# VORTEX

## Vertically Optimized Research, Testing, & EXploration

# Critical Design Review

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Advisor: Donna Gerren
Project Manager: Bill Chabot

**Team**

| | |
|---|---|
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| Cameron Kratt | Michael Patterson |
| Joseph Rooney | Justin Troche |

# Project Overview

# Mission Statement



In order to expand the capabilities of the IRISS center and TORUS project in gathering meteorological data and understanding the formation of supercell thunderstorms, the VORTEX team will bring Vertical Takeoff and Landing (VTOL) functionality and extended endurance to the RiteWing Drak airframe.

# Mission CONOPS



# Functional Requirements

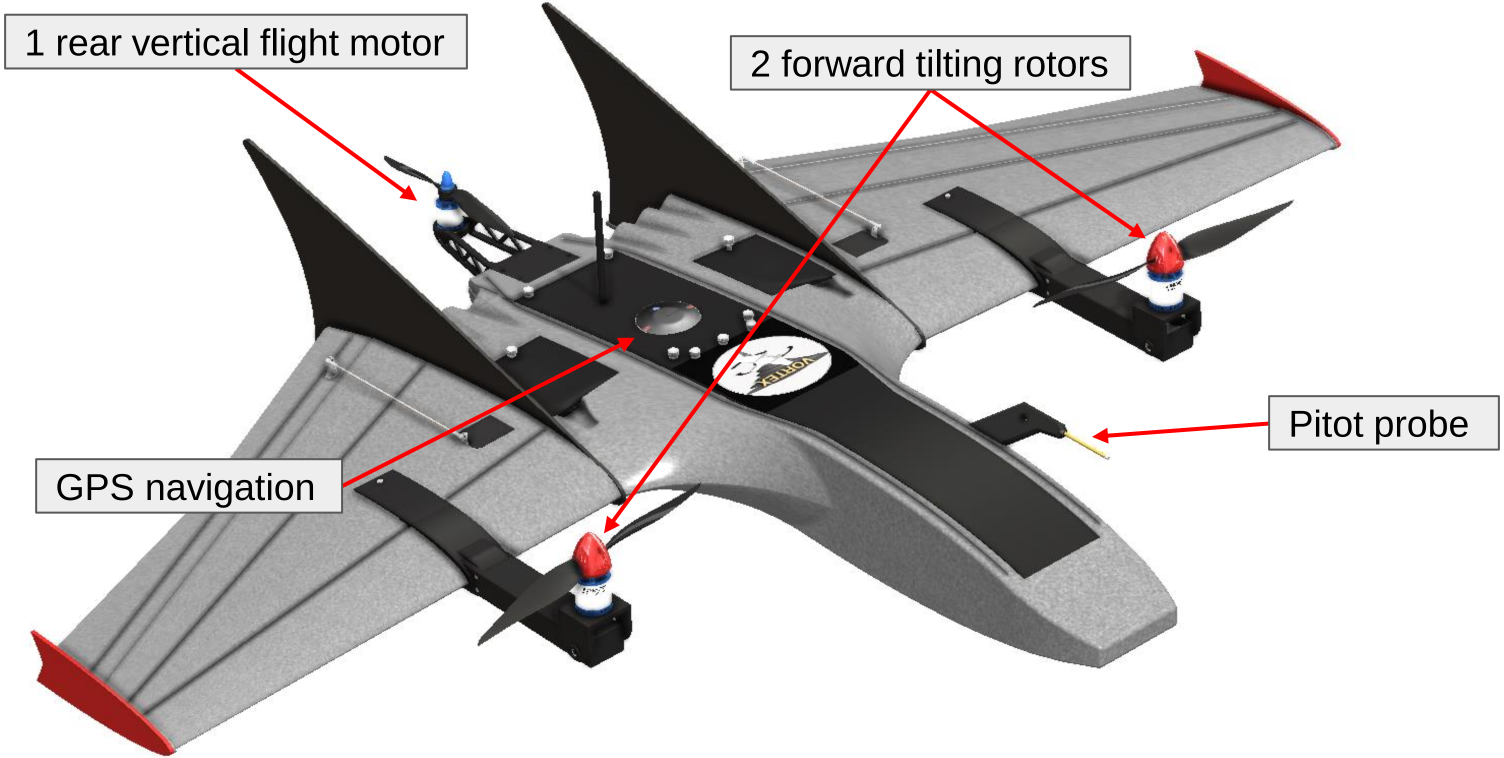


| | |
|---|---|
| **FR1** | The aircraft shall be a VTOL conversion of the COTS Ritewing RC “Drak” airplane kit |
| **FR2** | The aircraft shall have an endurance of 1 hour with 2 takeoffs and landings |
| **FR3** | The aircraft shall be able to autonomously execute all aspects of its mission from first takeoff through final landing |
| **FR4** | The aircraft shall maintain communication with the ground station up to a distance of 2km |
| **FR5** | The aircraft shall be capable of carrying a 0.5kg payload |
| **FR6** | The aircraft shall be capable of taking off from existing RAPCat launch system |
| **FR7** | The airframe, propulsion system, and required mounting hardware shall cost no more than $1000 per aircraft |

# Design Solution

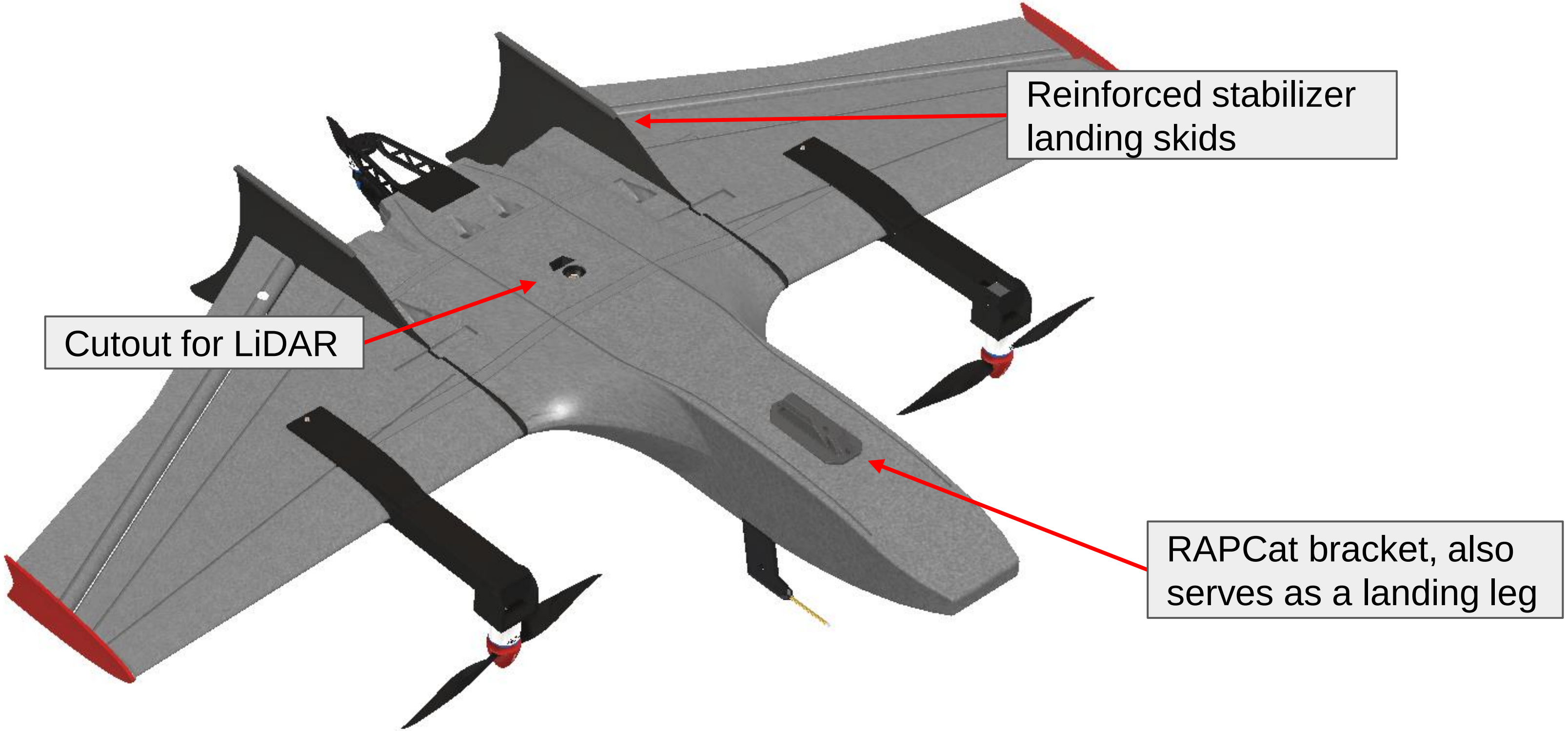
# CAD Overview



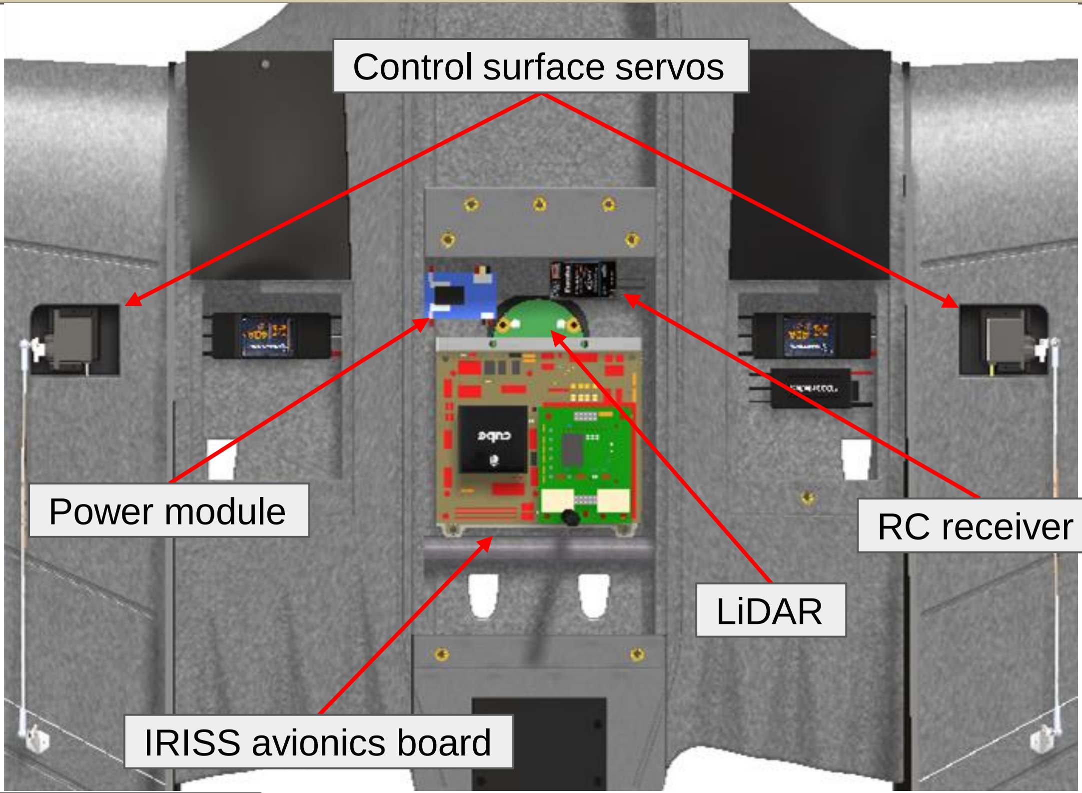


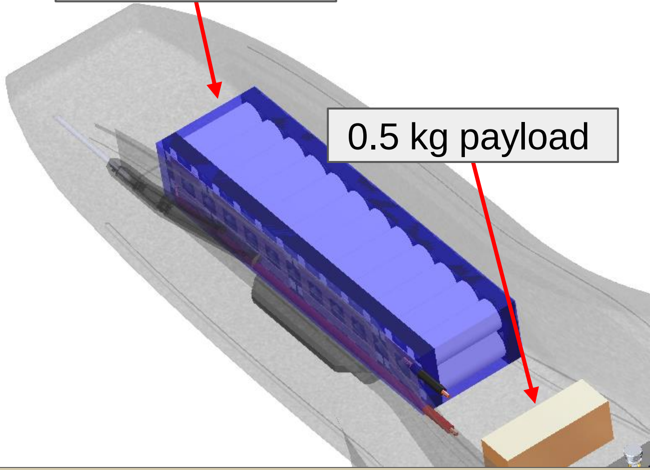
# CAD Overview





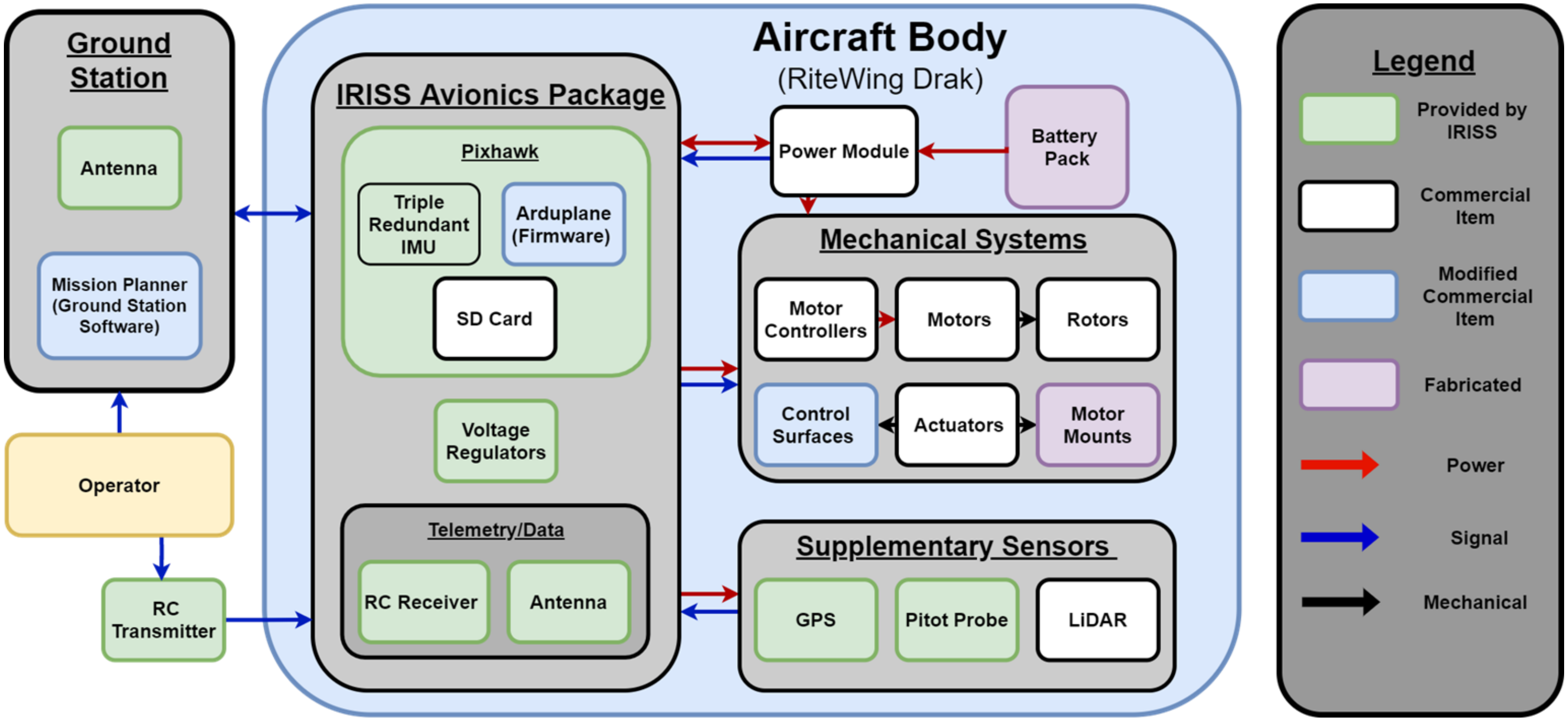
# CAD Overview - Avionics/Power



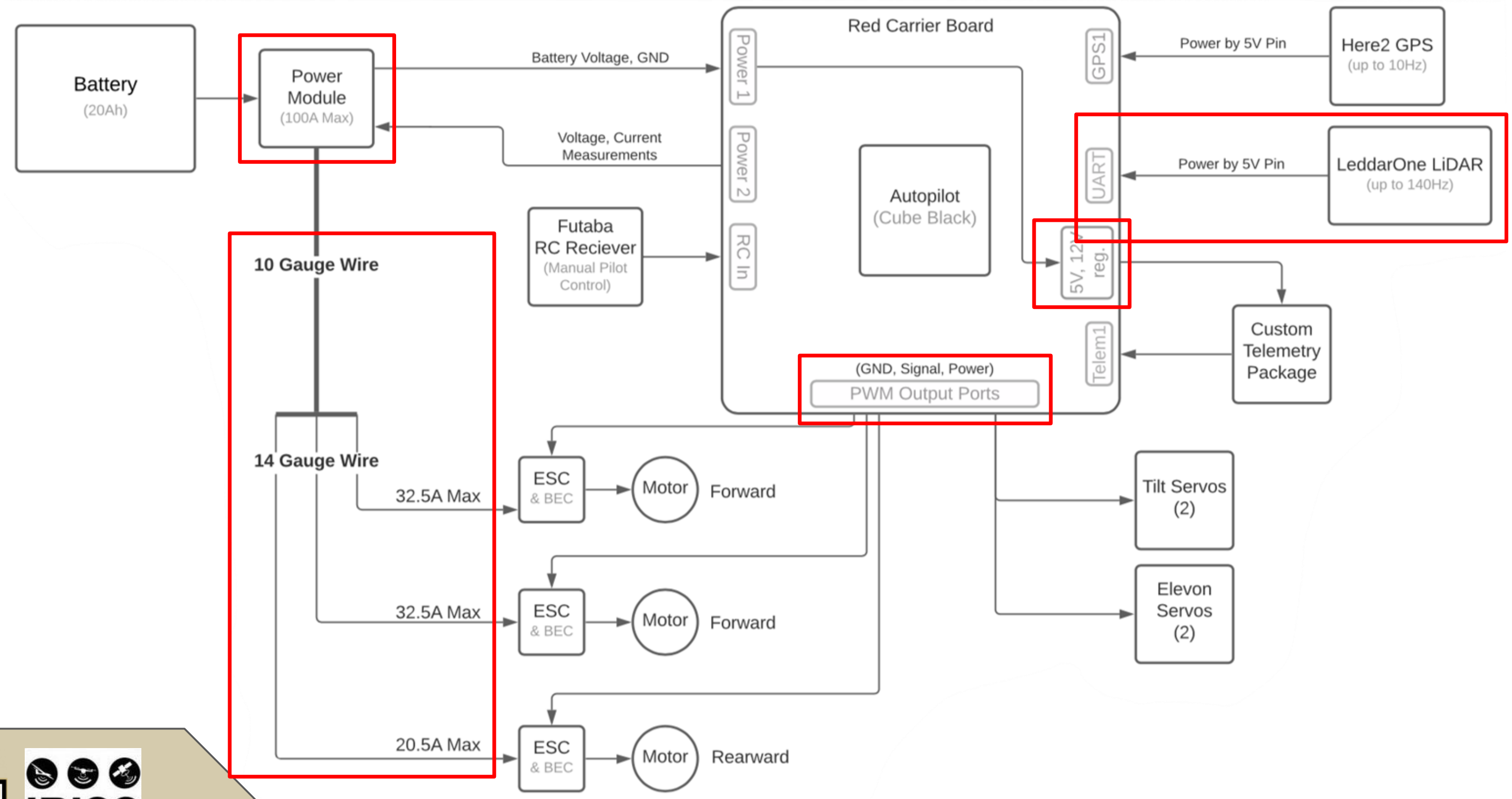
# System Functional Block Diagram





# Avionics: Functional Block Diagram



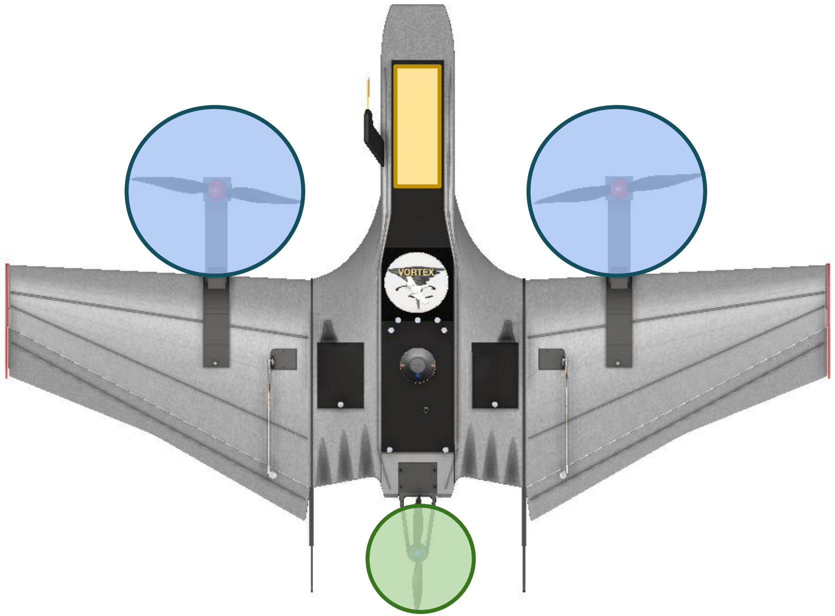


# Endurance Slide Components Overview



| Battery Pack | Forward Components | | |
|---|---|---|---|
| 6 Series<br>4 Parallel<br><br>Molicel 21700 P42A 4200mAh 45A *(cell)* | **ESC**<br>FLYFUN V5 ESC (3S-6S) 40A | **Motor**<br>SunnySky X Series V3 X2820 500KV | **Propeller**<br>aero-naut Cam Carbon blades 13x8 *(diameter x pitch)* |
| | **Rear Components** | | |
| | **ESC**<br>Platinum PRO V4 - 25A (3S-6S) | **Motor**<br>SunnySky X Series V3 X2216 880KV (Short Shaft) | **Propeller**<br>aero-naut Cam Carbon blades 9x7 *(diameter x pitch)* |

## Drive Shaft Breakdown



# Critical Project Elements

# Critical Project Elements



| Element | Justification |
|---|---|
| Vertical Takeoff and Landing **(VTOL)** | Primary deliverable of project. |
| Structure **(STR)** | Structure must withstand forces of takeoff, flight, and landing. |
| Endurance **(END)** | Aircraft must be able to maintain flight for the required duration of 1 hour plus takeoffs and landings. |
| Automation **(AUT)** | Aircraft must autonomously perform mission flight profile as well as controlling takeoff, landing, and transitions. |

# Satisfaction of Design Requirements

# [VTOL] - Critical Project Element: Vertical Takeoff and Landing



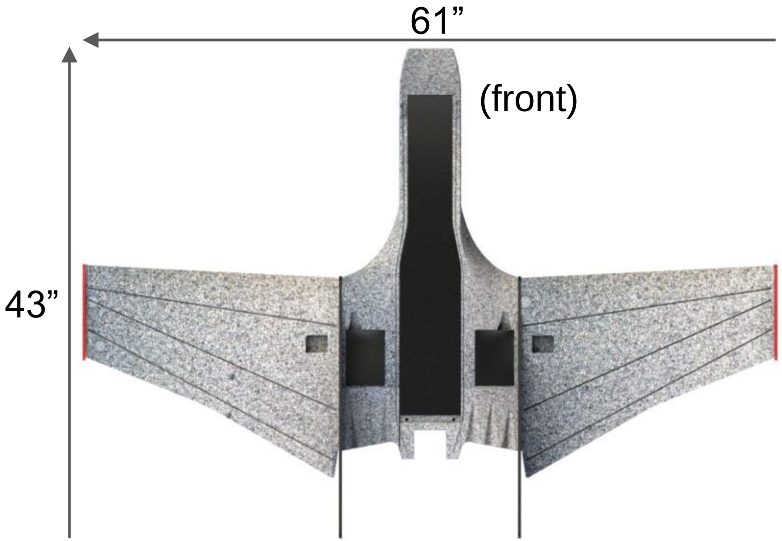
| Requirement | Description |
| --- | --- |
| FR 1 | VTOL Conversion of Drak wing kit |
| DR 1.1 | Maintain steady hover |
| DR 1.3 | Modification of COTS Drak |

Section Order

1. Modification of COTS Drak
2. Hover stability model
3. Thrust during hover

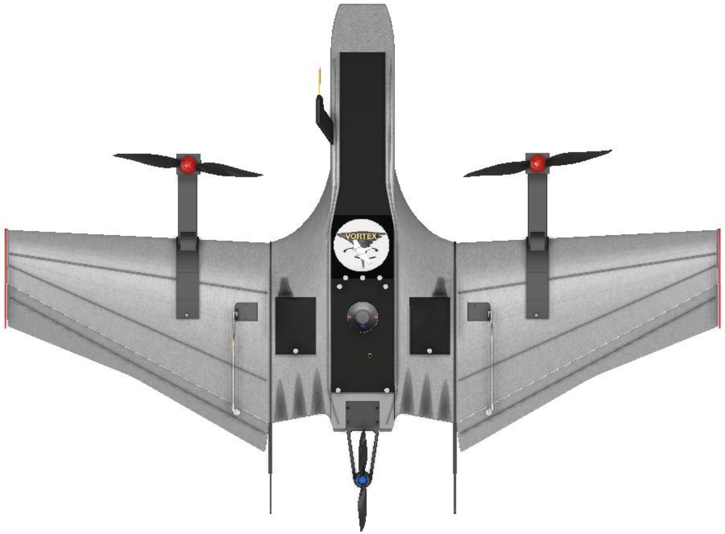
# [VTOL] - Conversion of COTS Drak

**Baseline Drak**




**Flying wing, made for single Pusher design, elevons, and two vert. stabilizers**

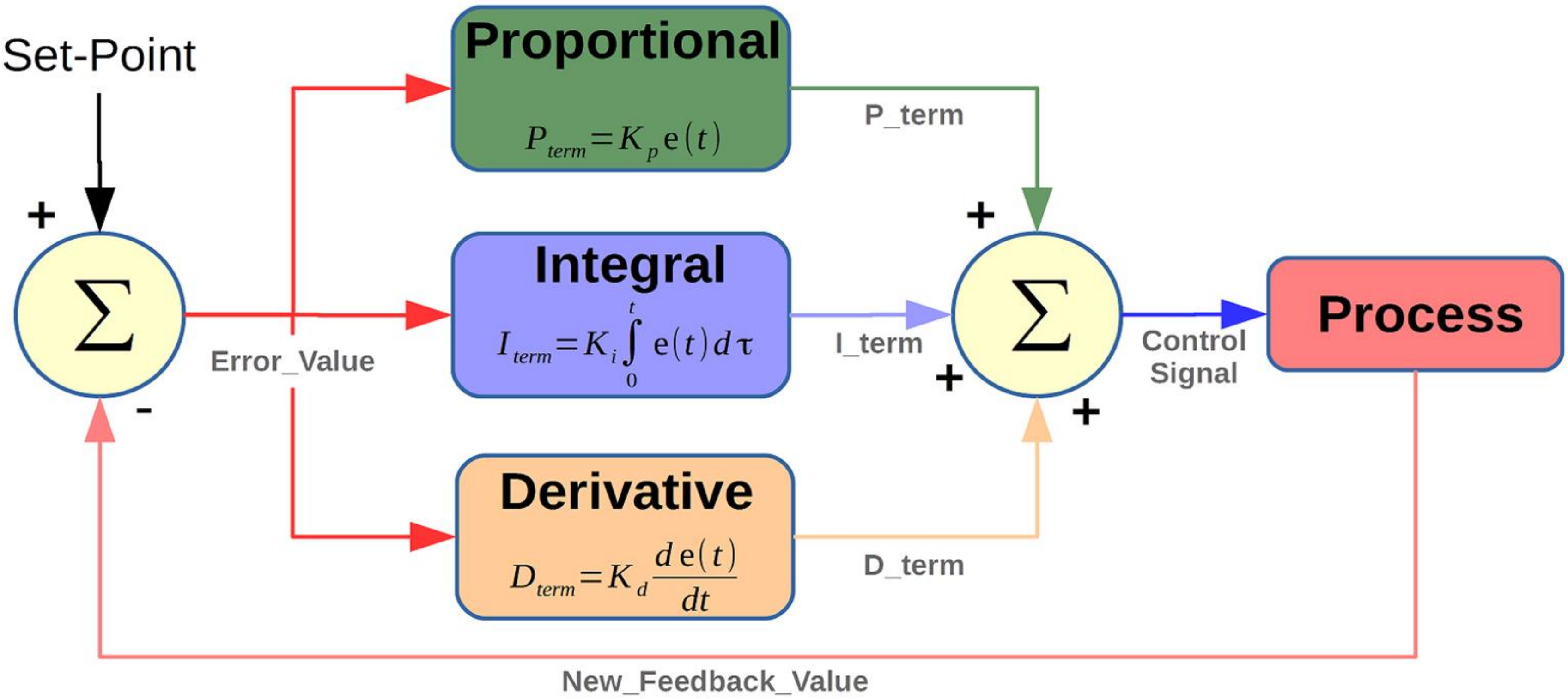
**VTOL Conversion**




**Tri-Motor Design, two front motors tilt.**

# [VTOL] - Hover Stability PID Control Model





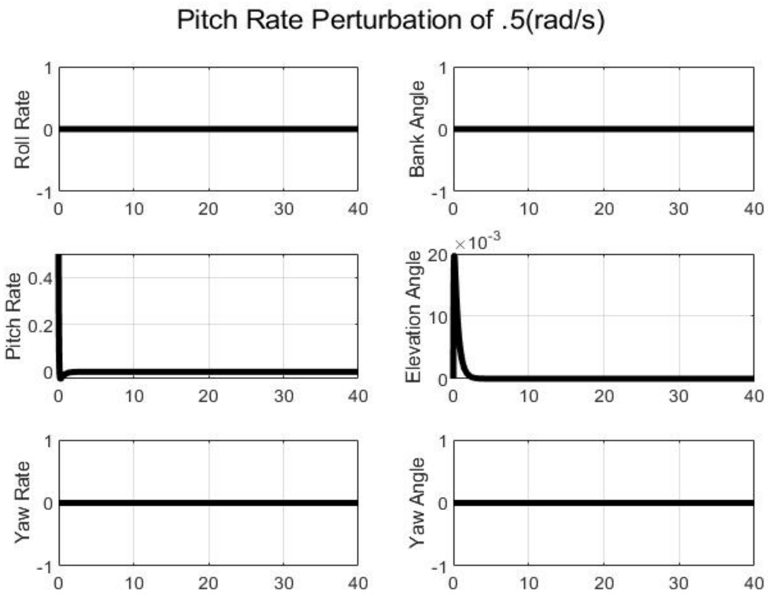
# [VTOL] - Hover Stability Preliminary Gain Determination

- **Hover Stability Model with updated inertia, mass, and motor positions**

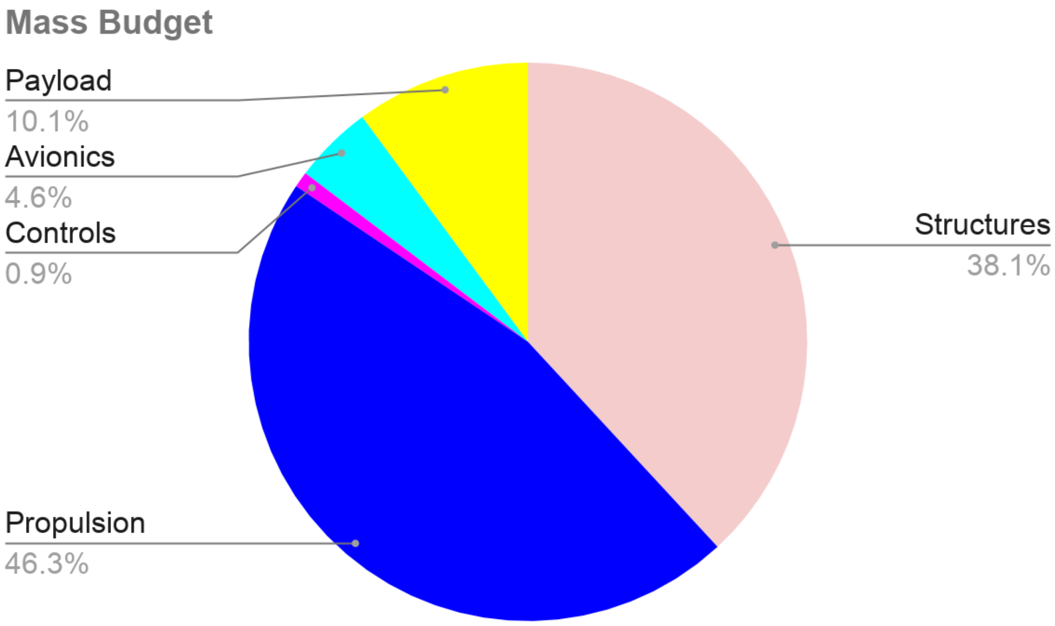
- **Active PD control with recommended ArduPilot values**

- **PD values tuned, Integral Control applied via AutoTune function and QuadCopter Parameters**

- **Results, P=1.8, D=1.2 (Recommended Copter Starting Gains)**



# [VTOL] - Thrust During Hover Mode




**Total Mass: 5167.8 grams, Weight: 50.69N**

## Power during Hover Mode

*Based on a 1.3 Thrust-to-weight ratio*

| | Motors | Expected Individual Thrust | Expected Individual Power |
|---|---|---|---|
| Forward Propulsion | 2 | 27.5N | 545.6W |
| Rear Propulsion | 1 | 10.8N | 219.4W |

| | |
|---|---|
| Max Capable Thrust | **65.8N** |
| Max Capable Power | **1310.6W** |

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# Critical Project Element: Structure

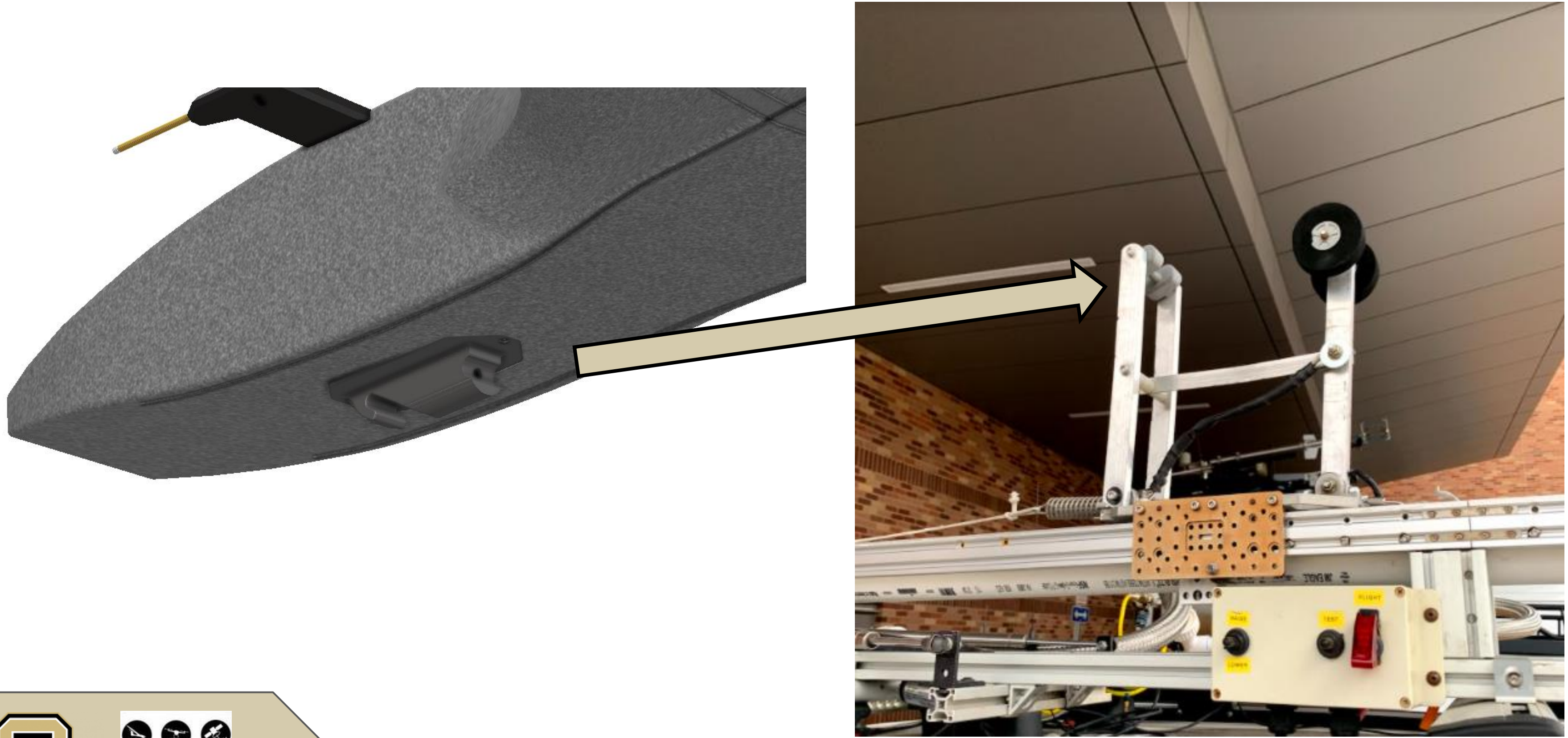
| Requirement | Description |
|---|---|
| FR 6 | RAPCat Compatibility |
| DR 6.2 | Withstand 5G acceleration during RAPCat launch |
| DR 6.5 | Withstand 10G during takeoff and landing operations |

Section Order

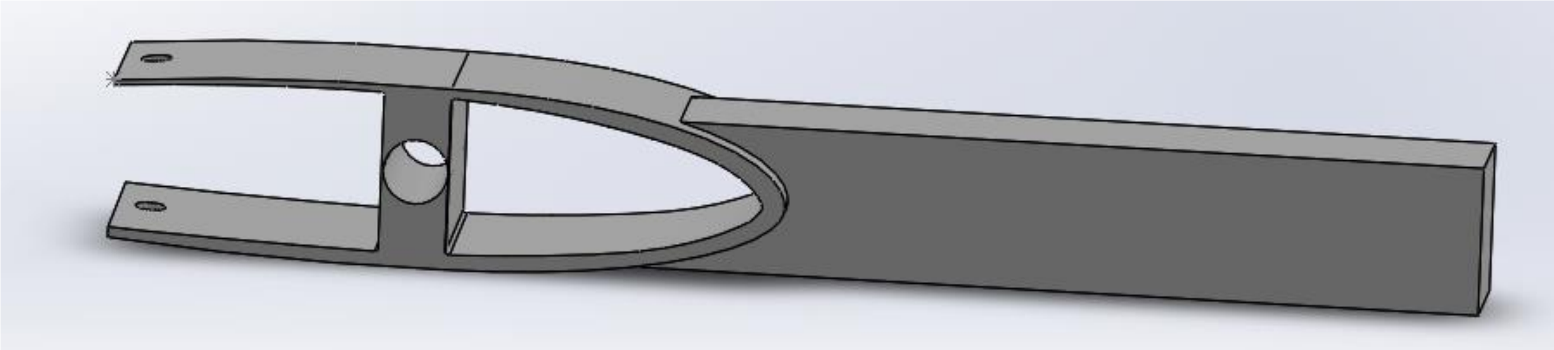
1. RAPCat hook mount
2. Factors of safety of wing motor mount
3. Factors of safety of rear motor mount

# [STR] - RAPCat Compatibility

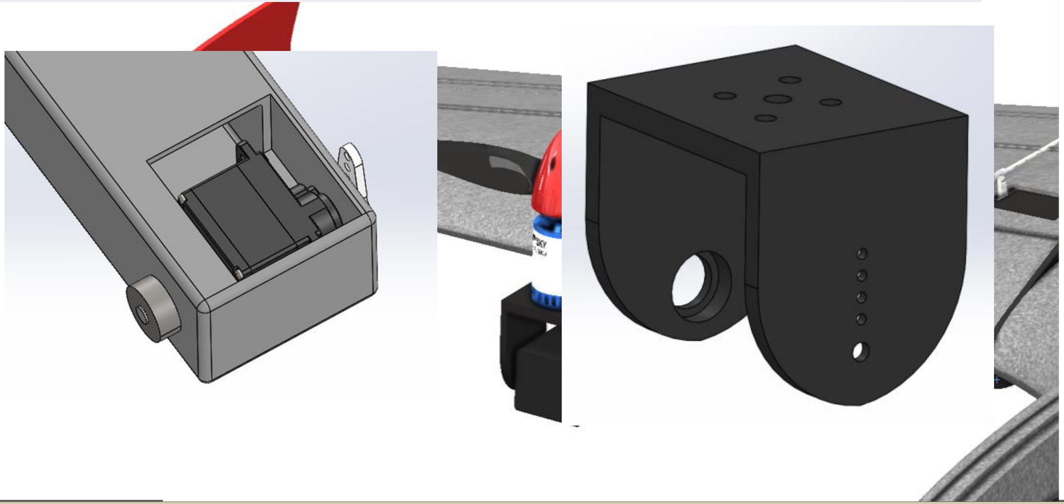




# [STR] - Wing Motor Mount



- Mounting over the wing with a bolt through the wing
- 3D Printed with PETG
- Servo mounted into the end of the arm, wires routed through a cavity in the arm.

