MIT Kestrel:
A SuperSTOL Solution to the Personal Electric Aircraft Market

May 16, 2019

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MIT AEROASTRO in partnership with Aurora FLIGHT SCIENCES A BOEING COMPANY

Urban Air Mobility: Demand for personal electric aviation is driving a boom in vehicle development


Vectored Thrust
Lilium Jet


Multicopter
Workhorse SureFly

Lift + Cruise
Pipistrel VTOL


Lift + Cruise
Aurora Flight Sciences Passenger Air Vehicle


Multicopter
Airbus CityAirbus

To be competitive in the Urban Air Mobility Market:

Specification	Minimum Requirement
Payload	4 pax + baggage
Range	100 nmi with reserves
Speed	120 kts cruise minimum
Runway	**300 ft maximum, push for 100 ft**
Takeoff	**400 ft over 50 ft obstacle**
Crosswind capability	20 kts
Weather	IFR capable

Vertiport Concept: Uber Elevate White Paper

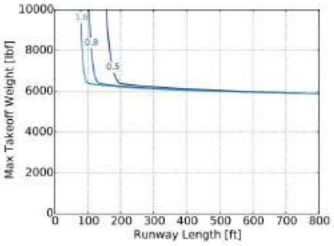
Instead of VTOL: **what about STOL?**

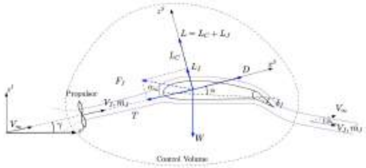
STOL for UAM applications is worth exploring

- Fixed wing has significant range and payload performance benefits over VTOL
- Certification path for fixed wing aircraft exists:
  - < 60kts stall speed
- Hybrid-electric allows battering sizing for takeoff and landing operations

NASA X-57 Maxwell

Fall 2017 16.886: Initial Feasibility Study





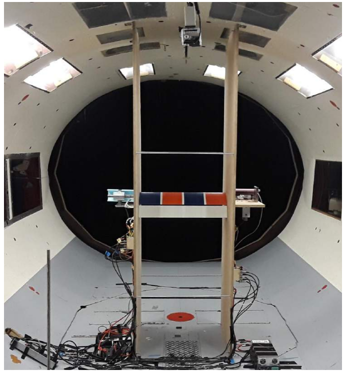
Spring 2018 16.82: Full Scale Conceptual Design

Requirements

Full Scale Design

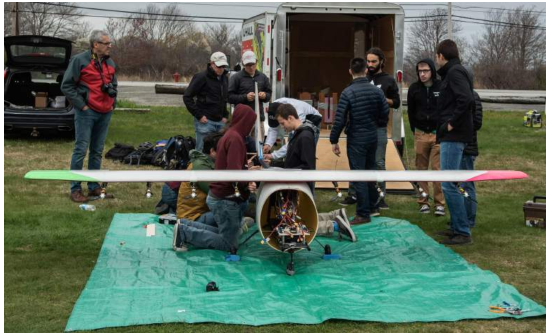
Design Updates

Fall 2018 16.82: 30% Design & Wind Tunnel Test

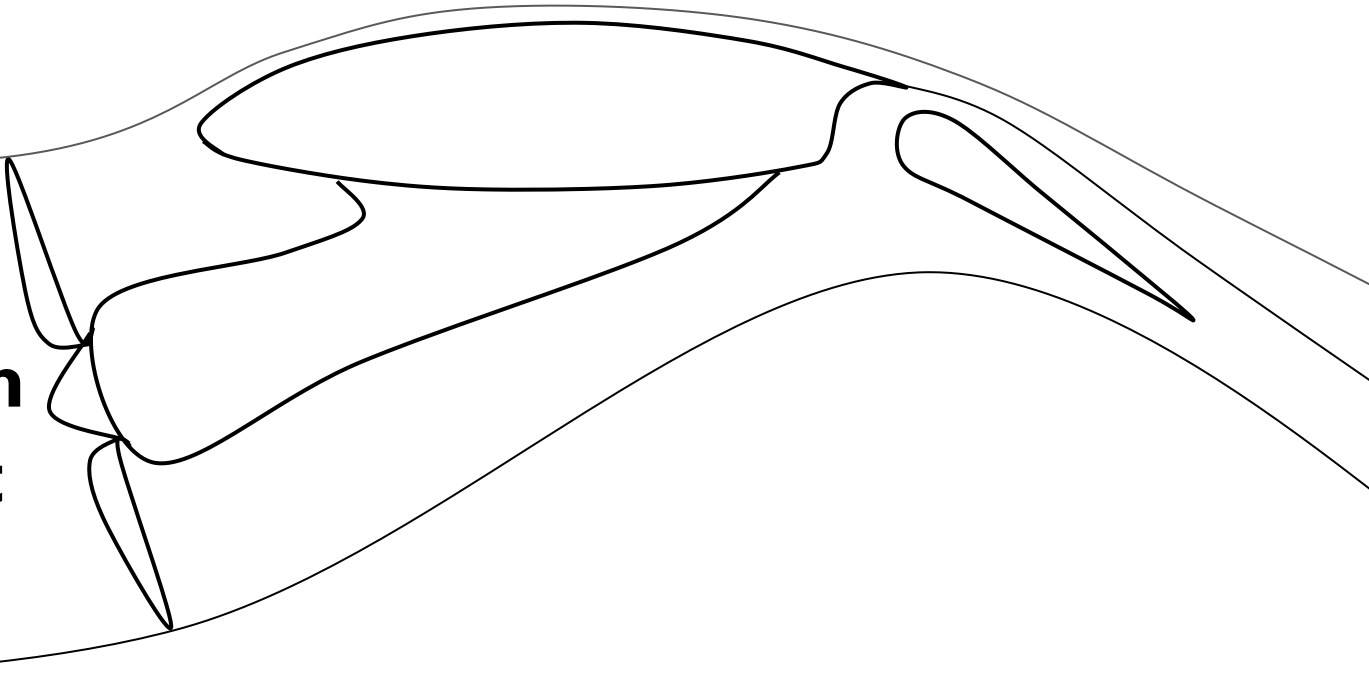


30% Design

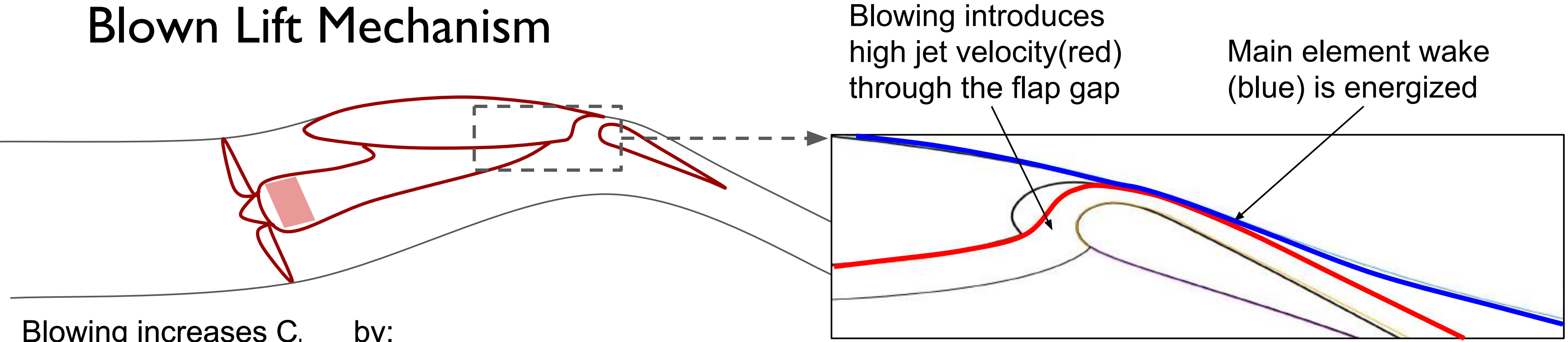
Spring 2019 16.821: 30% Scale Build & Flight Test



Introduction to blown lift

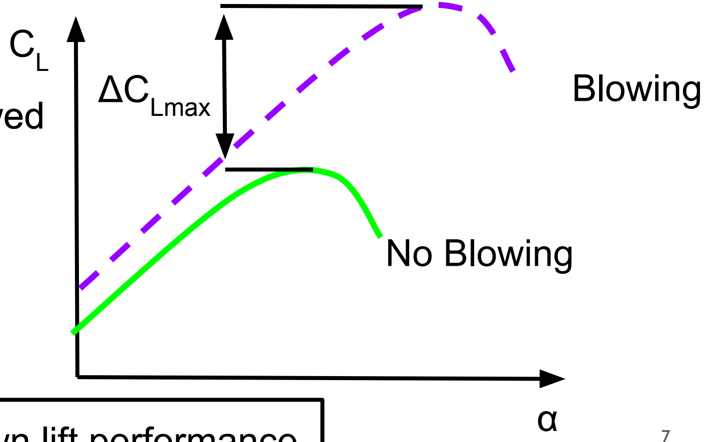


Blown Lift Mechanism



Blowing increases $C_{L_{max}}$ by:

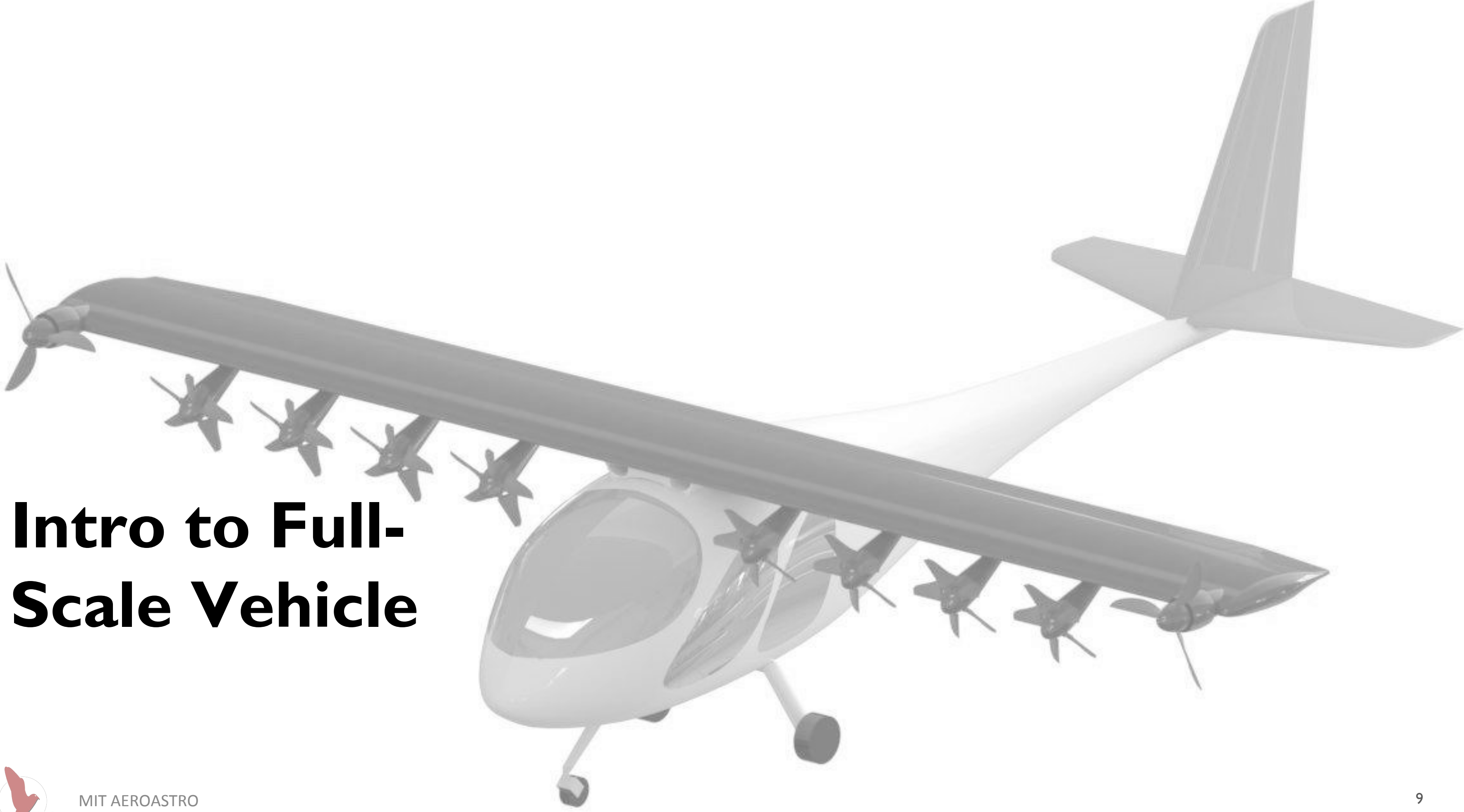
- Delaying stall
  - Higher angles of attack (α) and flap deflections (δ_f) allowed
- Deflecting blowing jet downwards
  - Jet increases downward momentum flux
    → Increased wing lift



JVL and XFOIL were used to model blown lift performance

Benefits of Blown Lift

- Takeoff and landing within rooftop dimensions due to high C_L and C_D
- Safety benefits of fixed-wing glide capability
- Newly-available option due to advances in electric power systems and aerodynamic simulations



Intro to Full-Scale Vehicle

Full-Scale Concept (Spring 2018)

Capability

- Carries 4 passengers
- 100 mi range
- Operate on ~80 ft runway
- 2700 lb MTOW

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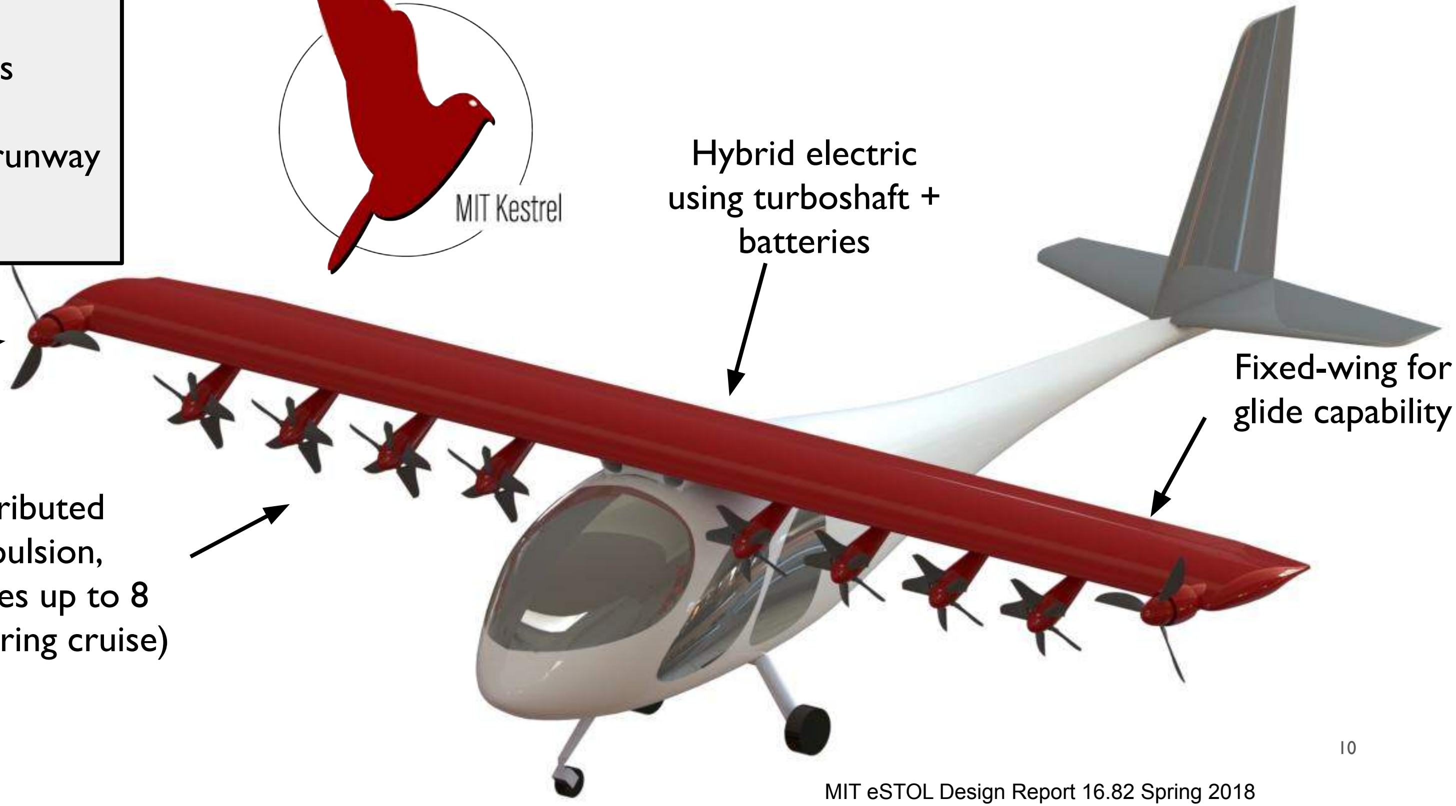


Hybrid electric using turboshaft + batteries

2 larger outer motors optimized for cruise

Fixed-wing for glide capability

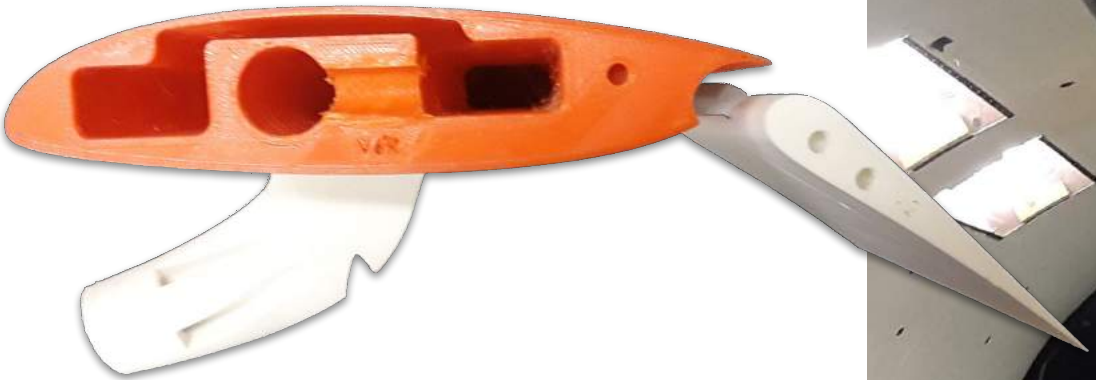
Distributed propulsion, C_L values up to 8 (folds during cruise)

Technical Risks

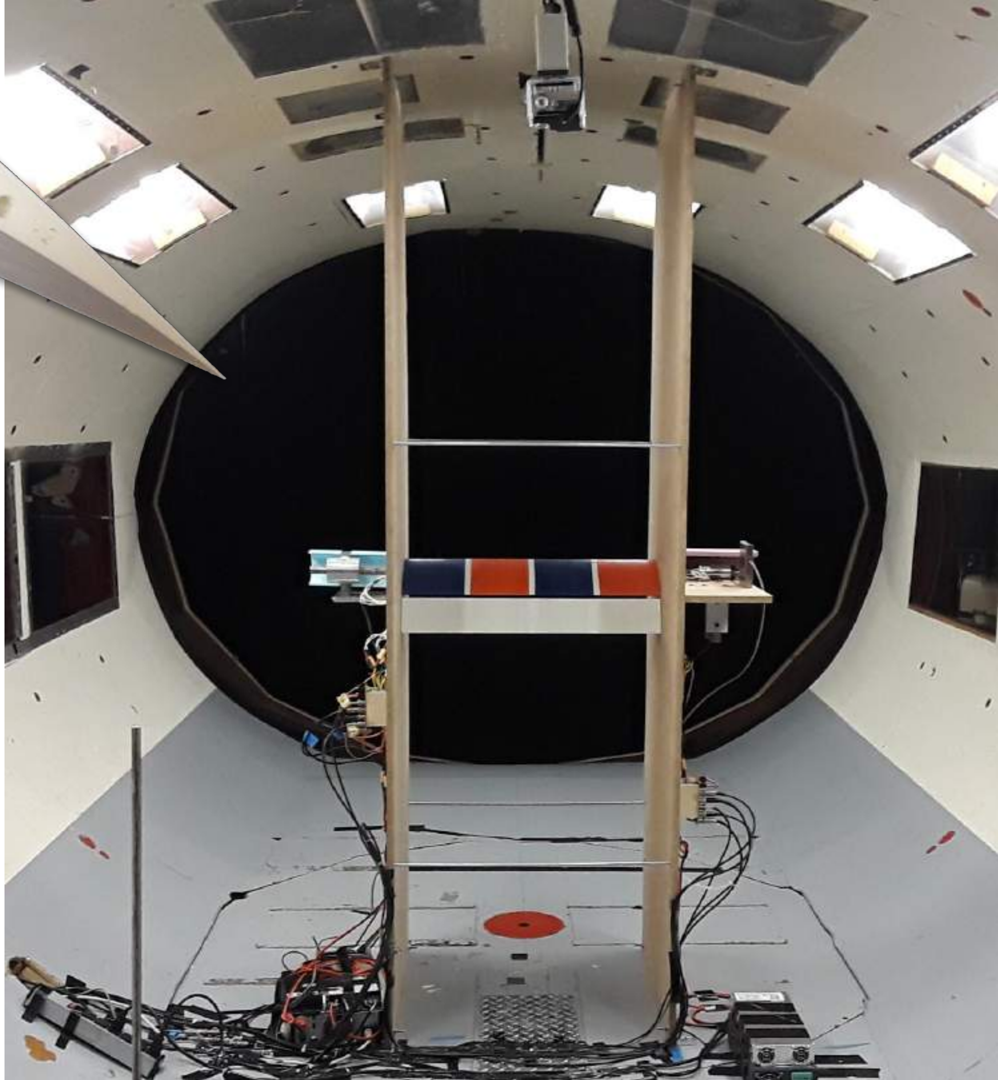
- Blown lift does not match prediction
  - JVL/theoretical models do not translate to real flight
- JVL tail sizing insufficient
  - Stability predictions find that flaps and blowing cancel, requiring a smaller tail than would be expected with either alone
- Control difficulty close to stall due to rapid pitching moment change
  - Pitching moment changes drastically when flow stalls
- Insufficient low-speed, lateral control
  - Controllability
- Difficulty controlling approach glide slope
  - Too many piloting inputs may make the landing difficult
- Insufficient precision landing capability
  - Aircraft must not only land in a short distance, but on a short runway

