BUBO BUBO
Spring Final Review

April 20^{th}, 2020

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Project Purpose and Objectives

Project Purpose

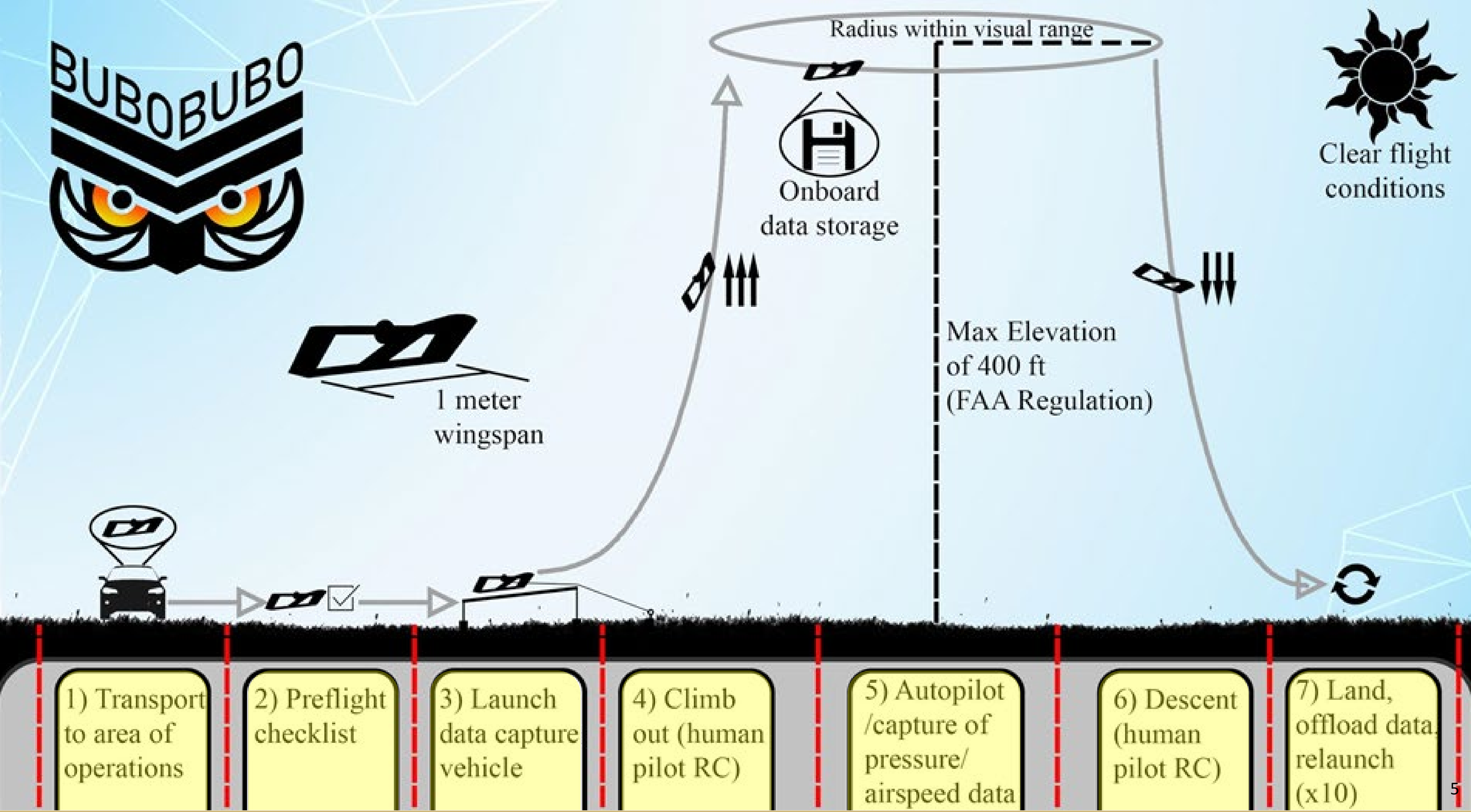
The goal of BUBO BUBO is to design, build, and test an unmanned, radio-controlled (RC), box-wing aircraft. The aircraft will be a scalable data collection platform for a Flush Air Data Sensing (FADS) system, which will collect pressure data to aid in the study of turbulence by Dr. Brian Argrow of the University of Colorado Boulder.

Potential Impact

- Current wind models do not model small aircraft at low altitudes well.
- This is needed to develop protocol for the safe operation of UAVs as they gain popularity.

The vision:

A fleet of BUBO's ranging from the size of your palm to several feet with integrated FADS systems, used to **directly measure turbulence** to help develop the needed models for small UAVs.


BUBOBUBO
Radius within visual range
Onboard data storage
Clear flight conditions
1 meter wingspan
Max Elevation of 400 ft (FAA Regulation)
1) Transport to area of operations
2) Preflight checklist
3) Launch data capture vehicle
4) Climb out (human pilot RC)
5) Autopilot /capture of pressure/ airspeed data
6) Descent (human pilot RC)
7) Land, offload data, relaunch (x10)

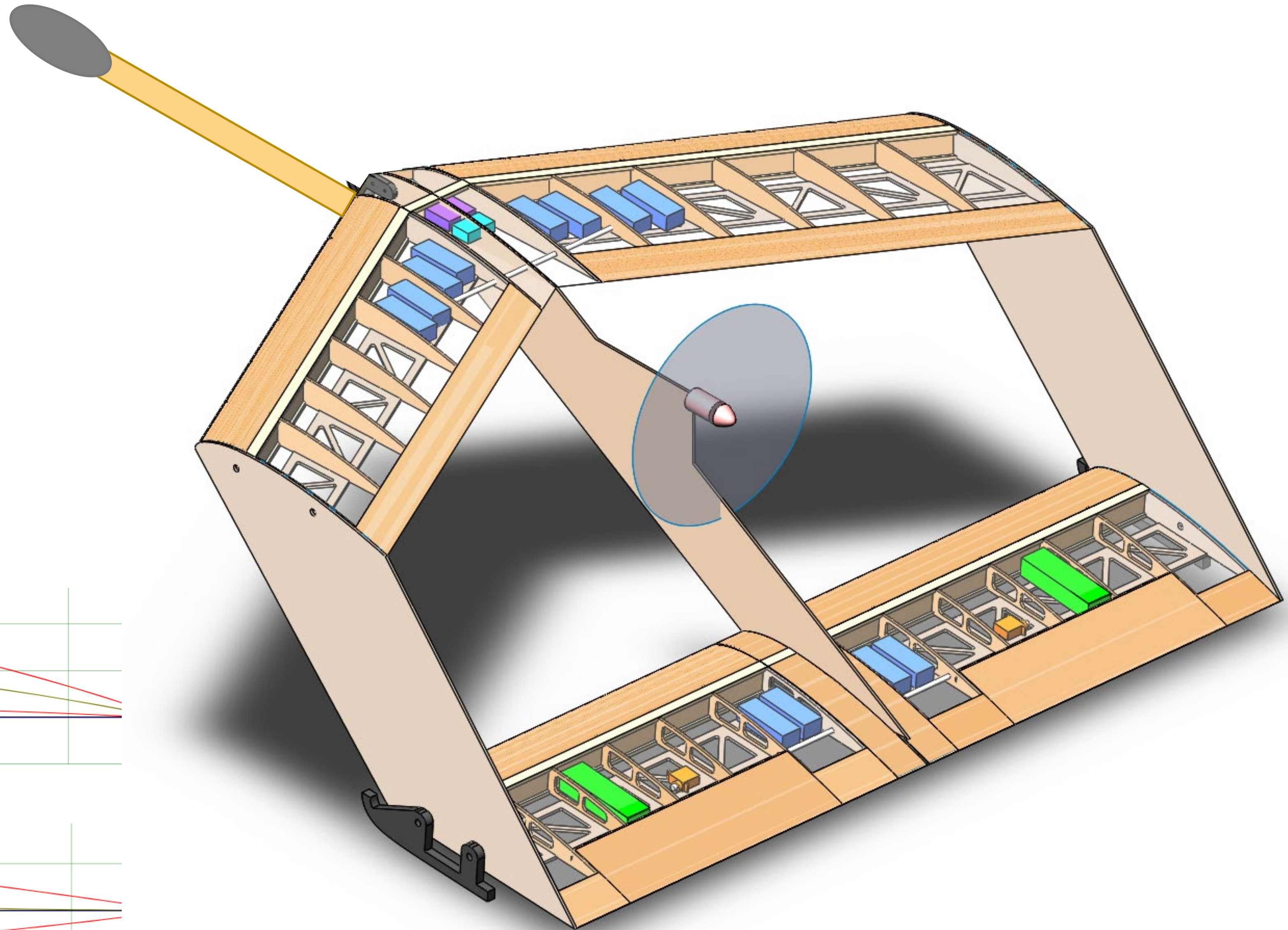
Specific Objectives – Levels of Success

	Navigation And Control	Sensor Data	Survivability	Flight	Airframe Scalability
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
Level 2	Flight with manual control	Able to collect and store data for one full flight	Lands with minimal field repairs (max. 15 minutes with field materials)	Aircraft achieves stable powered flight	Same as Level 1
Level 3	Autonomous control during cruise and loiter in-flight	Integration of sensors does not degrade accuracy by 5%	Survives 10 takeoff and landing cycles	Aircraft can sustain flight for a minimum of 1 hour	Feasibility study for scaled airframe

Design Description

Baseline Design

- Box-wing Configuration
  - Top wing swept back 30°
  - Bottom wing straight
- 1 m span
- 0.3 m chord
- 0.3 m stagger
- 0.3 m gap
- Total Mass: 3.11 kg



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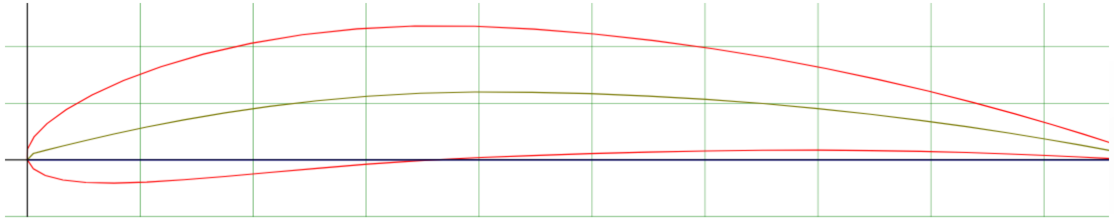

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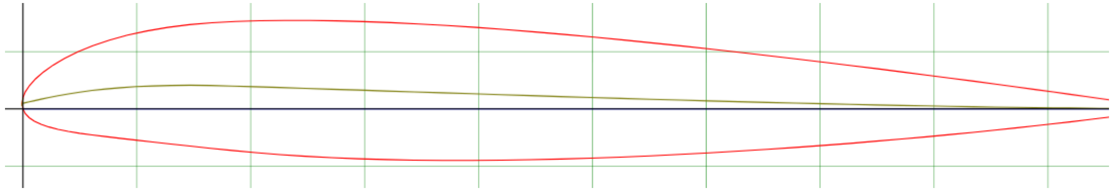
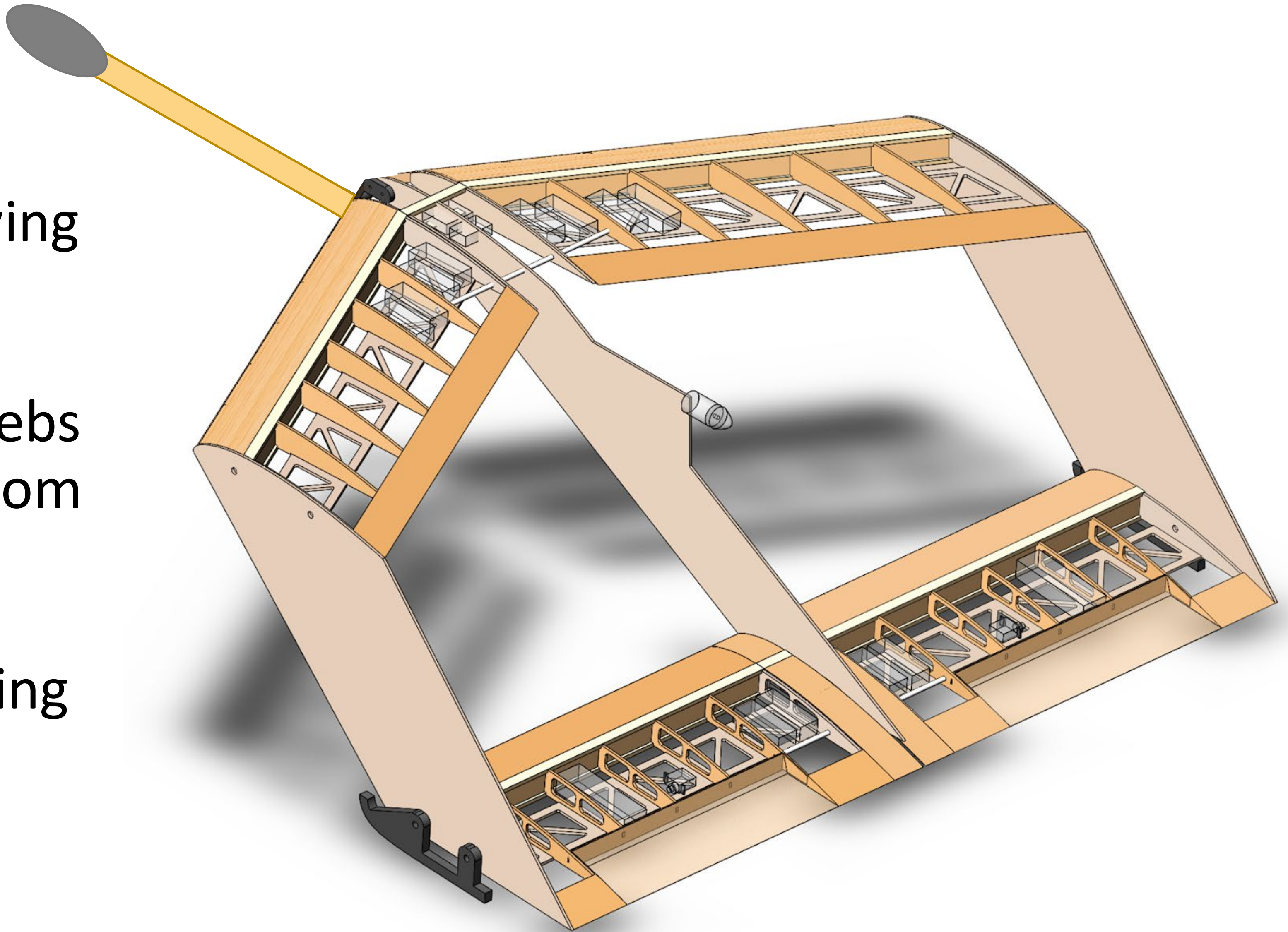


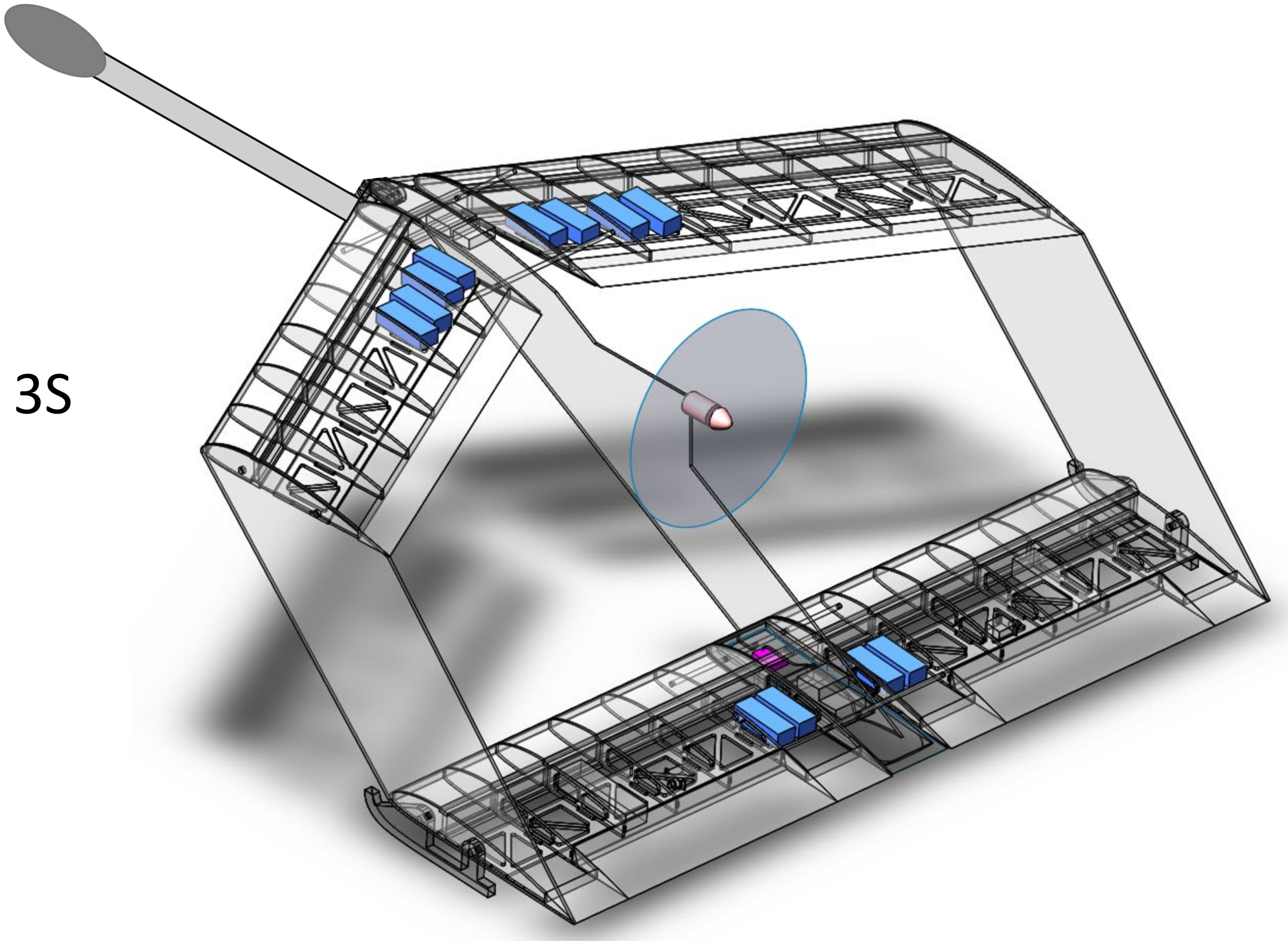
Structures

- Balsa wood ribs
- Plywood closeout ribs, wing bay floors, and vertical Members
- Spruce spar and shear webs
- Beech dowel used for boom
- Carbon fiber-aluminum connectors
- 3D printed skids for landing
- Monokote skin



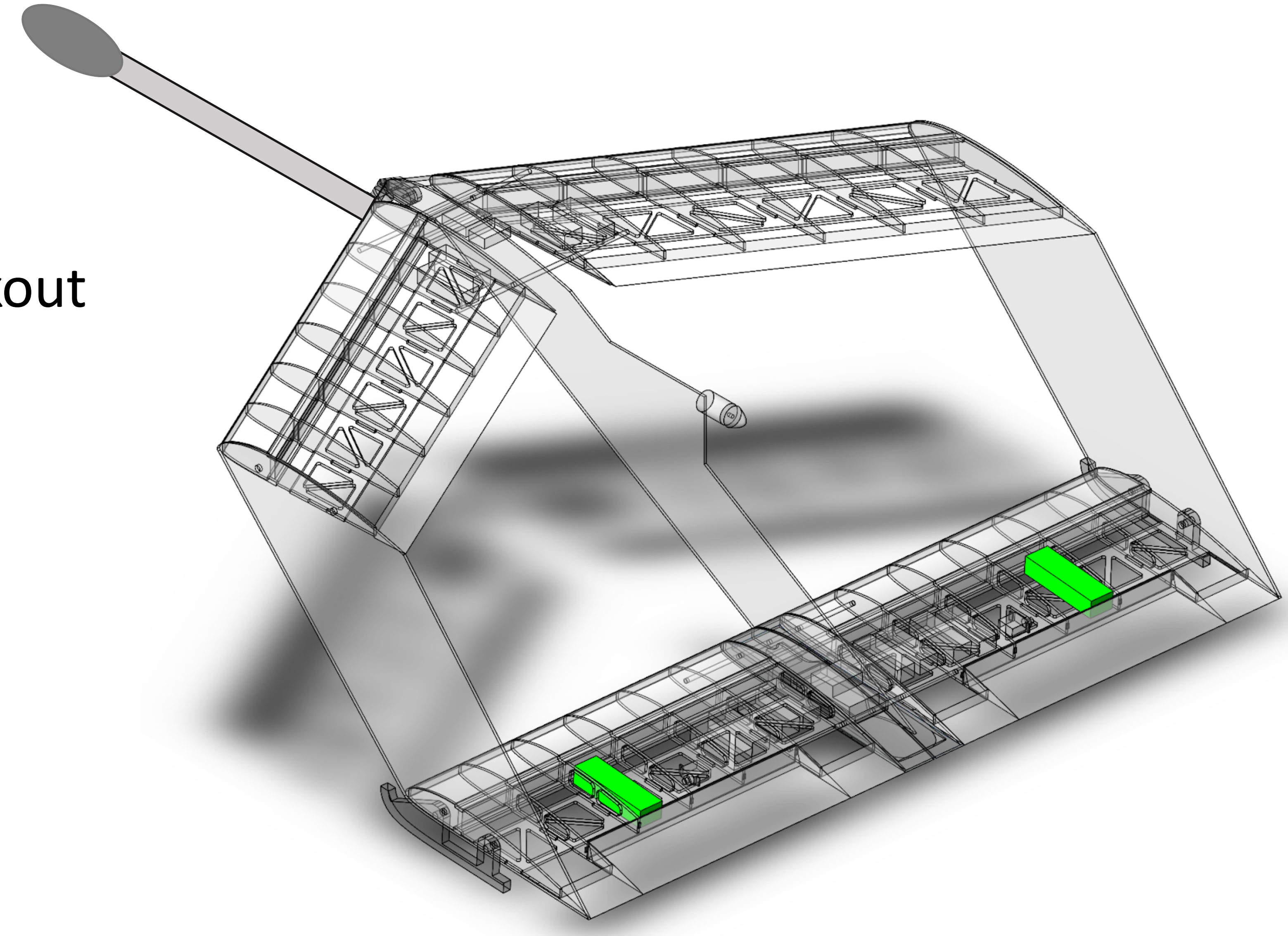
Power/ Propulsion

- Pusher configuration
  - Power 25 motor
  - APC 10x6E propeller
  - 60A ESC w/ 3A BEC
- Thunderpower 870 mAH 3S LiPo batteries



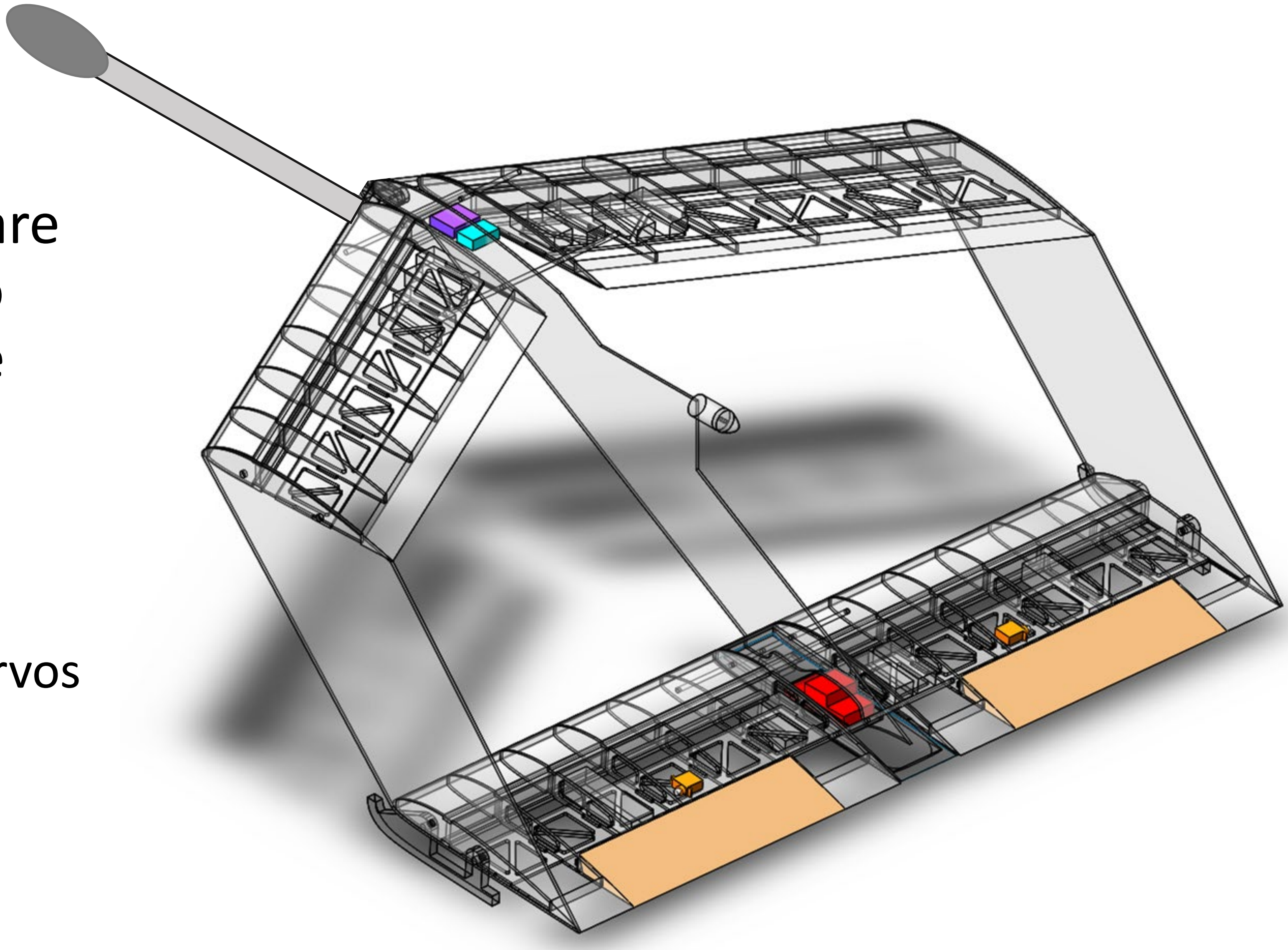
Flush Air Data Sensing System (FADS)

