# MK1 VTOL

Alexander Liou

Key Specs

- Span: 1.4m
- Mean Aero Chord: 0.22m
- Mass: 2.0 kg
- Battery: 2000 mAh 6s LiPO
- 3x 8” propellers + BLDC
- 2x thrust-tilt-control servos
- 4x control surface servos
- Hover Flight + Fixed Wing Flight

My Contributions: Everything

# Table of Contents

Project Scope

Aerodynamic Analysis + Design

Mechanical Design

Structural Analysis

Control

Next Steps

# Project Objectives and Scope

1. MD, Complete from-scratch design cycle including:
   a. Aero + Mech Design
   b. In-house Manufacturing (literally)
   c. Flight Controller Programming
   d. Testing + Tuning
2. Expand my technical knowledge
   a. Single person project - done in free time outside of work over summer
   b. Teensy 4.0 - modify open source controller
   c. Open VSP + MATLAB - aircraft configuration design
   d. Fusion - CAD
3. Mechanically and Aerodynamically Interesting
   a. VTOL, tiltrotor

## Requirements

### General

1. Budget: ~400$
2. 3D Printed + COTS
3. ESC: 60A
4. Battery: 200A
5. Mass: < 2.5 kg

### Aero

1. Steady Level Flight
2. Basic Aircraft Maneuvers
3. Aerodynamic Stability
4. Steady, Controlled Hover
5. Transition Flight

Project Scope

Aerodynamic Analysis + Design

Mechanical Design

Structural Analysis

Control

Next Steps

# Parameters of Interest

- Mass Approximation - Motor Sizing
- Wing Loading
- Aspect Ratio
- Stall Speed
- Load Factor
- Overall Dimensions
- Turning Rate
- Airfoils
    a. Wing: Clark-y http://airfoiltools.com/airfoil/details?airfoil=clarky-il#polars
        i. Reasonable low speed performance + Manufacturable
    b. Tail: NACA 0012 http://www.airfoiltools.com/airfoil/details?airfoil=n0012-il
        i. Symmetrical for pitch in both directions, no Cm0

# Mass Approx

Estimated Expected mass:

- 750g filament
- 210g motors
- 100g servos
- 100g other hardware
- 150g esc's
- 100g electronics
- 300g battery

Total: 1710g

Goal: 1800g aircraft

Final: 2000g aircraft

Thrust: hover combined ~9 kg (high thrust-to-weight)

V2808 Test Report

| Propeller | Type | Throttle | Voltage (V) | Current (A) | RPM | Thrust (g) | Power (W) | Efficiency (g/W) |
|---|---|---|---|---|---|---|---|---|
| GF8040-3 | 1300KV | 20% | 25.2 | 2.2 | 6550.4 | 237.1 | 54.5 | 4.35 |
| | | 40% | 25.1 | 8.2 | 10460.7 | 770.0 | 206.6 | 3.73 |
| | | 60% | 24.9 | 19.6 | 14102 | 1554.0 | 487.0 | 3.19 |
| | | 80% | 24.6 | 38.5 | 17229.6 | 2409.8 | 946.4 | 2.55 |
| | | 100% | 24.3 | 61.0 | 19222.2 | 3083.4 | 1479.9 | 2.08 |
| | 1500KV | 20% | 25.2 | 3.1 | 7279.6 | 325.9 | 76.9 | 4.24 |
| | | 40% | 25.1 | 11.1 | 11519 | 985.8 | 277.4 | 3.55 |
| | | 60% | 24.8 | 29.7 | 15043.4 | 1780.0 | 736.6 | 2.42 |
| | | 80% | 24.4 | 52.5 | 18009.6 | 2644.0 | 1282.9 | 2.06 |
| | | 100% | 24.0 | 74.3 | 19241.8 | 3069.0 | 1781.7 | 1.72 |
| | 1950KV | 20% | 16.8 | 3.2 | 6335.1 | 224.8 | 54.4 | 4.13 |
| | | 40% | 16.7 | 11.8 | 9960.7 | 696.9 | 196.6 | 3.54 |
| | | 60% | 16.4 | 26.9 | 13484.8 | 1352.3 | 441.7 | 3.06 |
| | | 80% | 16.0 | 51.5 | 16439.1 | 2049.7 | 825.9 | 2.48 |
| | | 100% | 15.6 | 79.4 | 18210.3 | 2631.1 | 1237.7 | 2.13 |

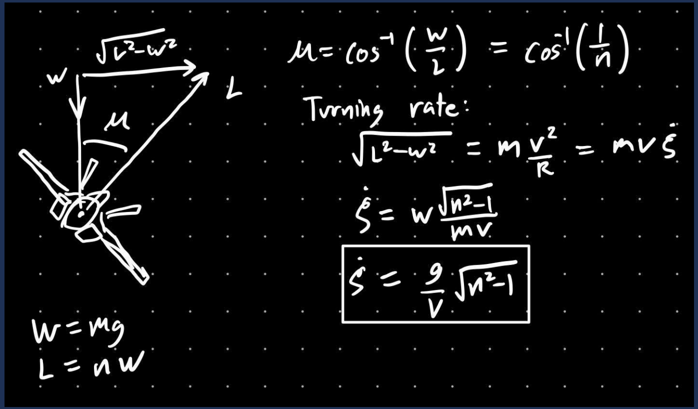
# Dynamic Analysis for Design

## Load Cases

1. Steady Level Flight
   a. L = W: ~18N
   b. Desire low stall speed
2. Turning Rate
   a. Desire max load factor of 5 without stall - nearly acrobatic
   b. Max bank angle for const altitude turn: 78 degrees
   c. Desire <20 m/s speed (I'm not a pilot)
   d. Obtain 2.4 rad/s turning speed = 138 deg/s -> 2.6s full circle

