VORTEX

Vertically Optimized Research, Testing, & EXploration

Preliminary Design Review

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Team

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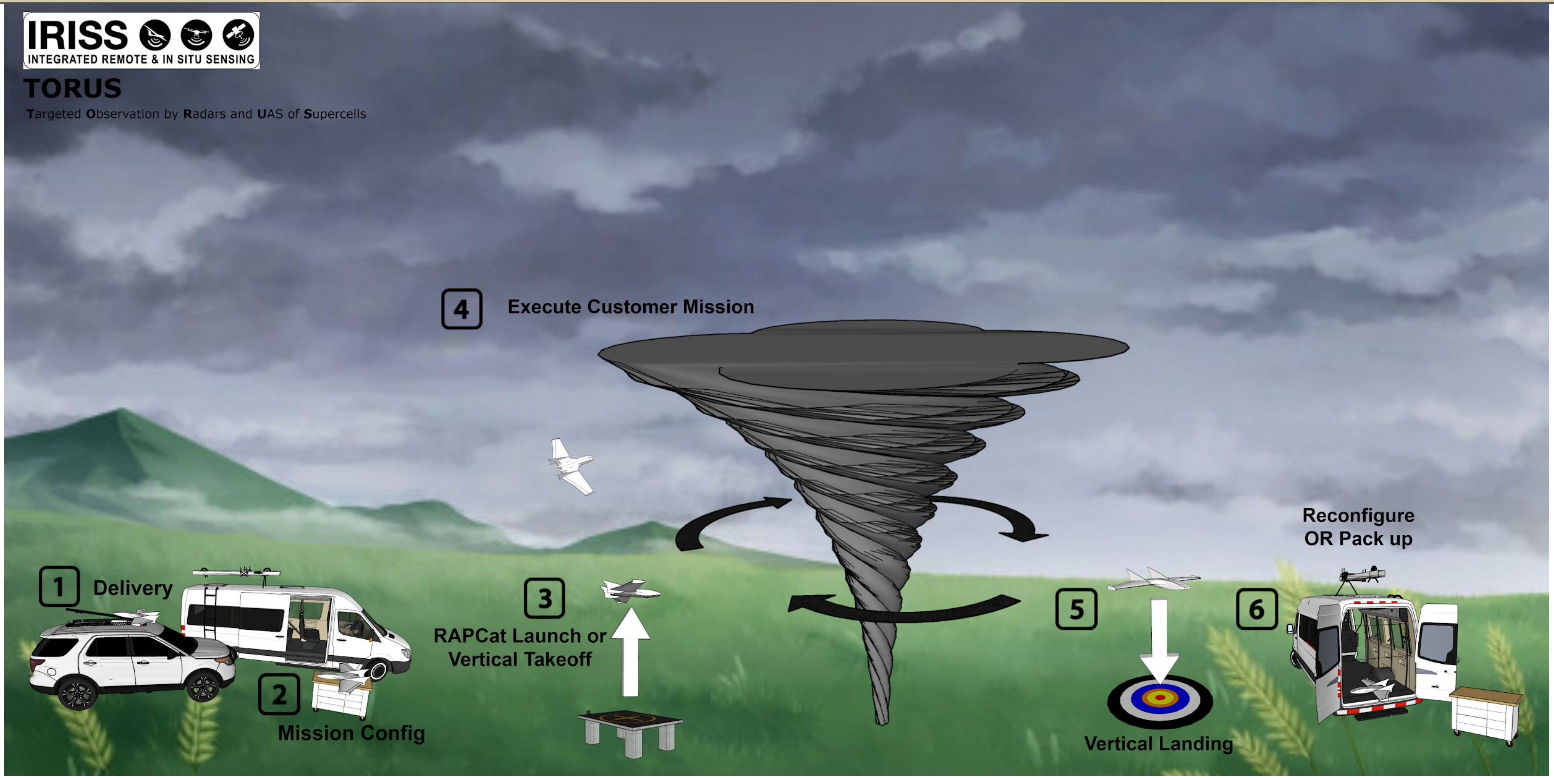
IRISS
INTEGRATED REMOTE
& IN SITU SENSING

Project Overview

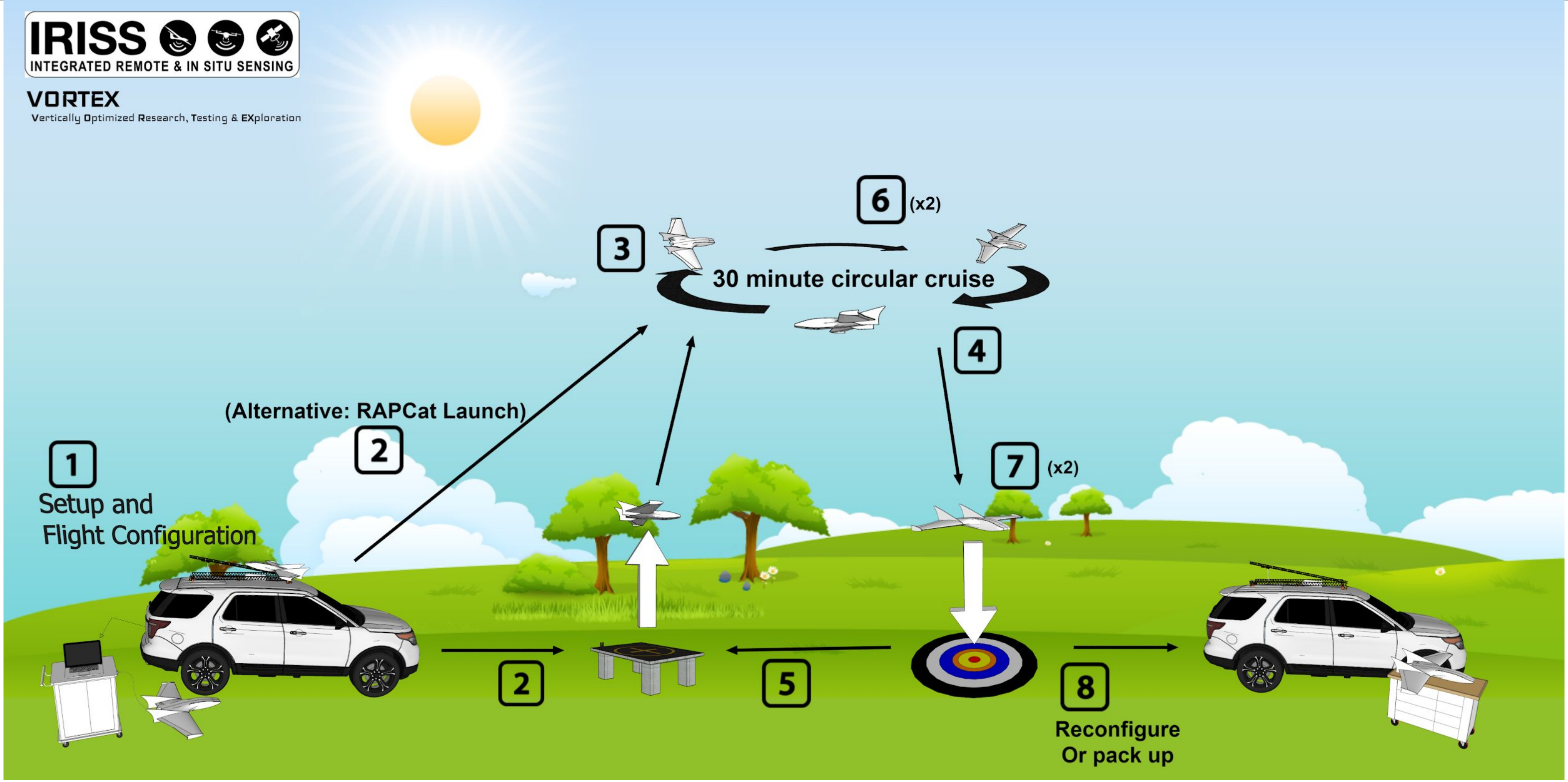
Mission Statement

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. By allowing IRISS to operate in previously inaccessible locations such as forest clearings or from the deck of a ship, the study of these storms will be accelerated, contributing to improved accuracy of meteorological modeling and forecasts.