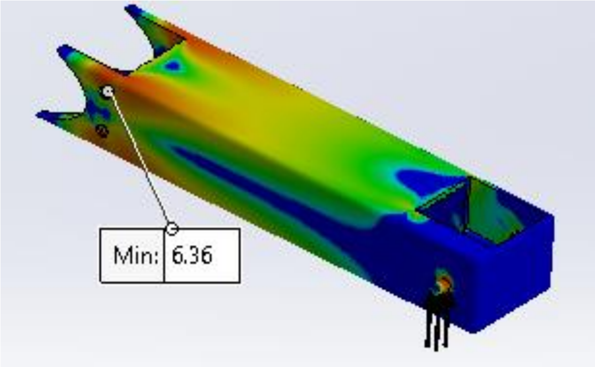


# [STR] - Rear Motor Mount

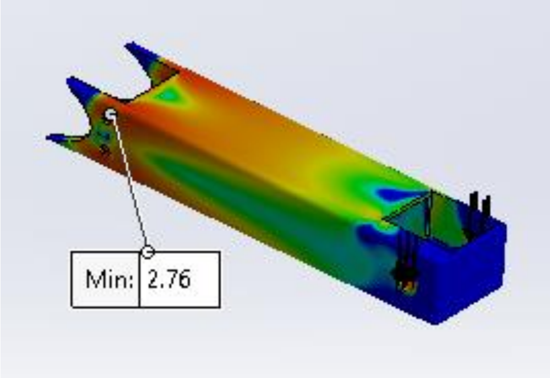

- 3D Printed with PETG
- Mounts to existing location on rear of the fuselage

# [STR] - Motor Arm, Various Load Cases - Factor of Safety

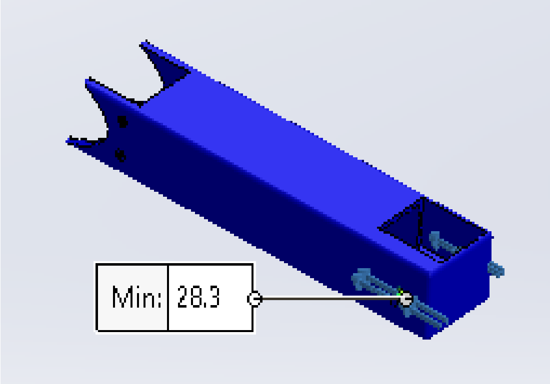




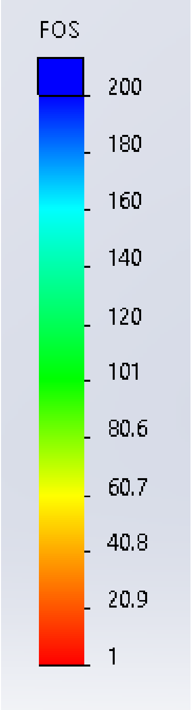

Takeoff



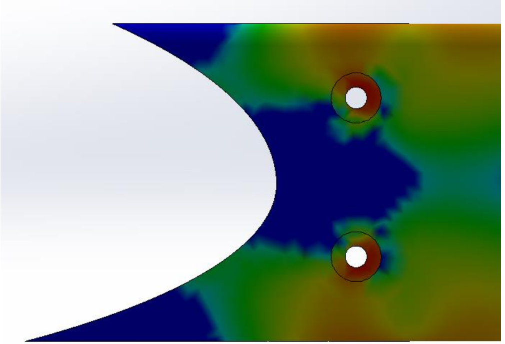

10G Landing

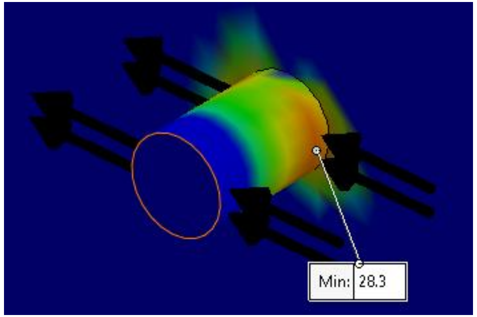



RAPCat Launch




Mesh size: 1.9mm
Standard, linear elastic
Material properties from the PETG manufacturer





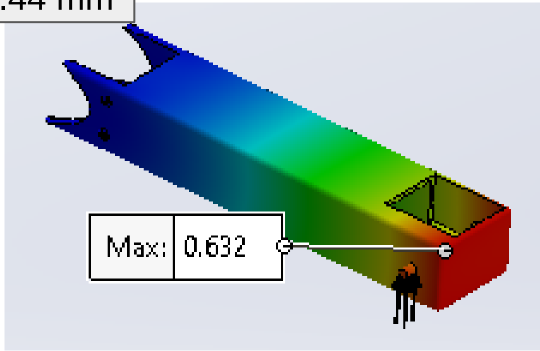
# FEA Analysis Accuracy Assessment



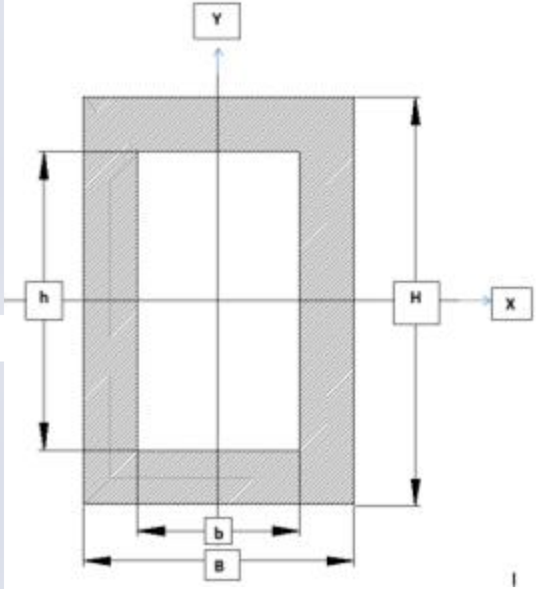
Takeoff load case, CantiLever Beam


$$\delta_{max} = \frac{PL^3}{3EI}$$

Tip def = .44 mm

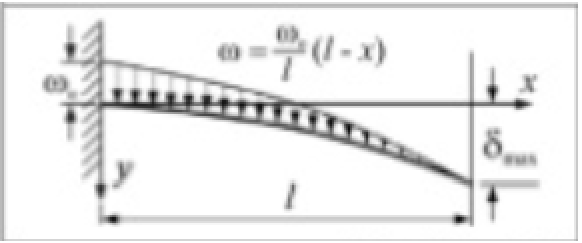



Model as hollow square

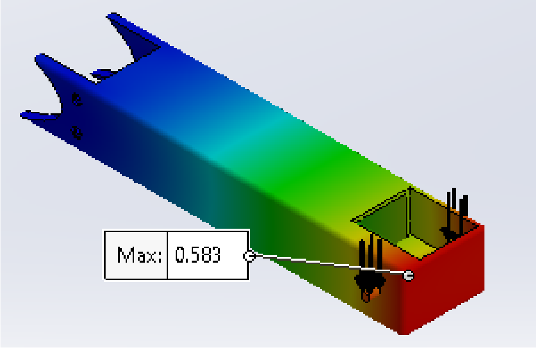



10g loading case

Tip def = .45 mm




$$\delta_{max} = \frac{\omega_0 l^4}{30EI}$$

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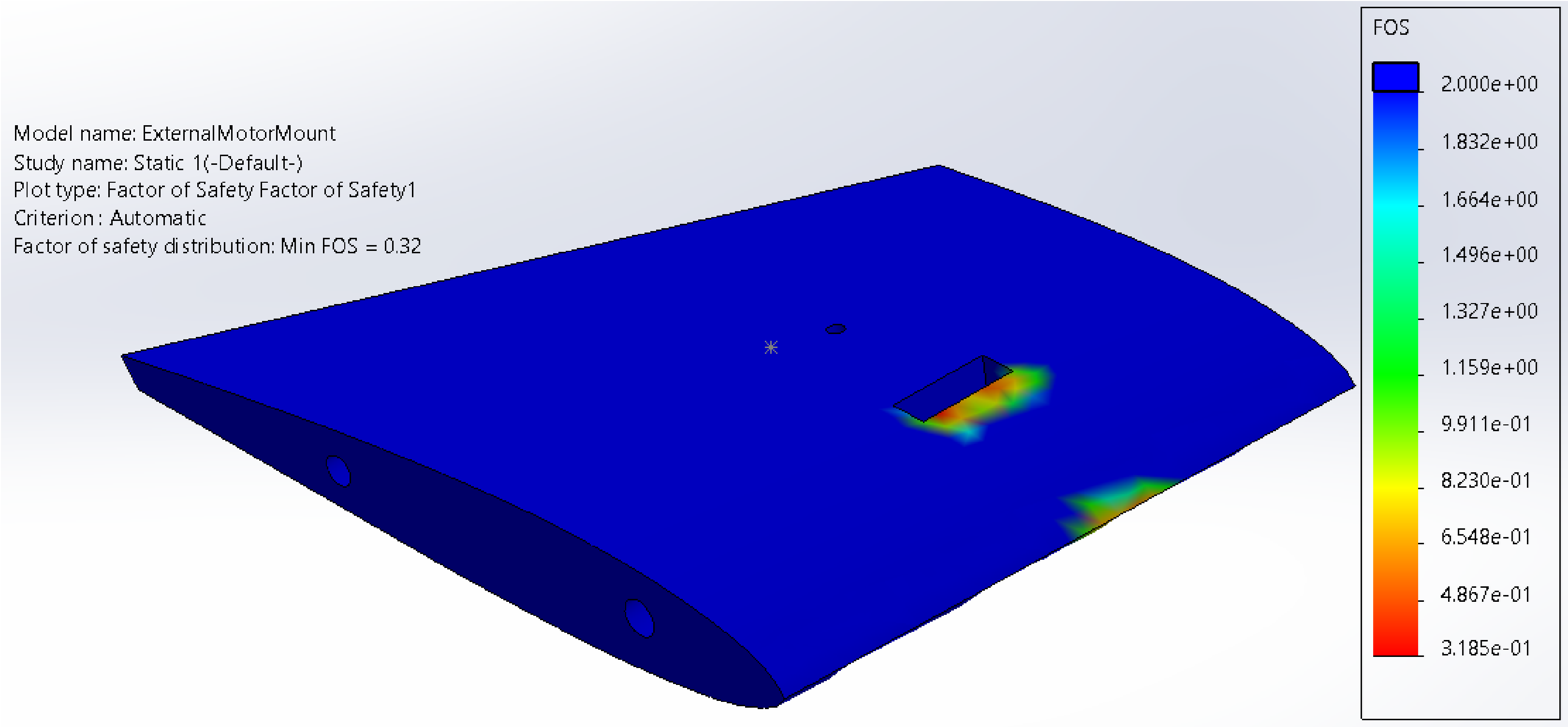
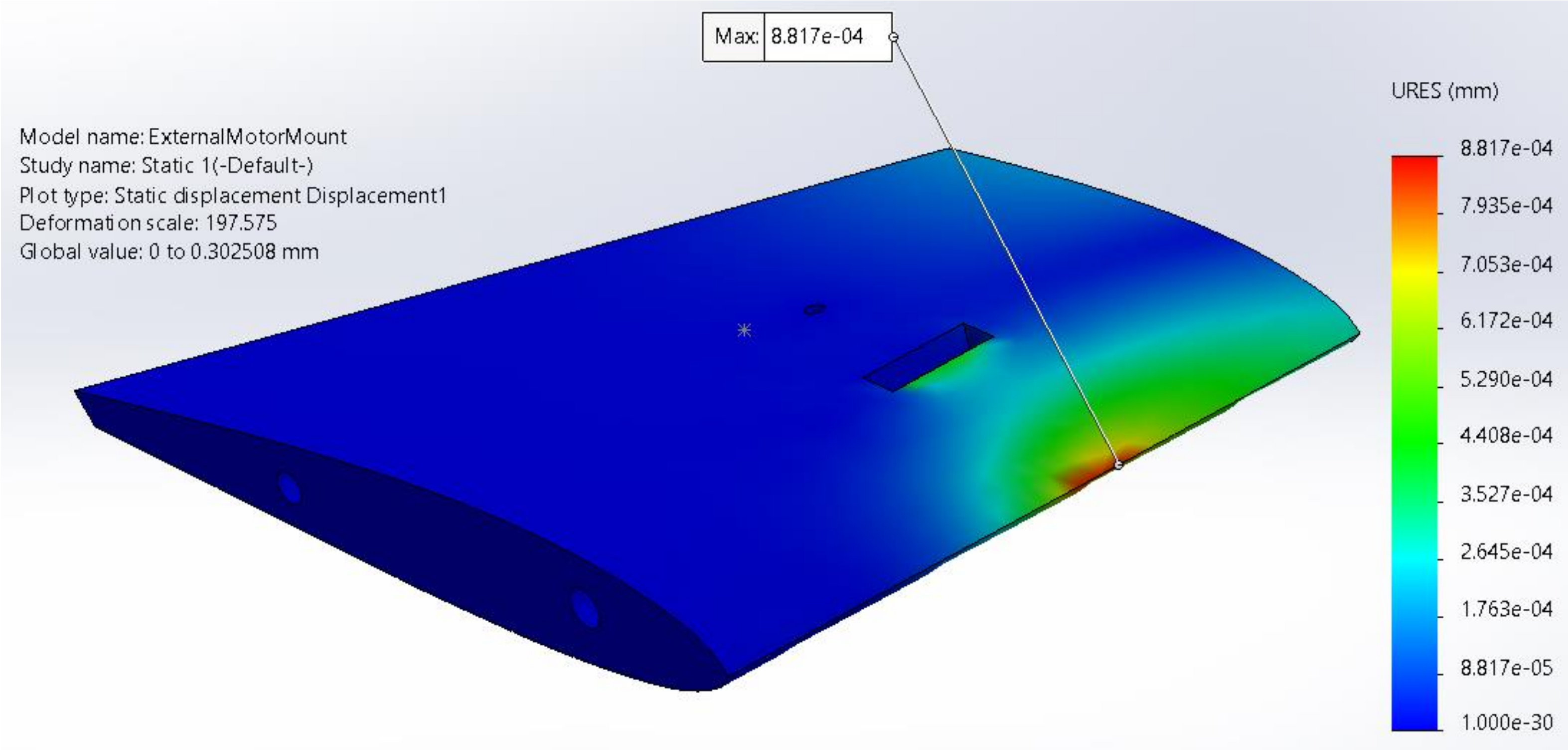
# [STR] - Wing Mount, 10g Force - Factor of Safety





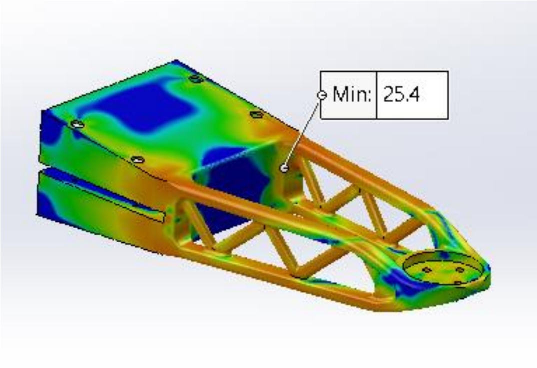
# [STR] - Wing Mount, 10g Force - Displacement



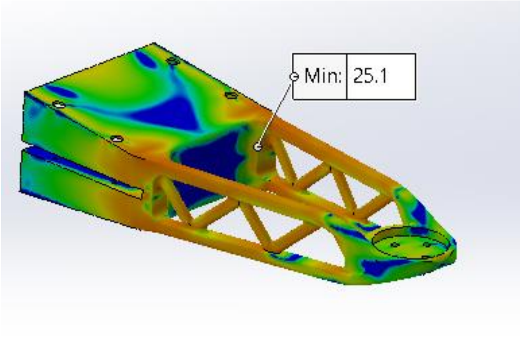


# [STR] - Rear Motor, Takeoff - Factor of Safety

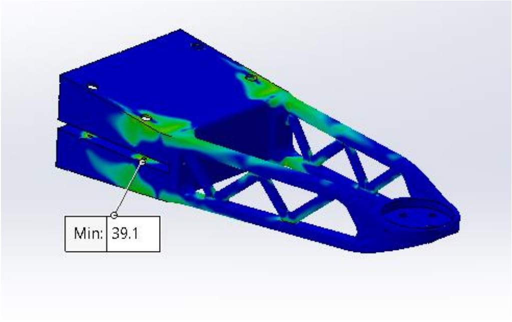




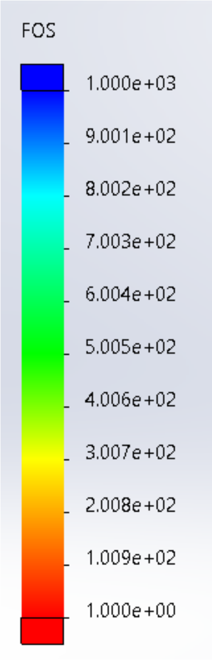

Take-off

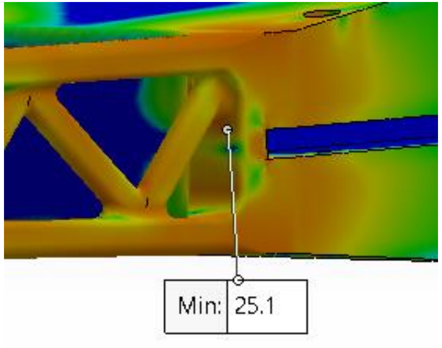


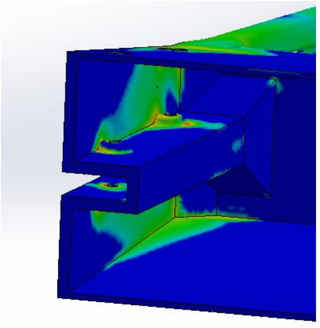

10G Landing




RAPCat Launch



Mesh size: 1.5 mm
Curvature based mesh
Material properties from the PETG manufacturer

# Critical Project Element: Endurance



| Requirement | Description |
| --- | --- |
| FR 2 | 1 Hour endurance, 2 Takeoffs and Landings |
| DR 2.2 | 1 Hour flight |
| DR 2.3 | 2 Takeoffs & Landings |
| DR 2.6 | Complete full mission without changing batteries |

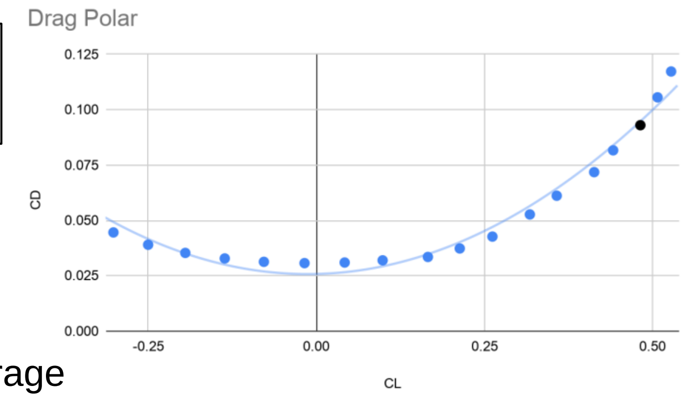
Section Order

1. Aerodynamic results
2. Endurance program model
3. Propulsion components modeled performance
4. Battery pack construction

# [END] - CFD Simulation

SolidWorks Flow Simulation
- RANS model
- ~1.3 million cells

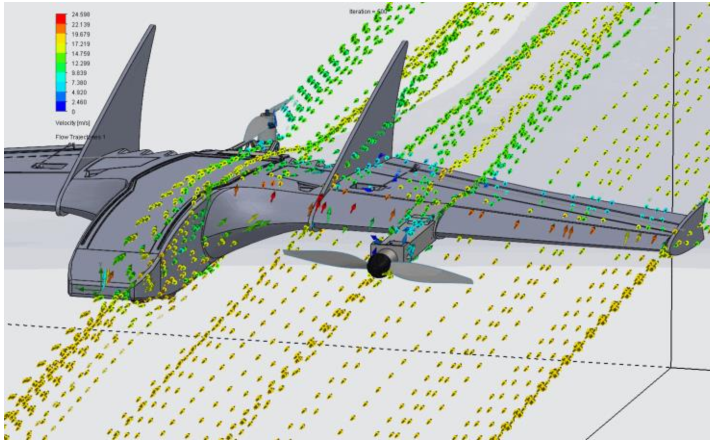
**Drag Polar**
$C_D = 0.029 + 0.220(C_L-(-0.0149))^2$

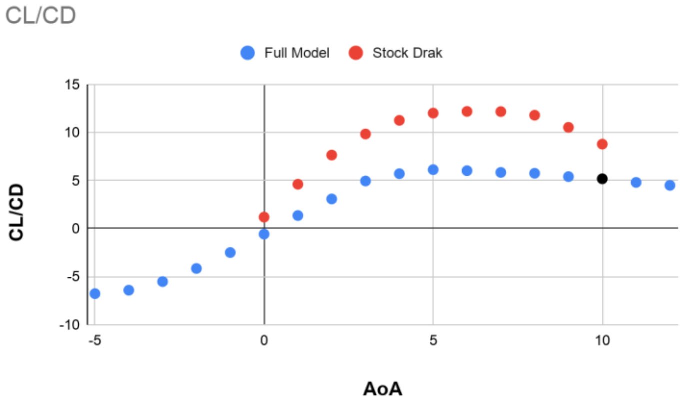



**Sources for verification**

Physical Data (different model)
- Lift Slope: low by 22%
- Drag: <5% error (average)
  - <13% max

Stock Drak CFD (from PDR)
- Lift slope: low by 25%
- Drag: 50% higher on average





# [END] - Aerodynamics: Cruise Configuration

Design parameters:

- Mass: 5.17 kg
- AoA: ~10 deg
  - Likely higher than actual
  - Expecting closer to 7 deg

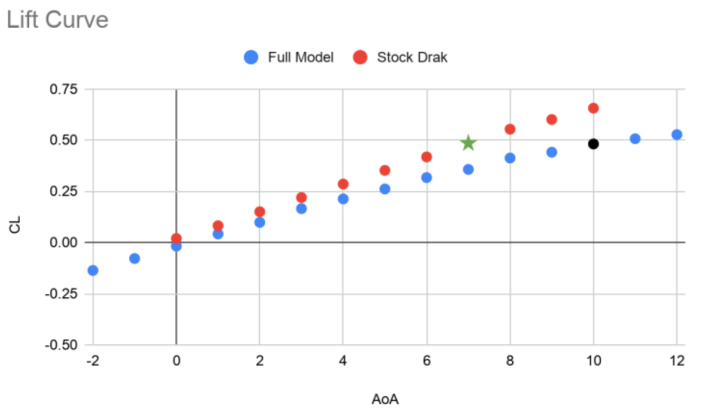
Max $C_L/C_D$: 6.12 at AoA = 5 deg

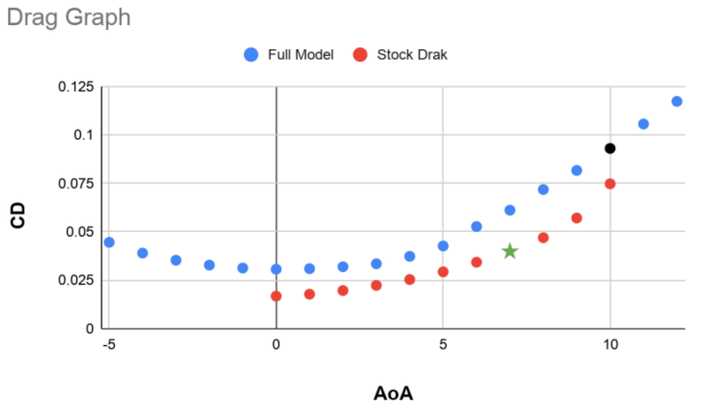
- 12 at AoA = 6 deg for stock Drak

At cruise AoA (10 deg):

- Elevon Deflection: ~15 deg
- Lift: 50.2 N
- Drag: 9.7 N (4.1 N based on stock Drak)

Simulations with a more refined mesh are in progress now

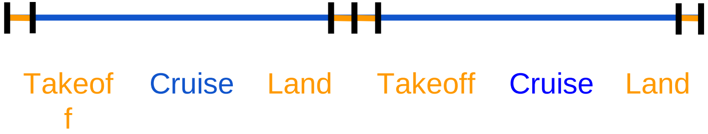


# [END] - Matlab Modeling GUI

## Flight mission profile

*60 minutes*



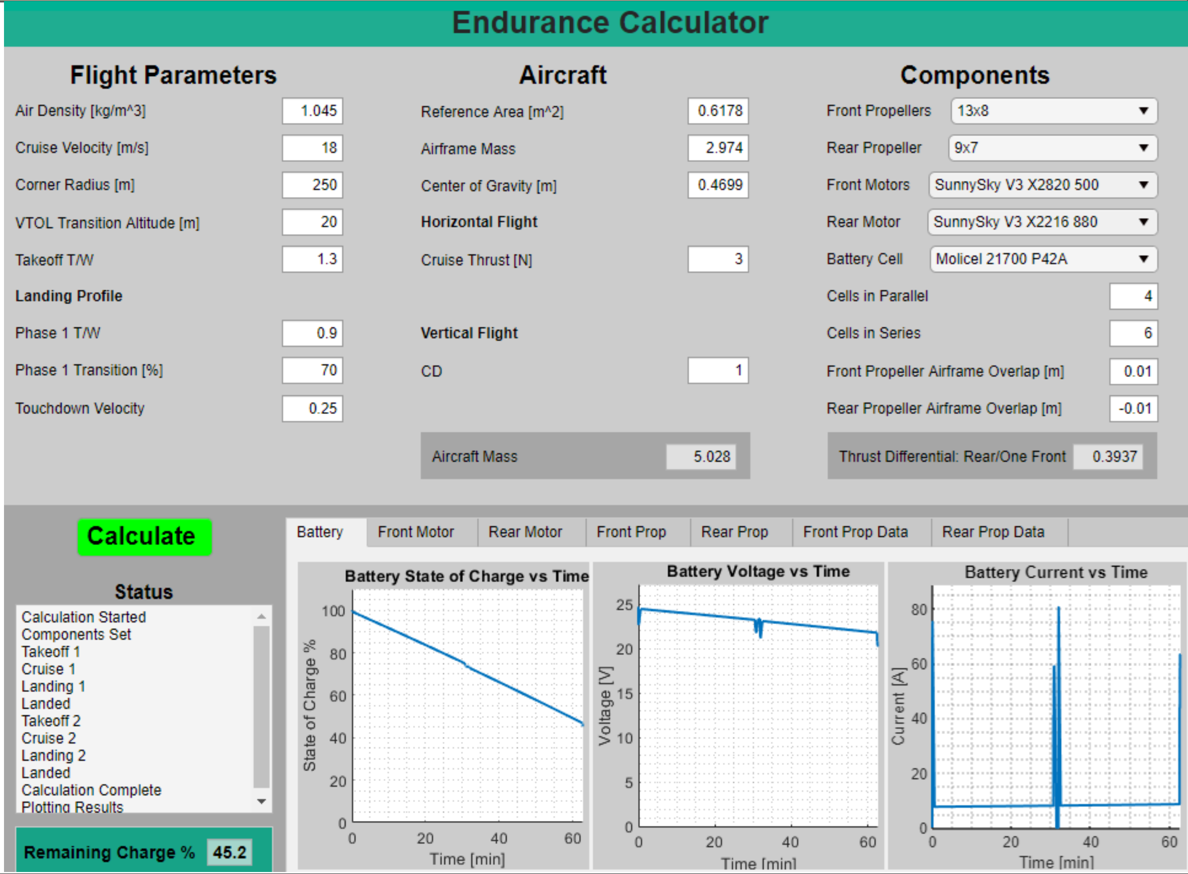

Vertical Flight ■ Cruise Flight ■

## Inputs

- ➢ Flight Parameters
- ➢ Aircraft Variables
- ➢ Components (Spec archive: 40 propellers, 47 motors, 5 batteries)

## Outputs

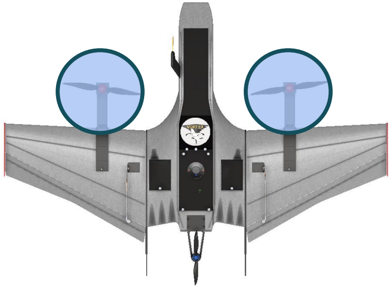
- ➢ Corresponding flight mission plots



# [END] - Front Propeller Performance

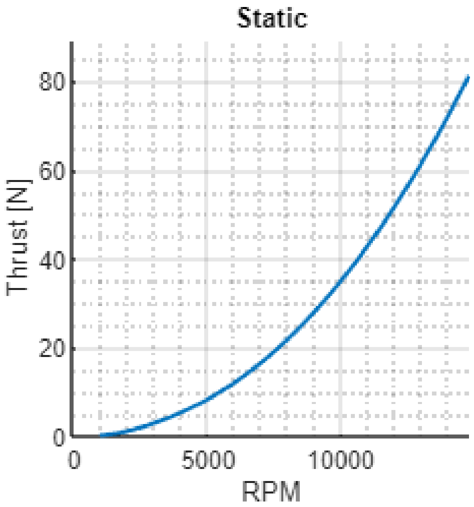


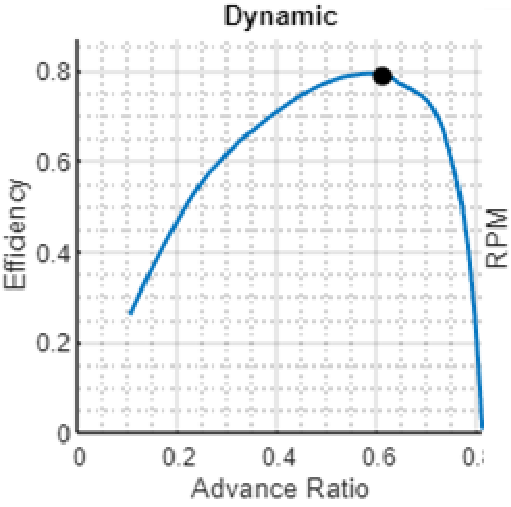
| Front Components | |
|---|---|
| ESC | V5 40A (3S-6S) |
| Motor | SunnySky V3 X2820 500KV |
| **Prop** | **Aero-naut Cam Carbon blades 13x8** |

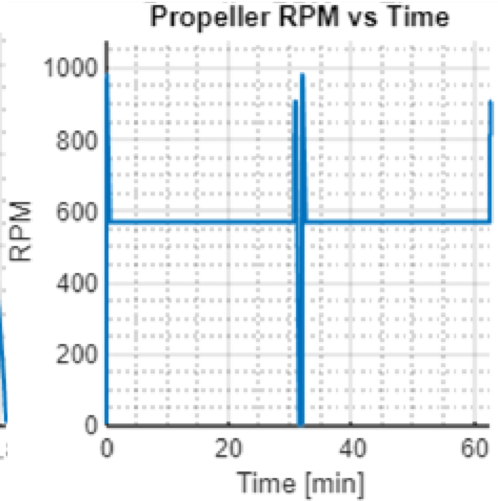


## Flight mission modeled performance

| | Target Vertical flight thrust | Target RPM | Max expected Torque |
|---|---|---|---|
| Vertical flight | 27.5N | 1041.7 | 0.58Nm |
| Cruise flight | 3N | 566.8 | 0.13Nm |



