VORTEX

Vertically Optimized Research, Testing, & EXploration

Spring Final Review

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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

Summary of Results

	Level 1	Level 2	Level 3
Avionics & Electronics	All motors and actuators shall be successfully integrated with the flight controller. The telemetry link shall be maintained with less than 50% packet loss within 2 km of the ground station.	All external (non-native) sensors are successfully integrated with the avionics system.	-
Autonomy	Both the VTOL and fixed-wing modes have valid dynamic models to ensure active stabilization is possible. Ensure that the chosen avionics package interfaces successfully with propulsion system, sensors, and connectivity with ground station.	The aircraft can autonomously execute a takeoff and landing.	The aircraft shall autonomously execute a full mission profile, transitioning between flight modes, and land within a 1.5 meter radius of a target location.
Safety	The aircraft shall have an autonomous return to loiter function if telemetry is lost for an extended period (90 seconds) as well as capability to terminate the flight immediately upon command from the GSE	-	-

Summary of Results

	Level 1	Level 2	Level 3
Flight	Show on a static test stand that the propulsion system is capable of producing enough thrust to provide a TWR greater than 1	Maintain tethered hover at 2 m of altitude for 30 seconds as well as demonstrate capability to transition to horizontal flight while aircraft is mounted to a test stand	Aircraft shall demonstrate takeoff ability via RAP-Cat launch system as well as demonstrate full transition from vertical to horizontal flight modes.
Budget	The aircraft shall cost no more than $1250, not including IRISS avionics package or batteries	The aircraft shall cost no more than $1000, not including IRISS avionics package or batteries	The aircraft shall cost no more than $900, not including IRISS avionics package or batteries
Endurance	The propulsion system shall maintain required thrust output for the equivalent of 1 hour cruise and 2 takeoffs and landings (approximately 1hr 16 minutes) on a static test stand in simulated freestream conditions of 18 m/s with >15% battery remaining	-	Demonstrate 1 hour of flight cruise as well as 2 takeoffs and landings
Airframe	A finite element analysis of the modified air-frame will be performed to demonstrate that it can withstand the required forces with a FOS of 1.7	The aircraft will have full integration capabilities with RAPCat launch system, and show that it can withstand the forces due to acceleration.	The airframe shall withstand axial and lateral forces up to 10G.

Design Description

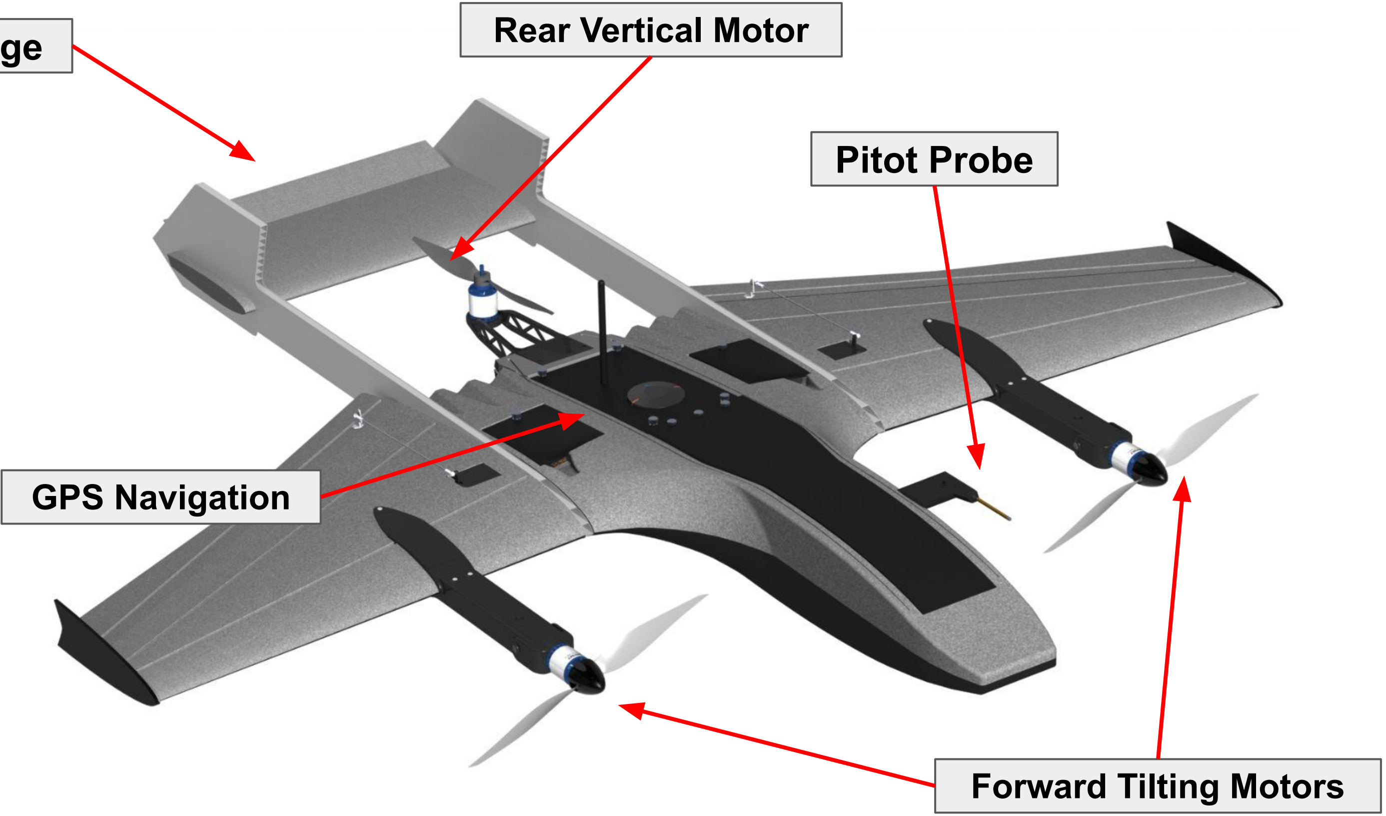
Critical Project Elements

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.