Technical Risk Mitigation Strategies for Full-Scale Concept

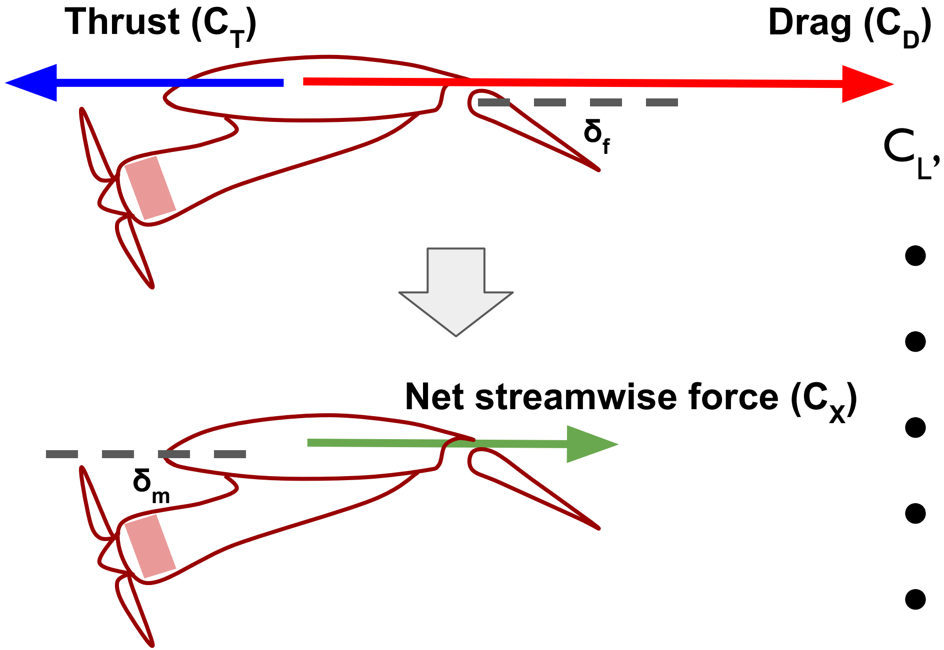
- Wind Tunnel Testing
  - Validate JVL model
  - Tail sizing and pitching moments
- Subscale Vehicle Flight Tests
  - Tail sizing and pitching moments
  - Lateral control at low speeds
  - Approach glide slope
  - Precision landing capabilities



Wind Tunnel Testing



Blown Wing Test Parameters

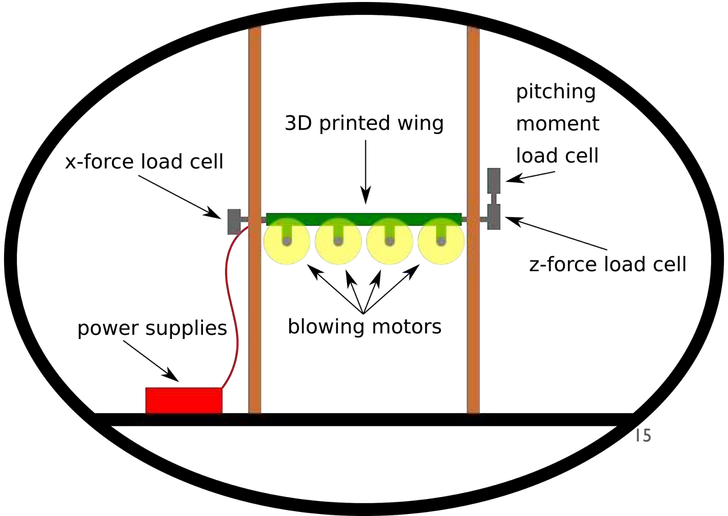


C_L, C_X, C_M depend on:

- $\boldsymbol{\Delta c_J}$: Jet momentum coefficient (blowing)
- $\boldsymbol{\delta_f}$: Flap deflection
- $\boldsymbol{\delta_m}$: Motor deflection
- $\boldsymbol{\alpha}$: Angle of attack
- Placement of blowing motors (fixed)

Wind Tunnel Model

- 4 spanwise sections held together by pins
- δ_f fixed for any set of flap supports
- δ_m fixed for any set of motor mounts
- Tested in WBWT, which has a 7'x10' elliptical cross-section
- Plywood shielding used to approximate 2D flow over the 2' wing span.



Wind Tunnel Test Plan

Test Matrix

- δ_m : 10°, 20°
- α : -5° $\rightarrow$ 25°
- δ_f : 0°,10°,20°,30°,45°,55°,60°,90°
- Δc_j : 0 $\rightarrow$ 6

Design Choices

- Motor mount angle δ_m
- Spanwise motor mount spacing
- Horizontal tail sizing

Flight Testing and Planning

- δ_f, α settings for takeoff and landing
- Stall and control characteristics

Wind Tunnel Results

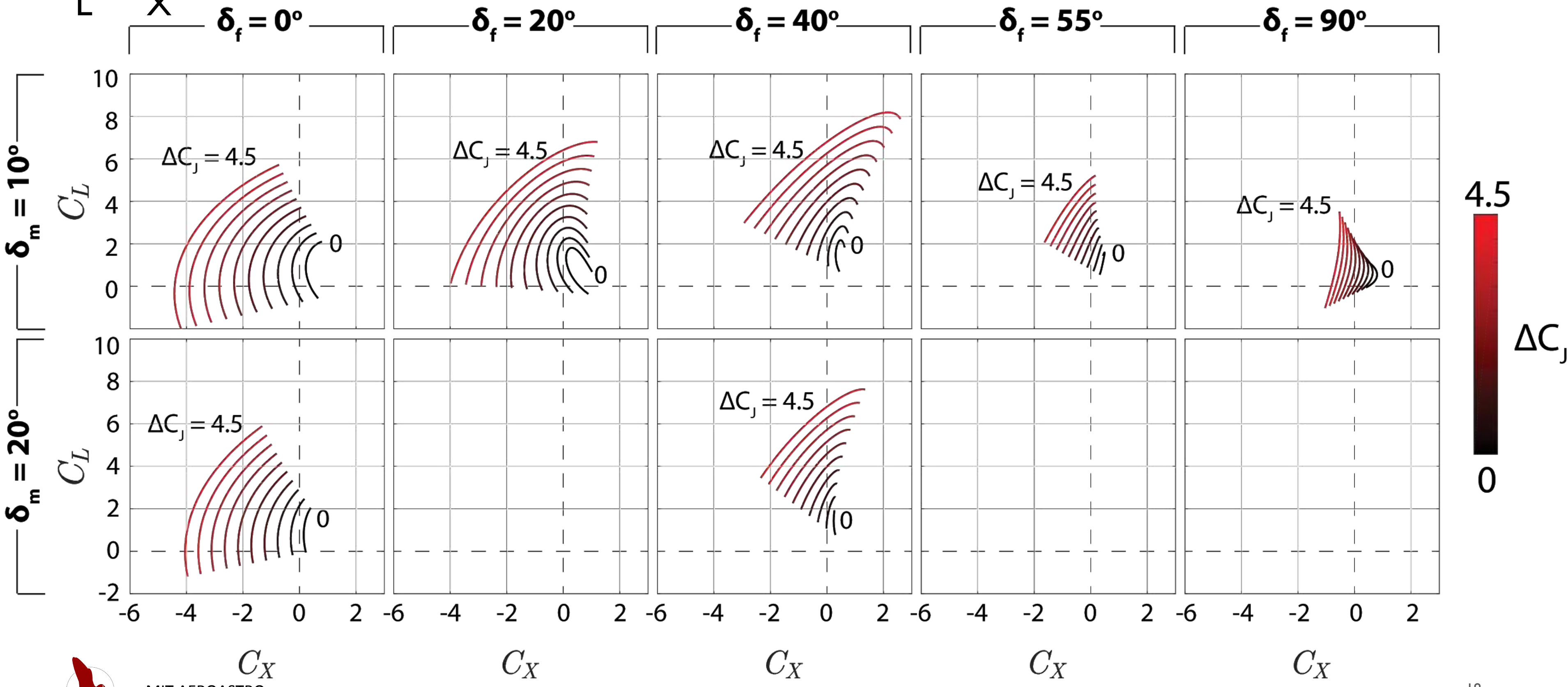
Conclusions

- $C_L(\Delta c_j)$ increases consistently until ~ δ_f= 55°
- C_X > 0 for chosen landing/takeoff configurations with high lift: $35^\circ \leq \delta_f \leq 55^\circ$
- C_L is relatively insensitive to δ_m between 10° and 20° → 10° δ_m used for aircraft
  - 30% demonstrator is able to use blower motors for cruise
- Spanwise performance is consistent enough to conclude that motor spacing on 30% demonstrator is acceptable

Issues

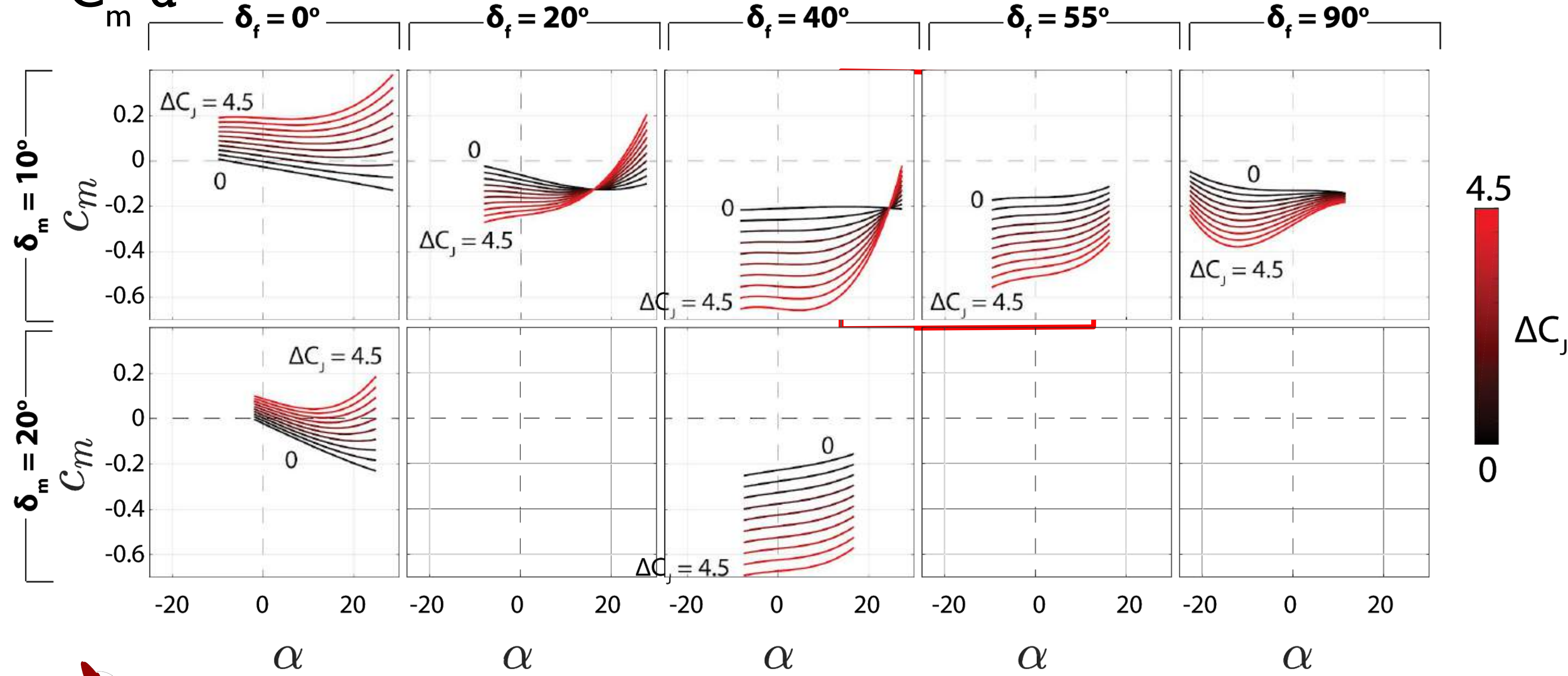
- Balance issues → data taken Spring 2019 unusable
- Time constraints → no new data taken since vehicle build began

C_L-C_X

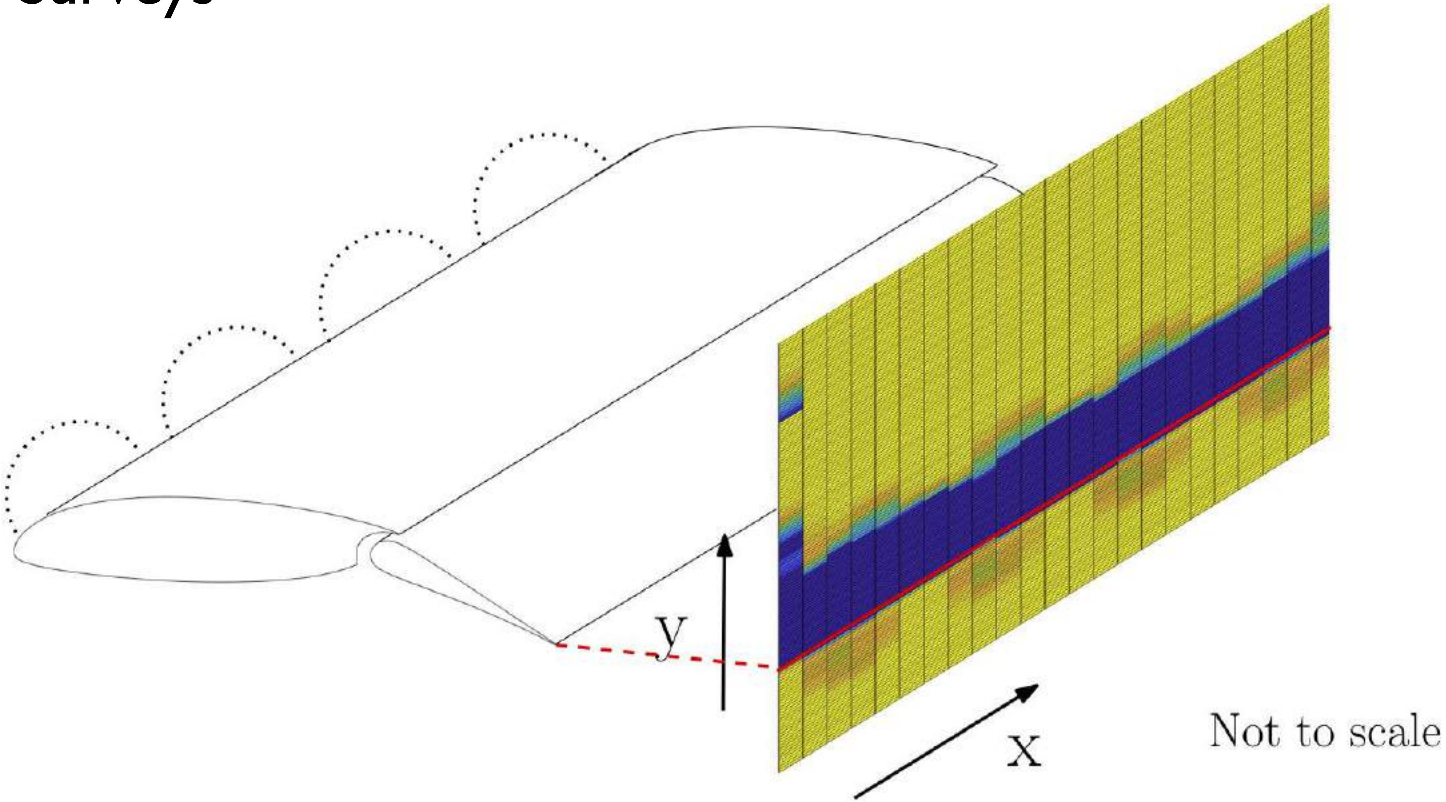


δf = 0°
δf = 20°
δf = 40°
δf = 55°
δf = 90°
δm = 10°
δm = 20°
ΔCJ = 4.5
0
CL
CX
10
8
6
4
2
0
-2
-6
-4
-2
0
2
4.5
0
ΔCJ

C_m-α


δf = 0°
δf = 20°
δf = 40°
δf = 55°
δf = 90°
δm = 10°
δm = 20°
cm
ΔCJ = 4.5
0
0.2
-0.2
-0.4
-0.6
-20
20
α
ΔCJ

Wake Surveys

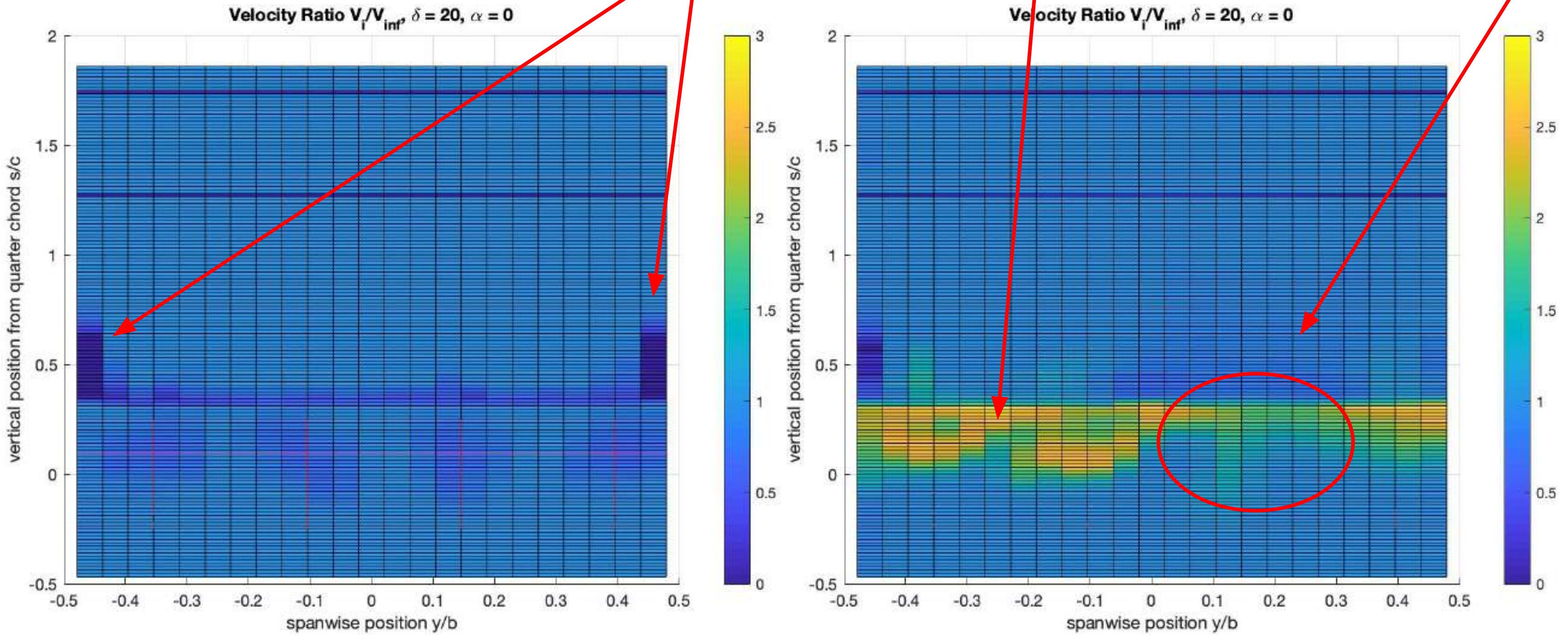


Motor Spacing

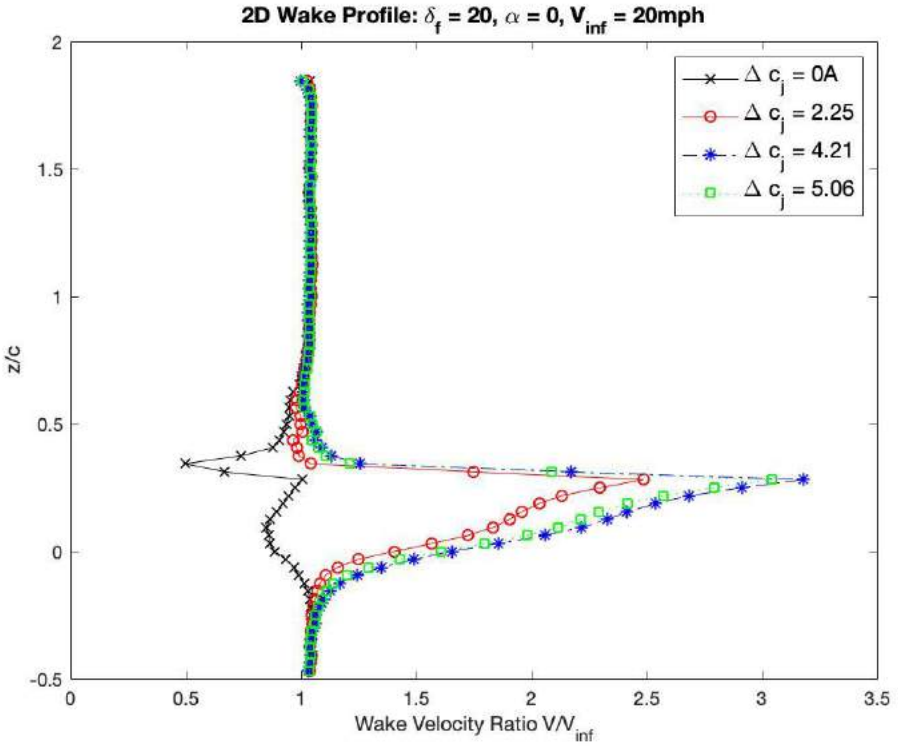
Wall effects

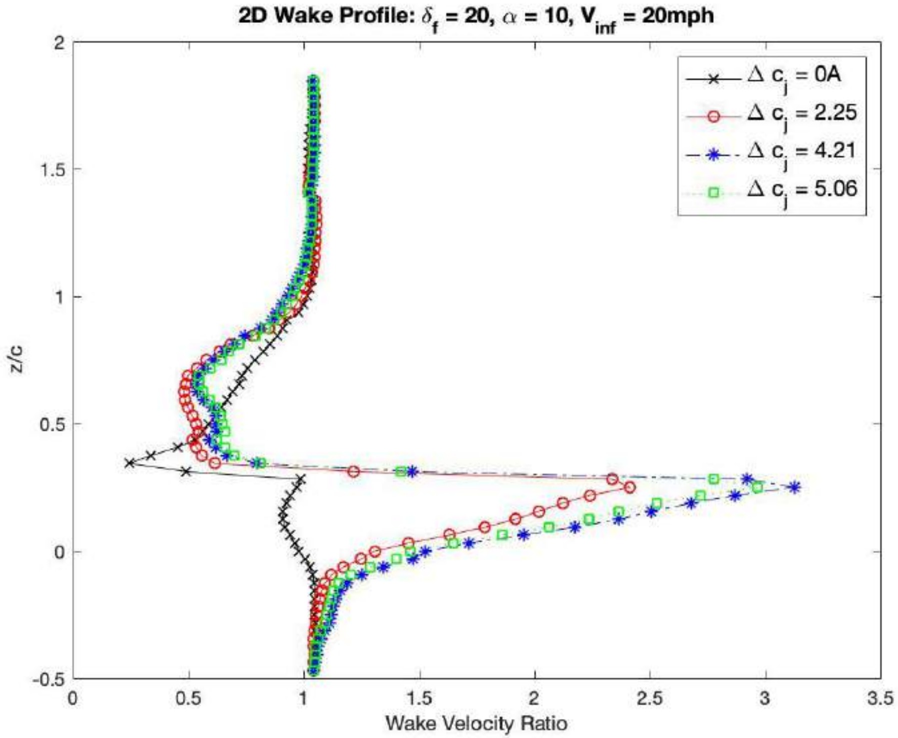
Consistent spanwise performance: motor spacing OK