- BME280 pressure transducers
- ADAFruit BME280 breakout boards



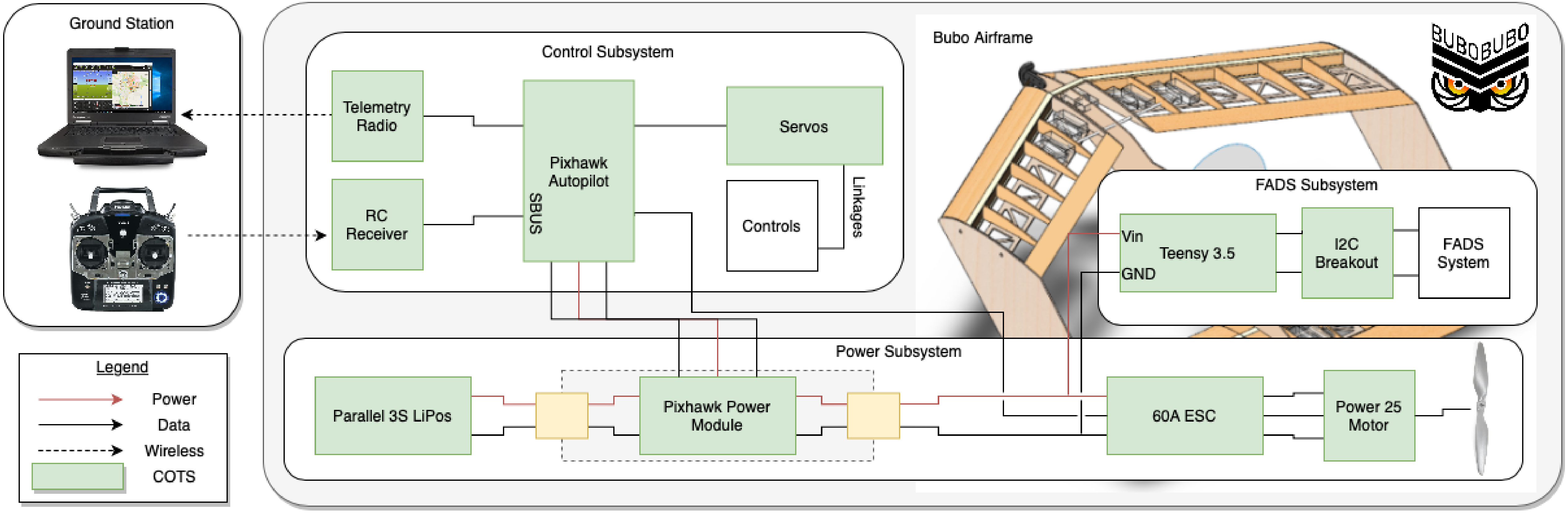
Controls

- Autopilot: PixHawk2 running ArduPilot software
- mRo SiK Telemetry Radio
- Here2 GNSS GPS Module
- Elevons located on the bottom wing
    - 61% of midspan
    - 30% of chord
    - Actuated using Hitec servos



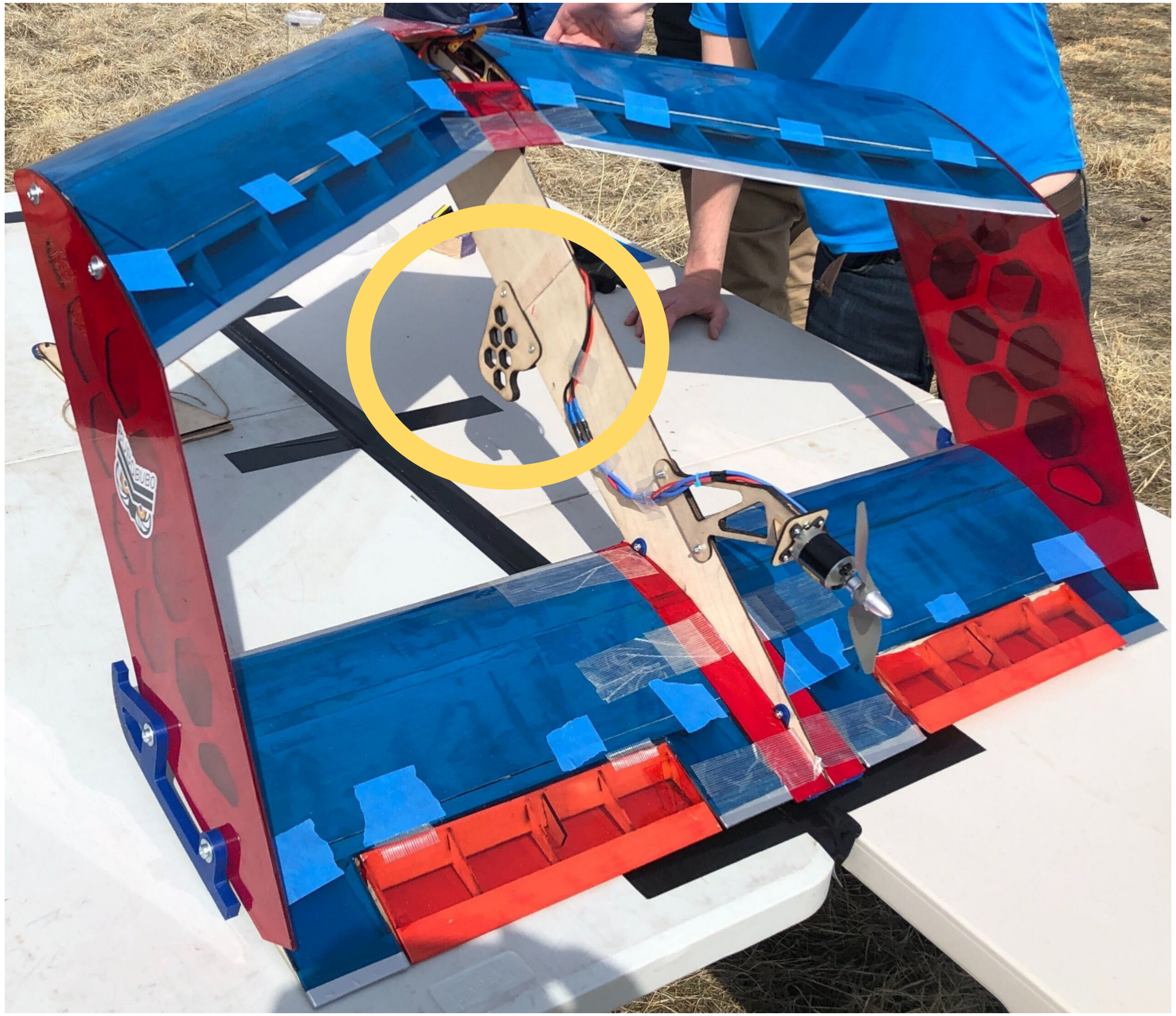
Functional Block Diagram

Of BUBO BUBO for Final Oral Review



Changes Since TRR – Launch Hook

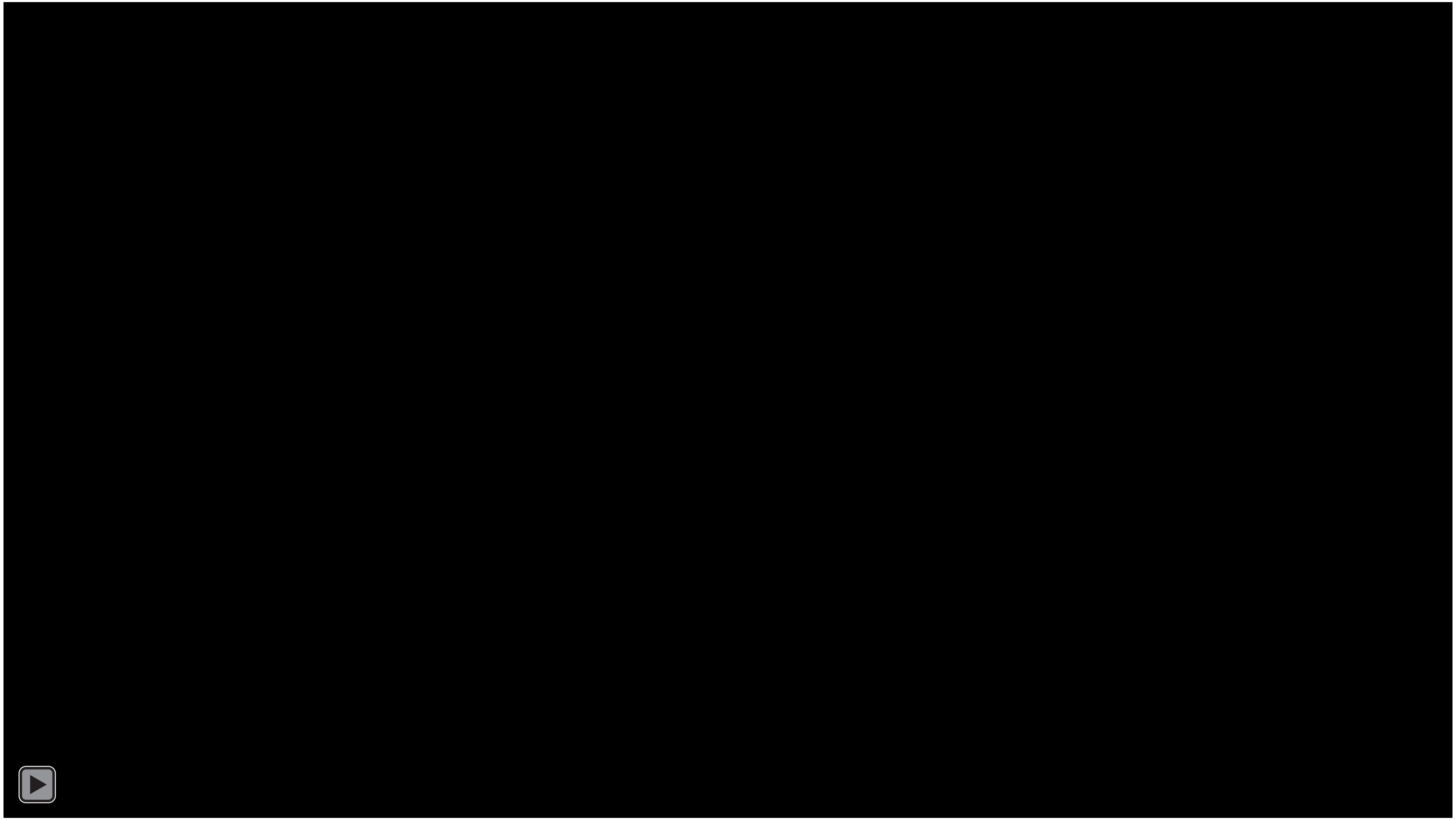
- Design finalized, including lightening holes
- Placement determined by force analysis
- Moved slightly forward after first failed launch based on pilot feedback
  - Aircraft stalled immediately upon launch due to too high of an angle of attack



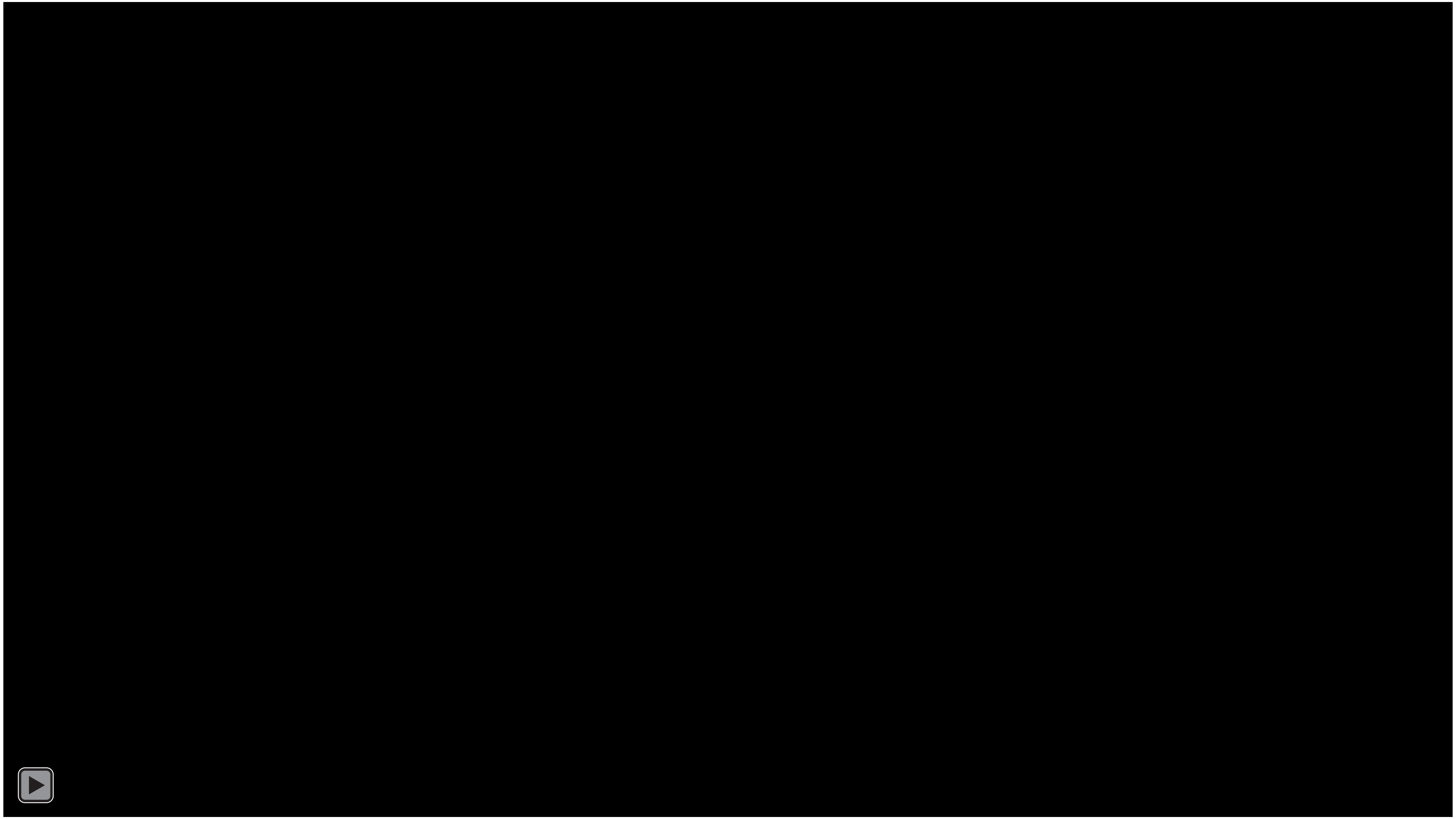
Changes since TRR – Added Launch Pogo

- Keeps nose up while leaving the launch table
- Mitigates problem seen in launch method test last semester
- Loose fit lets it fall off after aircraft leaves the table, so it won't hinder flight or add weight

Test Flight Takeoff



Test Flight



Critical Project Elements

- **Aerodynamics**
  - Configuration
  - Stability
  - Flight Performance
  - Pressure Distribution
- **Controls**
  - Gains
  - Stability
  - Flight Performance
  - Control Surfaces
- **Power**
  - Power Distribution
  - Component Placement
  - Endurance
- **Propulsion**
  - Propulsive Setup
  - Efficiency
- **FADS**
  - Placement
  - Integration
  - Relative Wind Recovery
- **Structures**
  - System Integration
  - Structural Integrity
  - Survivability
  - Materials

Testing

Testing Overview

Major Test Overview:

- Whiffletree
- Static Thrust
- Controls
- FADS
- Flight Test

Uncompleted Testing

- Full hour endurance test
- Autopilot loiter test
- Loiter FADS test
- Additional flight testing
- Scalability Study

	Navigation And Control	Sensor Data	Survivability	Flight	Airframe Scalability
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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Whiffletree Test

Functional Requirements Addressed:

FR 3: The aircraft shall be able to complete 10 flight cycles without major damage

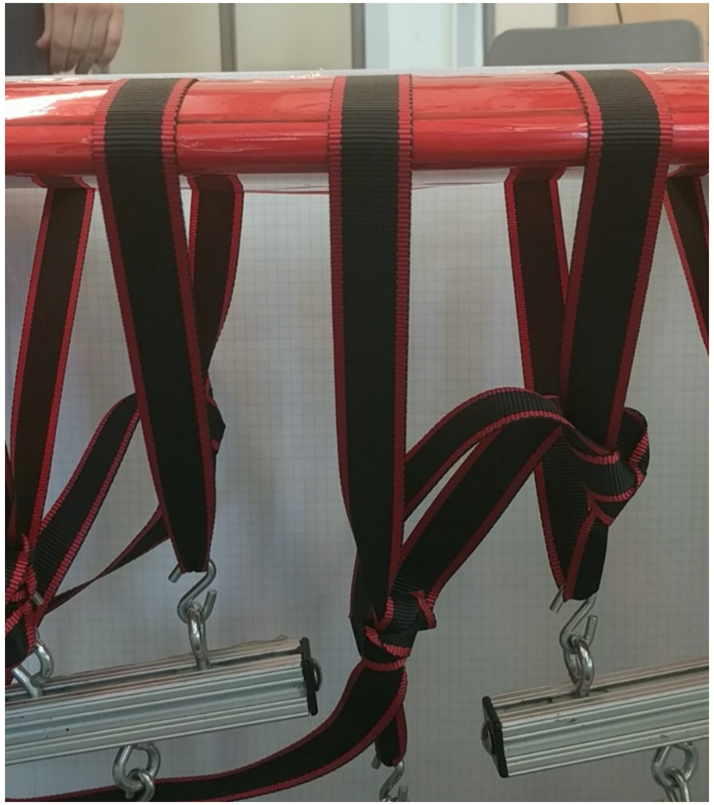
Test Setup

- Whiffletree used in ASEN 2001
- Weight distribution approximates expected wing loading
- Added weight in 2.5/5lb increments until failure
- Data collected:
    - Deflection
    - Load at failure
    - Failure mode

Test Results – Deflection

~2 lb loading (start of test)

65 lb loading (at failure)



Minimal (< 1cm) deflection throughout entire test

Test Results – Failure Modes

Failure occurred at **65 lb** total load

Cracked Ribs

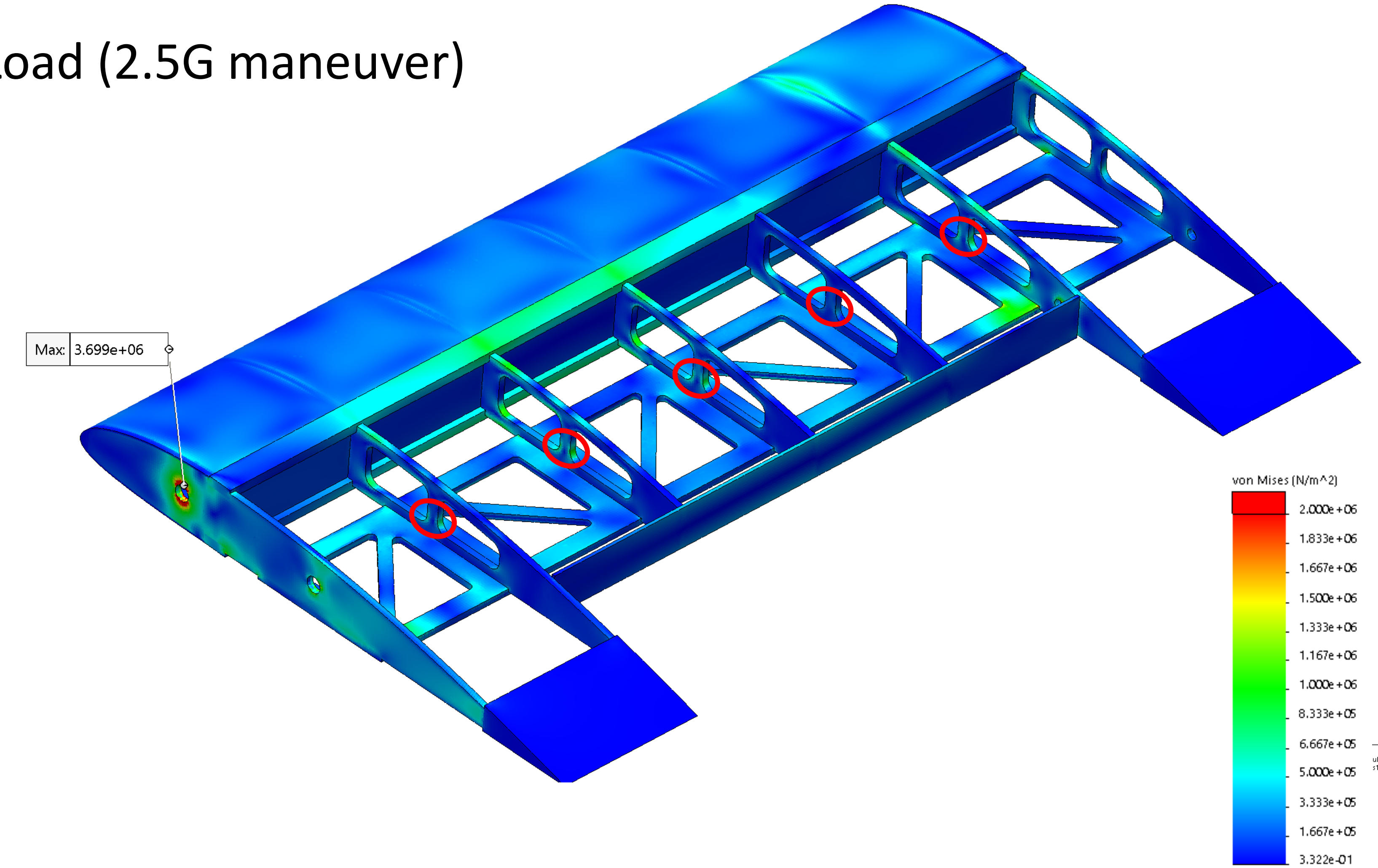
Crumpled Trailing Edge

Prior Modeling and Predictions - Stress

Von Mises Stress for ~8 lb dist. Load (2.5G maneuver)

- Stress concentrations on ribs
  - Correspond to broken ribs in test

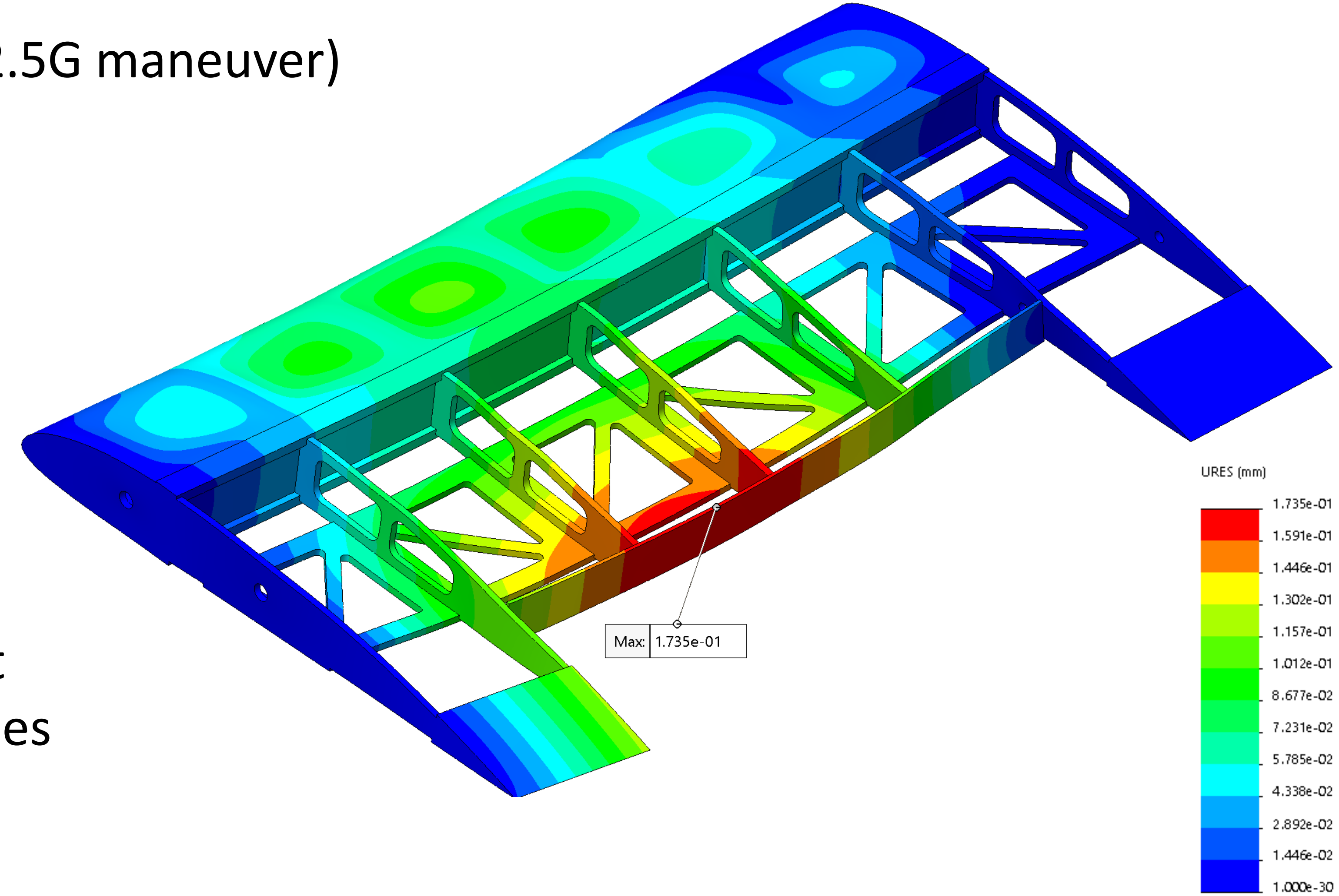
- 8lb max expected loading vs 65lb ultimate test load
  - Rough **FOS of 8**



Prior Modeling and Predictions - Deflection

Displacement for ~8 lb dist. Load (2.5G maneuver)

- Expected deflection of 0.17mm at 2.5G load
- Linearly scales up to 1.36mm deflection for 65 lb
- True deflection was appx. 1cm
    - More than model suggests, but still well within acceptable values for flight testing



Test Data Uncertainty

- Accuracy of weights
  - Affects precision of measured load
- Used 2.5/5lb plates for better precision

- Extra weight of straps, bucket, w-tree
  - Affects precision of measured load
- Estimated to be 3lb
  - <5% of ultimate load

- Inaccurate distributed load/w-tree
  - Could cause alternate failure modes
- MATLAB code implemented to compute positions of bars based on given distributed load

Can all be dismissed by our large FOS

Requirements Satisfied

- Addresses FR 3:

  The aircraft shall be able to complete 10 flight cycles without major damage.