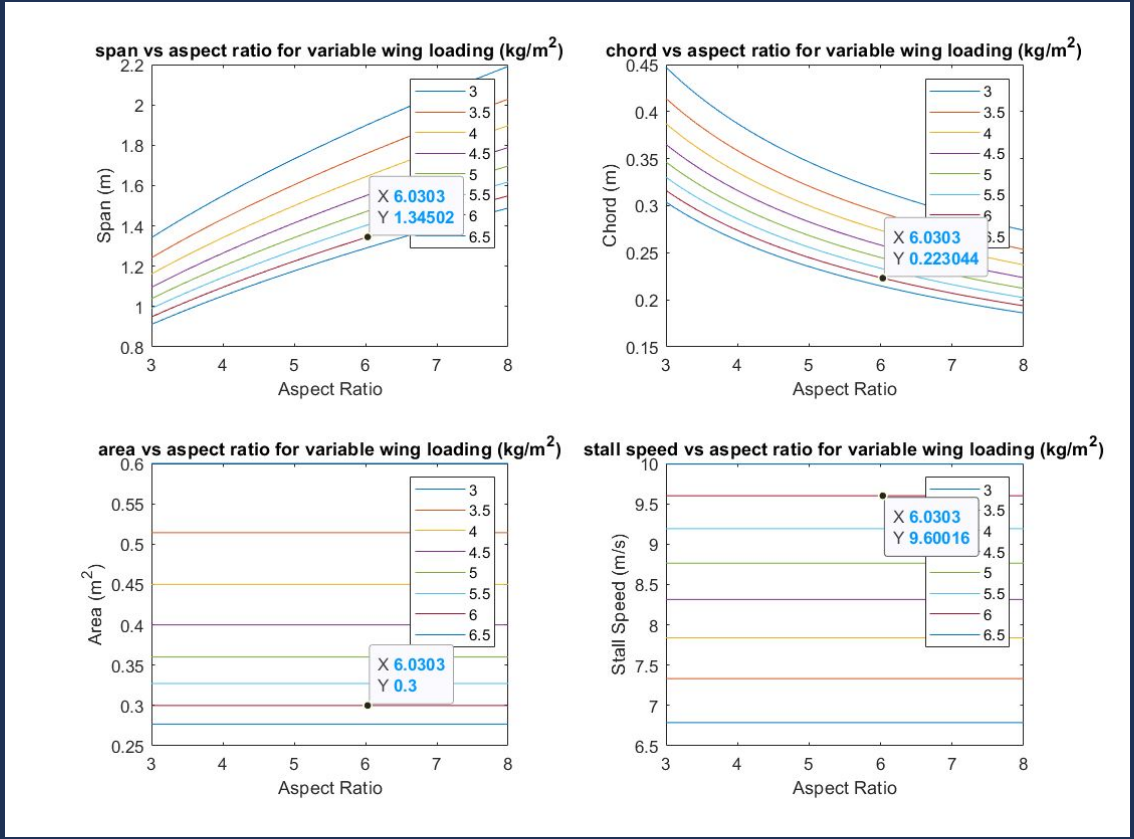
## Design Tradeoff

- Parameter: AR
  - Balance: stall speed, overall dimensions, area



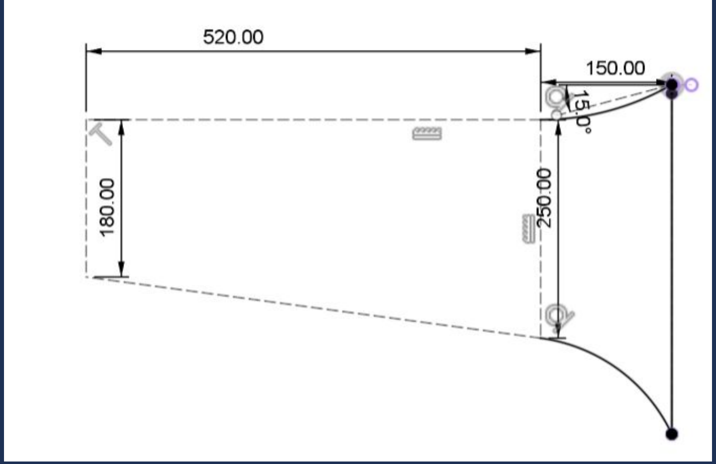
# Steady Flight Trades

- Chose 6 kg/m^2 wing loading
- Desire higher AR for reasonable efficiency (>5)
- Max dimensions limiting
- Error - mass is approx



# Wing Sizing

- From tradeoff and selected loading:
- b = 1.34m
  - Actual slightly different from winglet
- c (MAC) = 0.223m
  - Actual slightly different
- S = 0.3m^2
- Stall speed ~9-10 m/s
- 2 deg incidence




cm values

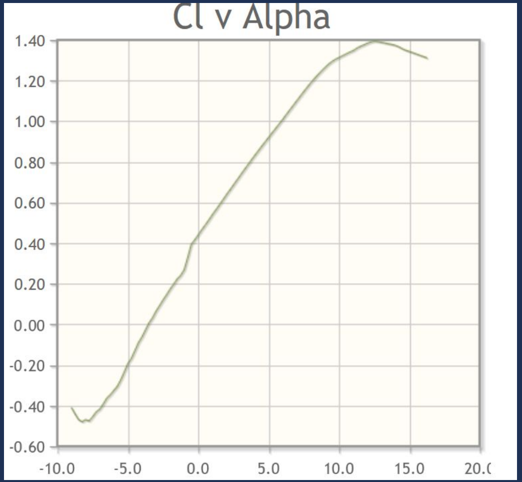
| Total Planform | |
|---|---|
| Span | 142.00000 |
| Proj Span | 140.92820 |
| Chord | 21.33333 |
| Area | 3203.0000 |
| Aspect Ratio | 6.20067 |

# Stall Calculations

$$C_{L_\alpha} = \frac{\pi AR}{\left[1+\sqrt{1+\left(\frac{AR}{2}\right)^2}\right]}$$

$$C_{L_\alpha} \triangleq \left(\frac{\partial C_L}{\partial \alpha}\right)_{3-D} = \frac{2\pi AR}{AR+2} = 2\pi\left(\frac{AR}{AR+2}\right)$$

- Assuming linear Cl
- Helmbold Equation + High AR inviscid approximation:
    - ClarkY Airfoil: camber introduces alpha0 = -3.5 deg
    - Give similar results, Cl3D max ~ 1.06
    - ClarkY Airfoil: stalls around >10 deg for given Reynolds Number
    - Stall Speed 10.1 m/s
- L = q S Cl




https://stengel.mycpanel.princeton.edu/MAE331Lecture3.pdf

# Tail Sizing

- Tail volume method:
- Given V-tail config, ~40 deg dihedral, ~60 cm between wing + tail
- Desire V_H ~ 0.4
  - Sxy ~ 440 cm^2 projected horiz area
- Desire V_V > 0.04
  - Sxz ~ 268 cm^2 projected vert area
- Actual:
  - Sxy = 439 cm^2
  - Sxz = 368 cm^2
  - Played with VSP parameters
- -3 deg incidence