Functional Requirements

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

Final Design



Key Parameters

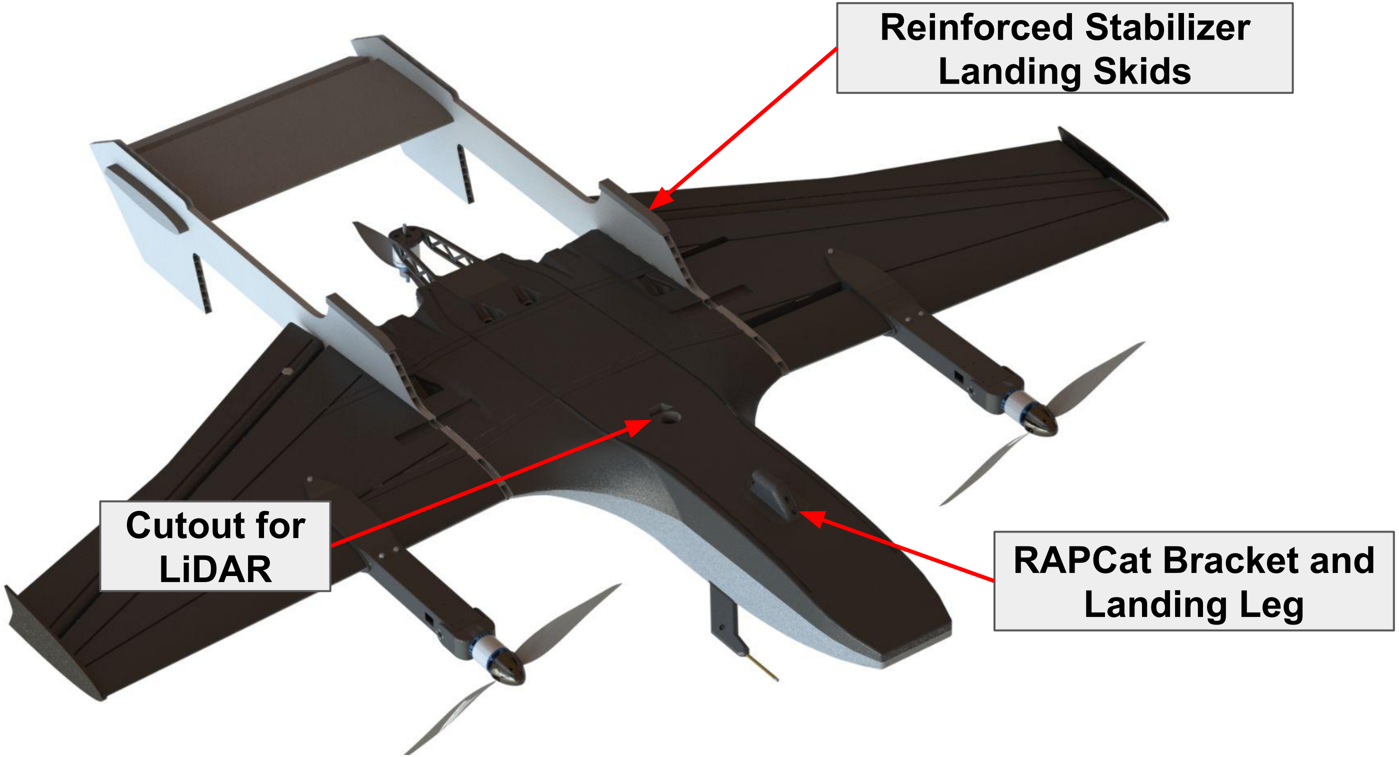
Dimensions:

- Wingspan: 1.55m
- Tip-to-Tail: 1.10m

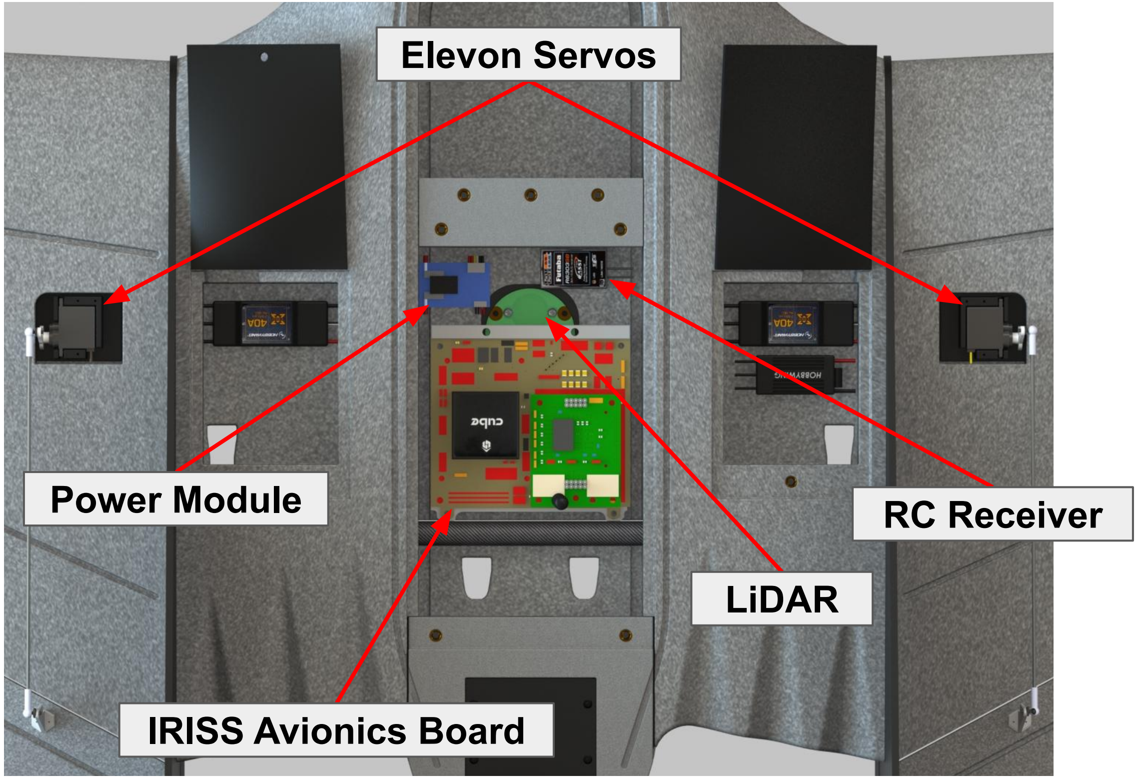
Weight:

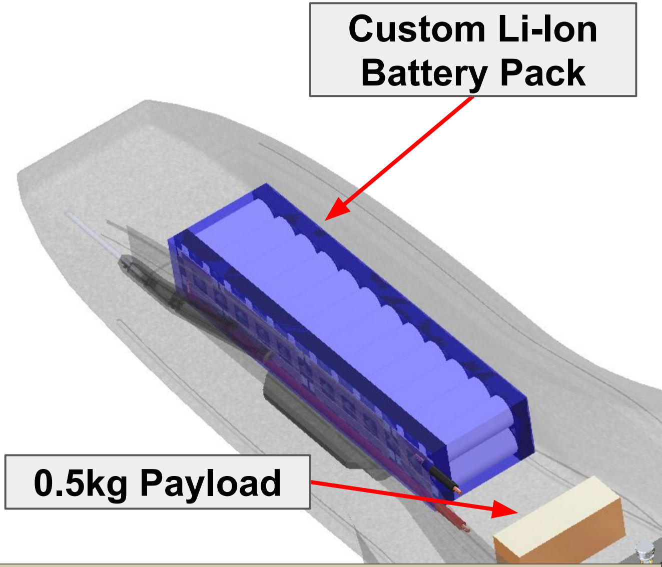
- 6.0kg

Final Design

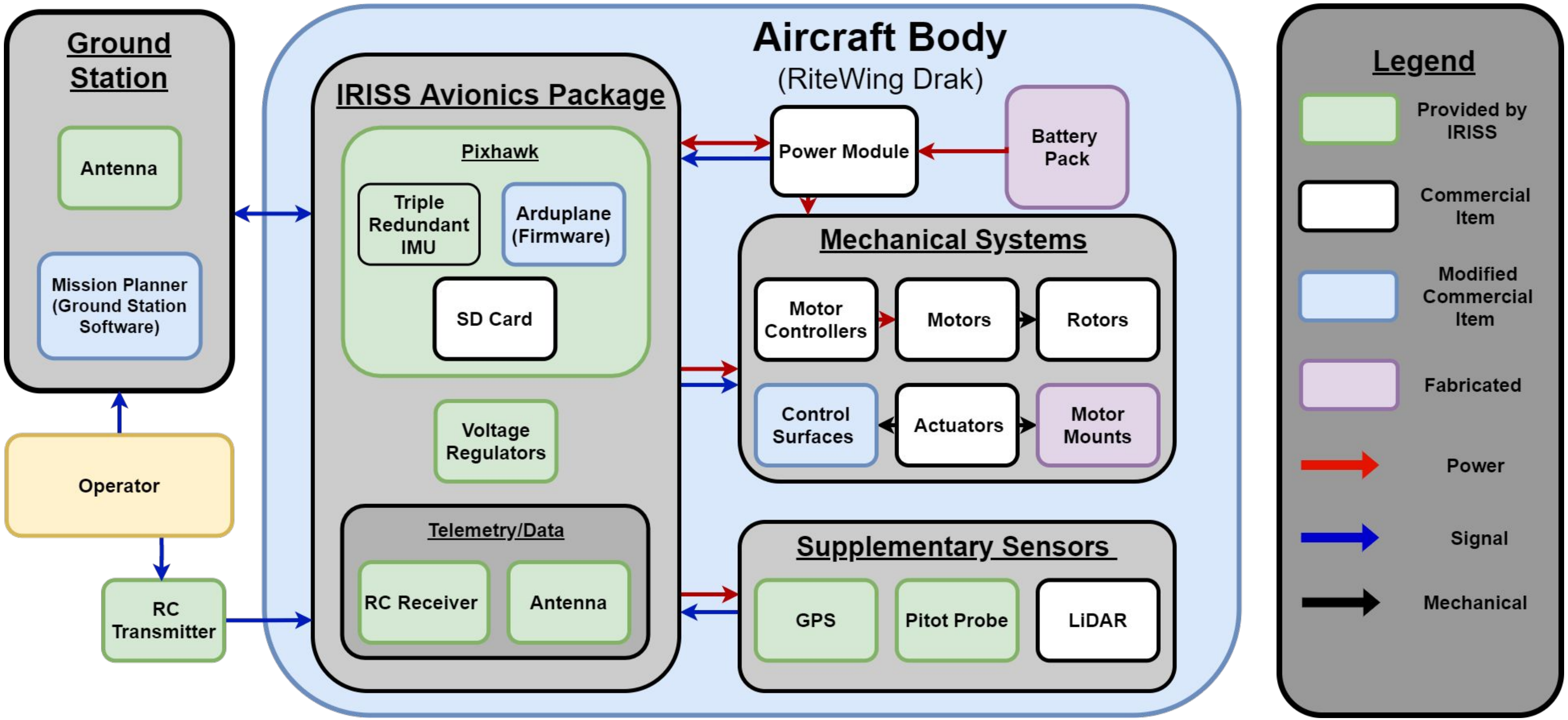


Final Design





System Functional Block Diagram



Changes Since TRR

Electronics

- Upgraded tilt servos for higher torque
- Airspeed sensor protocol changed to I^2C

Structures

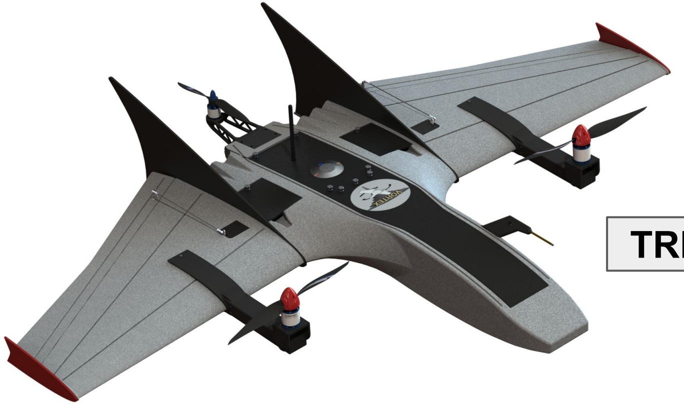
- Mass of tilt rotor wing mount reduced
- Reduced characteristic drag
- Increased structural support in rear motor mount

Aerodynamics

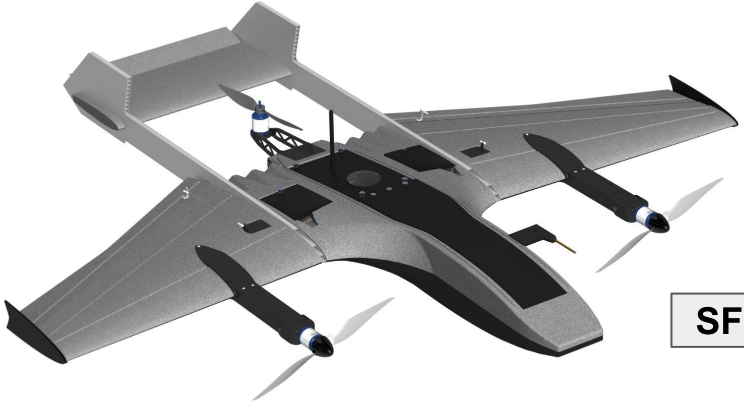
- Designed and manufactured empennage

Automation

- Initial aircraft tuning in hover
- Integrated LiDAR



TRR



SFR

Elements Critical for Project Success

Vertical Takeoff and Landing

- Tricopter configuration with tilting front motors
- High discharge custom battery

Structures

- Forward tilt motor mounts
- Rear vertical motor mount

Endurance

- Empennage for better stability and horizontal cruise
- High voltage custom battery

Automation

- Rangefinding lidar
- ArduPilot parameters tuned to match aircraft configuration
- Various flight mode settings and autonomous mission profiles

Test Overview

Test Overview

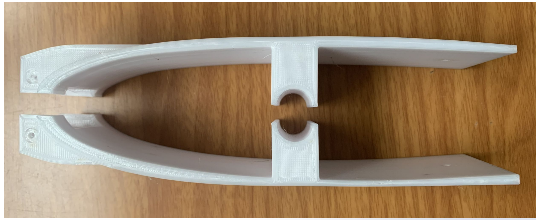
	Functional Requirement	Element	Test	Description	Status
1	FR6	STR	**Wing Motor Mount Stress**	Verification of FEM model and testing structural limits of wing motor mounts	Complete
2	FR2	END	**Battery Endurance**	Verify and prove the assembled battery meets modeled capacity performance	Complete
3	FR1	VTOL	**Static Motor**	Testing thrust and power draw in static conditions	Complete
4	FR3	AUT	**Controls**	Verify that control surfaces actuate properly	Complete
5	FR3	AUT	**LiDAR**	Testing LiDAR system for accuracy	Complete
6	FR4	AUT	**Telemetry**	Verify/test avionics package and communications	Complete