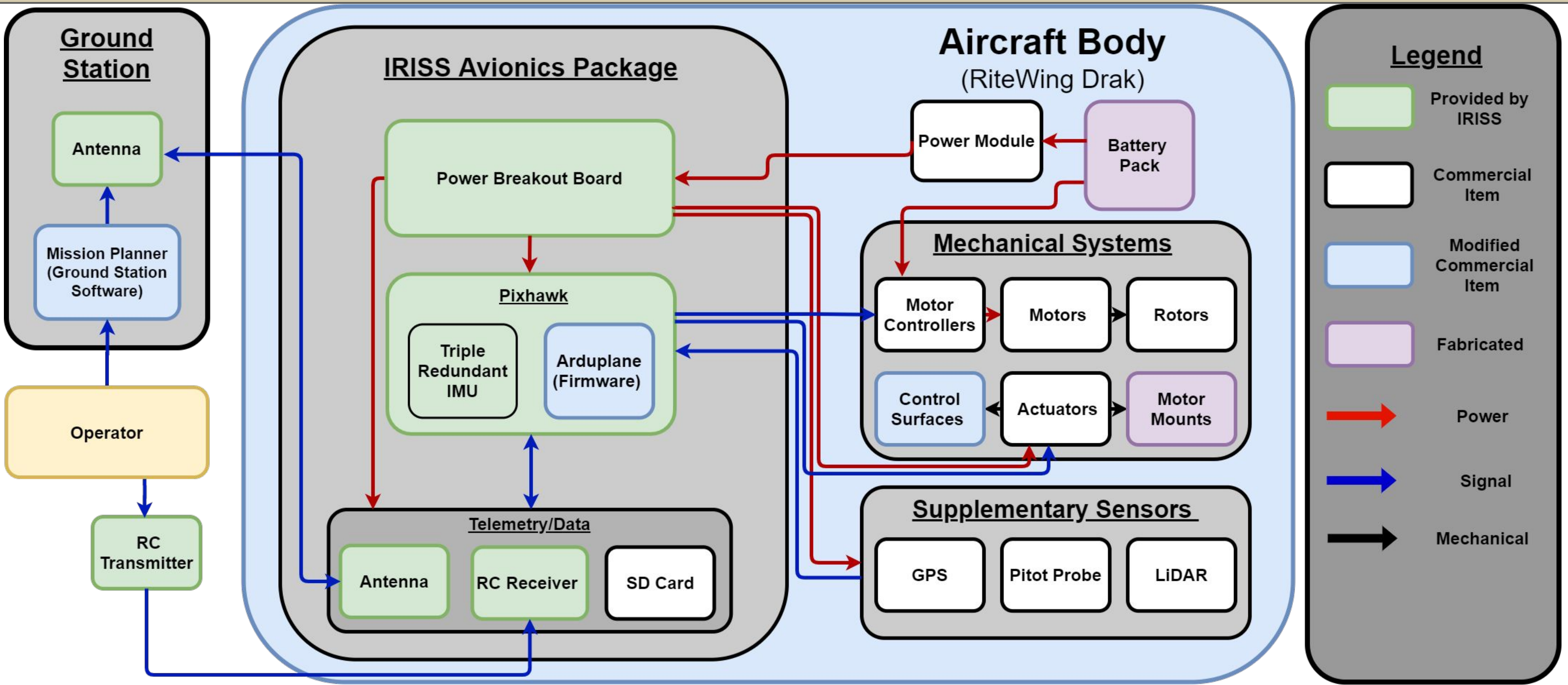
Use Case CONOPS



Verification CONOPS



Functional Block Diagram

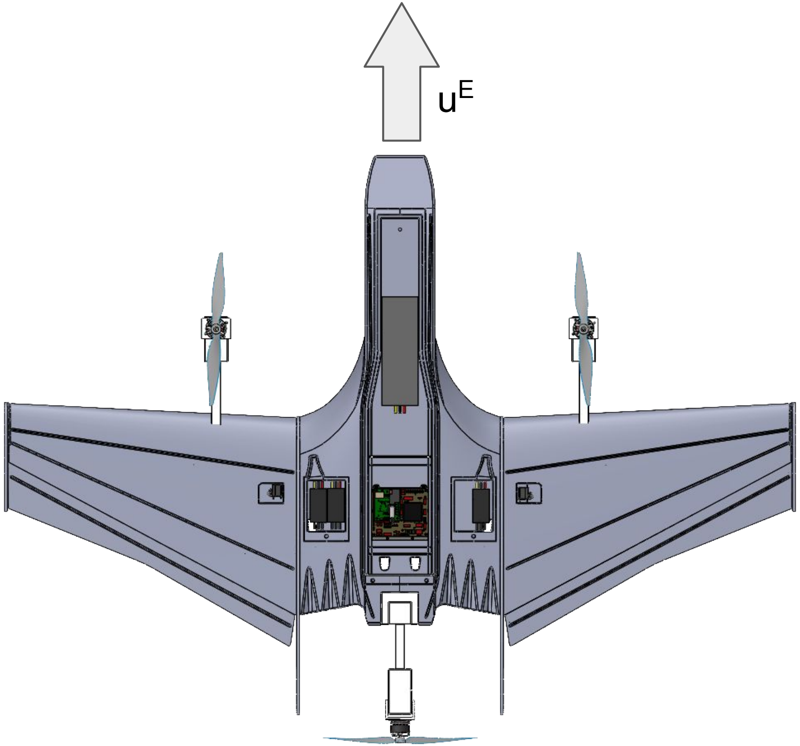


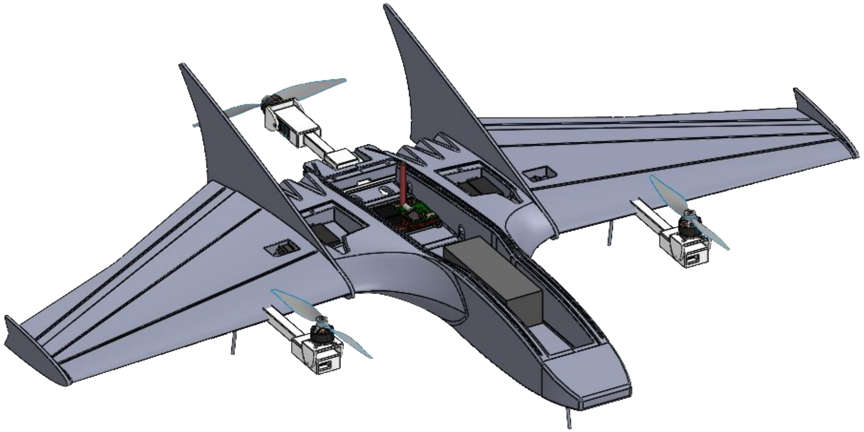
Functional Requirements

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

Baseline Design

CAD Assembly with Preliminary Component Choices

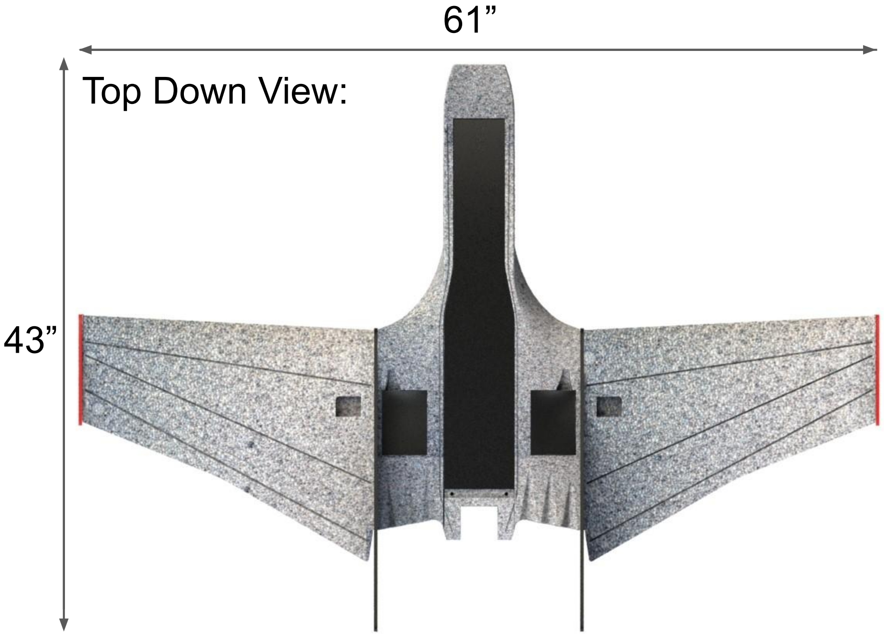


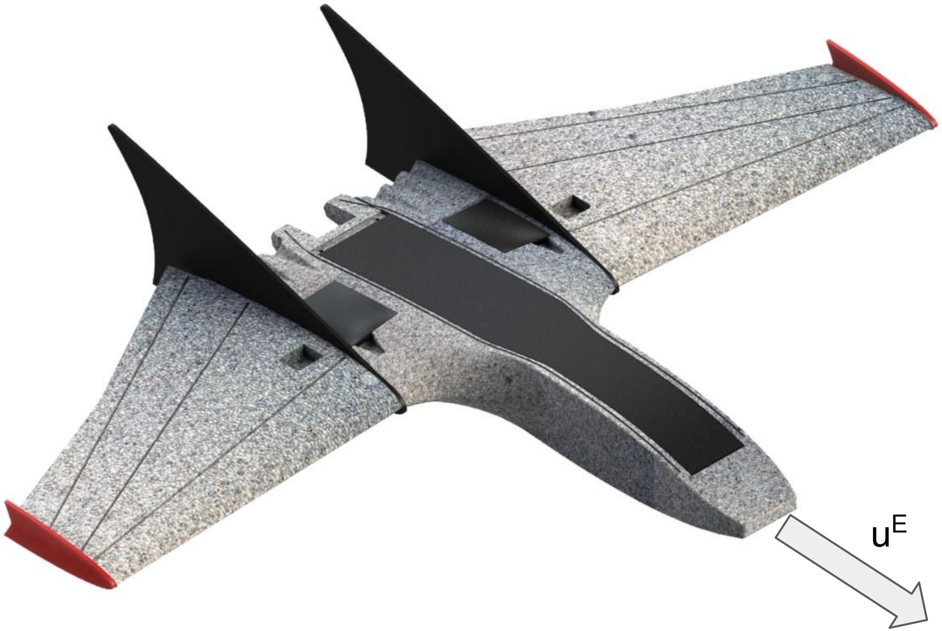


- 3 tilt rotors
- Control surface motors
- Avionics package
- ESCs

*Preliminary Design choices - Avoiding interference with RAPCat Launch system is considered in all aspects

Baseline RiteWing Drak Wing Kit





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

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.)

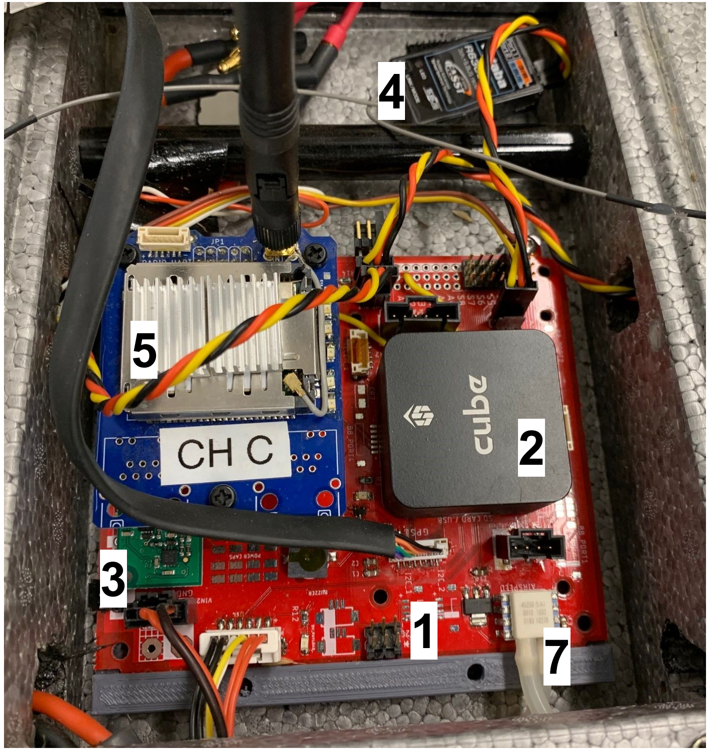
Selected Baseline Design: Tri Tilt Motor

Design Choice Reasoning

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

A tri-motor aircraft

Provided Avionics Package



What's Included

1. IRISS custom PCB (red)
2. HexCube Black
3. Power conditioning circuits
4. S-bus receiver
5. Telemetry package
6. GPS (not pictured)
7. Pitot tube

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

Flight Controller Firmware

Design Choices Considered

- Ardupilot
- PX4
- iNav
- PaparazziUAV

```
$(function(){cards();});
$(window).on('resize', function(){cards();});
function cards(){
    var width = $(window).width();
    if(width < 750){
        cardssmallscreen();
    }else{
        cardsbigscreen();
    }
}
function cardssmallscreen(){
    var cards = $('.card').length;
    var height = 0;
    var card2 = 2;
```

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

Flight Controller Firmware (cont.)

Selected Baseline Design: Ardupilot

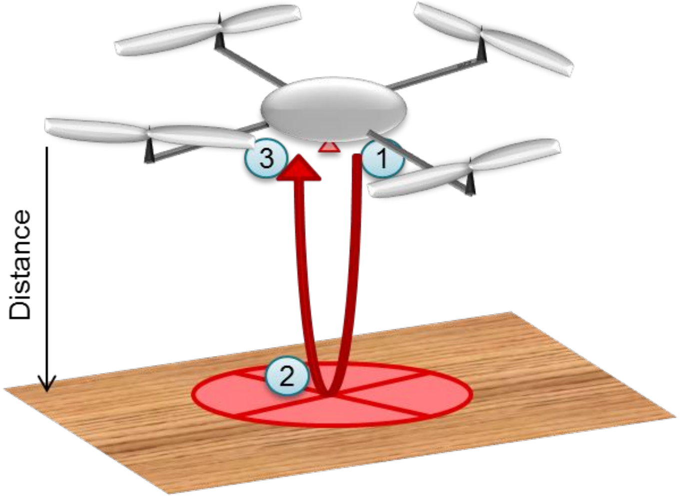
Design Choice Reasoning

- 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:

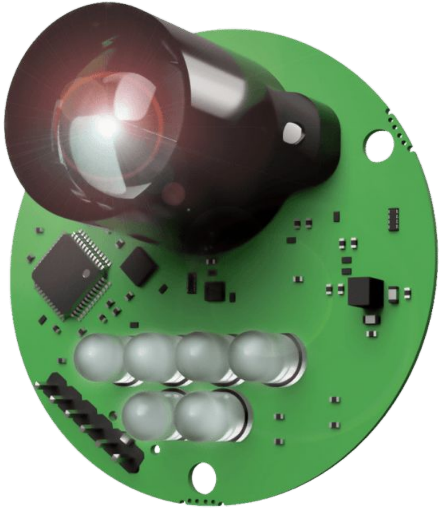
- LIDAR
- Micro Radar
- Sonar



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 to environmental 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

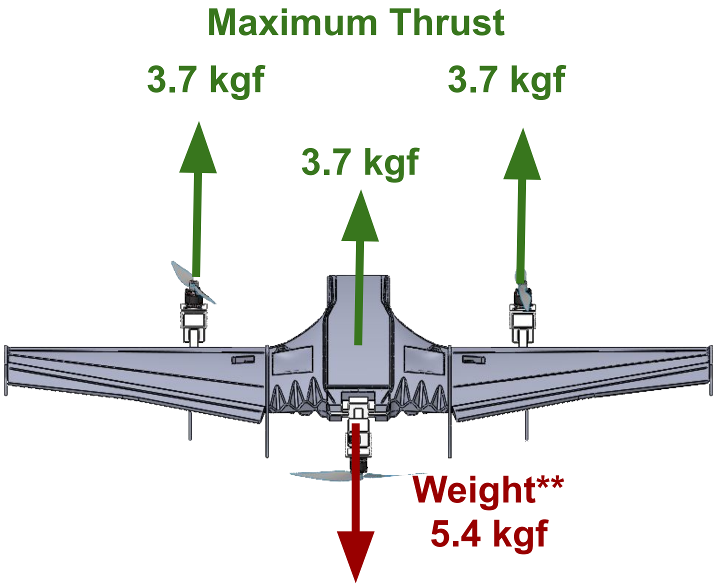
Feasibility Analysis

Summary of Feasibility Analyses

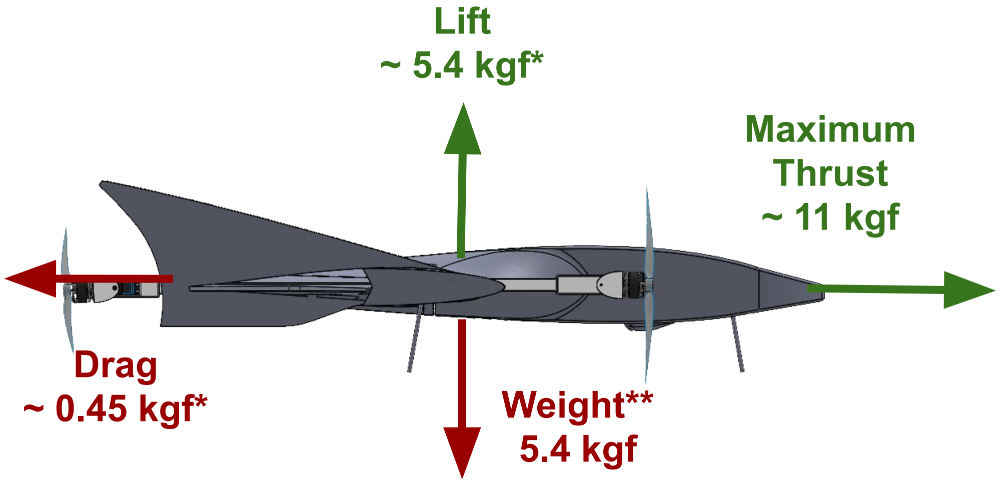
System	Feasible	Reasoning
VTOL Configuration	?	Configuration is modeled to be stable in both flight modes - Manufacturing complexity is manageable
Flight Controller Firmware	?	Capable of autonomous flight profiles using chosen VTOL configuration - Interfaces with external sensors
Mass	?	Propulsion system is capable of providing enough thrust for VTOL
Power	?	Battery pack provides enough power/current for motors - Motor and propeller sizing is achievable and readily available
Endurance	?	Battery pack can provide required energy for flight time required in vertical and horizontal flight
Cost	?	Replication cost is within allotted budget

VTOL Configuration: Lift Capability

Vertical flight/Hover



Horizontal flight/Cruise



3 motors offer sufficient thrust for both modes of flight

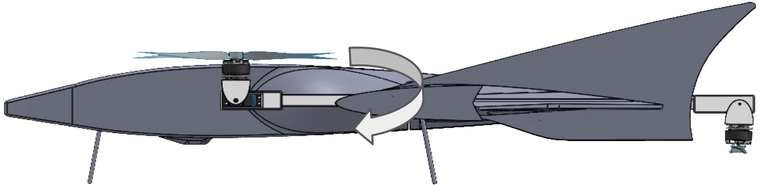
*Lift/Drag obtained from CFD calculations (in later slide, based on Cruise AOA ≈ 6.5°)

**Mass Budget is discussed later

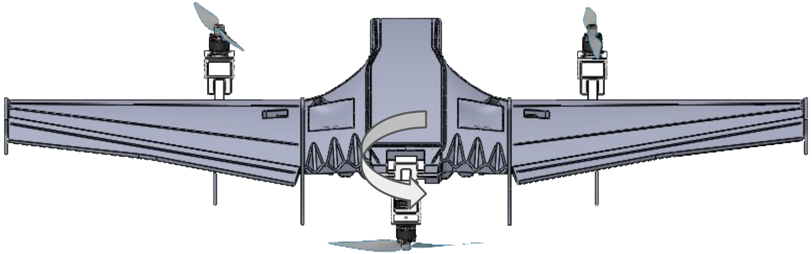
VTOL Configuration - Hover Stability

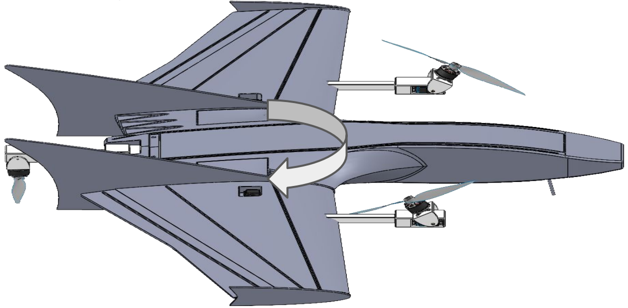
The tri-tilt motor configurations needs to maintain steady-level hover when landing or taking off. A basic dynamic model was derived to prove its feasibility.