$$V_H = \frac{S_t l_t}{S \bar{c}}$$

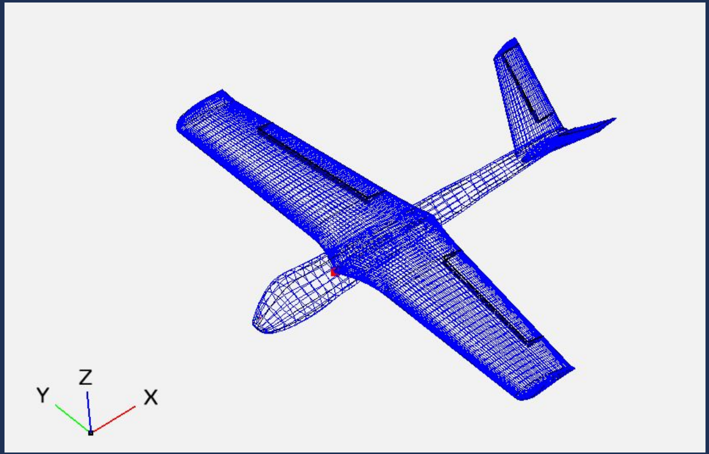
$$V_v = \frac{S_v L_v}{S b}$$

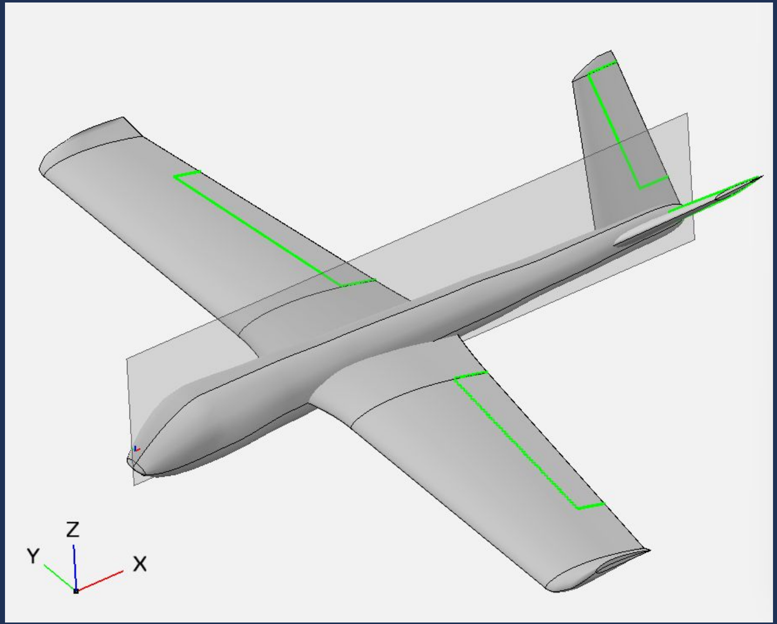
| No | Aircraft | Horizontal tail volume coefficient $(\overline{V_H})$ | Vertical tail volume coefficient $(\overline{V_V})$ |
|---|---|---|---|
| 1 | Glider and motor glider | 0.6 | 0.03 |
| 2 | Home-built | 0.5 | 0.04 |
| 3 | GA-single prop-driven engine | 0.7 | 0.04 |
| 4 | GA-twin prop-driven engine | 0.8 | 0.07 |
| 5 | GA with canard | 0.6 | 0.05 |
| 6 | Agricultural | 0.5 | 0.04 |
| 7 | Twin turboprop | 0.9 | 0.08 |
| 8 | Jet trainer | 0.7 | 0.06 |
| 9 | Fighter aircraft | 0.4 | 0.07 |
| 10 | Fighter (With canard) | 0.1 | 0.06 |
| 11 | Bomber/military transport | 1 | 0.08 |
| 12 | Jet transport | 1.1 | 0.09 |

https://www.vibgyorpublishers.org/content/ijaae/ijaae-3-019-table2.html

# Open VSP

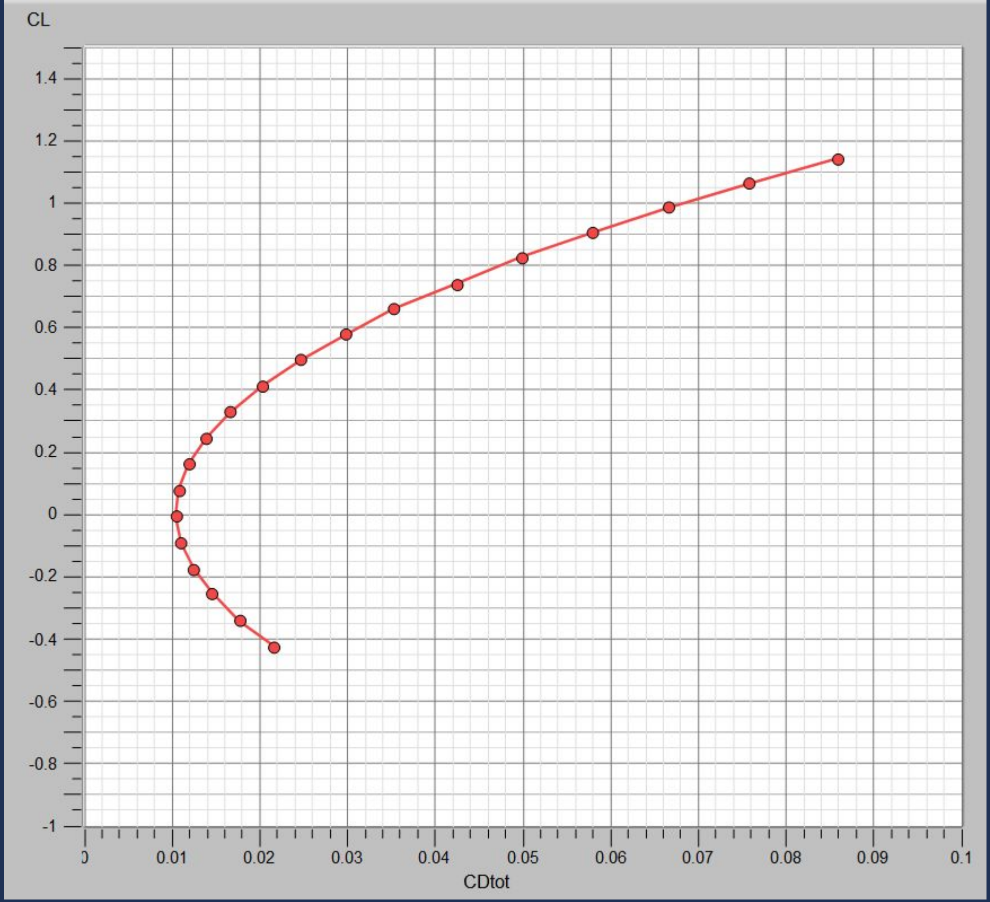
- Inviscid flow solver - vortex lattice method
- Modify aircraft configuration easily
- Once configuration decided, move to CAD