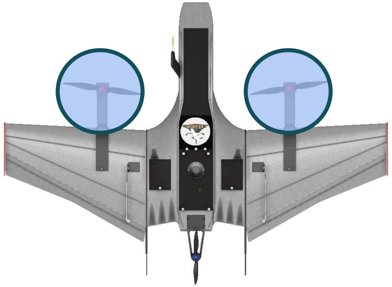



# [END] - Front Motor Performance

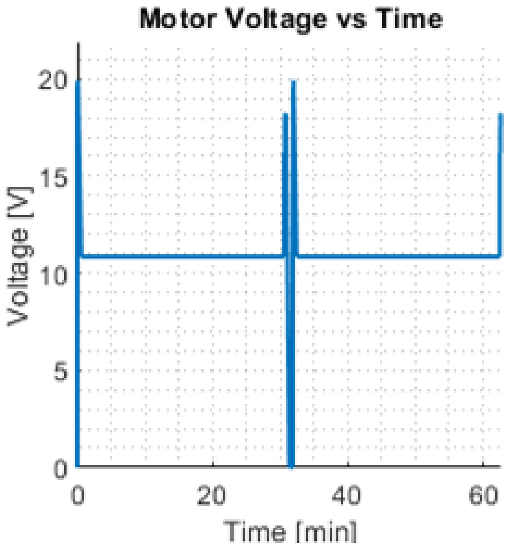


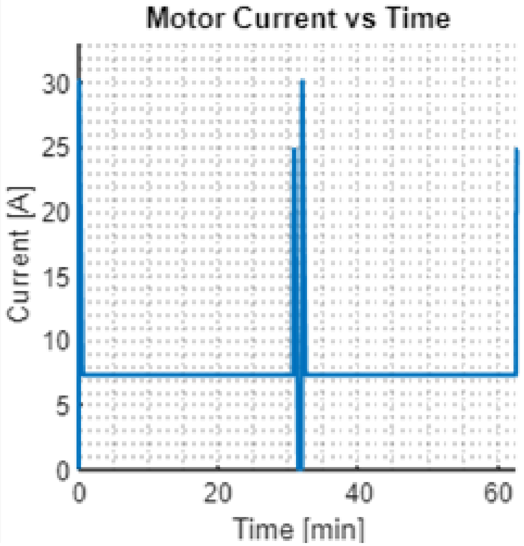
| Front Components | |
|---|---|
| ESC | V5 40A (3S-6S) |
| **Motor** | **SunnySky V3 X2820 500KV** |
| Prop | Aero-naut Cam Carbon blades 13x8 |

## Flight mission modeled performance

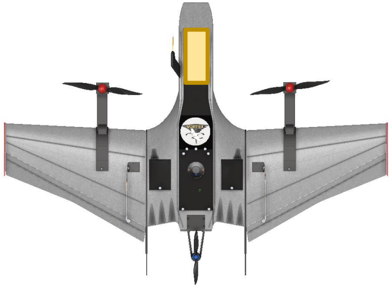
| Max Expected Voltage Input | Max Individual Motor Expected Current Draw | Max Expected Average Power |
|---|---|---|
| 20.2V | 30.8A | 623.0W |



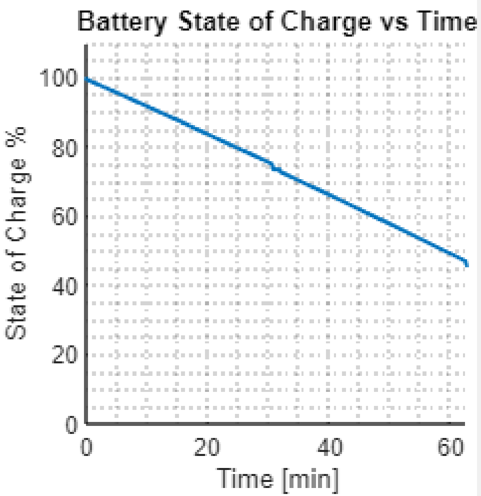
# [END] - Battery Pack Performance

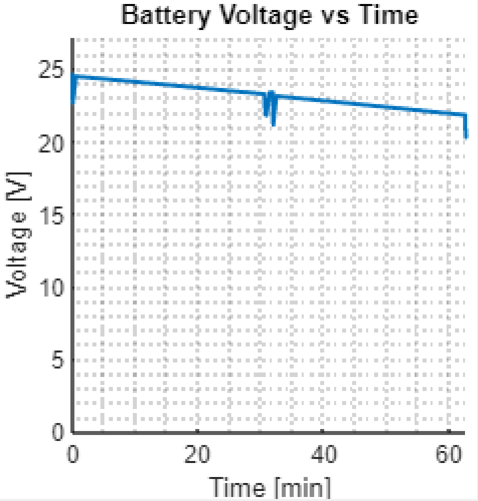
| Battery Pack | |
|---|---|
| Series | 6 cells |
| Parallel | 4 cells |
| Cell | Molicel 21700 4200mAh 45A |

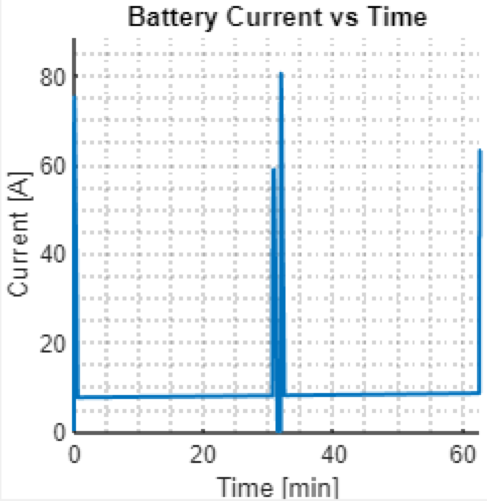


**Flight mission modeled performance**

| Battery Pack Capacity | Charged Voltage | Maximum Possible Current Draw | Total Weight |
|---|---|---|---|
| 16Ah | 24-25V | ~160A (80A used for takeoff) | ~1670g (3.68lb) |



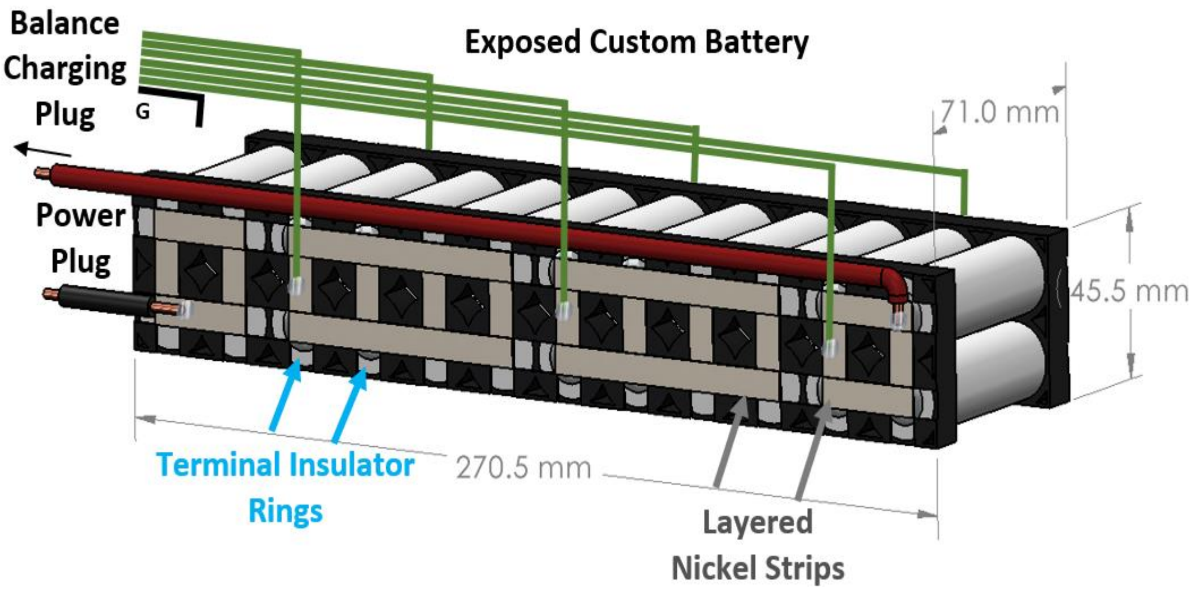




Remaining Charge **45.2%**

# [END] - Battery Construction



| Hazard | Mitigation |
|---|---|
| Mechanical abuse | Rigid frame spacers And heat shrink protection |
| Short Circuit | Protective terminal insulator rings and heat shrink over entire pack |
| Over-charge | Balanced charging and voltage monitoring |
| Overheating | Cell separation spacers and current regulation |




*Will be covered in Kapton tape and heat shrink

# Critical Project Element: Automation



| Requirement | Description |
|---|---|
| FR 3 | Autonomous mission execution |
| DR 3.2 | Flight controller commands propulsion system and flight control surfaces |
| DR 3.4 | Vertical accuracy of <10cm is desired in takeoff and landing when below GPS altitude of 5m |
| DR 3.5 | Complete mission profile without pilot input |

Section Order

1. Control Firmware/Hardware
2. Configuration and Parent Software
3. Mission Simulation
4. Processing Power and Rangefinder Integration
5. Starting Gains, and Fixed Wing Stability

# [AUT] - Control Firmware/Hardware

DR 3.5, 3.2, FR 3


## PixHawk Capabilities

- 14 PWM / Servo outputs
- 256 KB Ram
- Servo rail high-power (max. 10V) and high-current (10A+) ready

## ArduPilot Capabilities

- Multiple methods for navigation and active control
  - L1, Stabilize, EKF, Navigation Control
- Supports VTOL configurations and tri-copter configurations
- Gain tuning, allows for tight control
  - PID for all states
- Supports simulations and telemetry
  - Mission Planner

# [AUT] - Relevant Quadplane and Rangefinder Parameters



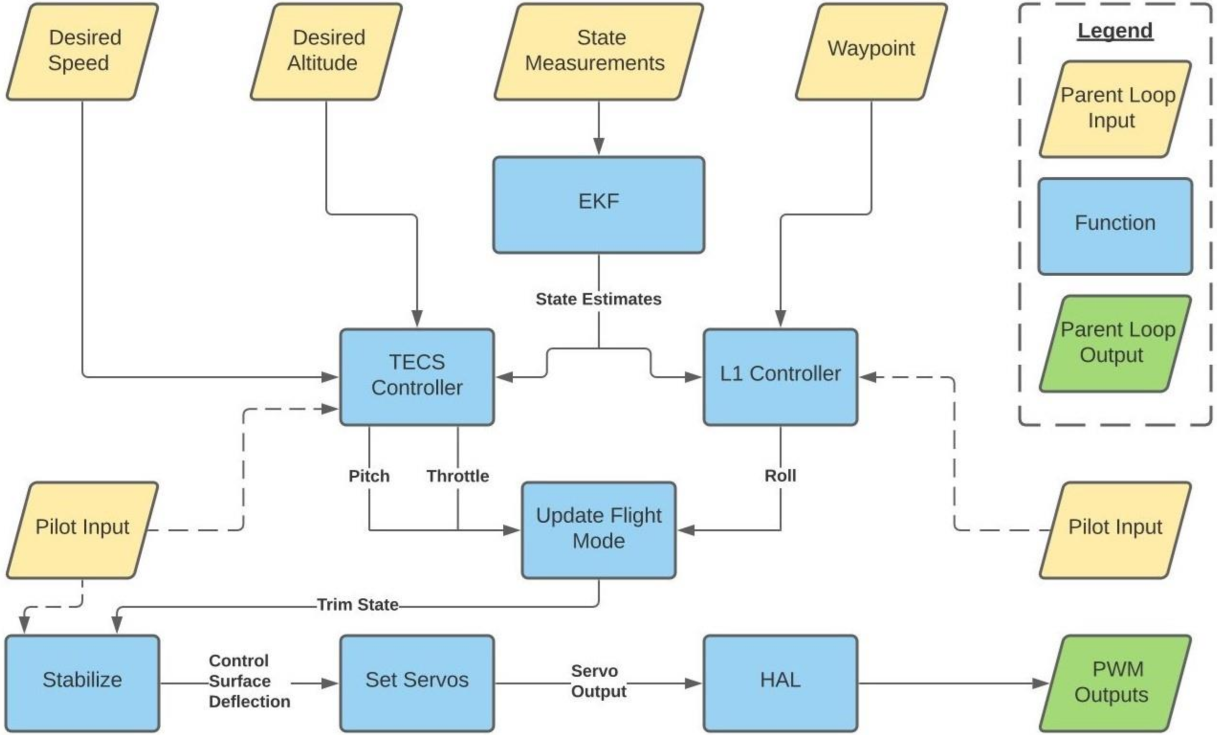
| Quadplane Parameters | | |
|---|---|---|
| Q_ENABLE | 1 | Enable Quadplane Capabilites |
| Q_FRAME_TYPE.Q_FRAME_CLASS | 7 | Relates to tricopter frame |
| Q_FRAME_CLASS | 7 | Tri Copter CLass |
| Q_TILT_MASK | 3 | Bitmask of tiltable motors |
| Q_TILT_TYPE | 2 | Left and Right motors move independently |
| Q_TILT_MAX | 45 | Angle at which motors are held until desired fixed wing airspeed is met |
| Q_TILT_RATE_UP | 15 | Rate at which servo tilts up, degrees per second |
| Q_TILT_RATE_DN | 15 | Rate at which servo tilts down, degrees per second |
| Q_TILT_YAW_ANGLE | 30 | Angle past 90 degrees that the servos can go to cancel inherent yaw moment |
| Q_THR_MIN_PWM | 1000 | Minimum pwm of quad motors, set to what ESCs expect |
| Q_THR_MAX_PWM | 2000 | Minimum pwm of quad motors, set to what ESCs expect |

| Rangefinder Parameters | | |
|---|---|---|
| SERIAL4_PROTOCOL | 9 | 9 for LiDAR |
| SERIAL4_BAUD | 115 | Baud rate of 115200 |
| RNGFND1_TYPE | 12 | 12 for LeddarOne |
| RNGFND1_SCALING | 1 | Scaling factor between rangefinder reading and distance |
| RNGFND1_MIN_CM | 5 | Accuracy (cm) |
| RNGFND1_MAX_CM | 4000 | The distance in cm the rangefinder can reliably read. Rangefinder will be used until range data exceeds this parameter |

DR 3.2, FR 3

# [AUT] - Ardupilot Parent Loop

DR 3.5, 3.2, FR 3



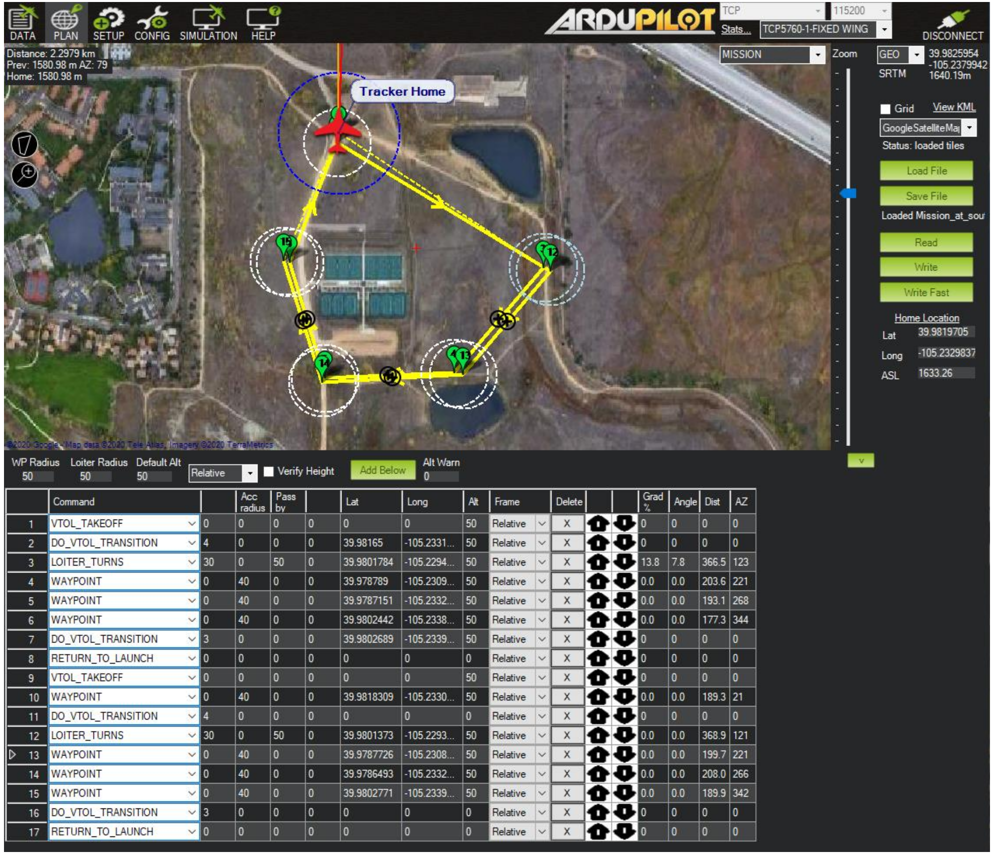
# [AUT] - Mission Planner Setup and Simulation



FR 3, DR 3.5

- The team prepared missions in Mission Planner
  - Takeoff and hover in AERO backyard
  - Full mission profile with 2 takeoffs and landings

- These missions were simulated using SITL
  - Used RAAVEN parameters with quadplane modifications

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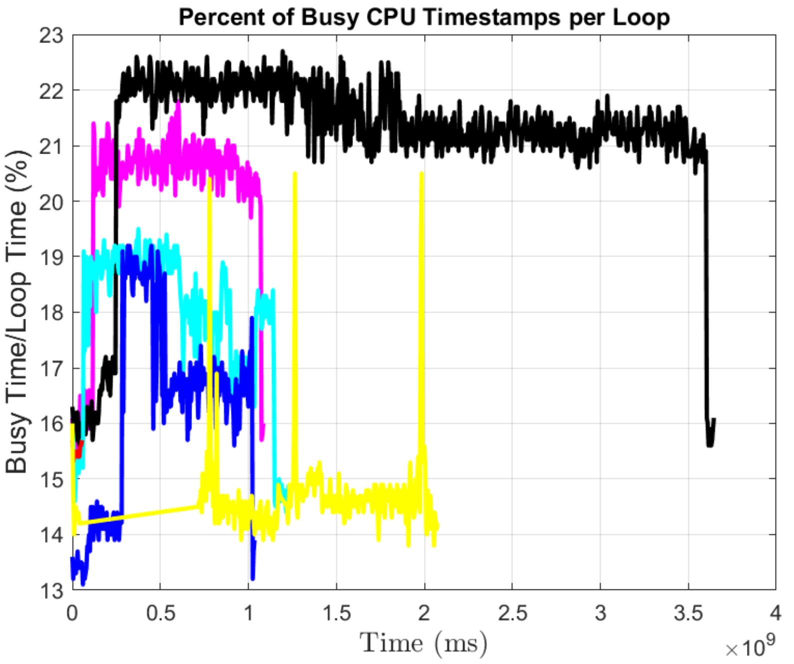
# [AUT] - Total Pixhawk CPU Load



- Will the additional lidar overload the flight controller?
- Processor data from a previous IRISS flights
  - Extra hardware:
    - LightWare Lidar at 20Hz
    - 2 IR Sensors
    - Multi-Hole Probe
    - 2 Radiosondes
    - VectorNav

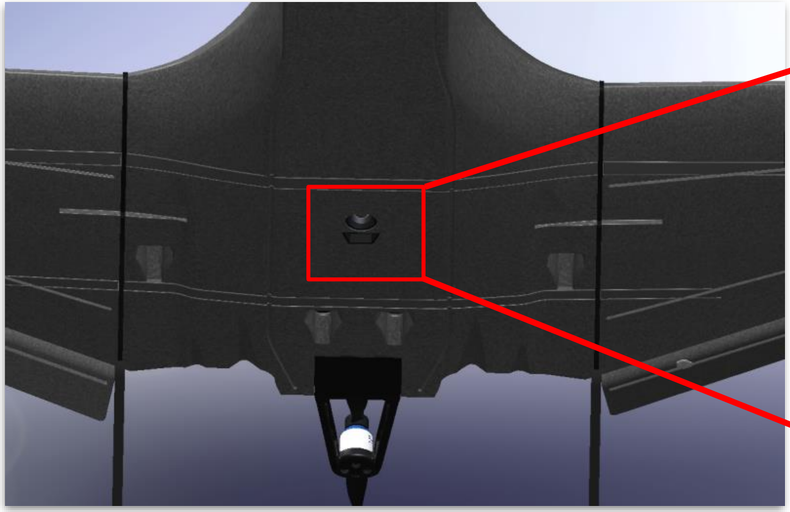



Maximum expected processor load with additional lidar:
**<25%**

DR 3.2, FR 3

# [AUT] - Lidar Configuration

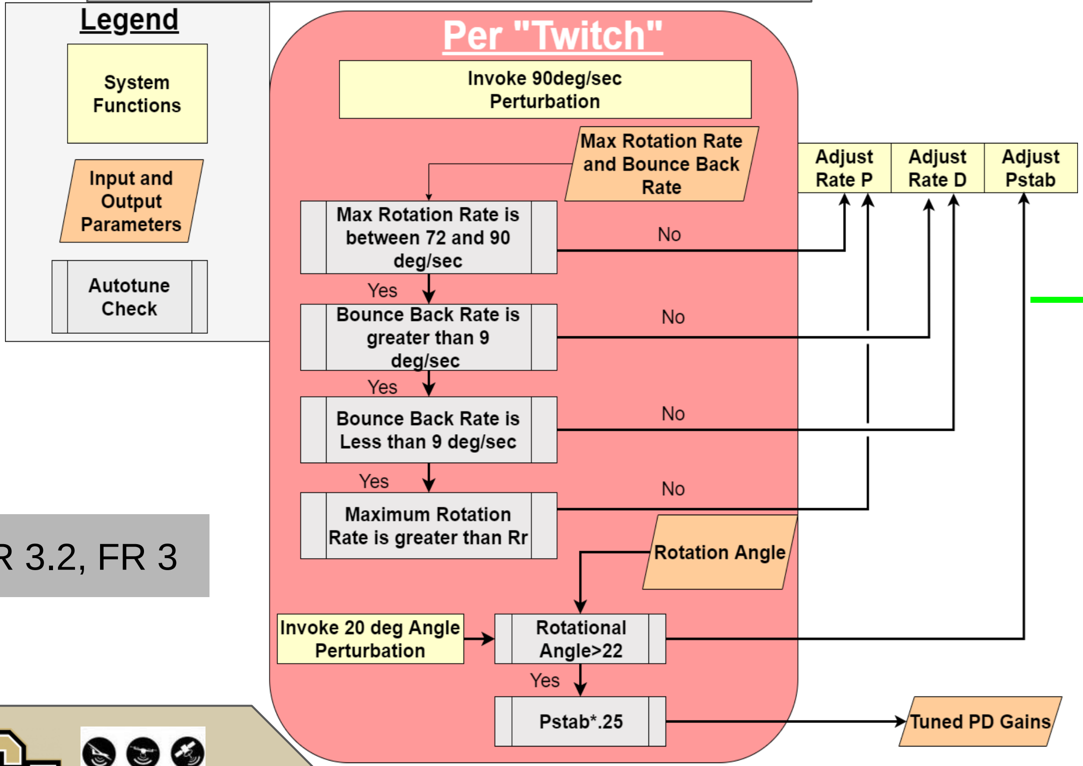
- Altitude data acquisition switches from lidar to barometer at 40m
- Mounted flush with the bottom of the aircraft, pointed down
- LeddarOne LiDAR has a vertical accuracy of ± 5 cm



DR 3.4, FR 3

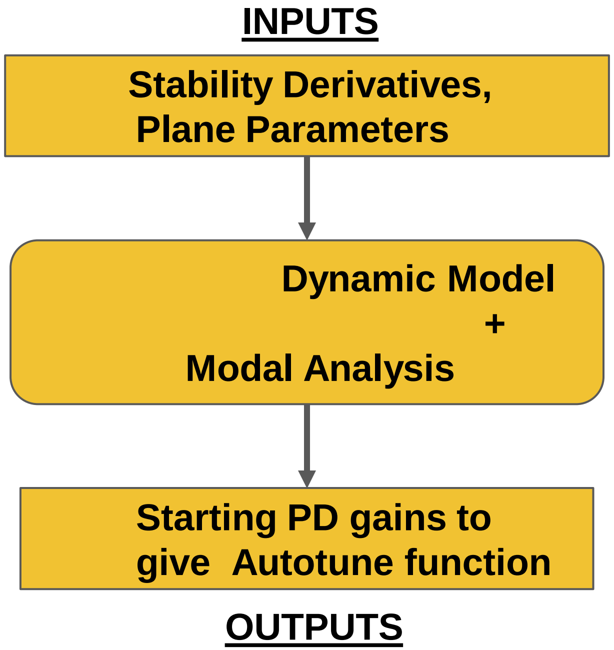
# [AUT] - Controls: PID Gain Tuning Via AutoTune

## Autotune Functional Block Diagrams




DR 3.2, FR 3

## Need Starting PD Gains



# [AUT] - Controls: Modal Analysis for Fixed Wing Mode



**Method**

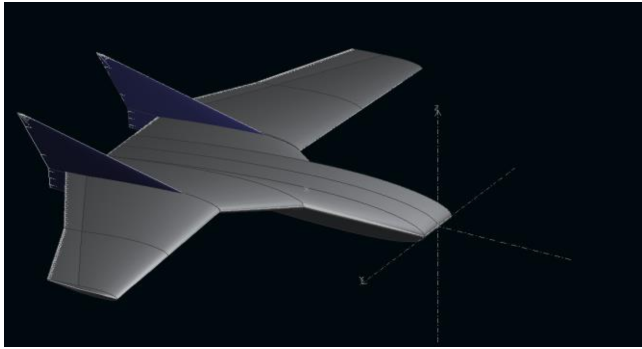
- Gather Stability Derivatives from XFLR5
- Construct Dynamic Model
- Input a range of gain values
- Pick gains/Test recommended gains

**Assumptions**

- Elevon deflection of 4 degrees
  - Minimum req for passive stability
- Analyze longitudinal and lateral modes separately
- No need for integral gains
  - Calculated in Autotune Function
- No rudder control
- No differential thrust in model

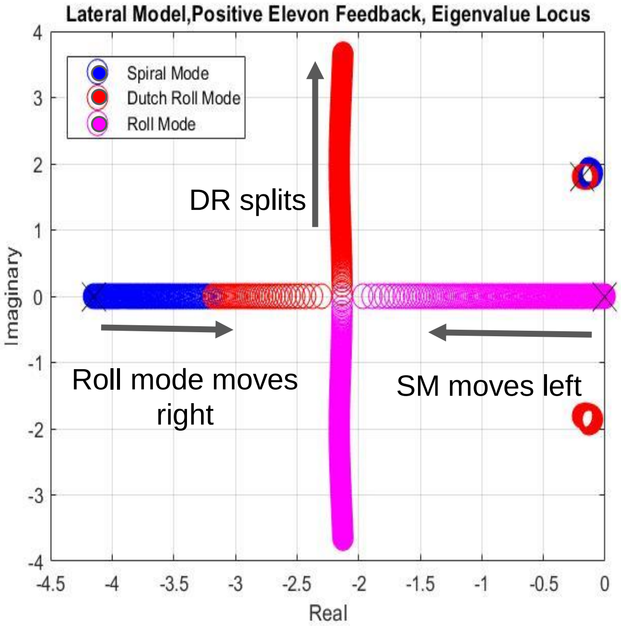
**Issues**

- Stability derivatives are inaccurate
  - Need wind tunnel
- XFLR5 is a low fidelity model

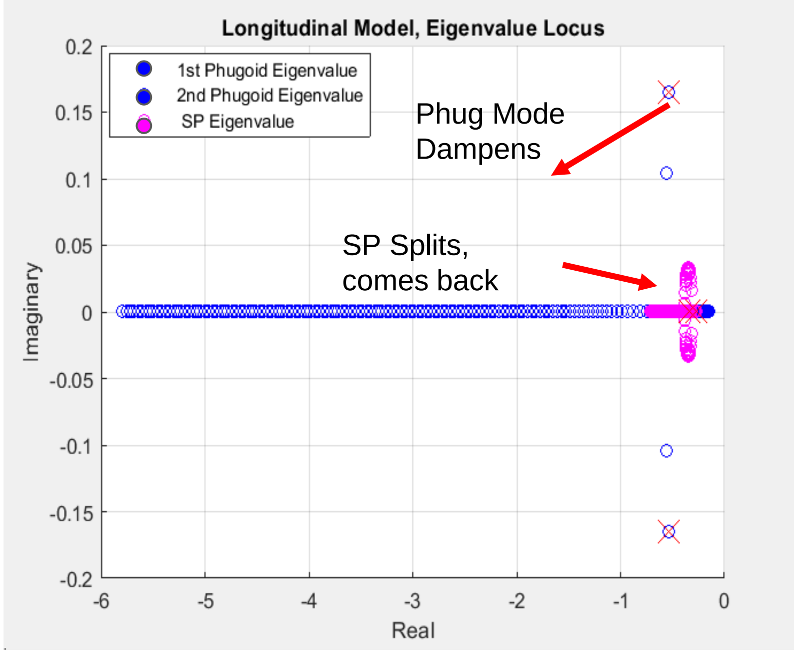


# [AUT] - Controls: Fixed Wing Modal Response

**Lateral Mode Locus** | **Recommended Gains Locus** | **Longitudinal Mode Locus**

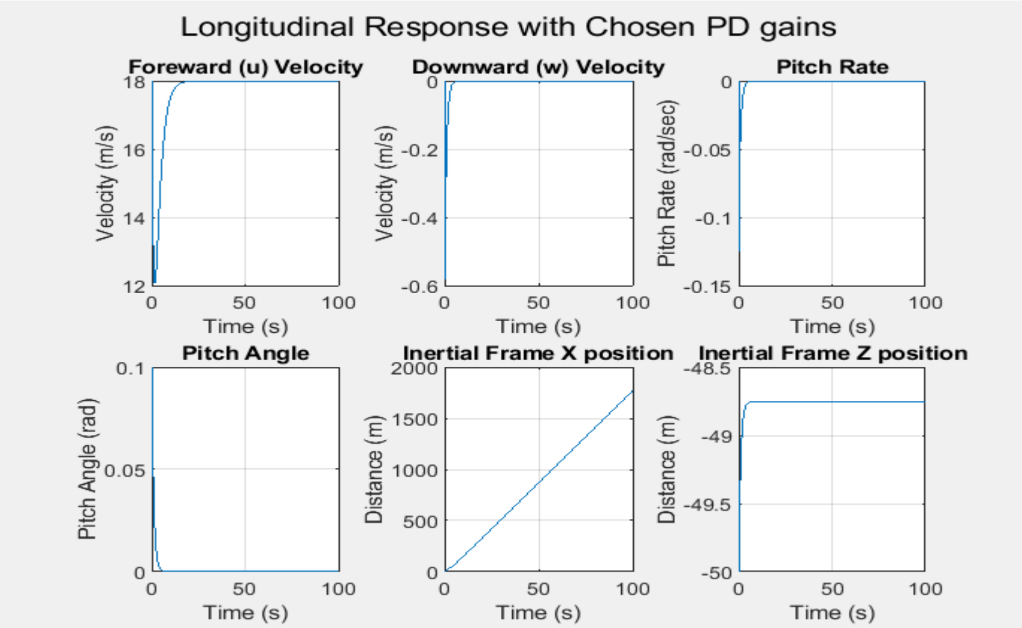



**P=1.8, D=1.2**



**State Response to Perturbations with P=1.8, D=1.2**

**Conclusions**

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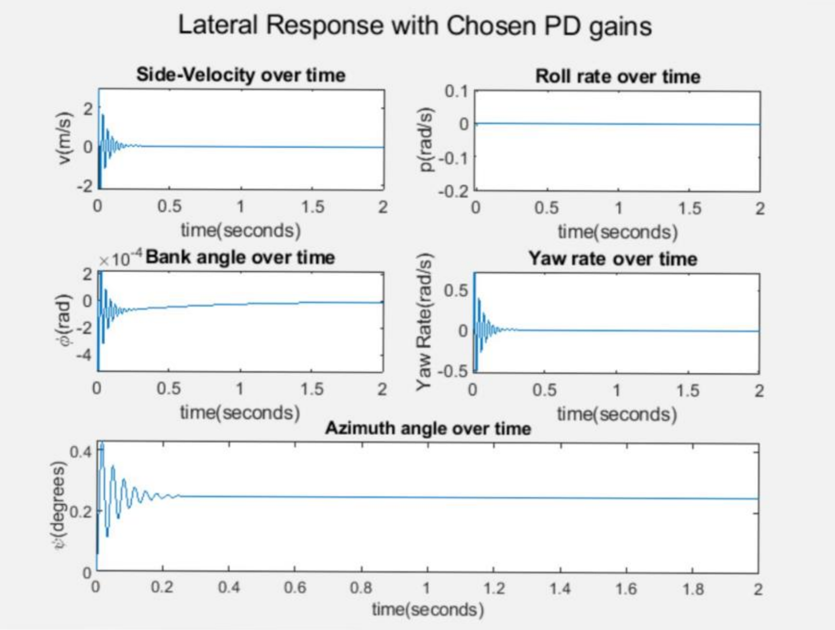


# Risk

| # | Category | Description | Consequence | Probability | Impact | Risk Level | Risk Modification Plan | Residual Risk |
|---|---|---|---|---|---|---|---|---|
| 5 | Supply/Struct | Drak kit backordered, potential supply difficulties | Would not be able to produce second deliverable for customer, may not have backup parts in case of destruction | High | Medium | High | Utilize IRISS' existing connection with RiteWing to obtain wing kits outside of standard commercial production | Medium |
| 8 | Propulsion | Battery damage during pack assembly | Fire/explosion in battery cells, injury to personnel | Low | High | High | Ensure spot welder is only used by properly trained individuals, follow strict safety protocols when working with battery cells | Medium |
| 11 | Testing | Car-top safety considerations | Damage to vehicles, test equipment, citations issued for property damage or other unknown reasons (?) | Low | High | High | Coordinate with department to create safe testing procedures and equipment, research local laws to ensure legality of test operations | Medium |
| 12 | Structures | Inaccurate FEM model | Possible material failure, could need to redesign parts | Medium | Medium | Medium | Compare FEM to known models and research minimizing FEM error, continually refine models | Low |

# Risk Assessment

# Risk Summary



| Likelihood | | Low | | Medium | | High |
|---|---|---|---|---|---|---|
| | Low | | | 4, 7 | 3 | |
| | | | | 12 | | 8, 11 |
| Likelihood | Medium | 2, 6, 13 | 10 | 1, 9 | | |
| | | | | | | |
| | High | | | 5 | | |

Consequence

Mitigation

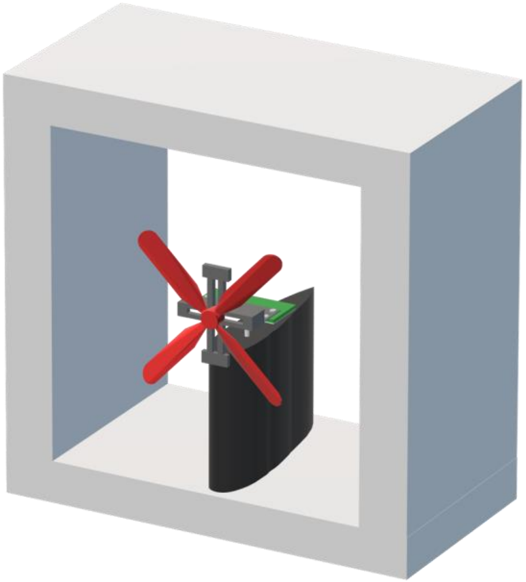
| Likelihood | | Low | | Medium | | High |
|---|---|---|---|---|---|---|
| | Low | | 4, 7, 12 | 1, 3, 11 | | |
| | | 2, 6, 13 | 10 | 5, 8 | | |
| Likelihood | Medium | | | | | |
| | | | | | | |
| | High | | | | | |