Power delivery inconsistency



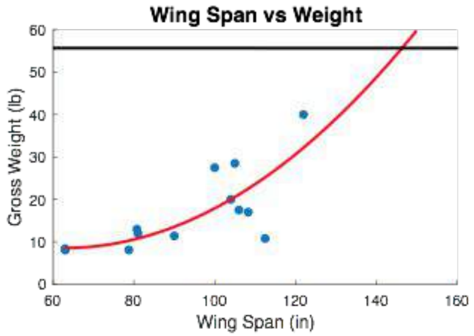
Average Spanwise Velocity



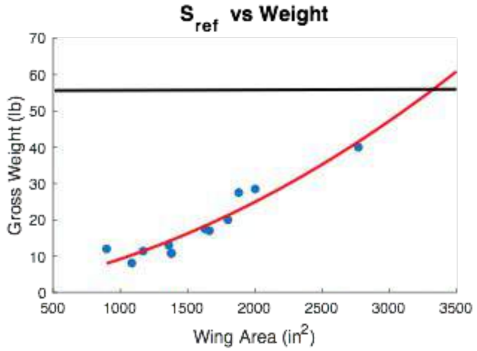


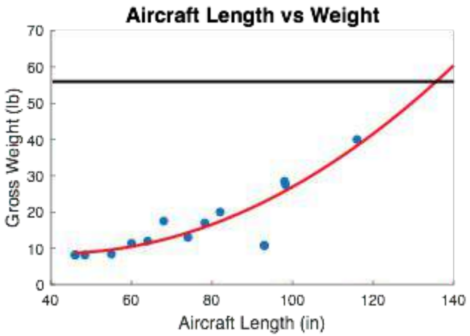
Intro to subscale vehicle design

Vehicle scaling, and decision for a 30% scale



3/10 scaling parameters:
S = 2480 in^2
b = 136 in



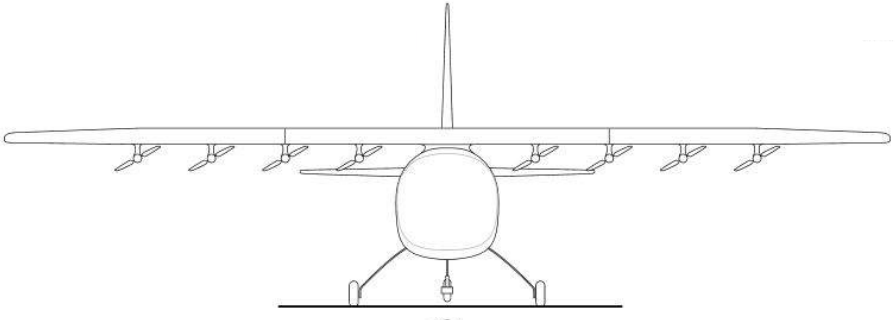


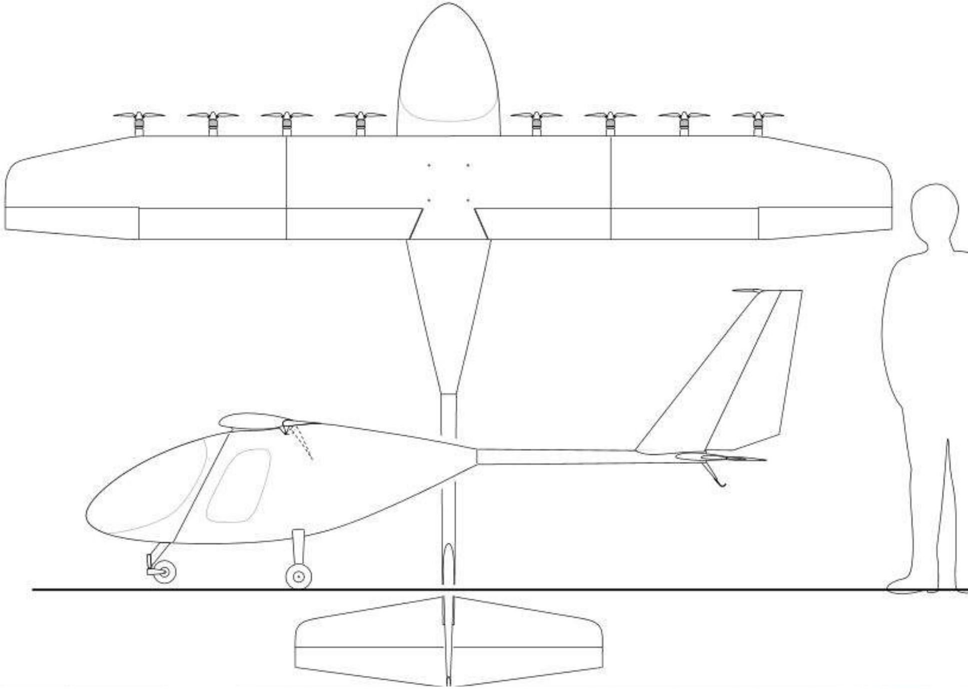
- Value was found by extrapolating RC planes on the market and finding required size to meet 55lb restriction
- 3/10 is the largest scaling we can build with margin
- Geometrically similar to the full-scale

30% scale vehicle 3-view

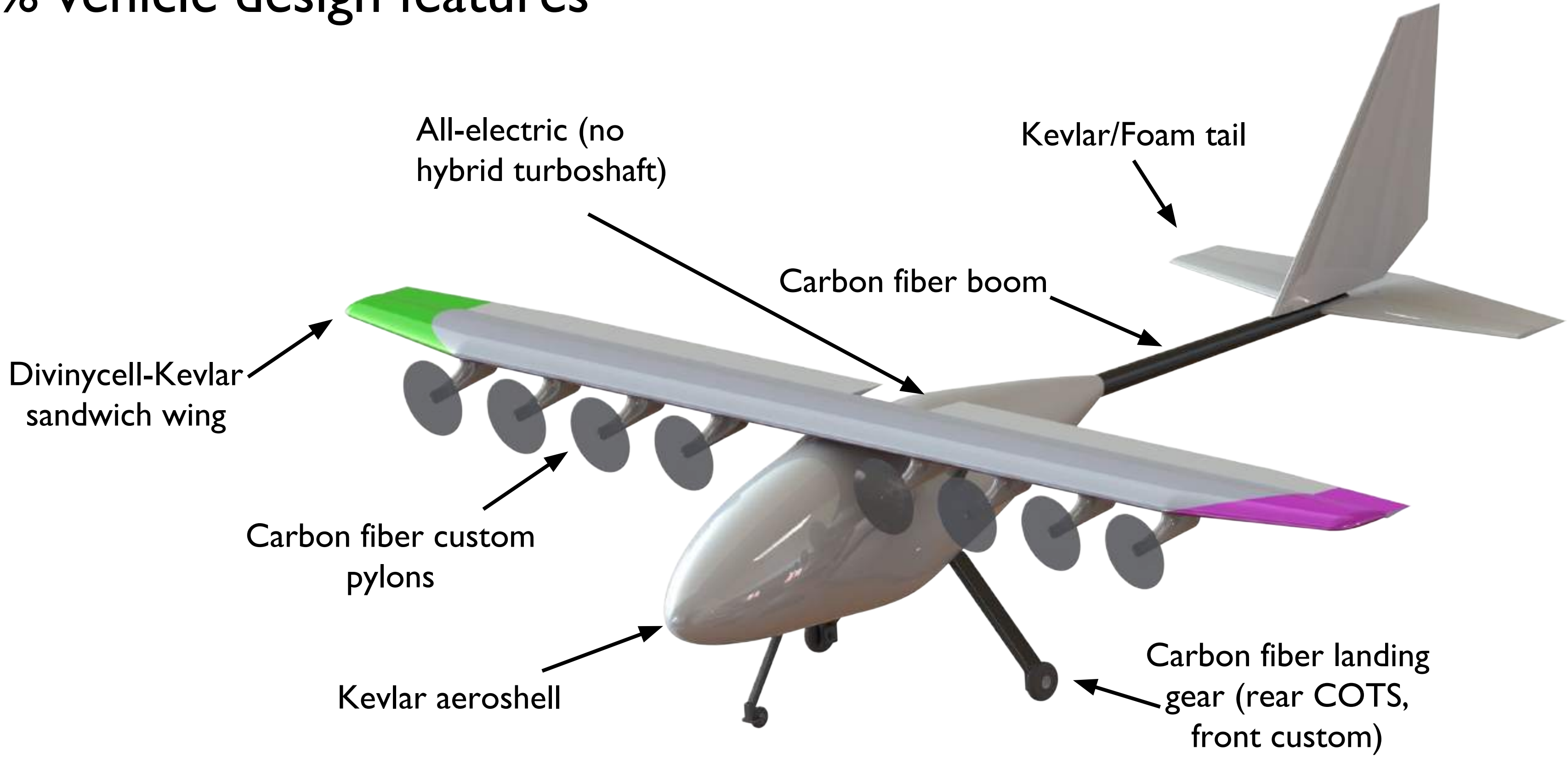
KESTREL
Hybrid eSTOL
30% scale POC

Weight = 37.0 lb = 16.8 kg
Span = 156 in = 13 ft = 3.96 m
Area = 2640 in^2 = 18.33 ft^2 = 1.70 m^2
Vmin = 5.15 m/s = 11.5 mph (CL = 6.0)
Vmax = 28.2 m/s = 63 mph (CL = 0.20)



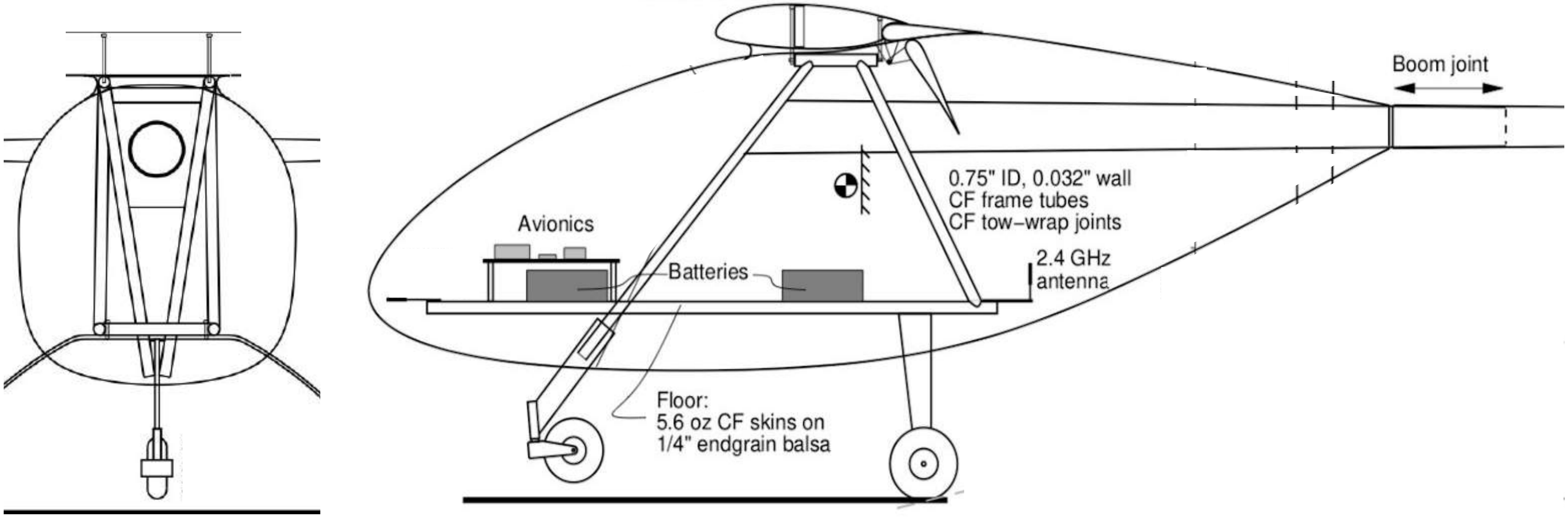


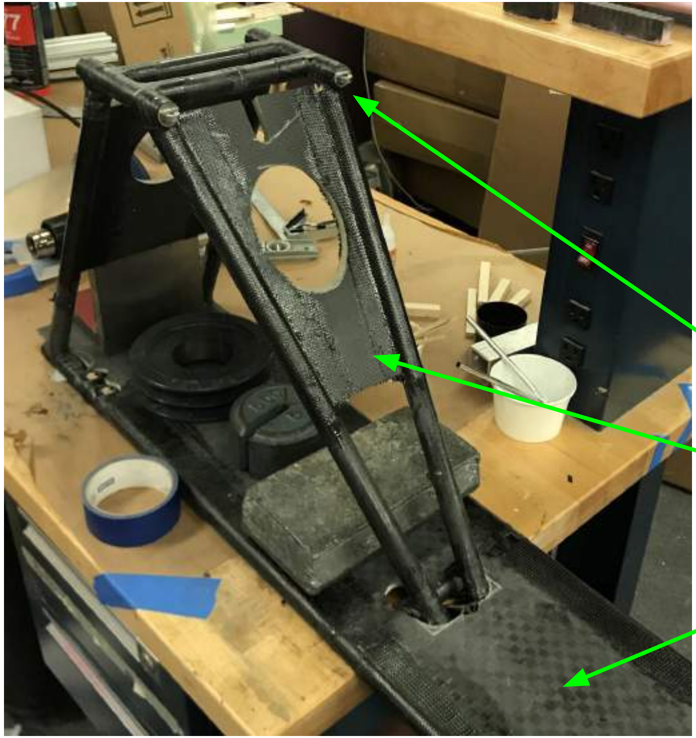
30% vehicle design features

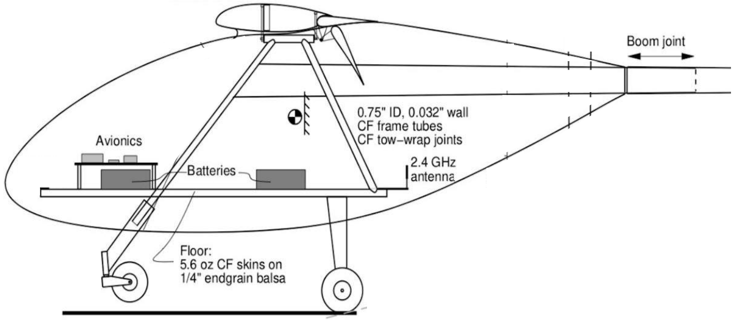


Build report

Truss - Motivation







CF tow joint wraps (all ¾” CF tubes)

CF skins on ¼” divinycell foam

CF skins on ¼” endgrain balsa

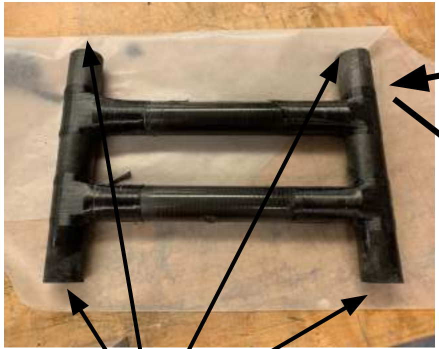
Truss - Joint Attachments (CF Tow Lashing)

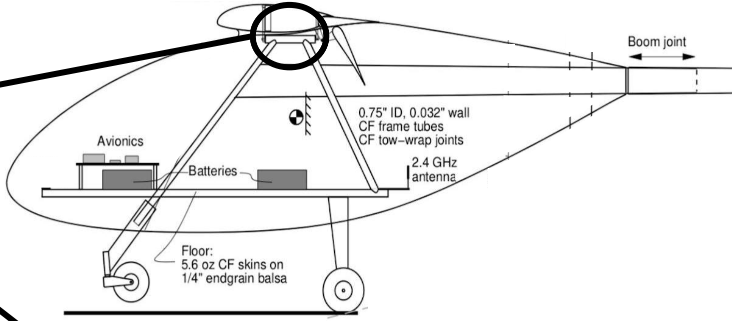
1. Sand and Miter

2. Wrap and Epoxy

3. Heat Gun and Dry

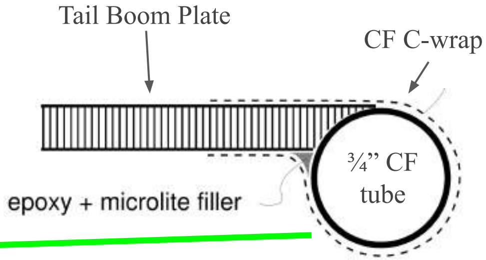
Wing Attachments

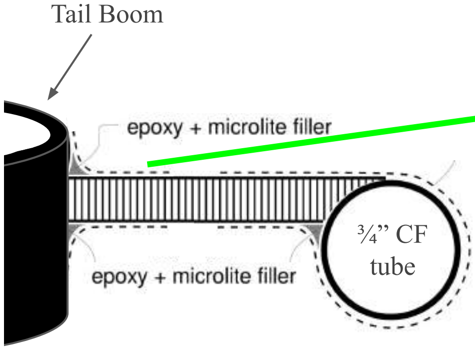




Epoxy in 4 steel 10-32 wing bolts

Tail Boom Plate Attachment

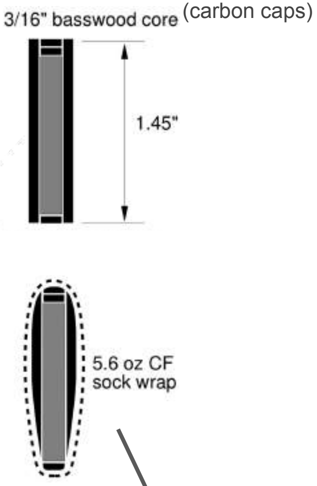


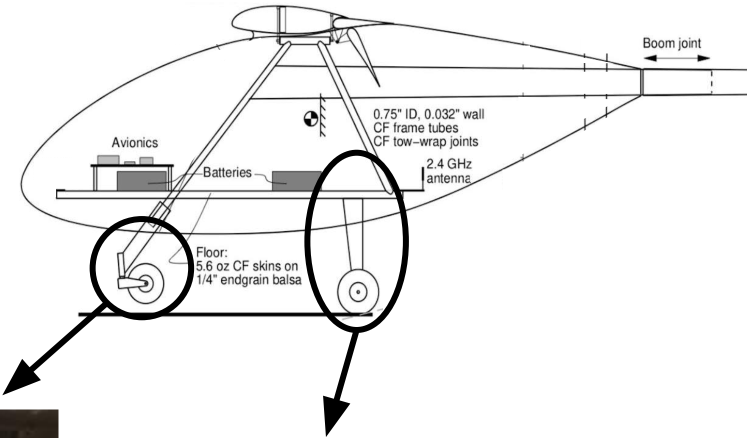


Tail Boom Attachment

Truss - Landing Gear

Nose Gear (made in-house)



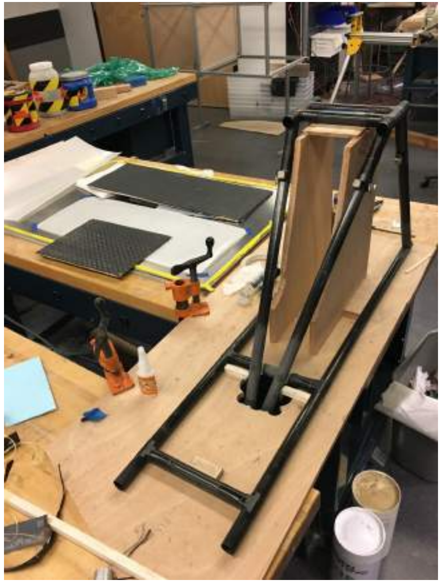


Main Gear (4.5” diameter wheels)

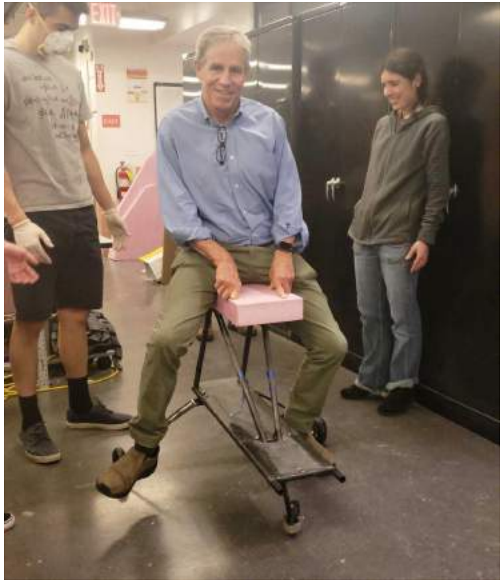
(Off-the-shelf for EDG 540 42% RC Aircraft)

ss - Summary

1 - BUILD

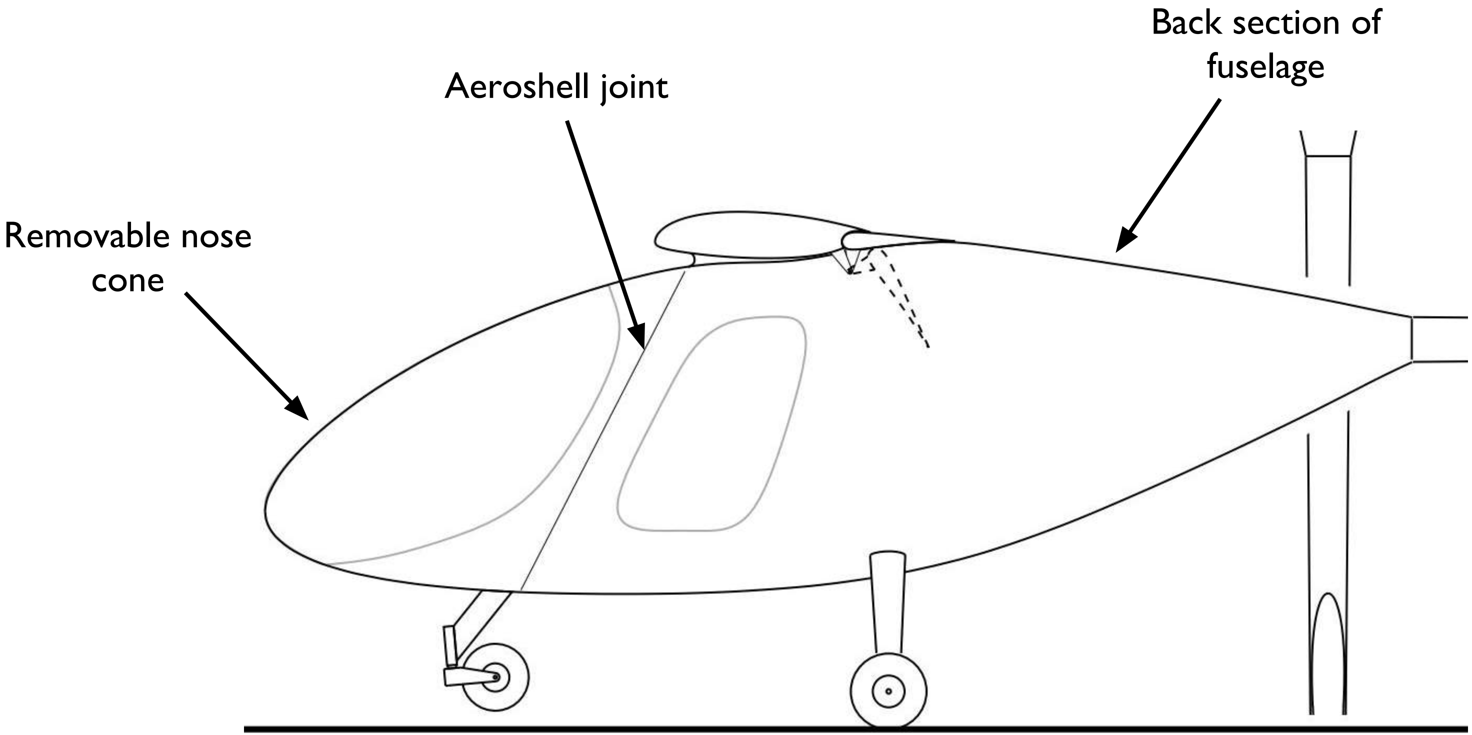


2 - TEST



3 - INTEGRATE

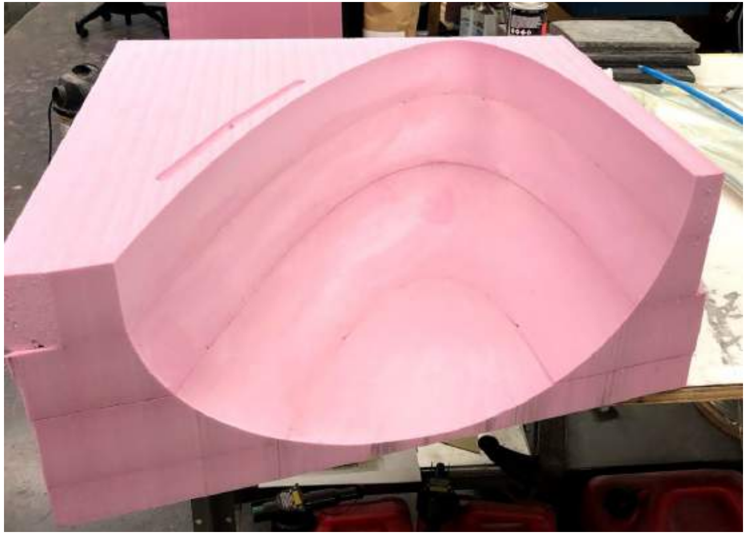
Aeroshell



Back section of fuselage
Aeroshell joint
Removable nose cone

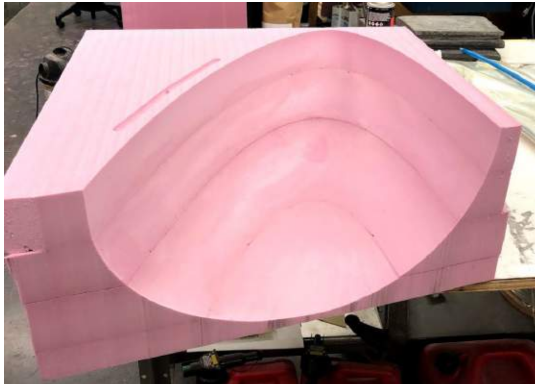
Aeroshell Mold

- Four part mold
  - Two for the nose cone
  - Two for the fuselage
  - Split vertically down the middle
- Foam molds
  - Renshape expensive and time-consuming
- Routed in 3 layers for each of the four parts