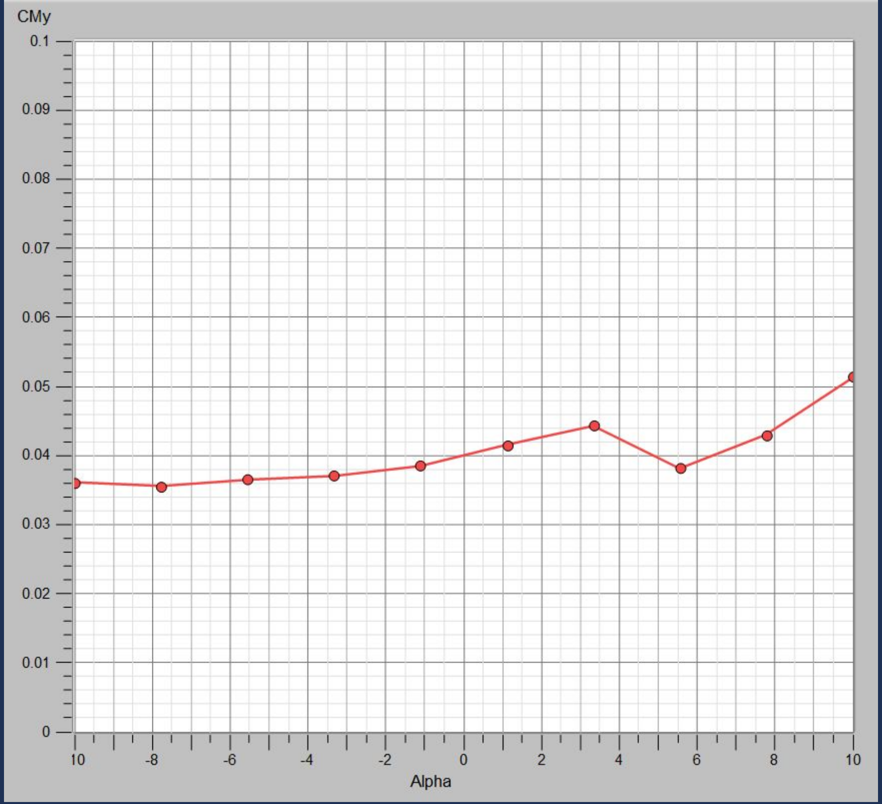
# Drag Polar

- Thrust is significantly more than induced drag for expected range of angles



# Neutral Point - M independent of alpha

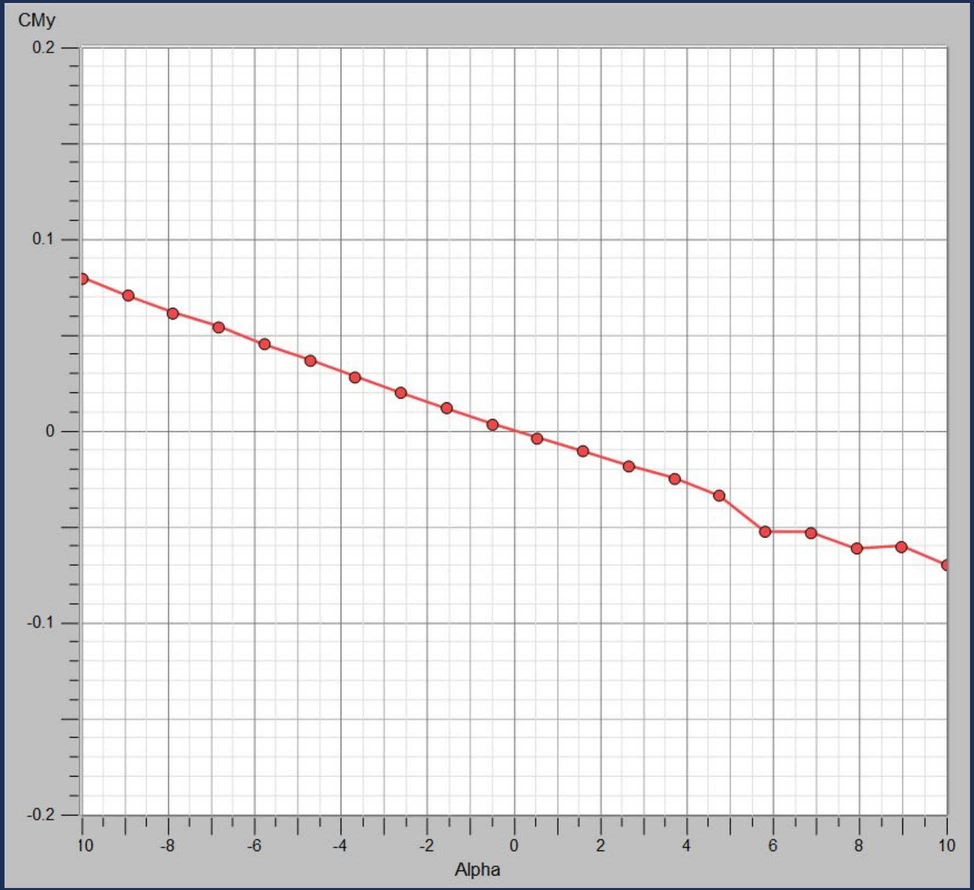
- Iteratively simulated for NP:
- Cm independent of Alpha
- 11 cm aft of root chord LE



# Aero Stability

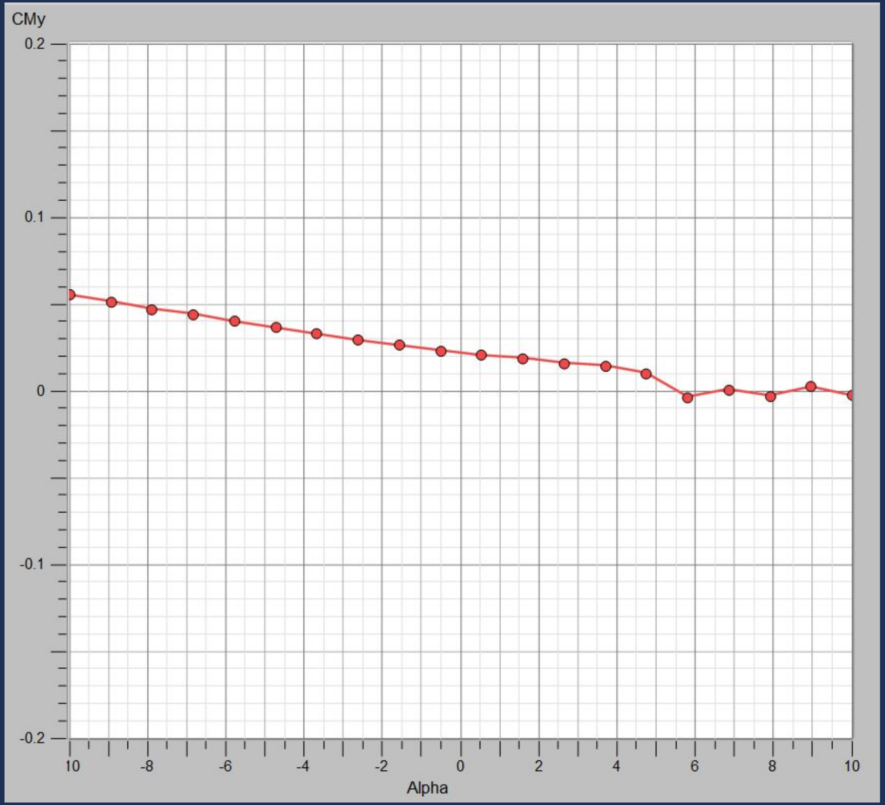
Restoring Aero Moment

- Pitch trim approx 0 deg
- Requires CG: ~8.75cm aft of root chord LE
- Static Margin: 0.1
  - Rule of thumb >5%
- Designed to be stick-free stable
- Changed tail incidence to trim aircraft



# Aero Stability for Most Efficient Flight

- Alpha for max L/D: 5 deg
- Required CG: 10cm aft of root chord LE
- Static margin: 0.045
    - Less stable, but more efficient
    - Move battery mount to move CG



This took a while

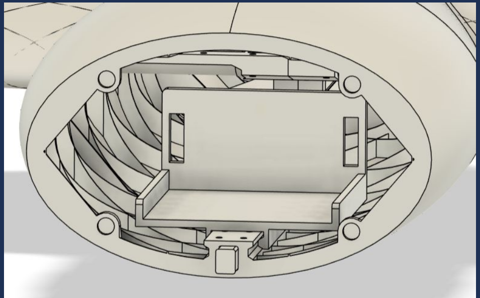
- Project Scope
- Aerodynamic Analysis + Design
- **Mechanical Design**
- Structural Analysis
- Control
- Next Steps

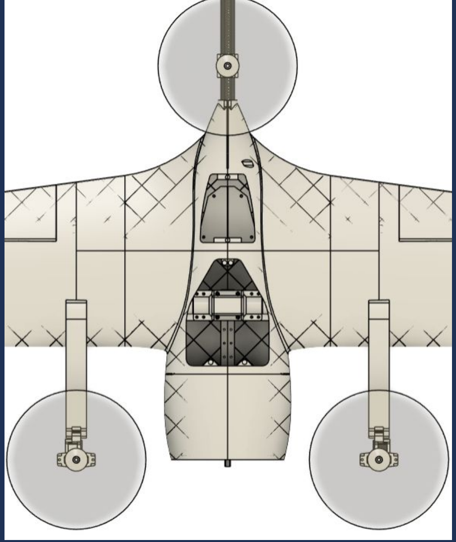
# Parametrization

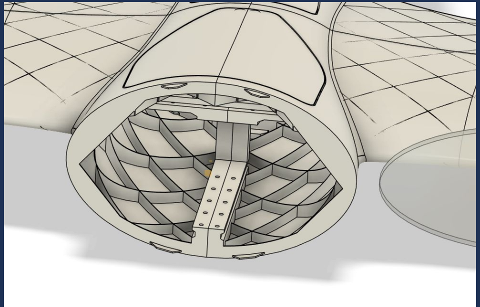
- Configuration Variables:
  - Main wing size, position, and incidence
  - Tail size, position, and incidence
  - Aileron and ruddervader size and position
- CAD organization
  - Airframe - high level master geometry
    - Wing + Fuselage
      - Wing + Fuselage Geo
      - Motors + tiltrotor Geo
    - Empennage
    - Rear Lift Prop
- Philosophy
  - Easily changed via parameters
  - Minimum mass