Differential thrust between front and back motors for **Pitch Control**



Differential thrust of front motors for **Roll Control**



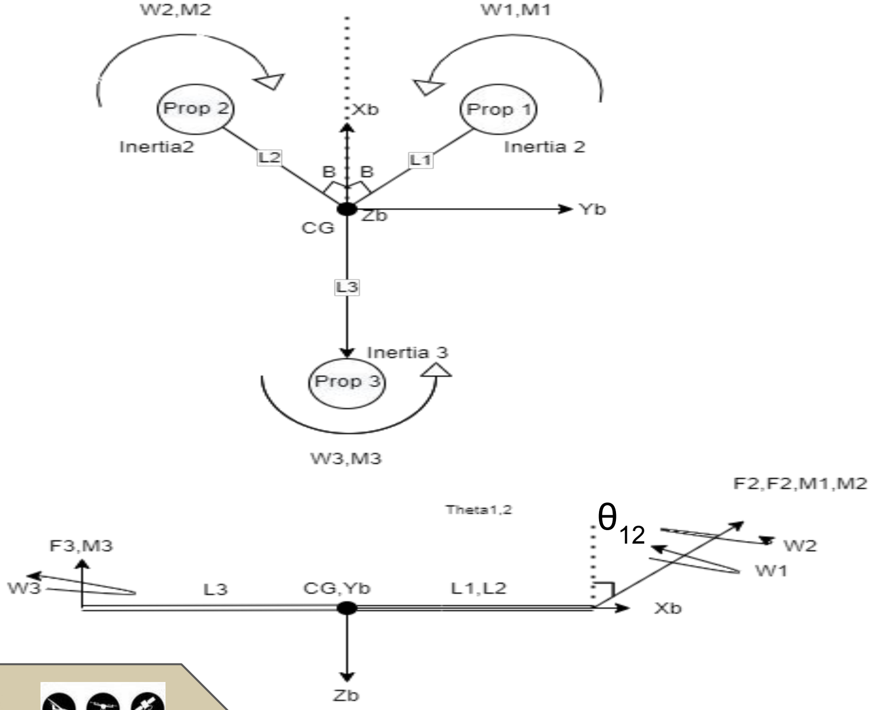


Front Motors tilt in opposing directions for **Yaw Control**

*Preliminary Design choices - Avoiding interference with RAPCat Launch system is considered in all aspects

VTOL Configuration - Hover Stability

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

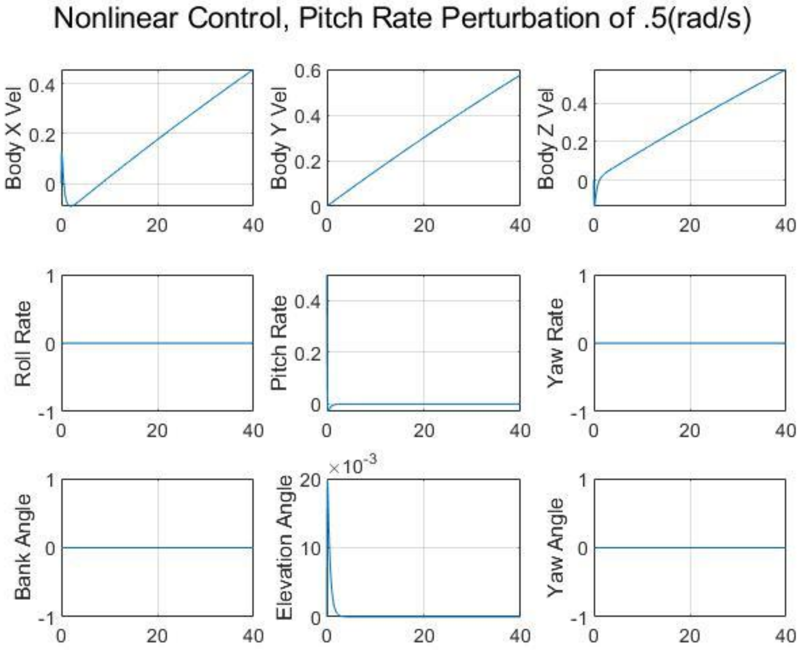


The Process

- 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

VTOL Configuration - Hover Stability

Conclusions:

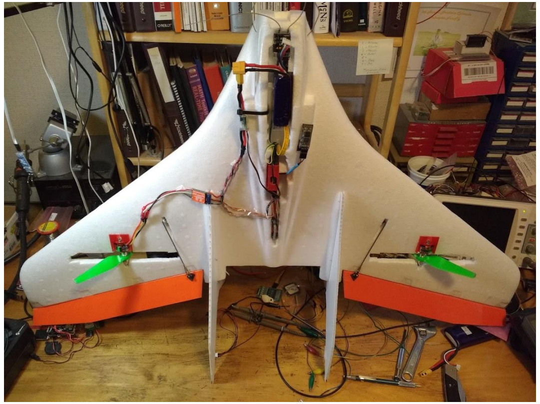
- Capable of rotational stability in the face of wind and other perturbations
- Two tilting motors is a valid method of controllability, and meets lift capability requirements
- Incapable of navigation without additional integral/navigation control
- ArduPilot can handle this, uses Kalman filters, PID control, guidance feedback loop

Hover Stability is feasible with this configuration, and the chosen flight controller is capable of controlling it.

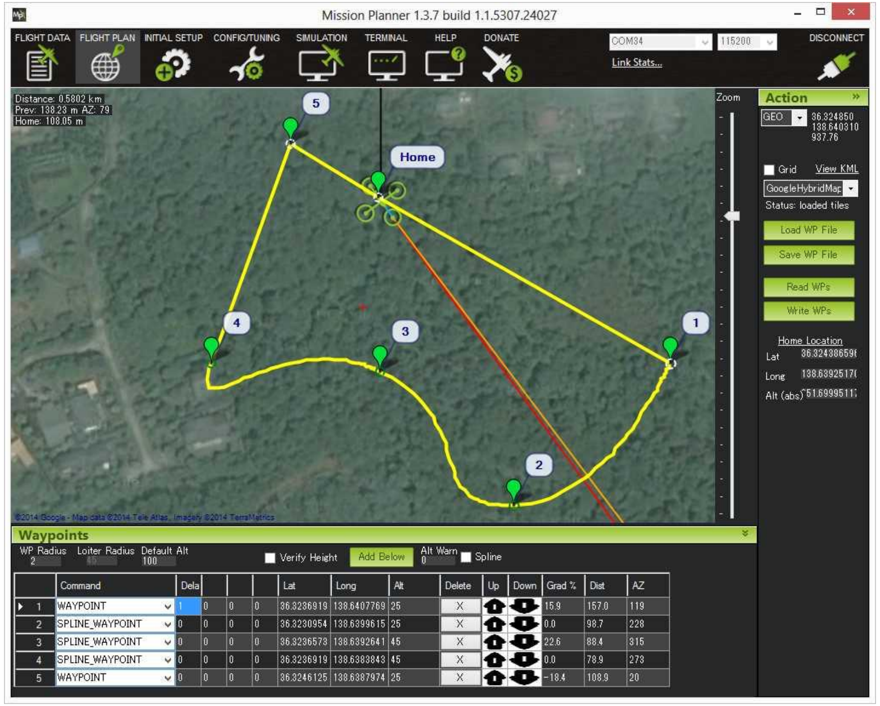
Flight Controller Firmware (Ardupilot) Feasibility

Configuration Resources

- Support for elevon control with gain calibration
- Tricopter motor tilting and frame setup
- Mode transition and integration support



Flight Controller Firmware (Ardupilot) Feasibility



COM34 115200

Distance: 0.5802 km
Prev: 138.23 m AZ: 79
Home: 108.05 m

GEO 36.324850
138.640310
937.76

☐ Grid

GoogleHybridMap

Status: loaded tiles

Lat 36.32438659
Long 138.63925170
Alt (abs) 51.6999511

WP Radius 2 Loiter Radius 45 Default Alt 100 ☐ Verify Height Alt Warn 0 ☐ Spline

	Command	Dela				Lat	Long	Alt	Delete	Up	Down	Grad %	Dist	AZ
▶ 1	WAYPOINT	1	0	0	0	36.3236919	138.6407769	25	X	⬆	⬇	15.9	157.0	119
2	SPLINE_WAYPOINT	0	0	0	0	36.3230954	138.6399615	25	X	⬆	⬇	0.0	98.7	228
3	SPLINE_WAYPOINT	0	0	0	0	36.3236573	138.6392641	45	X	⬆	⬇	22.6	88.4	315
4	SPLINE_WAYPOINT	0	0	0	0	36.3236919	138.6383843	45	X	⬆	⬇	0.0	78.9	273
5	WAYPOINT	0	0	0	0	36.3246125	138.6387974	25	X	⬆	⬇	-18.4	108.9	20

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

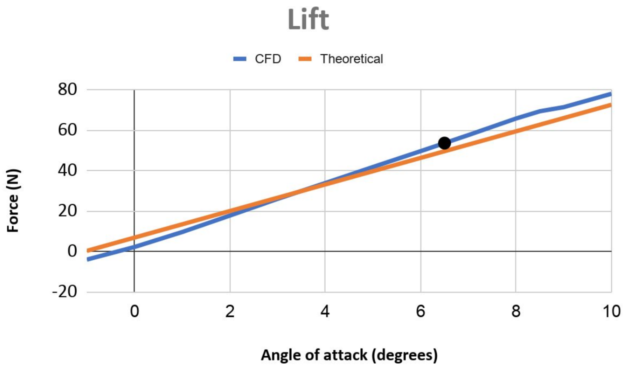
- Open source code
- Assistance in learning, testing, and debugging code
- Integrating companion computers as well as a huge amount of additional hardware

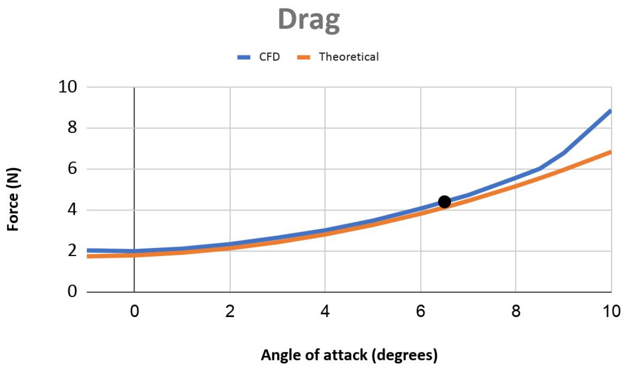
Ardupilot Feasibility - Tilt Rotor Example

Source: https://youtu.be/WMh8BiOLrns

The firmware is feasible for the chosen flight configuration and mission profile

Endurance Verification Part 1 - Drag Estimation





Design Variables

m = 5.4 kg
V ≈18 m/s

↓

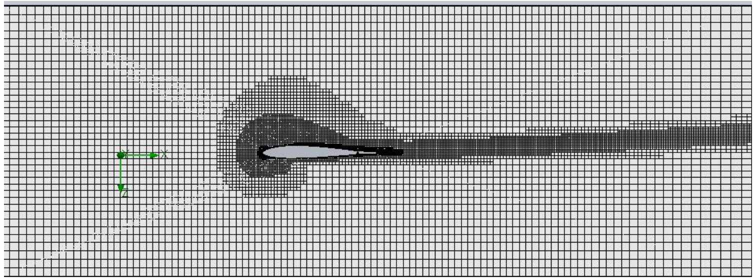
Theoretical Calculation

Vortex Panel and Prandtl Lifting Line Theory

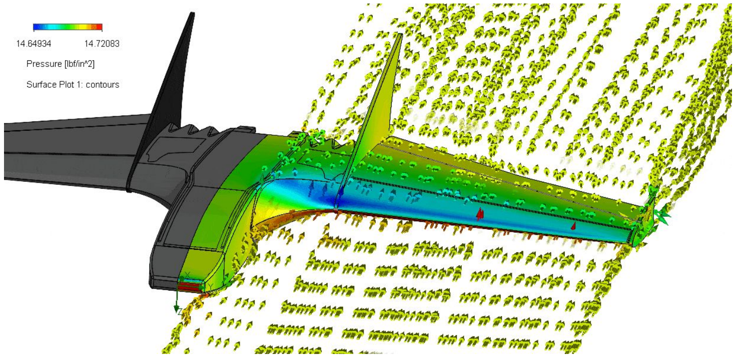
Solidworks Flow Simulation

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)**

Batteries (total)