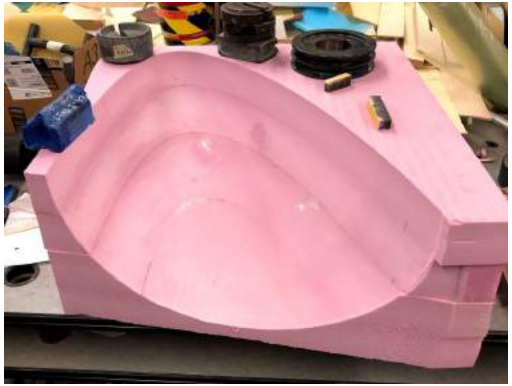


Aeroshell Mold Manufacturing

1. Route foam layers.



2. Align and glue layers together to create left and right molds.



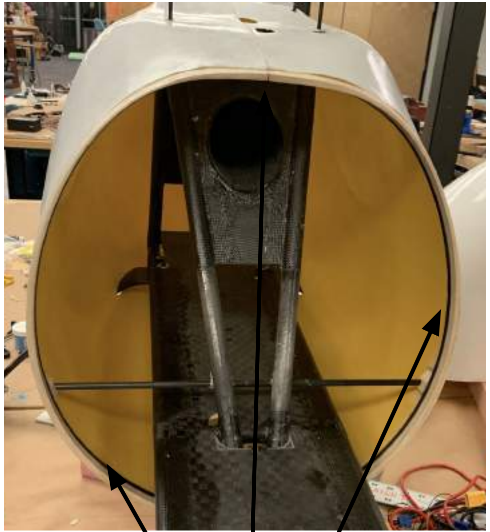
3. Add 2 layers of 3.5 oz satin-weave fiberglass (and epoxy).

4. Trim excess fiberglass.

5. Wet-sand.

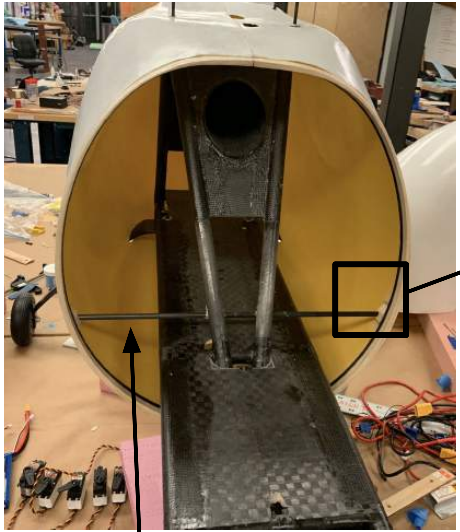
Aeroshell Manufacturing

Layup: 3 layers of 1.7 oz Kevlar with epoxy



Carbon/balsa strips coated in fiberglass and epoxy

Aeroshell - Truss Attachment



Hollow carbon tube attached to truss; tube filled with epoxy and threaded; screws pass through pads

Basswood pads coated in fiberglass attached to inside of aeroshell

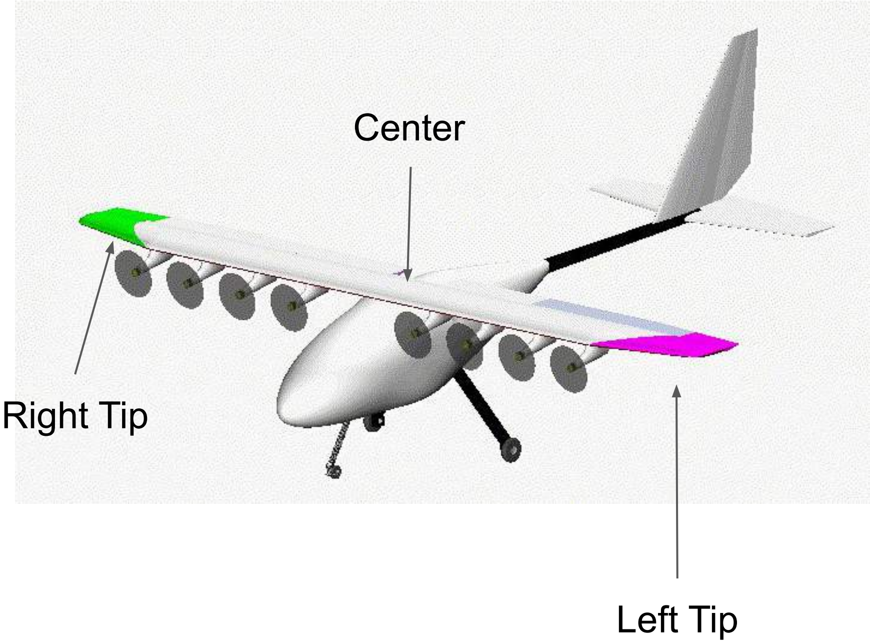
Aeroshell constrained by wing attachments

Cut-outs for truss/landing gear constrain the aeroshell

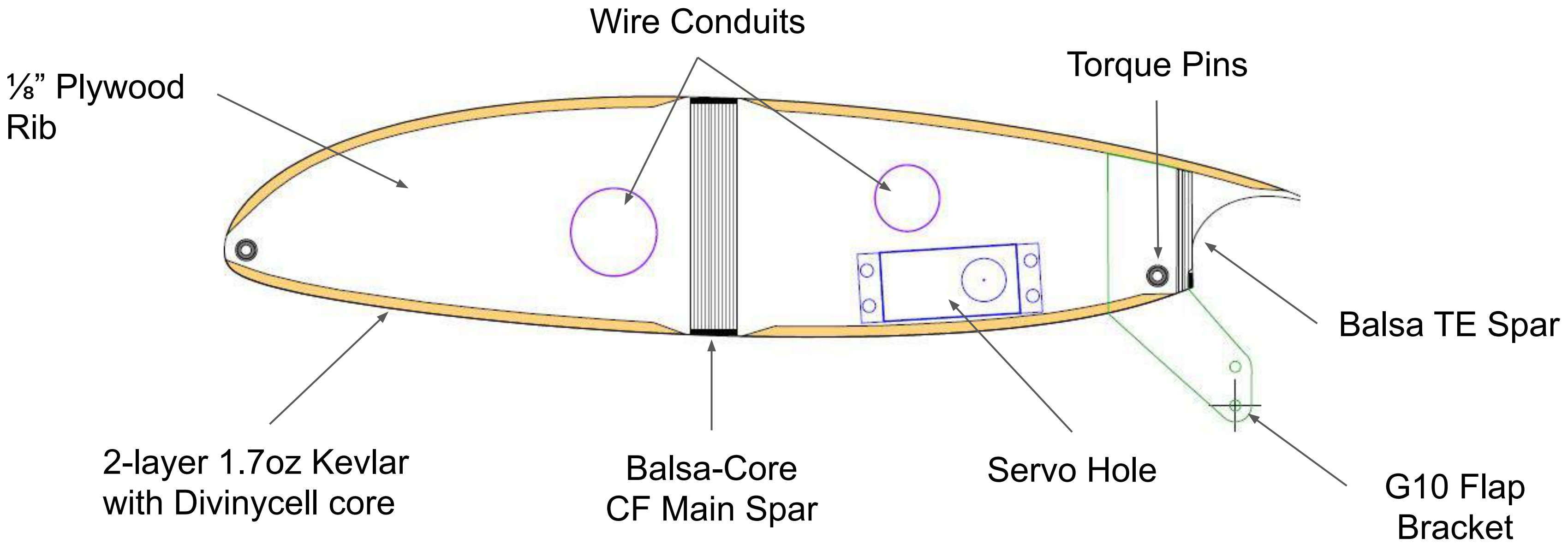
Wing

- Divided into 3 sections for:
  - Machinability
  - Transportability

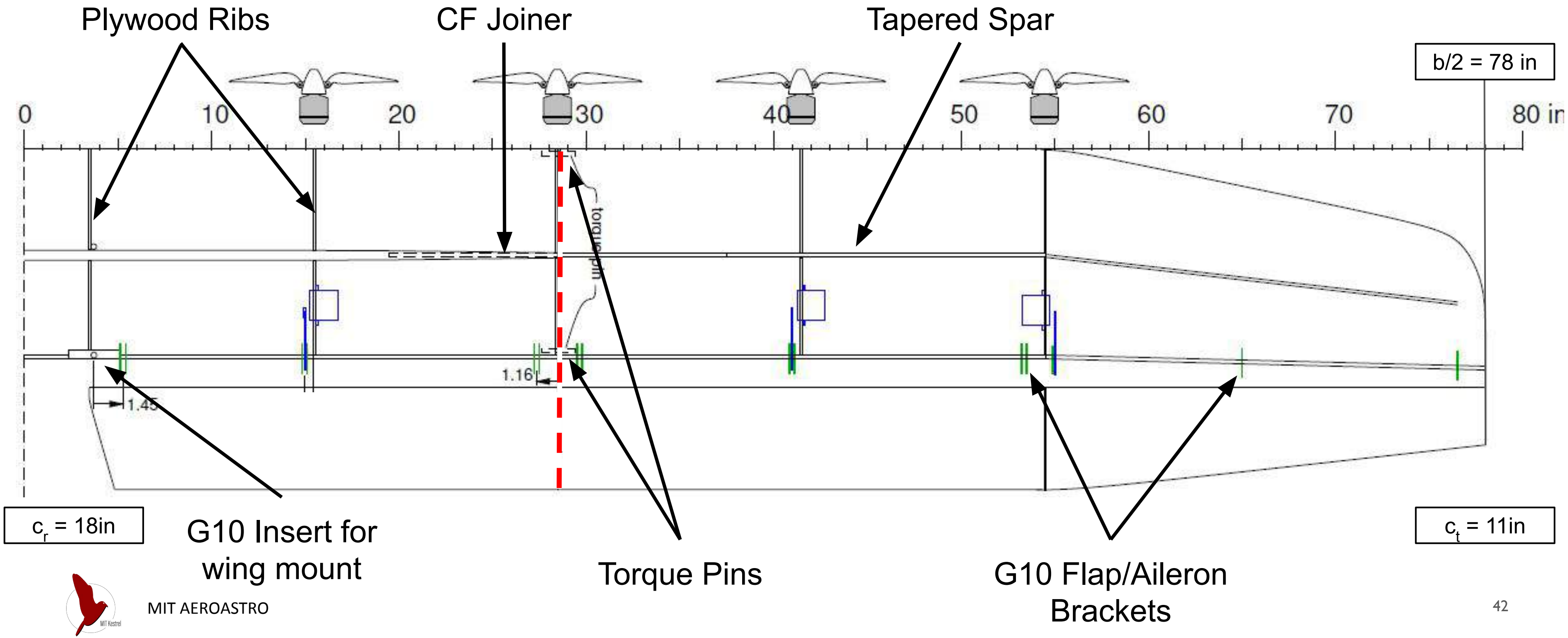
- Split top and bottom for manufacturing



Wing - Cross Section



Wing - Half-Span

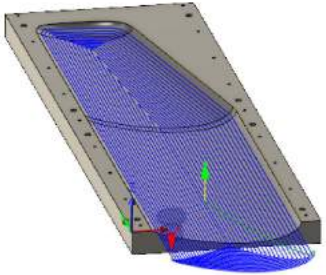


Wing - Molds

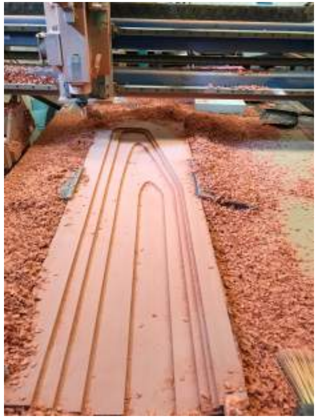
Wing CAD Model

Mold CAD Model

CAM Model



Route out of Renshape



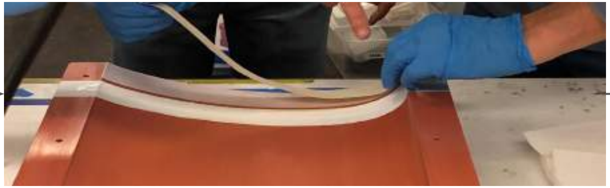
Sand, seal with epoxy, polish

Wax and Buff

Wing - Test Layup

Base epoxy on top of painted mold

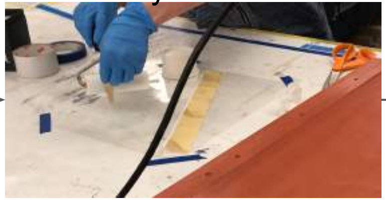
First Kevlar layer



Remove wax paper

Apply epoxy

Add foam core and prepare next layer of Kevlar



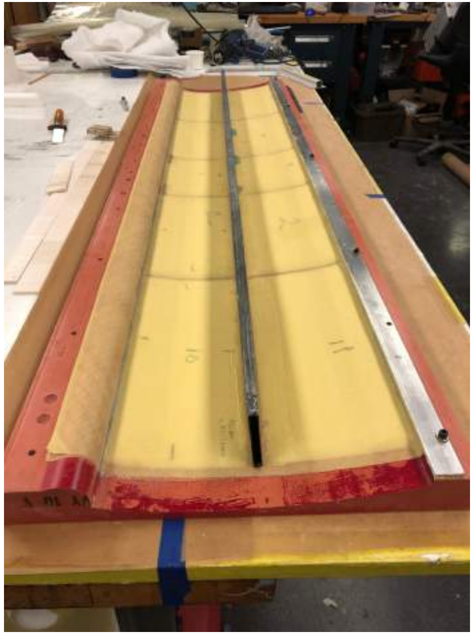
Hold foam core and second layer of Kevlar

Be careful not to move foam out of position

Add bleeder and breather

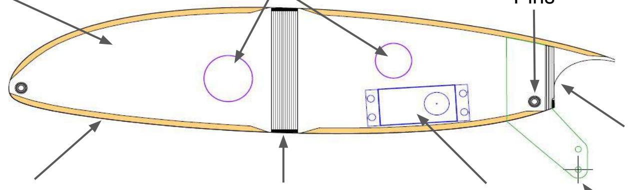
Seal mold in vacuum bag until cured

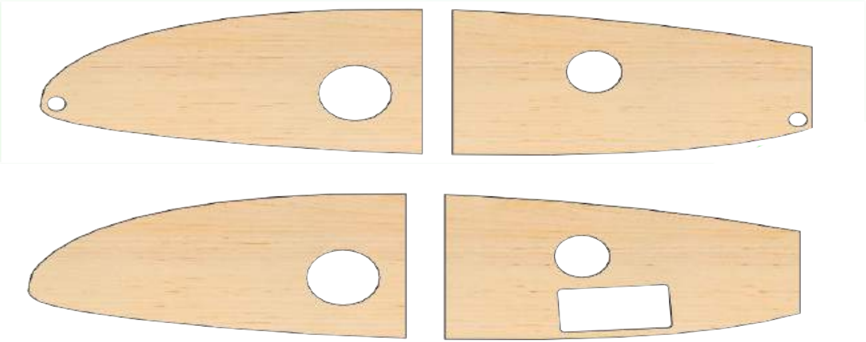
Wing - Layups



Wing - Internal Components

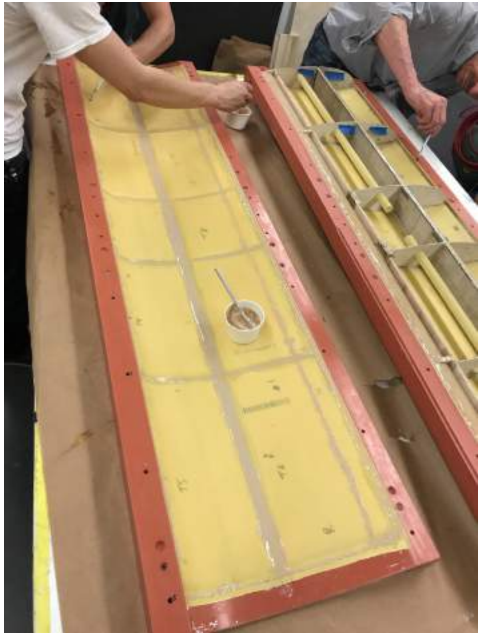
Cut out in TE spar for
flap bracket



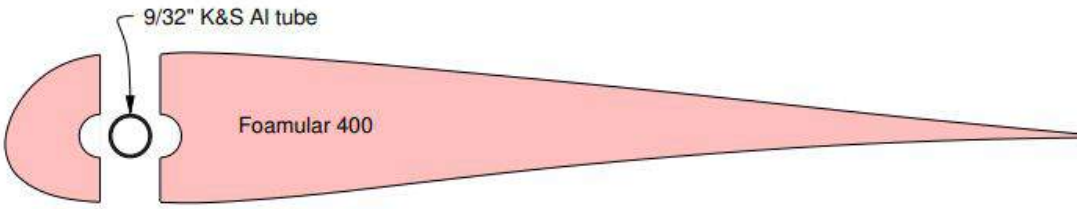


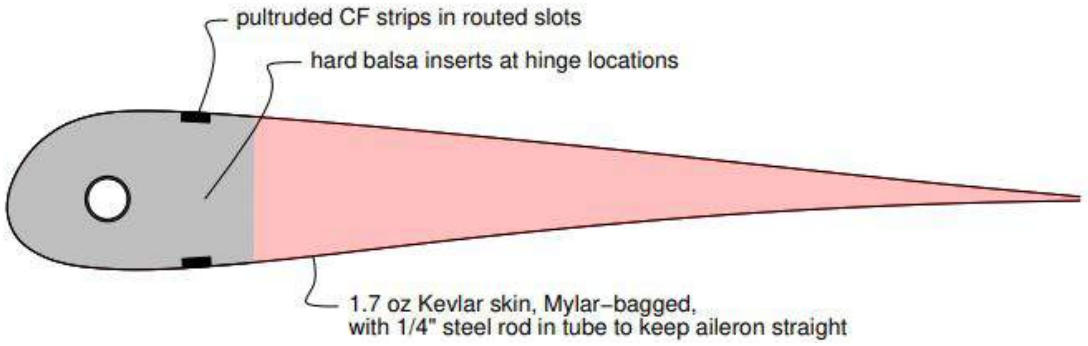
Wing - Closed and Joined

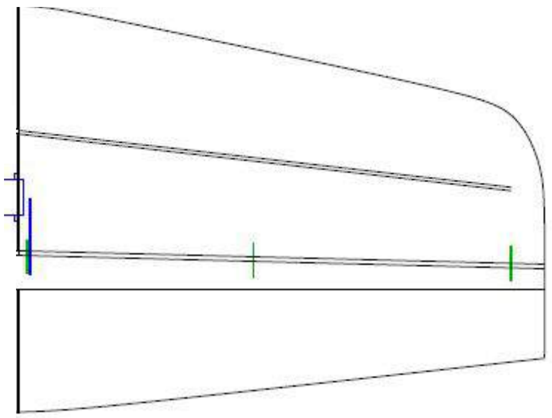
- Closing process
  - Epoxy everything with light-weight thickeners (cabosil)
  - Close
  - Re-epoxy
  - Close and clamp



Ailerons


9/32" K&S Al tube
Foamular 400


pultruded CF strips in routed slots
hard balsa inserts at hinge locations
1.7 oz Kevlar skin, Mylar–bagged,
with 1/4" steel rod in tube to keep aileron straight

