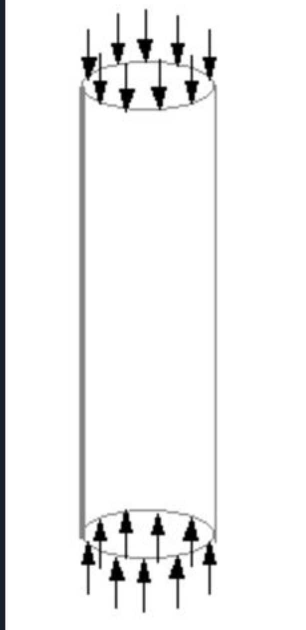
- Compressive Stress in Fuselage

$$\tau_{fail,\ fiberglass} > \frac{F_c}{\pi \cdot D_{fuselage} \cdot t_{fuselage}} \qquad t_{fuselage} > \frac{F_c}{\pi \cdot D_{fuselage} \cdot \tau_{fail,\ fiberglass}}$$

$$t_{fuselage} > 0.024\ (mm)$$

- Typical fiberglass rocket fuselage
  - 1.5 mm to 3 mm

- Design decision of ⅛ inches thickness to ensure component mounting success and large FOS



Thin-walled cylinder loaded in axial compression

Wing structural analysis

Lift force effects at maximum location

- Density = 0.0742 lb/ft^3
- V = 70 ft/s
- q= 181.8
- At AOA = 5 degrees,
- Cl at root = 0.42
- Cl at tip = 0.3
- Lift at root = 145.65 lbf
- Moment about the root = 195.08 lb*ft

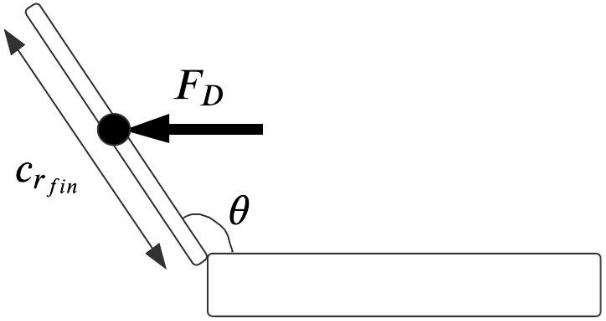
Drag force effects at maximum location

- V = 70ft/s
- q= 181.8
- Assume constant cl = 0.5
- Assume constant cd0 = 0.015
- AR = 5.4
- Cdi = 0.0135
- CD = 0.0285
- D max = 4.2lbf
- Stress max at root = 0.735 psi

Root I-beam analysis (Aluminum I beam support)

- Bending stress = M*c/I
- FOS = 1.5
- Thickness of root = 0.1125ft
- Thickness of base = 0.0563ft
- Stress allowable = 23,333.33 psi
- Area moment of inertia = 9.41*10^-3
- Base of I beam = 0.481ft

Servo-Actuator Torque Requirement



$$F_D = \frac{1}{2} * \rho * V^2 * C_D * A_c$$

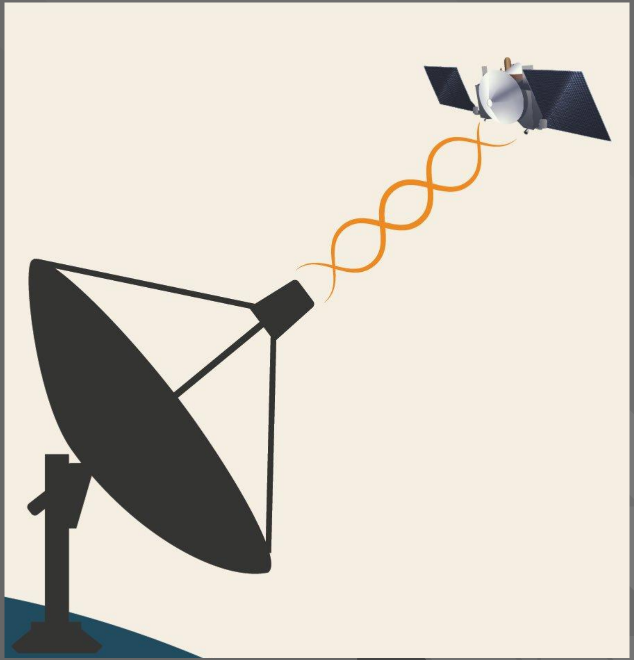
$$T = F_D * \frac{c_{r_{fin}}}{2} * cos(\theta - 90)$$

- Assumptions:
  - Rectangular control surface
  - Coefficient of drag for a flat plate perpendicular to the flow
  - V = 21.3 m/s
  - Sea level conditions
  - Servo-actuator is directly attached to the control surface's hinge
  - Maximum control surface deflection = 1 rad