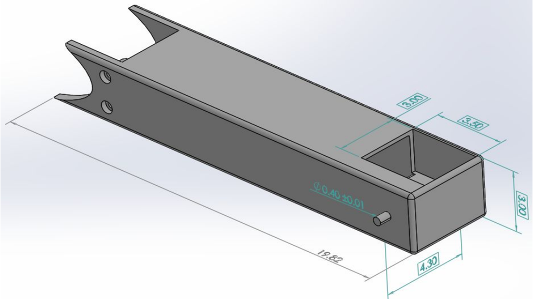
Test Overview

	Functional Requirement	Element	Test	Description	Status
7	FR2	END	**Dynamic Motor**	Testing thrust and power draw in flight conditions	Complete
8	FR2	END	**Car Top Aerodynamic**	Obtain aerodynamic forces to validate CFD	Complete
9	FR6	STR	**RAPCat Integration**	Validate that Drak fits into existing RAPCAT bracket and test launch procedure	Planned 4/19-4/23
10	FR1	VTOL	**Hover**	Verify stability in hover	Complete
11	FR2	END	**Full Flight**	Verify that Drak can execute the mission	Planned 4/21

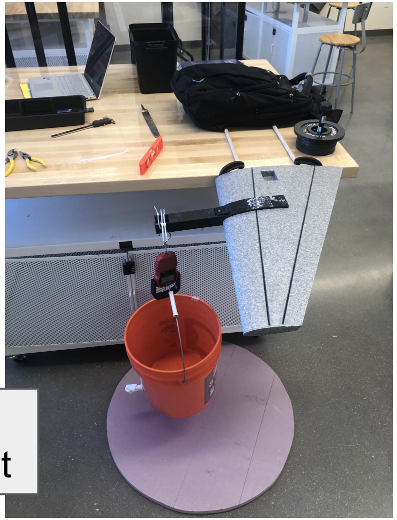
Wing Motor Stress Testing

What and Why:
- Verification of FEM simulations; ensuring requirements met
- Increasing load applied to end of motor arm / wing assembly
- Removes risk of failure during maximum loading in flight





Testing Procedure:
- Wing spars clamped to table
- Weight incrementally added to the end of the motor arm in 0.5kg increments



Motor mount structural test

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

Complete

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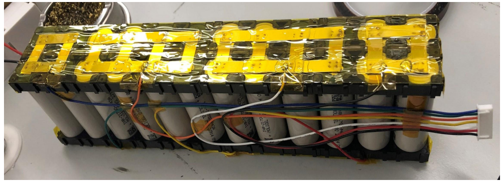
Battery Endurance Testing

What and Why:

- Verification of custom battery assembly functionality
- Reduces the risk of power capabilities for the aircraft

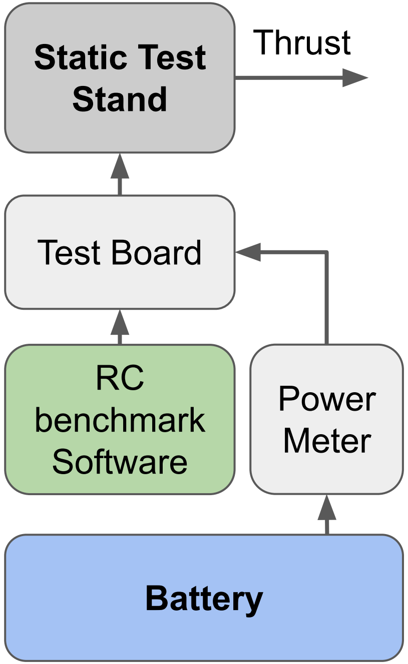
Testing Procedure:

- Verify battery cell balanced voltage
- Maintained a cruise condition current draw until battery voltage drops below 18V

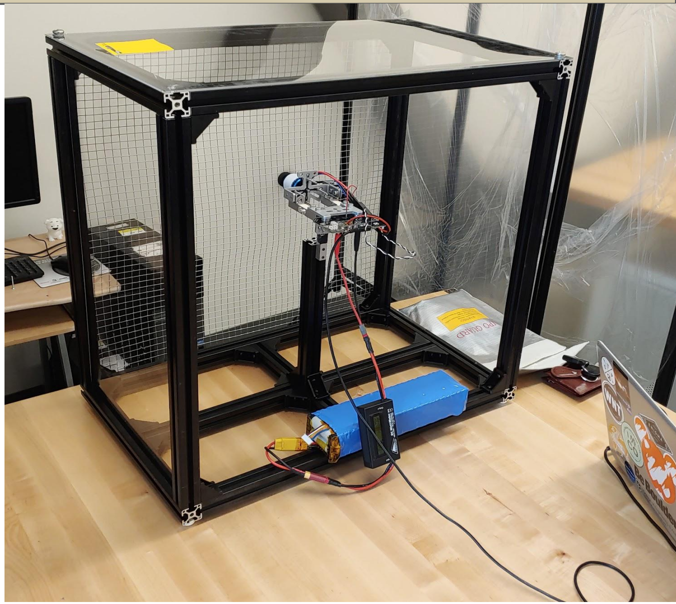


Exposed battery view

Complete



Test Overview



Static Test Setup (in-action)

Static Propulsion Test Stand

What and Why:

- Test for thrust, power, and endurance requirements for the propulsion subsystem
- Using RC Benchmark software to track specific test properties:
  - Current draw
  - Thrust
  - RPM
- Motor and load cells contained in plexiglass & chicken wire box