- Verified structural design and manufacturing quality is sufficient
  - Airframe can withstand expected flight loads
  - No design changes necessary
  - Gave green-light to continue manufacturing

Thrust Test

	Navigation And Control	Sensor Data	Survivability	Flight	Airframe Scalability
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Functional Requirements Addressed:

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour

Test Overview

- Verifies thrust against models and that flight is possible
- Confirmed motor/propellers were suitable for flight
- Simulation of first flight test (5 minutes)
- Test used DBF test stand (Series 1585)
    - Test performed outside aerospace building in test stand apparatus
    - Thrust throttled up in steps, checked for vibrations before increasing to max thrust

Prior Modeling and Predictions

Modeling based on vortex lattice method (NASA TAIR), provided by APC.

- Models used to inform motor and propeller selection.
- Paired with University of Indiana experimental dynomometer data for verification.
- Key Limitations:
  - Predictions hinge on RPM, which may not behave as expected.
  - Mechanical and electrical power assumed equal.

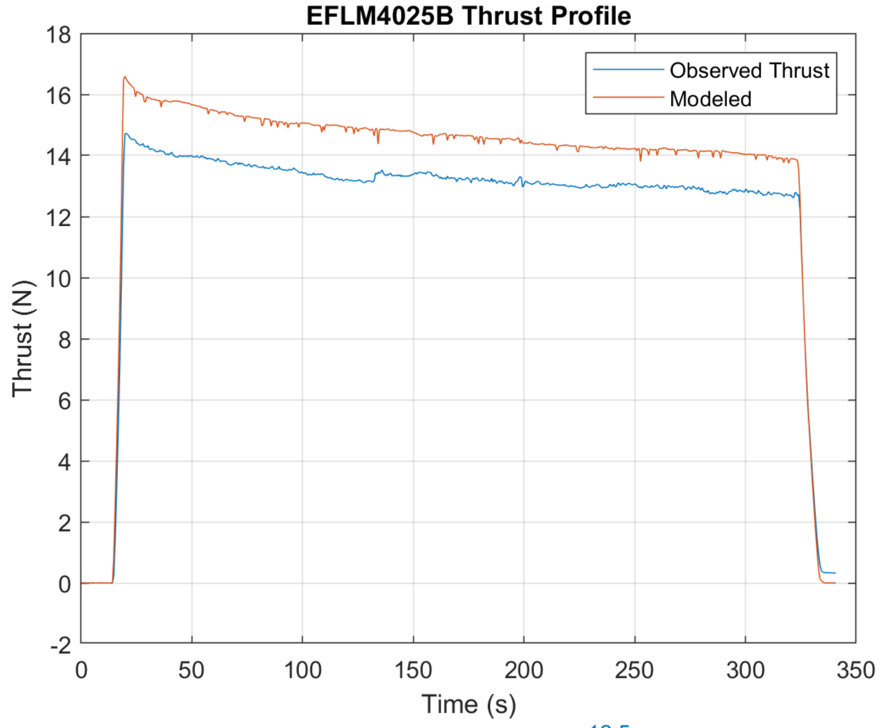
Test Data Analysis

Thrust

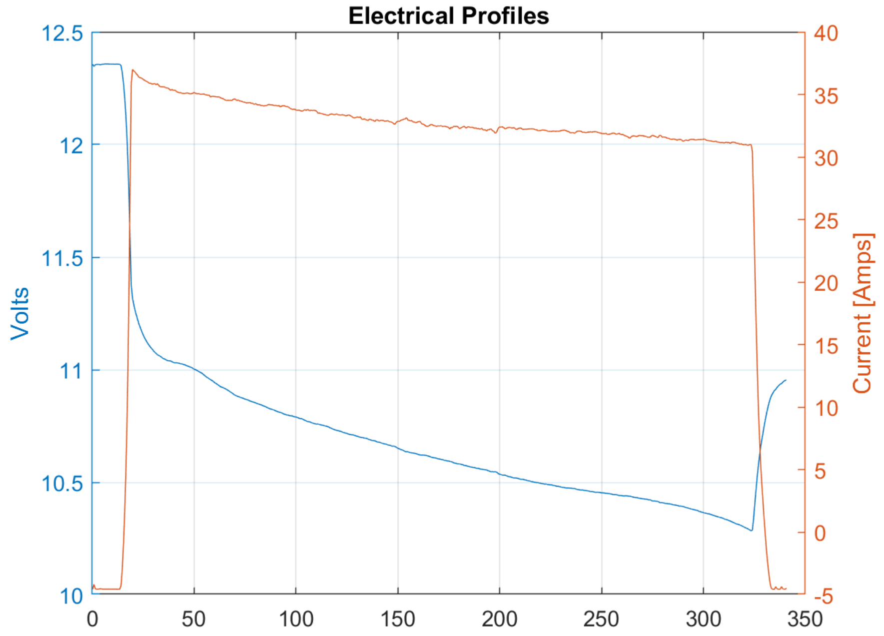
- Maximum thrust measured at nearly 15 N → **sufficient for flight requirements**
- 2 N offset from modeled expectations

Electrical

- Observed voltage drop of 1.5 V
- Well within expected range



Results for 5-minute endurance test



Test Data Uncertainty

RC Benchmark Series 1585 Dynomometer

- Maximum uncertainty in measured thrust values is 0.08 N
- DBF's dynomometer has parasitic current draw from a shorted component. We do not believe this is affecting our results.

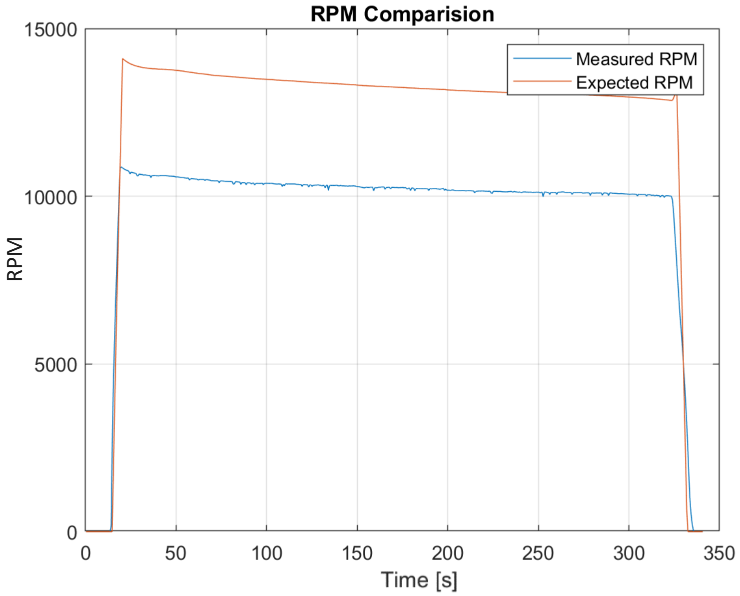
Table 1: Design specifications of the Series 1585 Dynamometer

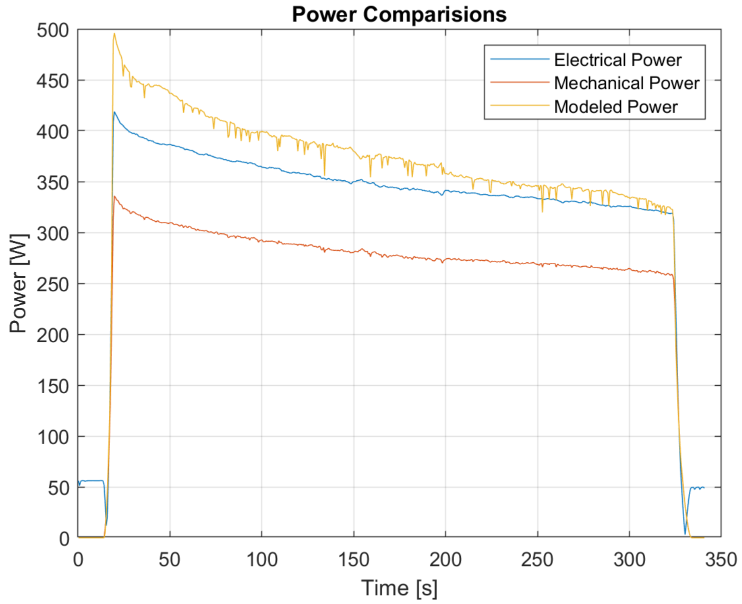
Specification	Min.	Max.	Tolerance	Unit
Thrust	-5	5	0.5%∓0.001	kgf
Torque	-1.5	1.5	0.5%∓0.001	Nm
Voltage	0	50	0.5%	V
Current	0	55	1%	A
Angular speed*	0	190k	1	eRPM
Coil resistance	0.003	240	0.5%	Ohm
Digital scale	0	3	0.5%	kgf

*Electrical RPM, divide by the number of motor poles to obtain true mechanical RPM.

Test Data compared to Predictive Modeling

- Modeled thrust found to be within 12.5% of measured values.
  - Overstatement of model likely stems from inaccuracies in Reynold's number adjustments and limitations of vortex lattice algorithm.
- Modeled power draw higher than observed values
  - Though measured electrical power draw is subject to wild uncertainty.
- Propulsion tests validate design parameters set by customer.





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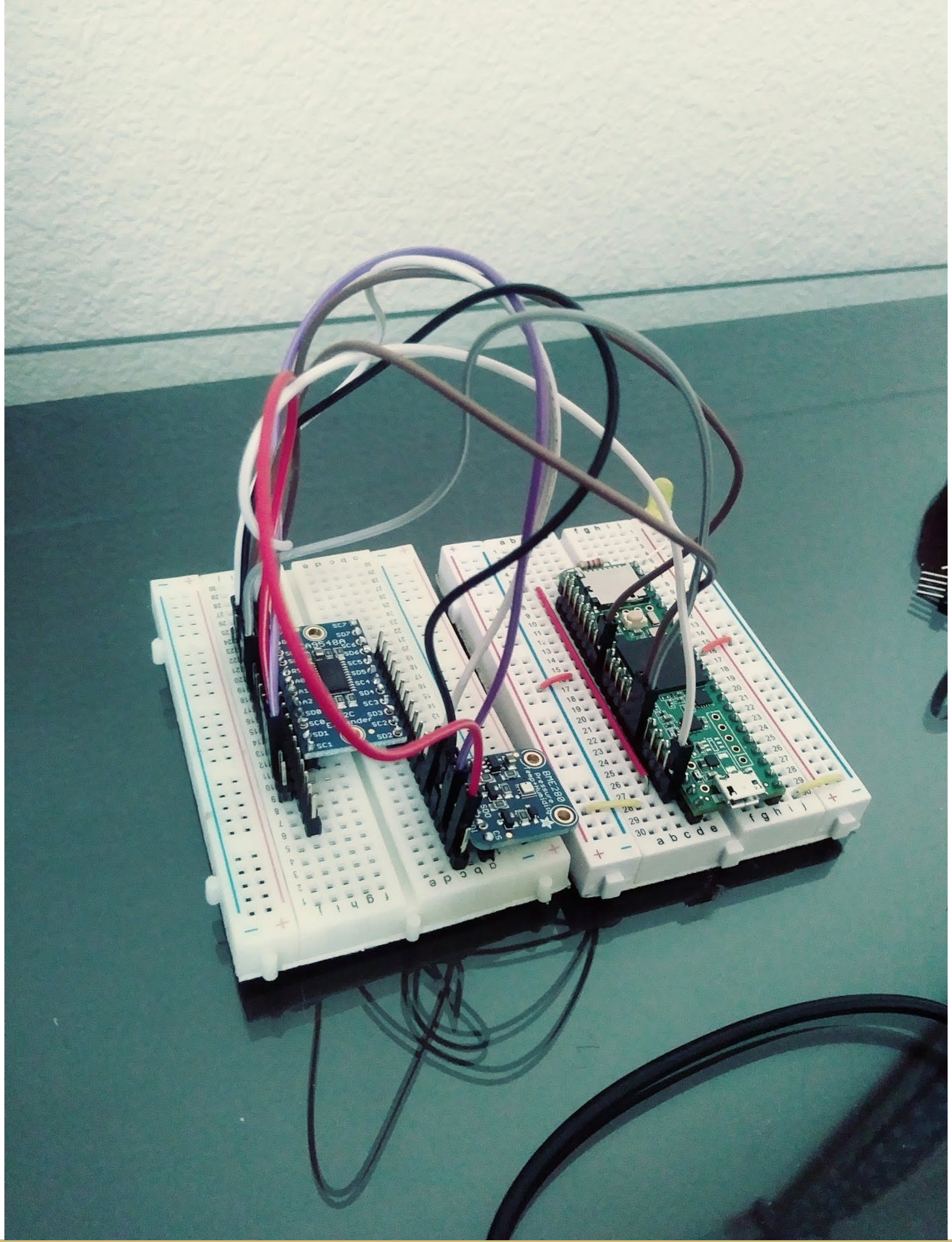
FADS Test

Functional Requirements Addressed:

FR 2: The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector

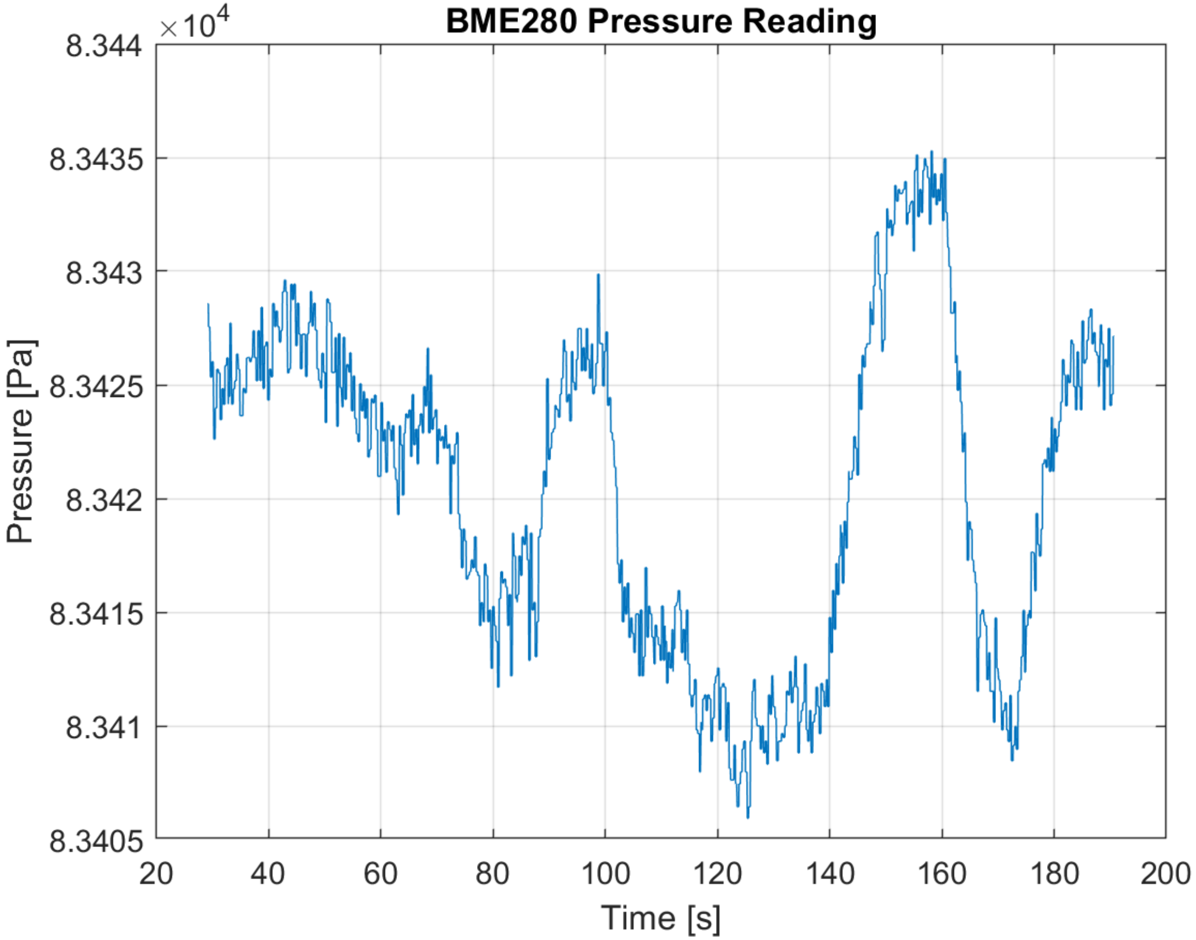
Test Overview

- Verify the FADS electrical circuit, and the capability of the BME-280 pressure transducers to gather data.
- Confirm that data storage space is sufficient for desired flight time.
- Conduct basic verification test for pressure values.



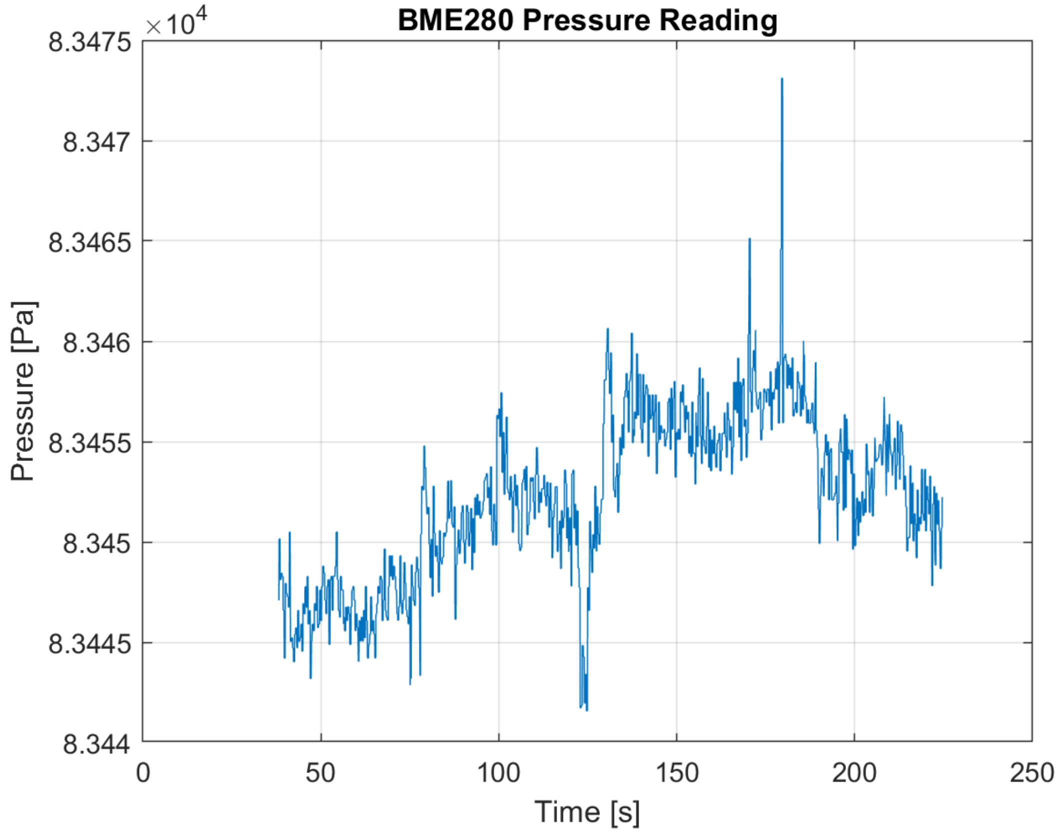
Test Data Analysis

- FADS circuit built with:
  - Arduino Teensy 3.5
  - Adafruit BME-280 Pressure Transducer
  - Adafruit TCA9548A
- Data stream written to SD card.
- Circuit raised and lowered to induce change in pressure.
- Magnitude of measured pressure approximately matches expected air pressure value.
- Profile matches circuit motions during test.
- Note that humidity and temperature data are also gathered.



Test Data Uncertainty

- BME-280 subject to absolute accuracy error of ±100 Pa, with noise on the order of 1.3 Pa. This is the same or better than the MS8607-02BA01 transducers used in Dr. Roger Laurence's research.
- Not implemented into full FADS system, which could pose accuracy issues.