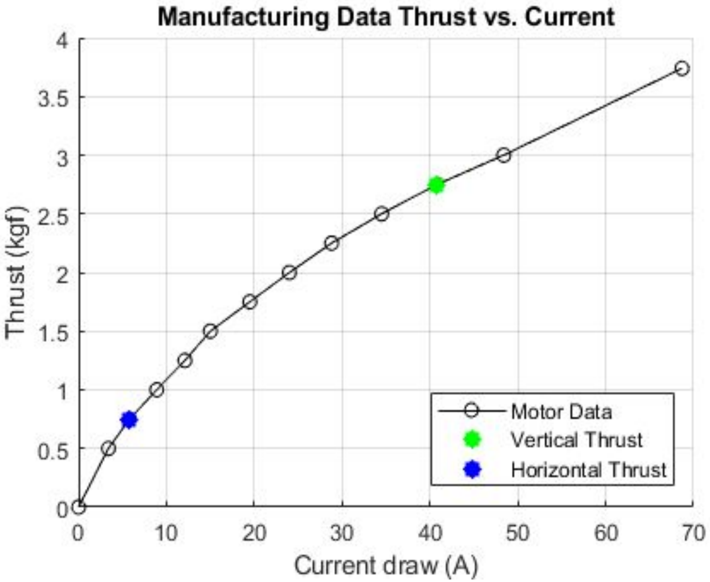
Samsung 40T 21700
*4000mAh 35A**

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*
***Based on 1.5 FOS*

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



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

VTOL Configuration: Mass Budget

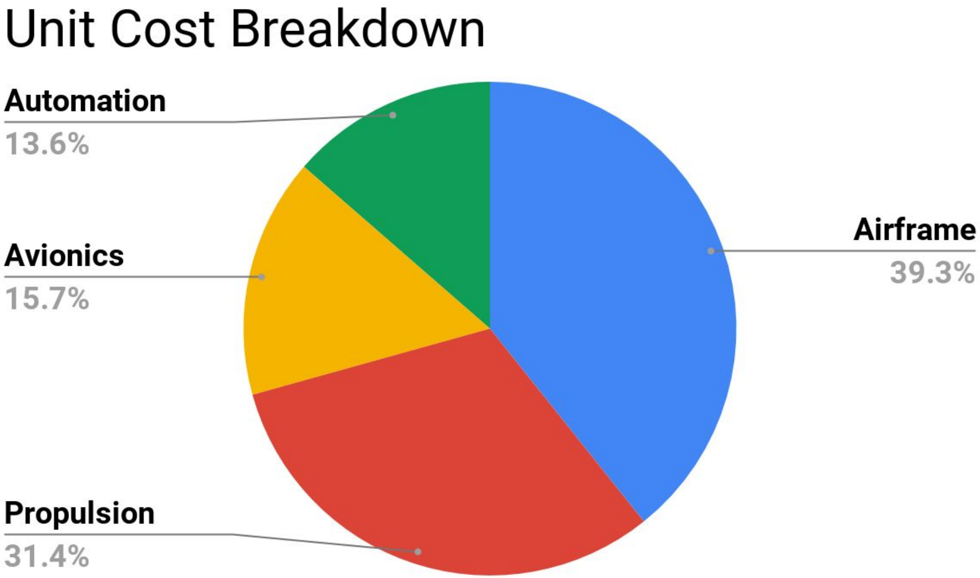
Grand total: 5391.7g

	Component	Mass (grams)	Quantity	Total Mass (grams)	Margin (grams)
Essentials	IRISS Board	70	1	70	0.7
	Hex Cube	35	1	35	0.35
	Telemetry Radio	58	1	58	0.58
Structure	Drak Kit	1440	1	**1440**	14.4
	Elevon Servos	11.2	2	22.4	0.224
Propulsion	Batteries	66.8	32	**2137.6**	21.376
	Front Motors	219	2	**438**	4.38
	Back Motor	219	1	**219**	2.19
	ESCs	60.1	3	180.3	1.803
	Front Servos	61	2	122	1.22
	Back servo	61	1	61	0.61
	Front Propellers	20	2	40	0.4
	Back Propeller	20	1	20	0.2
Payload		500	1	**500**	
Total				5343.3	48.4

Mass Budget is below propulsion system capabilities, showing feasibility

Cost Budget per Unit

System	Cost
Airframe	$375
Propulsion	$300
Avionics	$150
Automation	$130
Total	$955
Excess	$45



Summary of Baseline Design and Feasibility

System	Feasible	Reasoning
VTOL Configuration	Yes	Configuration is modeled to be stable in both flight modes - Manufacturing complexity is manageable
Flight Controller Firmware	Yes	Capable of autonomous flight profiles using chosen VTOL configuration - Interfaces with external sensors
Mass	Yes	Propulsion system is capable of providing enough thrust for VTOL
Power	Yes	Battery pack provides enough power/current for motors - Motor and propeller sizing is achievable and readily available
Endurance	Yes	Battery pack can provide required energy for flight time required in vertical and horizontal flight
Cost	Yes	Replication cost is within allotted budget

Testing and Verification

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.

Status Summary and Strategy

Schedule and Gantt Chart

VORTEX Gantt Chart

Task name	Task Number	Start date	Finish date	Owner	Dependency
Aerodynamics		**9/16**	**11/23**	Delaney	
Initial CFD Model Development	1	9/16	9/21	Michael	
Preliminary Lift/Drag Estimates	2	9/21	9/28	Michael	1
CFD Refinement	3	9/28	11/18	Delaney	2
Autonomy/Controls		**9/16**	**11/23**	Roland	
Firmware Selection	4	9/16	9/25	Joe	
Sensor Selection	5	9/16	9/25	Roland	
Sensor Testing	6	10/16	11/23	Mo	5
Firmware Configuration/Simulation	7	10/16	11/23	Joe B	4
Avionics		**9/16**	**11/23**	Cam	
IRISS Board Testing	8	10/16	11/23	Joe	
Servo Selection	9	10/13	11/3	Cam	
Propulsion		**9/23**	**11/23**	Brandon	
Endurance Estimation	10	9/23	9/25	Michael	
Preliminary Motor/Propeller Selection	11	9/25	10/7	Brandon	10
Preliminary Battery Selection	12	9/25	10/7	Brandon	10
Structures		**9/30**	**11/23**	Stephen	
CAD Model	13	9/30	10/9	Michael	
Motor Mount Design	14	10/5	11/16	Stephen	
Tilt Mechanism Design	15	10/7	11/16	Joe R	
Landing Gear Design	16	10/9	11/9	Joe R	
Safety & Testing		**10/7**	**11/23**	Colton	
Test Development and Scheduling	17	10/7	11/23	Colton	
Full Team		**9/16**	**12/7**		
CDD Due			**9/28**		
PDR Due			**10/12**		
CDR Due			**11/23**		

Legend

🟩 Complete

🟥 Needs immediate attention

🟩 On track

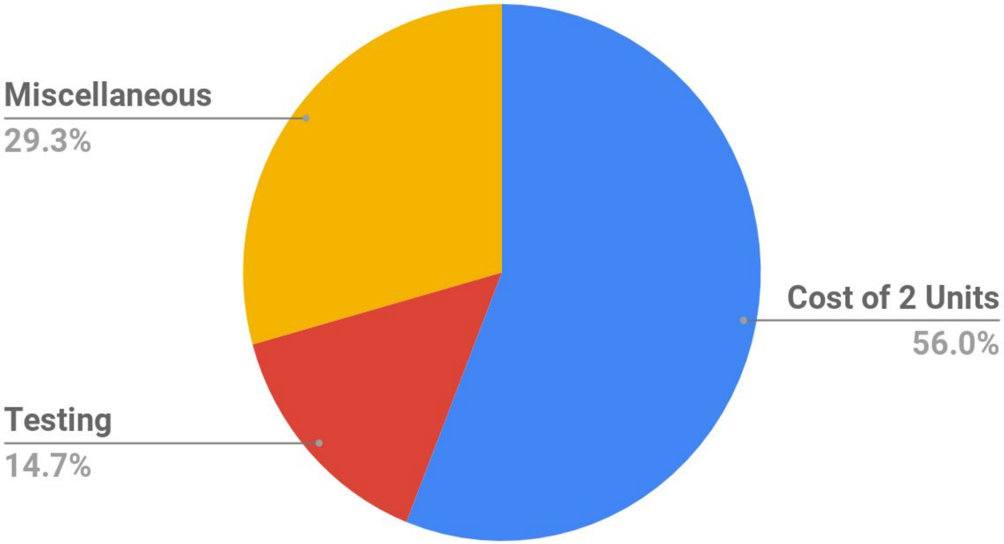
◆ Milestone

🟧 In trouble

Total Project Cost Budget

System	Cost
Unit Cost x2	$1,910
Testing	$500
Miscellaneous	$1,000
Total	$3,410
Excess	$1,590

Total Project Cost Breakdown



Acknowledgements

- VORTEX would like to thank Dr. G for her support and advice through the design development process.
- Thanks to Dakota Labine, Colin Claytor, and the WASP team for their feedback during PDR.
- Thanks to Danny Liebert, Dr Argrow, and Chris Klick for feedback on modeling and CFD.
- Thanks to Chris Choate and Michael Rhodes for meeting with us, providing a Drak kit for VORTEX to have on-hand, and answering dozens of questions about the Drak and RAAVEN.

References and Resources

“Archived: Advanced MultiCopter Design.” *Archived: Advanced MultiCopter Design - Copter Documentation*, ardupilot.org/copter/docs/advanced-multicopter-design.html.

“ArduPilot.” *ArduPilot Documentation - ArduPilot Documentation*, ardupilot.org/ardupilot/.

“BudgetLightForum.com.” *Test/Review of Samsung INR21700-40T 4000mAh (Cyan) | BudgetLightForum.com*, budgetlightforum.com/node/62458.

“New Photo by Mark Whitehorn.” *Google Photos*, Google, photos.google.com/share/AF1QipMJug81BLY1Wxtn136p5vZDixWOVy9ZMj3QAJvK4bMcUXS4gH5L69HPNeyROhdlbA?key=alVqYlZrVmlTZVVWNTdSQ1BtVjl4QlJ0aDBGZV9B.

“Pixhawk 2.” ProfiCNC, www.proficnc.com/.

“QuadPlane Support.” *QuadPlane Support - Plane Documentation*, ardupilot.org/plane/docs/quadplane-support.html.

References and Resources (Cont.)

“Samsung 40T 21700 4000mAh 35A Battery - INR21700-40T.” *18650BatteryStore.Com*, www.18650batterystore.com/21700-p/samsung-40t.html.

“SunnySky X Series V3 X3520 V3 Brushless Motors.” *SunnySky USA*, sunnyskyusa.com/collections/x-v3-motors/products/sunnysky-x3520.

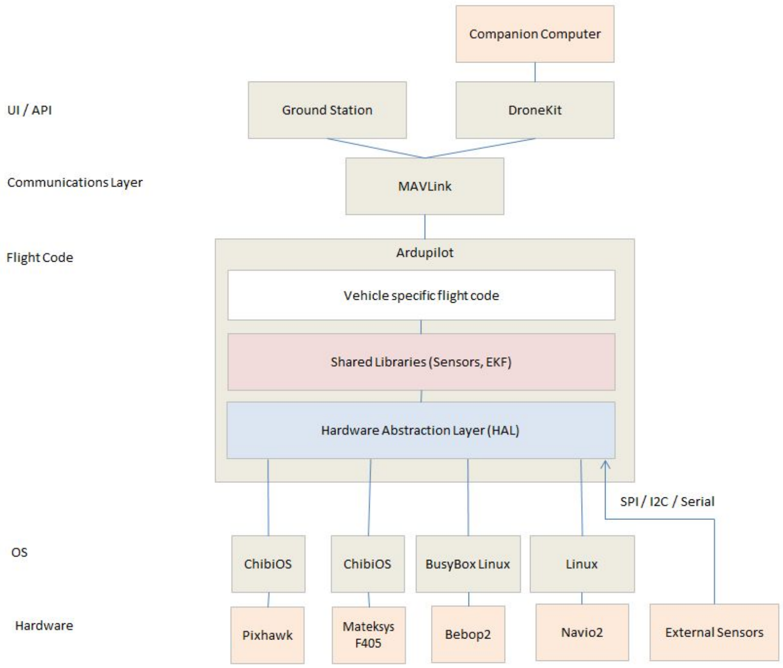
VTOL, gregcovey.com/vtol.html.

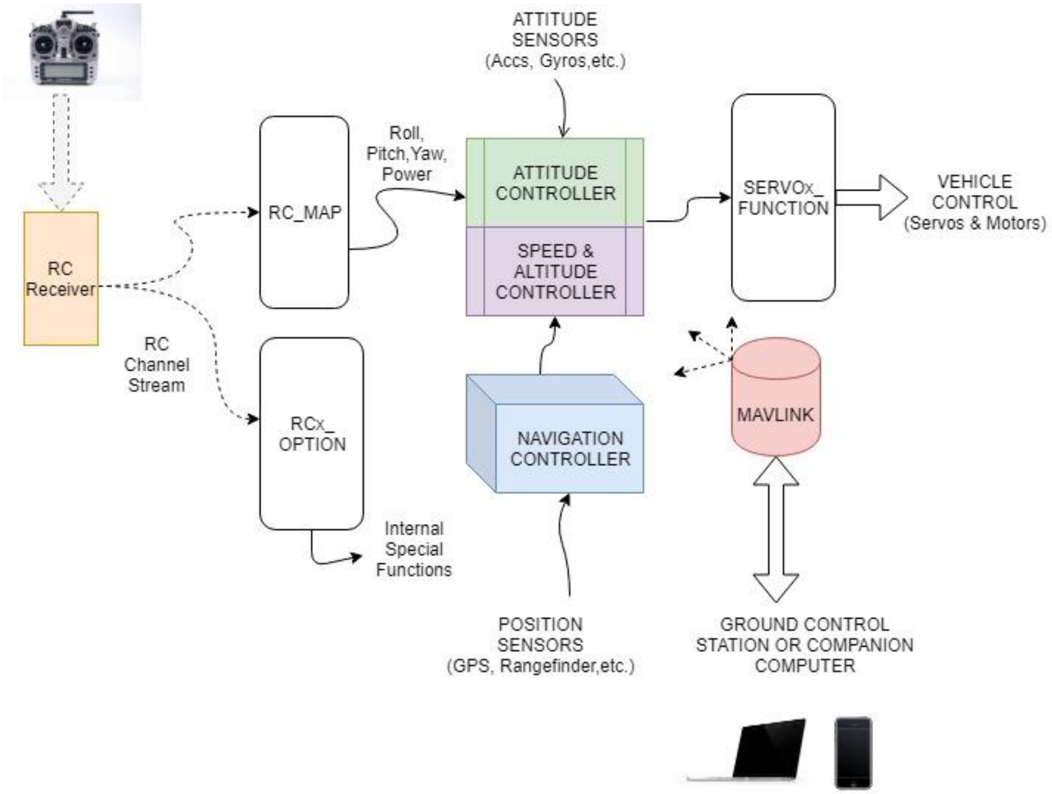
“What's the Best Battery?” *Advantages and Limitations of the Different Types of Batteries - Battery University*, batteryuniversity.com/learn/archive/whats_the_best_battery.