Consequence

# Verification and Validation

# Propulsion/Endurance: Propeller/Motor Testing

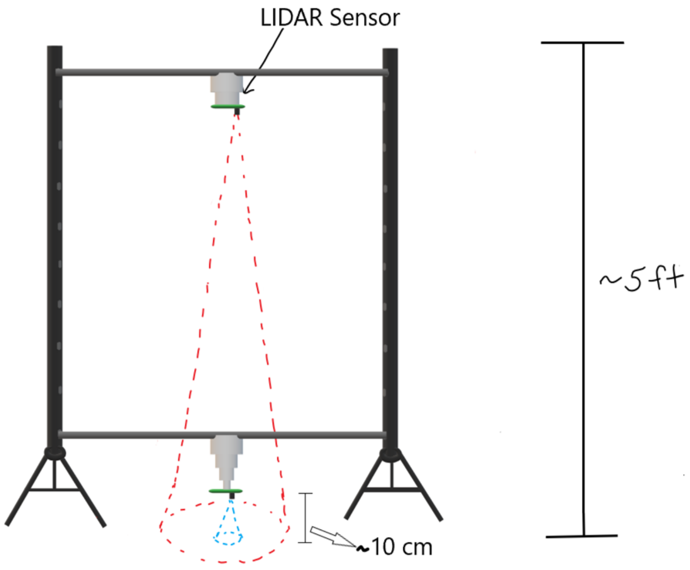




*Simple 3D model of static test stand*

| | |
|---|---|
| **Test Description:** | **Static:** Run motor on static test stand to measure the output thrust for vertical and horizontal flight<br>**Dynamic:** Run motor on mobile stand at cruise velocity for 1 hour |
| **Objective:** | Obtain thrust values for vertical and horizontal flight statically and the motor efficiency dynamically |
| **Model Compared To:** | Endurance Model |
| **Key Measurements:** | **Static:** Thrust [N]<br>**Dynamic:** Thrust [N], Propeller Efficiency [%] |
| **Expected Value:** | Static: 26.8N Vertical (13x8 prop)<br>Dynamic: 3 N Horizontal (13x8 prop)) |
| **Requirements Verified:** | FR1, FR2 |
| **Location:** | Static: Aero Building<br>Dynamic: TBD |

# Autonomy: LiDAR Verification



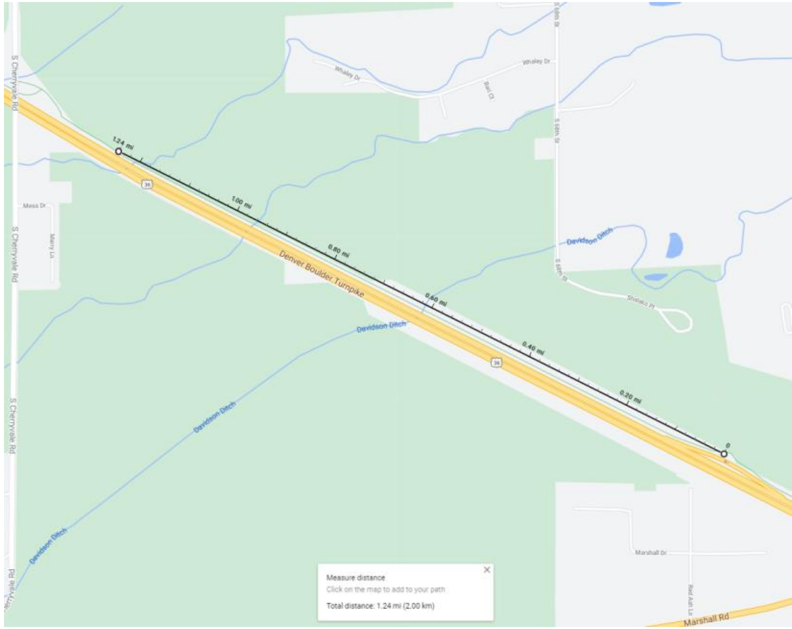

*Basic proof of concept for possible LIDAR testing stand apparatus*

| | |
|---|---|
| **Test Description:** | Take multiple sensor measurements at pre-measured distances over different types of surfaces with the sensor measuring both horizontally and vertically |
| **Objective:** | Show that the LIDAR sensor is accurate to <10cm over different surfaces |
| **Model Compared To:** | Pre-measured distance that is measured by something with reliable accuracy |
| **Key Measurements:** | Distance from sensor to target [m] |
| **Expected Value:** | Accurate to ±10 cm |
| **Requirements Verified:** | FR3 |
| **Location:** | Practically anywhere. Prioritize possible landing terrain (Grass, Dirt, etc.) |

# Autonomy: Telemetry Verification



| | |
|---|---|
| **Test Description:** | Perform ground test at a shorter known distance and a 2 km distance to compare amount of data sent to amount of data received by both aircraft and ground station |
| **Objective:** | Verify that packet loss is <50% at 2km |
| **Key Measurements:** | Packet Loss [%] |
| **Expected Value:** | <50% at 2km |
| **Requirements Verified:** | FR4 |
| **Location:** | East campus track scenic overlook along SH 36 |



# Aerodynamics: Scaled Wind Tunnel Testing



| | |
|---|---|
| **Test Description:** | Place scaled model of aircraft in wind tunnel to measure the aerodynamic forces acting on the model |
| **Objective:** | Obtain coefficients of lift and drag |
| **Model Compared To:** | CFD Simulations |
| **Key Measurements:** | $C_L$, $C_D$ |
| **Expected Value:** | Lift slope: 0.0648 $deg^{-1}$ |
| **Requirements Verified:** | FR2, FR5 |
| **Location:** | Pilot Lab Wind Tunnel |

- Scale Model
  - Small 3d printed version of modified Drak
  - There will be a discrepancy in skin friction drag since 3d printed material is different
- Reynolds Number
  - Must match expected value
  - Expected Re: 200,000
- Why?
  - Drak is too large

# Structures: Material Testing

*Tensile Test Specimens*

| | |
|---|---|
| **Test Description:** | Perform tensile tests on multiple identical material samples |
| **Objective:** | Obtain material properties of the carbon composite foam |
| **Model Compared To:** | N/A |
| **Key Measurements:** | Elastic modulus [MPa]<br>Yield Stress [kPa] |
| **Measured Value:** | Elastic modulus avg: 17.34 MPa<br>Yield Stress avg: 181.11 kPa |
| **Requirements Verified:** | FR1, FR5, FR6 |
| **Location:** | Pilot Lab |

# Next Semester Plan



- Safety during testing is top priority
- Flight test risk
  - RAPCat launch, tethered hover, full mission test
  - Any tests where aircraft leaves the ground brings a large risk
- 'Red Tape'/ Concerns
  - Need to:
    - Follow all FAA rules/regulations
      - Have a certified pilot
      - Have a place to fly
      - Altitude/speed/weight restrictions
      - Time restrictions
      - Limits on autonomous flight
  - Scheduling
  - COVID Restrictions/Unknown

# Tentative Testing Schedule

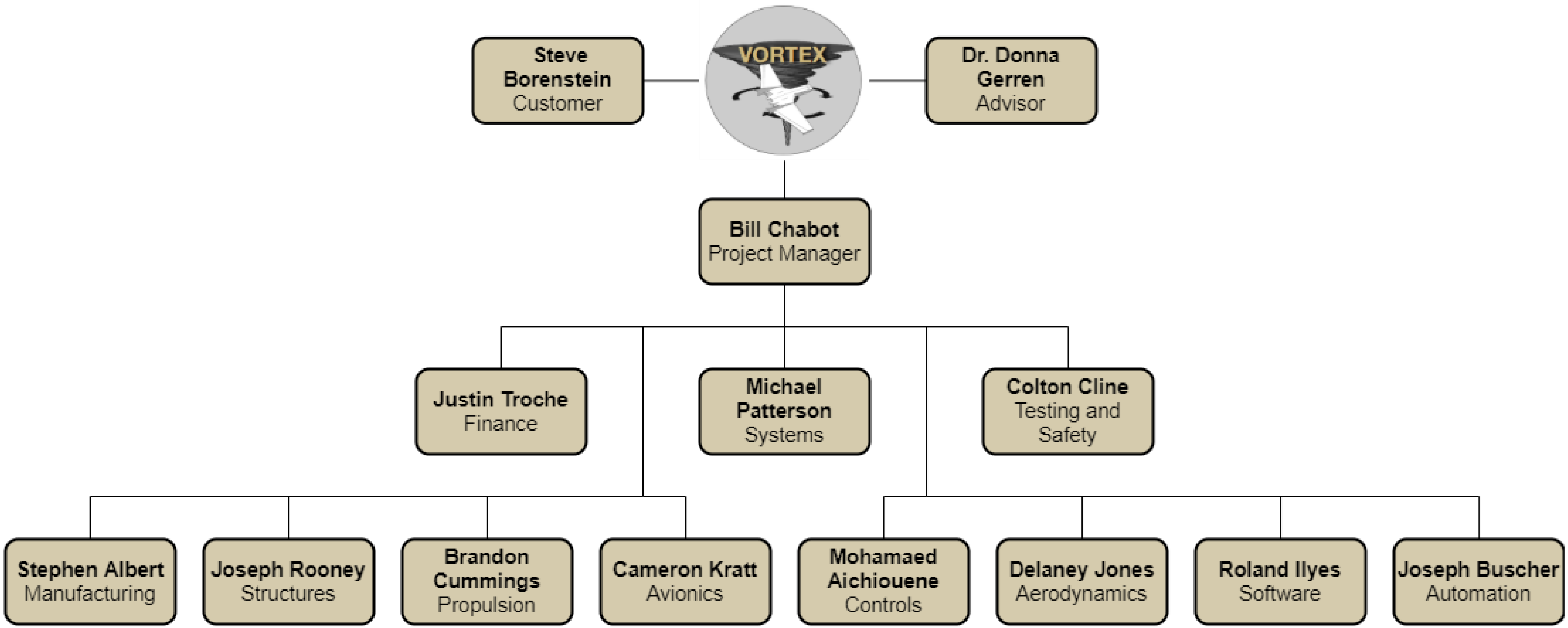


| Test | Date | Progress | Requirement |
|---|---|---|---|
| Material Testing | Nov 20 | Completed | Obtain material samples |
| Lift/Drag Test | Jan 15 - Feb 12 | Future Work | Scaled aircraft constructed |
| Telemetry | Jan 20 - Jan 28 | Future Work | |
| Endurance/Propulsion | Jan 23 - Feb 3 | Future Work | Test stand fabricated<br>Battery testing complete |
| LIDAR | Jan 27 - Feb 3 | Future Work | Test stand fabricated |
| Control Surfaces/Transition | Feb 28 - Mar 8 | Future Work | Full VTOL version of aircraft constructed |
| Flight Test | Apr 14 - Apr 22 | Future Work | All previous tests completed<br>All systems integrated |

# Project Planning

# Organizational Chart





# Work Breakdown Structure



**Deliverables**
- Project Definition Document
- Conceptual Design Document
- Preliminary Design Review
- Critical Design Review
- Fall Final Report
- Manufacturing Status Review
- Test Readiness Review
- Spring Final Review
- Project Final Report
- Senior Design Symposium
- AIAA Region V Conference Paper

**Administration**
- Organizational Chart
- Gantt Chart
- Risk Matrices
- Budget
- Ongoing Operations

**Endurance**
- CFD Verification
- CFD Analysis of Stock Drak
- Propulsion Model
- Component Selection
- CFD Analysis of Full System
- Battery Manufacturing
- Component Testing
- Integration
- Full System Testing

**Automation/Control**
- Component Selection
- Gain Parameters
- Mission Simulations
- Sensor Testing
- Integration
- Full System Testing

**Manufacturing/Structures**
- Full CAD Model
- Motor Mount Design
- Tilt Mechanism Design
- Materials Modeling
- Stress Analysis
- Preliminary Fabrication
- Fabricated Component Testing/Iteration
- Final Component Fabrication
- Integration
- Full System Testing

**Testing**
- Design Test Equipment
- Fabricate Test Equipment
- Subsystem Testing
- Full System Testing

**Legend**
- Completed
- In Progress
- Future Work

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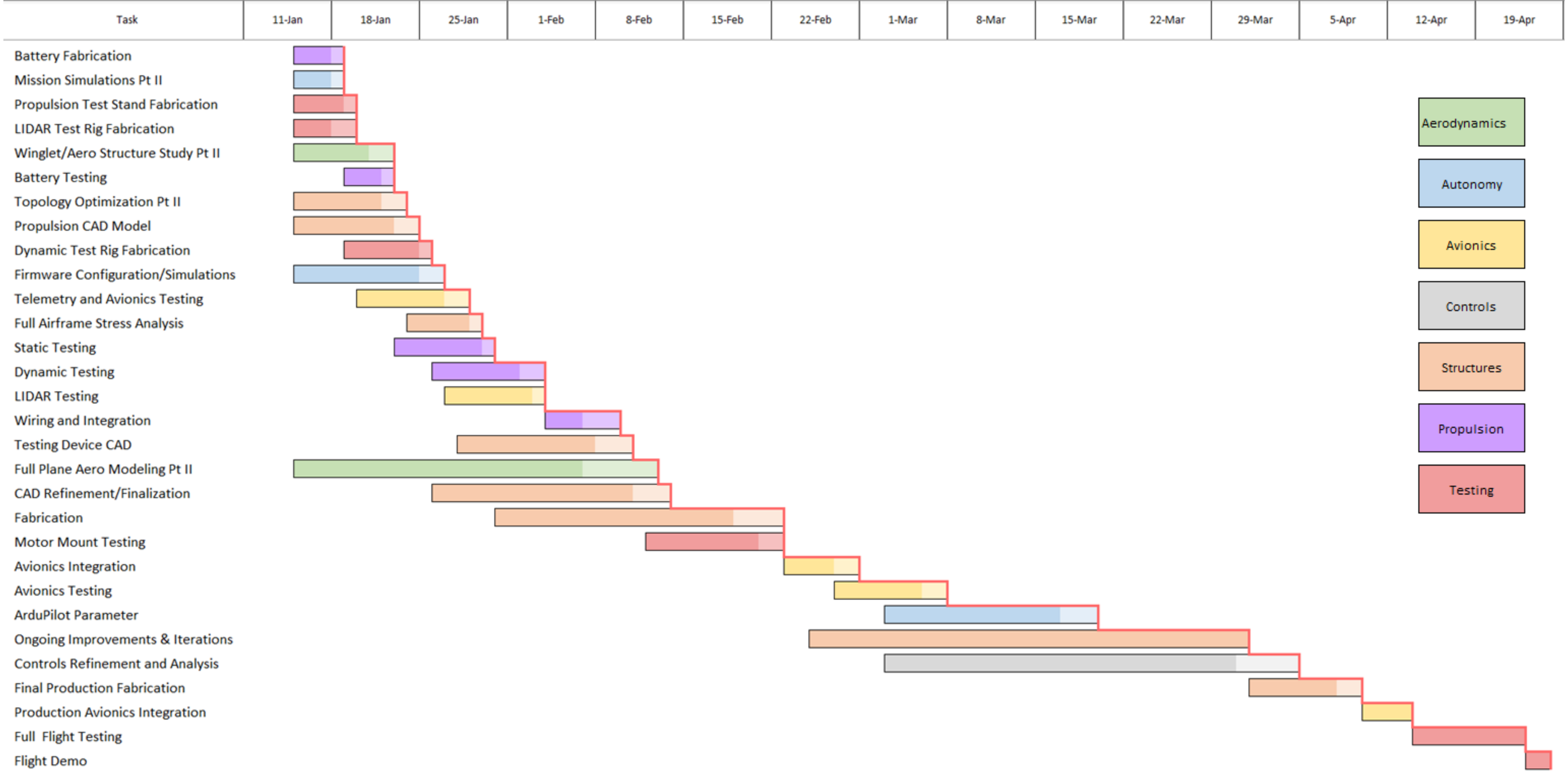
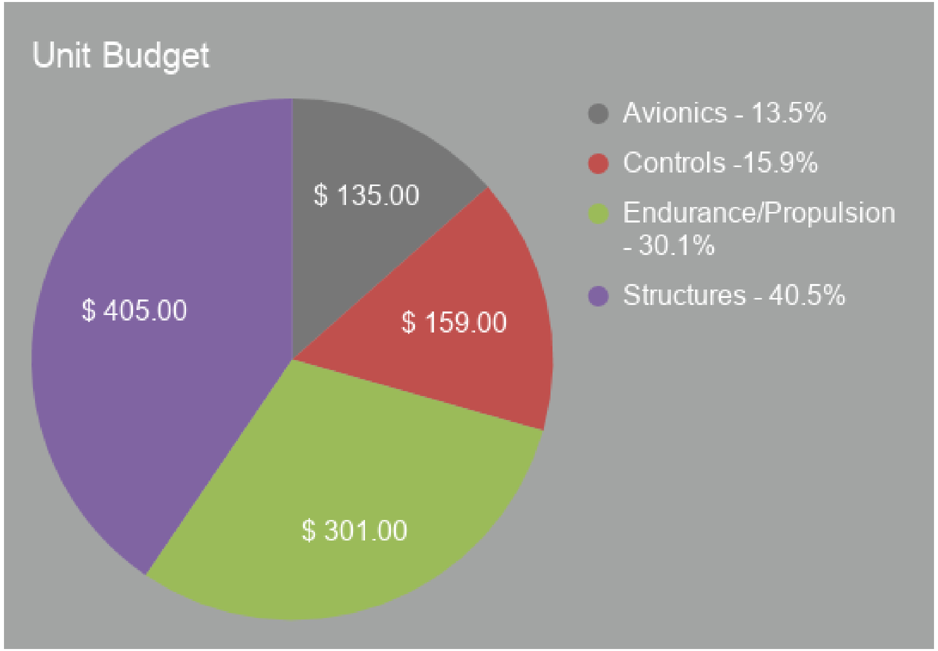
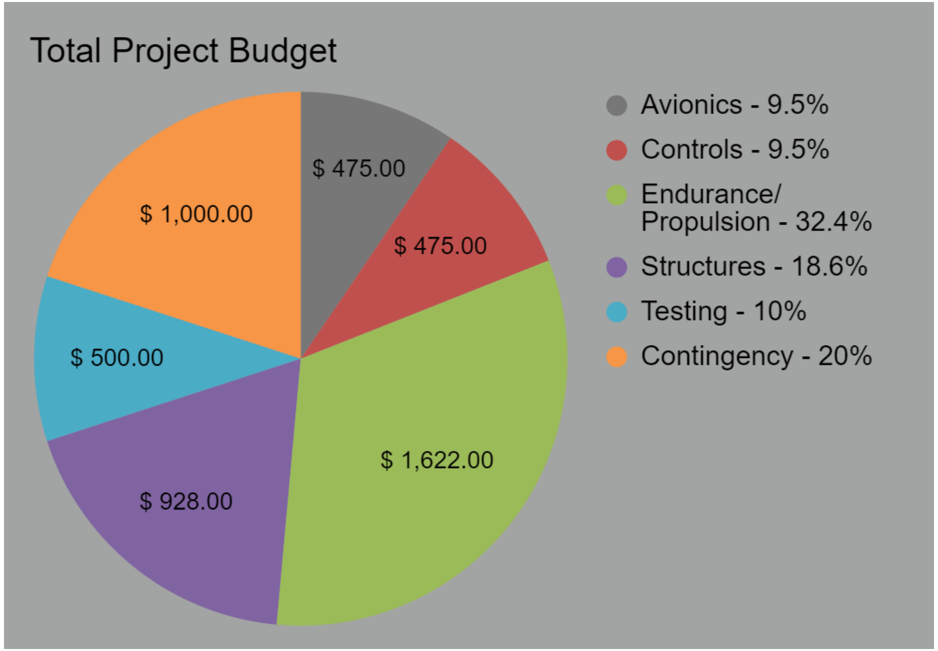



# Spring Semester Gantt Chart

# Cost Plan


Unit Budget
$ 135.00
$ 159.00
$ 301.00
$ 405.00
Avionics - 13.5%
Controls -15.9%
Endurance/Propulsion - 30.1%
Structures - 40.5%


Total Project Budget
$ 475.00
$ 475.00
$ 1,622.00
$ 928.00
$ 500.00
$ 1,000.00
Avionics - 9.5%
Controls - 9.5%
Endurance/ Propulsion - 32.4%
Structures - 18.6%
Testing - 10%
Contingency - 20%

# Total Project Cost Budget

| | | Per Unit | | | | | | Total | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Materials | | | | | | Materials | | | | | |
| WBS | Task | Units | $/Unit | Actual | Budget | Margin | Under/(Over) | Units | $/Unit | Actual | Budget | Margin | Under/(Over) |
| | | | | 894.88 | $ 1,000.00 | -10.51% | -$105.12 | | | $ 2,817.22 | [illegible],000.00 | -43.66% | -$2,182.78 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Avionics | | | $ 125.00 | $ 135.00 | -7.41% | -$10.00 |
| 1.1 | LIDAR Sensor | 1.0 | $125.00 | 125.00 | 135.00 | -7.41% | -10.00 |
| 1.2 | Current Measurement Board | 0.0 | $23.00 | - | - | | 0.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Structures | | | $ 392.00 | $ 405.00 | -3.21% | -$13.00 |
| 1.1 | Ritewing Drak Kit | 1.0 | $350.00 | 350.00 | 350.00 | 0.00% | 0.00 |
| 1.2 | 3D printing filament | 0.5 | $64.00 | 32.00 | 40.00 | -20.00% | -8.00 |
| 1.3 | Amazing Goop | 1.0 | $10.00 | 10.00 | 15.00 | -33.33% | -5.00 |
| 1.4 | Motor Mount Hardware | 0.0 | $10.00 | - | - | | 0.00 |

# Acknowledgements



Dr. G - Advising and continued feedback

Chris Choate & Michael Rhodes - Drak/Avionics/ArduPilot Information

KatieRae Williamson - Materials Testing + Data

Professors Schwartz & Rainville - Electronics Information

WASP Team - CDR Feedback + Review

Mitchell Jett Spencer - ArduPilot information

Chris Klick - Drak Information

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# Thank You

# Backup Slides

# VTOL Configuration



**Design Choices Considered**

| | |
|---|---|
| **Tilt Rotors** | Tri tilt motor ● Quad tilt motor ● Quint tilt motor |
| **Tail Sitters** | Quad motor puller ● Dual motor puller ● Dual motor pusher |
| **Hybrids** | Quad lift motor ● Single cruise motor ● Tri lift motor ● Single cruise motor |
| **Tilt Wings** | Inboard motors ● Wingtip motors |

FR1: **The aircraft shall be a VTOL conversion of the COTS Ritewing RC "Drak" airplane kit**

FR5: **The aircraft shall be capable of carrying a 0.5 kg payload.**

FR6: **Aircraft shall be capable of taking off from existing RAPCat launch system.**

# VTOL Configuration (cont.)

**Selected Baseline Design:** Tri Tilt Motor

**Design Choice Reasoning**

- Provides the necessary hover control and cruising efficienc
- Tilting motors can provide thrust in horizontal and vertical fl
- Minimizes added complexity and weight of additional motor
- Utilizes existing rear motor mounting capability


A tri-motor aircraft

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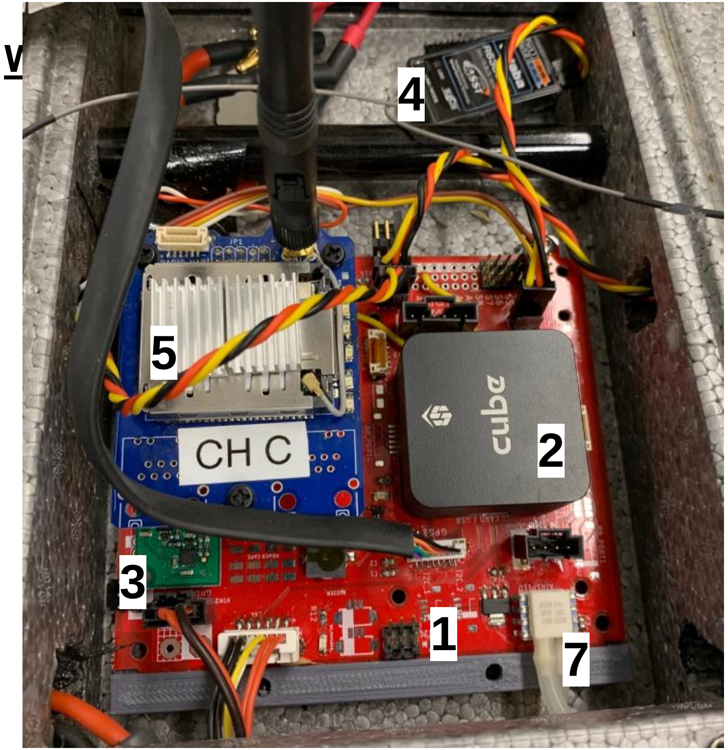



FR4: **The aircraft shall maintain communication with the ground station up to a distance of 2km (maintaining communication is indicated by <50% packet loss).**

# Avionics



| Port | Available | Required | Peripheral | Protocol |
|---|---|---|---|---|
| I2C | 2 | 0 | N/A | Synchronous Serial |
| Telem | 1 | 1 | Custom Telemetry Package | Combined UART + I2C |
| GPS | 1 | 1 | Here2 GNSS GPS | Combined UART + I2C |
| Main Output | 8 | 7 | 2 Tilt Servos, 2 Elevon Servos, 3 ESCs | PWM |
| Auxiliary Output | 6 | 0 | N/A | PWM |
| UART | 1 | 1 | LeddarOne LiDAR | Asynchronous Serial |
| Power 1 | 1 | 1 | Direct Battery Voltage | N/A |
| Power 2 | 1 | 1 | 5V Step Down | N/A |
| RC In | 1 | 1 | Futaba SBUS RC Receiver | SBUS |
| Micro USB | 1 | 1 | Connection to Mission Planner | N/A |

# Flight Controller Firmware



**Design Choices Considered**

- Ardupilot
- PX4
- iNav
- PaparazziUAV


FR3: **The aircraft shall be able to autonomously execute all aspects of its mission from takeoff through landing.**

# Flight Controller Firmware (cont.)



**<u>Selected Baseline Design:</u>** Ardupilot

**<u>Design Choice Reasoning</u>**

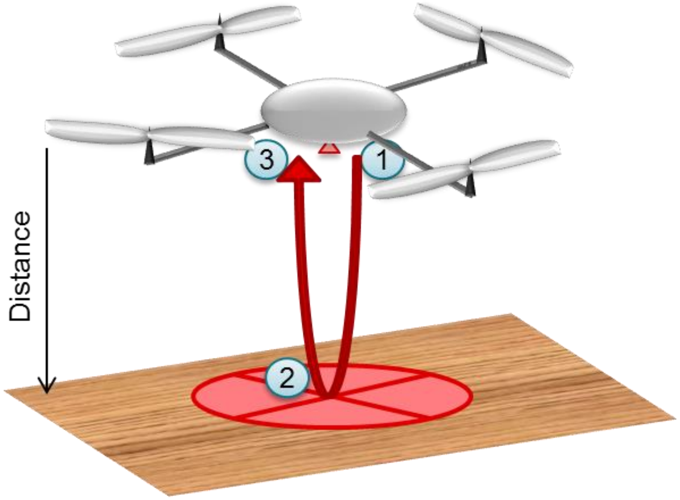
- Substantial documentation for flight control of various aircraft configurations
- Ardupilot forums contain abundant resources for handling VTOL aircraft and transitions
- Open source code using GPLv3
- Already used by the IRISS team
  - Easier to integrate the VTOL UAV into the existing fleet

# Landing Sensor Package



**Design Choices Considered:**

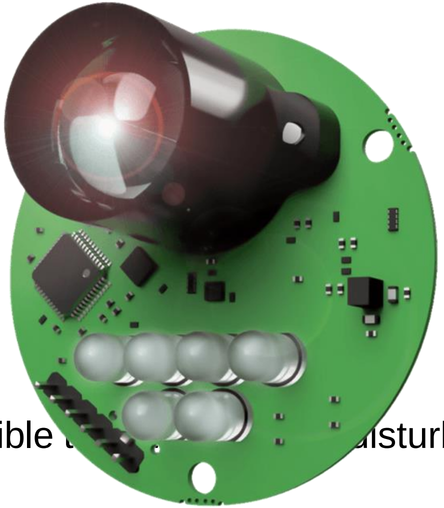
- LIDAR
- Micro Radar
- Sonar




FR3: **The aircraft shall be able to autonomously execute all aspects of its mission from takeoff through landing.**

# Landing Sensor Package (cont.)





**Selected Baseline Design:** LeddarOne LiDAR*

**Design Choice Reasoning**

- Ease of integration with current avionics package and ArduPilot
- Cost falls within budgetary constraints
- Provides reliable, accurate measurements that are less susceptible t[illegible] disturbances
- Satisfies the requirements of the project

| | |
|---|---|
| Accuracy | 0 - 40m |
| Acquisition Rate | 140Hz |
| Beam Diffusion | 3-degree |
| Protocol | UART |

*Preliminary Design choice ~ example of desired attributes

# Battery Chemistry



**Design Choices Considered**

- Li-Ion
- Li-Po
- NiMH
- NiCd
- $LiFePO_4$





FR2: **The aircraft shall have an endurance of one hour in addition to two takeoffs and landings.**

# Battery Chemistry (cont.)

**Selected Baseline Design:** Lithium-Ion

**Design Choice Reasoning**

- Readily available at a reasonable cost
- Provide a high energy density while maintaining the lowest weight
- Provides reasonable current discharge
- Industry standard. Large market (variability and customizability)
- Well tested and quantified, used in many applications


Lithium Ion Batteries

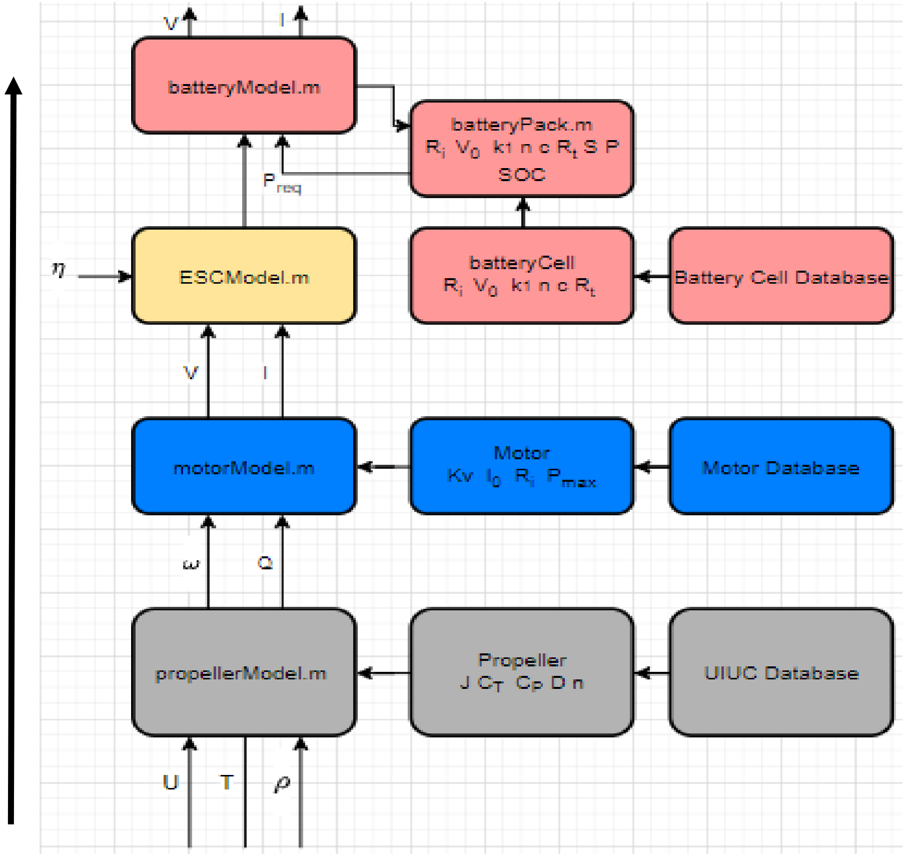
# Endurance Slide Endurance Model

**Function matlab models**

- ➢ Battery (Spec data and equations)
- ➢ ESC
- ➢ Motor (Spec data and equations)
- ➢ Propeller (UIUC database)

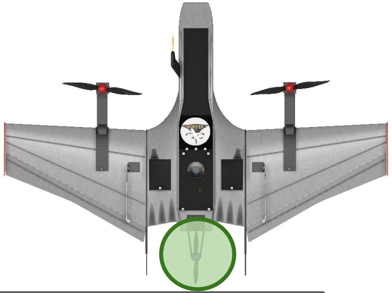
**Inputs**

| | |
|---|---|
| Required Thrust | T |
| Required Aircraft Velocity | U |
| Air density | $\rho$ |



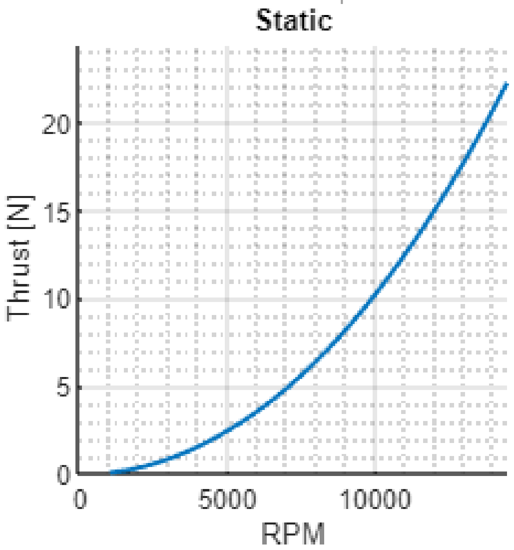
# Rear Propeller Performance

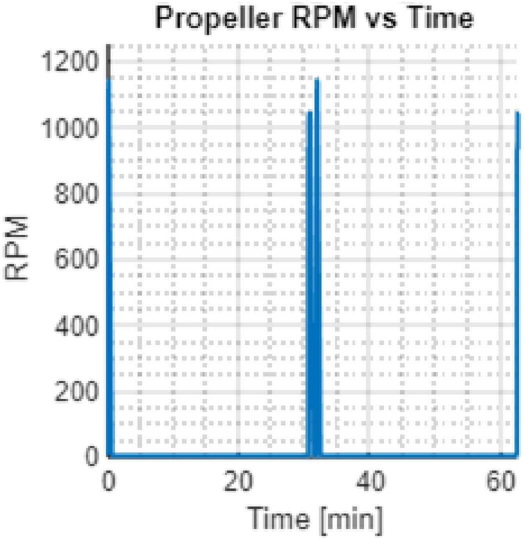
| Rear Components | |
|---|---|
| ESC | V4 25A (3S-6S) |
| Motor | SunnySky V3 X2216 880KV |
| **Prop** | **aero-naut Cam Carbon blades 9x7** |



## Flight mission modeled performance

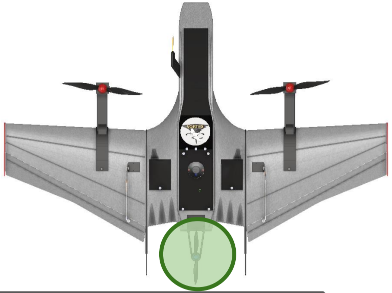
| Target Vertical flight thrust | Target RPM | Max expected Torque |
|---|---|---|
| 10.8N | 1154.0 | 0.2Nm |