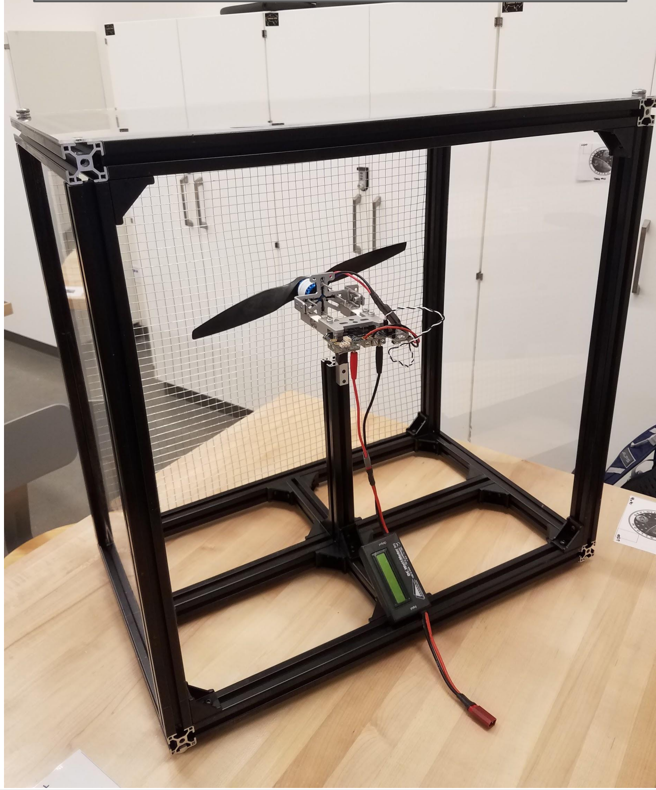
Testing Procedure:

- Configure battery, motor, ESC, and propeller
- Use RC benchmark software to manually toggle throttle power input