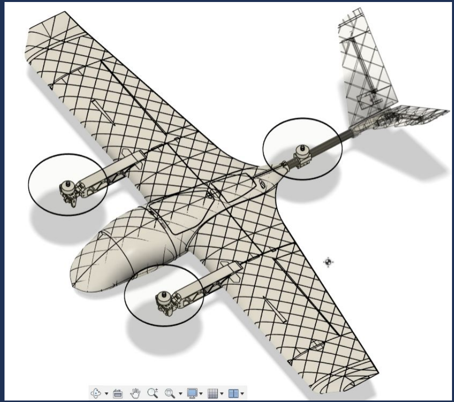
# Wing and Fuselage

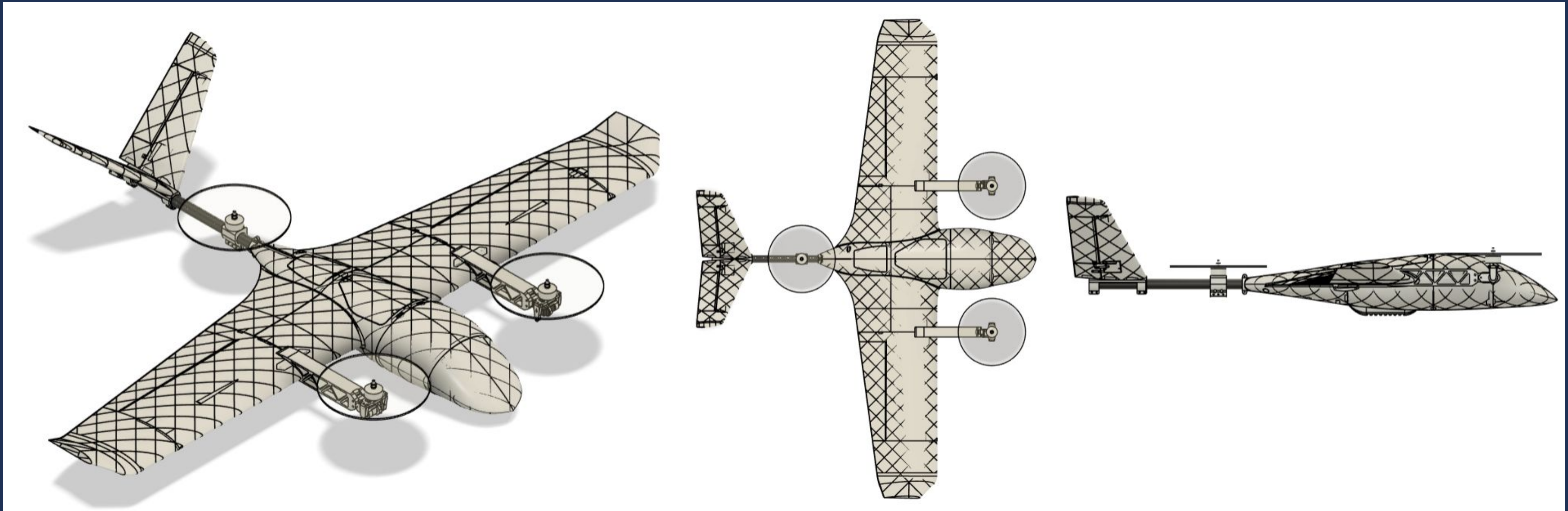
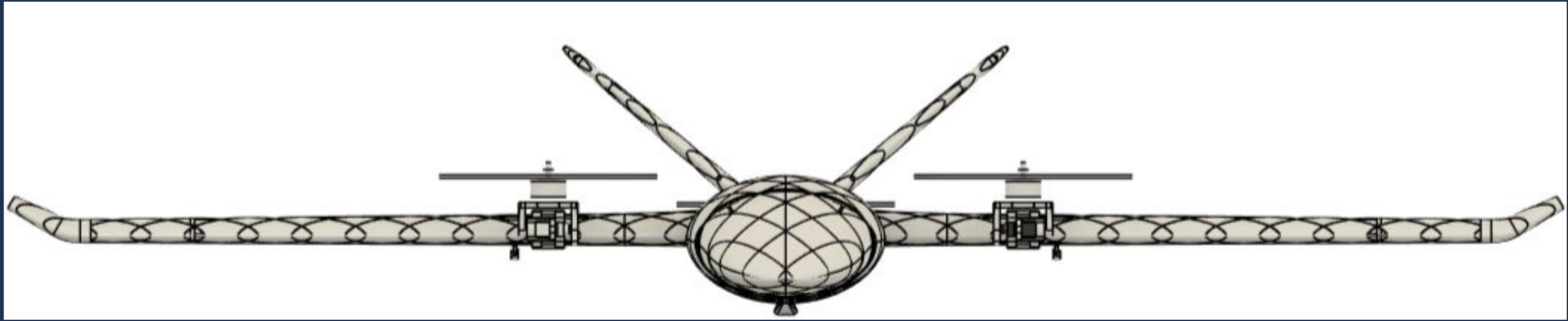
- Hover Prop Layout - equal thrust produces no moment
- Wing sections
  - Identical geometry to VSP, but slightly more blended
  - Designed-in ribs for structural rigidity to support skin
- Electronics + Battery slider - CG manipulation
  - Adjust battery tray and lock in - choose CG
  - Magnetic removable nosecone
- Sectioned for printing