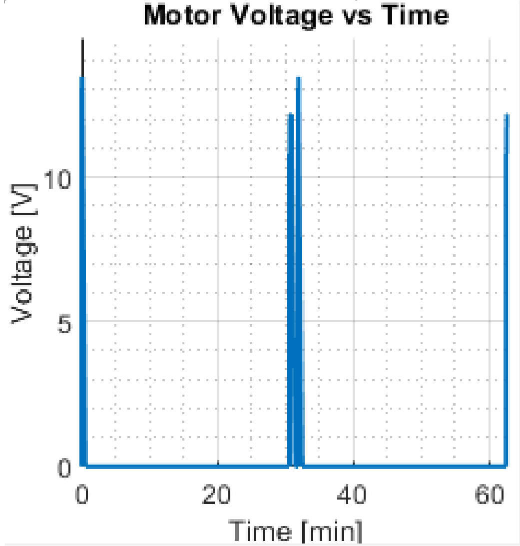
# Rear Motor Performance

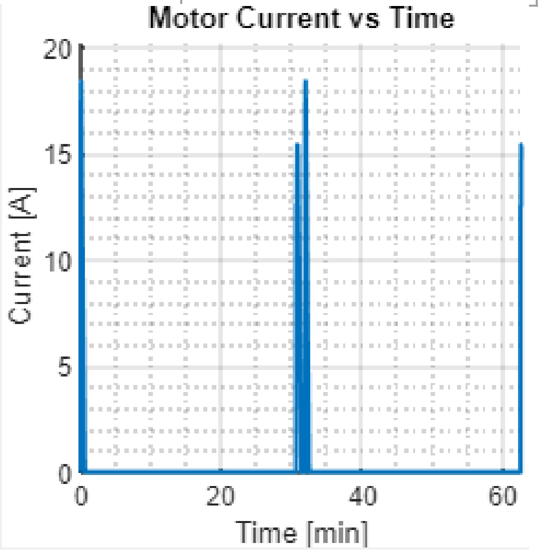
| Rear Components | |
|---|---|
| ESC | V4 25A (3S-6S) |
| **Motor** | **SunnySky V3 X2216 880KV** |
| Prop | aero-naut Cam Carbon blades 9x7 |

## Flight mission modeled performance

| Max Expected Voltage Input | Max Expected Current Draw | Max Expected Average Power |
|---|---|---|
| 13.6V | 18.8A | 257.0W |



# Endurance Additional Total Testing Components



## Props

*https://www.espritmodel.com/aeronaut-propellers-cam-electric-glow-tractor-pusher.aspx*

Rear Props:
9x5
9x6
**9x7**
10x8
Forward Props:
13x6
**13x8**
14x6
14x8

## Motors

- **SunnySky X Series V3 X2820 500 KV** *https://sunnyskyusa.com/collections/x-v3-motors/products/sunnysky-x2820*
- **SunnySky X Series V3 X2216 880KV Long Shaft Version** *https://sunnyskyusa.com/collections/x-v3-motors/products/sunnysky-x2216-v3-brushless-motors-long-shaft-version*

## Batteries

- **MOLICEL 21700 P42A 4200MAH 45A BATTERY** *https://www.18650batterystore.com/products/molicel-p42a*
- **SAMSUNG 40T 21700 4000MAH 35A BATTERY** *https://www.18650batterystore.com/products/samsung-40t*

## ESC

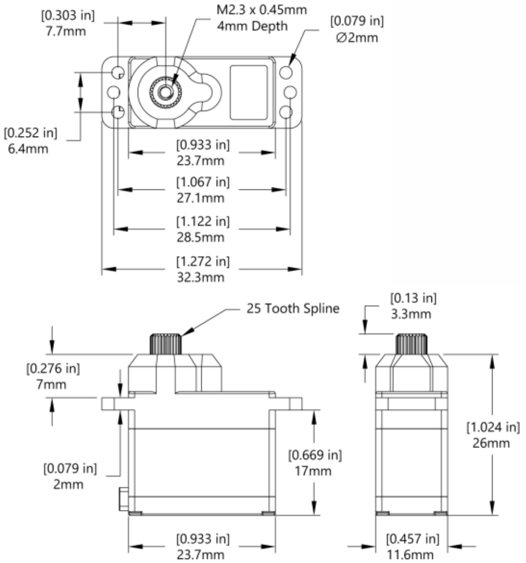
- **FLYFUN V5 ESC (3S-6S) 40A** *https://www.hobbywingdirect.com/products/flyfun-v5-esc-3s-6s?variant=37381905553*
- **Platinum PRO V4 - 25A (3S-6S)** *https://www.hobbywingdirect.com/products/platinum-pro-v4-25a?variant=37395576465*

# Front Motor Specifications


| SunnySky X2820 V3 KV500 Motor Test Data | |
|---|---|
| Specifications | X2820 V3 |
| Stator Diameter | 28mm |
| Stator Thickness | 20mm |
| No.of Stator Slots | 12 |
| No.of Rotor Poles | 14 |
| Motor Kv | 500 |
| NO-Load Current (A/10V) | 0.6A |
| Motor Resistance | 70mΩ |
| Max Continuous Current | 41A/30s |
| Max Continuous Power | 1025W |
| Weight | 149g |
| Rotor Diameter | 35mm |
| Body Length | 42mm |
| Max Lipo Cells | 6S |
| ESC | 50A |
| Recommend Propellers (inch) | APC12*8 EOLO13*7 12*6.5 |

# Front Motors Servo - HS 5065MG

| | | | |
|---|---|---|---|
| Output Shaft Style | B25T Spline | Current Drain - no-load (6V) | 200mA |
| Voltage Range | 4.8V - 6.0V | Current Drain - no-load (7.4V) | 240mA |
| No-Load Speed (4.8V) | 0.14 sec/60° | Current Drain - stall (4.8V) | 2A |
| No-Load Speed (6.0V) | 0.11 sec/60° | Current Drain - stall (6V) | 3A |
| Stall Torque (4.8V) | 24.99 oz-in (1.8 kg.cm) | Continuous Rotation Modifiable | No |
| Stall Torque (6.0V) | 30.55 oz-in (2.2 kg.cm) | Direction w/ Increasing PWM Signal | Clockwise |
| Max PWM Signal Range | 750-2250μsec | Deadband Width | 2μs |
| Travel per μs (Stock) | .085°/μsec | Motor Type | Carbon Brush |
| Travel per μs (Reprogrammed) | .121°/μsec | Feedback Style | 5KΩ Potentiometer |
| Max Rotation (Stock) | 128° | Output Shaft Support | Top Ball Bearing |
| Max Rotation (Reprogrammed) | 181° | Gear Material | Metal |
| Pulse Amplitude | 3-5V | Wire Length | 7" (178mm) |
| Operating Temperature | -20°C to +60°C | Weight | 0.42oz (11.9g) |
| Current Drain - idle (4.8V) | 3mA | Wire Gauge | 28AWG |
| Current Drain - idle (6.0V) | 3mA | Servo Size | Sub-Micro |

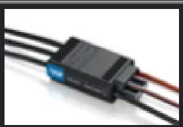
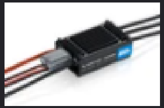



- Calculated required torque to support motor mount: 0.9kg-cm
    - FOS of 1.5 ---> 1.4kg-cm

# Front ESC Specifications



FLYFUN V5 ESC (3S-6S) 40A

| |  |  |  |  |
|---|---|---|---|---|
| | 120A V5 | 80A V5 | 60A V5 | 40A V5 |
| p/n | 30201400 | 30214201 | 30214101 | 30214002 |
| Cont./Peak Current | 120A/150A | 80A/100A | 60A/80A | 40A/60A |
| Input | 3-6S LiPo | 3-6S LiPo | 3-6S LiPo | 3-6S LiPo |
| BEC | Switch Mode: 5.2V/6V/7.4V, 8A/20A | Switch Mode: 5.2V/6V/7.4V, 8A/20A | Switch Mode: 5.2V/6V/7.4V, 8A/20A | Switch Mode: 5.2V/6V/7.4V, 8A/20A |
| Input /output wire | 12AWG-150mm | 12AWG-150mm | 14AWG-150mm | 14AWG-100mm/ 16AWB -75mm |
| Input connector | NO | NO | NO | NO |
| Output connector | 4.0 Gold Connectors (Female) | 4.0 Gold Connectors (Female) | 4.0 Gold Connectors (Female) | 3.5 Gold Connectors (Female) |
| Size (mm) | 77.2x34.6x19.2 | 69.8x34.6x19.2 | 68.8x34.6x18 | 47x28x14 |
| weight (g) | 93 | 92 | 73.5 | 44 |

# Rear Motor Specifications



SunnySky X Series V3 X2216 V3 Brushless Motor 880 KV


| | | | |
|---|---|---|---|
| Stator Diameter | 22mm | Rotor Diameter | 27.7mm |
| Stator Thickness | 16mm | Body Length | 34mm |
| No.of Stator Slots | 12 | Max Lipo Cell | 3-4S |
| No.of Rotor Poles | 14 | ESC | 50A |
| Motor Kv | 880 | Recommended Prop(inch) | APC11*4.7 /APC1047 /APC9047/APC9045 |
| No-load current | 0.5A/10V | Weight for aerobatics air plane | 850g(4S 9060\1047\1050) |
| Motor Resistance | 89mΩ | Single weight for multirotors | 500g(3S 1038\1047) |
| Max Continuous Current | 32A/30s | Single weight for multirotors | 550g(4S 8038\8043\8045\9047) |
| Max Continuous Power | 450W | Weight for 3D airplane | 800g(3S 1147) |
| Weight | 67.5g | | |

# Rear ESC Specifications



Platinum PRO V4 -25A (3S-6S) 25 A

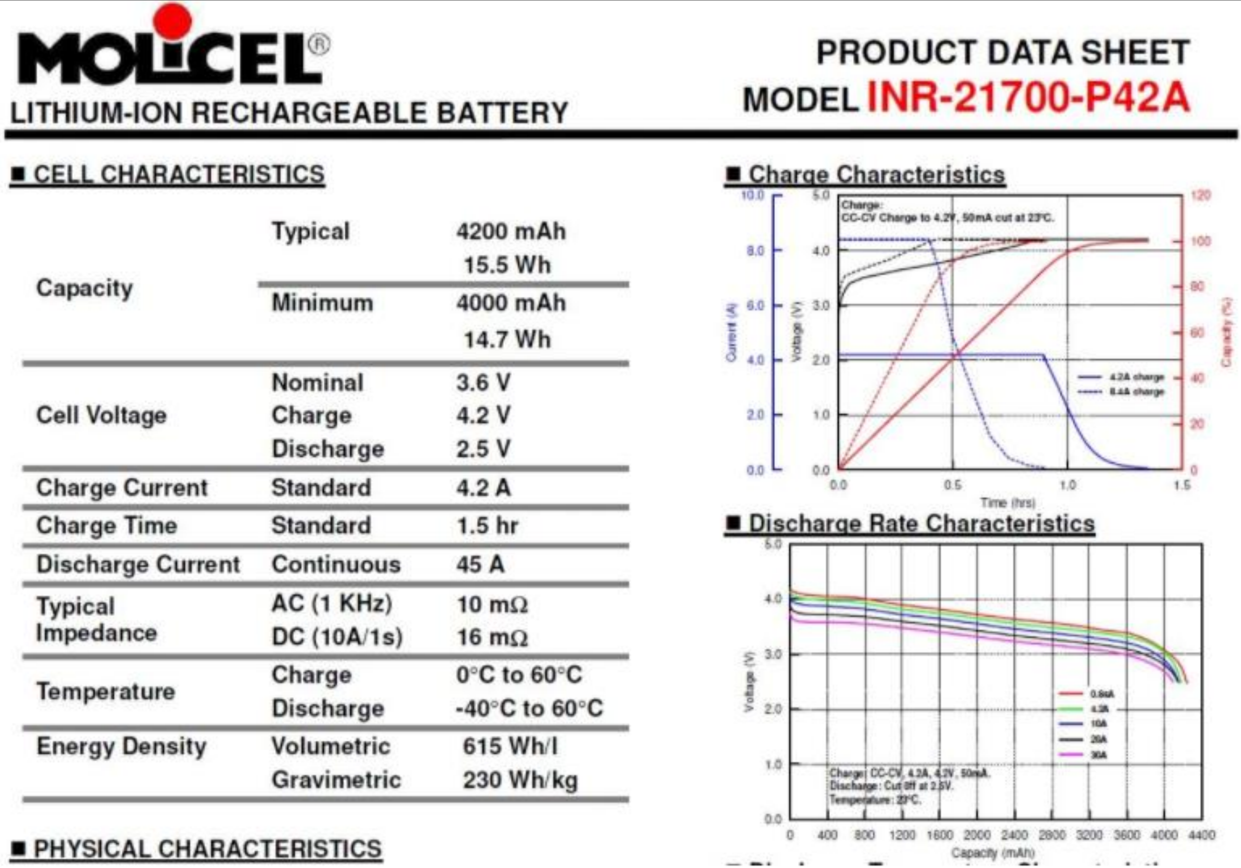

- 3-6S LiPo
- Built-in BEC 6V-7.4V
- Firmware upgrade and programming via WiFi Express module or LCD program box (purchase separately)

| | |
|---|---|
| Model | Platinum 25A ESC V4 |
| Input Voltage | 3-6S LiPo |
| Cont./Peak Current (10s) | 25A/40A |
| Application | > 450 heli or a small fixed wings aircraft |
| (Switch-mode) BEC | Switch Mode:6V/7.4V, 3A/7A |
| PWM | 18KHz |
| Separate Programming Port | For connecting LCD Program Box/WIFI Express |
| Throttle Signal/BEC Output/RPM Signal Transmission Wire(s) | White Throttle Signal Wire/Red & Black BEC Output Wires/ Yellow RPM Signal Transmission Wire |
| Input Wires | Red-16AWG-100mm*1/Black-16AWG-100mm*1 |
| output wires | Black-18AWG-75mm*3 |
| Output connectors | 3.5mm Gold Connectors (Female) |
| Weight/Size | 27g / 47x22x10mm |

IRISS
INTEGRATED REMOTE & IN SITU SENSING

MOLICEL 21700 P42A

4200MAH 45A BATTERY

MOLICEL®

LITHIUM-ION RECHARGEABLE BATTERY

PRODUCT DATA SHEET

MODEL INR-21700-P42A

■ CELL CHARACTERISTICS

| | | |
|---|---|---|
| Capacity | Typical | 4200 mAh<br>15.5 Wh |
| | Minimum | 4000 mAh<br>14.7 Wh |
| Cell Voltage | Nominal | 3.6 V |
| | Charge | 4.2 V |
| | Discharge | 2.5 V |
| Charge Current | Standard | 4.2 A |
| Charge Time | Standard | 1.5 hr |
| Discharge Current | Continuous | 45 A |
| Typical Impedance | AC (1 KHz) | 10 mΩ |
| | DC (10A/1s) | 16 mΩ |
| Temperature | Charge | 0°C to 60°C |
| | Discharge | -40°C to 60°C |
| Energy Density | Volumetric | 615 Wh/l |
| | Gravimetric | 230 Wh/kg |

■ PHYSICAL CHARACTERISTICS

■ Charge Characteristics



■ Discharge Rate Characteristics

# Props Specifications

## Aeronaut CAM-carbon Light Prop


This range of propellers is intended for electric motors, and has been developed to generate high levels of thrust even at low rotational speeds. This is accomplished by using a thin blade section of wide chord. This series represents light, strong and torsionally rigid carbon-reinforced propellers. They are also an excellent choice for multicopter models, and certain sizes can be used in pairs (left and right-hand rotation).

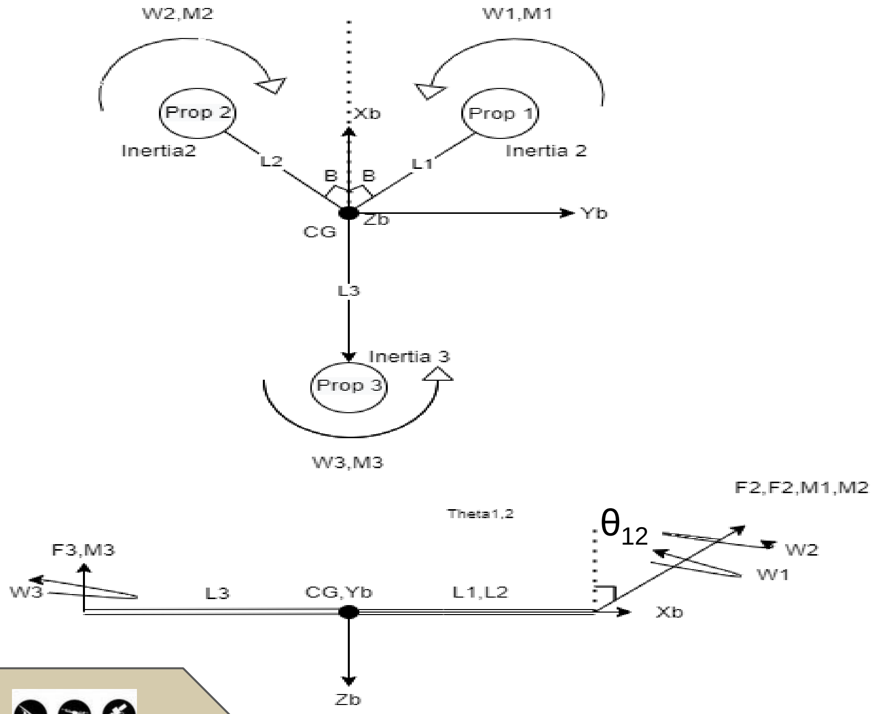
These propellers were developed using a CAD system in order to ensure accurate blending of blade pitch and airfoil. The blade shape is identical to that of our proven Cam-Carbon folding propellers, but the hubs are smaller and therefore lighter. The moulds - produced using CNC machines - and the carbon fibre reinforced propellers themselves are manufactured exclusively in Germany. Each propeller is supplied with a set of spacer rings to suit the following shaft diameters: 5, 6, 6.3 and 7 mm.

### Sizes

| size | ccw | cw | | | |
|---|---|---|---|---|---|
| 8,4,5" | 7216/12 | 7217/12 | 12x4,5" | 7216/33 | 7217/33 |
| 9x4,5" | 7216/15 | 7217/15 | 12x5" | 7216/34 | 7217/34 |
| 9x5" | 7216/16 | 7217/16 | 12x6" | 7216/35 | 7217/35 |
| 9x6" | 7216/17 | | 12x7" | 7216/36 | |
| 9,5x4,5" | 7216/18 | 7217/18 | 13x5" | 7216/40 | 7217/40 |
| 10x4,5" | 7216/20 | 7217/20 | 13x6" | 7216/41 | 7217/41 |
| 10x5" | 7216/21 | 7217/21 | 13x7" | 7216/42 | 7217/42 |
| 10x6" | 7216/22 | | 13x8" | 7216/43 | 7217/43 |
| 10x7" | 7216/23 | | 14x5" | 7216/46 | 7217/46 |
| 11x4,5" | 7216/27 | 7217/27 | 14x6" | 7216/47 | 7217/47 |
| 11x5" | 7216/28 | 7217/28 | 14x8" | 7216/50 | |
| 11x6" | 7216/29 | | 14x9" | 7216/51 | |
| 11x7" | 7216/30 | | 15x6" | 7216/53 | 7217/53 |

# VTOL Configuration - Hover Stability

## Creating the model using Aircraft Dynamics, trim condition is steady level hover.

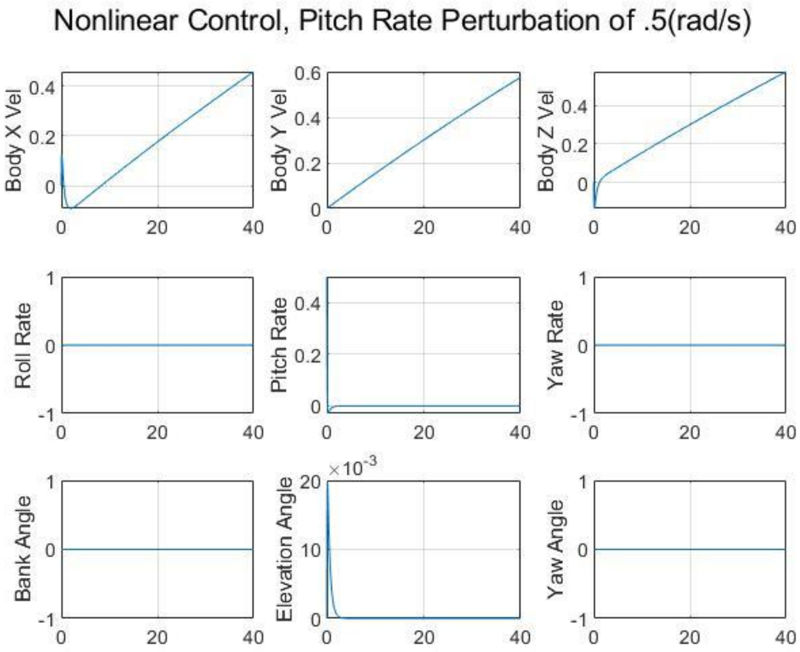



**The Process**

- Net moments and forces found from free body diagrams
- Thrust and tilt angle to achieve trim conditions
- Linear Proportional gain control applied to nonlinear equations
- Nonlinear Aircraft Dynamics equations solved using numerical integrator

# VTOL Configuration: Hover Stability, Results and Verification

## Results

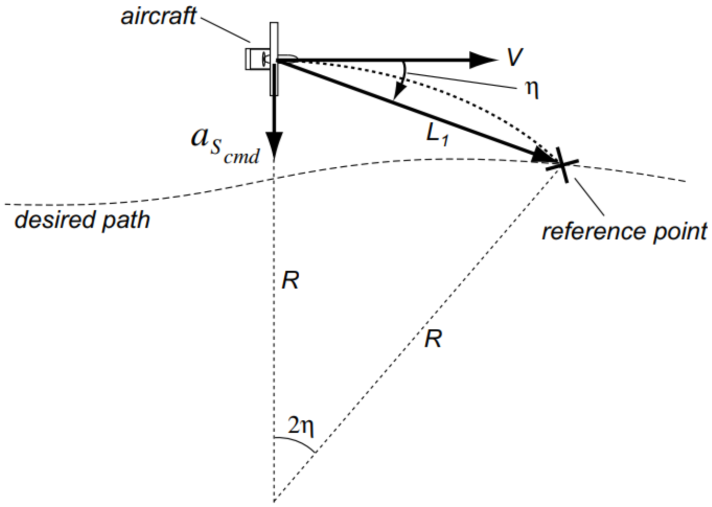


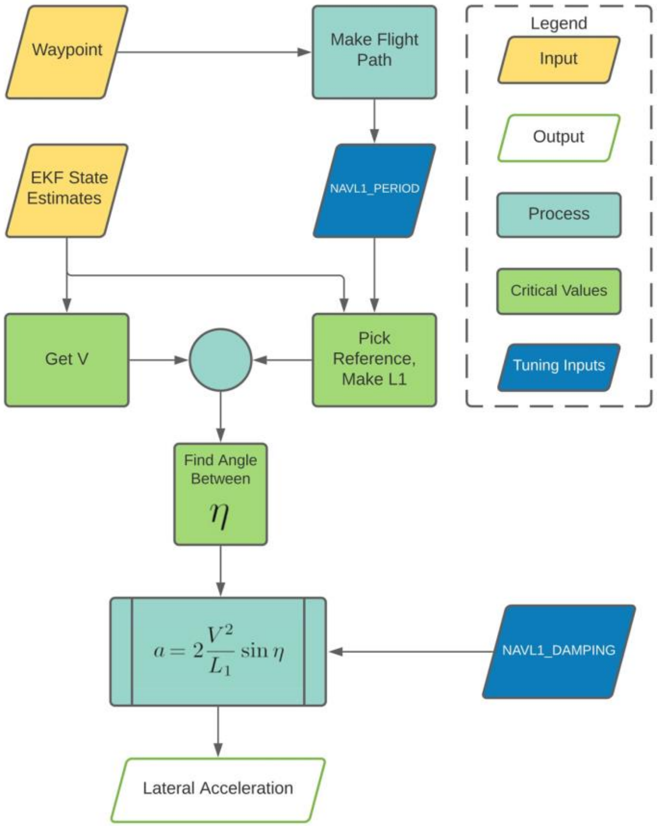

## Verification

- Steady trim condition is met (L,M,N=0)
- Lack of derivative/integral control is apparent
- Analysis uses code taught by Professor Lawrence (ASEN 3128)
- Only difference was FBD forces/moments. Which were verified

# ArduPlane - L1 Controller



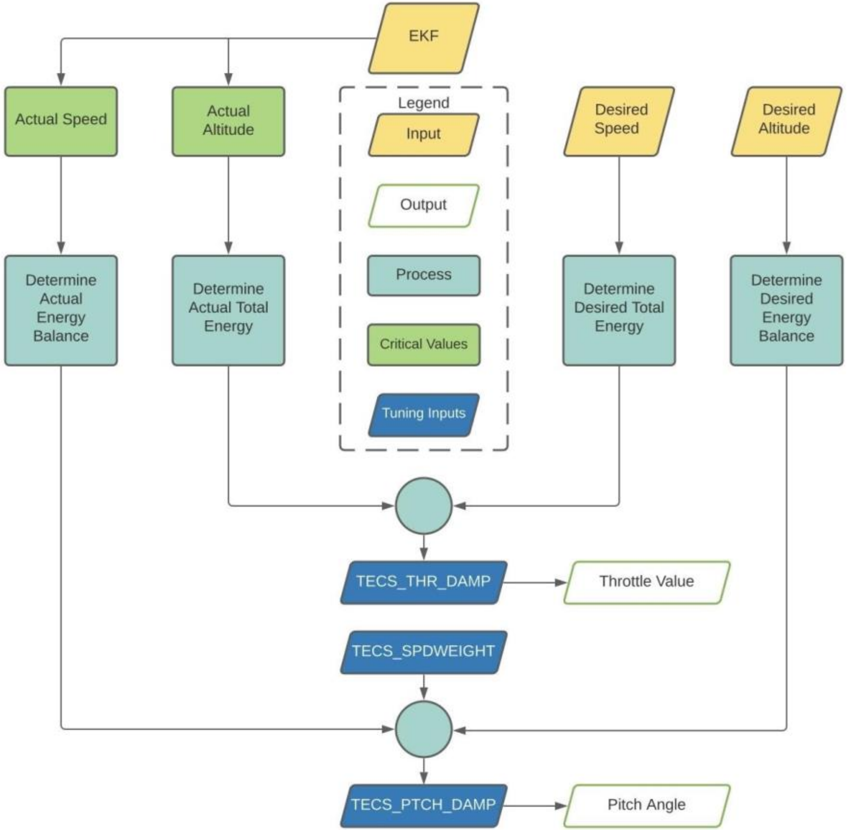



https://pdfs.semanticscholar.org/c9bd/e4cac35afc70379a02adc1d977ec1aadd07f.pdf

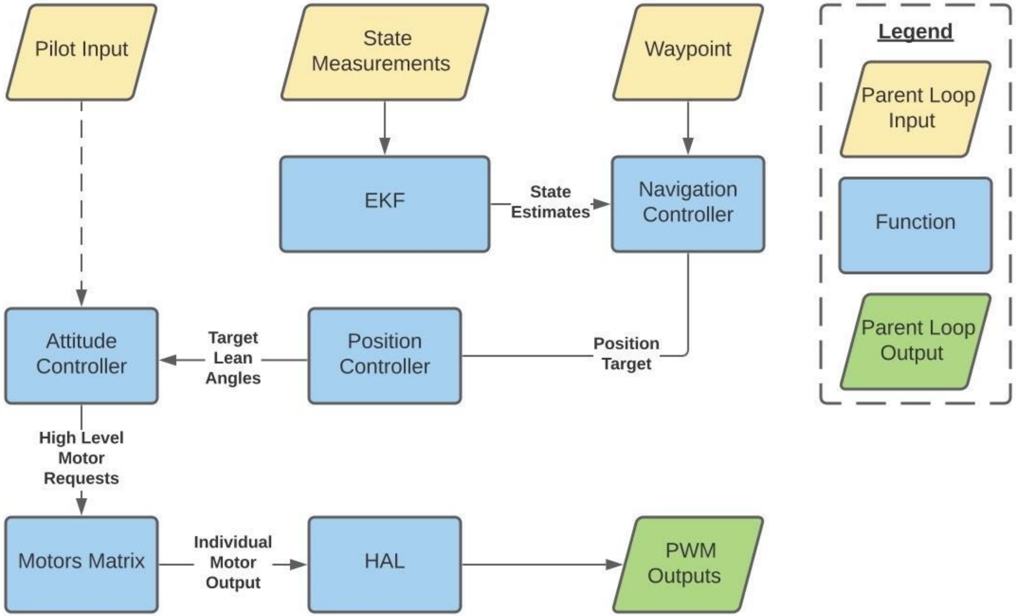
# ArduPlane - TECS Controller



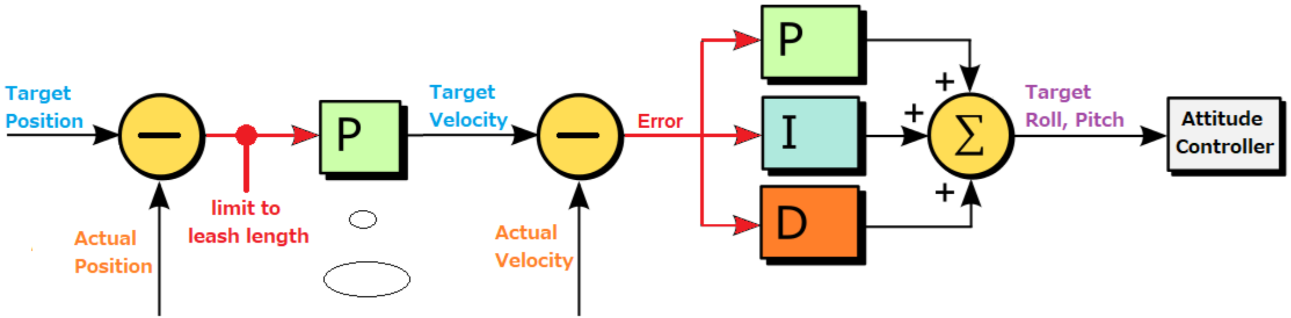


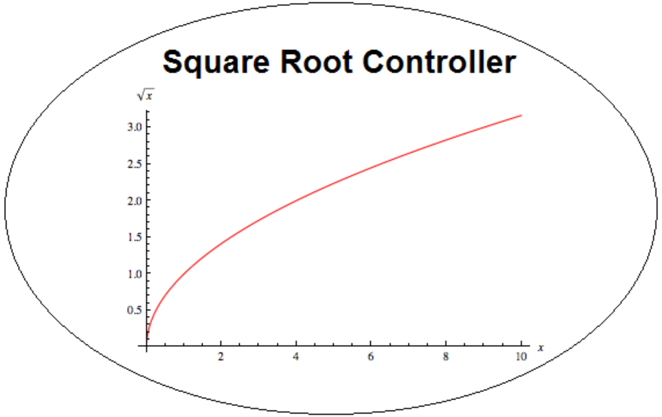
# Ardupilot - Copter Parent Code





# Copter Navigation Controller




$$Leash = \frac{acceleration}{(2 * P^2)} + \frac{speed^2}{2 * acceleration}$$

**Actual Parameter Defaults**

PSC_POSXY_P = 1

PSC_VELXY_P = 2

PSC_VELXY_I = 1

PSC_VELXY_D = 0.5

https://ardupilot.org/dev/docs/code-overview-copter-poscontrol-and-navigation.html

# Tilt Rotor Stability: Nonlinear, Time -Variant Dynamics



**Challenges**

1) Must handoff from thrust based commands to surface deflection based commands
2) Low speed is difficult flight regime
3) Mid tilt coupling
    - Differential thrust couples roll and yaw
    - Symmetric thrust couples altitude and airspeed.
        - Vertical thrust and lift both contribute to net vertical force
4) Possible to not generate enough lift

**Solutions**

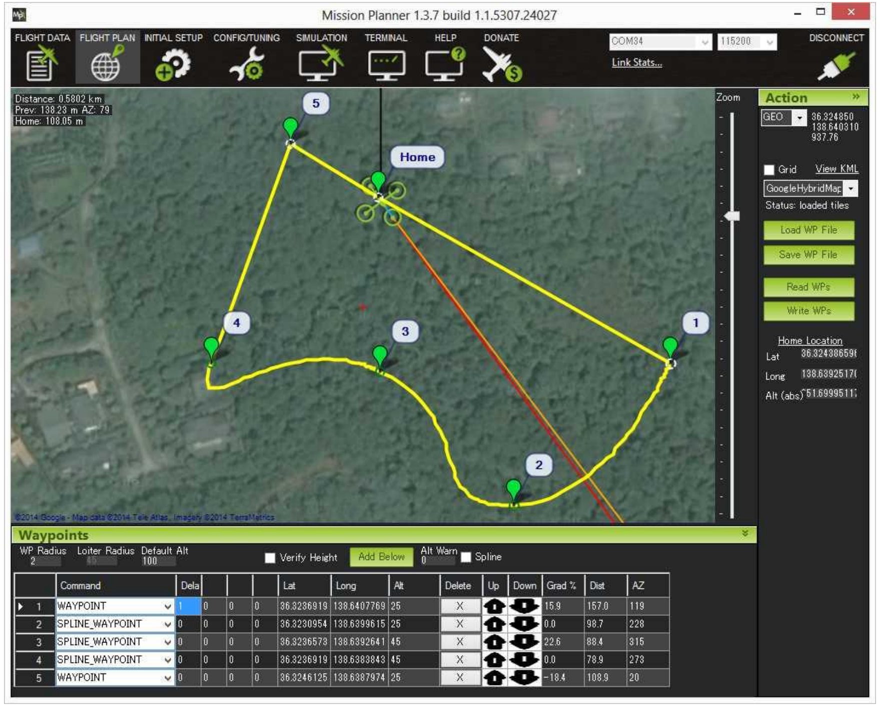
1) Redundant control outputs (function of thrust/airspeed) must be suppressed
2) Arducopter architecture to stabilize at low speeds.
3) Angle controller demands two inputs (yaw + roll) that result in one output (roll).
    - Manipulate rate errors to eliminate cross coupling
4) Thrust vector angle limiting
    - Limit lowest angle to ensure net vertical force preserves climb capability

# RAPCat - Ardupilot Implementation

- TKOFF_THR_MINACC - Minimum acceleration required to engage throttle
- TKOFF_THR_DELAY - Additional time delay to prevent rotor interference with catapult
- Auto takeoff mission command - throttle begins suppressed until conditions are satisfied

# Flight Controller Firmware (Ardupilot) Feasibility






## Mission Resources

- Graphic User Interface (GUI) with waypoints and events called Mission Planner
- Autonomous Takeoffs & Landings at GPS coords.
- Includes Loiter function desired by customer

## Developer Resources

- Open source code
- Assistance in learning, testing, and debugging code
- Integrating companion computers as well as a huge amount of additional hardware

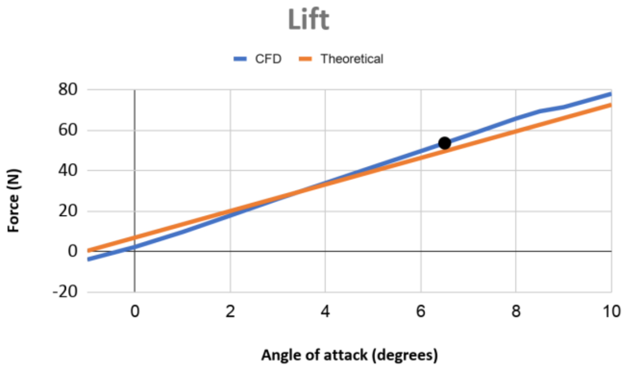
# Ardupilot Feasibility - Tilt Rotor Example