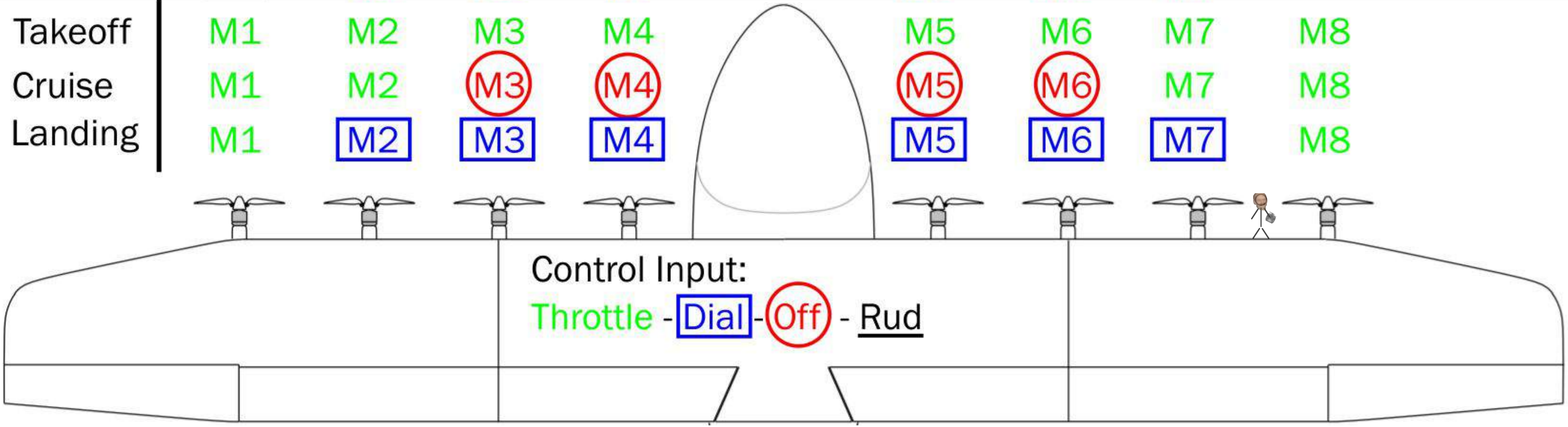


Avionics: Vehicle Control Modes

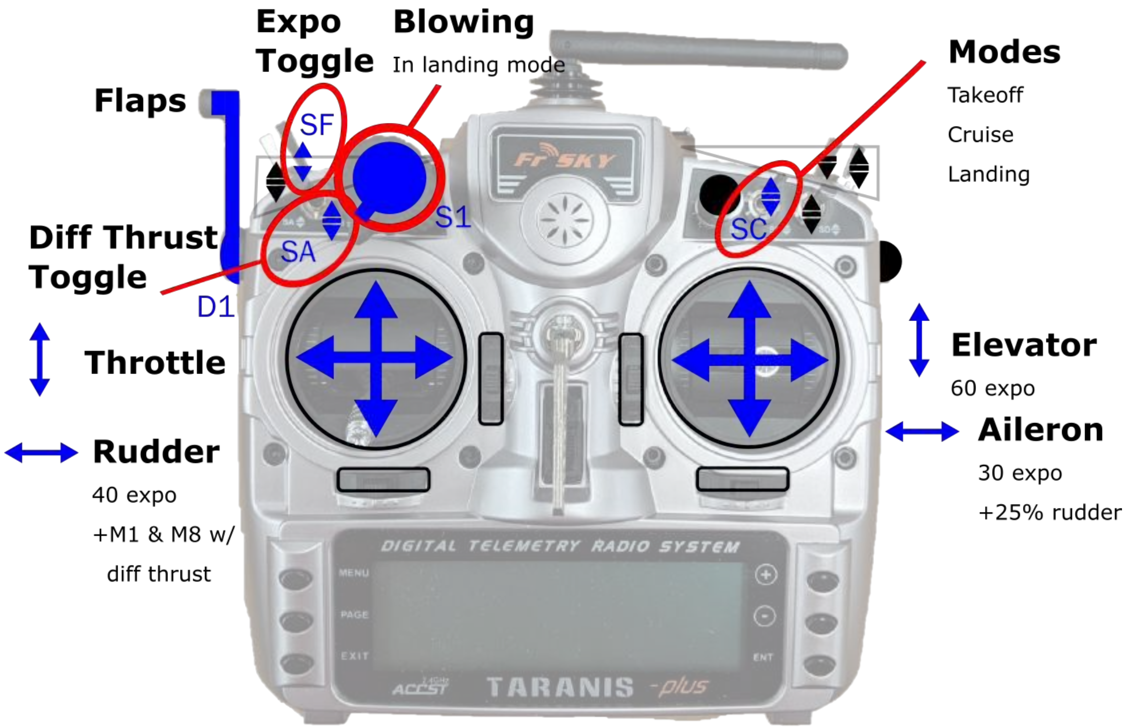
Taxi	Take-off	Cruise	Landing
- Differential thrust switch on transmitter - Addable in any mode - Used in "Take-off" mode	- Allows full blowing take-off - All motors tied to throttle stick	- Allows steady flight at less than full thrust - Outer four motors tied to throttle stick	- Allows blowing and glide-path control in landing - Outer two motors tied to throttle stick - Inner six motors tied to upper dial
All Modes: Normal RC control for pitch, yaw and roll. Flaps tied to dial on left side of Tx. Exponential toggle and differential thrust toggle available in all modes.			

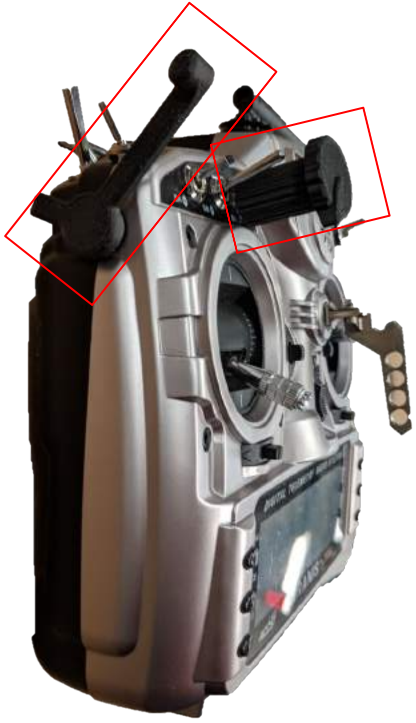
Avionics: Vehicle Control Modes

Mode:	Motor:							
Taxi	M1	M2	M3	M4	M5	M6	M7	M8
Takeoff	M1	M2	M3	M4	M5	M6	M7	M8
Cruise	M1	M2	M3	M4	M5	M6	M7	M8
Landing	M1	M2	M3	M4	M5	M6	M7	M8

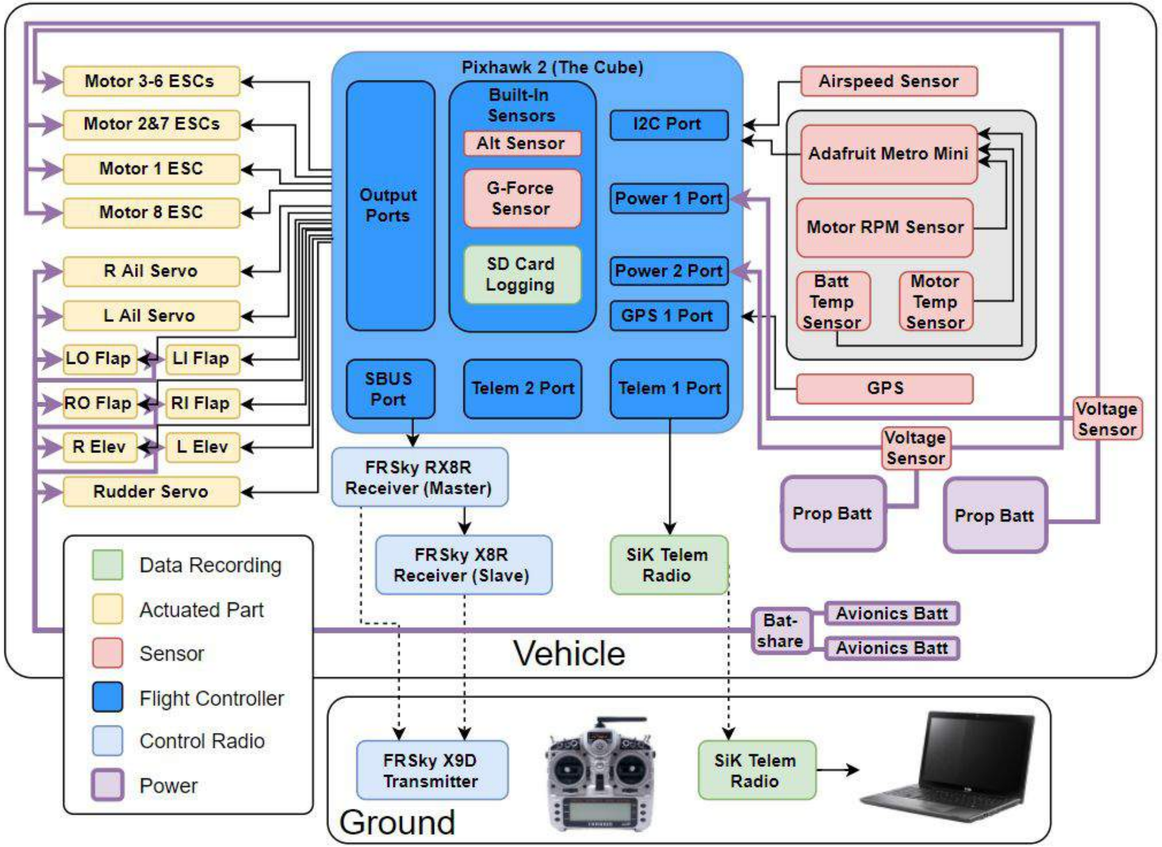


Avionics: Vehicle Control

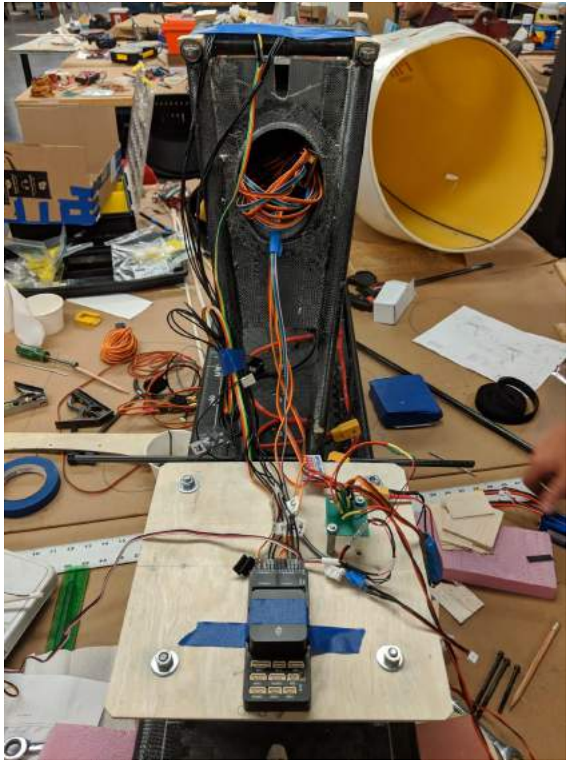


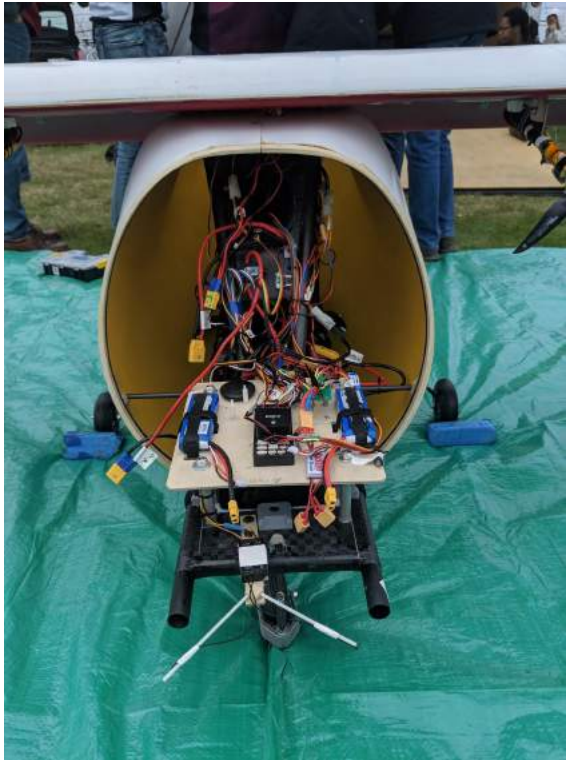


Avionics: Block Diagram



Avionics: Implementation





Avionics: Software and Flight Controller

Pixhawk 2 “The Cube”

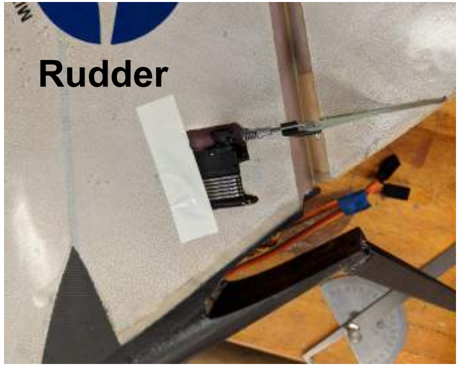
- Serves as RC signal passthrough
- Collects telemetry including PWM levels, airspeed, GPS, orientation, and battery status
- Powered on 7.7V avionics bus with 5V BEC

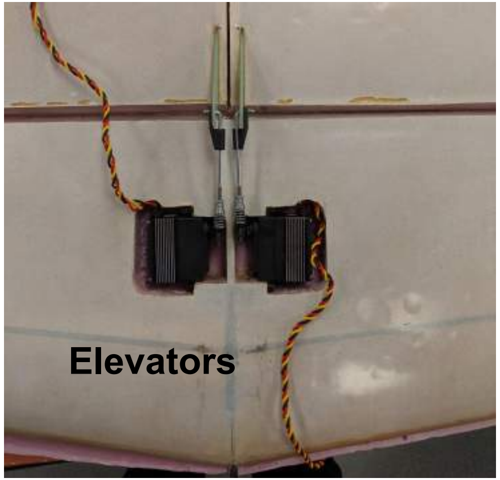
Arduplane:

- “RCPassThru” for Aux and Main servo pins
- Relatively closed but user friendly flight control software
- Working on custom telemetry for propulsion

Avionics: Servos

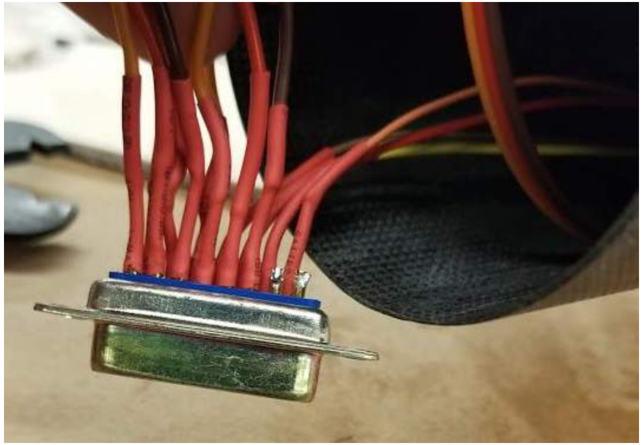
- HiTech HS-7955 and 7950 high torque servos
- Installed post-production
- Powered by two 2200mAh 2s LiPo batteries on a 7.7V avionics bus
- Reversed in transmitter
- Tuned with transmitter
- Jitter issue

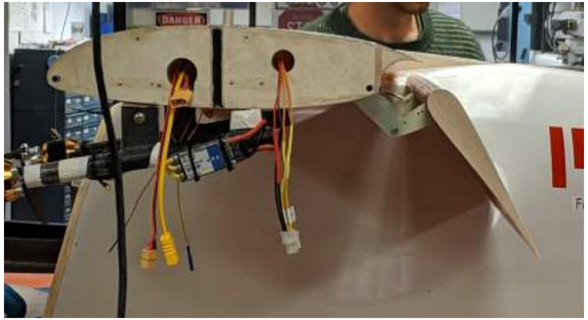


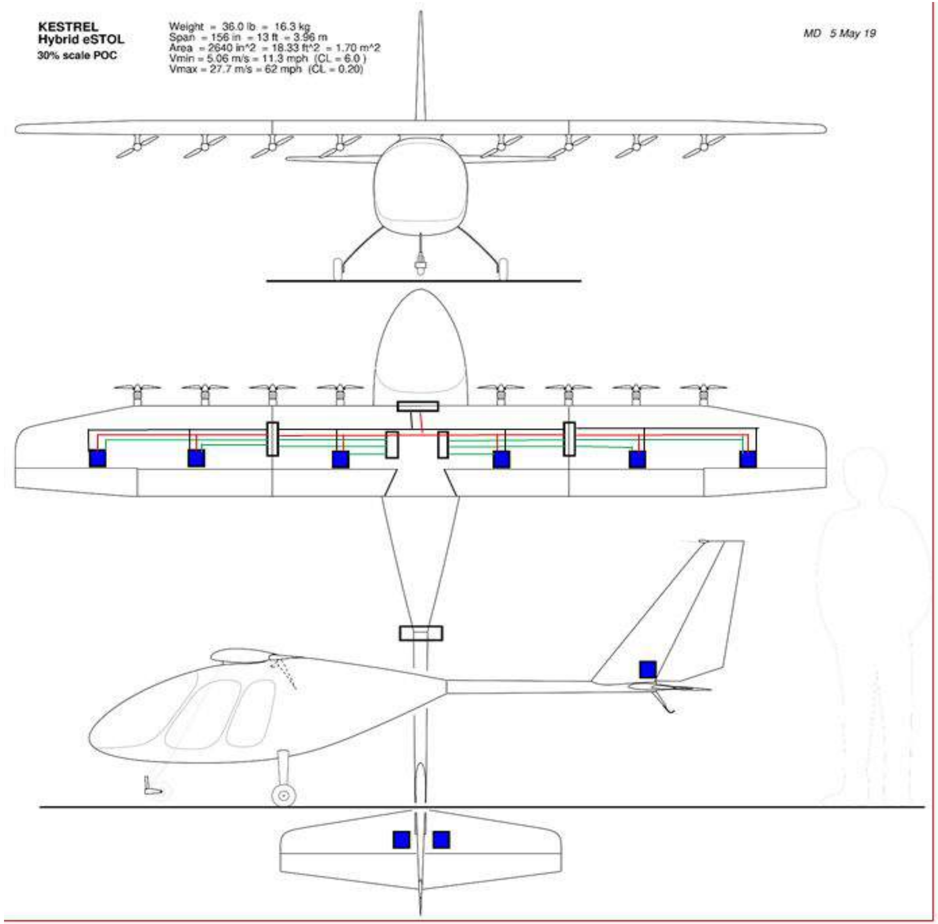


Avionics: Signal and Power Routing

- Rear wing conduit: servo signal and power wires 4 pin connectors coming from the wing center
- 4 pin connector at the wing break for the aileron and outer flap
- Elevator, rudder, pitot tube routed through the tail to a 15 pin connector 3x3 servo wires 4 for the pitot tube at the tail break
- Goes to aeroshell to plug into the pixhawk
- Power distribution and sensing




DANGER

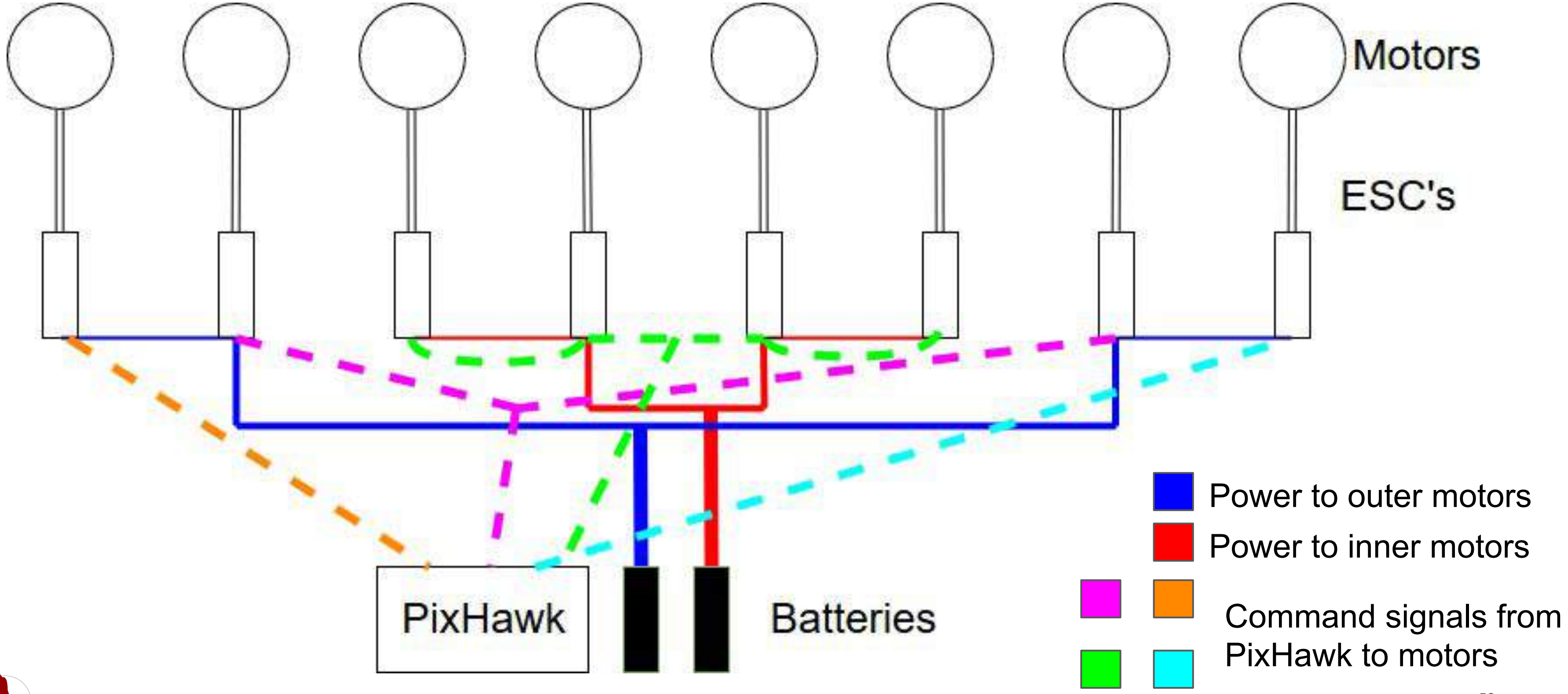

KESTREL
Hybrid eSTOL
30% scale POC
Weight = 36.0 lb = 16.3 kg
Span = 156 in = 13 ft = 3.96 m
Area = 2640 in^2 = 18.33 ft^2 = 1.70 m^2
Vmin = 5.06 m/s = 11.3 mph (CL = 6.0)
Vmax = 27.7 m/s = 62 mph (CL = 0.20)
MD 5 May 19

Propulsion Overview

- 5000 W Nominal Installed Power - 8 motors x 625W per motor
- As designed: 11 minutes of full power flight time
- Carbon fiber pylons for attachment to the wing
- Two batteries powering 4 motors each