Complete

Requirement	Description
FR2	Endurance of one hour with two takeoffs and landings

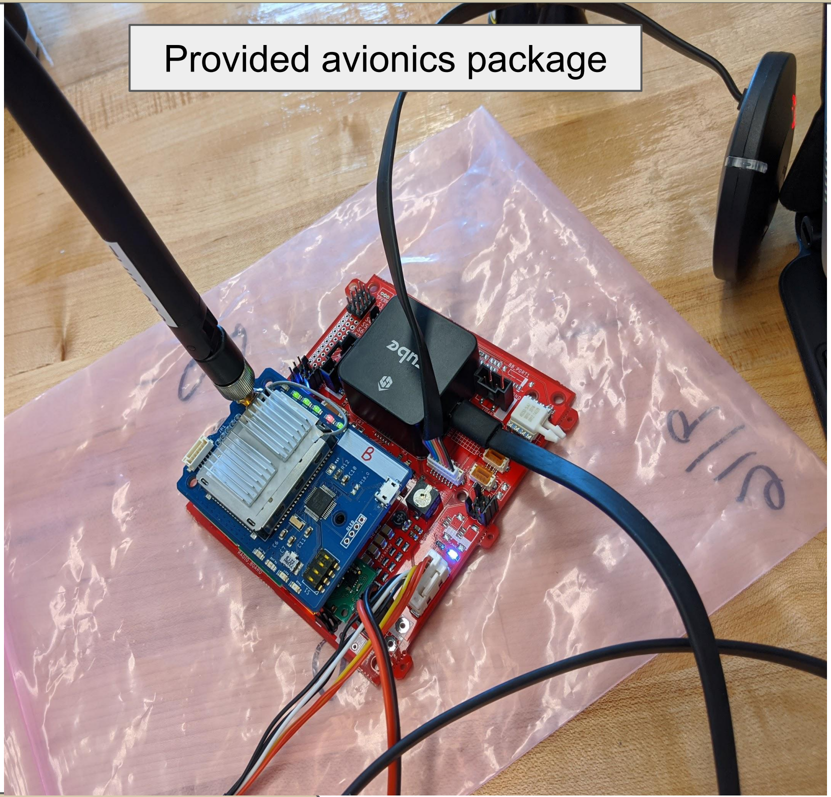
Propulsion test stand setup

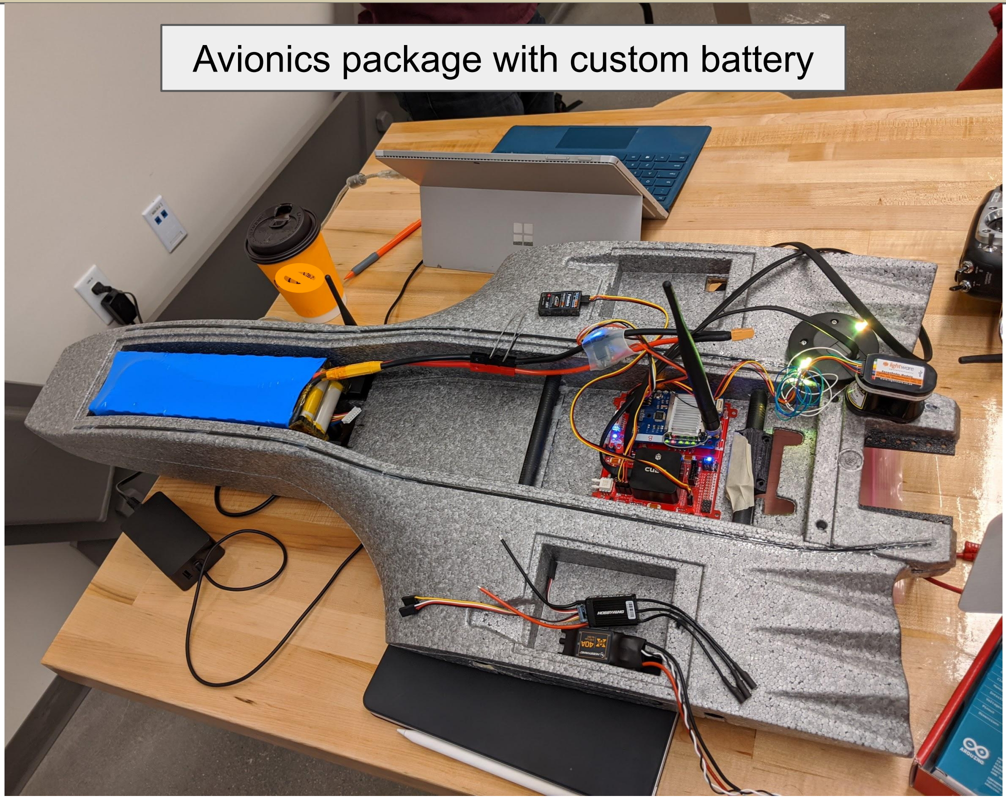


Avionics System Progress

Component	Progress	Details
Servos	Functional	Actuating and Connecting, calibrated and trimmed.
Telemetry	Functional	Mission Planner & Ground Station Communicating
GPS	Functional	GPS verified on Mission Planner, Showing position accurately
Pitot-Static Tube	Functional	Calibrated and Installed on VORTEX aircraft.
Lidar	Functional	Reporting data accurately.
Battery	Functional	Powering system without issue.
ESC's/Motors	Functional	Driving motors as expected and producing sufficient thrust.
Other	Functional	EKF & IMU calibration completed (Pre-flight check)

Avionics System





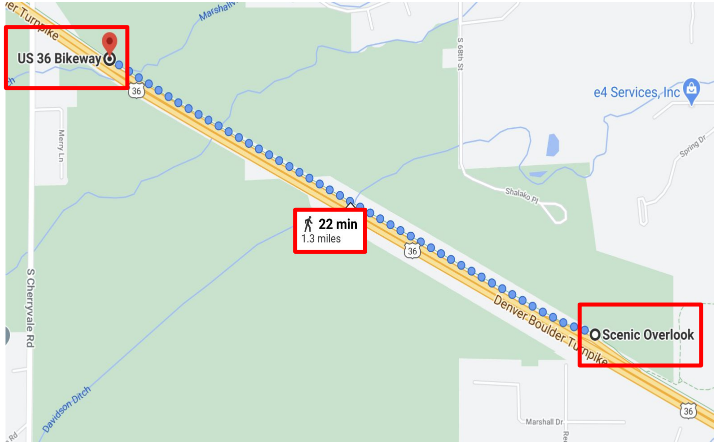
Telemetry Test Overview

What and Why:

- Aircraft must to maintain communication with GS computer up to 2km with <50% packet loss

Testing and Verification:

- Acquire AC-DC auxiliary power outlet convertor
- Take plane and avionics out to road with 2km stretch
- Initialize powered avionics at ground station
- Drive powered avionics 2km away
- Check telemetry package connection



Requirement	Description
FR 4	The aircraft shall maintain communication with the ground station up to a distance of 2km

Complete

Controls Overview

What and Why:

- All 5 servos need to be actuating within physical range
- Elevons and tilt servos need to be trimmed
- ESC's range and trim values need to be set
  - Values too high can damage the ESC's

Complete

Prediction and Verification:

- Find servo travel per (μs). Example: $\Delta\Theta$ = 0.085°/μsec
- Find the endstop of the servo: 0 angle
- Find angle of zero to flat with the wing mount. Example: 76°
- Program angles as PWM signals. Example:
  - Minimum: -7° from X-Y plane: 69°/$\Delta\Theta$ = 811.8μs
  - Maximum: 125° from X-Y plane: 201°/$\Delta\Theta$ = 811.8μs
- Set Trim angle. Example: 76°/$\Delta\Theta$ = 2364.7μs
- Trim expected output to physical output

Requirement	Description
FR 3	Verify that control surfaces actuate properly

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LiDAR Test Overview

What and Why:

- Needs to handle reflective, disjointed, high debris surfaces
- Height set using tape measure, static testing
- Measurements recorded on LeddarTech Configurator

Testing Procedure:

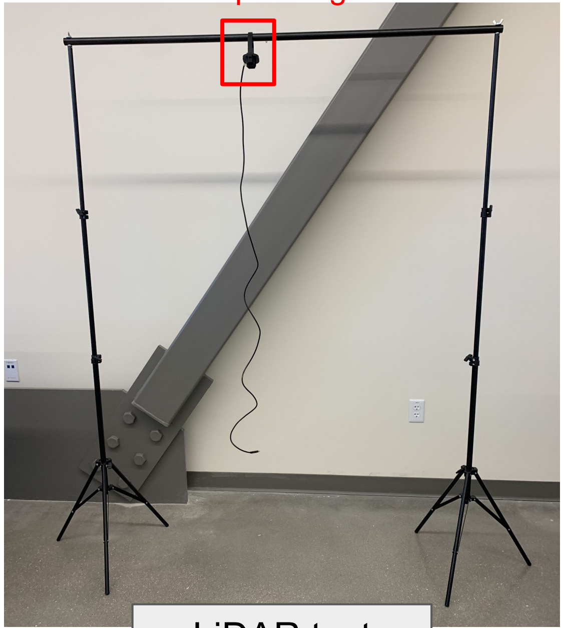
- Set LiDAR at known distance
- Test distances read off
- Verify accuracy is within range
- Perform test over multiple surfaces

3D printed LiDAR mount

Complete

Requirement	Description
FR 3	Autonomous mission execution
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