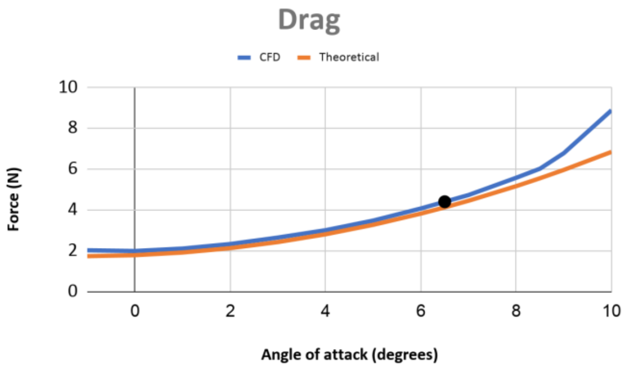


**<u>The firmware is feasible</u>** for the chosen flight configuration and mission profile

Source: https://youtu.be/WMh8BiOLrns

# Endurance Verification Part 1 - Drag Estimation




**Design Variables**

m = 5.4 kg
V ≈18 m/s

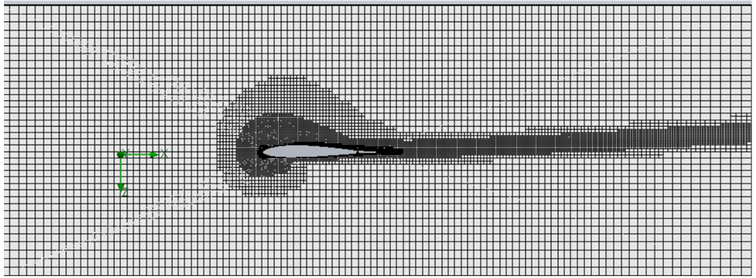
**Theoretical Calculation**

Vortex Panel and Prandtl Lifting Line Theory

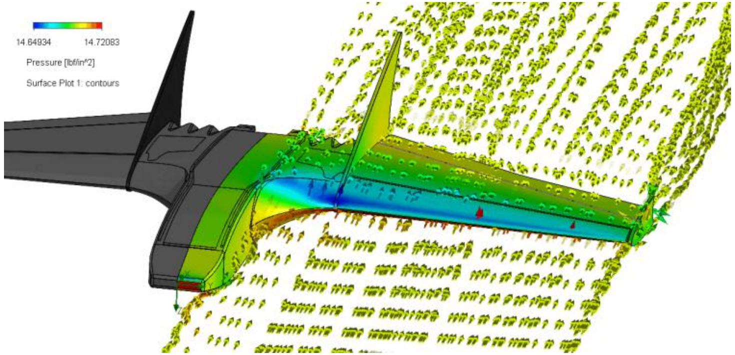
**Solidworks Flow Simulation**

Stock Drak
2 Million cell mesh
Mesh convergence study is ongoing

**AOA ≈ 6.5°**
**D ≈ 4.4 N**
**L ≈ 55 N**



Mesh Cut Plot




Flow Simulation

# Endurance Verification Part 2 - Propulsion Specifications

**Motors & Props (each)**

*SunnySky X Series V3 X3520 780Kv (APC 14x7)**

***Based on 1.5 FOS*

**Batteries (total)**

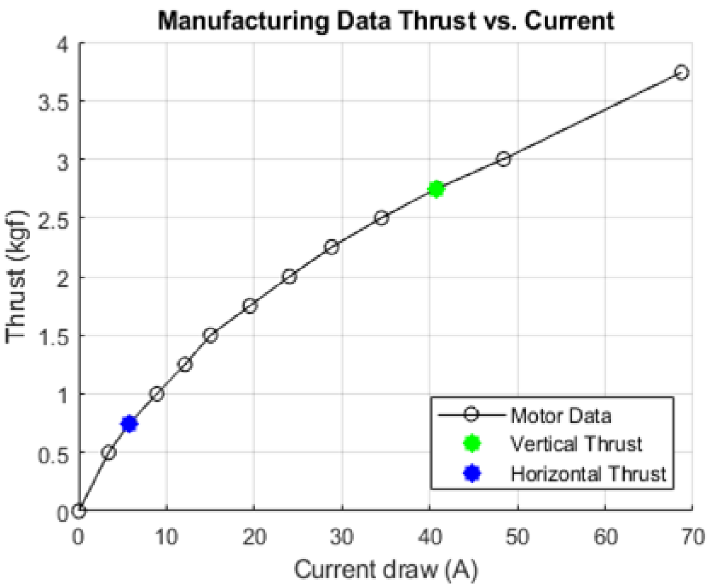
*Samsung 40T 21700 4000mAh 35A**

**Based on 4s8p pack**

| Flight Mode | Thrust Required | Power Required | Current Required | Total Capacity | Estimated Life |
|---|---|---|---|---|---|
| VTOL flight | 2.75 kgf** | 603.8 W | 40.8 A | 32 Ah | 15.6 min |
| Horizontal Cruise | 0.25 kgf** | 35 W | 2 A | 32 Ah | 320 min |

**Placeholder components for feasibility*

$$\text{Endurance [h]} = \frac{\text{Capacity [Ah]}}{\text{Current [A]}}$$




**Remaining Battery = 17%**
8 minutes of VTOL flight
60 minutes of Horizontal Cruise

# Endurance Verification Part 3 - Batteries

Samsung 40T Lithium ion battery cell

- Customized battery pack
- Optimizable

**4 series 8 parallel battery pack**
Meets expected motor voltage, current, and capacity

**Battery Design and Estimations**

| | Per cell | Total pack |
|---|---|---|
| **Size (L x W x Z)** | 21 x 21 x 70.0mm | 84 x 147 x 70.0mm (3.3 x 5.8 x 2.7in) |
| **Reviewed Capacity** | 3800 mAh | 30,400 mAh |
| **Reviewed Max Current** | 25 A | 200 A |
| **Weight** | 67 g | 2,144 g |
| **Cost** | $5.75 | $184 |

# Testing and Verification



| Functional Requirement | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| **FR1: VTOL Conversion** | Thrust Validation: Show in static testing that propulsion system can produce sufficient thrust to lift aircraft | Flight Test: Demonstrate transition to horizontal mode from takeoff and back to vertical | |
| **FR2: Endurance** | Static Test: Verify that the aircraft can run for 1 hour while statically mounted. | Hover Endurance: Perform a tethered hover for 4 minutes or until failure. | Flight Endurance: Perform a full mission demonstration as outlined in the CONOPS. |
| **FR3: Autonomy** | Flight Controller Verification: Verify that the flight controller can command the aircraft's control surfaces and propulsion system. | Mission Verification: While mounted, show that the flight controller can execute full mission profile including transitions without pilot input. | Vertical Accuracy Verification: Show that the LiDAR data is accurate to <10cm. |

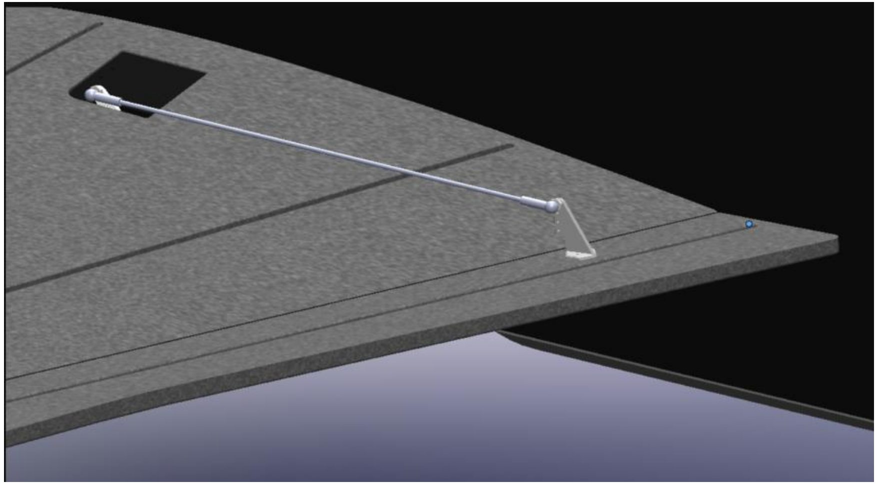
# Testing and Verification (cont.)



| Functional Requirement | Test 1 | Test 2 |
|---|---|---|
| **FR4: Communication** | Ground Test: Show that the Ground Station can receive telemetry data up to 2 km with <50% packet loss. | Data Verification: Verify that the received data matches the data stored on the onboard SD card. |
| **FR5: Payload** | Validation: All verification tests involving flight, power, or endurance will be performed with and without the 0.5kg payload. | |
| **FR6: RAPCat** | Compatibility Verification: Without launching, show that the modified Drak is capable of interfacing with the RAPCat launch system. | Force Analysis: Using models, show that the aircraft can withstand axial loading of 5G and vertical loading of 10G without plastic deformation. |

# Mission Execution and Mechanisms Verification





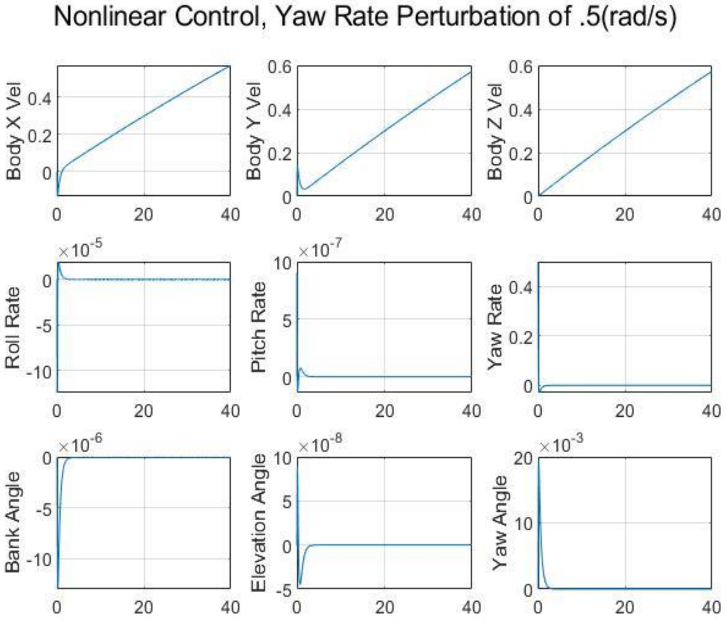
*Drak Elevon*

| | |
|---|---|
| **Test Description:** | Actuate servos using a transmitter to monitor motor tilt and CS deflection and monitor power draw. |
| **Objective:** | Servo deflection, max CS throw, power draw on avionics package, control computer verification |
| **Key Measurements:** | Servo/CS deflection [deg]<br>Power Draw [V,I] |
| **Expected Value:** | CS throw: 25 deg<br>Servo Def: 45 deg |
| **Requirements Verified:** | FR1, FR2, FR3 |
| **Location:** | Pilot Lab |

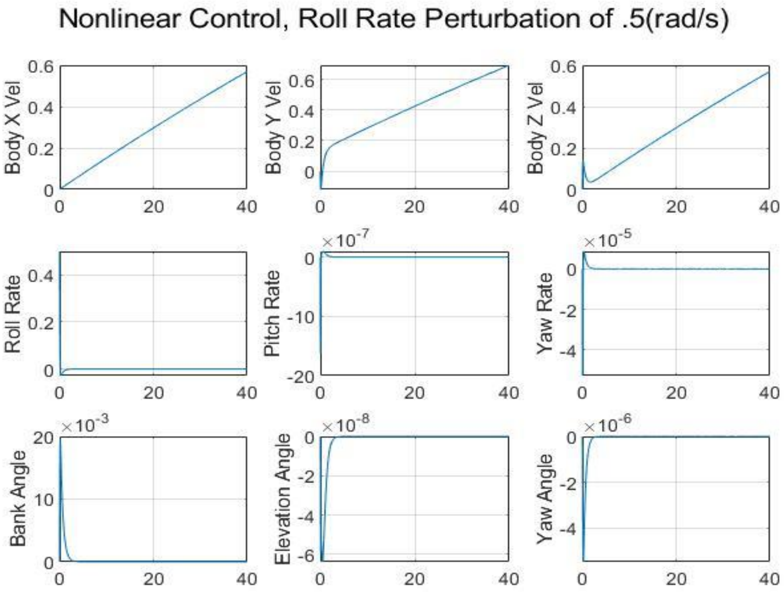
# Avionics: Ports Required vs Ports Available



| Port | Available | Required | Peripheral | Protocol | Pinouts |
|---|---|---|---|---|---|
| I2C | 2 | 0 | N/A | Synchronous Serial | 5V SCL SDA GND |
| Telem | 1 | 1 | Custom Telemetry Package | Combined UART + I2C | 5V Tx Rx SCL SDA GND |
| GPS | 1 | 1 | Here2 GNSS GPS | Combined UART + I2C | 5V Tx Rx SCL SDA GND |
| Main Output | 8 | 7 | 2 Tilt Servos, 2 Elevon Servos, 3 ESCs | PWM | 5V Signal GND |
| Auxiliary Output | 6 | 0 | N/A | PWM | 5V Signal GND |
| UART | 1 | 1 | LeddarOne LiDAR | Asynchronous Serial | 5V Tx Rx GND |
| Power 1 | 1 | 1 | Direct Battery Voltage | N/A | 5V GND |
| Power 2 | 1 | 1 | 5V Step Down | N/A | 5V 5V CURR VOLT GND GND |
| RC In | 1 | 1 | Futaba SBUS RC Receiver | SBUS | 5V Signal GND |
| Micro USB | 1 | 1 | Connection to Mission Planner | N/A | N/A |



Nonlinear Control, Yaw Rate Perturbation of .5(rad/s)
Body X Vel
Body Y Vel
Body Z Vel
Roll Rate
Pitch Rate
Yaw Rate
Bank Angle
Elevation Angle
Yaw Angle

Nonlinear Control, Roll Rate Perturbation of .5(rad/s)
Body X Vel
Body Y Vel
Body Z Vel
Roll Rate
Pitch Rate
Yaw Rate
Bank Angle
Elevation Angle
Yaw Angle

# Backup Slides: VTOL Configuration, Hover Stability



$$X_0 + \Delta X - mg(\sin\theta_0 + \Delta\theta\cos\theta_0) = m\Delta\dot{u} \qquad (a)$$
$$Y_0 + \Delta Y + mg\phi\cos\theta_0 = m(\dot{v} + u_0 r) \qquad (b)$$
$$Z_0 + \Delta Z + mg(\cos\theta_0 - \Delta\theta\sin\theta_0) = m(\dot{w} - u_0 q) \qquad (c)$$
$$L_0 + \Delta L = I_x\dot{p} - I_{zx}\dot{r} \qquad (a)$$
$$M_0 + \Delta M = I_y\dot{q} \qquad (b)$$
$$N_0 + \Delta N = -I_{zx}\dot{p} + I_z\dot{r} \qquad (c)$$
$$\dot{\theta} = q \qquad (a)$$
$$\dot{\phi} = p + r\tan\theta_0, \qquad p = \dot{\phi} - \dot{\psi}\sin\theta_0 \qquad (b)$$
$$\dot{\psi} = r\sec\theta_0 \qquad (c)$$
$$\dot{x}_E = (u_0 + \Delta u)\cos\theta_0 - u_0\Delta\theta\sin\theta_0 + w\sin\theta_0 \qquad (a)$$
$$\dot{y}_E = u_0\psi\cos\theta_0 + v \qquad (b)$$
$$\dot{z}_E = -(u_0 + \Delta u)\sin\theta_0 - u_0\Delta\theta\cos\theta_0 + w\cos\theta_0 \qquad (c)$$

$$\overline{G_B} = \begin{bmatrix} L \\ M \\ N \end{bmatrix}$$

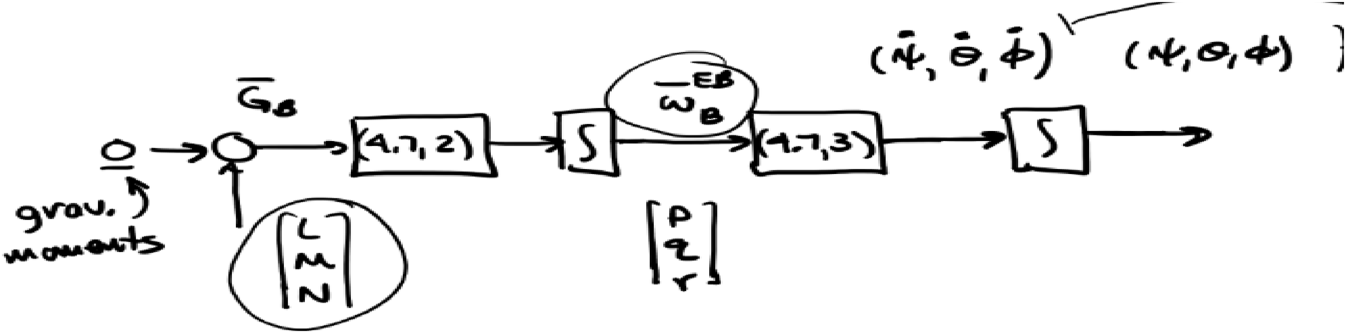
$$\overline{w_B^{EB}} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$I_B \frac{d}{dt}\overline{w_B^{EB}} + \overline{w_B^{EB}}\mathbf{x}(I_B \overline{w_B^{EB}}) = \overline{G_B}$$

$$\overline{f_d} = \frac{1}{2}\rho\left|\overline{V}\right| * \overline{V}$$

$$\overline{G_A} = -\alpha\left|\overline{W_B^{EB}}\right| * \overline{W_B^{EB}}$$

$$L_C = -kF_{1_z} - F_{1_z} l_1 \sin(\beta) + kF_{2_z} + F_{2_z} l_2 \sin(-\beta)$$
$$M_C = -F_{1_z} l_1 \cos(\beta) - F_{2_z} \cos(-\beta) + l_3 F_{3_z}$$
$$N_C = -kF_{1_z} + kF_{2_z} - kF_{3_z}$$
$$X_C = F_{1_x} + F_{2_x}$$
$$Z_C = F_{1_z} + F_{2_z} + F_{3_z}$$



# Fixed Wing Stability Verification



$$(C_{l_\beta})_F = -a_F\left(1-\frac{\partial\sigma}{\partial\beta}\right)\left(\frac{S_F\, z_{ac_F}}{S\, b}\right)\left(\frac{V_F}{V_\infty}\right)^2$$

$$(C_{l_\beta})_F = -a_F\left(1-\frac{\partial\sigma}{\partial\beta}\right)\left(\frac{S_F\, z_{ac_F}}{S\, b}\right)\left(\frac{V_F}{V_\infty}\right)^2$$

$RAD^{-1}$ $\approx 1$

$$(C_{l_\beta})_\Lambda \approx -2(C_L)_{wing}\left(\frac{y_{ac_w}}{b}\right)\sin(2\Lambda_{LE})$$

NEG AFT SWEEP + FWD SWEEP

LIFT COEF WING

WING SWEEP IN RAD!

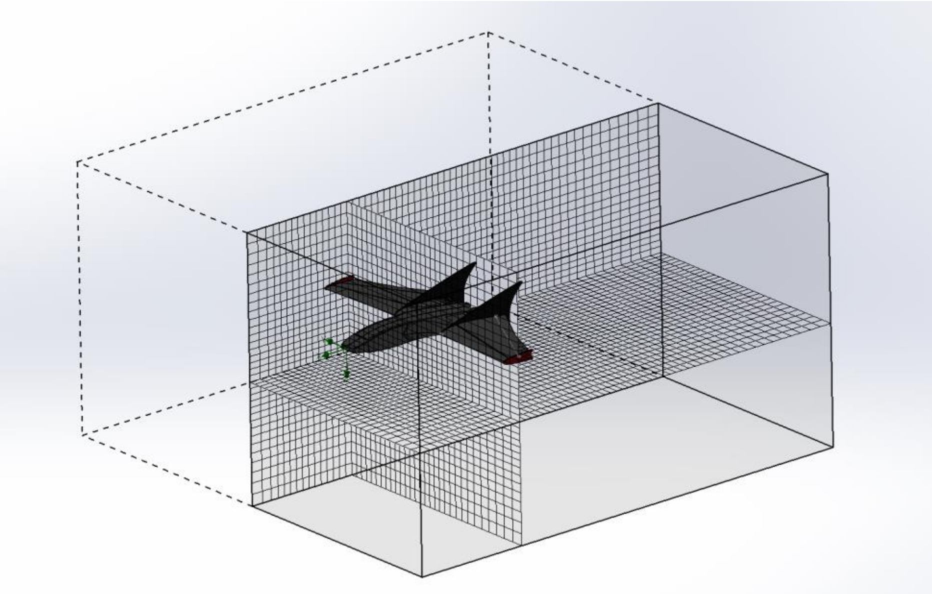
- Hand Calculation to estimate Clb and compare with XFLR5
- No dihedral effects, because there is no dihedral
- Hand Calc: Clb=-1.277
- XFLR5: Clb=-.13922

- XFLR5 uses well known methods for viscous/stability aircraft analysis
  - Euler and Rans methods
  - Low CFD numerical Errors
  - ARC study done showing it produces relatively well compared to similar programs

# Solidworks Flow Simulation

Basic Mesh and Computational Domain:

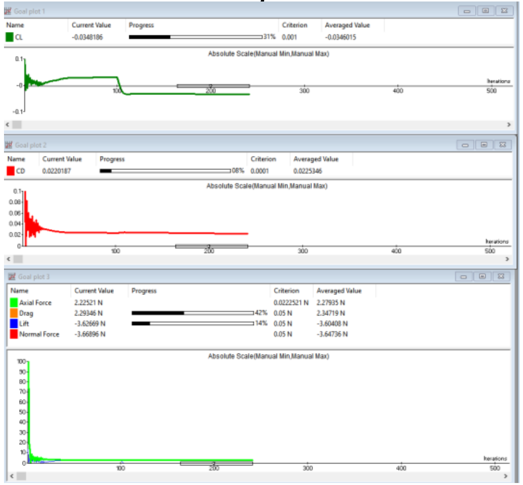
- Takes advantage of symmetry



Initial Conditions:

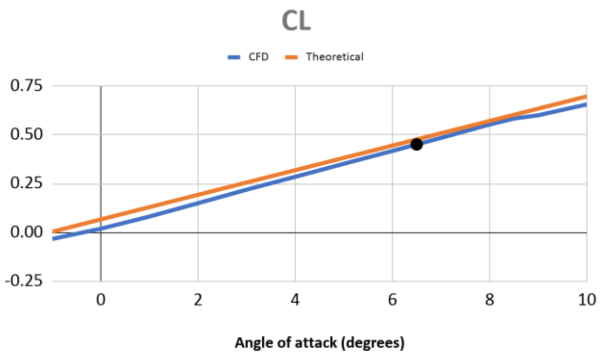
| Parameter | Value |
|---|---|
| Parameter Definition | User Defined |
| Thermodynamic Parameters | |
| Parameters | Pressure, temperature |
| Pressure | 83277.5 Pa |
| Temperature | 277.594 K |
| Velocity Parameters | |
| Parameter | Velocity |
| Defined by | Aerodynamic angles |
| Velocity | -18 m/s |
| Longitudinal plane | ZX |
| Longitudinal axis | X |
| Angle of attack | 0.5 ° |
| Angle of sideslip | 0 ° |
| Turbulence Parameters | |

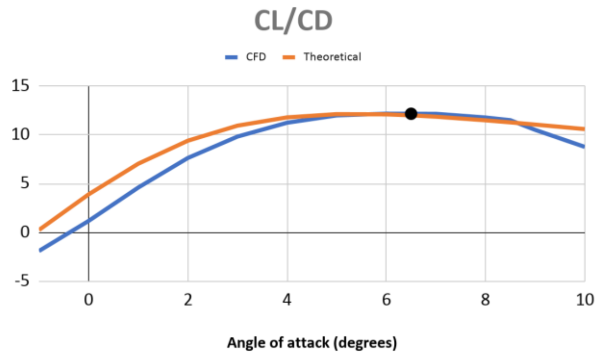
Results Convergence at AoA = -1° at ~300,000 cells

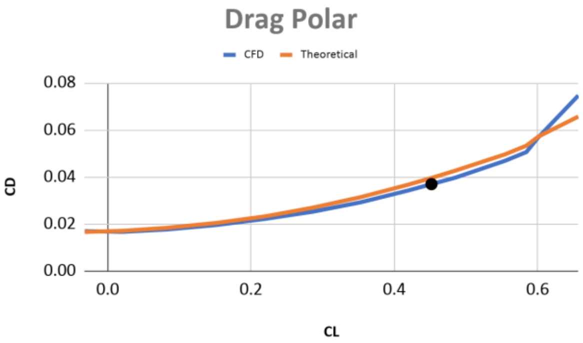


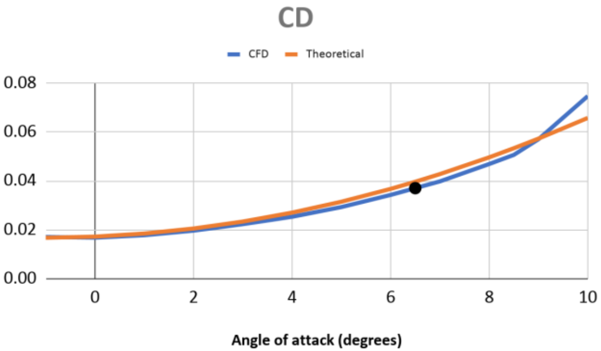
# Stock Drak CFD Results

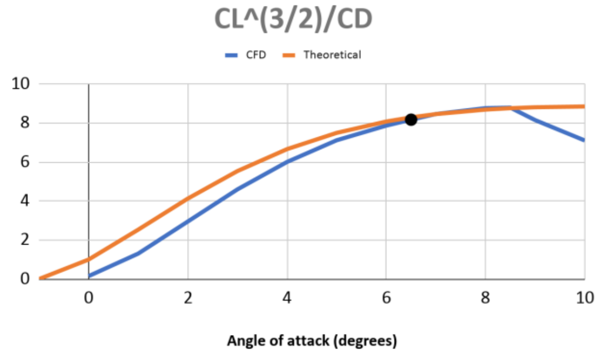





Design Point

- m = 5.9 kg
- AOA ≈ 7°
- D ≈ 4.7 N

# Mesh convergence study

Motivation:

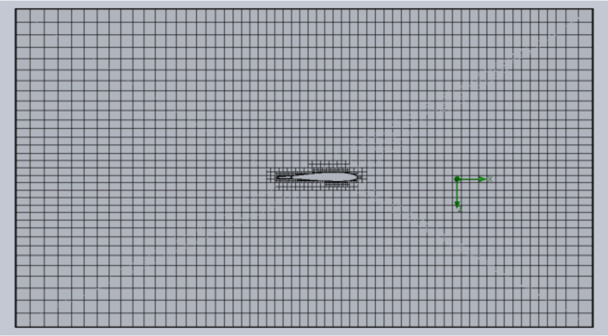
- Mesh creation is critical to CFD simulation
- Balance computational time and accuracy

Procedure

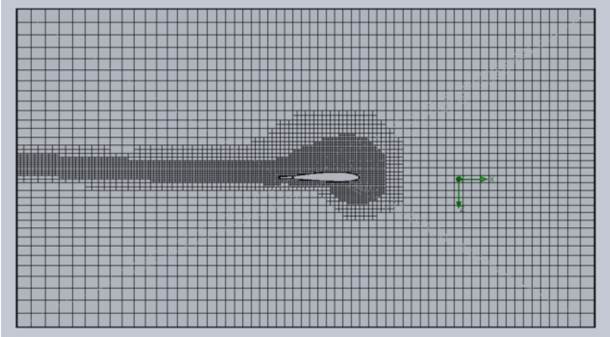
1. Run meshes at different sizes and degree of refinement
2. Compare results and computational time

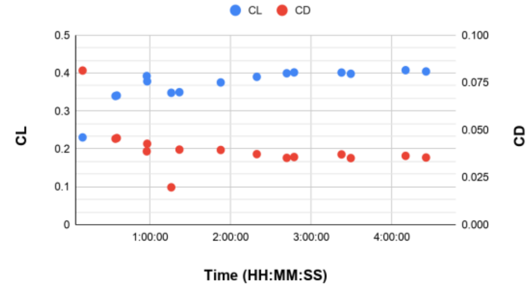
Using SolidWorks' built in mesh refinement system

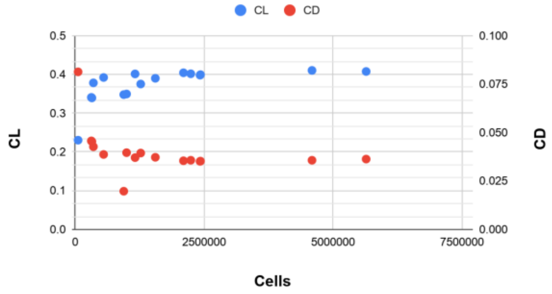
Before:



After:



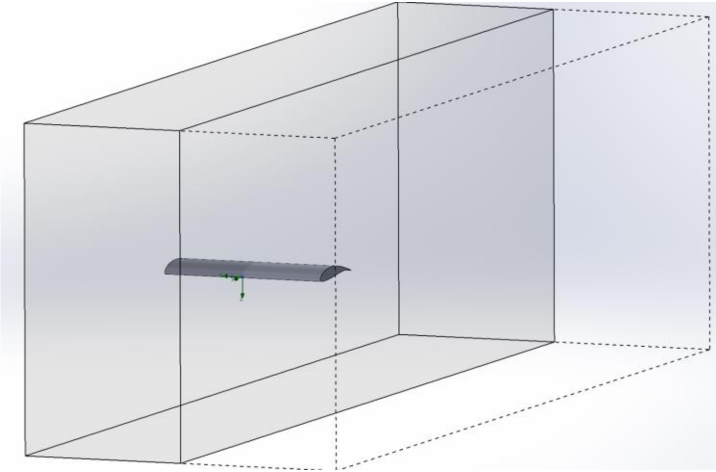


# CFD Drag Verification

Verification model: Existing data

- 1985 AGARD Report: Low Reynolds Number Vehicles
- 3D finite wing
- Re: 200000 (Sim Re: 228112)
- Airfoil: Wortmann FX 63-137
- AR: 2



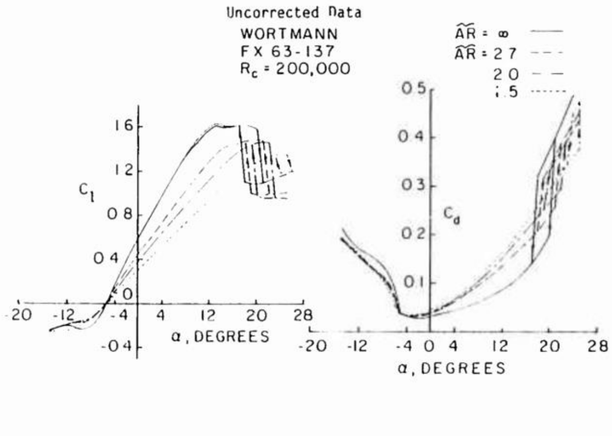
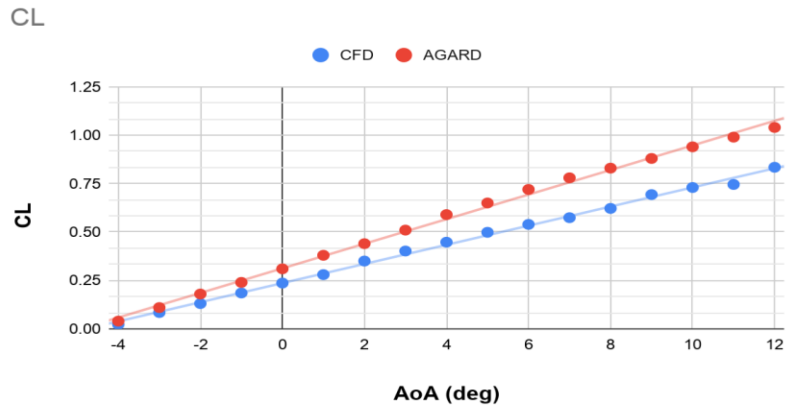


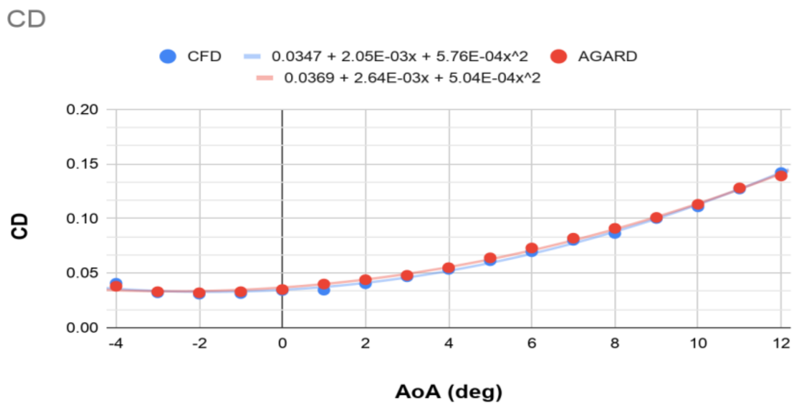

Figure 68. The Effect of Semi-Span Aspect Ratio on the Rectangular Wing Lift and Drag Coefficients versus Angle of Attack for $R_c$ = 200,000.