- Torque Required = 0.4211Nm = 59.77 oz-in

Telemetry Test

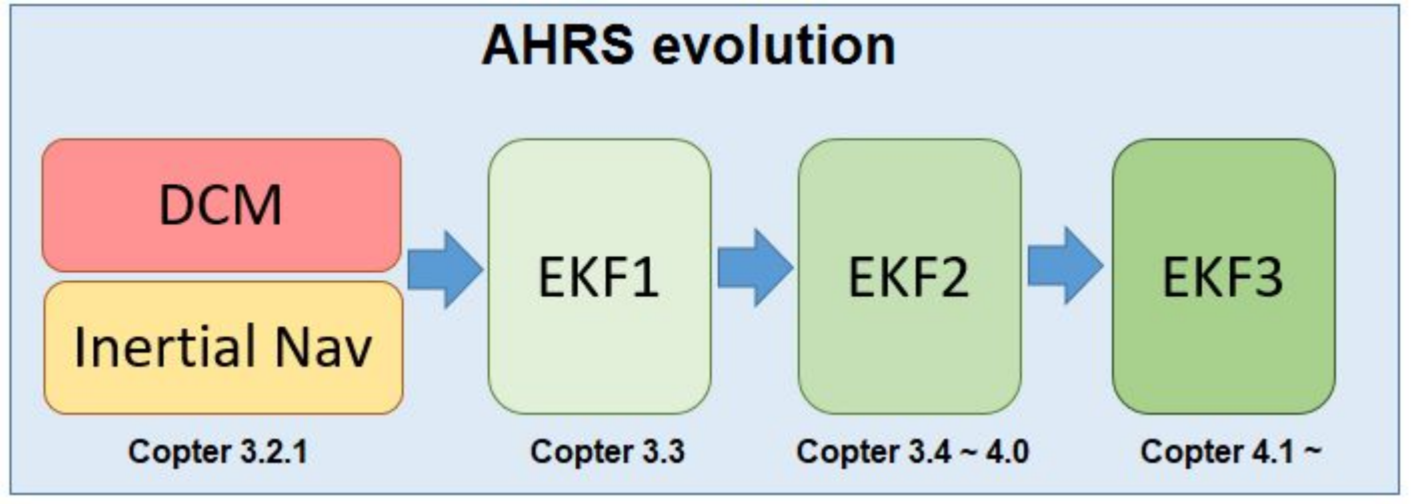
- Drive 2.5 miles down South Boulder Rd. with avionics in rocket body.
- Ensure that avionics can communicate location throughout drive.
- Simulates distance between launch team and avionics in flight.



Avionics Survivability

- Put avionics components inside L1 rocket for certification.
- Same layout as design.
- Ensures vibrations/forces during launch do not compromise mission.

Extended Kalman Filter (EKF)



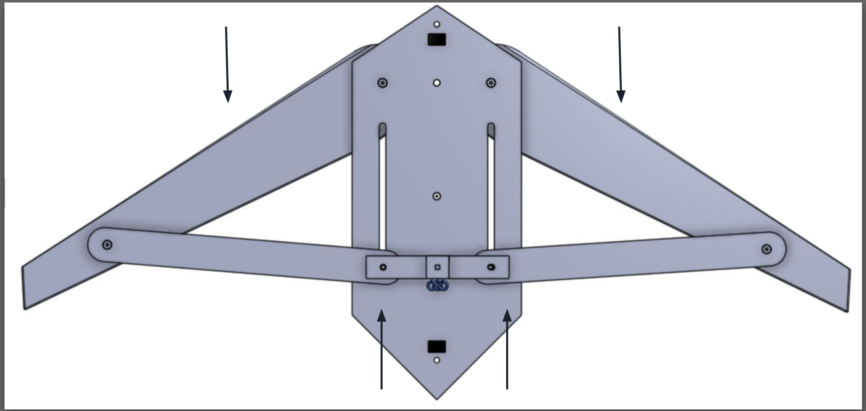
- Used by ardupilot to update system state for nonlinear dynamics and measurements
- If the autopilot has two (or more) IMUs available, two EKF "cores" (i.e. two instances of the EKF) will run in parallel, each using a different IMU. At any one time, only the output from a single EKF core is ever used, that core being the one that reports the best health which is determined by the consistency of its sensor data.

Drag Force on Sliding Block

- Total Drag Resisting Deployment = 20.31 lbs
- Force needed to counter drag during deployment >= Total Drag
- Minimum Distance = 11 inches
- Maximum Distance = 24 inches
- Spring Constant Needed = 2 lb/in
- Spring Force at max extension = 48 lbs
- Spring Force at minimum extension = 22 lbs

D = 20.31 lbs

D = 20.31 lbs



F = 20.31 lbs