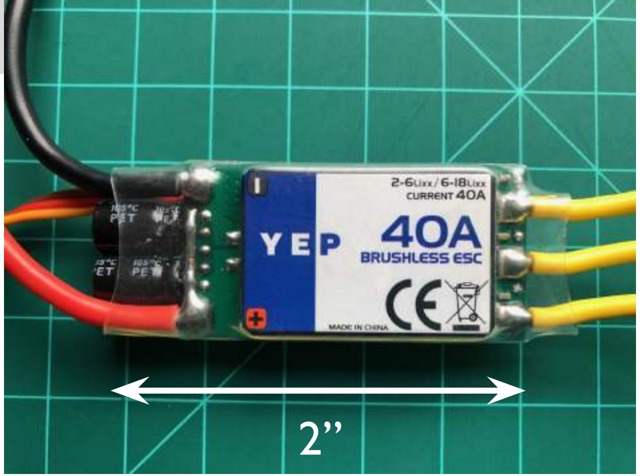
Motor on test stand in front of 1.5'x1.5' wind tunnel

Propulsion wiring



Propulsion components

- **ESC model:** YEP 40A
- **Motor model:** Scorpion SII-3014-830KV
- **Propellers:** Aeronaut 9x6 folding props
- **Batteries:** MaxAmps 6S 16,000 mAh (x2)

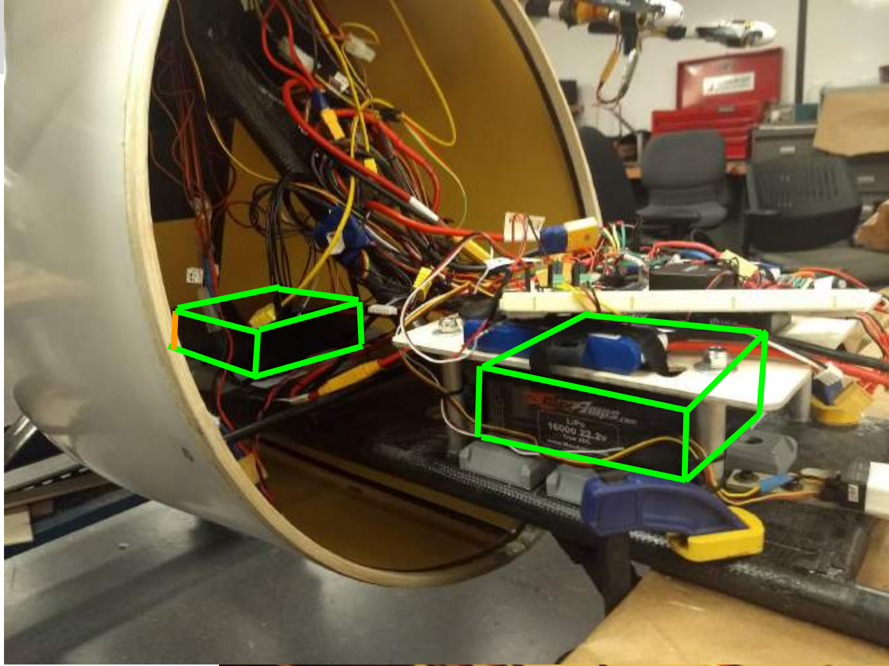


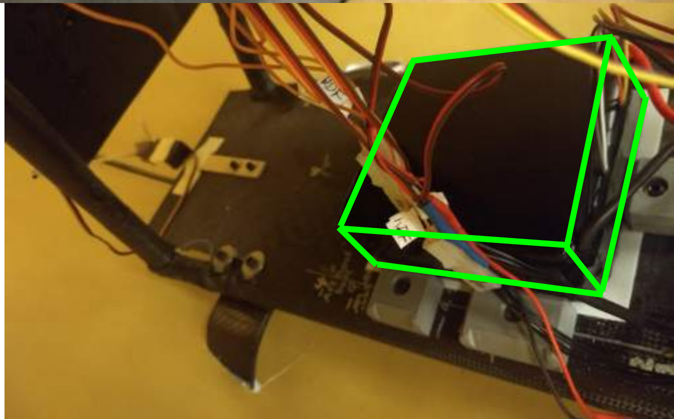
1.5"

6" x 6" x 1.5"

Battery Sizing:

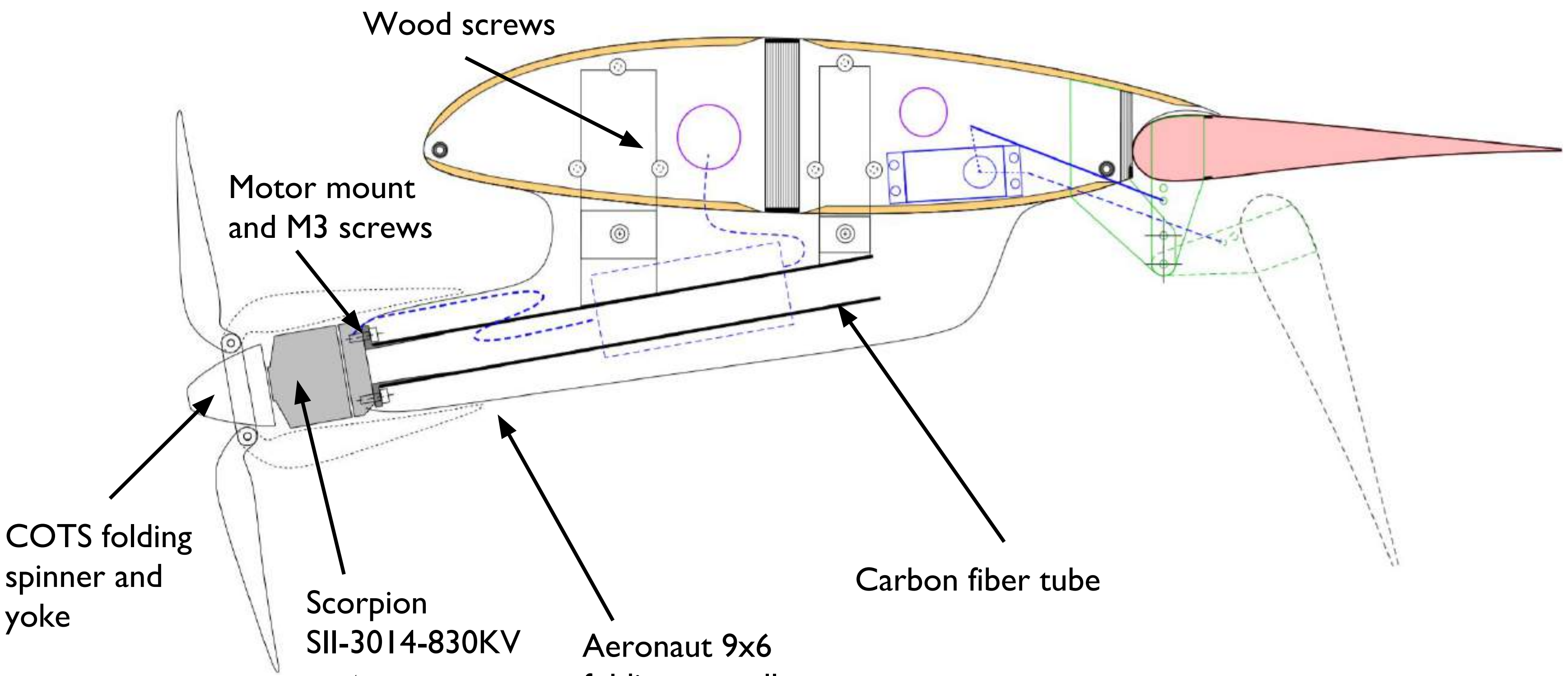
- 6S batteries for power delivery
- Full power flight time scales linearly with capacity
- 2x 4.4lb batteries provide a total of 32 amp-hours capacity and 11 minutes flight time
- Can upscope to 4x batteries to provide 22 minutes flight time



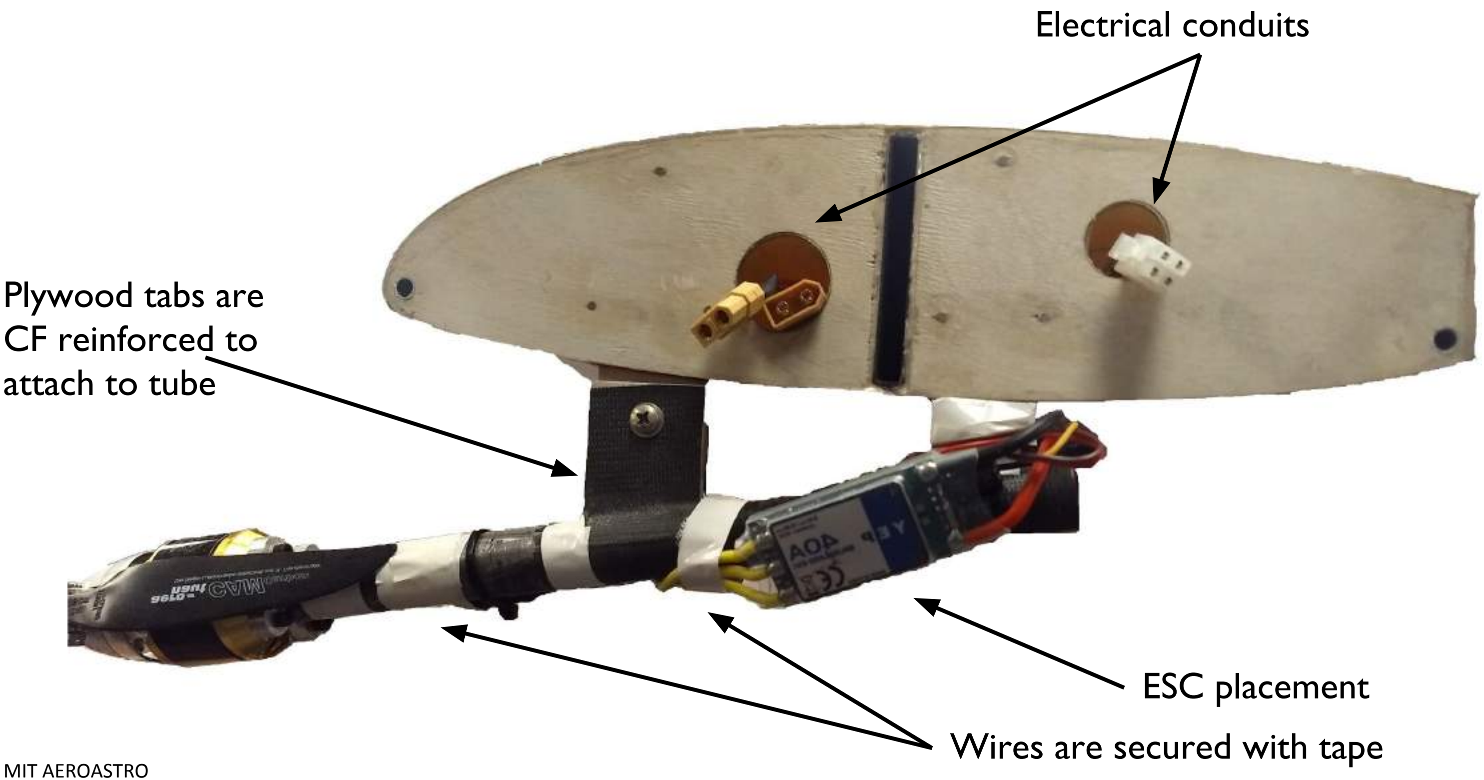


Rear battery can be moved to adjust CG

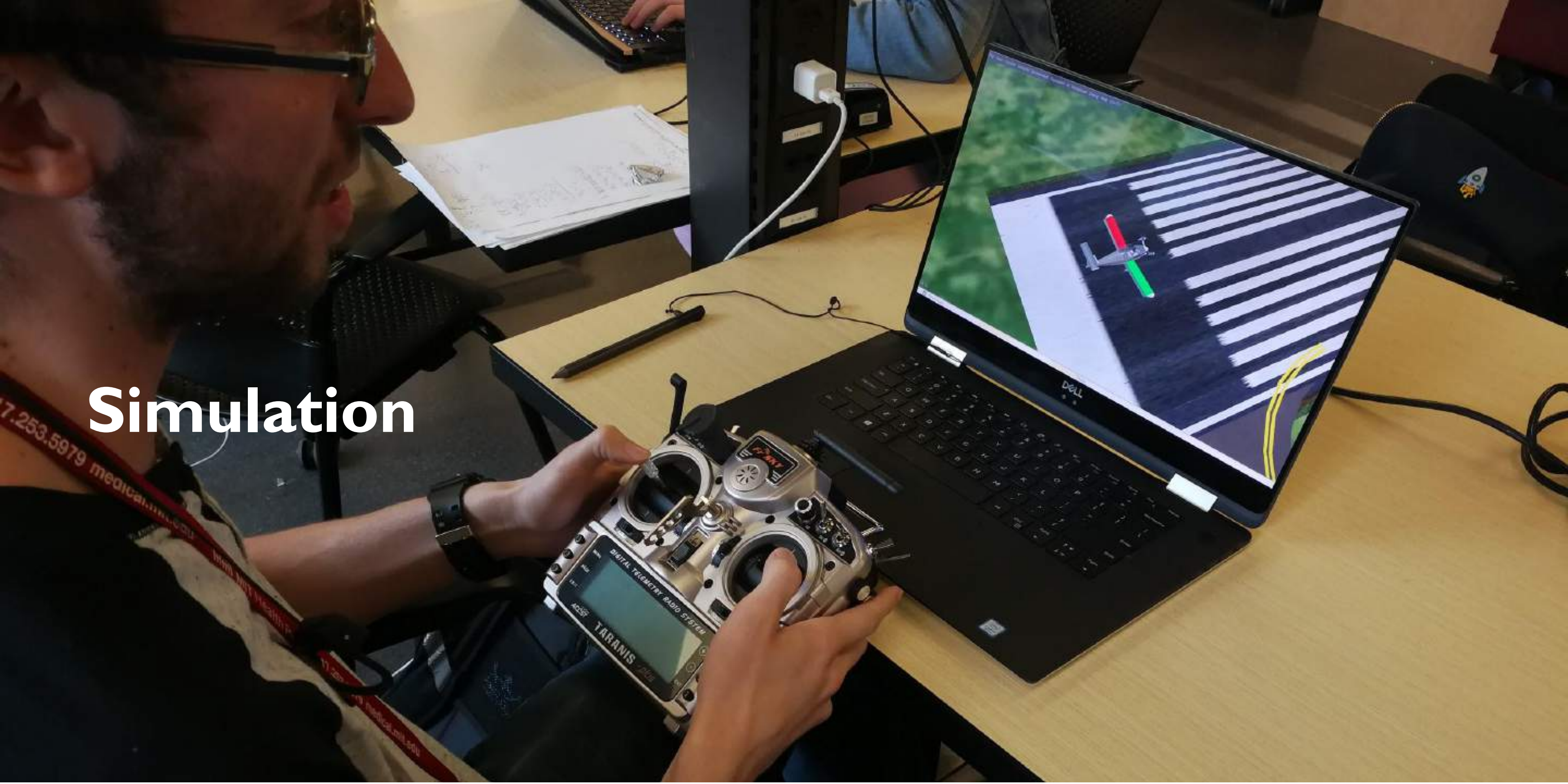
Propulsion hardware: as-designed



Propulsion hardware: as-built



Simulation



Goal of simulation

- Risk mitigation for the 30% scale flight test
  - Risk of damage to aircraft
  - Time risk of ‘figuring out’ aircraft
- Train pilot prior to flying the 30% scale vehicle
  - Get a ‘feel’ for the aircraft
  - Establish a comfortable control scheme
  - Determine aircraft configurations for different maneuvers

**Initial idea was to use simulation as a primary program-level risk mitigation for aircraft, but time delays prevented this*

Why build a simulator?

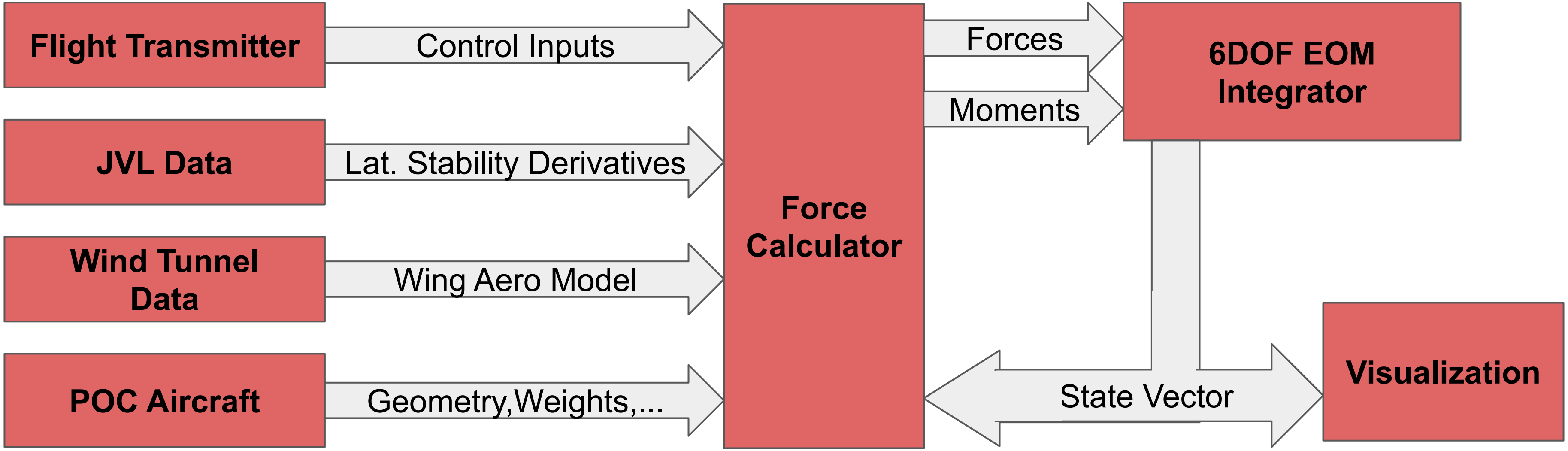
- The vehicle has atypical C_L, C_X, C_Y, C_m, C_n, C_ℓ values due to blowing
- Need to model these coefficients using mainly WT data (when possible)
- For example, before stall: $C_L = C_{L(wing)} + C_{L(tail)}$

From WT best-fit (function of δ_f, α, ΔC_J)

From JVL

- Additional control inputs
  - Flaps
  - Different distributed propulsion modes (individual inboard/outboard motor control)

Overview of simulator



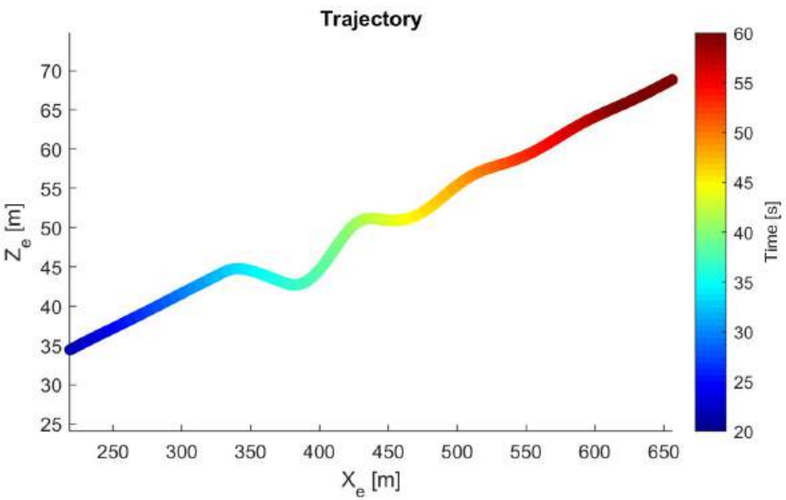
Simulator features

- 6-DOF simulation
- **Aerodynamic model:** Incorporates 16.82 WT data, JVL derivatives and post-stall experimental data
- **Propulsion model:** modelled from QPROP
- **Control input:** FrSky Taranis X9D Plus (closely replicate flight test control scheme)
- **Visualization:** Optimized for RC piloting through FlightGear (takes place in a poorly rendered Plum Island!)