# CFD Drag Verification (cont.)



Results at finest mesh




| | Lift Slope ($Deg^{-1}$) | %Dif | CD0 | %Dif | k | %Dif | Drag SEM |
|---|---|---|---|---|---|---|---|
| AGARD | 0.0628 | - | 0.0333 | - | 0.144 | - | - |
| CFD | 0.0487 | 22.445% | 0.0324 | 2.493% | 0.281 | 94.44% | 0.00567 |

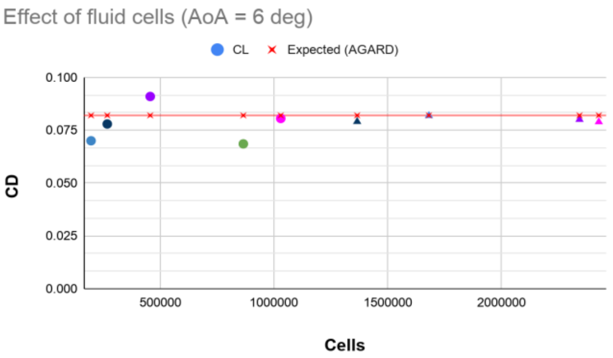
# CFD Drag Convergence

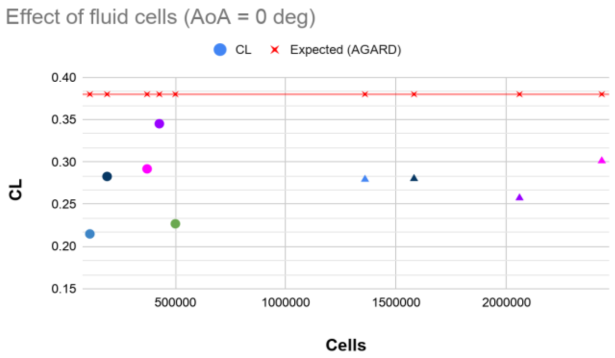


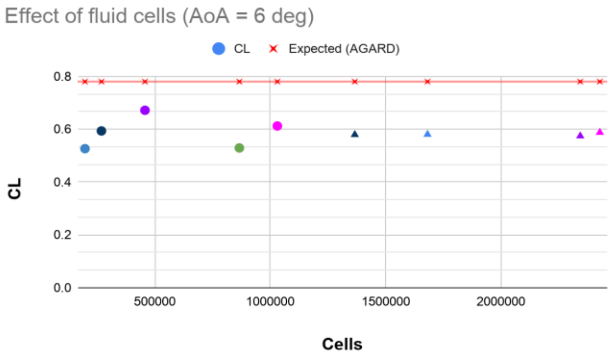
Results over various meshes

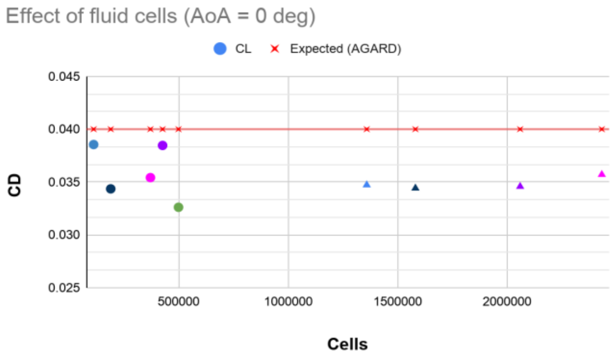
Circles: 2 Refinements
Triangles: 4 Refinements

| Color | Mesh |
|---|---|
| Blue | Small |
| Dark Blue | Small Fine |
| Purple | Small Very Fine |
| Green | Very Small |
| Magenta | Very Small Fine |



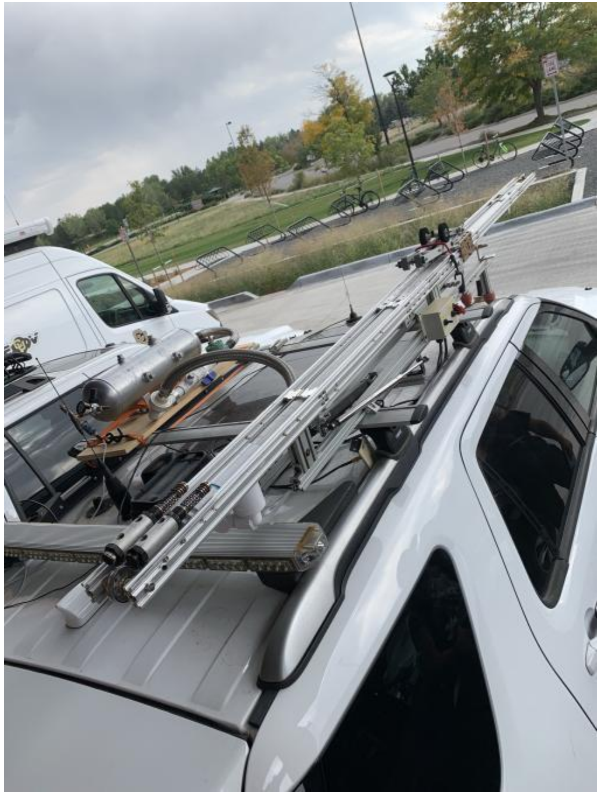
# CFD Mesh Definitions



| Name | Basic size | Solid border refine | Solid Small Feature | Curvature Level | Curvature Criterion | Fluid Cells | Solid Cells |
|---|---|---|---|---|---|---|---|
| Big Baseline | 0.15 m | 3 | 3 | 3 | 3 deg | | |
| Baseline | 0.10 m | 3 | 3 | 3 | 3 deg | 19613 | 6209 |
| Baseline Fine | 0.1 m | 4 | 4 | 4 | 3 deg | 56824 | 25344 |
| Baseline Very Fine | 0.1 m | 5 | 5 | 5 | 3 deg | | |
| Small Baseline | 0.05 m | 3 | 3 | 3 | 3 deg | 112451 | 27468 |
| Small Baseline Fine | 0.05 m | 4 | 4 | 4 | 3 deg | 272836 | 110183 |
| Small Baseline Very Fine | 0.05 m | 5 | 5 | 5 | 3 deg | 900742 | 442752 |
| Very Small Baseline | 0.025 m | 3 | 3 | 3 | 3 deg | 689563 | 110137 |
| Very Small Baseline Fine | 0.025 m | 4 | 4 | 4 | 3 deg | 1335361 | 442674 |
| Very Small Baseline Very Fine | 0.025 m | 5 | 5 | 5 | 3 deg | 4124336 | 1772291 |

# RAPCat Launch System Images





# Objectives & Levels of Success



| | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| **Flight** | Static test stand TWR > 1 | Steady hover for 30 sec<br><br>Static test stand flight mode transition | Takeoff from RAPCat<br><br>Full flight mode transition |
| **Budget** | Replication cost <$1250 | Replication cost <$1000 | Replication cost <$900 |
| **Endurance** | Static thrust for 1 hour cruise, 2 takeoffs/ landings with >15% battery remaining | N/A | Full flight 1 hour cruise with 2 takeoffs/landings with >15% battery remaining |

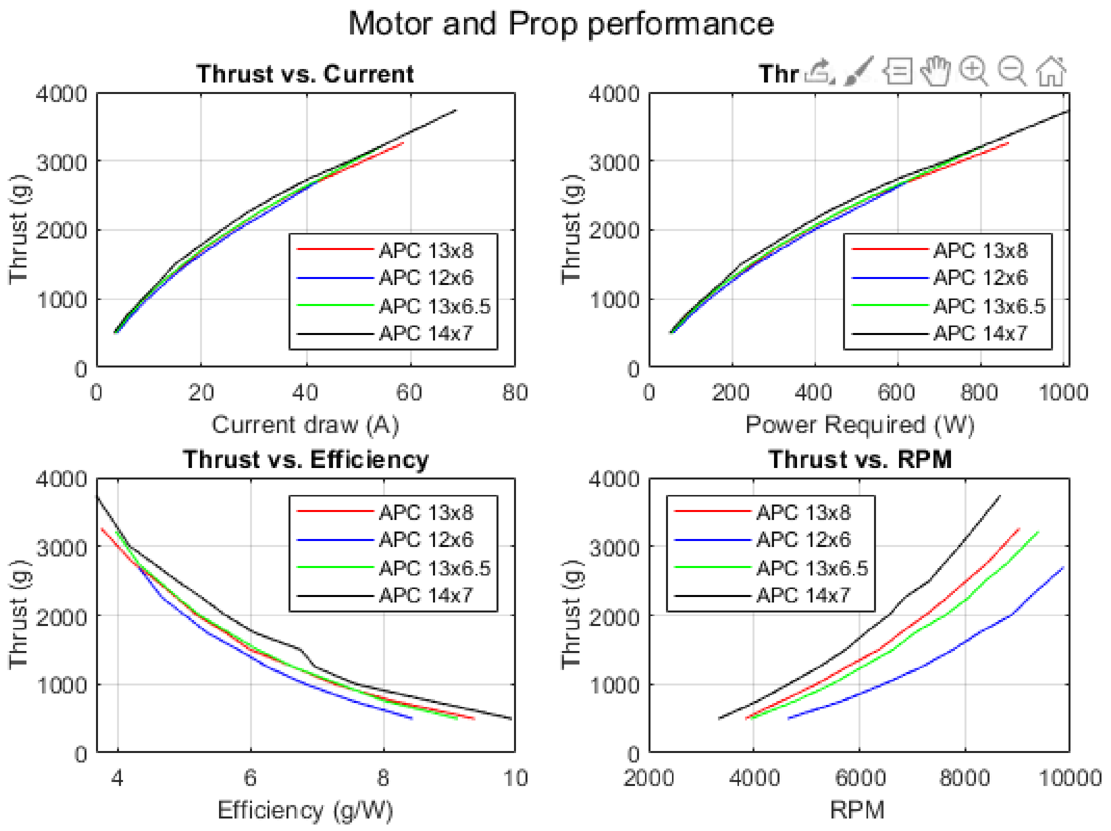
**Safety:** Autonomous return-to-loiter function if telemetry lost for 90 seconds. Ability to terminate flight immediately upon ground station command.

# Objectives & Levels of Success Cont.



| | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| **Airframe** | FEM analysis of modified airframe for RAPCat launch (~10g) | Compatibility with RAPCat launch system | Survival of physical load testing of aircraft up to 10g |
| **Avionics** | Motors and actuators integrate with flight controller hardware and firmware | Non-native sensors and MCUs integrate with flight controller hardware and firmware | N/A |
| **Autonomy** | Models show stability for VTOL and fixed wing flight modes | Executes VTOL without further pilot input | Executes full mission profile with transition between flight modes<br><br>Lands within 1.5m radius |

# Power Budget



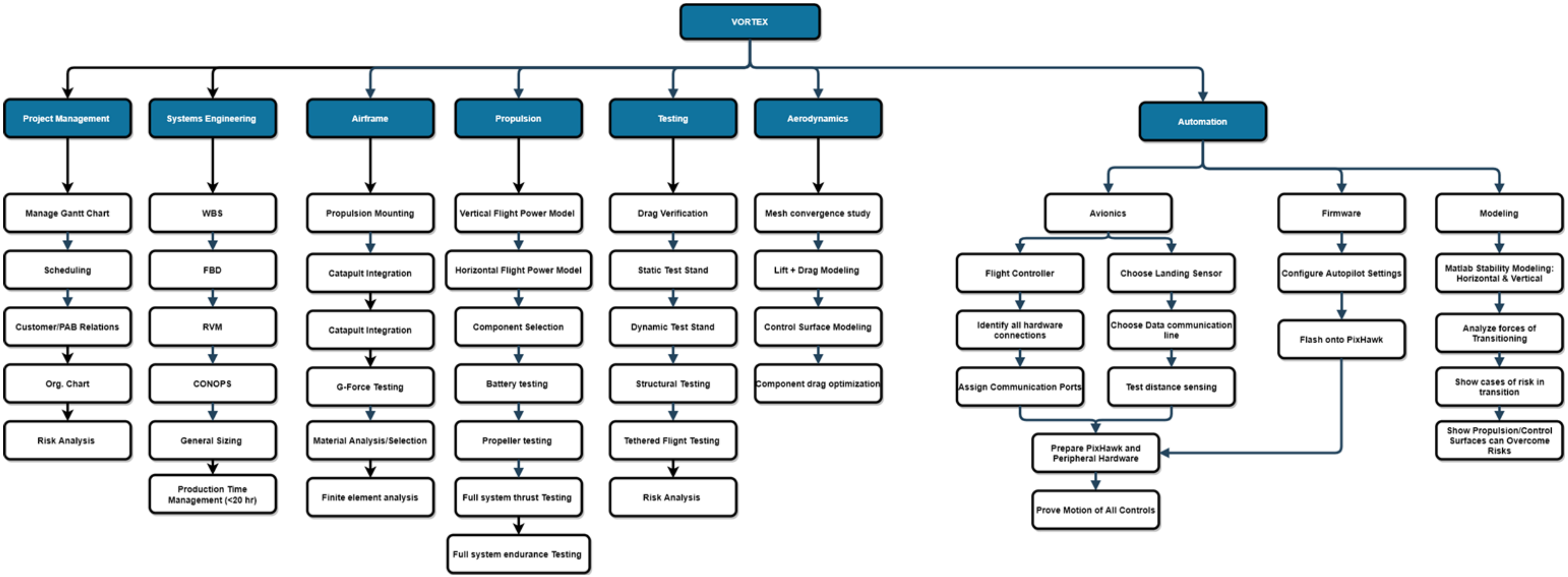
# Battery Study



| Battery Name | attery cell weight ( | attery cell voltage (' | attery cell capacity (mA | ax current draw (/ | attery cell cost (: | st. min lifetime (mi | otal pack weight (( | otal max current (/ | otal capacity (mA | otal voltage (\ | otal cost ($ | Link |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Panasonic NCR18650 | 47.5 | 3.6 | 3400 | 4.9 | 4.5 | 41.63 | 1140 | 29.4 | 20400 | 14.4 | 108 | https://www.1865 |
| Efest 18650 | 47 | 3.7 | 3500 | 20 | 7 | 10.50 | 1128 | 120 | 21000 | 14.8 | 168 | https://www.1865 |
| Samsung 35E 18650 | 50 | 3.6 | 3500 | 8 | 4 | 26.25 | 1200 | 48 | 21000 | 14.4 | 96 | https://www.1865 |
| Sanyo NCR18650GA | 48 | 3.6 | 3500 | 10 | 4.25 | 21.00 | 1152 | 60 | 21000 | 14.4 | 102 | https://www.1865 |
| Samsung 35E 18650 | 48.5 | 3.6 | 3500 | 8 | 5.5 | 26.25 | 1164 | 48 | 21000 | 14.4 | 132 | https://www.1865 |
| Samsung 35E 18650 | 51 | 3.6 | 3500 | 8 | 5.5 | 26.25 | 1224 | 48 | 21000 | 14.4 | 132 | https://www.1865 |
| Panasonic NCR18650 | 47.5 | 3.6 | 3550 | 8 | 5.75 | 26.63 | 1140 | 48 | 21300 | 14.4 | 138 | https://www.1865 |
| Panasonic NCR18650 | 46 | 3.6 | 3400 | 4.9 | 5.5 | 41.63 | 1104 | 29.4 | 20400 | 14.4 | 132 | https://www.1865 |
| MXJO 18650 | 47.1 | 3.7 | 3500 | 10 | 7.5 | 21.00 | 1130.4 | 60 | 21000 | 14.8 | 180 | https://www.1865 |
| Panasonic NCR 1865( | 48.1 | 3.6 | 3400 | 4.9 | 6 | 41.63 | 1154.4 | 29.4 | 20400 | 14.4 | 144 | https://www.1865 |
| Imren 18650 | 46.9 | 3.7 | 3500 | 30 | 6.5 | 7.00 | 1125.6 | 180 | 21000 | 14.8 | 156 | https://www.1865 |
| Samsung 36G 18650 | 46 | 3.6 | 3600 | 10 | 6 | 21.60 | 1104 | 60 | 21600 | 14.4 | 144 | https://www.1865 |
| Vapcell 18650 | 46 | 3.7 | 3500 | 10 | 7.35 | 21.00 | 1104 | 60 | 21000 | 14.8 | 176.4 | https://www.1865 |
| Sanyo NCR18650GA | 46 | 3.6 | 3500 | 10 | 6 | 21.00 | 1104 | 60 | 21000 | 14.4 | 144 | https://www.1865 |
| Sanyo NCR18650GA | 46 | 3.6 | 3500 | 10 | 7 | 21.00 | 1104 | 60 | 21000 | 14.4 | 168 | https://www.1865 |
| Vapcell M34 18650 | 46 | 3.7 | 3400 | 10 | 8 | 20.40 | 1104 | 60 | 20400 | 14.8 | 192 | https://www.1865 |
| Epoch 18650 | 46 | 3.7 | 3500 | 10 | 7.25 | 21.00 | 1104 | 60 | 21000 | 14.8 | 174 | https://www.1865 |
| Epoch 18650 | 46 | 3.7 | 3500 | 8 | 7.25 | 26.25 | 1104 | 48 | 21000 | 14.8 | 174 | https://www.1865 |
| Samsung 40T 21700 | 66.8 | 3.6 | 4000 | 35 | 5.25 | 6.86 | 1603.2 | 210 | 24000 | 14.4 | 126 | https://www.1865 |
| Samsung 50E 21700 | 69 | 3.6 | 5000 | 9.8 | 5.1 | 30.61 | 1656 | 58.8 | 30000 | 14.4 | 122.4 | https://www.1865 |
| Molicel 21700 P42A | 67.8 | 3.6 | 4200 | 45 | 5.3 | 5.60 | 1627.2 | 270 | 25200 | 14.4 | 127.2 | https://www.1865 |
| Epoch 21700 | 68.2 | 3.7 | 5000 | 10 | 5.5 | 30.00 | 1636.8 | 60 | 30000 | 14.8 | 132 | https://www.1865 |
| Sony \| Murata VTC6A | 68.2 | 3.6 | 4000 | 30 | 7.49 | 8.00 | 1636.8 | 180 | 24000 | 14.4 | 179.76 | https://www.1865 |
| Epoch 21700 | 68 | 3.6 | 5000 | 10 | 7.25 | 30.00 | 1632 | 60 | 30000 | 14.4 | 174 | https://www.1865 |
| Molicel 21700 M50A | 68 | 3.6 | 5000 | 15 | 7 | 20.00 | 1632 | 90 | 30000 | 14.4 | 168 | https://www.1865 |

# Work Breakdown Structure





# Nomenclature

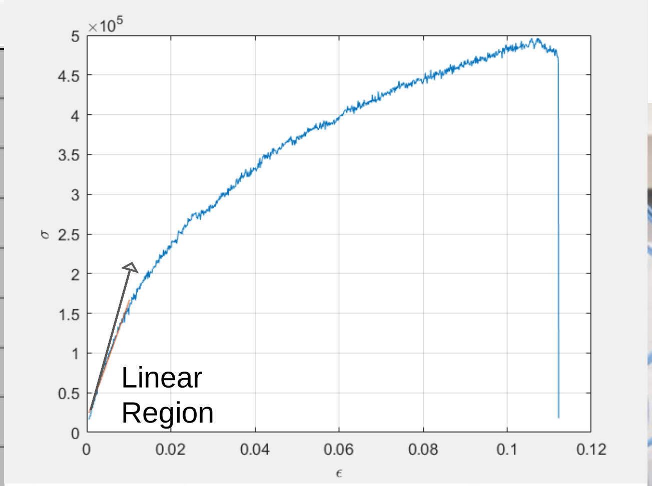


**IRISS** - Integrated Remote & In Situ Sensing
**TORUS** - Targeted Observation by Radars and UAS of Supercells
**VTOL** - Vertical Takeoff and Landing
**RAPCat** - Rapid Aircraft Pneumatic Catapult
**IMU** - Inertial Measurement Unit
**ESC** - Electronic Speed Controller
**Li-Ion** - Lithium Ion
**Li-Po** - Lithium Polymer
**NiMH** - Nickel Metal Hydride
**NiCd** - Nickel Cadmium
**LiFePO4** - Lithium Iron Phosphate

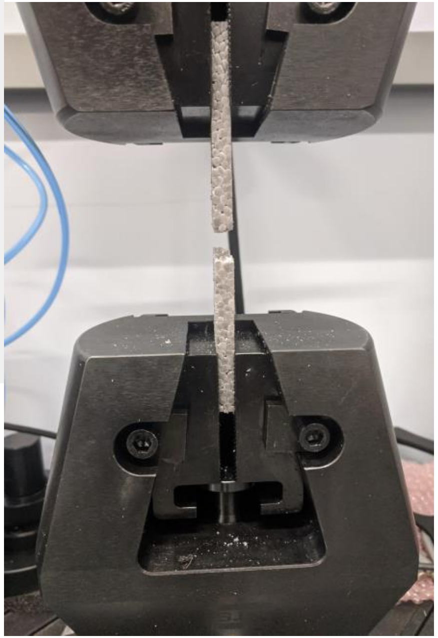
# Foam Properties



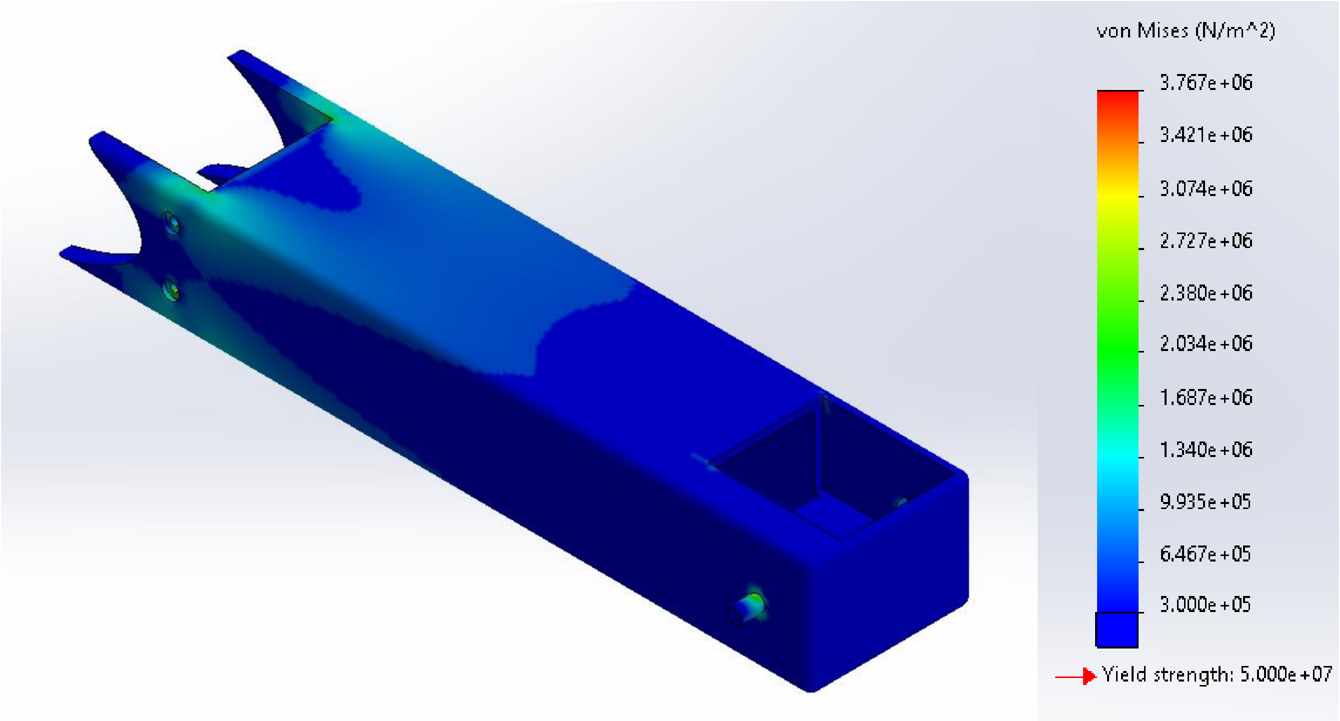
| Property | Value | Units |
|---|---|---|
| Elastic Modulus | 1.734e+10 | N/m^2 |
| Poisson's Ratio | 0.49999999 | N/A |
| Shear Modulus | 318900000 | N/m^2 |
| Mass Density | 40 | kg/m^3 |
| Tensile Strength | 600000 | N/m^2 |
| Compressive Strength | 180000 | N/m^2 |
| Yield Strength | 181000 | N/m^2 |
| Thermal Expansion Coefficient | | /K |
| Thermal Conductivity | | W/(m·K) |
| Specific Heat | | J/(kg·K) |
| Material Damping Ratio | | N/A |



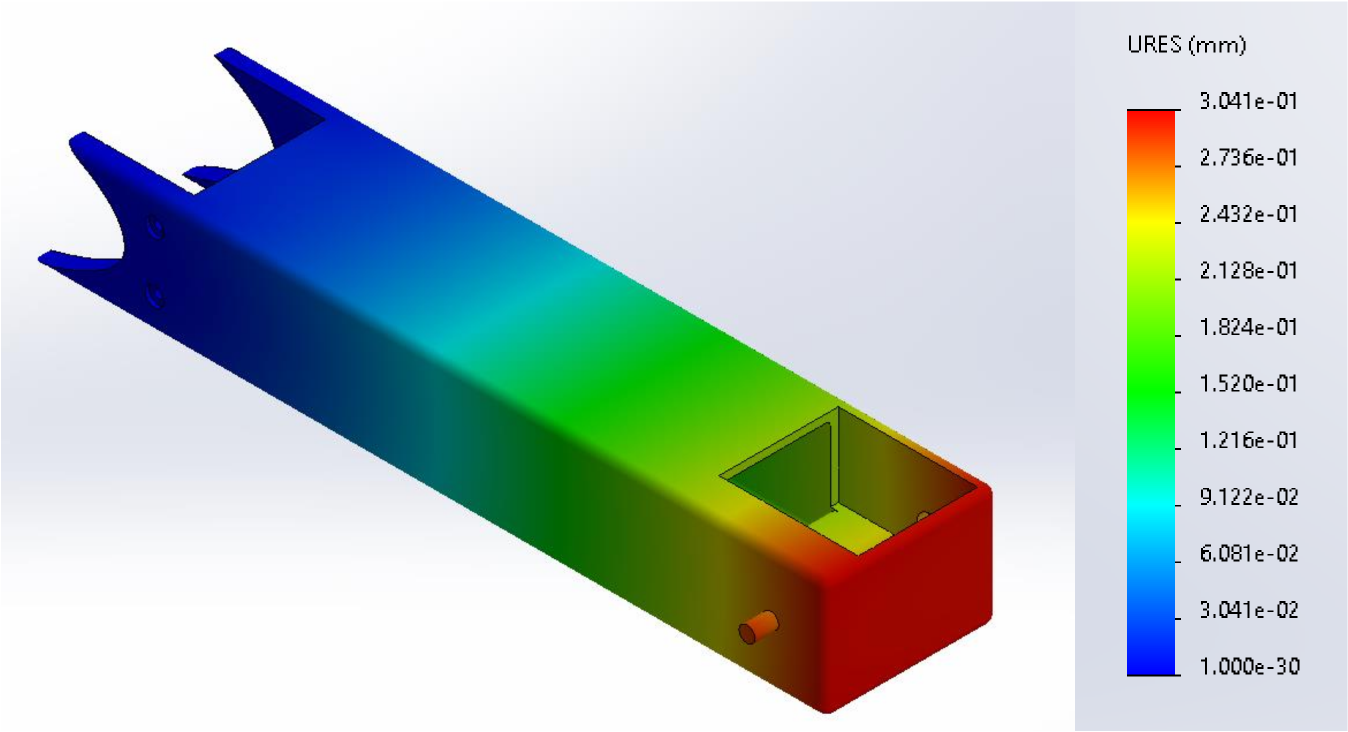

| Run | E(GPA) | $\sigma_Y$(kPA) |
|---|---|---|
| 1 | 14.73 | 162.99 |
| 2 | 18.74 | 224.69 |
| 3 | 17.75 | 201.61 |
| 4 | 16.67 | 117.03 |
| 5 | 17.91 | 188.74 |
| 6 | 18.23 | 191.57 |
| Average | 17.34 | 181.11 |



# Motor Arm Load Case - Takeoff - Stress

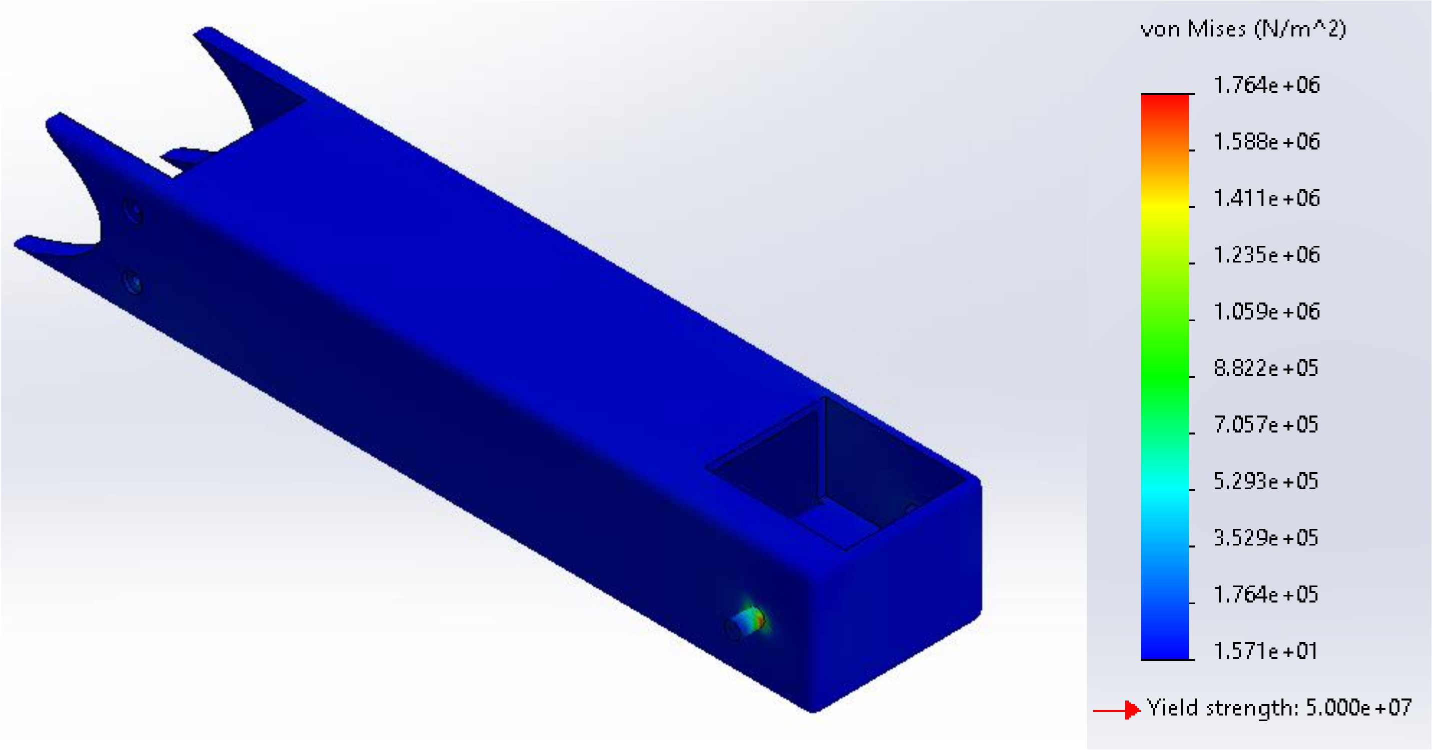


# Motor Arm Load Case - Takeoff - Displacement



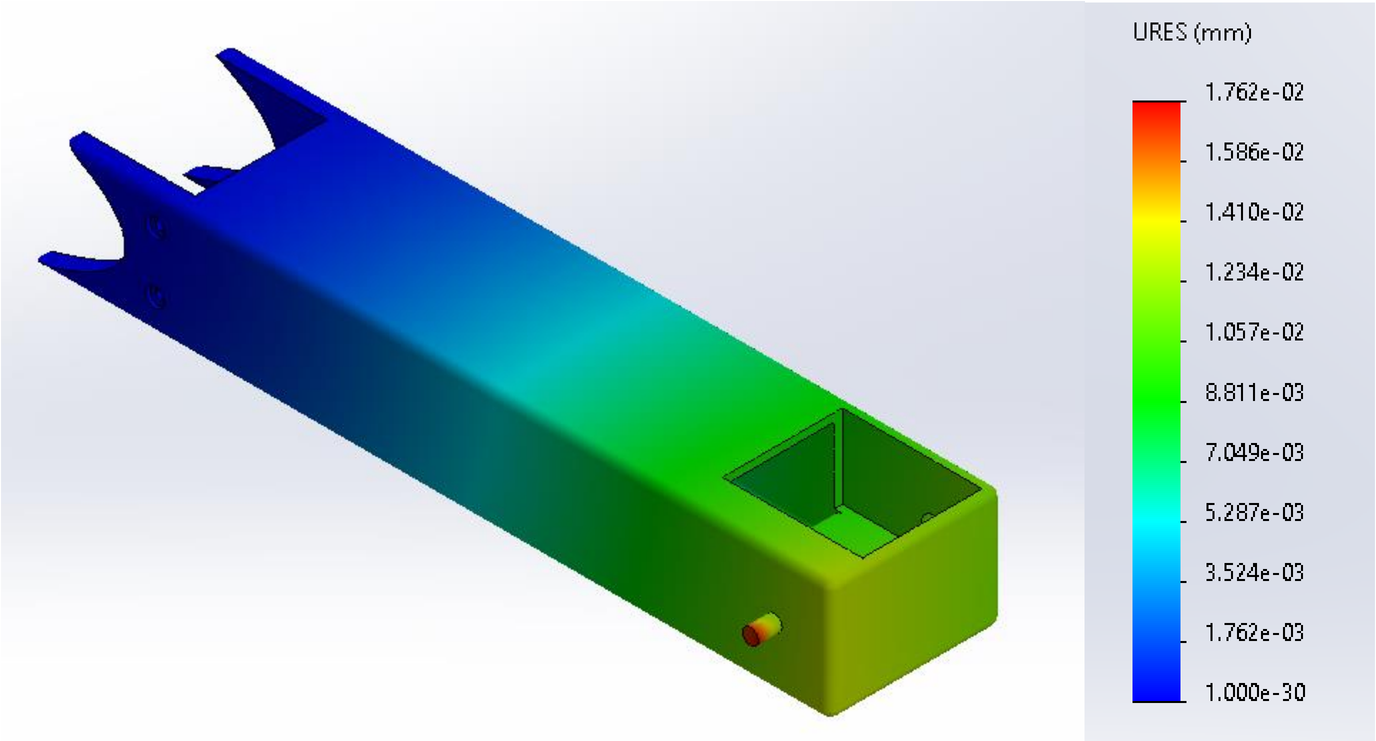
# Motor Arm Load Case - RAPCat Launch - Stress





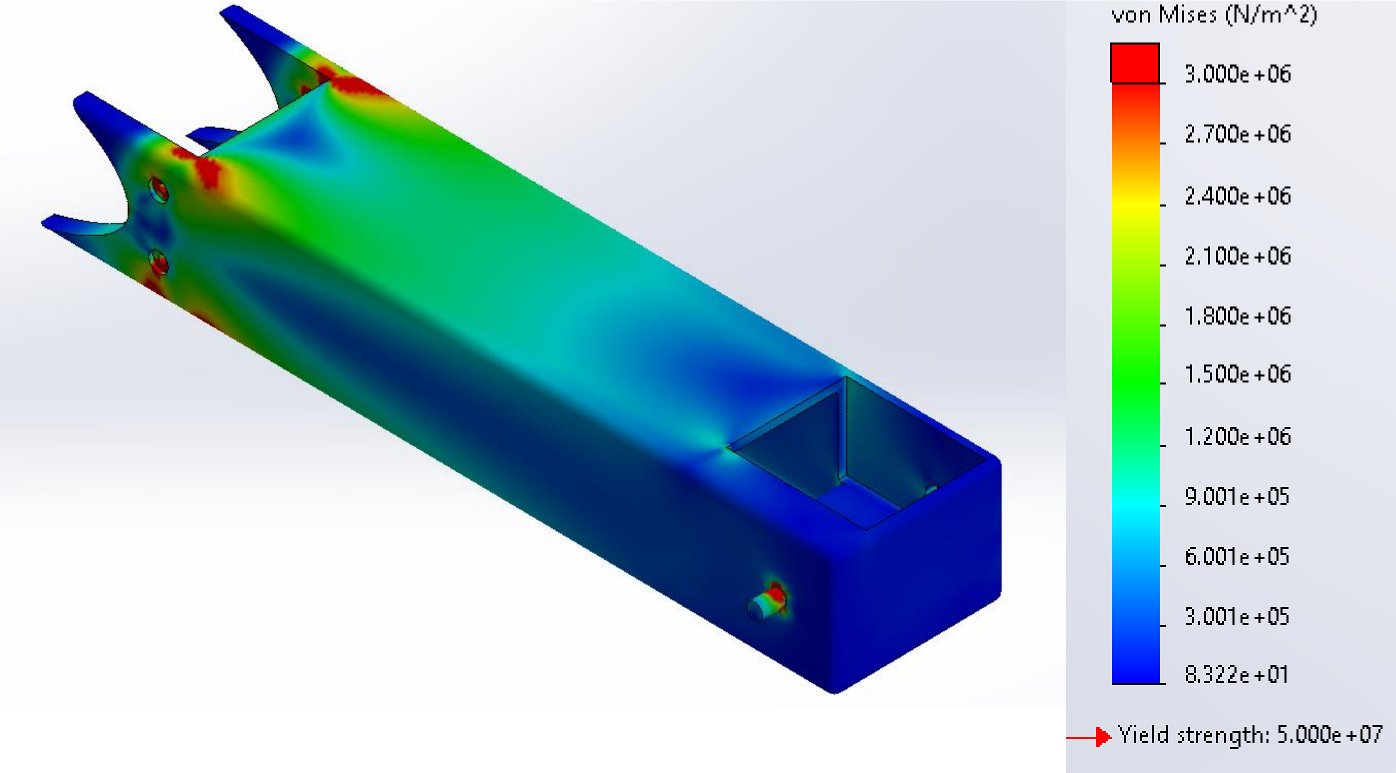
# Motor Arm Load Case - RAPCat - Displacement