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Flight Test

Functional Requirements Addressed:

- FR 1: The aircraft shall be a box-wing configuration with a scalable span
- FR 3: The aircraft shall be able to complete 10 flight cycles without major damage

Test Overview

- Validated overall airframe feasibility for flight and survivability
- Proved flight-worthiness, handling, and rugged survivability of aircraft
- Flight took place at CU Boulder South
  - Launched from IRISS table bungie
  - Obtained Cooper-Harper ratings for maneuvers during flight
  - Performed field repairs to determine re-flight time
  - Identified methods, materials for streamlining future flight tests and repair

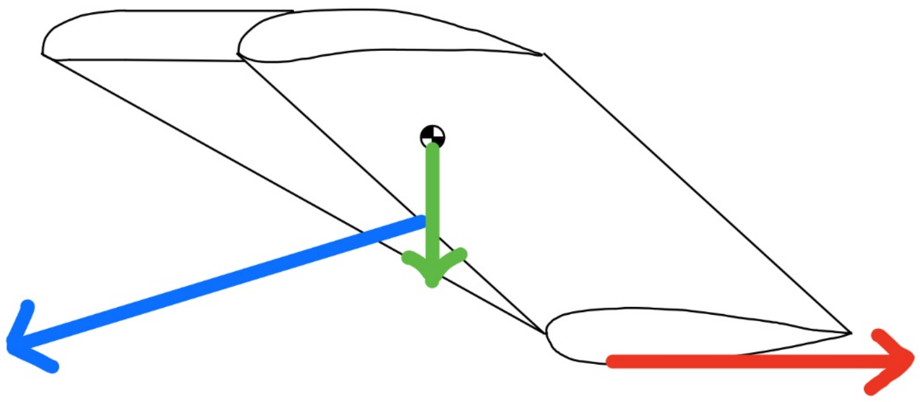
Rating	Performance	Pilotability	Improvement?
1-3	Desired	Easy	Satisfactory
4-6	Adequate	Moderate	Warranted
7-9	Control	Difficult	Required
10	No Control	Impossible	Required

Cooper-Harper ratings descriptions

Launch Method

Launch Method – Prior Modeling and Predictions

- Simple force and moment balance of the aircraft as it is on the launch table



- Main forces acting during launch:
  - Tension from bungee
  - Friction from table
  - Gravity
- Resulted in following equation for tension for a given table length (l), table inclination (θ), dynamic coefficient of friction (μ), and desired velocity (V_{cr}):

$$T = \left(\frac{V_{cr}^2}{2l} + gsin(\theta) - \mu gcos(\theta)\right)$$

Launch Method - Data

- IRISS table bungie
  - Used 45-50 lb launch force
- First launch failed to achieve takeoff
  - Engine did not ramp up fast enough to accelerate after launch
  - Aircraft pitched upward, causing immediate stall → bad pull angle
- For second launch, launch hook location adjusted and engine ramped up before launch
  - Launch hook location was optimized
  - For future tests, slightly higher launch force could be used

Launch Method - Uncertainty

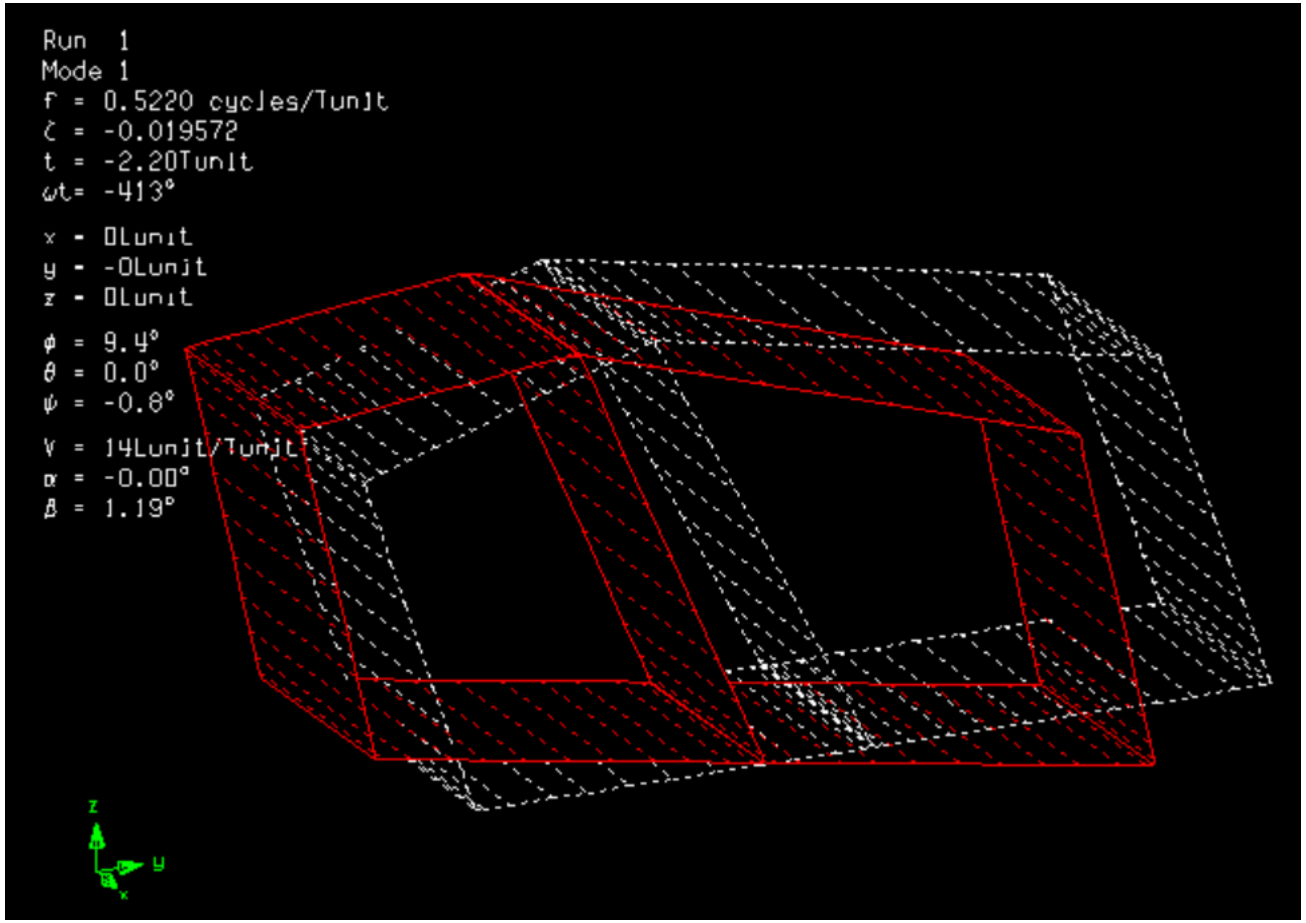
- Launch force and angle was approximate
  - Length of rope pulled gave good indication of force, but ultimately was not precise
  - Angle was not precisely measured
- Single launch gives limited data on other conditions
  - How much did wind help/harm takeoff?
  - Is takeoff easier/more successful with higher launch force?

Flight Stability

Stability Modeling and Prediction

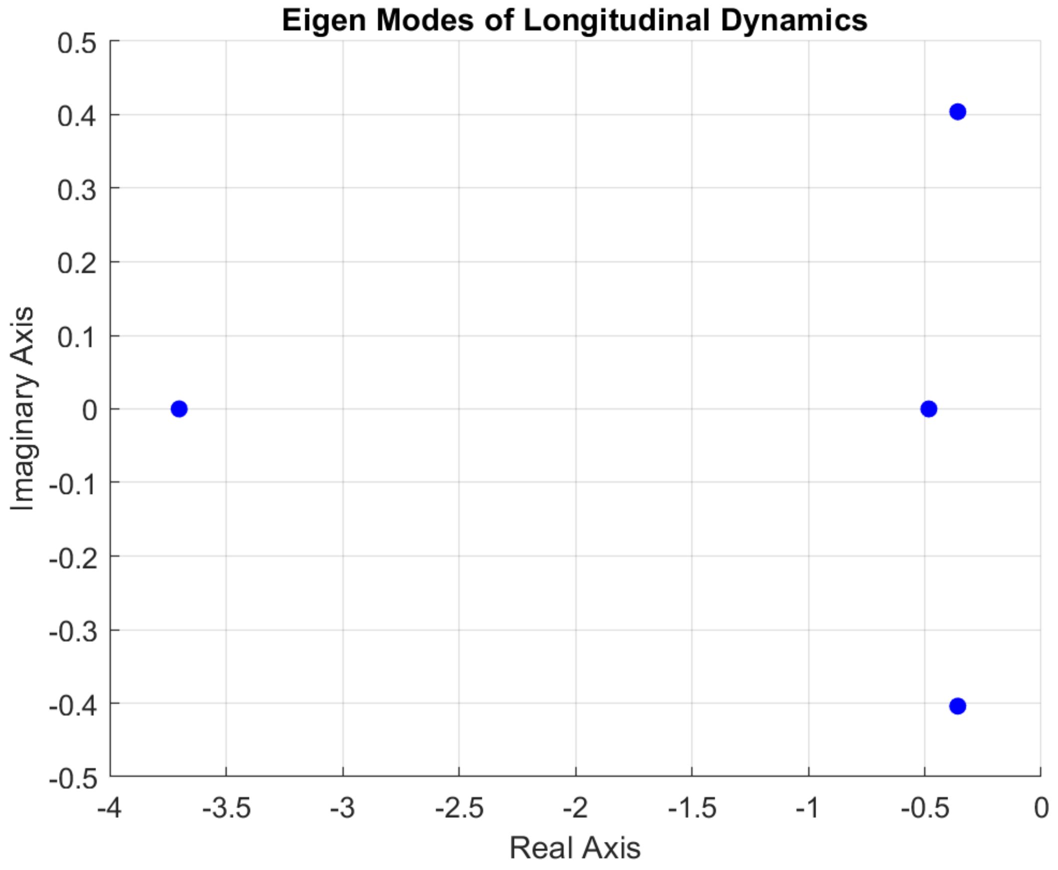
- AVL predictions with flight test configuration
  - Stall speed = 7.64 m/s
  - Cruise Speed of 1.85*Stall = 14.15 m/s
  - Trim Angle of Attack = 5°

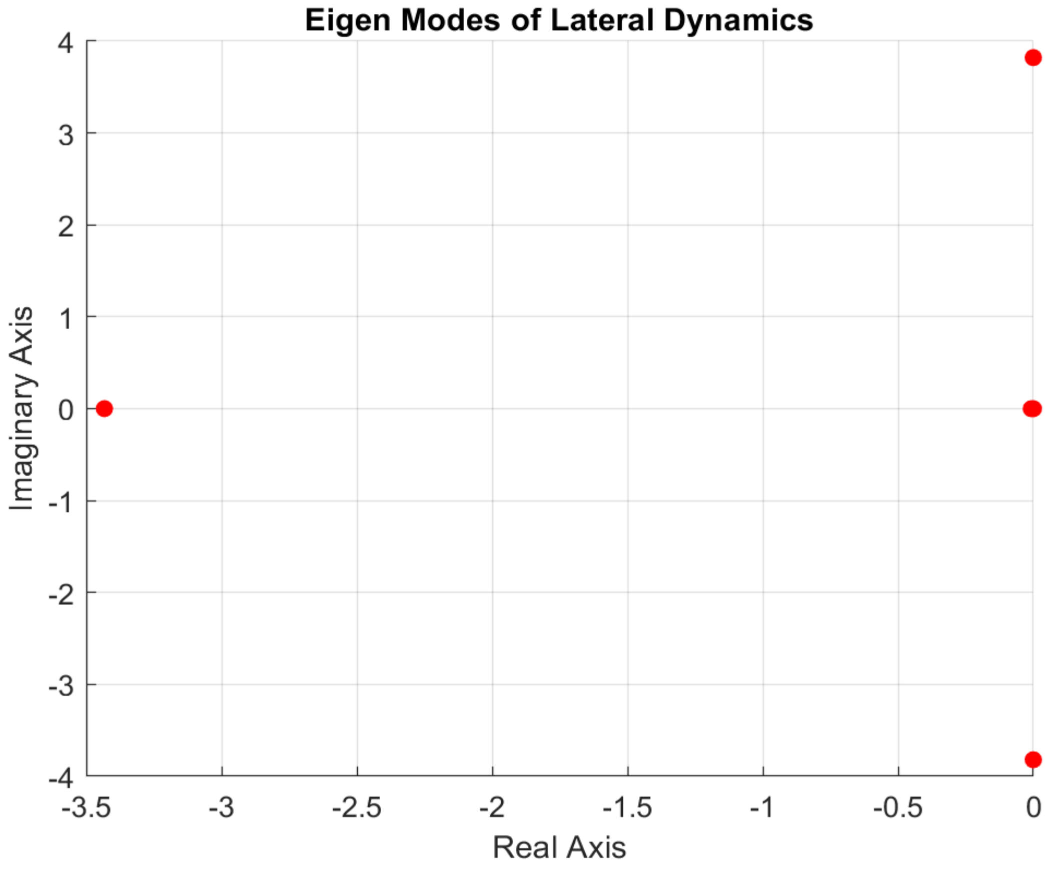
- Model aligns with low cruise speed and docile stall characteristics experienced in flight.



AVL Stability Mode Visualization

Modeled Stability Modes



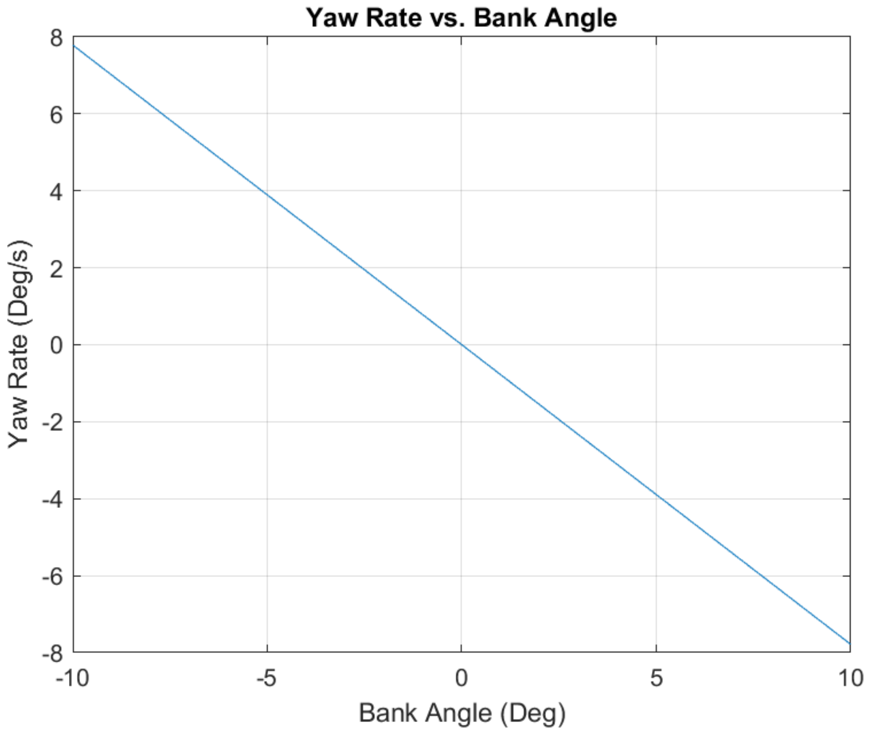


Pre-Flight Ballasting

- Boom is necessary for longitudinal stability
  - Provides positive static margin: cg forward of cp
- Preflight Installation
  - Balance aircraft about cp by adding/subtracting ballast
  - Favor forward pitching moment for positive static margin
- Final ballast weight was 1.04% greater than model
  - Model = 300g
  - Actual Ballast = 313.51g
  - Difference likely due to boom length

Stability - Cooper Harper Ratings

Maneuver	Rating	Description
Takeoff	7	Major deficiencies
Ascent	4	Minor deficiencies
Steady flight	2	Good
30° banked turn	5	Moderate deficiencies
Descent	3	Fair
Landing	4	Minor deficiencies
Steady level stall	1	Excellent



Explanation for poor banked turn performance

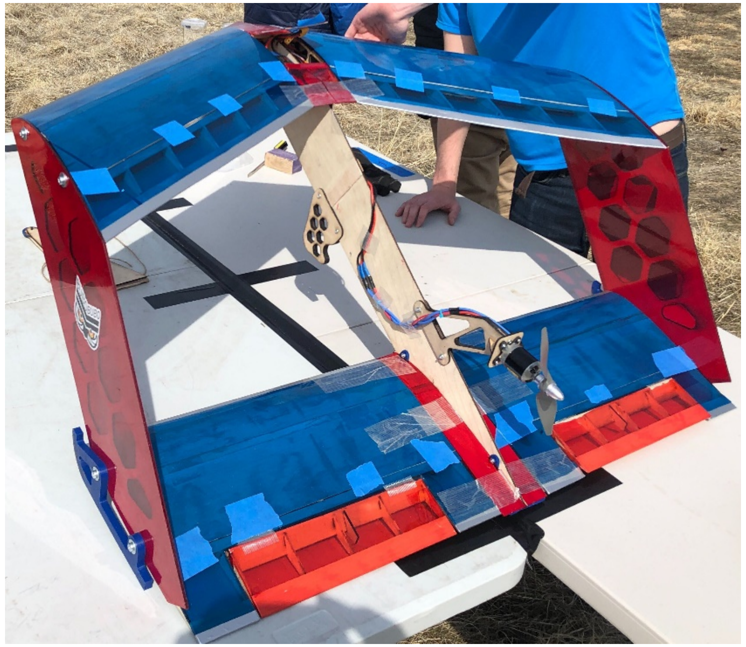
The model predicts a linear relationship between the bank angle and the yaw rate. However, wind disturbances affected this behavior and negatively impacted the controllability.

Stability – Stall Characteristics

- No tendency to drop a wing (tip stall)
- Nose drops dependably, glide ratio is very good into the wind
- Only tested power off stall, but very stable

Stability – Suggested Design Optimizations

- Motor vertical placement/incidence angle
  - Noticed throttle-induced down moment → backing off throttle aircraft floats upward
- Launch method wasn't reliable, barely had enough force
  - Switching to a conventional runway launch would be easier for the autopilot
    - Obviously has cons as well → less places to launch
  - Conventional landing would also allow smoother landings
    - Currently must be slowed as close to stall as possible → impact



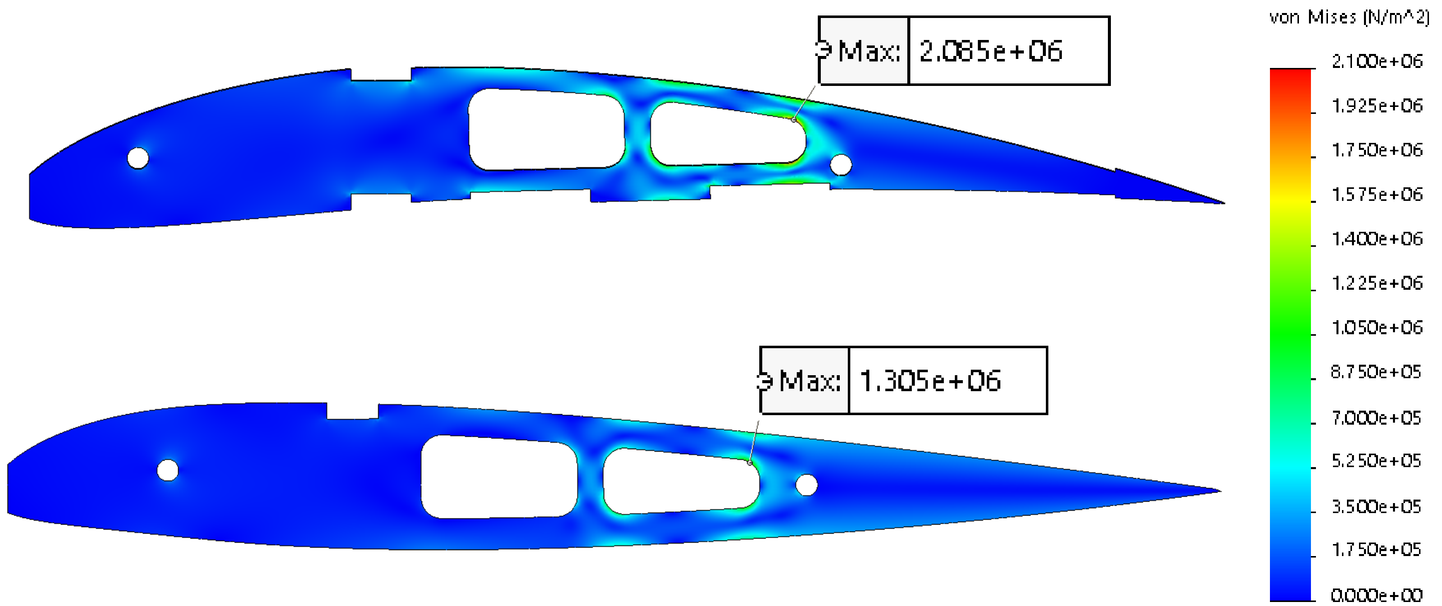
Stability – Predictive Modeling and Uncertainty

- Flight test shows stability and controllability
  - Aircraft is ready for autopilot control
  - All customer requirements could have been met with further optimization
- Uncertainty and Model Comparison
  - Cooper-Harper ratings are subjective
  - Limited flight data
    - No power-on stalls, only basic flight maneuvers
  - No instrumentation to verify stability numerically with IMU data

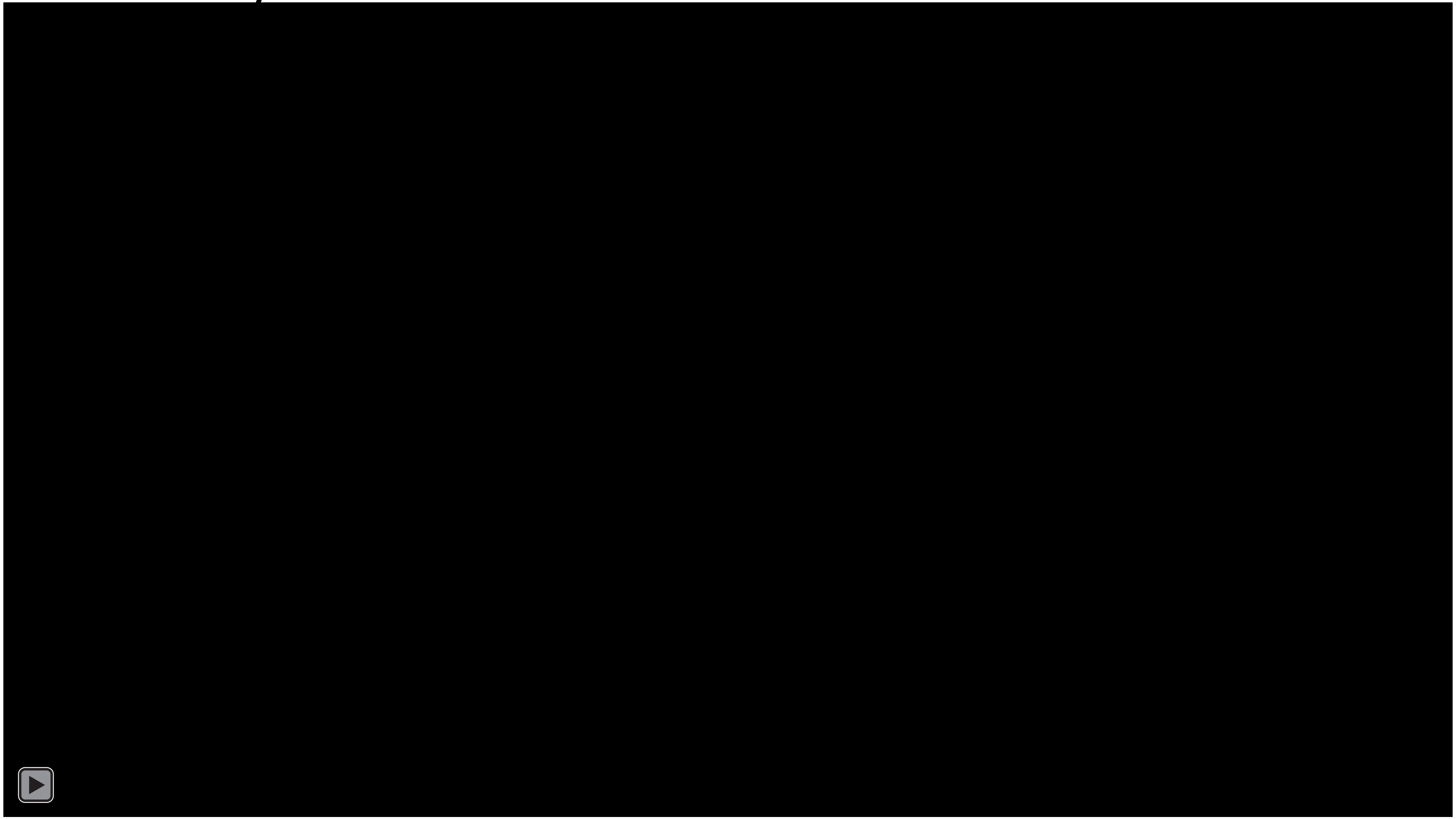
Landing Survivability

Survivability – Modeling

- Factor of safety of 8 during flight (Von Mises)
- Wings withstood +60 lbs during whiffle test
- Assumed that damage taken would be minimal



Survivability - Data



Survivability - Uncertainty

- Two successful ground impacts of two flight tests
  - Boom broke at the correct position
  - Boom was the only component to undergo damage
- Wooden airframe experienced no damage
- Uncertainty Sources
  - Airspeed
  - Angle of attack
  - Ground hardness

Unfinished Tests

FR included on individual tests

List of tests planned but not conducted here:

- Full hour endurance test (ground and air)
- Autopilot loiter test (HITL and air)
- Loiter FADS data collection test (ground and air)
- Additional flight testing
- Feasibility for scaled airframe

One-hour endurance ground and flight test

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour

- Ground portion – same set up and procedures as other propulsion testing, just letting it run for an hour
- Flight portion
  - Same operations, goals as flight test
  - Aircraft outfitted with Pixhawk, full suite of batteries
    - Flight, complete other tests
    - FADS data collection and Cooper-Harper ratings

	Navigation And Control	Sensor Data	Survivability	Flight	Airframe Scalability
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
Level 2	Flight with manual control	Able to collect and store data for one full flight	Lands with minimal field repairs (max. 15 minutes with field materials)	Aircraft achieves stable powered flight	Same as Level 1
Level 3	Autonomous control during cruise and loiter in-flight	Integration of sensors does not degrade accuracy by 5%	Survives 10 takeoff and landing cycles	Aircraft can sustain flight for a minimum of 1 hour	Feasibility study for scaled airframe

Autopilot testing (HITL and air)

FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile.