Benchmark test (3°, 4 sec down elevator singlet @0° flaps)

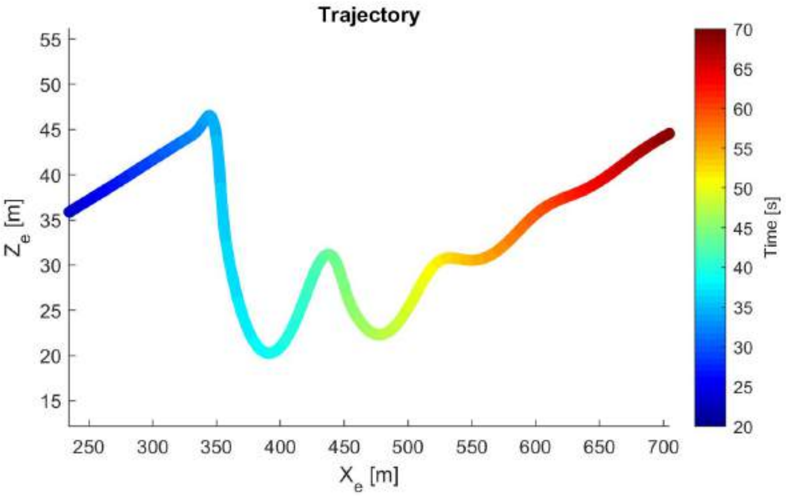
Main takeaway: simulator accurately captures aircraft's phugoid

$f_{analytic} \approx 0.16$ Hz (only an approximation), $f_{simulator} = 0.142$ Hz



Benchmark test (stall /w 7°, 4 sec up elevator singlet @ 0° flaps)

Main takeaway: aircraft stalls as expected, exhibits natural fixed-stick stall recovery



Pilot feedback

- Professor Drela accumulated ~1 hour of flight time on the simulator
- Simulator aided in getting a feel for the aircraft's:
  - Response characteristics
  - Control throws
  - Damping
  - Flap-pitch coupling effects & associated trims
  - General behaviour
- Reduced time taken to get used to aircraft from 10 min to 30 sec
- 30% scale vehicle felt similar to simulator

Next Steps for Simulation

- Now have more confidence in physical accuracy of simulator due to similarity with flight test
- Still, flight data can be used to inform and improve the simulation dynamics
- Next focus of the simulator is to help determine optimal flap-blowing configurations for SSTOL objectives
  - To help mitigate the descent glide path risk

15% scale

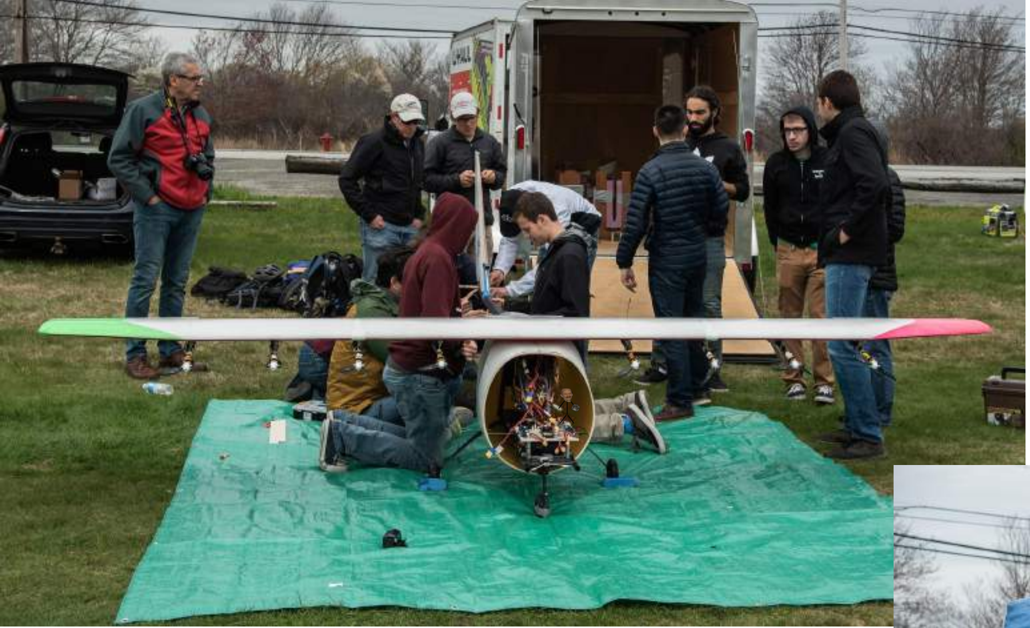
73

Motivation for and fabrication of 15% scale vehicle

- Motivation
  - Prepares pilot to fly larger-scale vehicle
  - 15% scale flies "visually similar" to 30% scale
    - Proportional mobility
- Manufacturing
  - Foam fuselage, wings, flaps, and ailerons
  - Balsa tail
  - Plywood brackets and horns
  - 4 servos on wings (2 flaps, 2 aileron)
  - 2 servos on fuselage (1 rudder, 1 elevator)
  - Four motors total (2 on each wing)

First Test Flight

PLUM ISLAND, MA (2B2) | May 4th, 2019



Aircraft Assembly

Avionics and Telemetry Center

MIT Kestrel

MIT AEROASTRO

Propulsion Anomaly

- Motors would repeatedly cut out momentarily, resulting in effectively ~50% thrust being delivered
- Cause has been traced to PixHawk's inability to deliver sufficient power to its output pins
  - PWM signal should be 0-3.3V, actual outputs are 0-2V when loaded
  - ESC receiving weak signal causes it to stop outputting briefly
- Preliminary troubleshooting has shown that placing Line Driver IC's on Pixhawk motor outputs removes voltage sag and results in stable motor response

Servo Jitter

- Tail servos (primarily elevator servos) buzzed and jittered while powered up
    - Oscilloscope revealed signal from Pixhawk is clean; servos generated the noise

- Solution: program larger dead band into servos
    - Digital servos are highly programmable
    - Programming module ordered

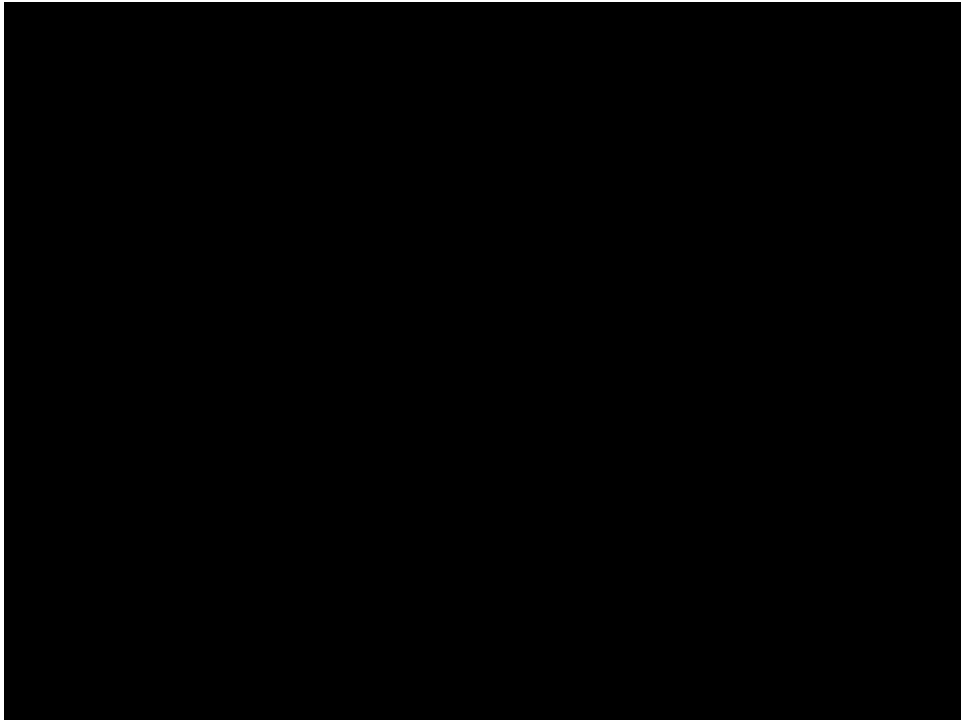
Flight Test - Summary

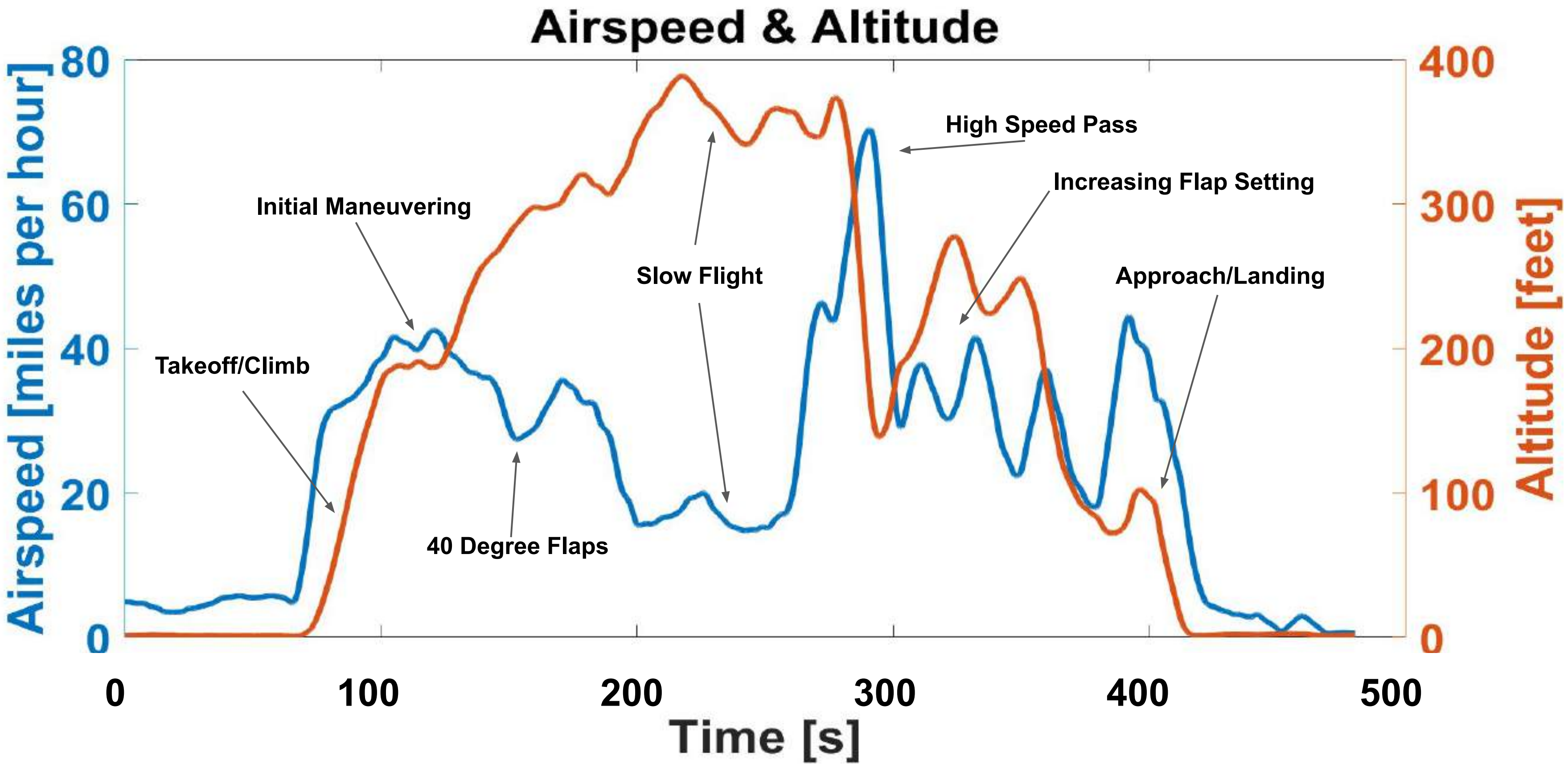
One test flight out of Plum Island Aerodrome (2B2):

- 20° Flap Takeoff
- 40° Flap Maneuvering
- Full Flap “Slow Flight”
- 0° Flap High Speed
- Full Flap Landing

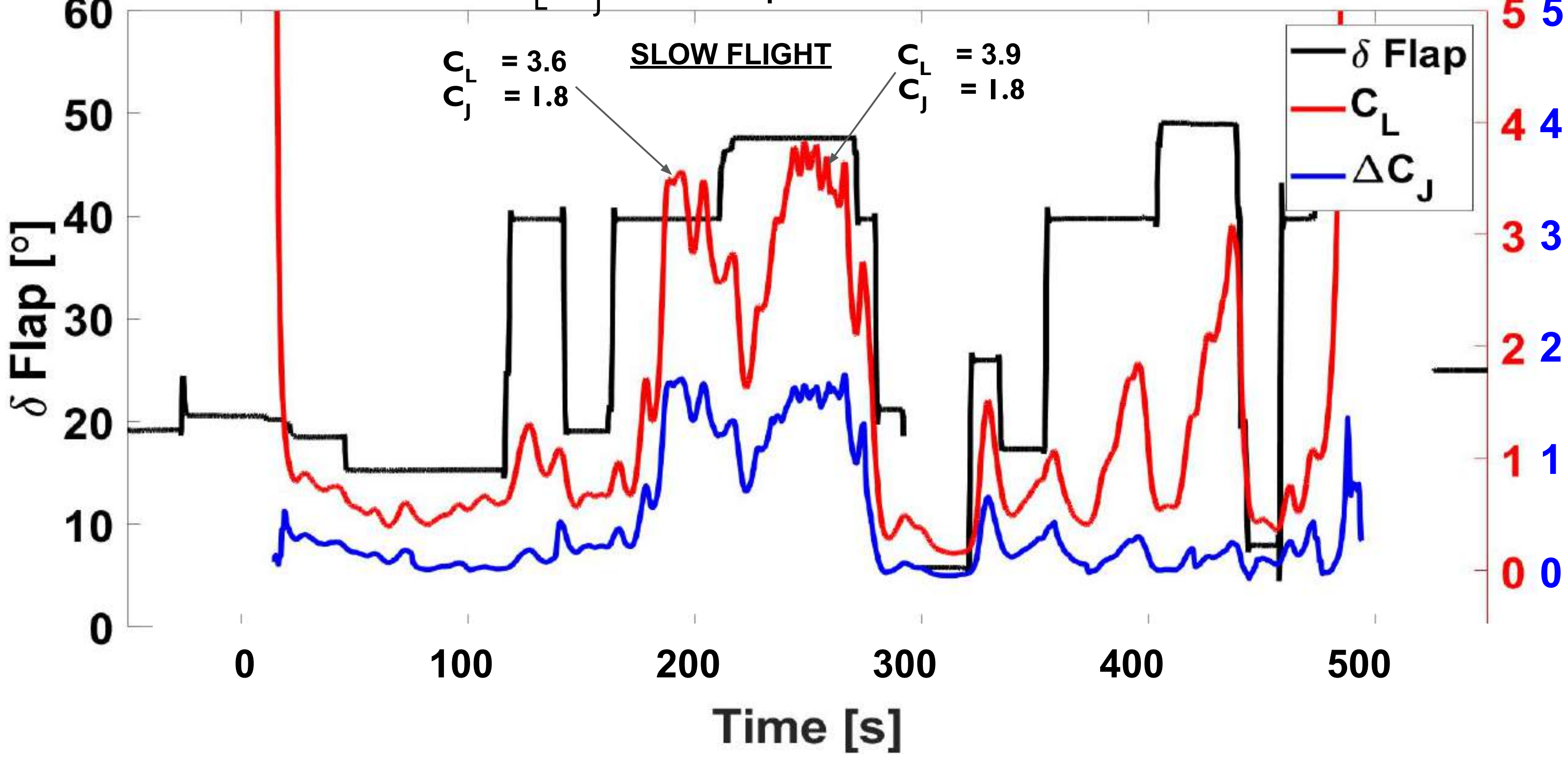
Again, we were operating under 50% power

Flight Test Video- Summary



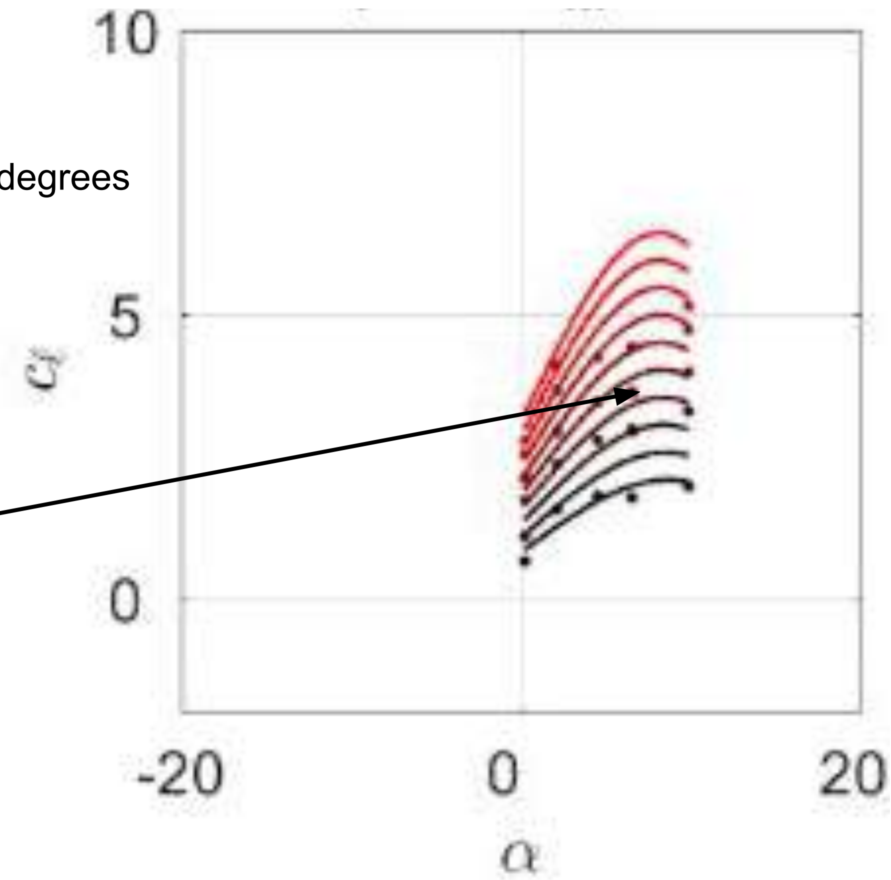

Airspeed & Altitude
Airspeed [miles per hour]
Altitude [feet]
Time [s]
0
20
40
60
80
100
200
300
400
500
Takeoff/Climb
Initial Maneuvering
40 Degree Flaps
Slow Flight
High Speed Pass
Increasing Flap Setting
Approach/Landing

C_L C_J with Flap Positions



High C_L Performance Conclusions

Flap Deflection: 45 degrees

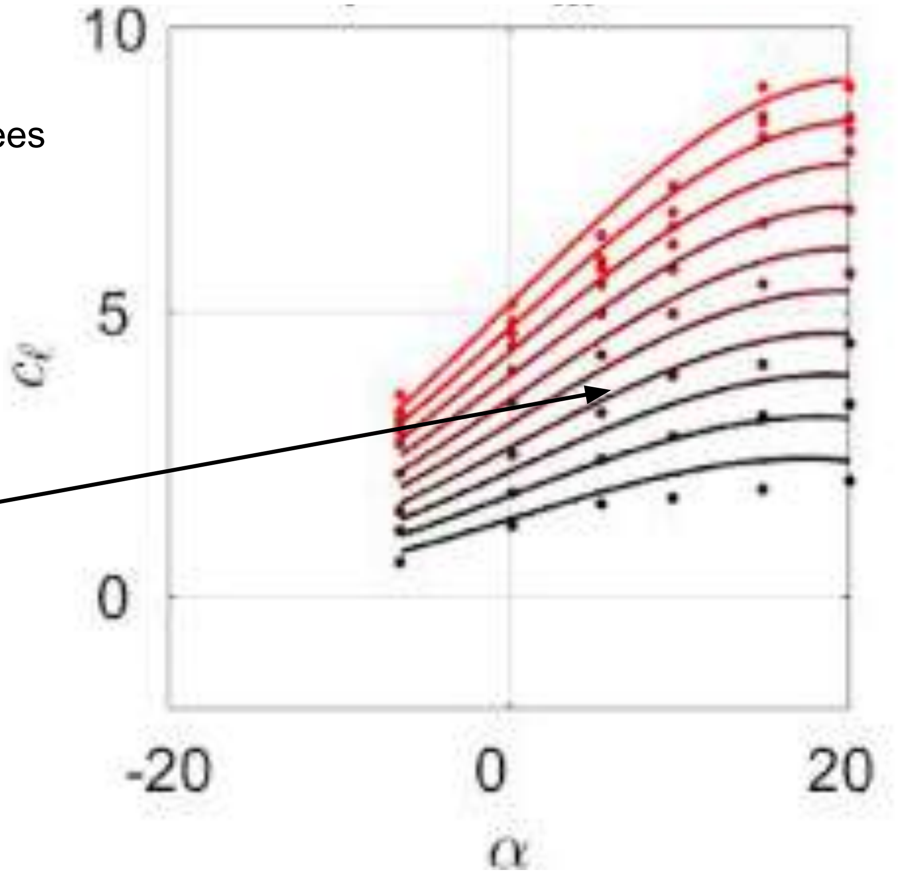


<u>Slow Flight</u>
C_L = 3.9
C_J = 1.8

- Matches data closely when angle of attack between 5° and 10°.
-1 to 0.9 conversion from wind tunnel data to real world expected value.
-Once power issue resolved expect to move up the plot.

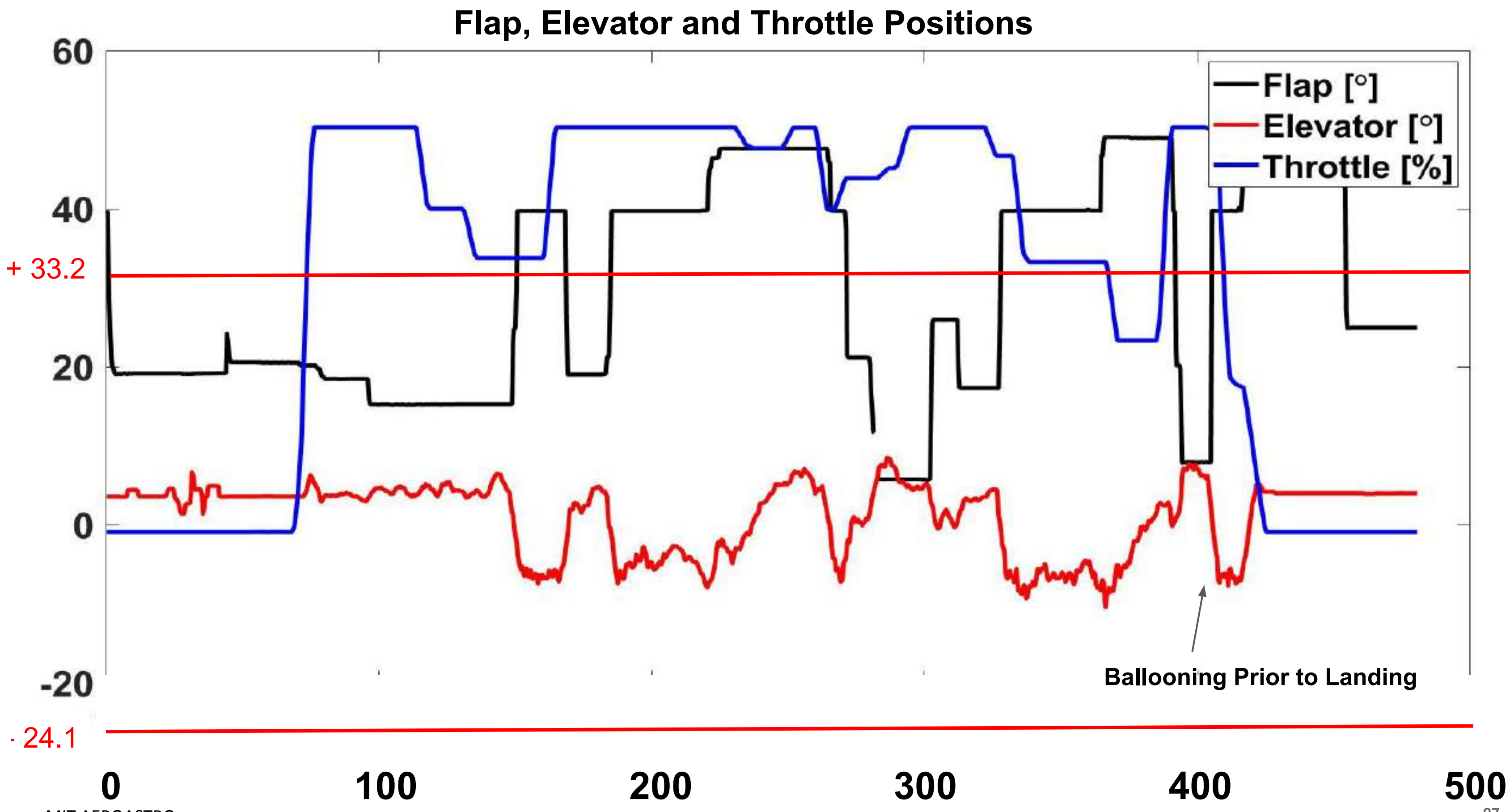
High C_L Performance Conclusions

Flap Deflection: 40 degrees



<u>Slow Flight</u>
C_L = 3.6
C_J = 1.8

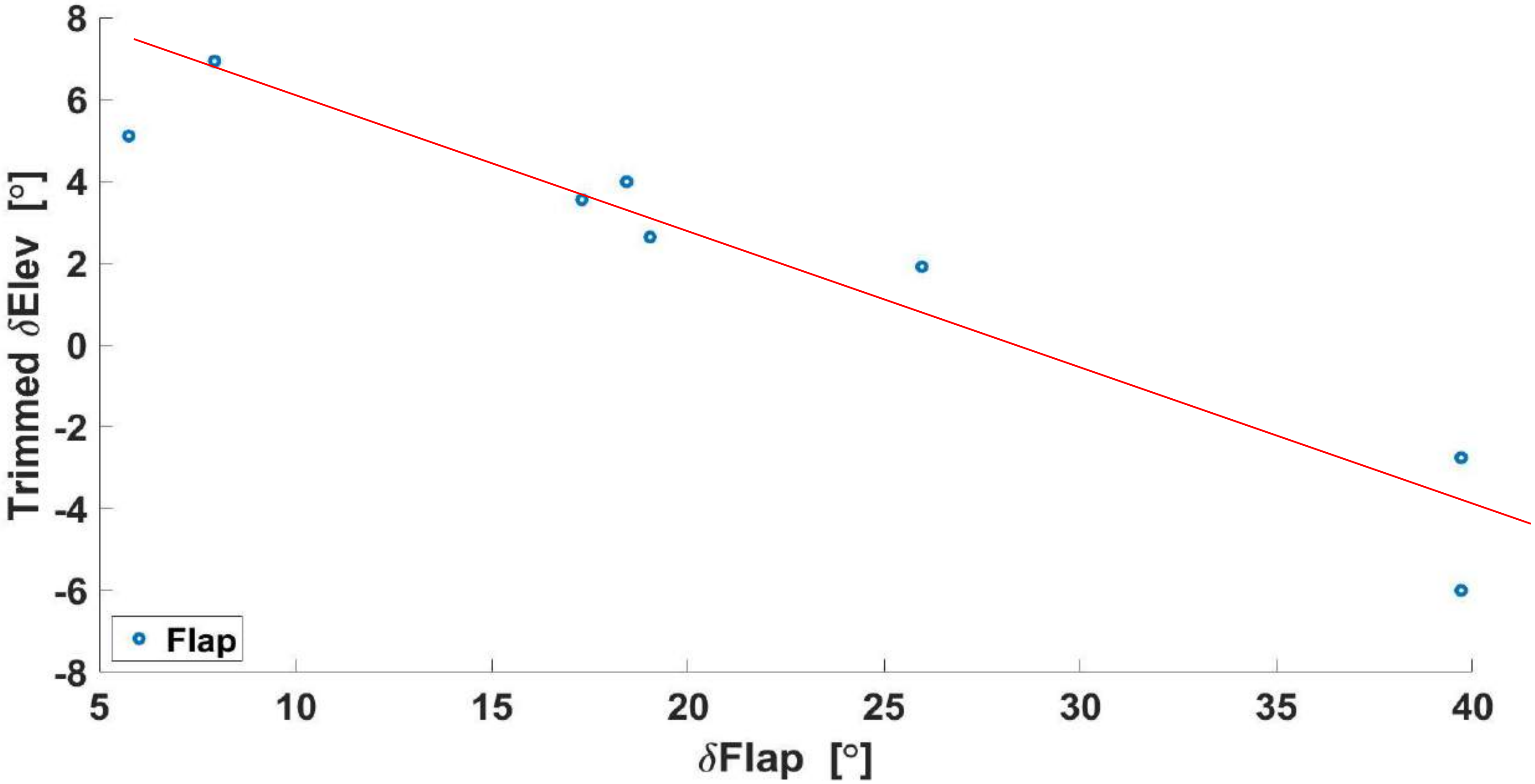
-Demonstrates correlation for 40 degree flap setting within reasonable angle of attack range.