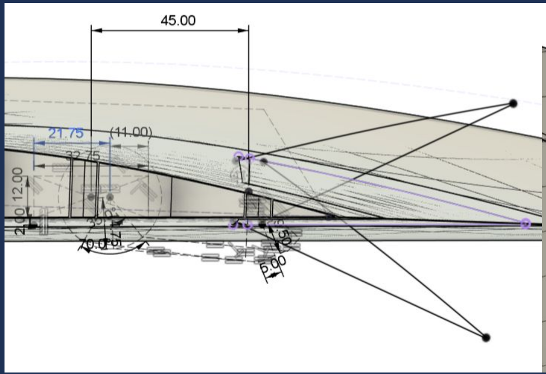


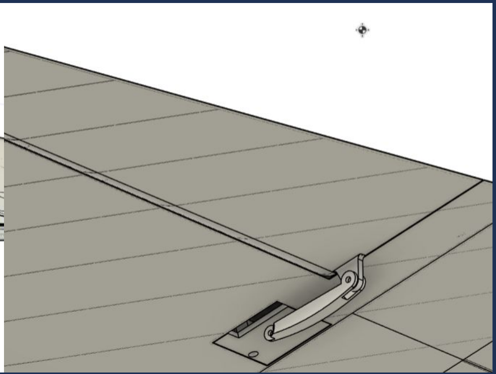


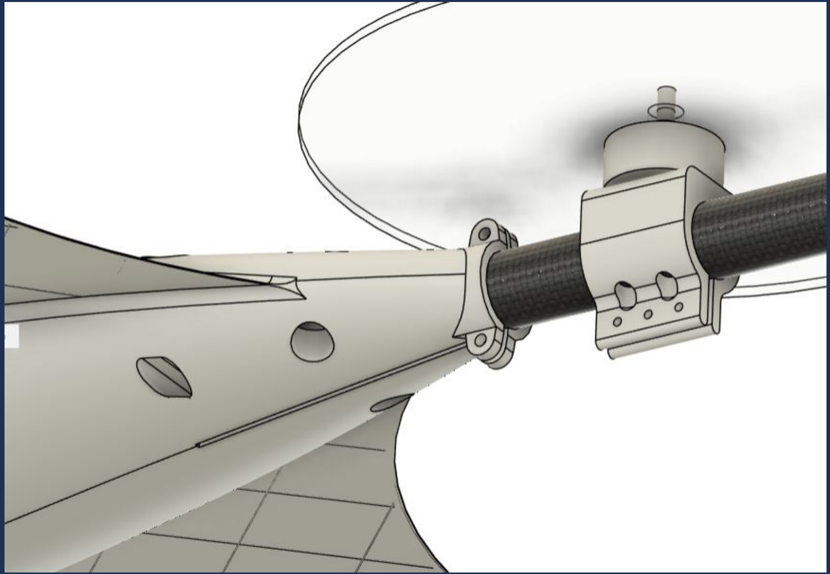



# Wing and Fuselage

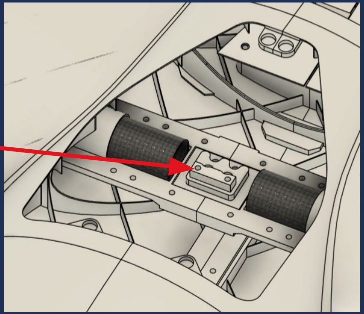
- Control Surfaces: parallel four-bar for identical motor-surface angle
- Clamping to CF tubes - no tools available for proper cutting of carbon