- Ground test: Control system behavior compared with models (quantitively)
  - Measure elevon deflection in response to physically moving Pixhawk
  - Allows comparison between commanded values from autopilot to deflection of actual elevons
- Flight test: IMU data comparing with models

	Navigation And Control	**Sensor Data**	**Survivability**	**Flight**	**Airframe Scalability**
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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FADS integration test

FR 2: The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector

- Test Performance:
  - Large fan with FADS system independent of and integrated into aircraft
  - Compare data set
- Test different locations and port configurations
- Test during flight

	Navigation And Control	**Sensor Data**	**Survivability**	**Flight**	**Airframe Scalability**
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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Additional Flight Testing

FR 3: The aircraft shall be able to complete 10 flight cycles without major damage
FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour
FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile

- Further Cooper-Harper ratings for stall
  - Power on/off - nose up
  - Power on/off - nose up from 30° bank
- Streamline operations to reduce re-flight time
  - Potential materials needed for repairs
  - Better/more detailed pre-flight checklist
- Design Optimization

	Navigation And Control	**Sensor Data**	**Survivability**	**Flight**	**Airframe Scalability**
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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Feasibility Study

FR 1: The aircraft shall be a box-wing configuration with a scalable span

- Analysis would have included
  - Aerodynamic force modelling
  - Stability modelling
  - Control requirements modelling and potential resizing
  - Weight change estimate
- Performance Metrics Recalculated
  - Stall Speed
  - Power Requirements
  - Control Response (Yaw Rate/Bank Angle)

	Navigation And Control	**Sensor Data**	**Survivability**	**Flight**	**Airframe Scalability**
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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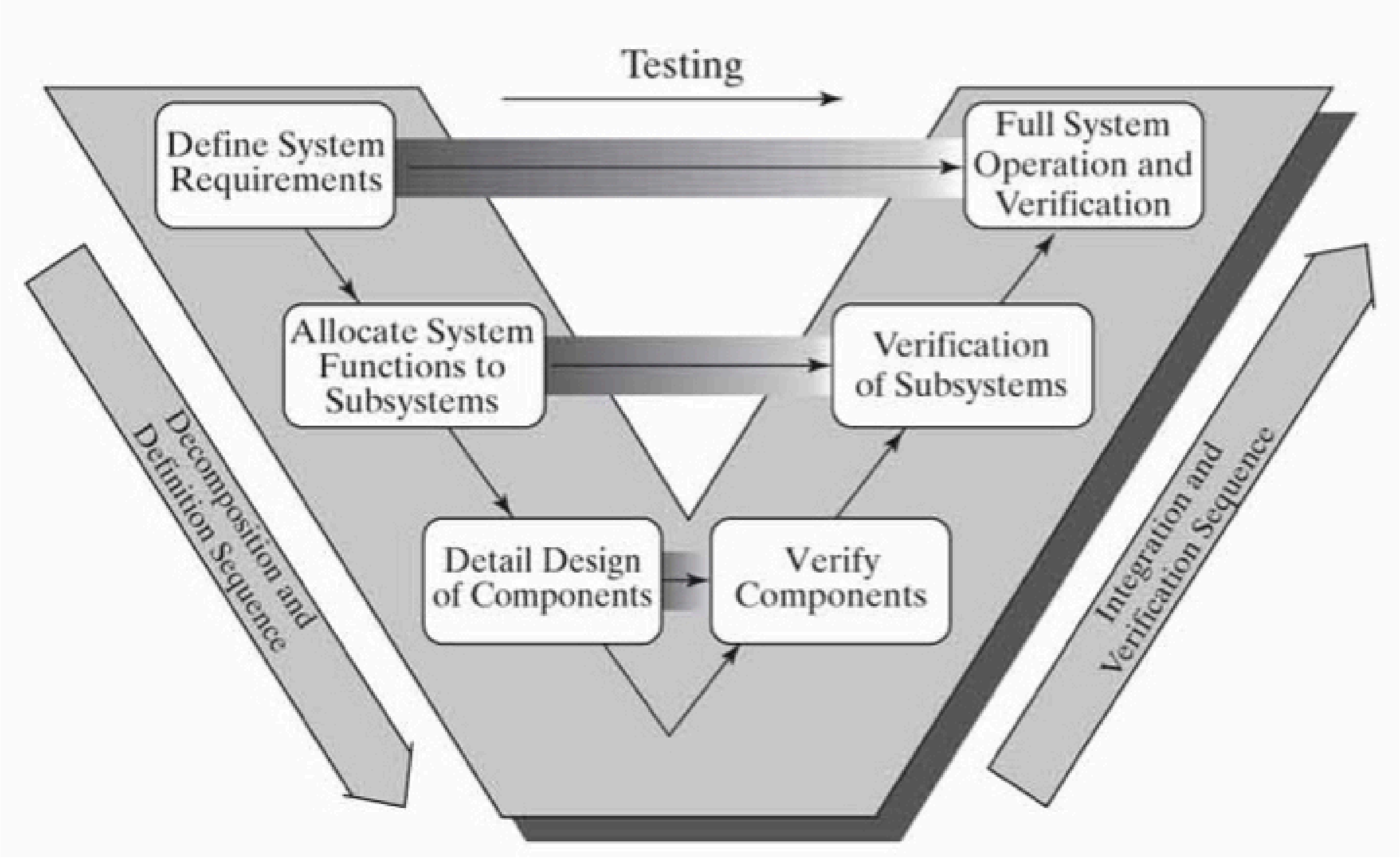
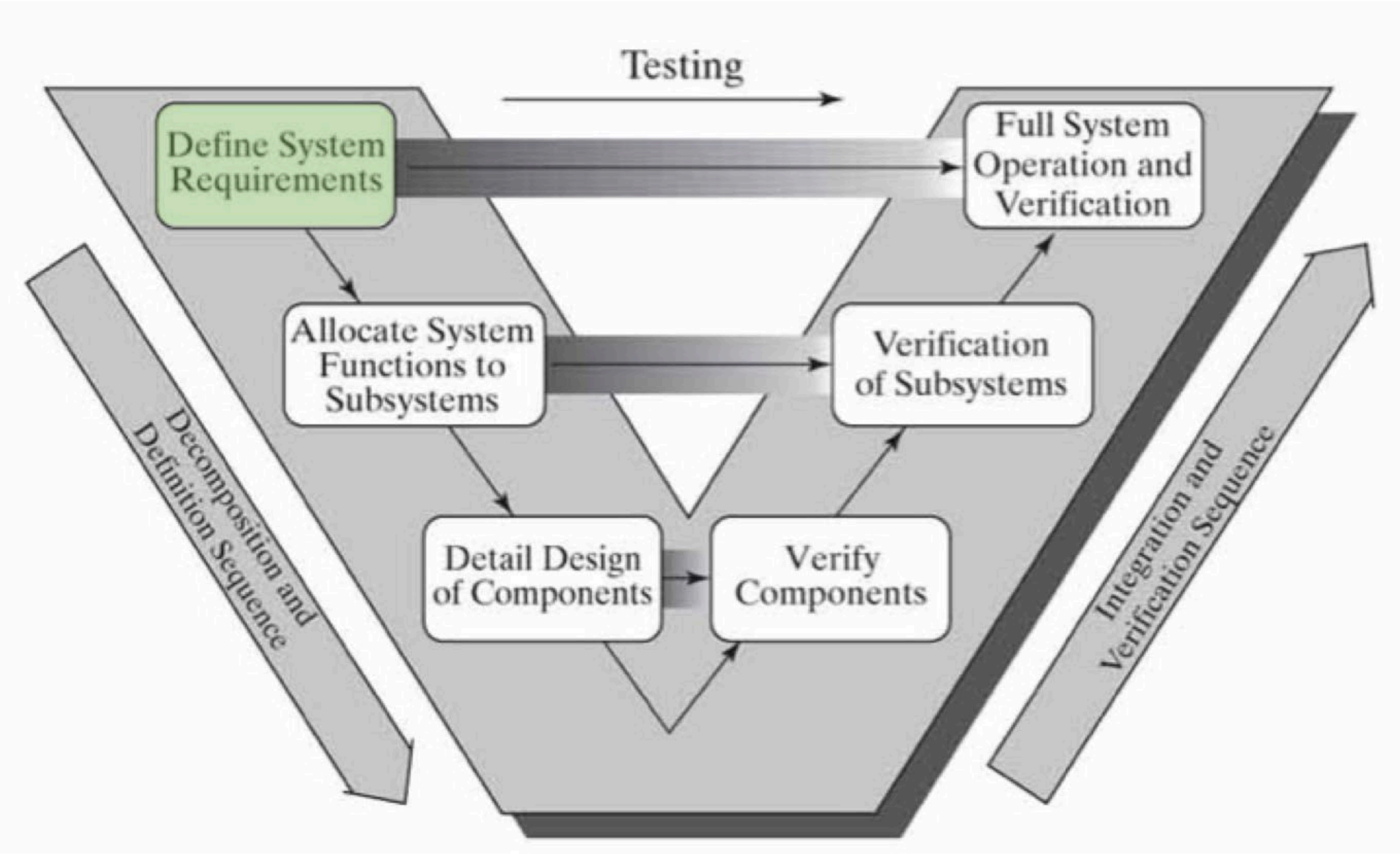
Systems Engineering

Systems Engineering Approach



Source: Van Atten W., 2019, *Engineering Design Method and Tools,* .pptx, EMEN 4405, University of Colorado, Boulder, Oct. 22, 2019

Systems Engineering Approach

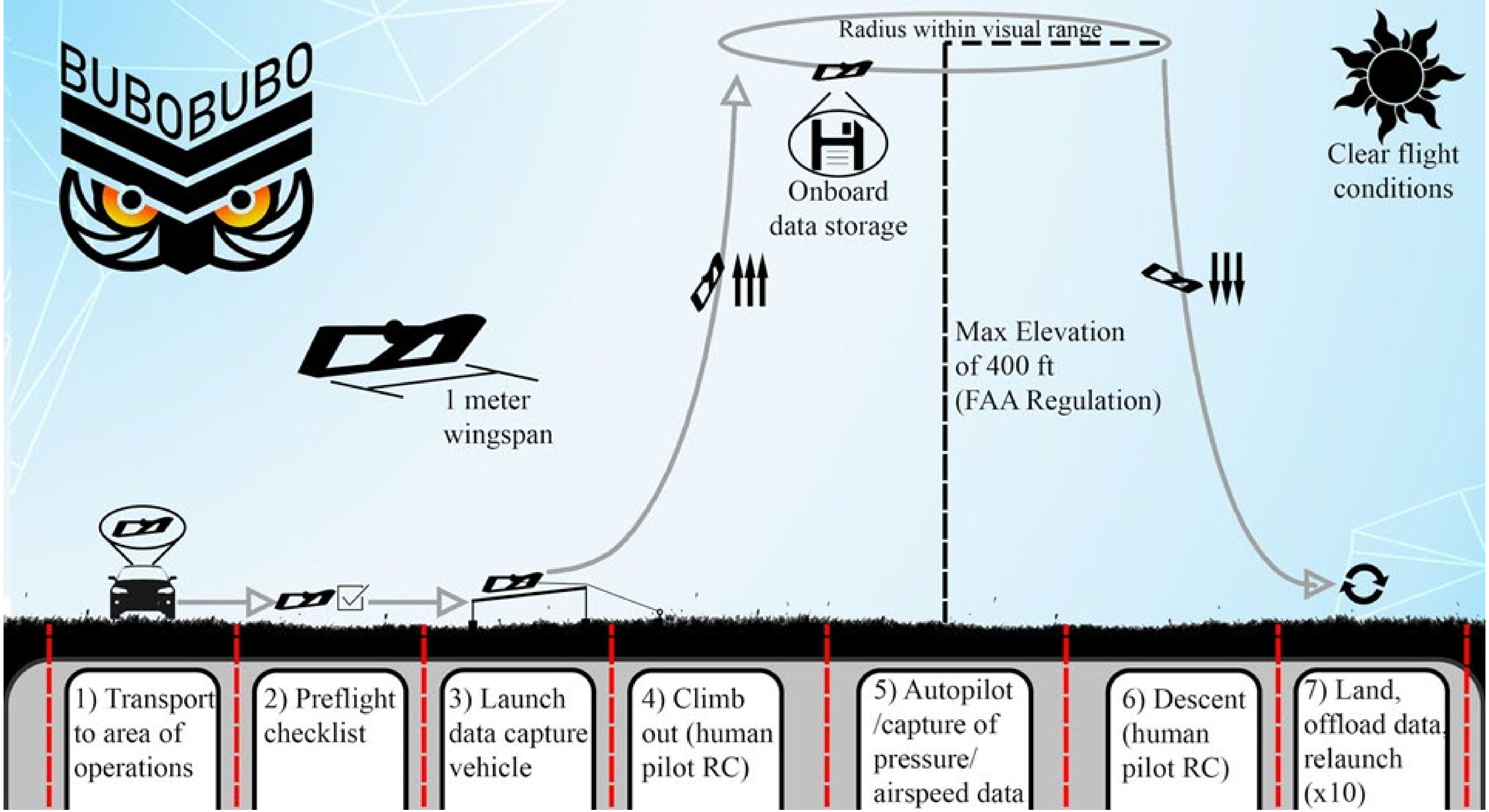


System Requirements Definition

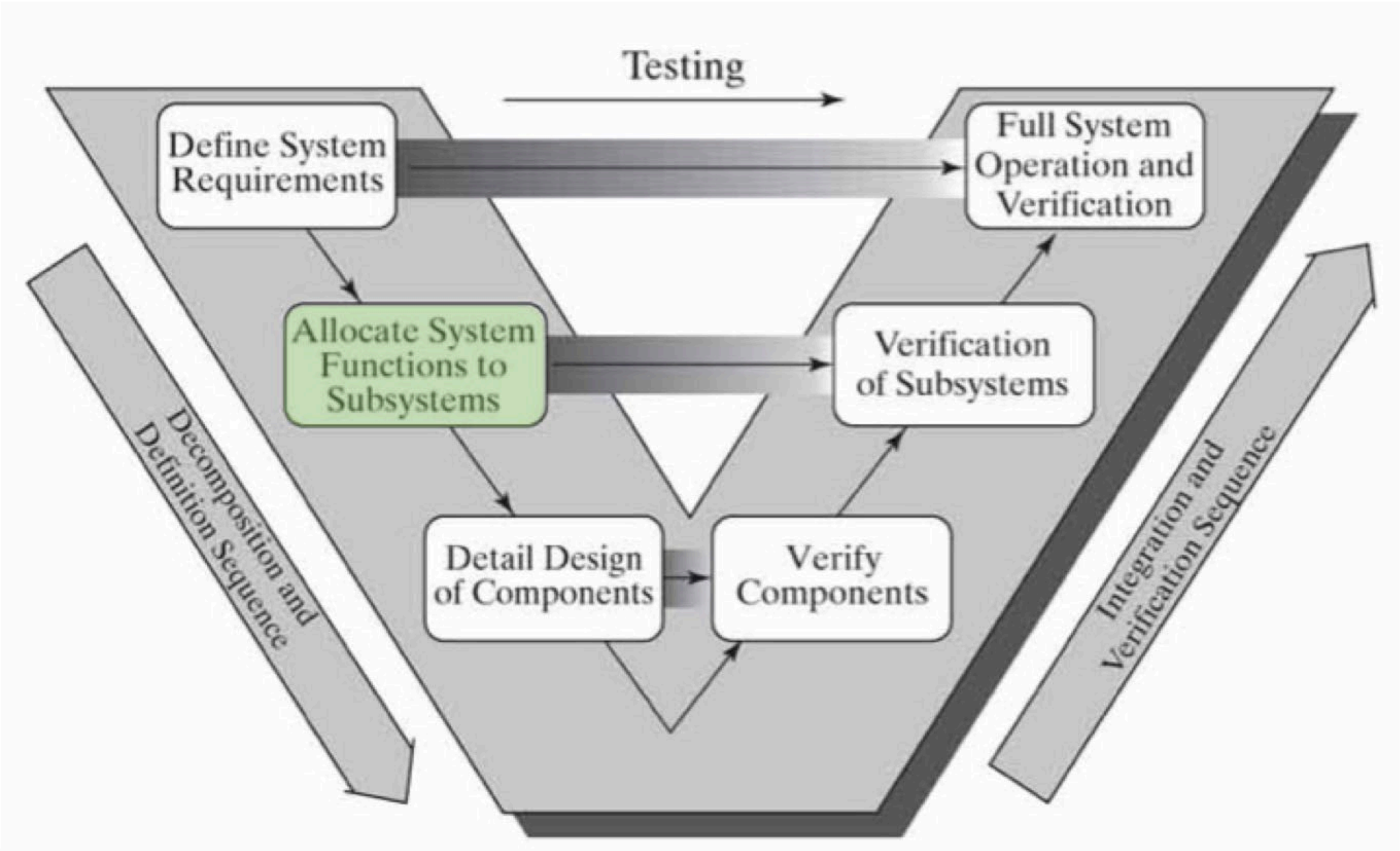
- Sat down with our customer, worked out functional requirements to drive airplane's design:

    1. The aircraft shall be a box-wing configuration with a scalable span
    2. The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector
    3. The aircraft shall be able to complete 10 flight cycles without major damage
    4. The aircraft shall be capable of sustained powered flight with an endurance of 1 hour
    5. The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile

System Requirements Definition



Systems Engineering Approach



Subsystem Allocation

FR 1: The aircraft shall be a box-wing configuration with a scalable span

1.1 The aircraft shall have two vertically separated lifting surfaces connected by struts and outer walls.

1.2 A one-meter and two-meter wingspan shall be investigated.

- 1.2.1 Either a one-meter or two-meter span aircraft shall be constructed and flight tested. The size of the aircraft being constructed will be determined by trade study.
- 1.2.2 The span which is not built shall have a feasibility study conducted.
    - 1.2.2.1 The feasibility study shall include physical alterations that must be made to change the span, such as values for the size of the scaled aircraft's airframe, values for the new power requirements, and placement locations of major subsystem components on the airframe
    - 1.2.2.2 The feasibility study shall include an analysis of the air-worthiness of the scaled aircraft.

Main subsystems concerned: **Structures, Aerodynamics**

Subsystem Allocation

FR 2: The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector.

2.1 The FADS system shall be integrated into the wing of the aircraft such that the sensors are flush with the wing surface.

- 2.1.1 An array of pressure transducers shall be integrated into the airframe at locations of high coefficient of pressure (C_p) gradient.

2.2 An on-board processor shall be integrated with the sensors to capture data.

- 2.2.1 The on-board processor shall be capable of recording sensor data at a rate of at least 6 Hz.
- 2.2.2 The on-board processor shall be capable of storing at least a one-hour flight's worth of data.

Main subsystems concerned: **FADS,** Electronics, Aerodynamics

Subsystem Allocation

FR 3: The aircraft shall be able to complete 10 flight cycles without major damage

3.1 The aircraft shall demonstrate a manually controlled takeoff.

- 3.1.1 The launch method shall produce a consistent launch force and angle to within 2 lbf and 10 degrees.
- 3.1.2 The launch system shall be deployable in the field in less than 15 minutes.
- 3.1.3 The launch system shall integrate with the airframe such that no major damage is imparted to the aircraft.

3.2 The aircraft shall demonstrate stable flight in an approximately circular loiter pattern.

- 3.2.1 The aircraft shall have dynamically stable flight characteristics upon small perturbations (less than 10%) to the aircraft's pitch, yaw, and roll.

3.3 The aircraft shall land and be able to fly again within 15 minutes.

- 3.3.1 Any necessary repairs shall be made in the field with readily available materials, defined by a repair kit, whose contents will be determined by the final design.
- 3.3.2 The power source shall be interchangeable.
- 3.3.3 The aircraft shall be able to land in a field.

Main subsystems concerned: **Structures, Controls,** Aerodynamics

Subsystem Allocation

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour.

4.1 The aircraft shall possess a self-sufficient internal power system.

4.1.1 Power shall be distributed to each subsystem that requires it such that the needs of each powered system are met.

4.2 The propulsion system shall support sustained flight for a minimum of one hour at standard operating loads.

4.2.1 The propulsion system shall generate sufficient thrust to overcome the expected drag forces on the aircraft.

4.2.2 The propulsion system shall be positioned to minimize potential damage to the aircraft.

Main subsystems concerned: **Propulsion, Electronics**

Subsystem Allocation

FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile.

5.1 The flight controller shall receive manual commands from the RC pilot during ascent and descent from loitering altitude.

5.2 The autopilot flight controller shall contain the sensors necessary to implement feedback control for a steady flight.