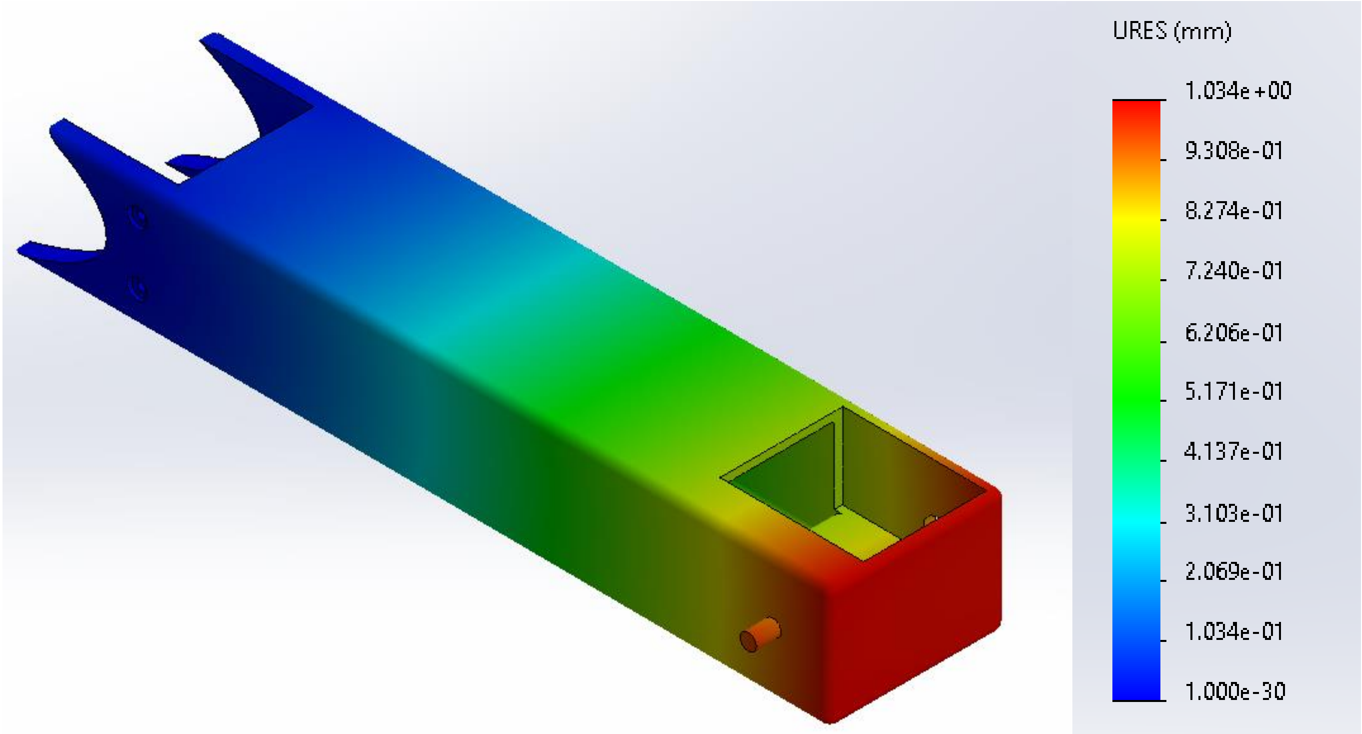
# Motor Arm Load Case - 10G Load - Stress





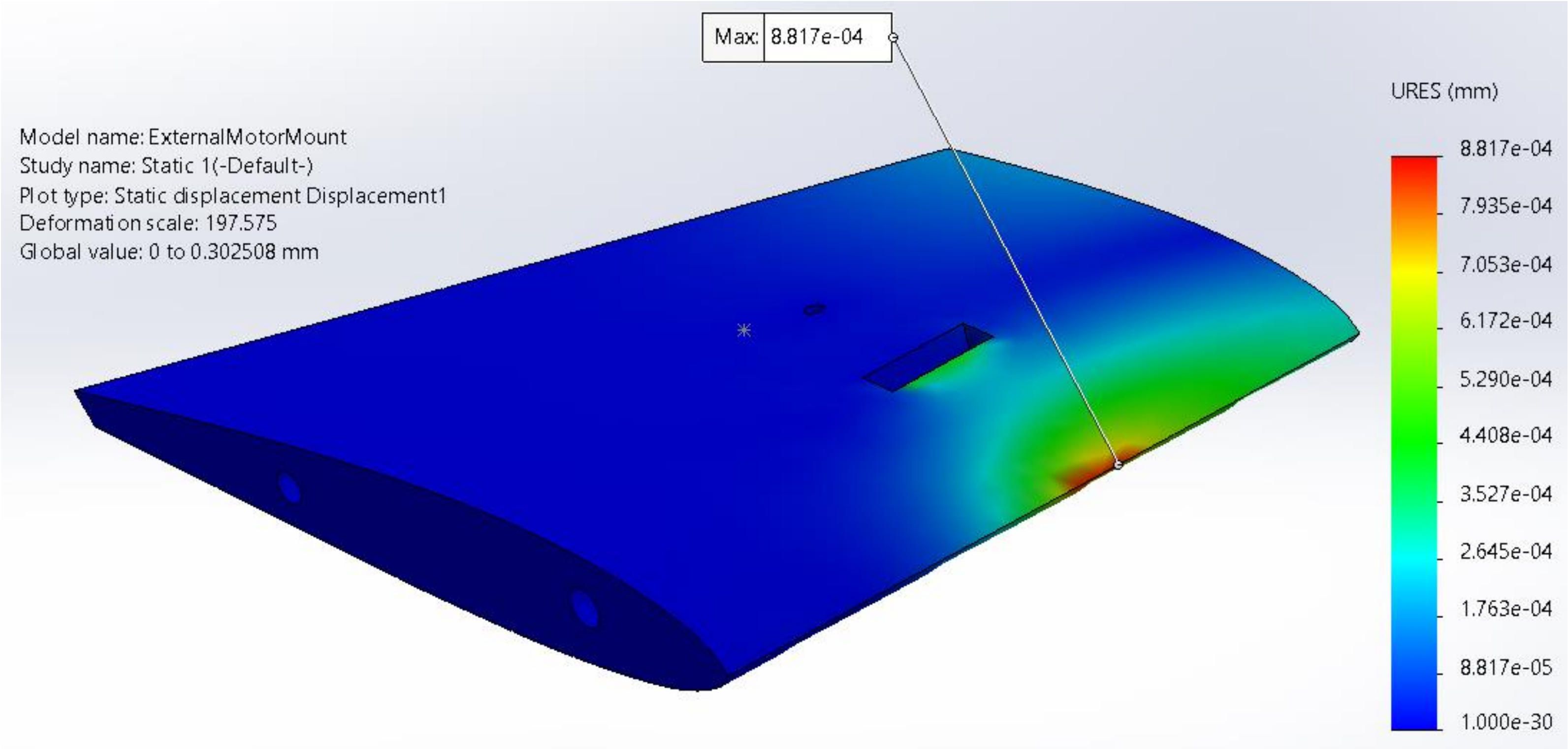
# Motor Arm Load Case - 10G Load - Displacement





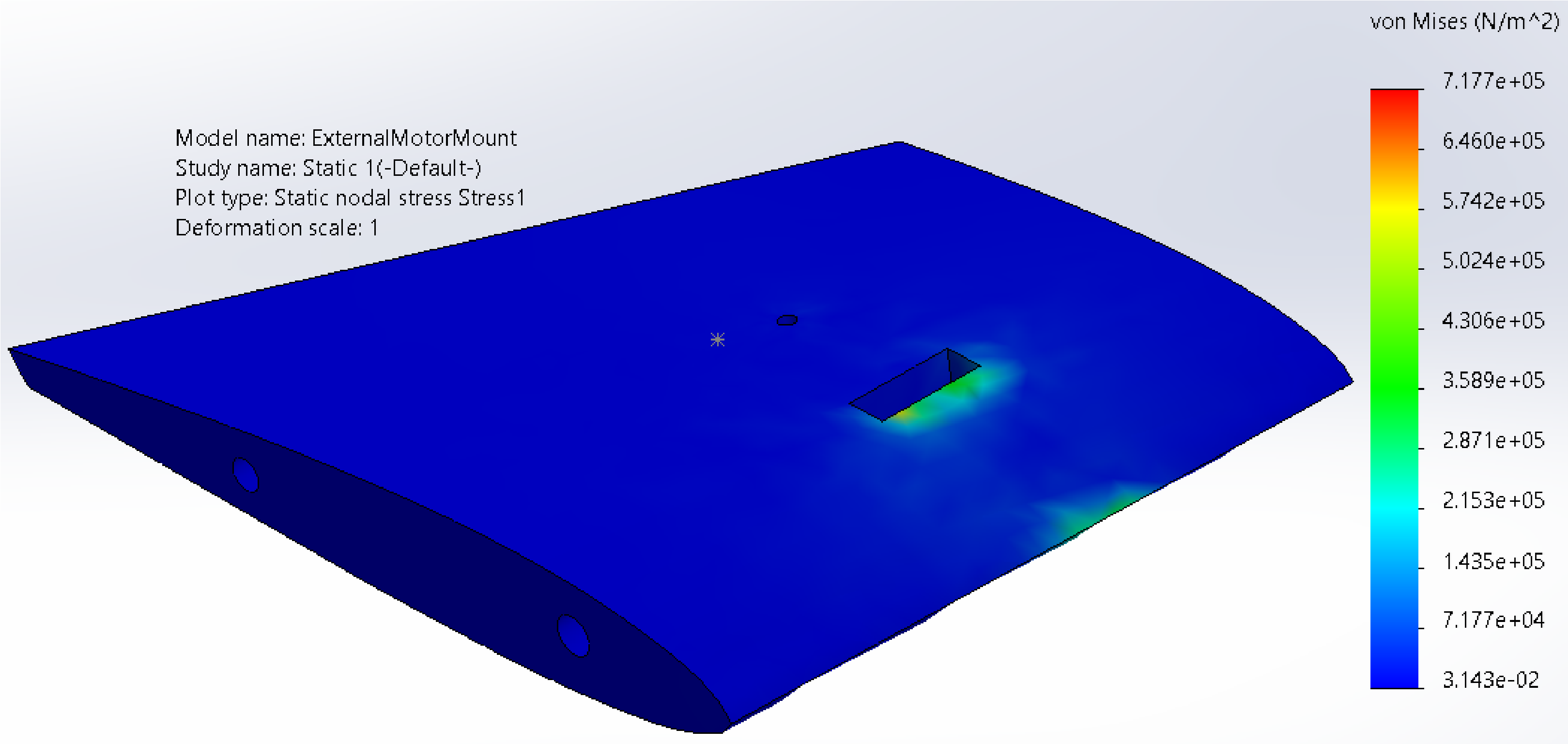
# Wing Mount - 10g Landing - Displacement





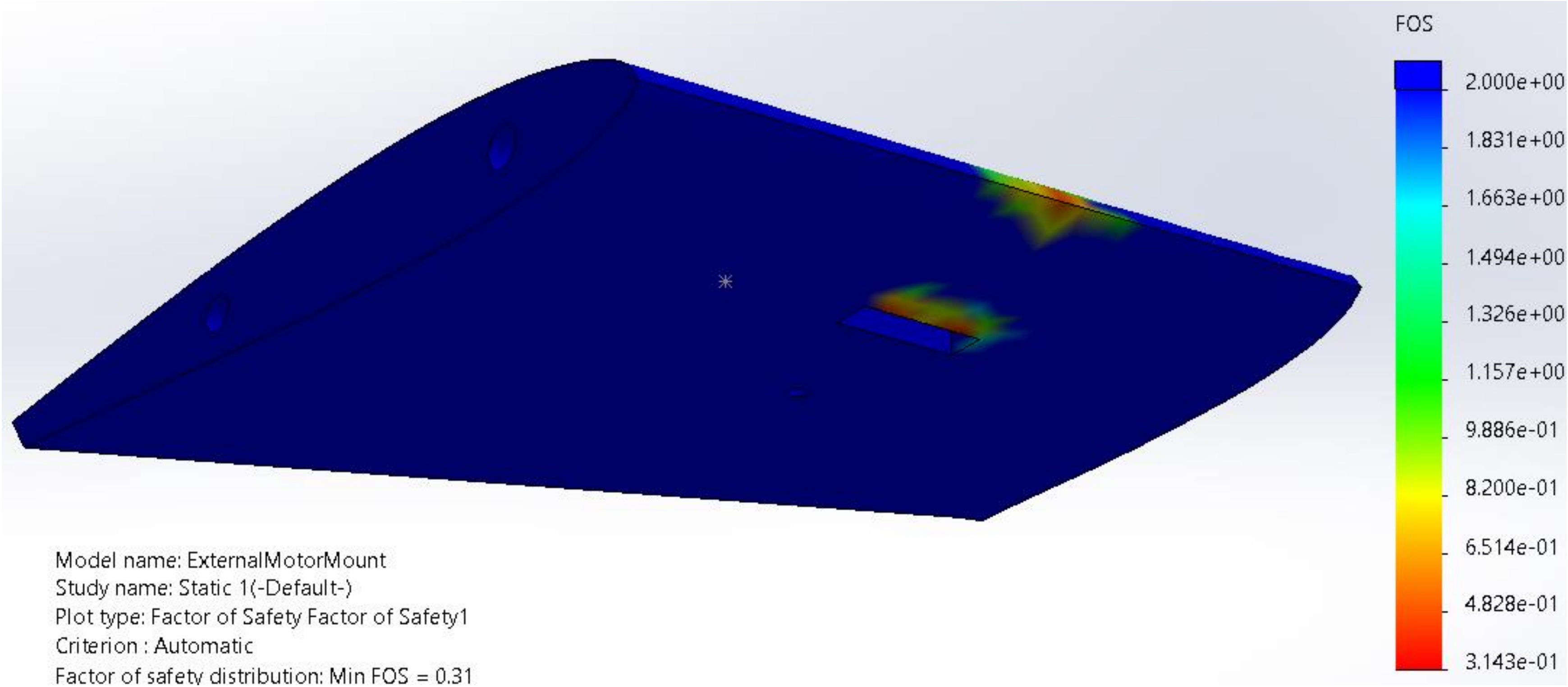
# Wing Mount - 10g Landing - Stress





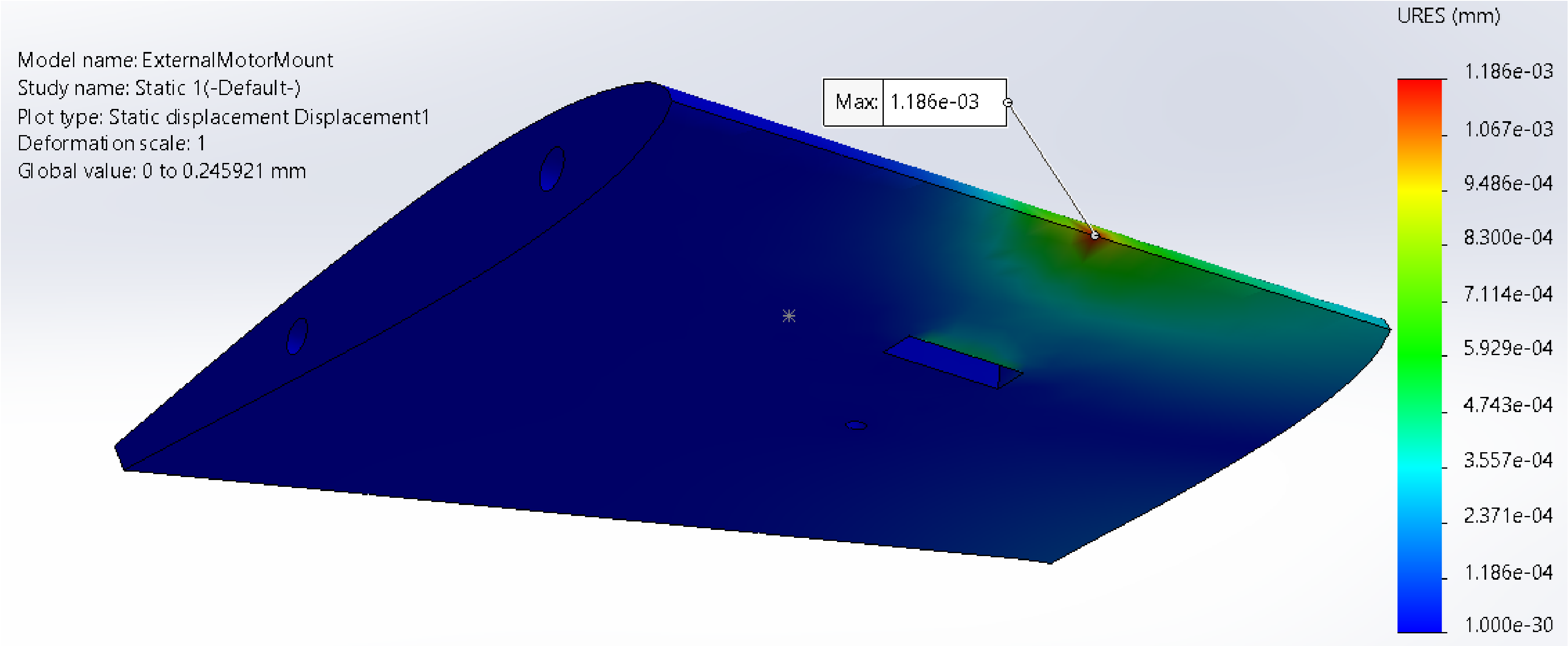
# Wing Mount - 10g takeoff - Factor of Safety



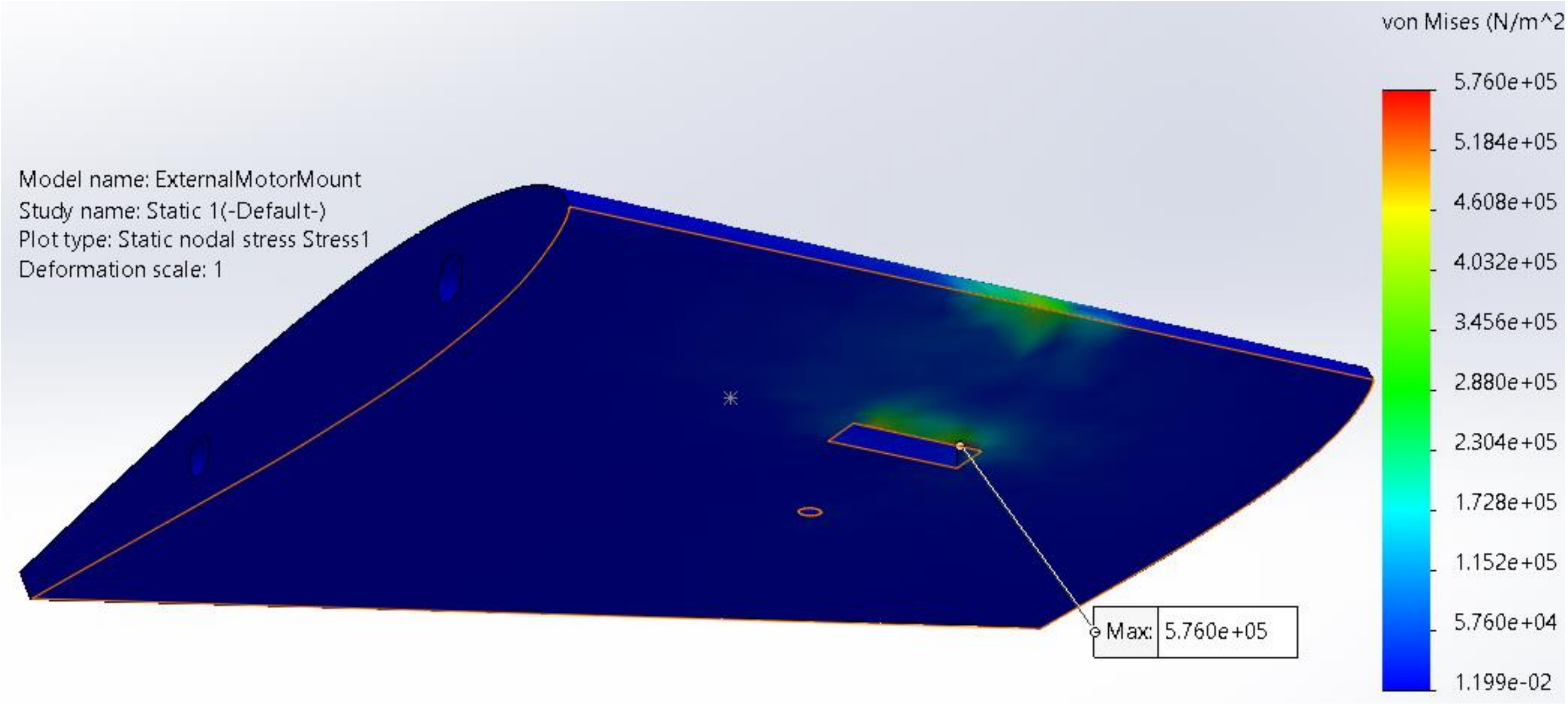


# Wing Mount - 10g takeoff - Displacement

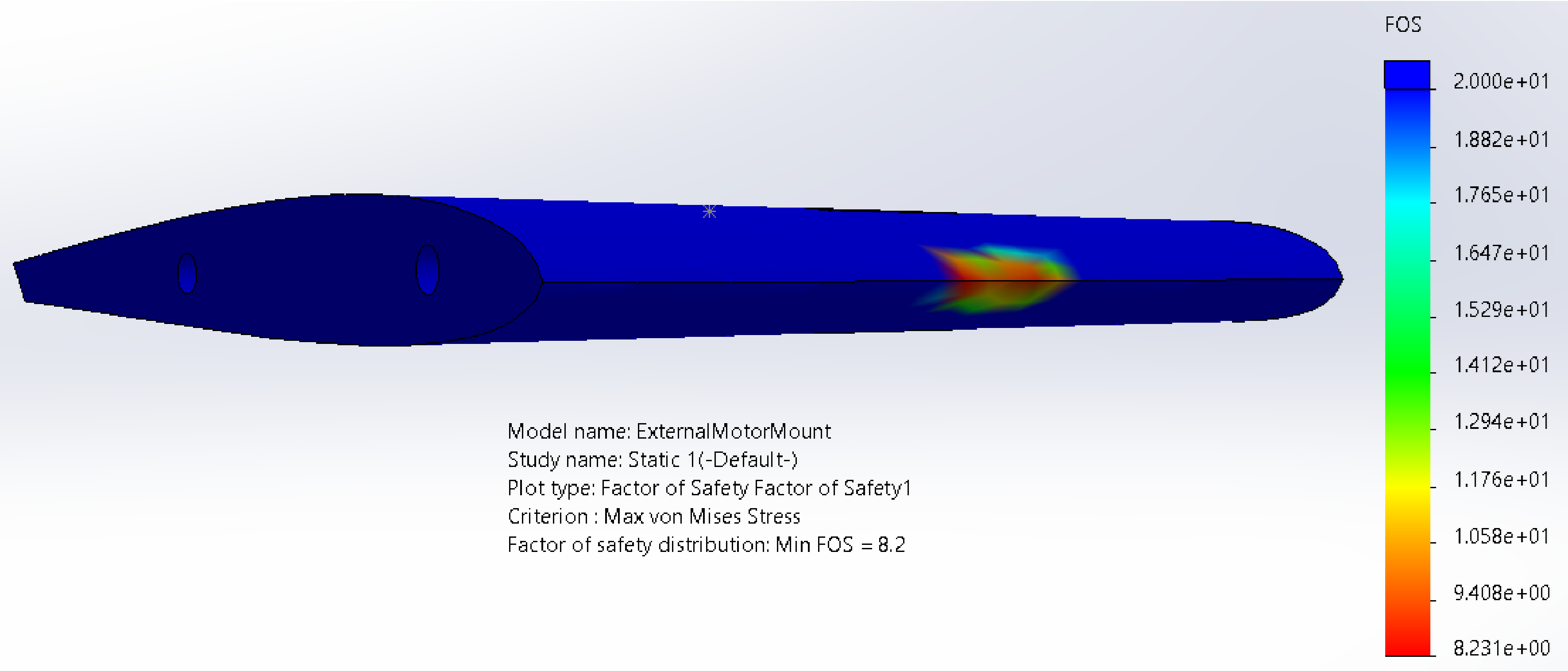




# Wing Mount - 10g takeoff - Stress

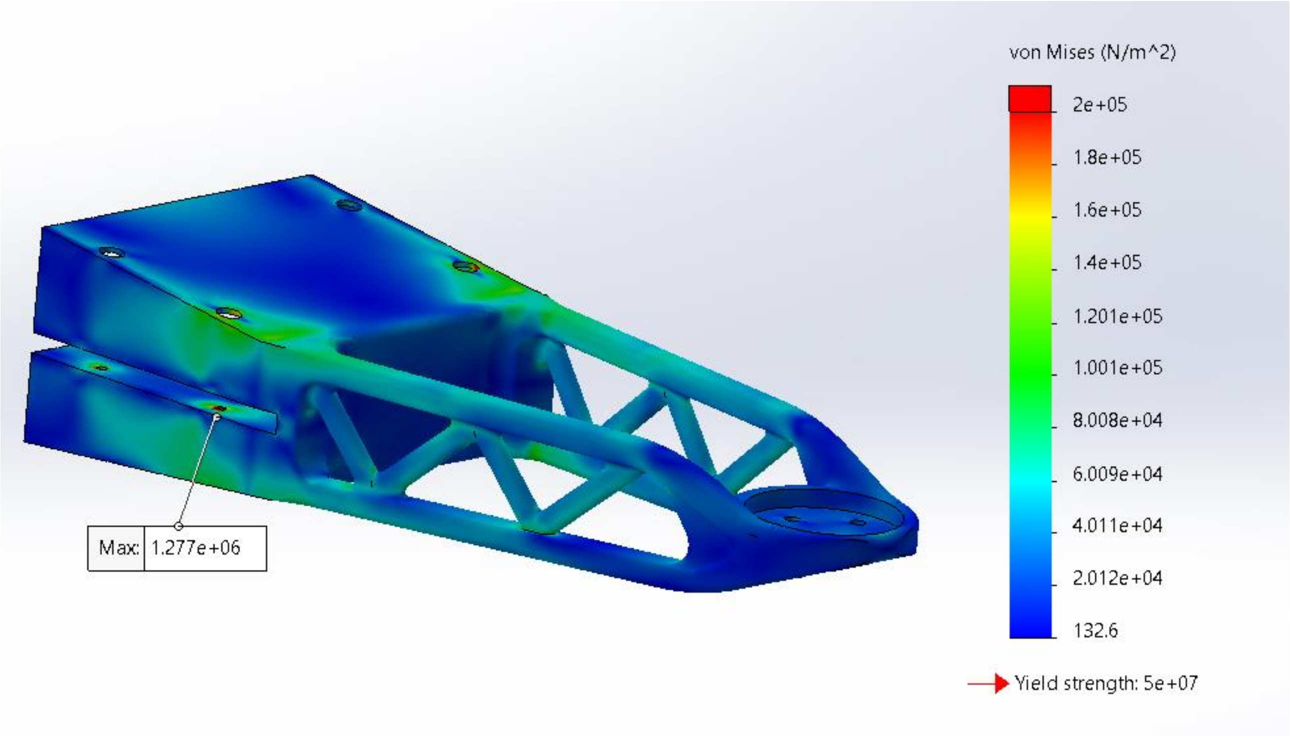


# [STR] - Wing Mount, RAPCat Launch - Factor of Safety

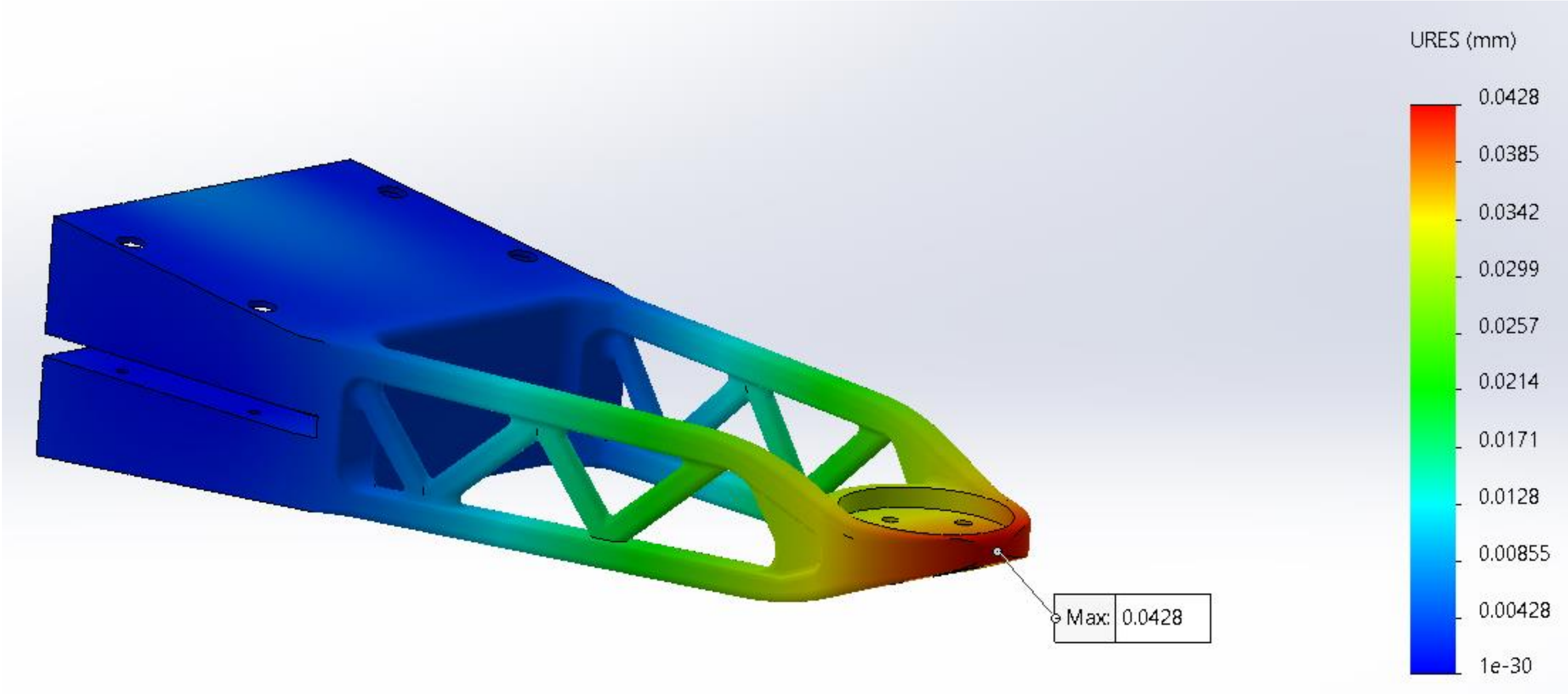


# Rear Motor Load Case - RAPCat Launch - Stress



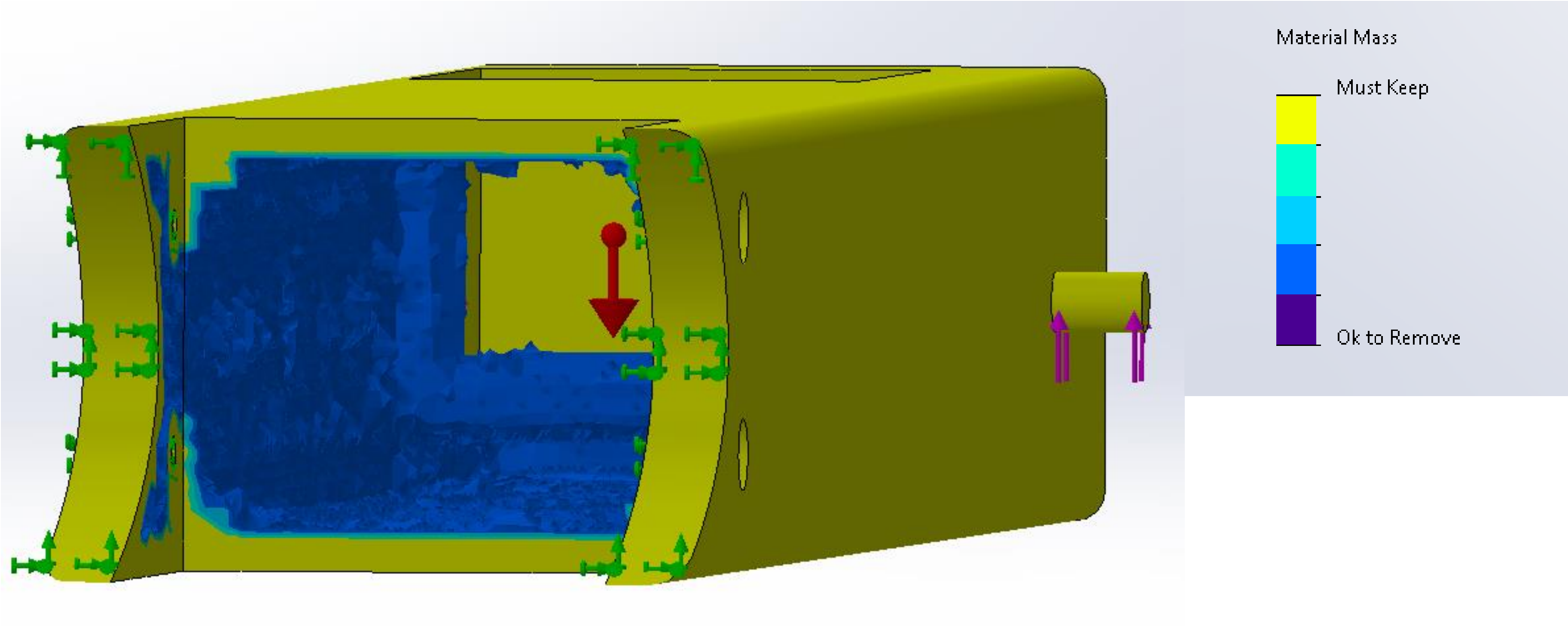


# Rear Motor Load Case - RAPCat Launch -



# Front Motor Arm Topology





# Risk Breakdown



| # | Category | Description | Consequence | Probability | Impact | Risk Level | Risk Modification Plan | Residual Risk Level |
|---|---|---|---|---|---|---|---|---|
| 1 | Autonomy | Data rate from sensor exceeds pixhawk's capabilities | Data overload sent to flight controller, could cause crash on landing or other unpredictable flight performance | Medium | Medium | Medium | Simulate sensors and mission aspects, model computing power using desktop hardware, use companion computing device if necessary | Low |
| 2 | Endurance | Accurate model not finished or model results are incorrect to a significant margin | Battery needs are not fully met resulting in reduced endurance or potential failure during flight | Medium | Low | Medium | Test models against experimental data, refine model to reflect observations to ensure accuracy | Low |
| 3 | Structures | RAPCat integration design | Structural damage to aircraft/launch vehicle | Low | Medium | Medium | Ensure clearance of aircraft with regards to RAPCat structure, low intensity test of compatibility | Low |
| 4 | Testing | Scheduling conflicts with pilot | Less flight testing than desired, unfinished testing | Low | Medium | Medium | Plan flights as far ahead as possible and maintain clear communincation with pilot regarding expectations | Low |
| 5 | Supply/Struct | Drak kit backordered, potential supply difficulties | Would not be able to produce second deliverable for customer, may not have backup parts in case of destruction | High | Medium | High | Utilize IRISS' existing connection with RiteWing to obtain wing kits outside of standard commercial production | Medium |
| 6 | Autonomy | Failure to obtain avionics hardware from IRISS | Inability to test computational speeds and fully functional avionics package in first semester | Medium | Low | Medium | Simulate sensor output in MissionPlanner, utilize desktop capabilities to ensure functionality | Low |
| 7 | Structures | Material Failure | Flight failure, damage to property, personnel injury | Low | Medium | Medium | Ensure accurate materials simulation by obtaining experimental test results to validate design specs | Low |

# Risk Breakdown



| # | Category | Description | Consequence | Probability | Impact | Risk Level | Risk Modification Plan | Residual Risk Level |
|---|---|---|---|---|---|---|---|---|
| | Propulsion | Battery damage during pack assembly | fire/explosion in battery cells, injury to personnel | Low | High | High | Ensure spot welder is only used by properly trained individuals, follow strict safety protocols when working with battery cells | Medium |
| | Propulsion | testing safety considerations | improper charging, overdrawing current, or undervolting cells may cause permanent damage to cells | Medium | Medium | Medium | Design test procedures within margin of safety of battery capabilities to ensure they are not exceeding capacity | Low |
| | Supply/Prop | Motors or propellers on backorder/hard to obtain | alternatives may need to be selected that are not ideal component choices | Medium | Low | Medium | Design margin into propulsion system to allow for varied component selection | Low |
| | Testing | Car-top safety considerations | Damage to vehicles, test equipment, citations issued for property damage or other unknown reasons (?) | Low | High | High | Coordinate with department to create safe testing procedures and equipment, research local laws to ensure legality of test operations | Medium |
| | Structures | Inaccurate FEM model | Possible material failure, could need to redesign parts | Medium | Medium | Medium | Compare FEM to known models and research minimizing FEM error, continually refine models | Low |
| | Aerodynamics | Inaccurate CFD | Less performance than predicted from vehicle, additional energy expenditure or increased flight velocity would be required | Medium | Low | Medium | Model CFD against known experimental data, ensure mesh convergence, account for variance between CFD and known data | Low |