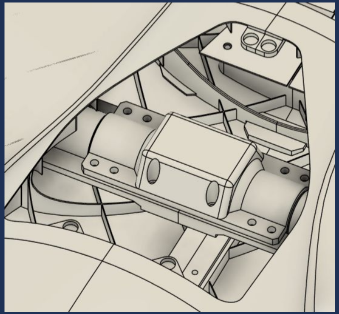


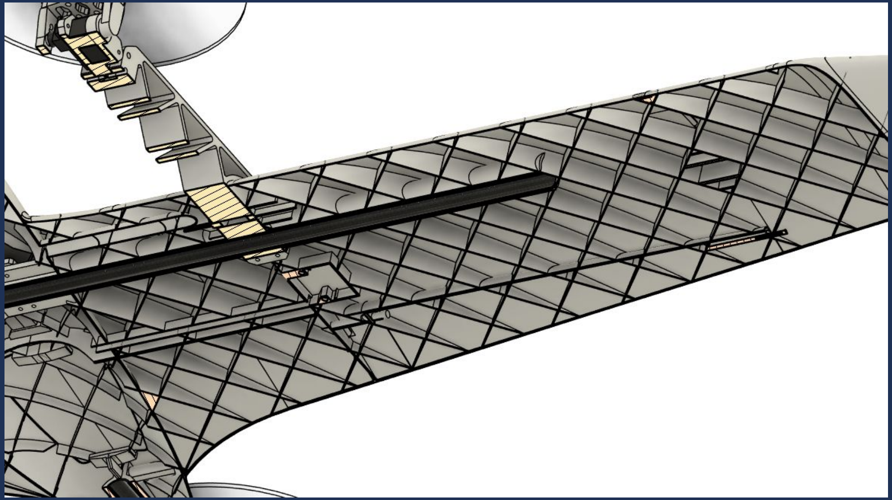



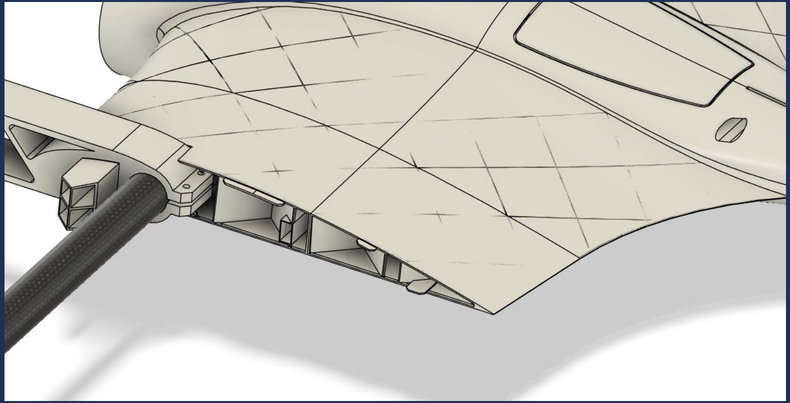


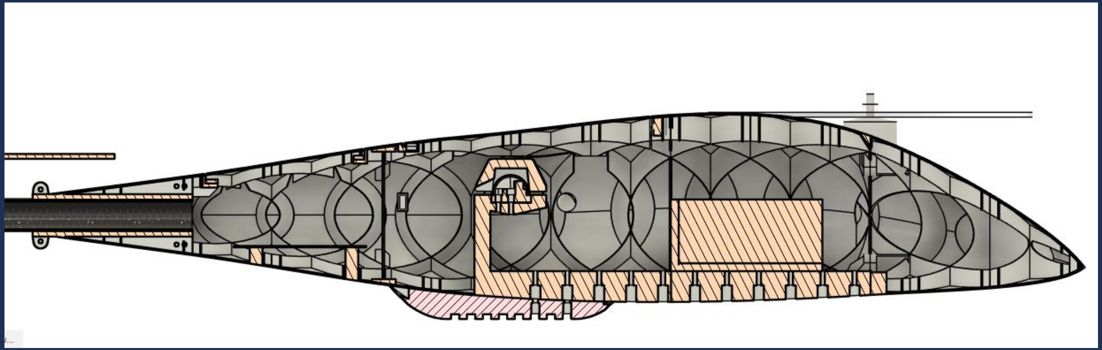
IMU
Mount

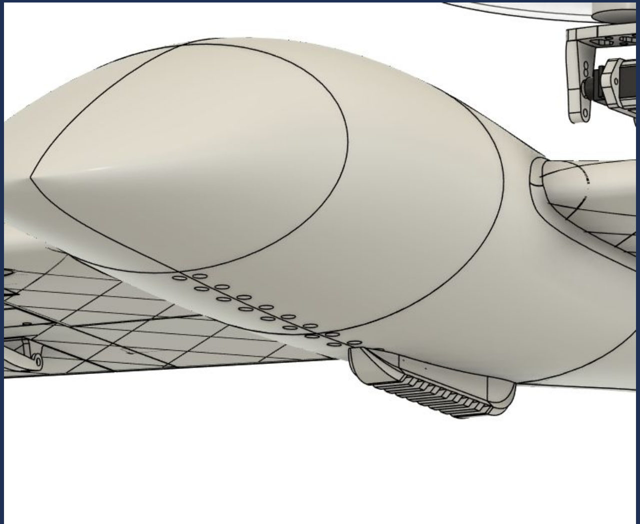






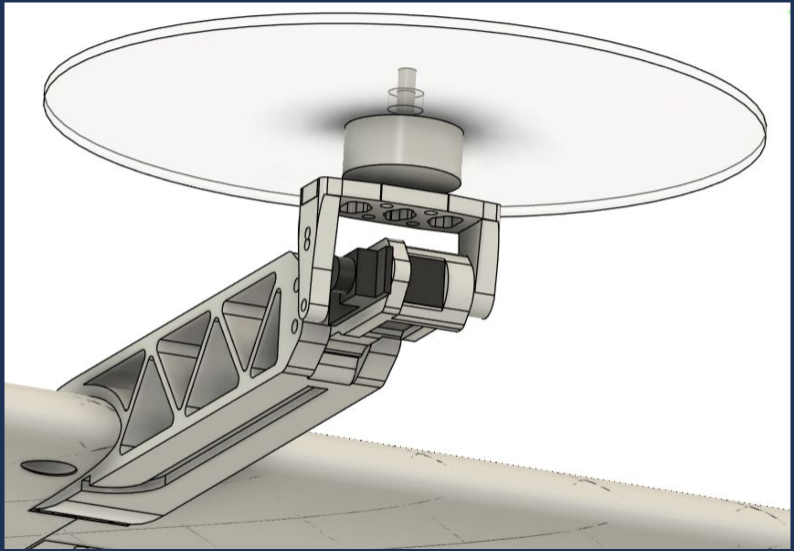


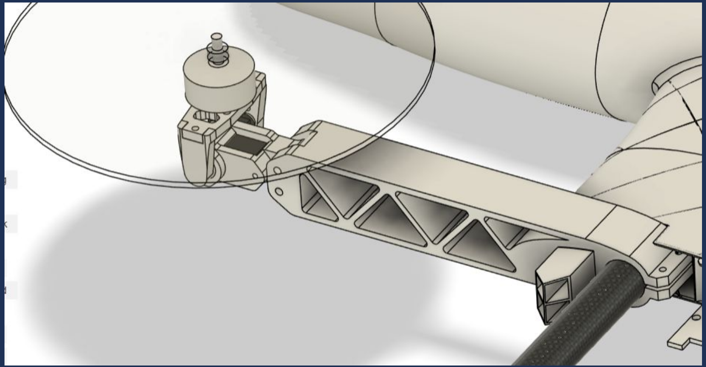


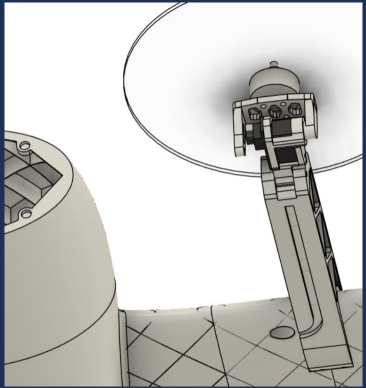


# Tilt Rotors

- 3.4 kg-cm torque servos, 20g
- Bearing-less doubly supported joining
- Clamping truss boom
- Cable routing: through wing

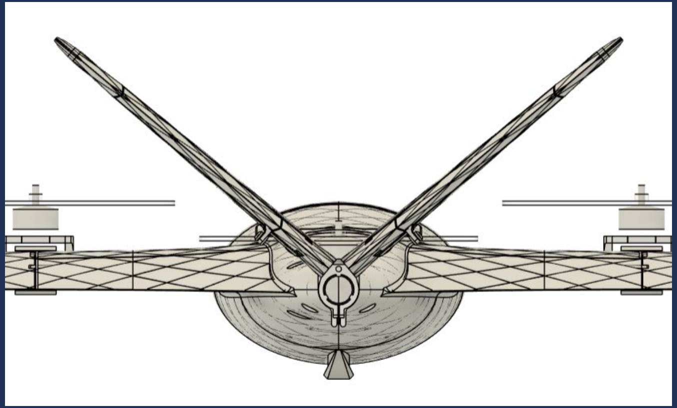






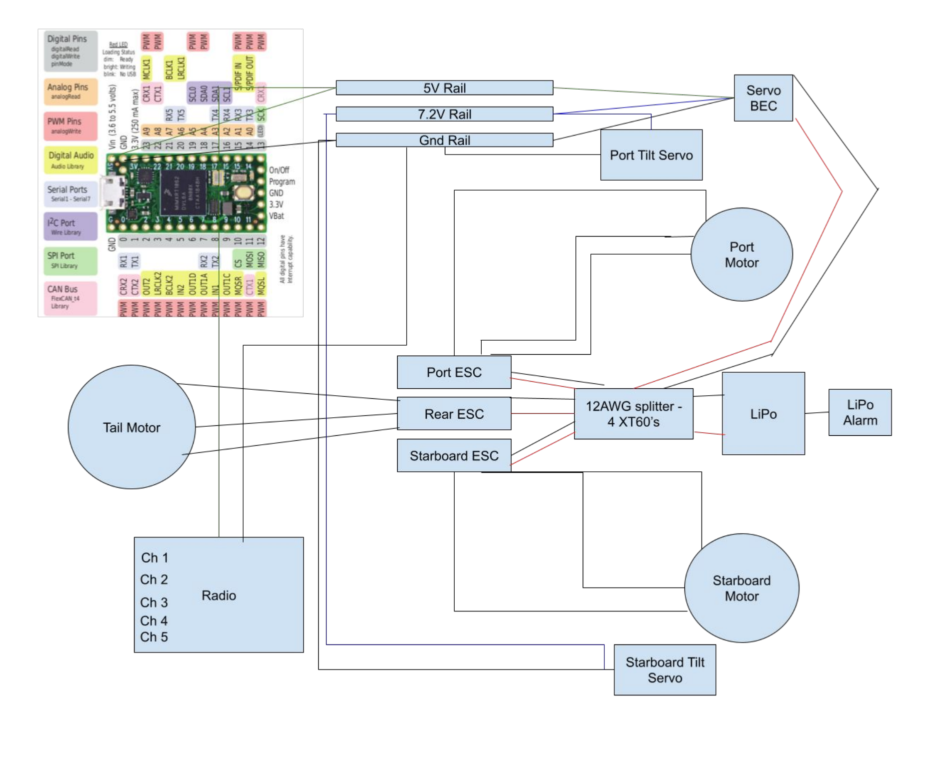
# Tail

- Clamped to boom
- Control surfaces used for pitch and yaw control
- 40 deg dihedral



# Electrical

- Layout sketch:




Battery: 2000 mAh

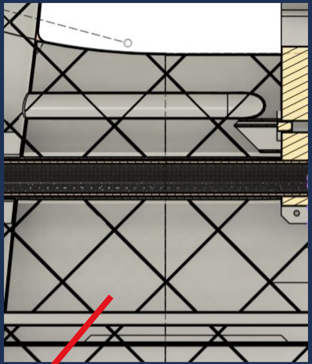
- 70% use: 84 A-min
- 24A hover: roughly 3.5 min hover
- Fixed wing efficiency much higher