Thank You

Backup Slides

Ardupilot Feasibility- FBD





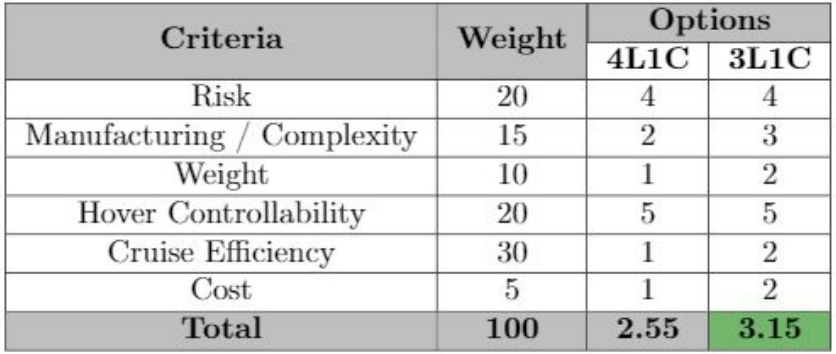
Backup Slides - VTOL Configuration Trade Study A

Criteria	Weight	Options		
		Tri	Quad	Quint
Risk	20	2.5	2.5	2
Manufacturing / Complexity	15	4	3	2
Weight	10	4	3	1
Hover Controllability	20	5	5	4
Cruise Efficiency	30	4	3	2
Cost	5	3	2	1
Total	**100**	**3.85** 🟩	**3.25**	**2.25**

Backup Slides - VTOL Configuration Trade Study B

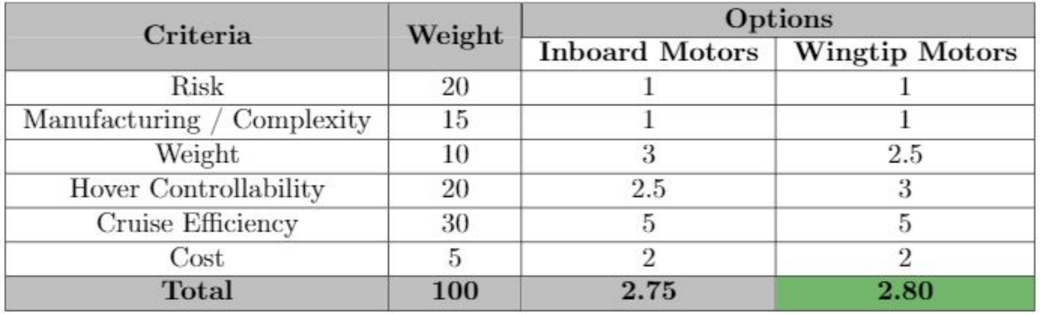
Criteria	Weight	Options			
		Quad	Double Push	Double Pull	Single
Risk	20	2	1.5	4	1
Manufacturing / Complexity	15	1.5	1	4	5
Weight	10	2.5	2.5	4	5
Hover Controllability	20	3.5	1	2	1
Cruise Efficiency	30	2.5	4	4.5	5
Cost	5	2	4	4	3
Total	**100**	**2.43**	**2.30**	**3.75**	**3.30**

Backup Slides - VTOL Configuration Trade Study C

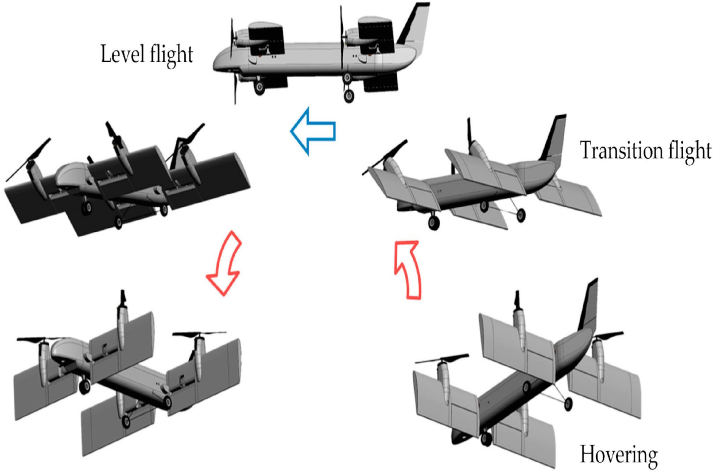


Criteria	Weight	Options	
		4L1C	3L1C
Risk	20	4	4
Manufacturing / Complexity	15	2	3
Weight	10	1	2
Hover Controllability	20	5	5
Cruise Efficiency	30	1	2
Cost	5	1	2
Total	**100**	**2.55**	**3.15**

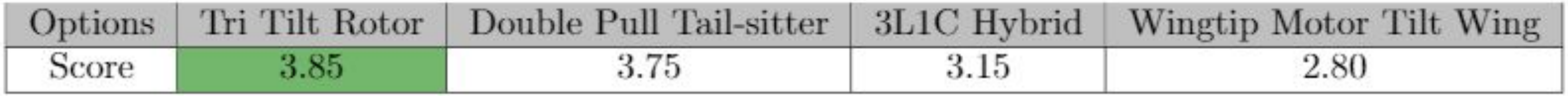
Backup Slides - VTOL Configuration Trade Study D



Criteria	Weight	Options	
		Inboard Motors	Wingtip Motors
Risk	20	1	1
Manufacturing / Complexity	15	1	1
Weight	10	3	2.5
Hover Controllability	20	2.5	3
Cruise Efficiency	30	5	5
Cost	5	2	2
Total	**100**	**2.75**	**2.80** 🟩

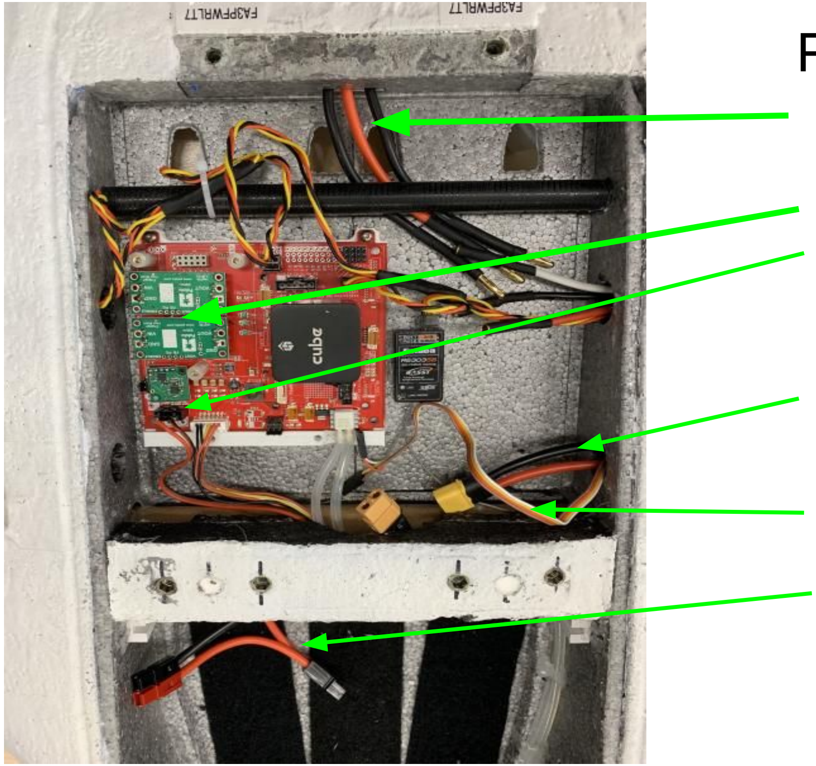


Backup Slides - VTOL Configuration Trade Study E



Options	Tri Tilt Rotor	Double Pull Tail-sitter	3L1C Hybrid	Wingtip Motor Tilt Wing
Score	3.85	3.75	3.15	2.80

Provided Avionics Package (cont.)



POWER Distribution

- Power cables to motor from ESC - 3-phase power
- 12V-0 and 3.3 V convertors on supplied board
- Power going into the board: stock Power module from PixHawk to provided avionics board
- Power to ESC from PixHawk Power Module; we will want to Consider a Power Distribution Board(PDB)
- ESC communication and control from PixHawk(More)
- Cables for 2 batteries in series going PixHawk Power Module

Provided Avionics Package (cont.)

HexCube Black Features:

- 3x Inertial measurement unit (IMU)
- 2x Internal Barometer
- 14 PWM / Servo outputs (8 with failsafe and manual override, 6 auxiliary, high-power compatible)
- Many options for additional peripherals using UART, I2C, CAN
- 32bit STM32F427 Cortex-M4F® core with FPU

Provided Avionics Package (cont.)

Power to Receiver and output for conventional system to distribution Board

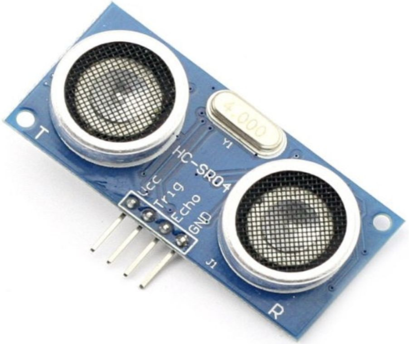
Antennas Again

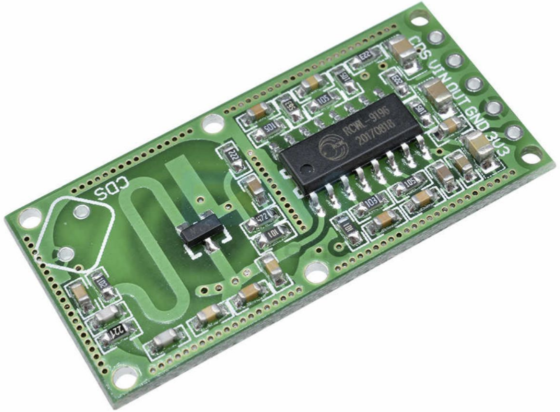
Cable to Singular ESC

Pitot Probe tubes and interface to board, not valuable during flight; Used for validation of data in post processing

Backup Slides - Landing Sensor Trade Study

Criteria	Weight (%)	Options		
		LiDAR	Micro Radar	Sonar
Complexity	25	3	3	3
Accuracy and Consistency	25	4	5	2
Size & Weight	20	5	3	5
Resiliency	15	4	5	2
Cost	15	5	3	5
Total	**100**	**4.1**	**3.8**	**3.3**

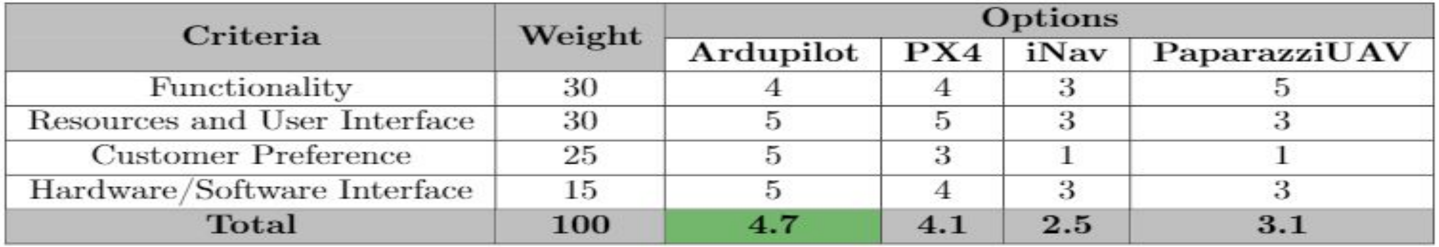




Backup Slides - Battery Chemistry Trade Study

Criteria	Weight	Options				
		Li-Po	Li-ion	NiMH	NiCd	LiFePO4
Discharge Rate (per cell)	25	5	2	2	3	3
Energy Density	25	2	4	2	1	2
Cost battery (per cell)	20	3	2	4	3	2
Lifespan (discharge cycles)	20	1	4	3	4	5
Safety	15	2	4	5	3	4
Total	**100**	**2.85**	**3.3**	**3.15**	**2.85**	**3.25**

Backup Slides - Flight Controller Firmware Trade Study



Criteria	Weight	Options			
		Ardupilot	PX4	iNav	PaparazziUAV
Functionality	30	4	4	3	5
Resources and User Interface	30	5	5	3	3
Customer Preference	25	5	3	1	1
Hardware/Software Interface	15	5	4	3	3
Total	**100**	**4.7**	**4.1**	**2.5**	**3.1**