5.2.1 The flight controller shall have the ability to ensure path deviations in loitering are under 15 meters.

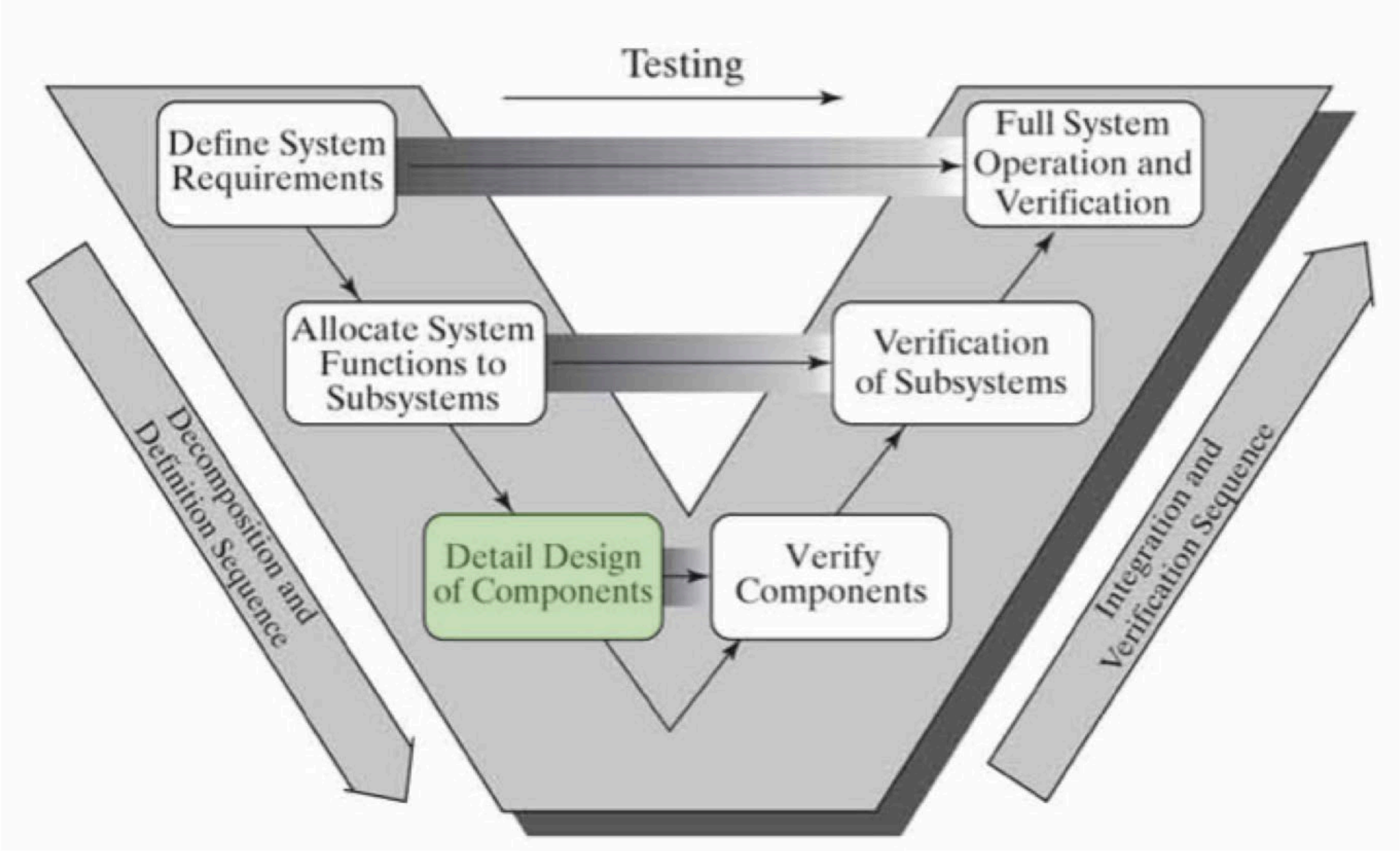
5.3 The RC pilot shall be able to switch from manual control to autopilot control for cruise and loitering flight

Main subsystems concerned: **Controls,** Aerodynamics

Trade Studies

- Performed 10 formal trade studies
- One example: Wing Configuration
  - Straight top and bottom wing (*Big Dumb Rectangle ™*)
  - Positively swept top, straight bottom wing (*Single Sweep*)
  - Positively swept top, negatively swept bottom wing (*Diamond*)
  - Pentagonal top and bottom wing (*Delta*)
  - Positively swept top and bottom wing *(Symmetric Sweep*)
- Evaluated based on 4 categories
  - Flight Performance (35%)
  - Structural Integrity (30%)
  - System Integration (20%)
  - Manufacturability (15%)
- Ultimately the Single Sweep design was selected

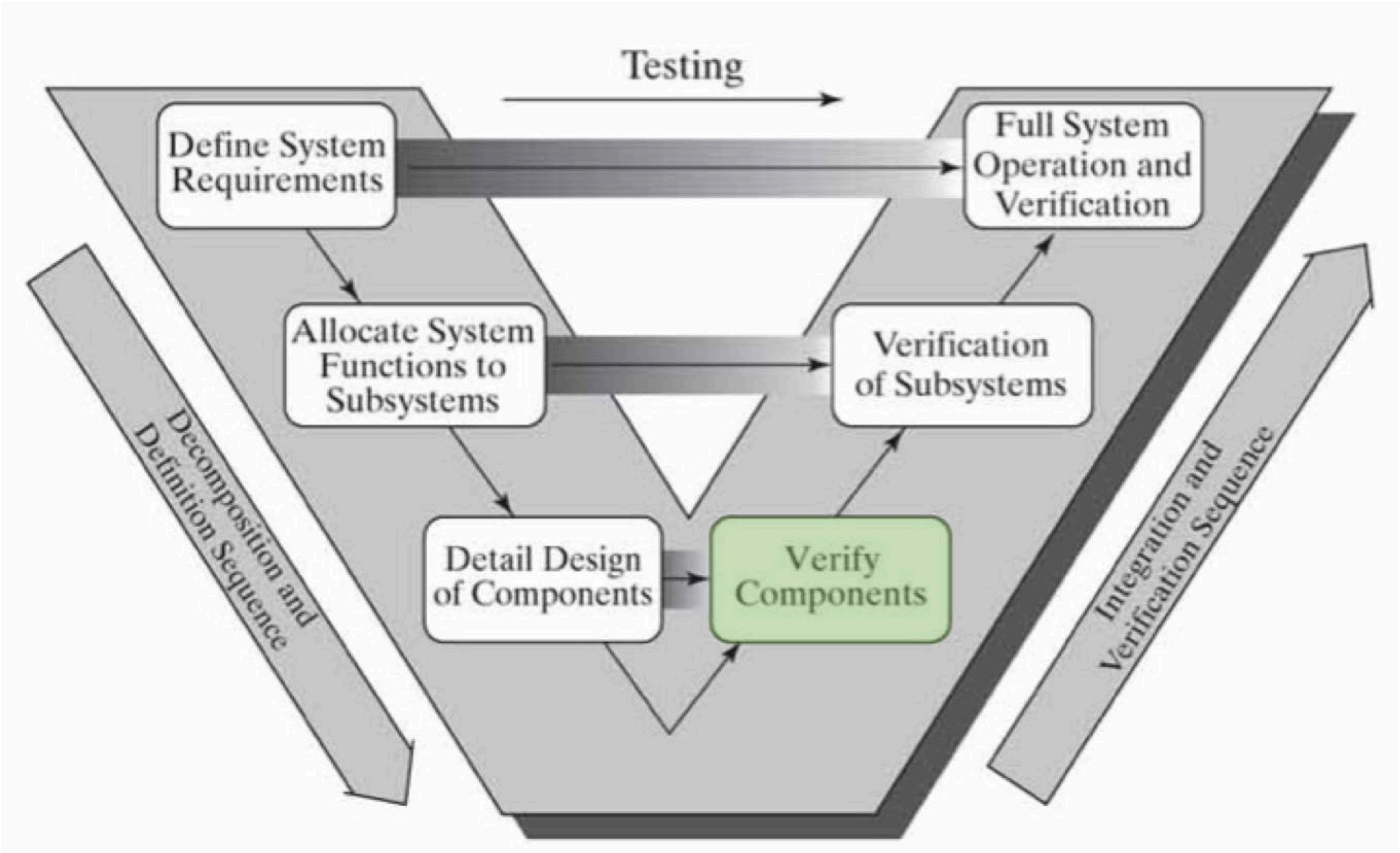
Systems Engineering Approach



Detailed Component Design

- Sub-teams met to work out designs of components used to make up subsystems
- Design geared to meet lowest level of flow down requirements
- Examples of individual component design by subsystem:
  - Structures: shape of airfoil to be laser cut, including all attachment point cut outs and pass throughs
  - Electronics: Selected type batteries to be used (Parallel 3S LiPos)
  - FADS: Selected specific sensors to be used to collect pressure data
  - Propulsion: Selected motor to be used
  - Controls: finalized control surface configuration (elevons on back wing)

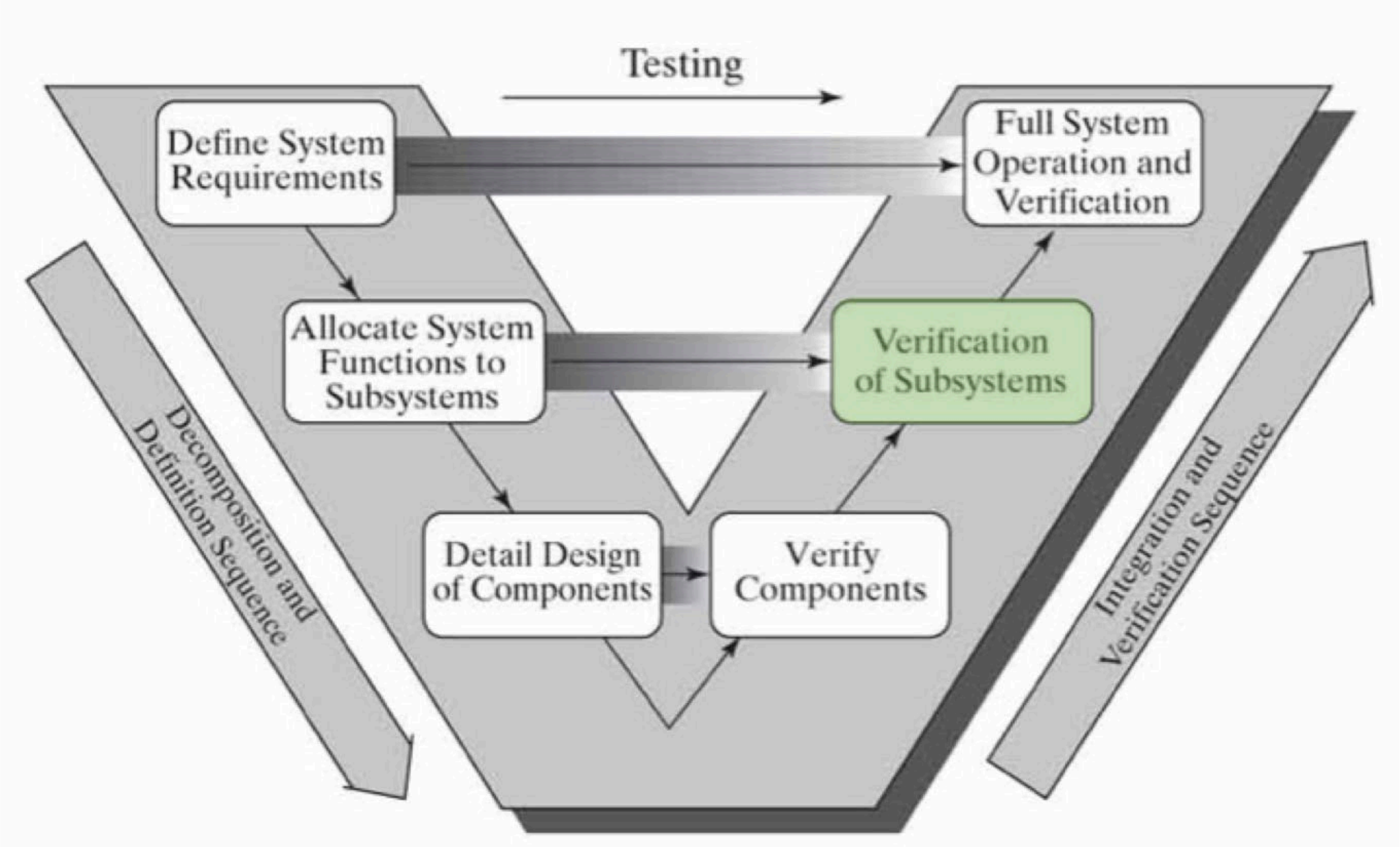
Systems Engineering Approach



Component Verification

- Tested separate components before integrating them into subsystems
- Verified that lowest level flow down requirements are met
- Individual component verifications:
  - Structures: verified laser cut pieces not warped, fit within tolerancing
  - Electronics: ensured batteries have expected voltages
  - FADS: verified that individual sensors successfully captured data
  - Propulsion: motor produces expected rpm rates
  - Controls: verified that servo arms provide adequate range of motion

Systems Engineering Approach



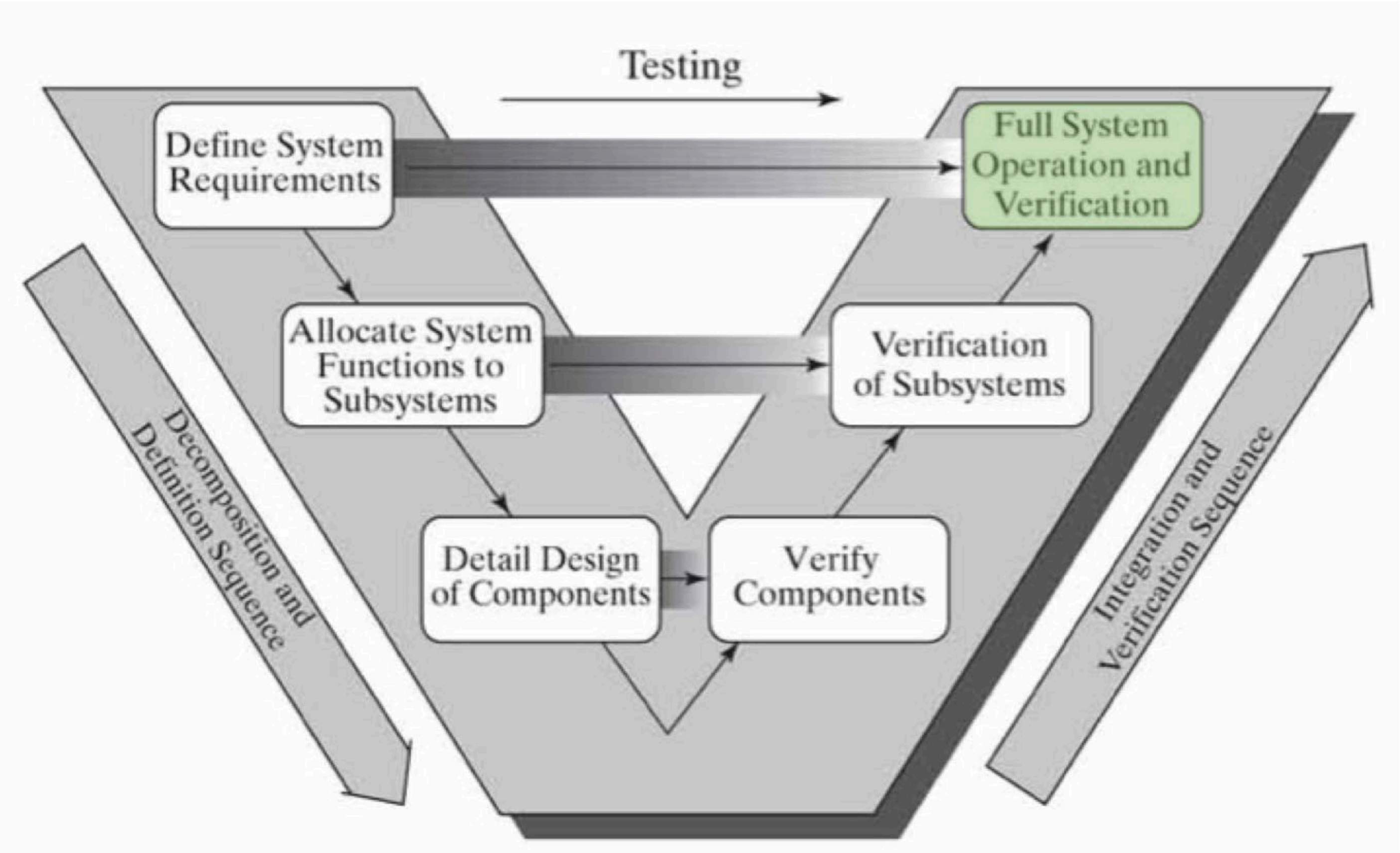
Subsystem Verification

- Testing done on entire subsystems to ensure functionality, validate models
- Verify higher level flow down requirements
- Satisfied most of Level 1 success criteria
- Subsystem verifications:
  - Structures: whiffletree test done on wing section to ensure flight loads could be supported
  - Electronics: circuit fully built outside of aircraft for testing
  - FADS: verified capture and storage of data from ports
  - Propulsion: ran short endurance test to simulate first flight
  - Controls: verified servo responses to physical PixHawk movement

Interface Control

- Main subsystem interaction occurred between electronics, controls, and propulsion subsystems
- All through the PixHawk for autonomous flight; inputs and outputs tracked and adapted accordingly
- Control-Propulsion interfaces, autonomous flight (PixHawk) :
  - Inputs: Speed, attitude information from PixHawk
  - Outputs: desired motor throttle level
- Controls-Propulsion interfaces, manual flight (Receiver-throttle) :
  - Inputs: RC controller throttle setting from receiver
  - Outputs: desired motor throttle level

Systems Engineering Approach



Full System Operation and Verification

- Verified that entire system operates as planned, meets functional requirements
- Satisfies Levels 2 and 3 of success criteria
  - Level 3 not met due to cutoff preventing further testing
- Subsystem verifications:
  - Structures: Airframe did not fall apart during flight testing
  - Electronics: Power provided to whole airframe for entire flight test
  - FADS: System fully integrated into airframe: only planned, not completed due to cutoff
  - Propulsion: Motor provided adequate thrust throughout flight test
  - Controls: Aircraft demonstrated adequate control during flight

Assessed Risks

- Predetermined risks inherent with all aircraft projects:
  - Weight
  - Timeline
  - Controls/general stability
- Predetermined risks specific to this project:
  - FADS system development
  - Unknown aerodynamic phenomena associated with box-wing
- Unforeseen risks that arose:
  - Pitching moment imparted by boom
  - Propulsion test stand

Assessed Risks: Mitigation

- **Weight:** took precautions to lighten every component
- **Timeline:** ensured team members had adequate help with all tasks to ensure team could stay as on track as possible
- **FADS:** ensured development of flying platform was priority, so FADS development didn’t hinder any flight-testing capability
- **Controls/stability:** added ballasted boom to improve static margin and longitudinal stability
- **Boom pitching moment:** changed airfoil shapes; cambered on top, reflexed on bottom
- **Propulsion test stand:** furthered fidelity of models so that absolute data from testing no longer flight critical

Systems Challenges

- Changes made to airfoil came late in the design phase
  - Many later design elements dependent on the originally defined foils
  - Made implementing change very tricky, even with change control processes in place
- Testing of motor repeatedly delayed due to issues with test stand
  - Had to alter verification process for chosen motor prop combination
  - Away from absolute testing and more focused on models, given data, relative test data

Key Lessons Learned: Systems Engineering

- Ensure that changes can be implemented easily from the very first design iteration; full top-down approach
- Always be ready to adapt and change quickly should the need arise

Project Management

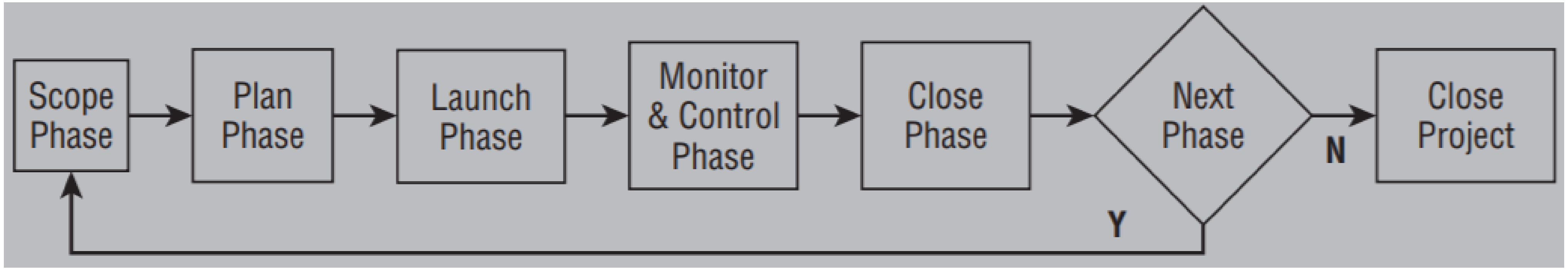
Project Management Approach

Team Culture

- Cooperative
- Collaborative
- Open and Honest

Extreme Project Management Approach

- Commonly used in R&D projects
- Project required scoping at the beginning of each phase
- Each phase was dependent on the completion of the previous phase



Project Phases

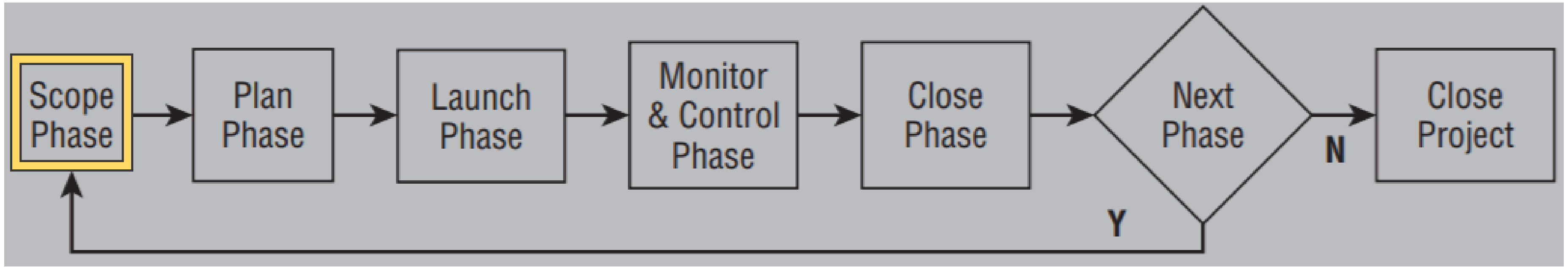
1. Project Set Up
2. Configuration Design 1 (initial design)
3. Configuration Design 2 (ballast added)
4. Configuration Design 3 (airfoil change)
5. System Integration Feasibility
6. Physical Testing for Configuration Design 3 Subsystems
7. FADS integration
8. Aircraft Optimization/Redesign
9. Scalability Study
10. Close Project

Scoping

- Each individual phase required a scoping within the confines of the overall project

- Met with systems lead to discuss
  - How each phase could move towards satisfying requirements
  - Detailing tasks that needed to be done for the current phase to be considered successful

- Met with client at beginning of each phase to discuss
  - Current position
  - Plan going forward
  - How we can redefine/prioritize certain expectations

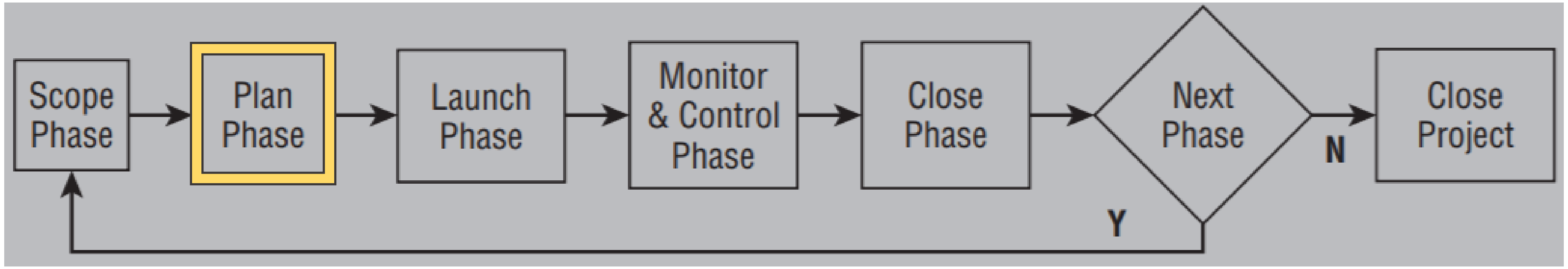


Planning

- Established timeline/schedule
  - Sequenced backwards from next big deliverable to ensure enough time was allocated
  - Assessed high risk activities and added schedule margin

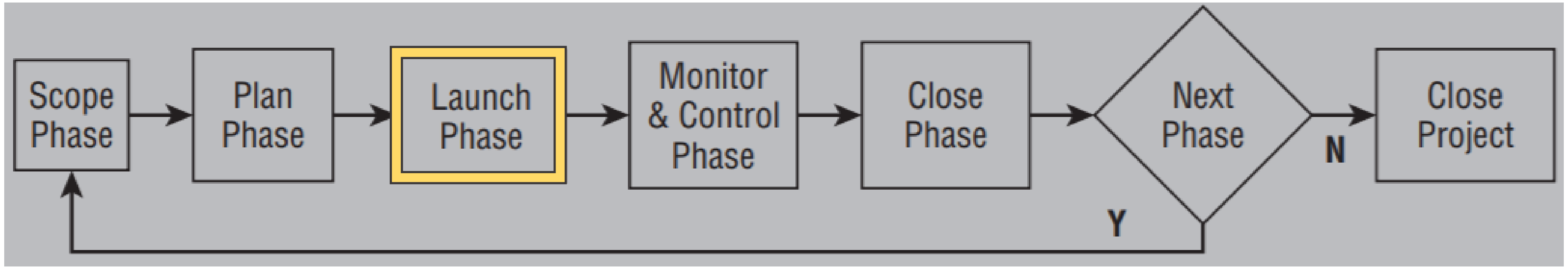
- Met with team at beginning of each phase to present
  - Goals for current phase
  - Timeline/schedule for each phase
  - Budget allocated for each phase

- Human resource reallocation
  - How each person's skills could be best applied to solve the current problem
  - Assigned individuals to work with subteam leads on different parts of the project



Launching

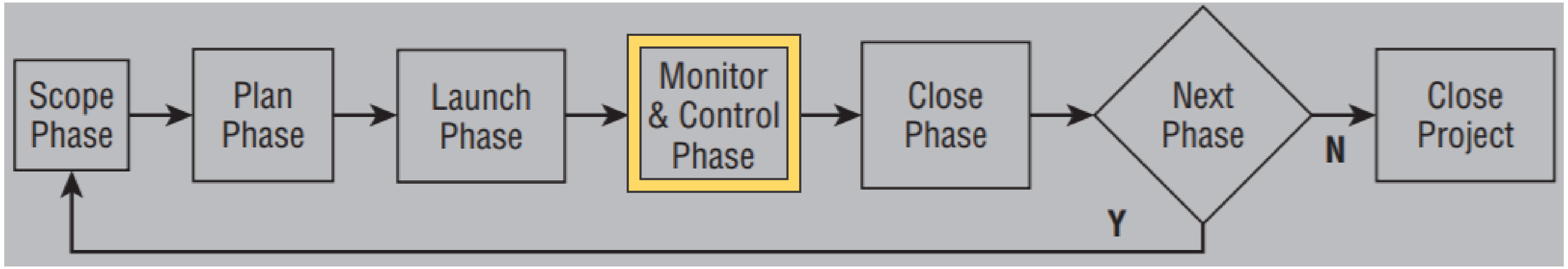
- Commence bulk of analysis/modeling/manufacturing of that phase
- This looked a bit different for each phase
- Team rules re-emphasized:
  - Open communication
  - Ask questions and give constructive feedback
  - Document all work in google drive
  - Use slack
  - Attend all meetings as directed by project manager



Monitoring & Controlling

- Performance and reporting system
  - Weekly team meeting
  - Weekly client meetings
  - Weekly advisor meetings
  - Weekly schedule updates

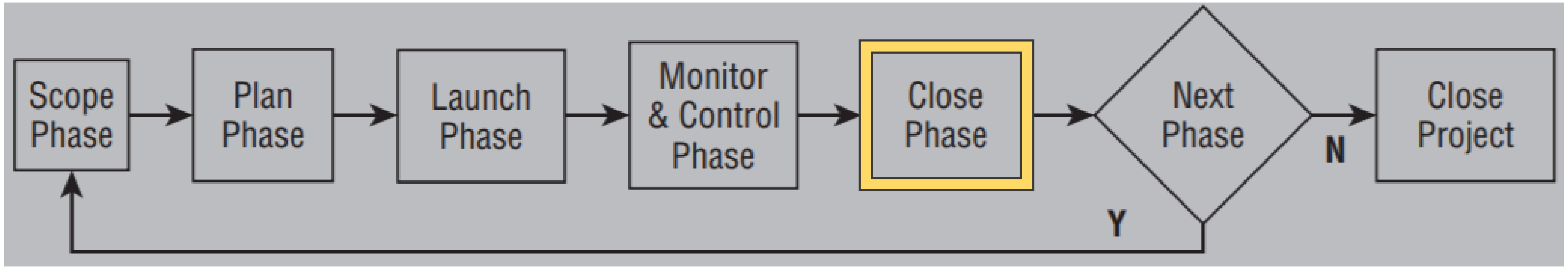
- In the event of a problem or delay:
  - Systems lead and project manager informed
  - If needed, emergency team meeting called
  - Mitigation strategy discussed and chosen
  - Team informed of decision



Closing

- Team meeting called to discuss:
  - How we are/are not meeting requirements of project.
  - What the next phase needs to be.
  - What we did well.
  - What we can improve on.