https://www.ufinebattery.com/blog/useful-overview-of-lipo-battery-voltage/

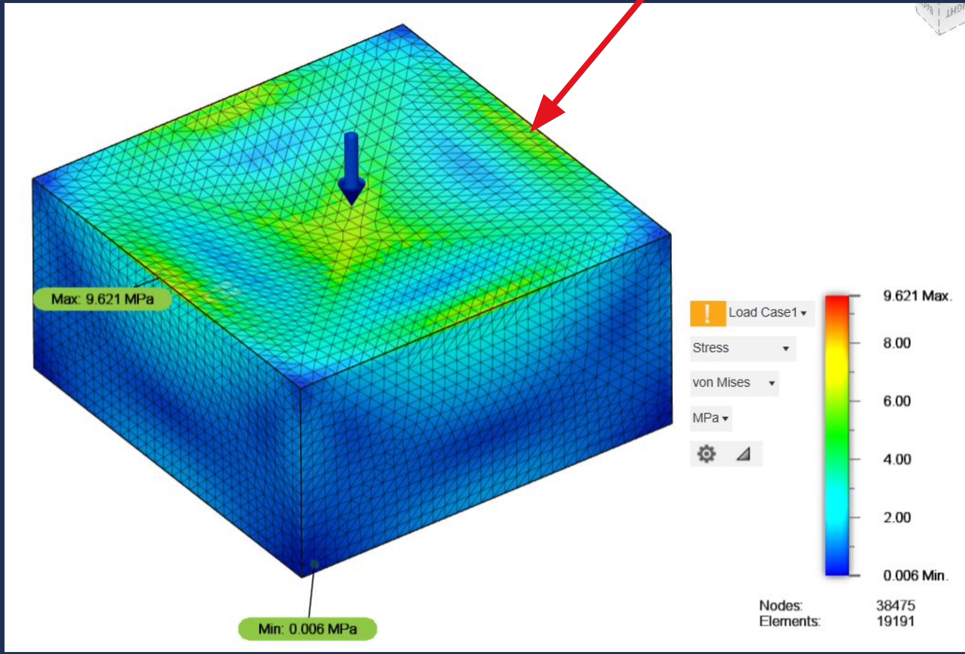
- Project Scope
- Aerodynamic Analysis + Design
- Mechanical Design
- **Structural Analysis**
- Control
- Next Steps

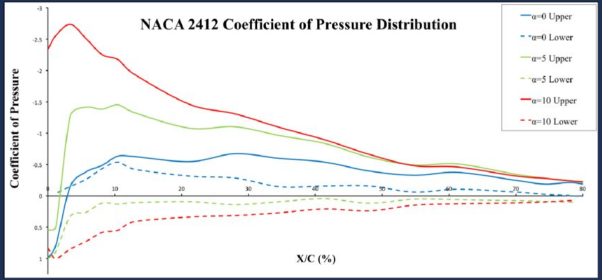
# Wing Pressure Analysis

Rib pattern



- Approx max pressure:
  - ~3.5 * dynamic pressure (20m/s)
- 50mm rib squares
  - 2.1N per square at max
- LW-PLA: 46 MPa yield
- SF > 3



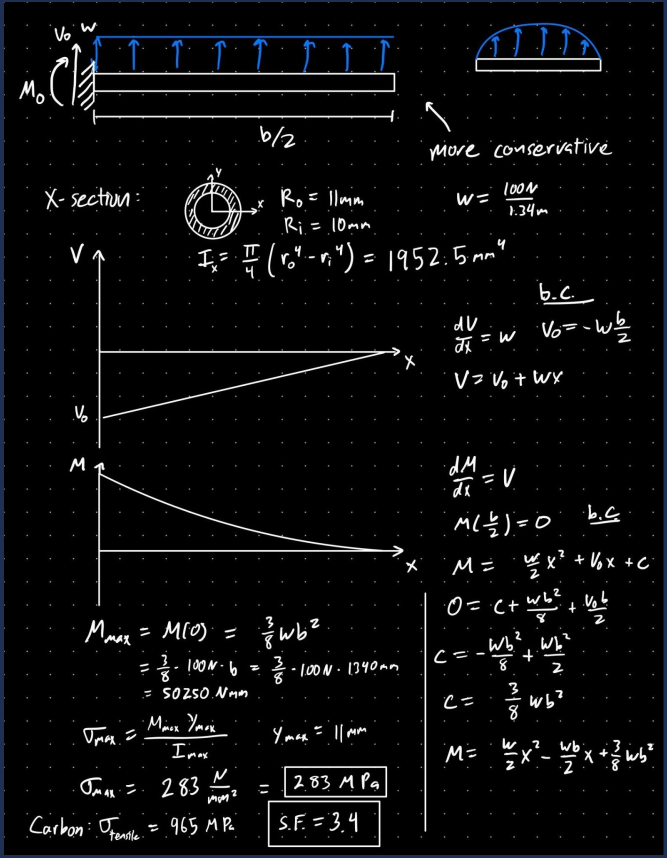




Example Cp Distribution (not mine)

# Dynamic Loads Analysis - Spar

- Uniform loading assumption - more conservative than actual
    - Wing taper reduces max moment
- Load factor n = 5: wings produce ~ 100N of lift
- Carbon fiber spar: safety factor of 3.4

Boom tube: much lower moment




https://www.matweb.com/search/datasheettext.aspx?matguid=39e40851fc164b6c9bda29d798bf3726

Project Scope

Aerodynamic Analysis + Design

Mechanical Design

Structural Analysis

Control

Next Steps

# Control Summary

- Modified open source controller
- Hover mode:
  - Attitude control
- Fixed wing modes:
  - Manual control
  - Attitude stabilized

- PID control
- PWM signal 50Hz
- MPU 6050 IMU
- PWM radio inputs
- Theoretically zero steady state error

# Control Mixer

```
s1_command_scaled = 0.1777 + yaw_PID; // STARBOARD TILT SERVO
s2_command_scaled = 0.8333 + yaw_PID; //port
m1_command_scaled = thro_des - pitch_PID - roll_PID; // testir
m2_command_scaled = thro_des - pitch_PID + roll_PID;
m3_command_scaled = thro_des + pitch_PID;
s3_command_scaled = s3_zero;
s4_command_scaled = s4_zero;
s5_command_scaled = s5_zero;
s6_command_scaled = s6_zero;
```

## Hover

- Yaw control:
  - Tilts thrust vector rotors opposite directions
  - Rate control, good performance (first order system)
- Pitch + Roll control:
  - Integrates gyro to get angular position
  - Applies PID to errors, which ports to motor and servo PWM

## Fixed

- Manual control: ports desired stick position to control surface angle
- Stabilized control: uses attitude mixer but outputs to control surface servos instead of propellers

# Control Surfaces

# Tuning

# Tuning to be continued…

- Teensy broke (no time to fix before leaving for school)
- Gains too small

Project Scope

Aerodynamic Analysis + Design

Mechanical Design

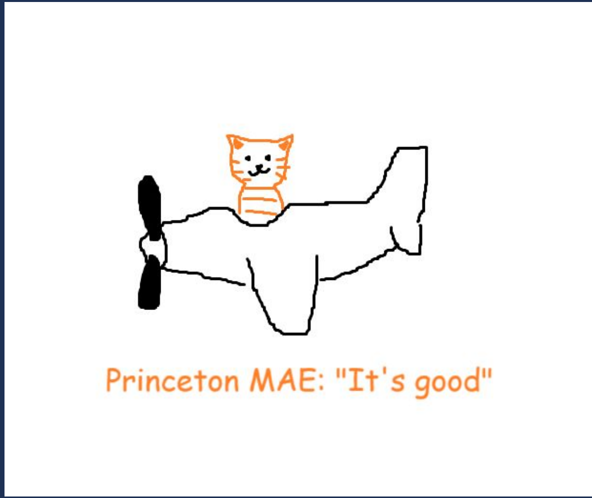
Structural Analysis

Control

Next Steps

# Next Steps

- Fixed wing flight testing
- Transition software
- Princeton: Independent work with design - Spring 2025



# Lessons Learned

- Spend the extra money for double spar and longer boom
- New knowledge gained from aircraft dynamics course
- Find other modes of instability
  - Quantify roll + yaw stability
  - Find eigenvalues of linearized dynamic system = find frequencies that excite oscillation
- Consider thermal load of motors on mounts for prolonged use
- Modal analysis to prevent resonance
  - Relatively confident that physical systems have low enough natural freq relative to prop vibration
- More detailed dynamics model would be nice

# Questions?