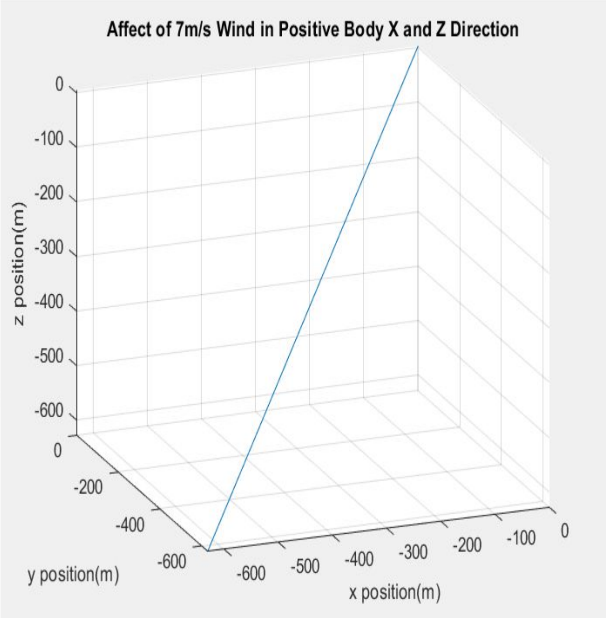
Backup Slides: VTOL Configuration, Hover Stability

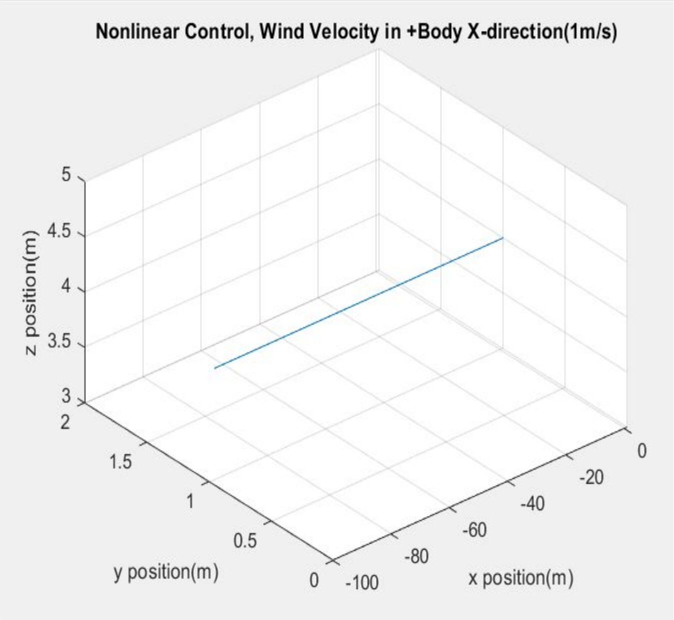
$$\lambda^2 + \lambda * \frac{k1}{Ix} + \frac{k2}{Ix}$$

$$e^{\lambda\tau} \rightrightarrows \lambda = \frac{-1}{\tau}$$

$$\dot{y}\begin{bmatrix} \frac{-2}{Ix} & \frac{1}{Ix} \\ \frac{-20}{Ix} & \frac{1}{Ix} \end{bmatrix} * \begin{bmatrix} k1 \\ k2 \end{bmatrix} = \begin{bmatrix} -4 \\ -400 \end{bmatrix}$$

Effect of Wind





- Heavy winds greatly affect inertial position of the craft

Backup Slides: VTOL Configuration, Hover Stability

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

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

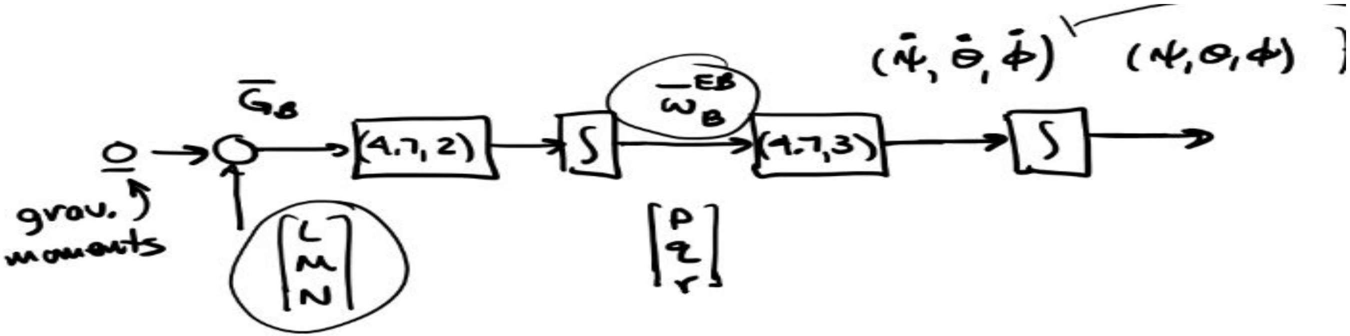
$$I_B\frac{d}{dt}\overline{w_B^{EB}} + \overline{w_B^{EB}}\mathbf{x}(I_B\overline{w_B^{EB}}) = \overline{G_B}$$

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

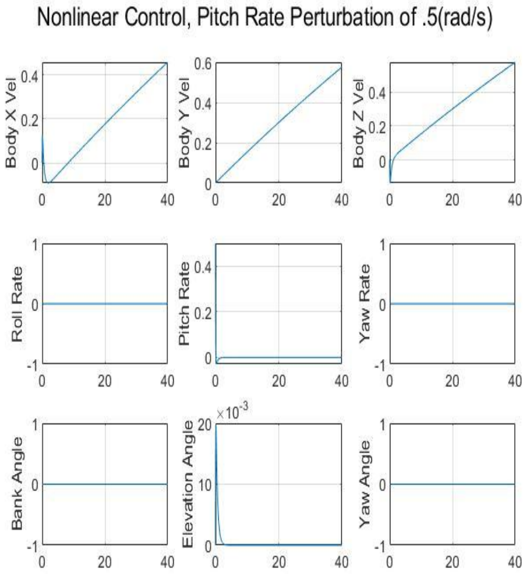
$$\overline{w_B^{EB}} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

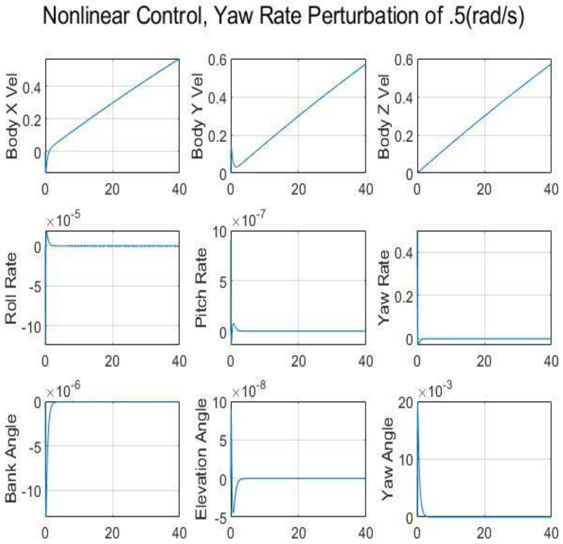
$$\overline{G_A} = -\alpha\left|\overline{W_B^{EB}}\right| * \overline{W_B^{EB}}$$

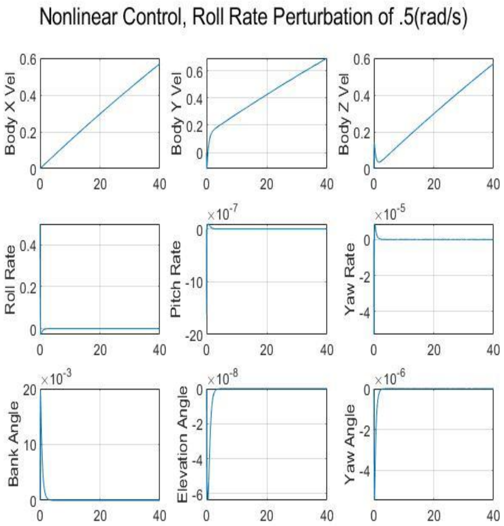
$$L_C = -kF_{1_x} - F_{1_z}l_1\sin(\beta) + kF_{2_x} + F_{2_z}l_2\sin(-\beta)$$
$$M_C = -F_{1_z}l_1\cos(\beta) - F_{2_z}\cos(-\beta) + l_3F_{3_z}$$
$$N_C = -kF_{1_z} + kF_{2_z} - kF_{3_z}$$
$$X_C = F_{1_x} + F_{2_x}$$
$$Z_C = F_{1_z} + F_{2_z} + F_{3_z}$$



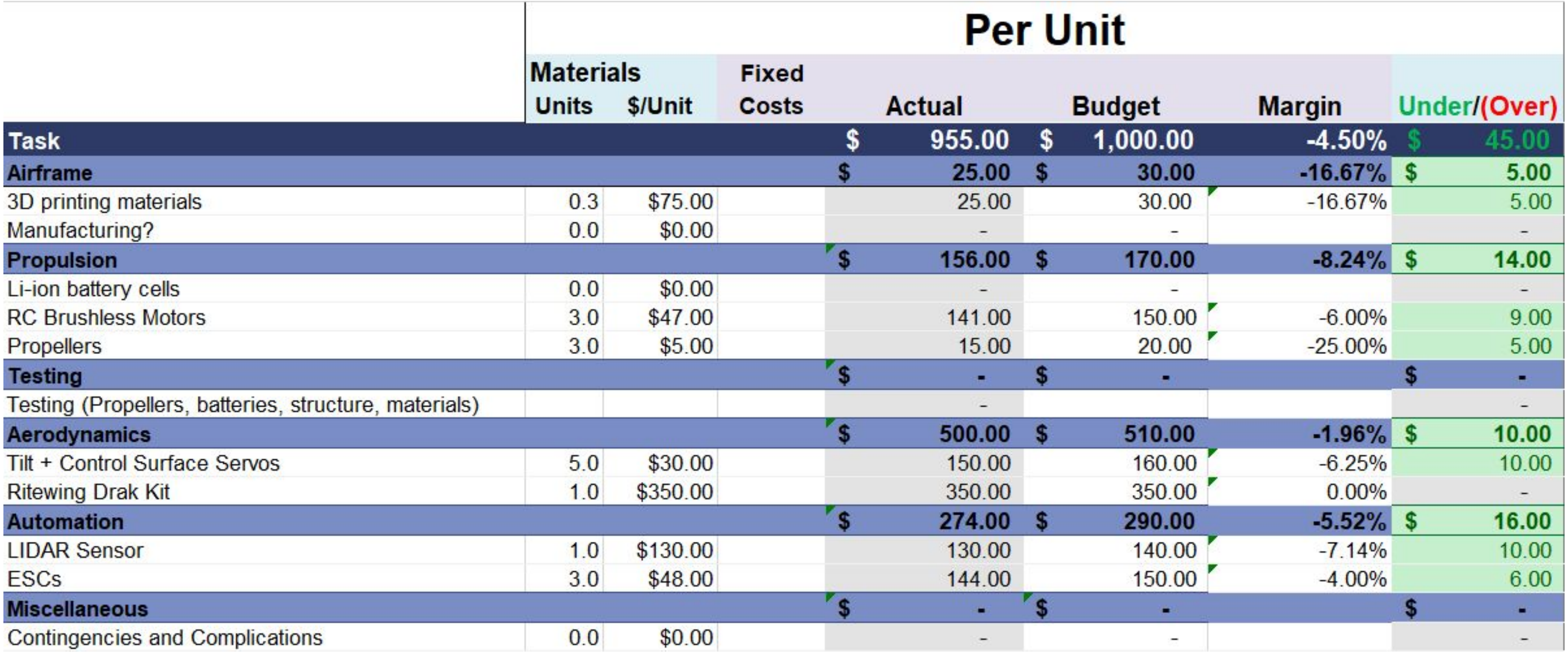
Backup Slides: VTOL Configuration, Hover Stability(More Graphs)


Nonlinear Control, Pitch Rate Perturbation of .5(rad/s)


Nonlinear Control, Yaw Rate Perturbation of .5(rad/s)

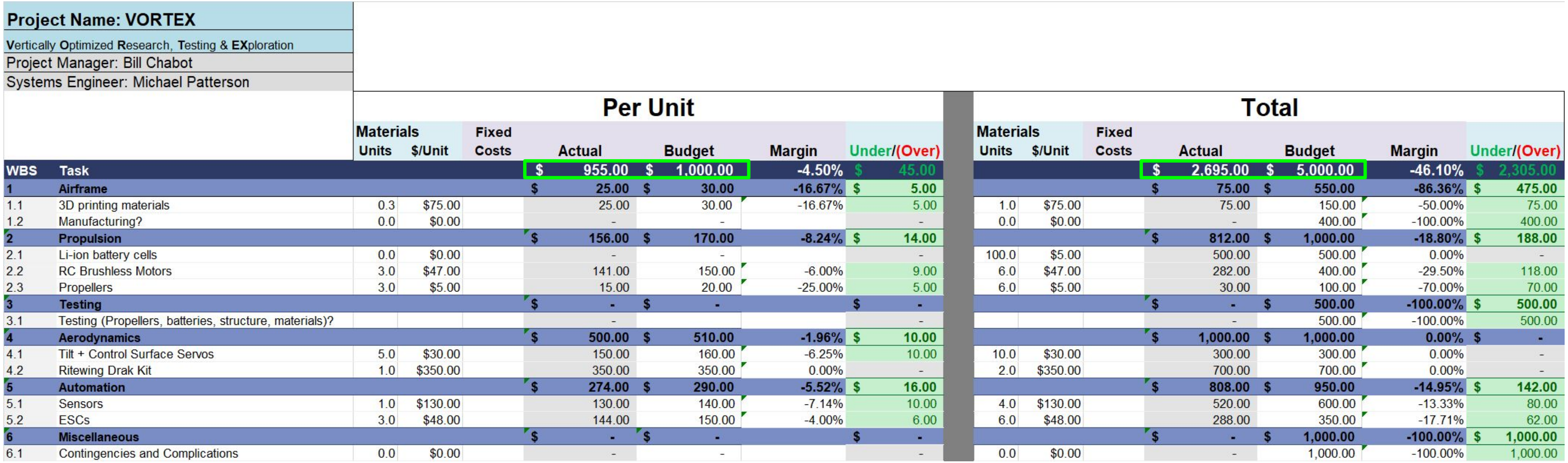

Nonlinear Control, Roll Rate Perturbation of .5(rad/s)