- Used this meeting to determine
  - What we need to change in the next phase.
  - What we need to keep in the next phase.



Key Management Successes

- Scoping
  - Drastically reduced initial project scope from two aircrafts to one
  - Addition of development of FADS system worked into project well

- Customer relations
  - Weekly meetings kept customer up to date on project progress
  - Kept open line of communication to get input from customer
  - Worked with customer to access key resources

- Scheduling
  - Kept to schedule very well despite several setbacks
  - Included enough margin
  - Accelerated schedule when COVID-19 seemed to threaten timeline in order to ensure test flight could occur

Key Management Difficulties

- Scope widened after starting project to include development of FADS
  - Originally planned for integration only
  - Previous FADS system had been lost so a new one had to be constructed
  - Required full rework of schedule, requirements, levels of success, and human resource allocation to ensure it could be done

- Testing apparatus availability
  - Not able to secure wind tunnel usage – had to create testing alternatives
  - Thrust testing apparatus
    - None available in the department set up to measure thrust of a propeller
    - Originally tried to build our own
    - Transitioned to DBF test stand but had to help them fix it
    - Even after repairs, data from DBF stand was questionable for some time

Lessons Learned

- Do NOT rely on people outside your team to accommodate you. Consider potential alternatives in case the person you are waiting on cannot adequately assist you and follow up often with people who you are waiting on.

- Keep and document everything (and keep it organized)! You (or future heritage projects) may need to go back to previous design work! Keeping all the work you have done in an easy to understand and organized format will make future referencing much easier.

Expected Budget

Expected Single BUBO	
Electronics	$757.71
Power	$451.54
Structural	$237.90
FADS	$966.08
Total Expected	$2,413.23

This estimate considers EEF funding

Actual Budget

Actual Single BUBO	
Electronics	$521.47
Power	$525.69
Structural	$304.12
FADS	$455.08
Total Single Aircraft	$1,806.36

This estimate considers EEF funding

Single Aircraft - Expected vs Actual Budget

Subsystem	Expected	Actual	Difference	% change
Electronics	$757.71	$521.47	-$236.24	-31.18%
Power	$451.54	$525.69	+$74.15	+16.42%
Structural	$237.90	$304.12	+$66.22	+27.84%
FADS	$966.08	$455.08	-$511.00	-52.89%
Total	$2,413.23	$1,806.36	-$606.87	-25.15%

The comparison is done for a single aircraft. Any analysis involving the entire project would render inaccurate data due to the early finish.

Industry Cost of our Project

Including expected work following Final Oral Review Submittal:

Total Hours = 5230

Hourly Cost* = $163,437.50

200% Overhead = $326,875.00

Materials Cost = $2,728.57

Total Industry Cost = $493,041.07

* Using an average yearly salary of $65,000 for 2080 hours of work, or $31.25/hour

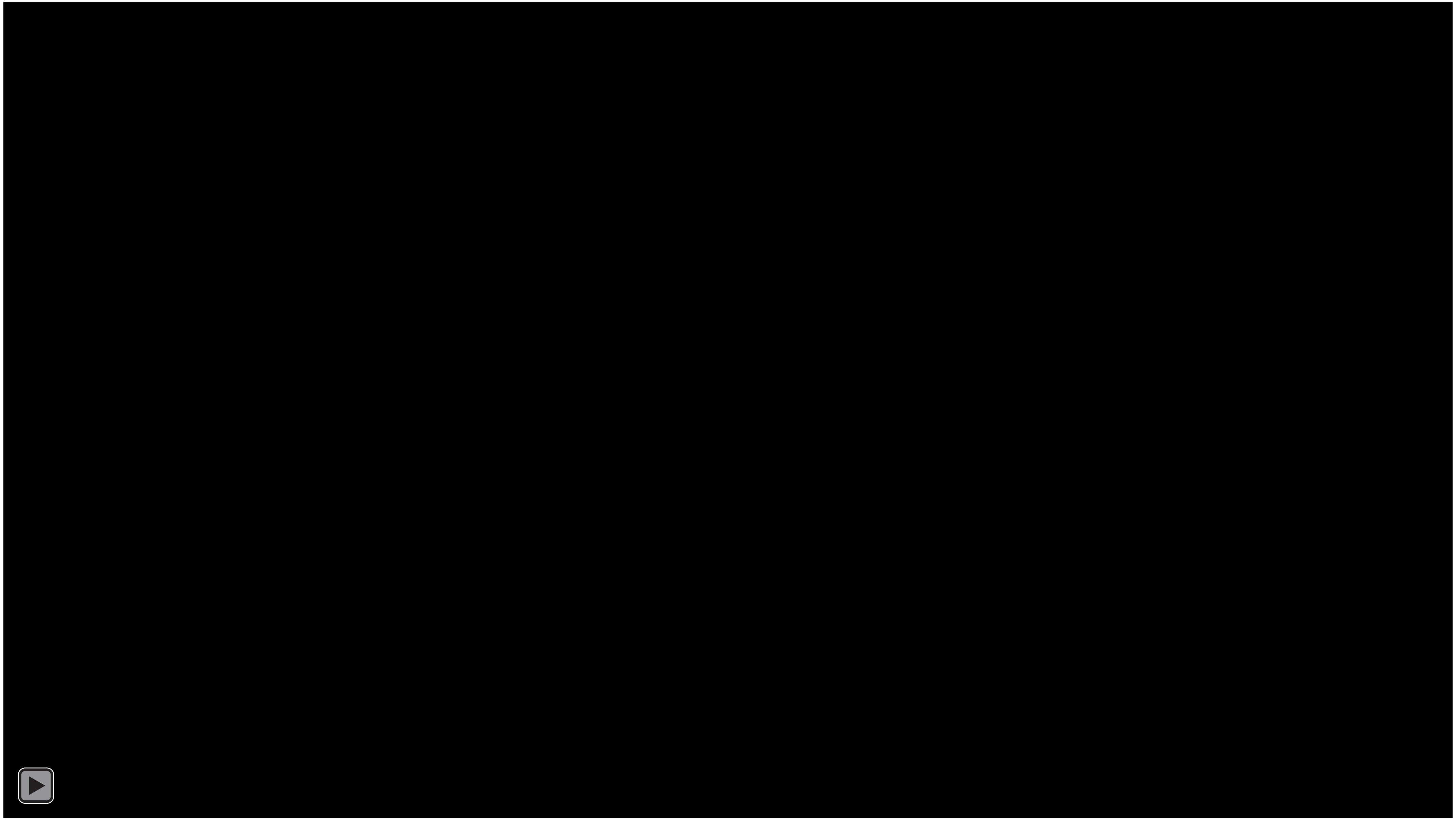
Thank You

Questions?

Directory

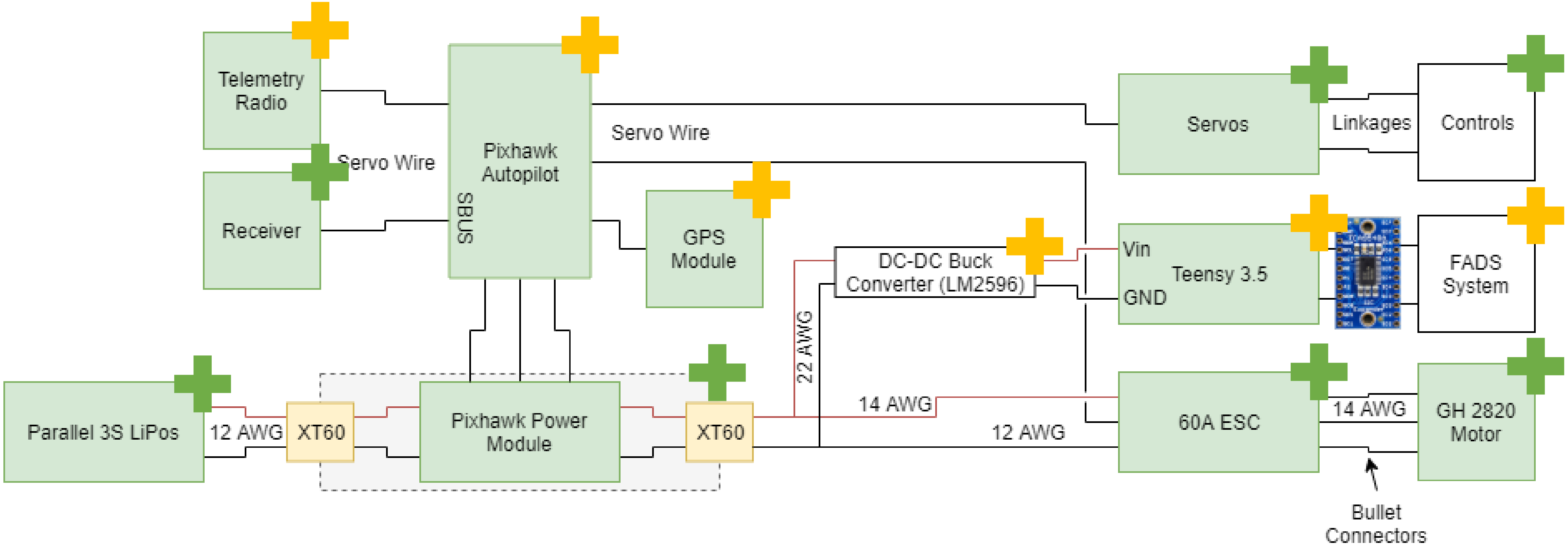
Flight Test Videos Backup

Stall Characteristics



Electronics Backup

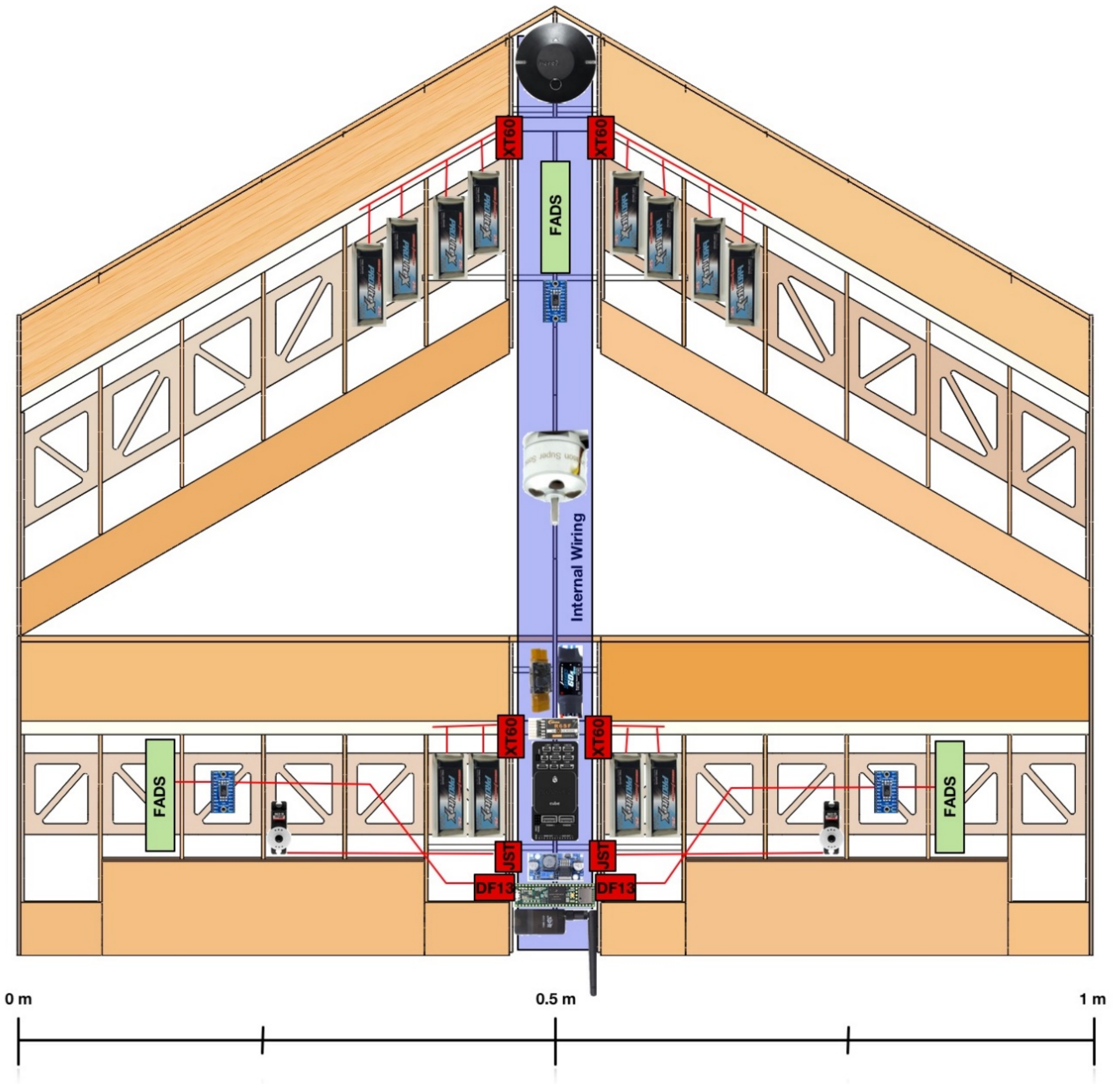
Electronics Design



= fully tested and integrated

= tested but not integrated

Electronics Integration



Controls Test

	Navigation And Control	Sensor Data	Survivability	Flight	Airframe Scalability
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural test	Models demonstrate aircraft achieves steady level flight	Build 1 or 2 meter span box-wing airframe
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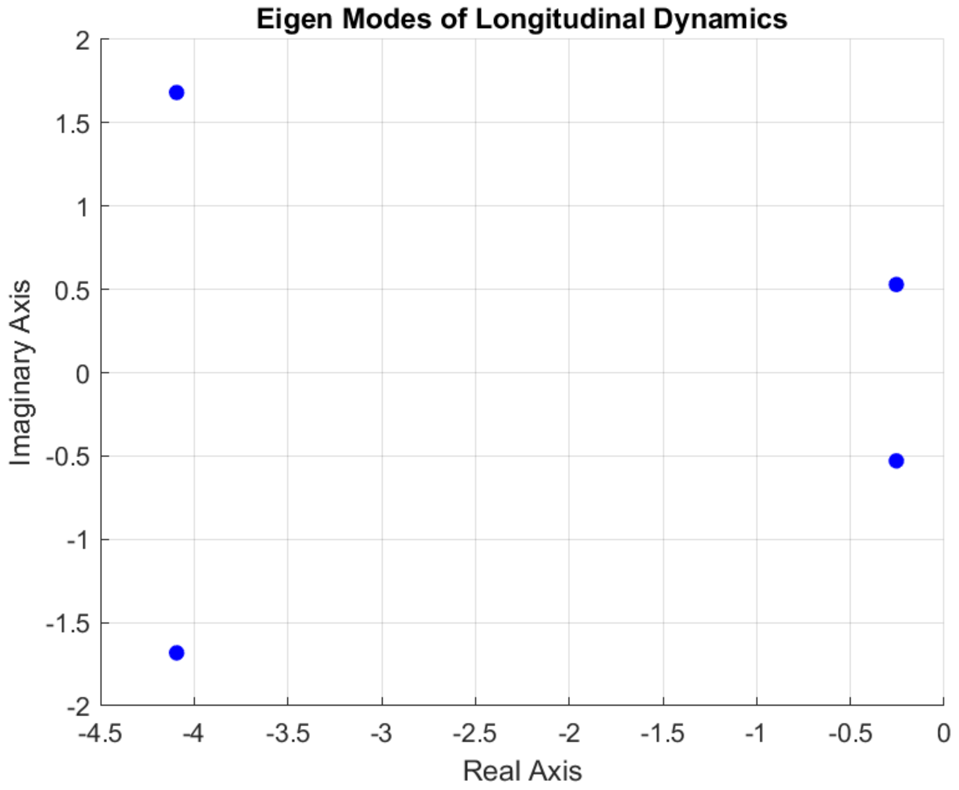
Level 3	Autonomous control during cruise and loiter in-flight	Integration of sensors does not degrade accuracy by 5%	Survives 10 takeoff and landing cycles	Aircraft can sustain flight for a minimum of 1 hour	Feasibility study for scaled airframe

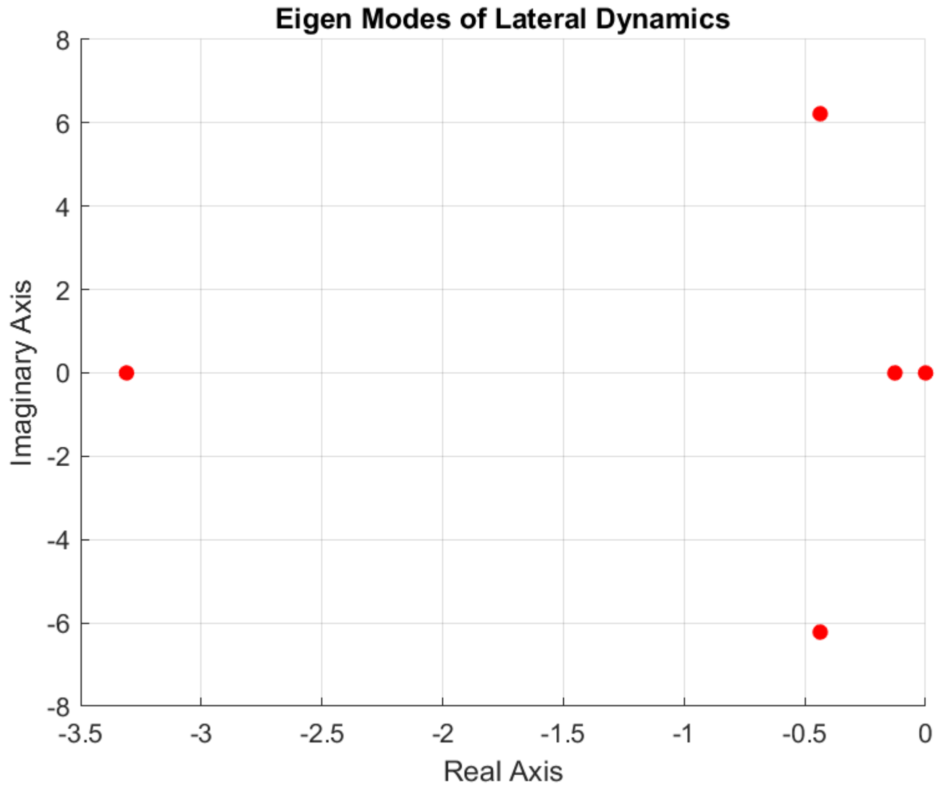
Functional Requirements Addressed:

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour

FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile

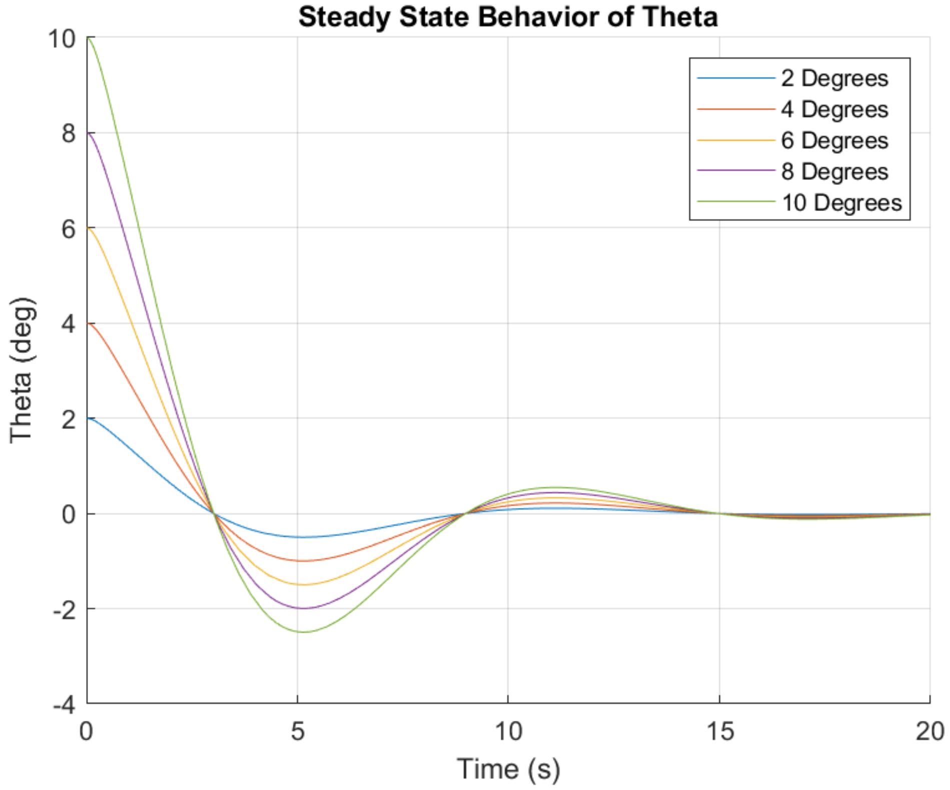
Model and Predictions (Stability)

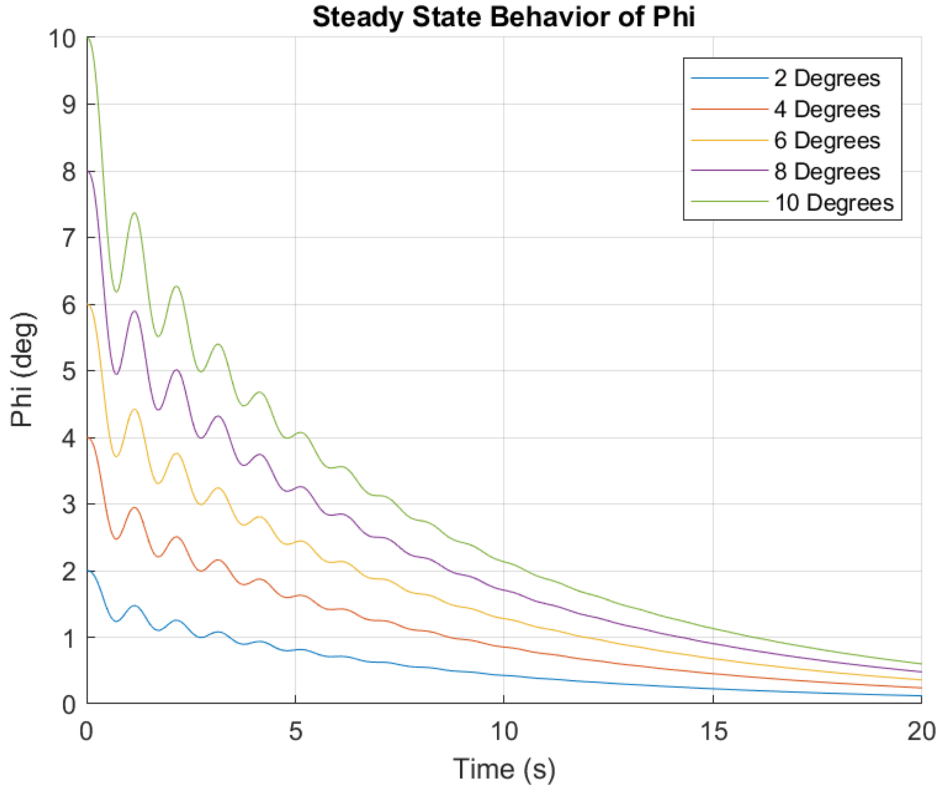




Model predicts a stable behavior for the aircraft

Model and Predictions (Dynamic Behavior)