Flap, Elevator and Throttle Positions
60
40
+ 33.2
20
0
-20
- 24.1
0
100
200
300
400
500
Flap [°]
Elevator [°]
Throttle [%]
Ballooning Prior to Landing

Tail Sizing Conclusions

- Demonstrated sufficient tail sizing for pitch control.
- 41% maximum required elevator for the entire flight.
- Largest elevator inputs occur during transitions to higher flap settings
- Can use servo information to mix elevator with flap deflection.



Trimmed δElev [°]
8
6
4
2
0
-2
-4
-6
-8
Flap
5
10
15
20
25
30
35
40
δFlap [°]

Aircraft Controllability Assessment

	20° Flap Takeoff	40° Flap Maneuvering	Full Flap "Slow Flight"	0° Flap High Speed	Full Flap Landing
Cooper-Harper Rating	3	5	6	4	4
Cooper-Harper Description	Minimal pilot compensation required for desired performance	Adequate performance requires considerable pilot compensation	Adequate performance requires extensive pilot compensation	Desired performance required moderate pilot compensation	Desired performance required moderate pilot compensation

Aircraft Controllability Conclusions

- Qualitative analysis shows aircraft was controllable under all flight modes
- Pilot was able to perform all of the maneuvers attempted on first flight without loss of control
- Very positive for outcome under 100% during future testing

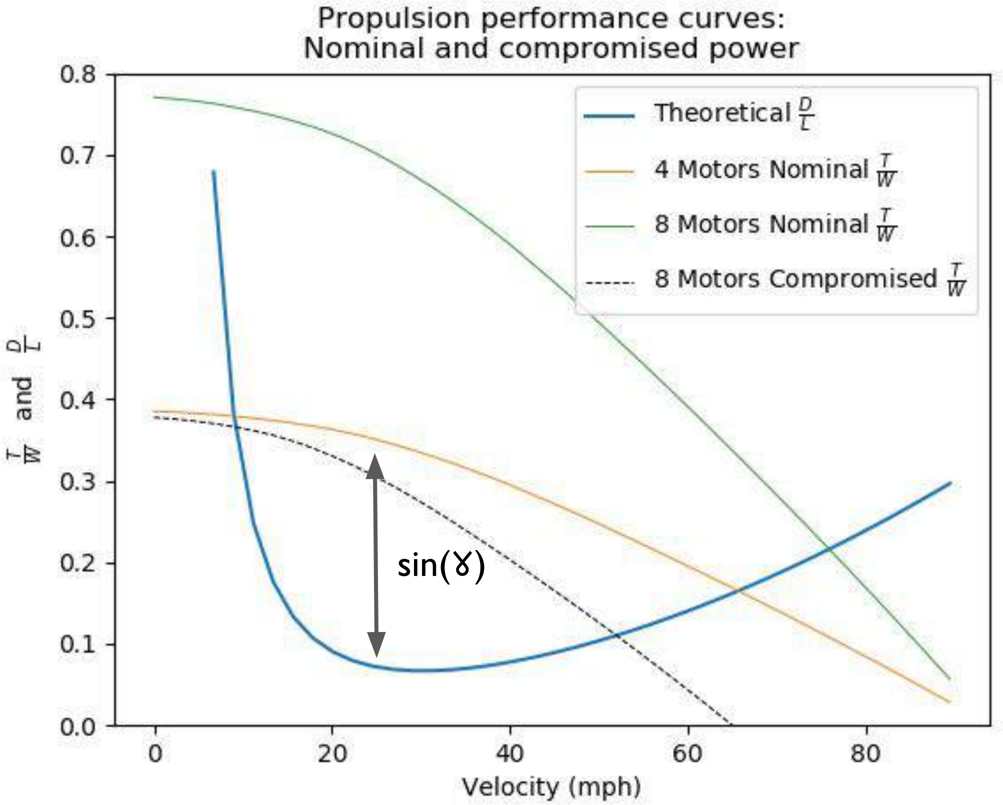
Summary of Results From Flight Test

Addressed primary risks for POC vehicle: high C_L performance, sufficient tail sizing and controllability.

- Despite operating below 50% of max power, demonstrated a C_L of 3.9.
- Once Pixhawk motor output resolved, expecting to see even higher values.
- Demonstrated sufficient tail sizing.
- Never required more than 41% elevator deflection to control pitch.
- Can use servo information to mix elevator with flap deflection.
- Remained controllable throughout different flight regimes.

Possible propulsive performance improvements

- T/W calculated from QPROP
  - Nominal and compromised power levels extrapolated from fish-scale thrust test
- D/L generated from drag-buildup and assuming steady-level flight
- Intersection of T/W and D/L curves = theoretical cruise speeds
- Significant climb angle, ɣ, improvements with power fix



Key Design Risks and Current Assessment

LOW/ VALIDATED
MILD/ PARTIALLY VALIDATED
MEDIUM/ TO BE TESTED
HIGH

Risk	Assessment
Blown lift performance does not match prediction	Wind tunnel validated
Tail Sizing Insufficient	Lack of full power during flight test prevented testing of tail size sufficiently
Control difficulty near stall due to rapid pitching moment change	One stall maneuver was performed and control difficulty was fair, but lack of full power and oscillating motors prevent conclusion
Excessive difficulty controlling approach glide slope	Unable to test due to lack of full power
Insufficient low-speed lateral control	Oscillating motors affected pilot's ability to control at low-speeds
Insufficient precision landing capability	Did not test during initial flight test

The Path Forward

Aircraft modifications:

- Resolve servo jitter
- Stabilize motor signals

The Second Flight:

- Testing of tail size sufficiency under high flaps, high blowing, slow airspeed configuration
- Testing of control difficulty near full-power stall
- Testing controllability of approach glide slope
- Testing of lateral control with servo jitter removed
- Testing of precision landing capacity

Thank you!

Professors Mark Drela and John Hansman

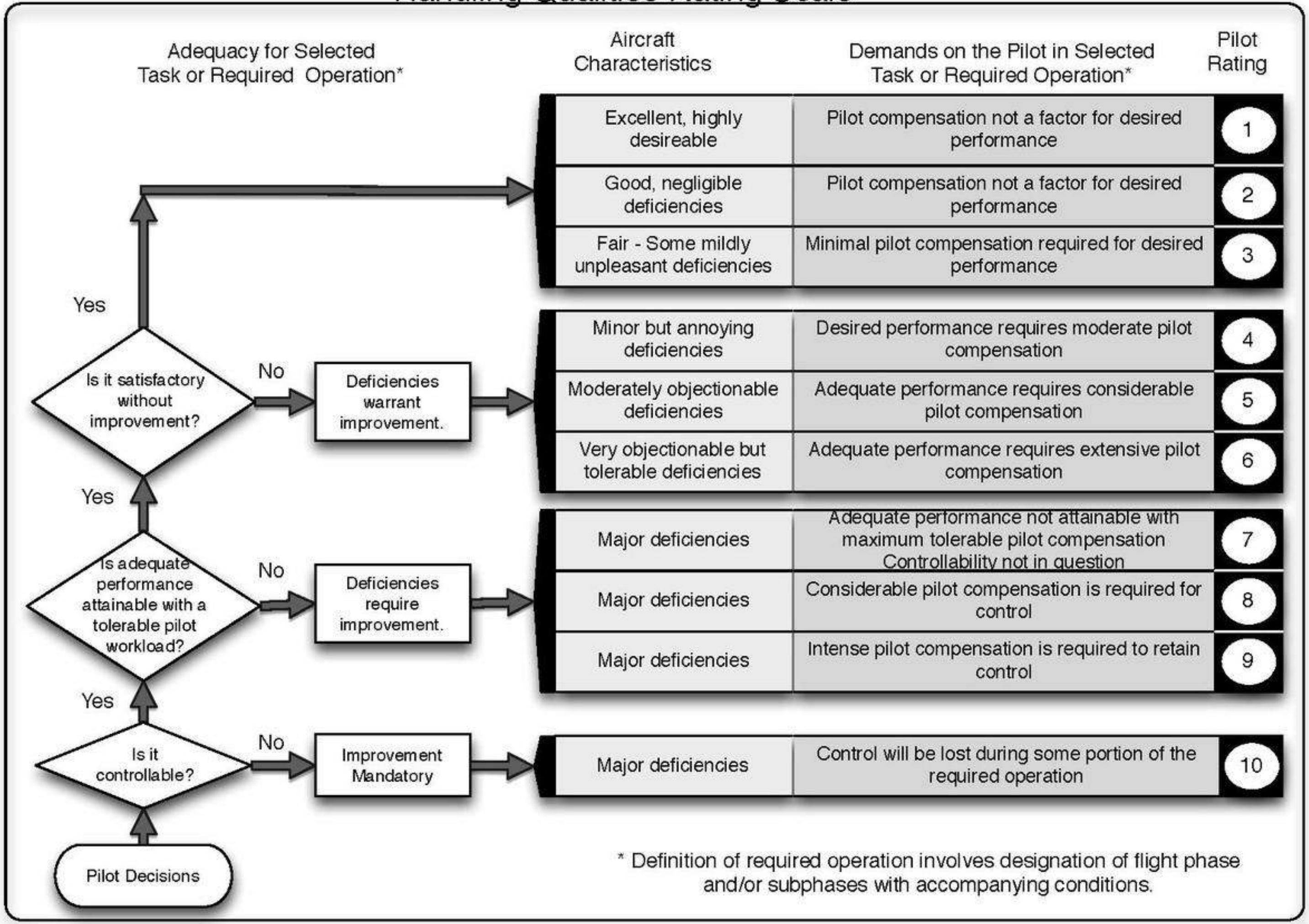
Communication Instructor Jennifer Craig

Teaching Assistants Chris Courtin and Jacquie Thomas

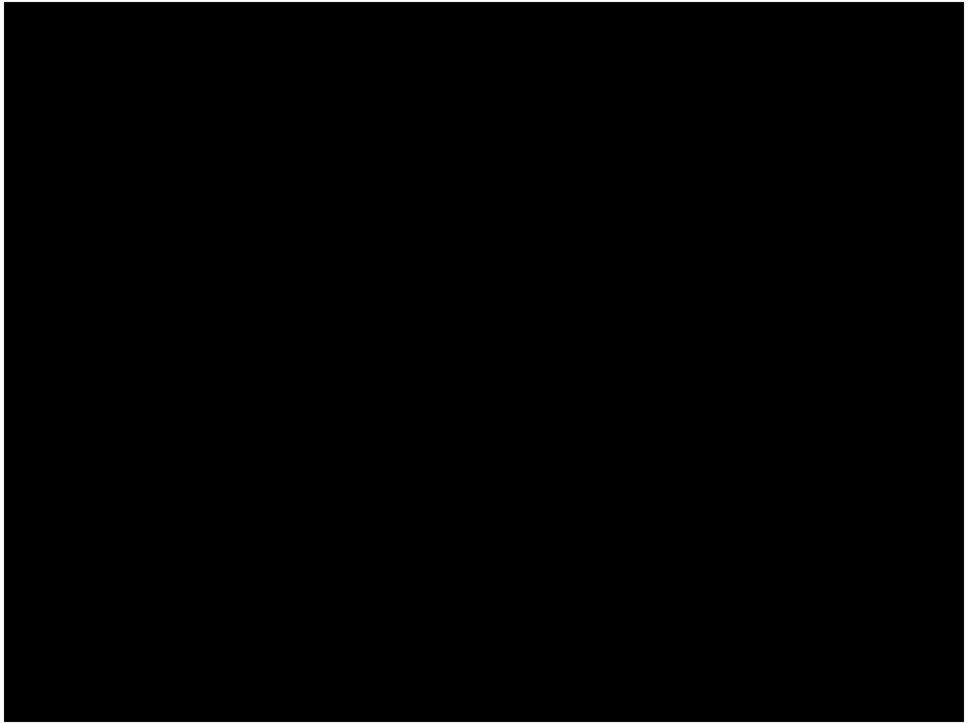
Aurora Flight Sciences

Appendix

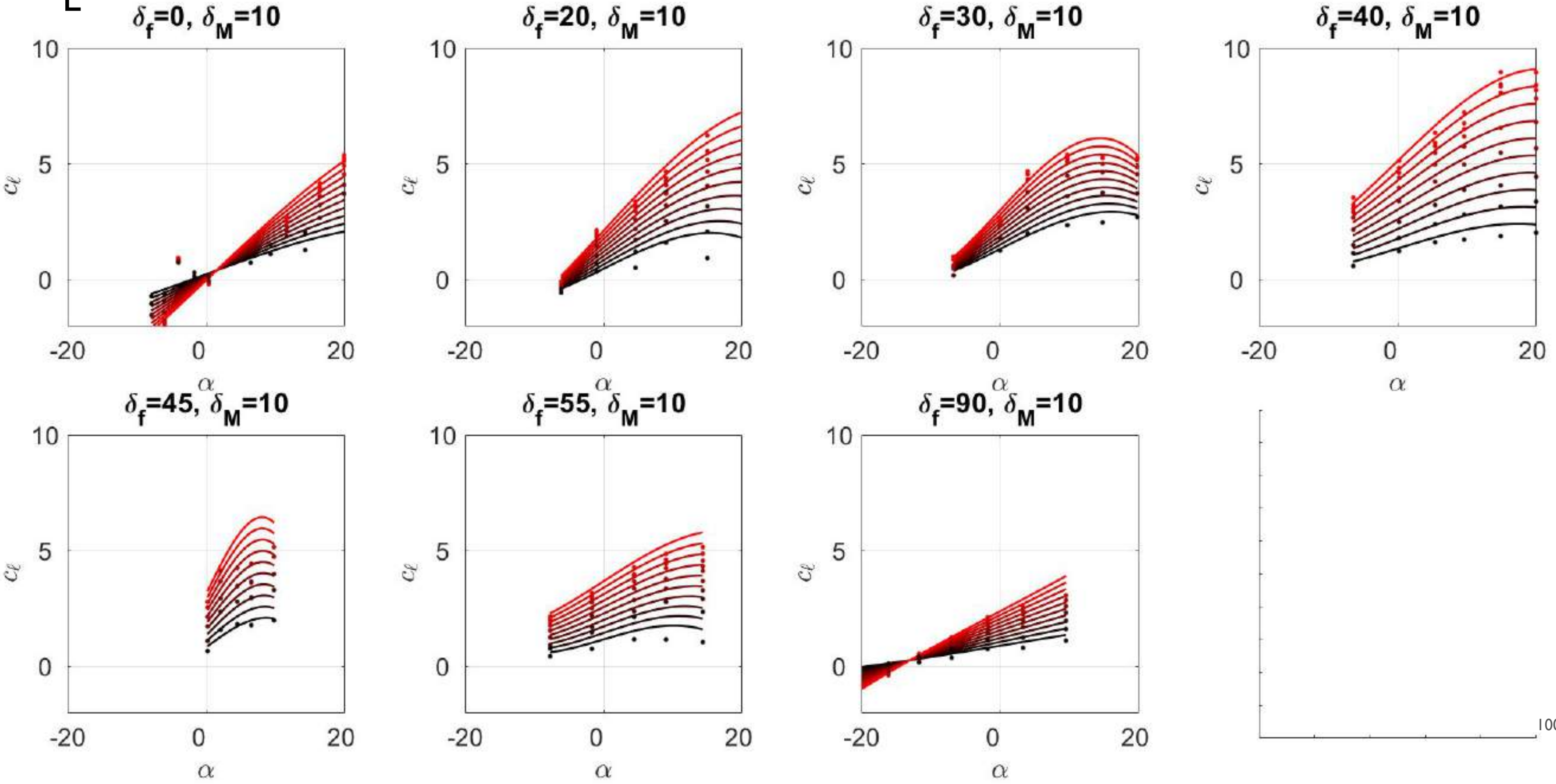
Handling Qualities Rating Scale



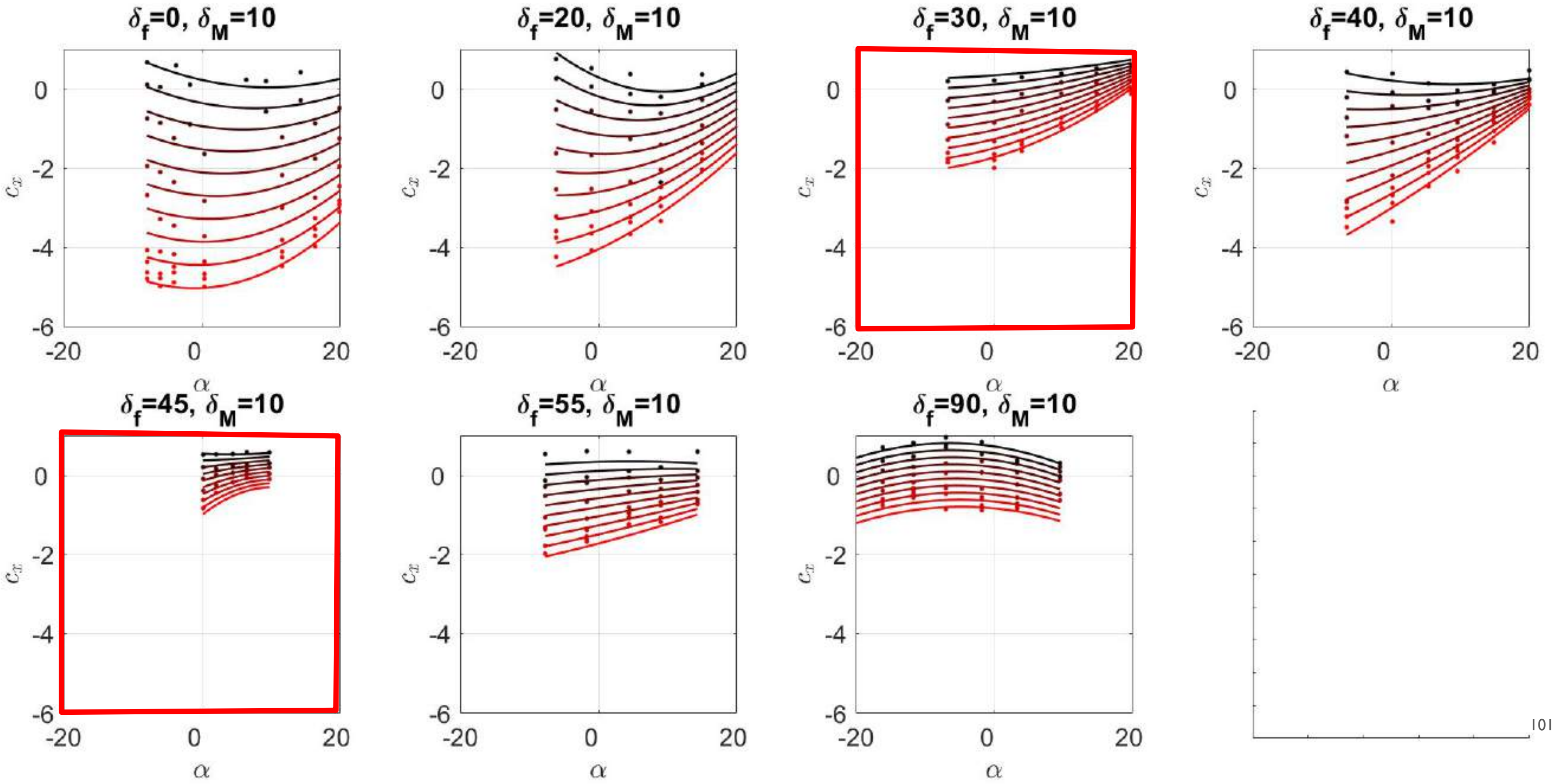
Post Flight Analysis



C_L-α


δf=0, δM=10
δf=20, δM=10
δf=30, δM=10
δf=40, δM=10
δf=45, δM=10
δf=55, δM=10
δf=90, δM=10
cℓ
α
10
5
0
-20
0
20

c_x-α



δ_f=0, δ_M=10
δ_f=20, δ_M=10
δ_f=30, δ_M=10
δ_f=40, δ_M=10
δ_f=45, δ_M=10
δ_f=55, δ_M=10
δ_f=90, δ_M=10
c_x
α
0
-2
-4
-6
-20
20