Replication Cost



	Per Unit						
	Materials		Fixed				
	Units	$/Unit	Costs	Actual	Budget	Margin	Under/(Over)
Task				**$ 955.00**	**$ 1,000.00**	**-4.50%**	**$ 45.00**
Airframe				**$ 25.00**	**$ 30.00**	**-16.67%**	**$ 5.00**
3D printing materials	0.3	$75.00		25.00	30.00	-16.67%	5.00
Manufacturing?	0.0	$0.00		-	-		-
Propulsion				**$ 156.00**	**$ 170.00**	**-8.24%**	**$ 14.00**
Li-ion battery cells	0.0	$0.00		-	-		-
RC Brushless Motors	3.0	$47.00		141.00	150.00	-6.00%	9.00
Propellers	3.0	$5.00		15.00	20.00	-25.00%	5.00
Testing				**$ -**	**$ -**		**$ -**
Testing (Propellers, batteries, structure, materials)				-			-
Aerodynamics				**$ 500.00**	**$ 510.00**	**-1.96%**	**$ 10.00**
Tilt + Control Surface Servos	5.0	$30.00		150.00	160.00	-6.25%	10.00
Ritewing Drak Kit	1.0	$350.00		350.00	350.00	0.00%	-
Automation				**$ 274.00**	**$ 290.00**	**-5.52%**	**$ 16.00**
LIDAR Sensor	1.0	$130.00		130.00	140.00	-7.14%	10.00
ESCs	3.0	$48.00		144.00	150.00	-4.00%	6.00
Miscellaneous				**$ -**	**$ -**		**$ -**
Contingencies and Complications	0.0	$0.00		-	-		-

Total Cost Budget



Project Name: VORTEX

Vertically **O**ptimized **R**esearch, **T**esting & **EX**ploration

Project Manager: Bill Chabot

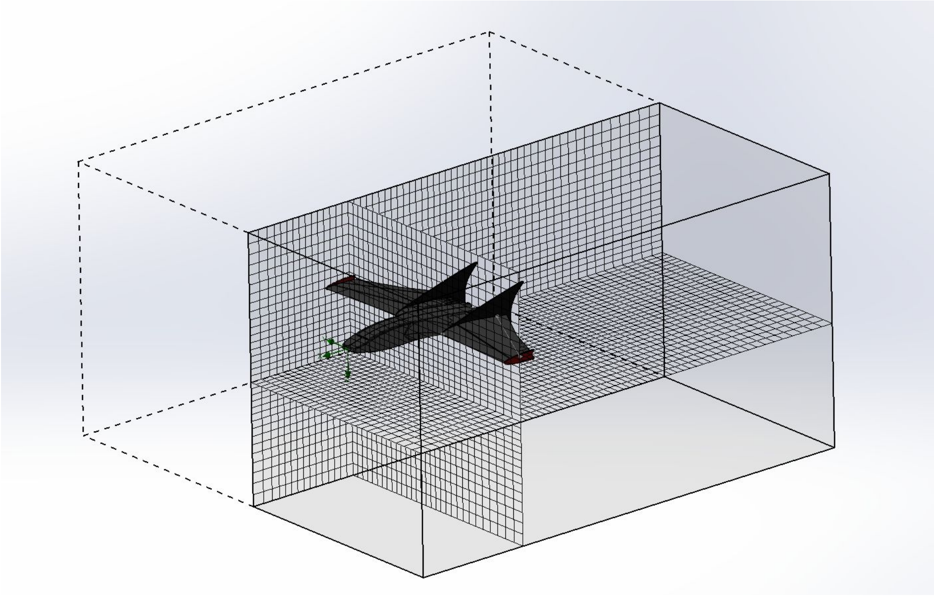
Systems Engineer: Michael Patterson

		Per Unit							Total						
		Materials Units	Materials $/Unit	Fixed Costs	Actual	Budget	Margin	Under/(Over)	Materials Units	Materials $/Unit	Fixed Costs	Actual	Budget	Margin	Under/(Over)
WBS	**Task**				$ 955.00	$ 1,000.00	-4.50%	$ 45.00				$ 2,695.00	$ 5,000.00	-46.10%	$ 2,305.00
1	**Airframe**				**$ 25.00**	**$ 30.00**	**-16.67%**	**$ 5.00**				**$ 75.00**	**$ 550.00**	**-86.36%**	**$ 475.00**
1.1	3D printing materials	0.3	$75.00		25.00	30.00	-16.67%	5.00	1.0	$75.00		75.00	150.00	-50.00%	75.00
1.2	Manufacturing?	0.0	$0.00		-	-		-	0.0	$0.00		-	400.00	-100.00%	400.00
2	**Propulsion**				**$ 156.00**	**$ 170.00**	**-8.24%**	**$ 14.00**				**$ 812.00**	**$ 1,000.00**	**-18.80%**	**$ 188.00**
2.1	Li-ion battery cells	0.0	$0.00		-	-		-	100.0	$5.00		500.00	500.00	0.00%	-
2.2	RC Brushless Motors	3.0	$47.00		141.00	150.00	-6.00%	9.00	6.0	$47.00		282.00	400.00	-29.50%	118.00
2.3	Propellers	3.0	$5.00		15.00	20.00	-25.00%	5.00	6.0	$5.00		30.00	100.00	-70.00%	70.00
3	**Testing**				**$ -**	**$ -**		**$ -**				**$ -**	**$ 500.00**	**-100.00%**	**$ 500.00**
3.1	Testing (Propellers, batteries, structure, materials)?				-			-				-	500.00	-100.00%	500.00
4	**Aerodynamics**				**$ 500.00**	**$ 510.00**	**-1.96%**	**$ 10.00**				**$ 1,000.00**	**$ 1,000.00**	**0.00%**	**$ -**
4.1	Tilt + Control Surface Servos	5.0	$30.00		150.00	160.00	-6.25%	10.00	10.0	$30.00		300.00	300.00	0.00%	-
4.2	Ritewing Drak Kit	1.0	$350.00		350.00	350.00	0.00%	-	2.0	$350.00		700.00	700.00	0.00%	-
5	**Automation**				**$ 274.00**	**$ 290.00**	**-5.52%**	**$ 16.00**				**$ 808.00**	**$ 950.00**	**-14.95%**	**$ 142.00**
5.1	Sensors	1.0	$130.00		130.00	140.00	-7.14%	10.00	4.0	$130.00		520.00	600.00	-13.33%	80.00
5.2	ESCs	3.0	$48.00		144.00	150.00	-4.00%	6.00	6.0	$48.00		288.00	350.00	-17.71%	62.00
6	**Miscellaneous**				**$ -**	**$ -**		**$ -**				**$ -**	**$ 1,000.00**	**-100.00%**	**$ 1,000.00**
6.1	Contingencies and Complications	0.0	$0.00		-	-		-	0.0	$0.00		-	1,000.00	-100.00%	1,000.00

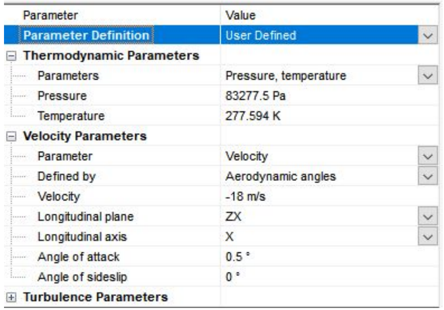
Solidworks Flow Simulation

Basic Mesh and Computational Domain:

- Takes advantage of symmetry

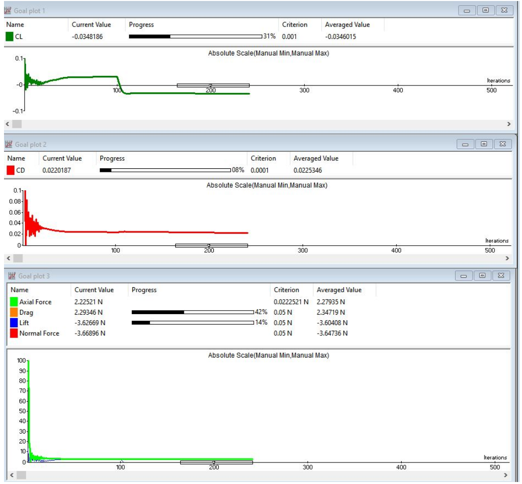


Initial Conditions:



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



Goal plot 1

Name	Current Value	Progress	Criterion	Averaged Value
CL	-0.0348186	31%	0.001	-0.0346015

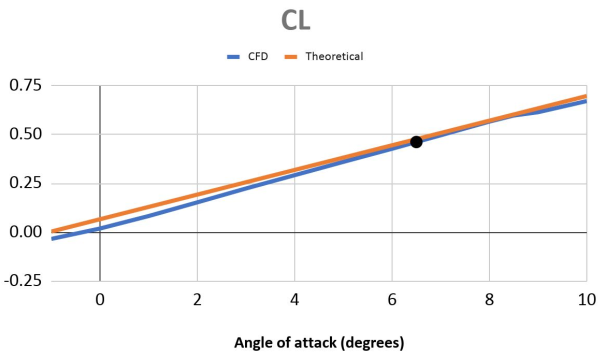
Goal plot 2

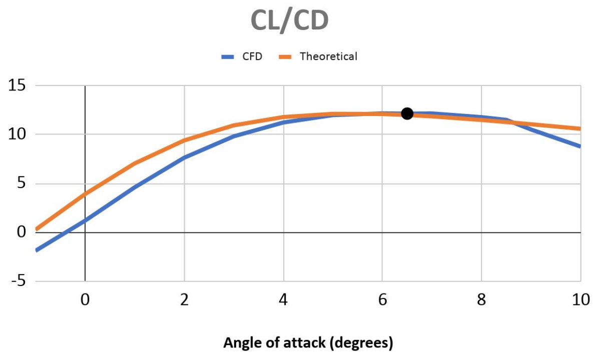
Name	Current Value	Progress	Criterion	Averaged Value
CD	0.0220187	08%	0.0001	0.0225346

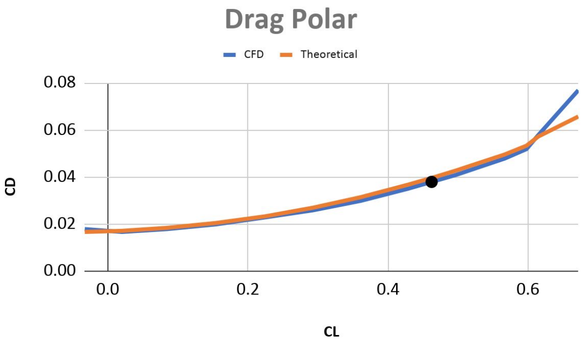
Goal plot 3

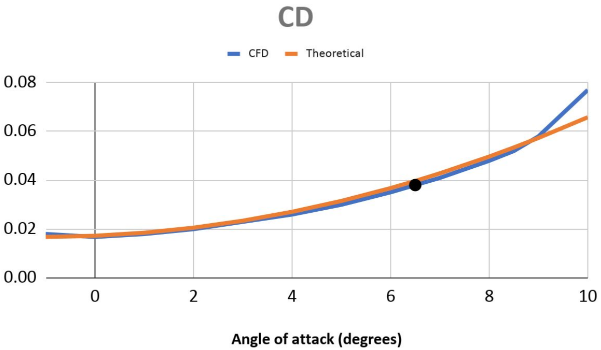
Name	Current Value	Progress	Criterion	Averaged Value
Axial Force	2.22521 N		0.0222521 N	2.27935 N
Drag	2.29346 N	42%	0.05 N	2.34719 N
Lift	-3.62669 N	14%	0.05 N	-3.60408 N
Normal Force	-3.66896 N		0.05 N	-3.64736 N

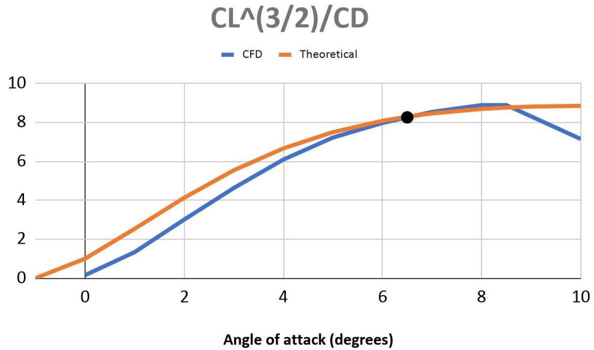
Stock Drak CFD Results











Design Point

- m = 5.9 kg
- AOA ≈ 7°
- D ≈ 4.7 N

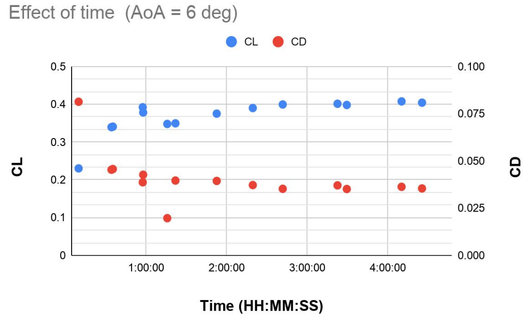
Mesh convergence study

Motivation:

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

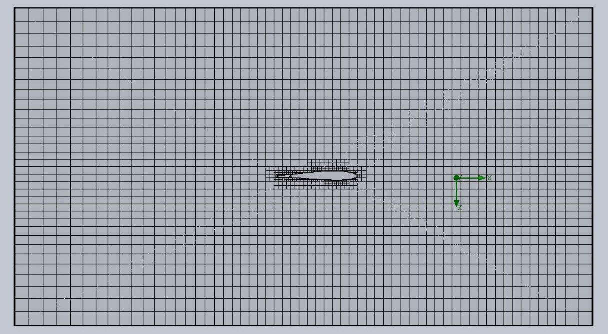
Procedure

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

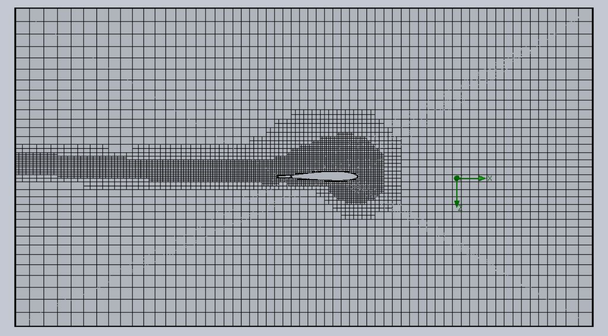


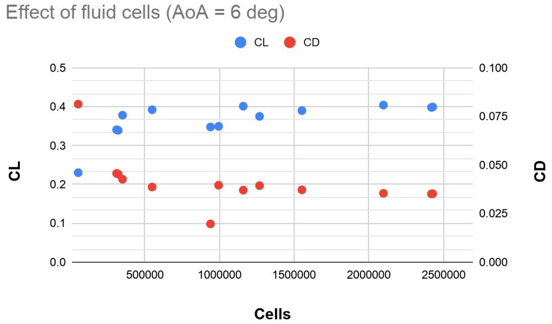
Using SolidWorks' built in mesh refinement system

Before:

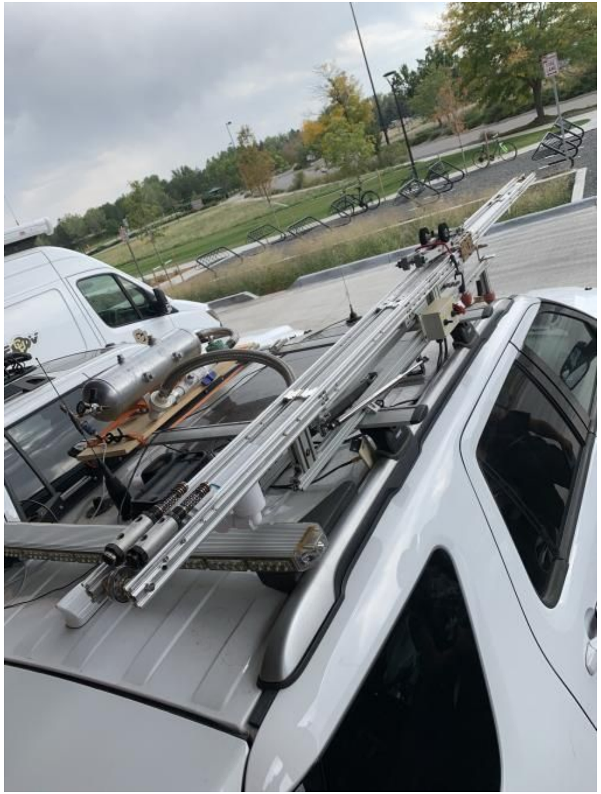


After:





RAPCat Launch System Images



Objectives & Levels of Success

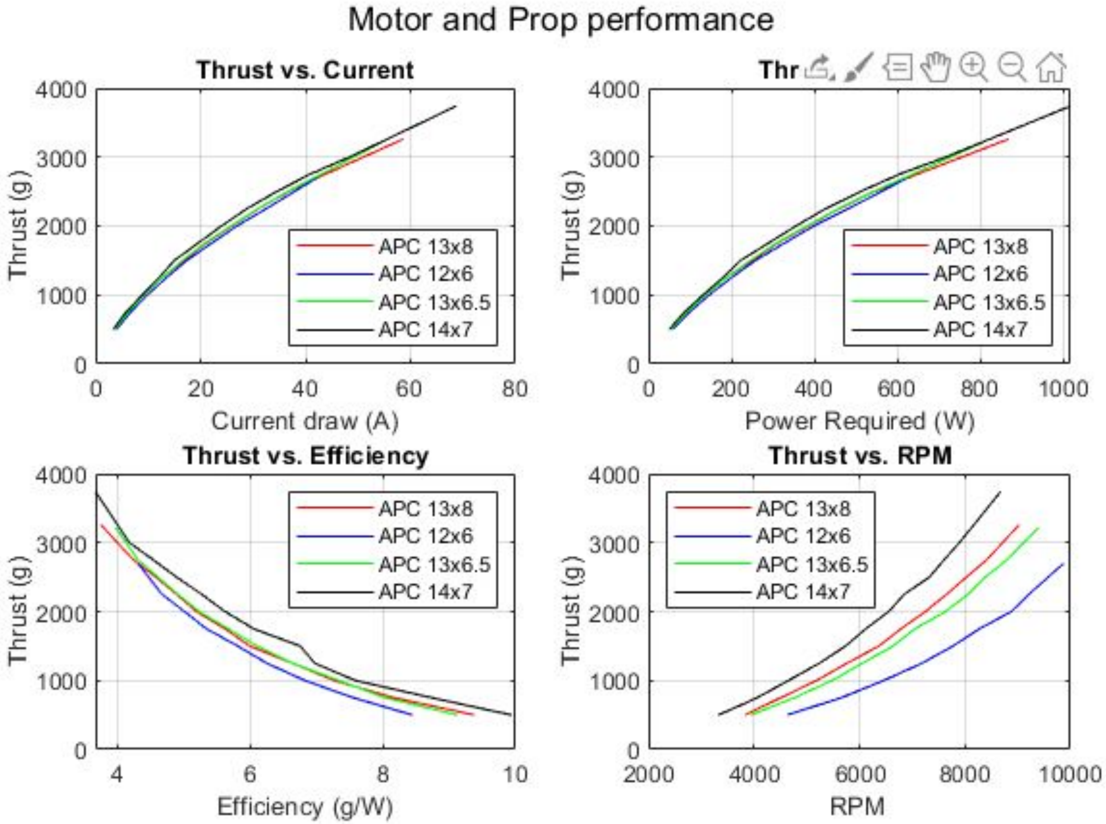
	Level 1	Level 2	Level 3
Flight	Static test stand TWR > 1	Steady hover for 30 sec Static test stand flight mode transition	Takeoff from RAPCat Full flight mode transition
Budget	Replication cost <$1250	Replication cost <$1000	Replication cost <$900
Endurance	Static thrust for 1 hour cruise, 2 takeoffs/ 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.

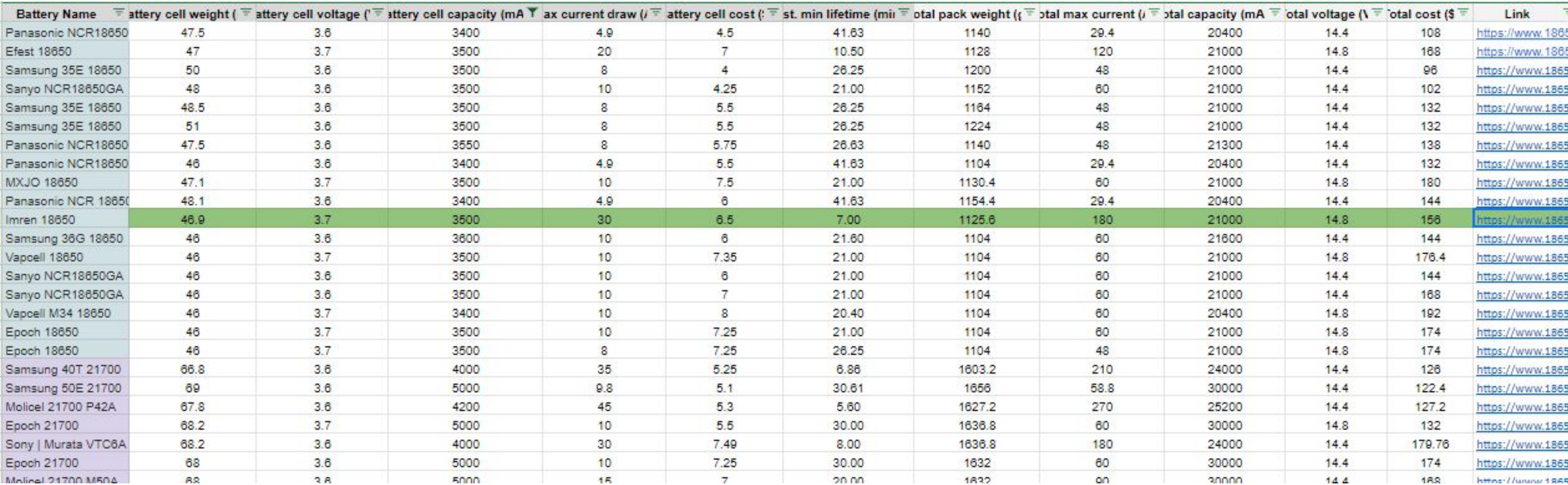
Objectives & Levels of Success Cont.

	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 Lands within 1.5m radius

Power Budget

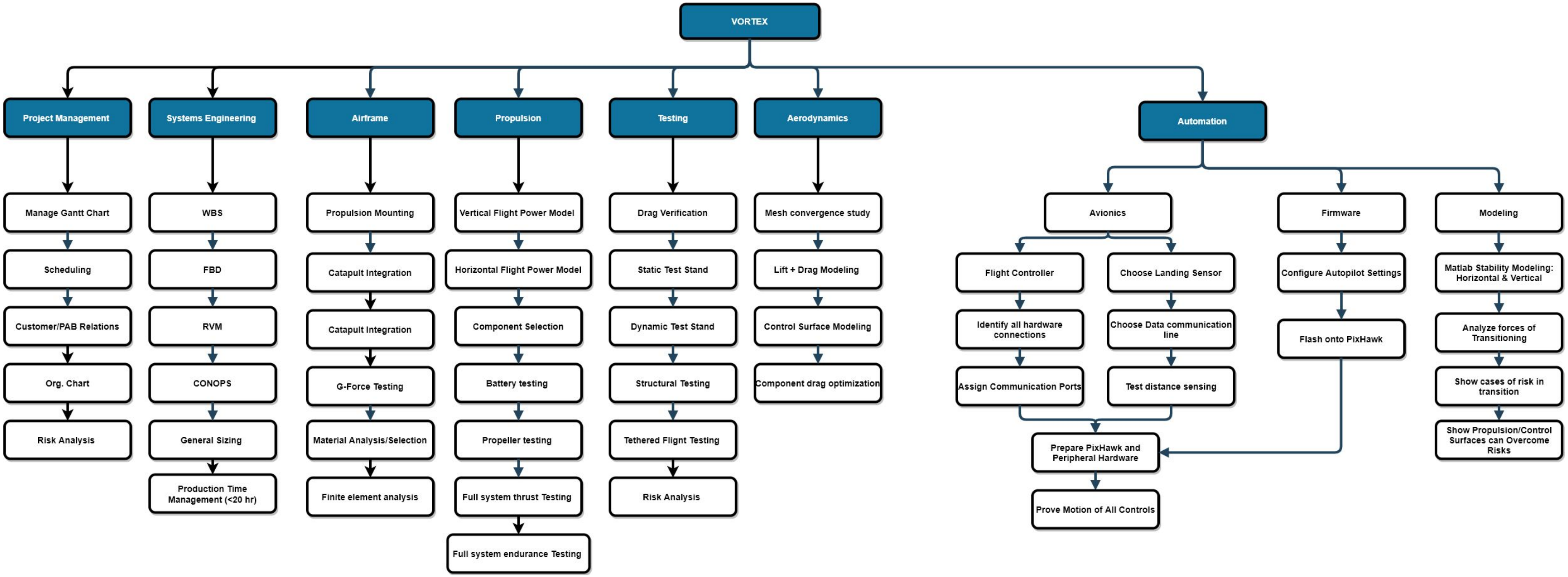


Battery Study



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 (ç	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



- VORTEX
  - Project Management
    - Manage Gantt Chart
    - Scheduling
    - Customer/PAB Relations
    - Org. Chart
    - Risk Analysis
  - Systems Engineering
    - WBS
    - FBD
    - RVM
    - CONOPS
    - General Sizing
    - Production Time Management (<20 hr)
  - Airframe
    - Propulsion Mounting
    - Catapult Integration
    - Catapult Integration
    - G-Force Testing
    - Material Analysis/Selection
    - Finite element analysis
  - Propulsion
    - Vertical Flight Power Model
    - Horizontal Flight Power Model
    - Component Selection
    - Battery testing
    - Propeller testing
    - Full system thrust Testing
    - Full system endurance Testing
  - Testing
    - Drag Verification
    - Static Test Stand
    - Dynamic Test Stand
    - Structural Testing
    - Tethered Flight Testing
    - Risk Analysis
  - Aerodynamics
    - Mesh convergence study
    - Lift + Drag Modeling
    - Control Surface Modeling
    - Component drag optimization
  - Automation
    - Avionics
      - Flight Controller
        - Identify all hardware connections
        - Assign Communication Ports
      - Choose Landing Sensor
        - Choose Data communication line
        - Test distance sensing
      - Prepare PixHawk and Peripheral Hardware
      - Prove Motion of All Controls
    - Firmware
      - Configure Autopilot Settings
      - Flash onto PixHawk
    - Modeling
      - Matlab Stability Modeling: Horizontal & Vertical
      - Analyze forces of Transitioning
      - Show cases of risk in transition
      - Show Propulsion/Control Surfaces can Overcome Risks

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

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