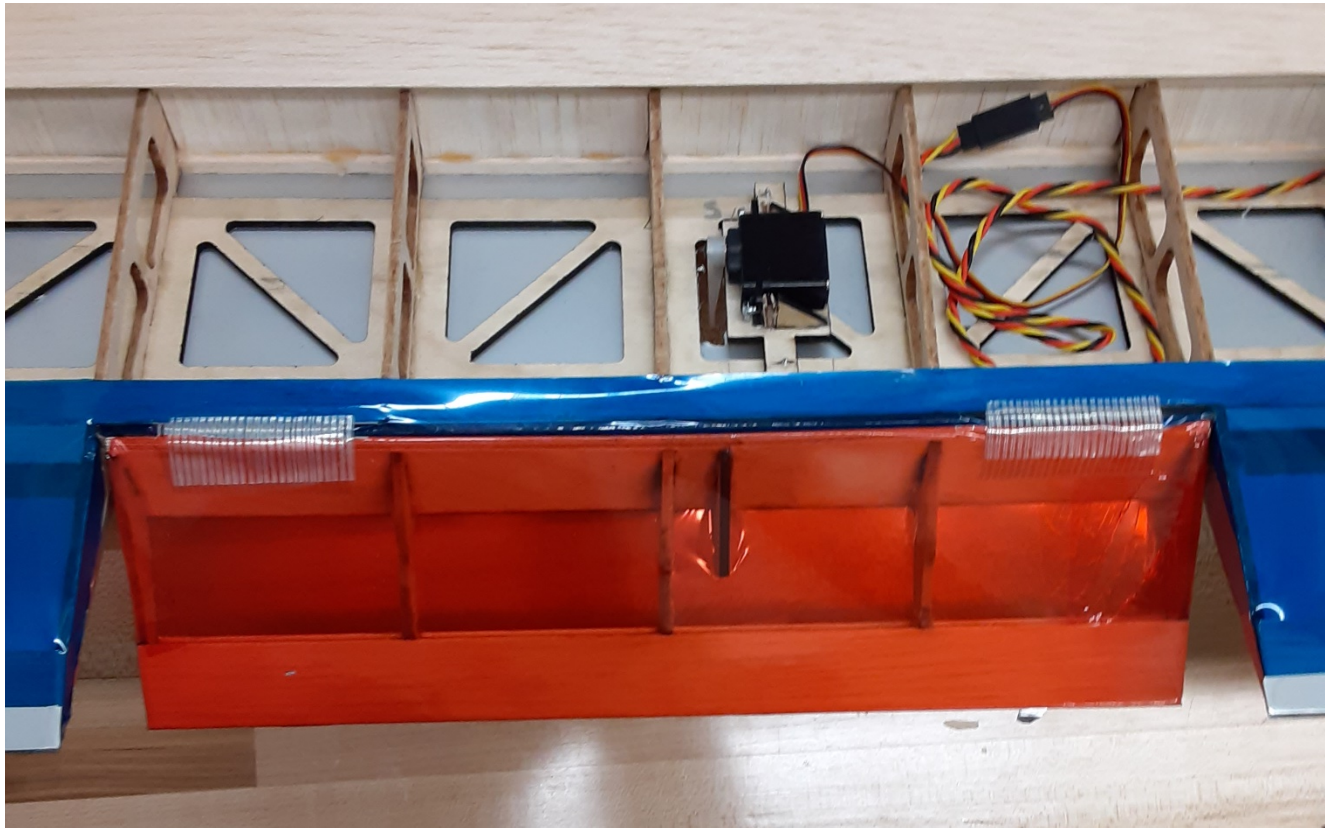
Expected maximum deflection of 30 degrees for the elevons/Stable Eigen Modes

Completed Tests

- Functionality and Integration test of the PixHawk, Telemetry, GPS, Servos, and Manual control.

Controls Results

- Verified correct elevon responses
- Lengthened servo arms to reach desired maximum deflection of at least 30 degrees



Unfinished Tests

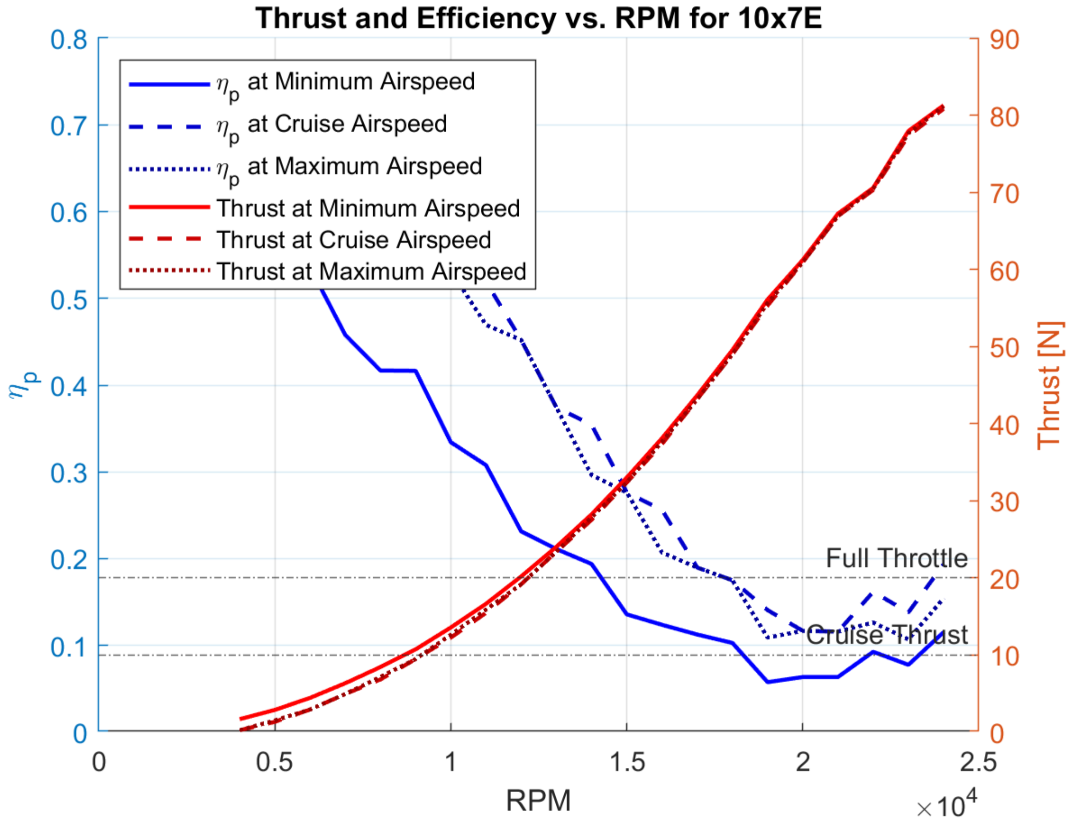
- Ground Test: Setup with the entire control system post software configuration for comparison with models
- Flight Test: Data capture of the attitude (roll, pitch, yaw) of the aircraft for comparison with model

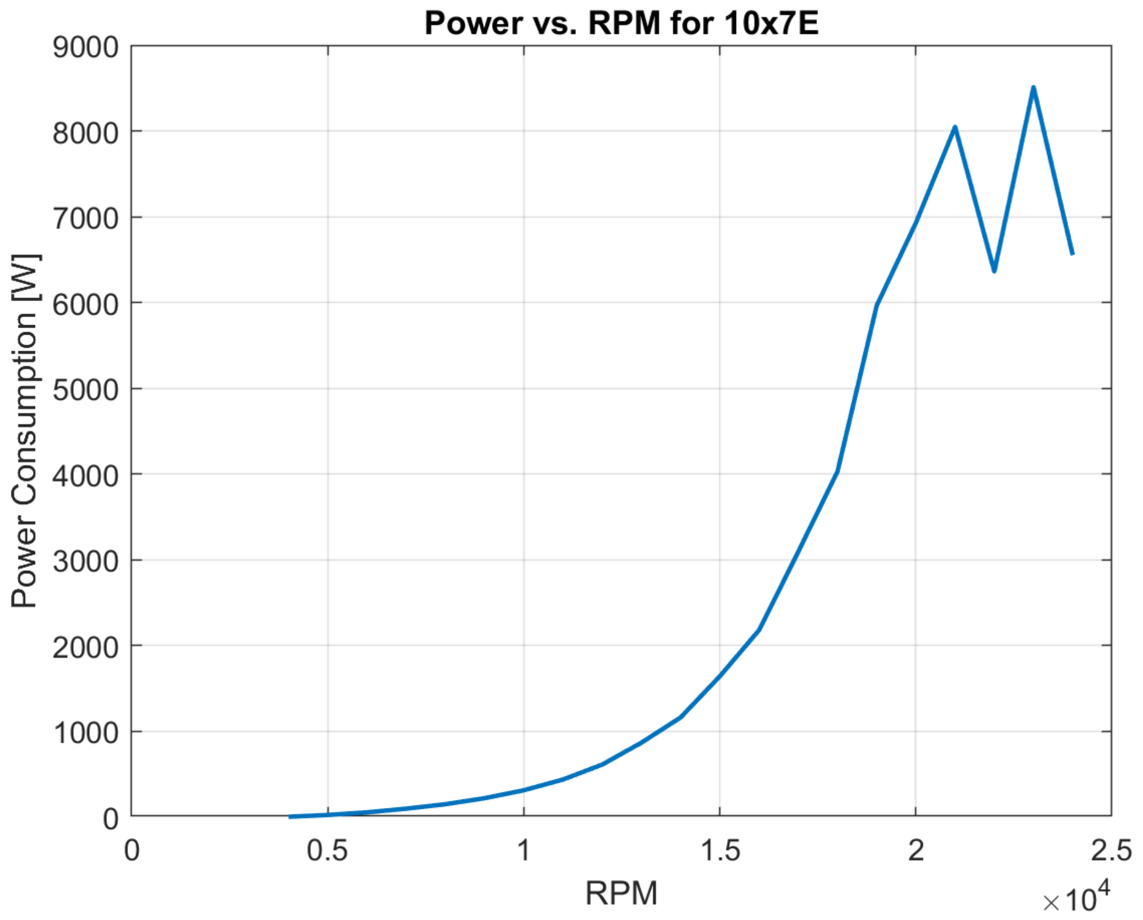
Uncertainty

- PixHawk: Data sheets for PixHawk contain uncertainty pertaining to the sensors and the onboard IMU
- Instrument physical measurements such as the elevon deflection measurement

Propulsion and FADS Backup

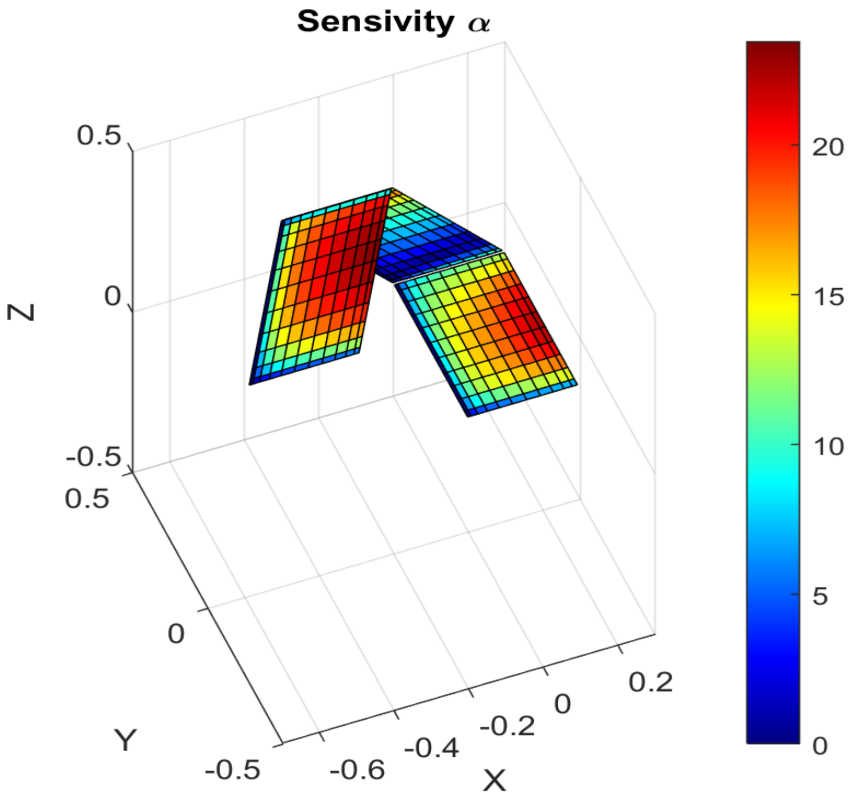
Propulsion Modeling





FADS Pressure Port Selection Modeling

- Used to determine placement of FADS pressure ports, based on pressure grdaients as defined in research by Dr. Roger Laurence.
- Pressure values generated using AVL.
- Unfortunately not implemented or verified by practical testing.



Project Management Backup

Phase 1

Project Set Up

a. Scope: defining what needs to be done overall to determine success/figuring out what the client wants/figuring out what the team is capable of doing with the given time and resources

b. Planning: considering what we feel we are able to do with budgetary options/time constraints/available resources

c. Launch: meeting with client , starting slack, starting google drive, assigning team roles

d. Monitor and Control: adapt as much as possible what client wants and what team is able to do to be one goal

e. Close cycle: establishing one plane will be built and the scalability study done for the other, writing requirements

f. Next phase: initial design

Phase 2

Configuration Design 1 (initial design)

a. Scope: designing boxwing plane able to fly/be stable including all subsystems

b. Planning: trades done for CDD, modeling done for PDR

c. Launch: started analysis and modelling, had weekly client/team/advisor meetings

d. Monitor & Control: Most subsytems working out well, eventually discovered catastrophic unstable mode and discussed in team meeting.

e. Close cycle: Decided configuration needed to change otherwise plane wouldn’t fly

f. Next phase: will change airfoils because all other configuration decisions would massively impact all other areas of design

Phase 3

Configuration Design 2 (ballast added)

a. Scope: Redesigning plane to remove instability → adding ballast

b. Planning: trades on how to add ballast (boom type, number, etc.), needed to be done by CDR

c. Launch: analysis and modeling, had weekly client/team/advisor meetings

d. Monitor & Control: Ballast addition created pitching moment → called team meeting to discuss mitigation

e. Close cycle: Decided to keep ballast and change airfoils

f. Next phase: changing airfoils

Phase 4

Configuration Design 3 (new airfoils)

a. Scope: Redesigning plane to remove pitching moment → changing airfoils
b. Planning: trades on potential for new airfoils, needed to be done by FFR
c. Launch: new analysis and modelling, had weekly client/team/advisor meetings
d. Monitor & Control: New airfoils made aircraft stable
e. Close cycle: Changed airfoils
f. Next phase: System integration with new airfoils

Phase 5

System Integration Feasibility

a. Scope: figure out how all subsystems will fit together with given design and within budget

b. Planning: relatively short timeline because systems had been designed in parallel with other design changes and therefore should have take design changes into consideration, need to be done before FFR

c. Launch: analysis and modeling, had team meetings

d. Monitor and Control: went well, small adjustments to chosen components due to size/weight/budgetary considerations but nothing big

e. Close cycle: Can move forward with current configuration design

f. Next phase: Manufacturing

Phase 6

Physical Testing for Configuration Design 3 Subsystems

a. Scope: Build test articles for subsystems, build 1 meter plane that can be test flown

b. Planning: Procurement possibilities, manufacturing tool availability, human resource reallocation as modeling winds down, testing schedule established → need to be complete by TRR

c. Launch: parts ordered, manufacturing expectations and safety rules established, locker organization established

d. Monitor and Control: went well, 1m plane was built and flown with minimal components to prove design feasibility completed, would have integrated full design

e. Close cycle: COVID-19 suspended all operations, would have showed design works/does not work with full number of batteries

f. Next Phase: would have been FADS if worked or Aircraft Optimization/Redesign design if did not work

Planned but uncompleted phase

FADS integration

a. Scope: include FADS to design

b. Planning: Procurement possibilities, manufacturing tool availability, human resource reallocation, manufacturing schedule established

c. Launch: manufacturing expectations and safety rules established

d. Monitor and Control: integrate FADS and complete testing on ground and in flight

e. Close cycle: Determine any changes needed to be made to FADS system/integration based on testing data

Planned but uncompleted phase

Aircraft Optimization/Redesign

a. Scope: optimize current design to fly better/meet all requirements

b. Planning: time restraints, procurement possibilities, manufacturing tool availability, human resource reallocation, manufacturing schedule established, figure out where improvements can be made

c. Launch: analysis of improvement options begins

d. Monitor and Control: keep track of potential design optimizations, enact ones which are most helpful/what is most possible, building and test flying chosen design changes

e. Close cycle: chose final aircraft design

Planned but uncompleted phase

Scalability Study

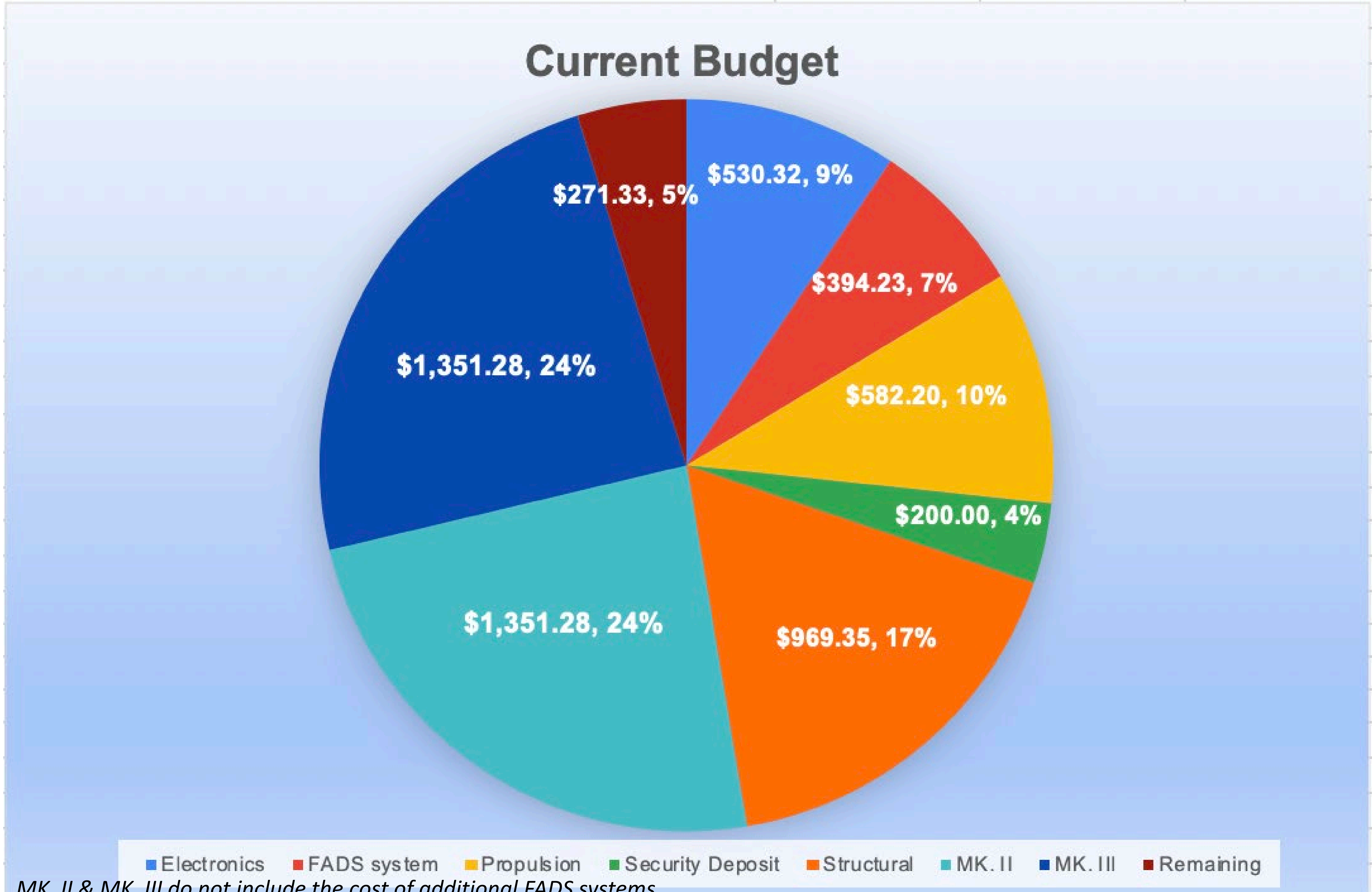
a. Scope: establish needed changes when structure is scaled up by 2

b. Planning: human resource allocation, schedule development

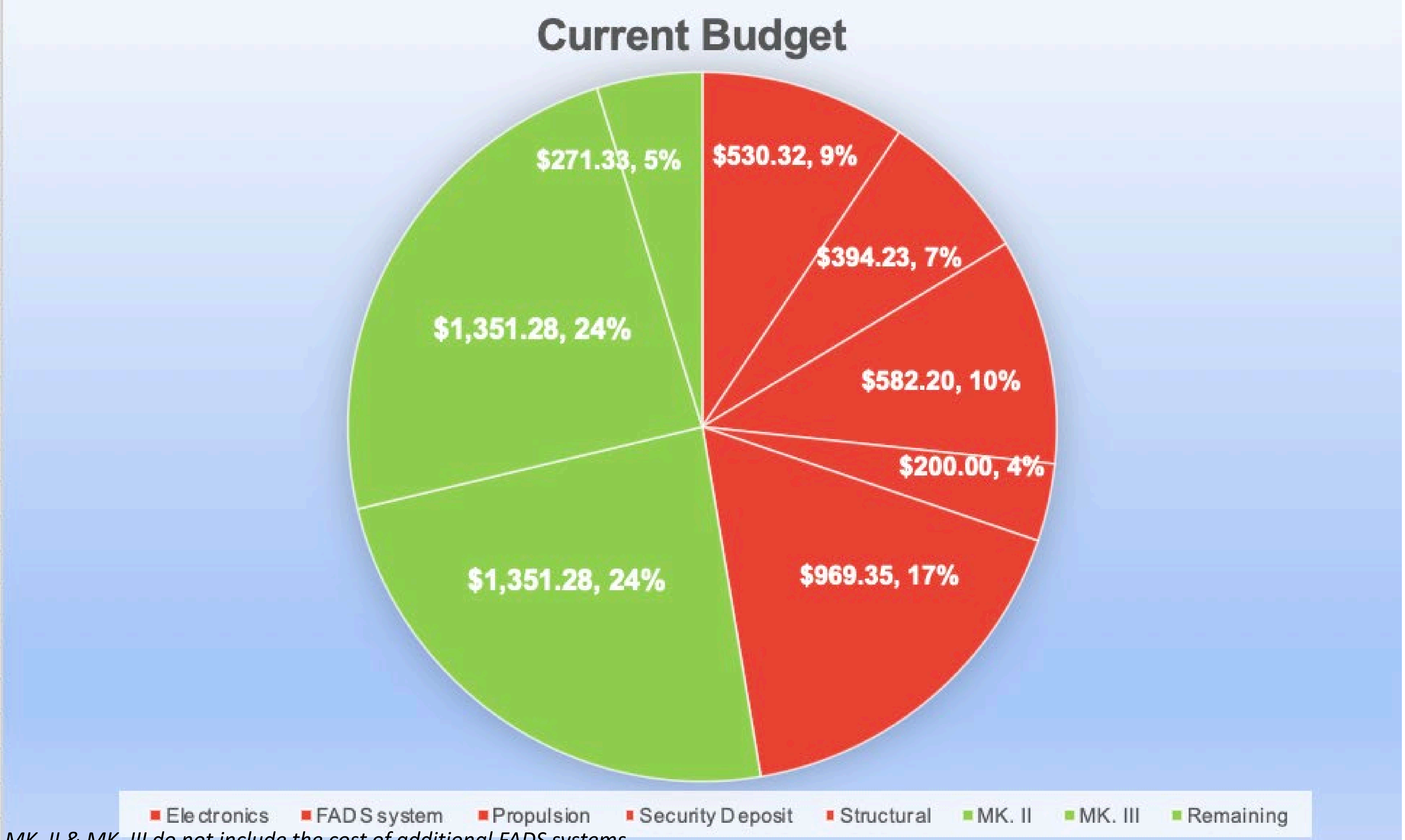
c. Launch: analysis of how each subsystem will need to change

d. Monitor and Control: updates on how each subsystem will need to change/be modified

e. Close cycle: compile scalability study



MK. II & MK. III do not include the cost of additional FADS systems.



MK. II & MK. III do not include the cost of additional FADS systems.