Downward pointing LiDAR

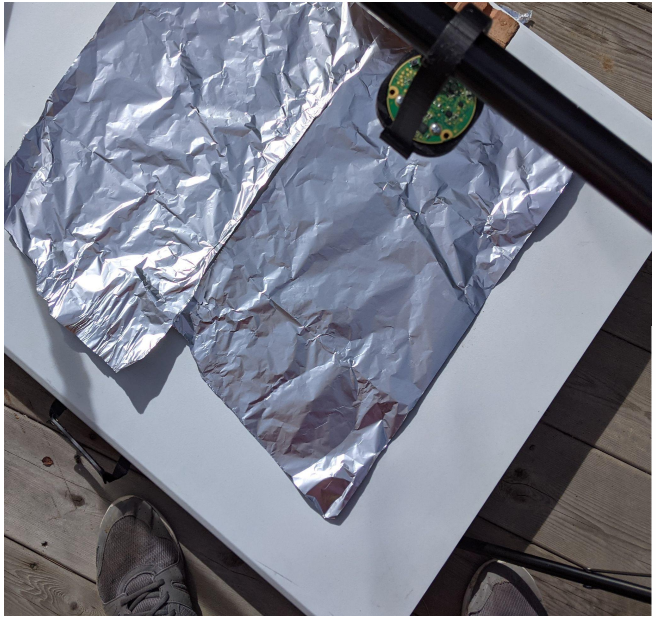


LiDAR test stand assembly

LiDAR Test Overview

Readings Over Water

Highly Reflective Surfaces



Testing in variable conditions

- Branches/bushes
- Water
- Aluminum foil

LeddarOne LiDAR

Dynamic Motor Testing Overview

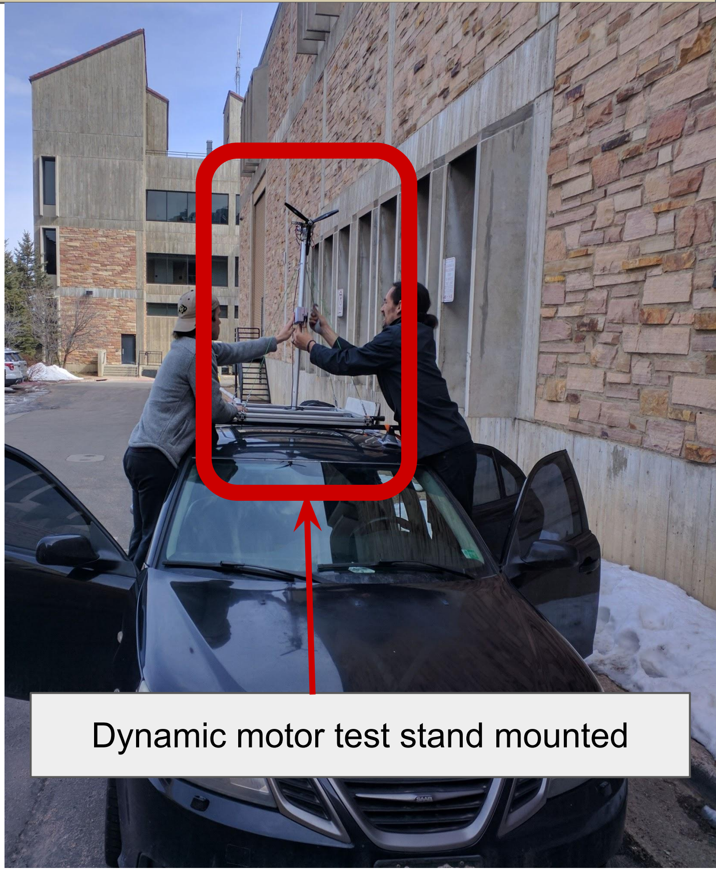
Summary:

- Test thrust requirements in dynamic cruise conditions (loss in efficiency)
- Using RC Benchmark software to track specific test properties
- Motor and load cells elevated on car top test stand traveling at cruise speeds (40 mph)

Testing Procedure:

- Similar to static test stand: configure battery, motor, ESC, and propeller
- Use RC benchmark software to manually toggle throttle power input

Complete



Dynamic motor test stand mounted

Aerodynamic Test Stand Overview

What and Why:

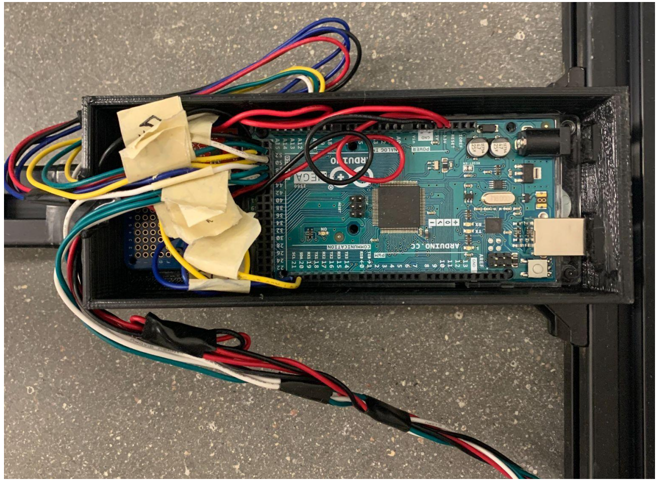
- Lift and drag produced from aircraft need verified
- Dynamic testing data is crucial without wind tunnel testing
- Accelerometer on roof for imparted vibration data

Calibration and Testing:

- 4-Load cells & accelerometer connected to ArduinoMega
- Testing:
  - AoA is set on structure
  - Load cells and Accelerometer are tared before
  - Test is run at nominal speed; Data is saved

Complete

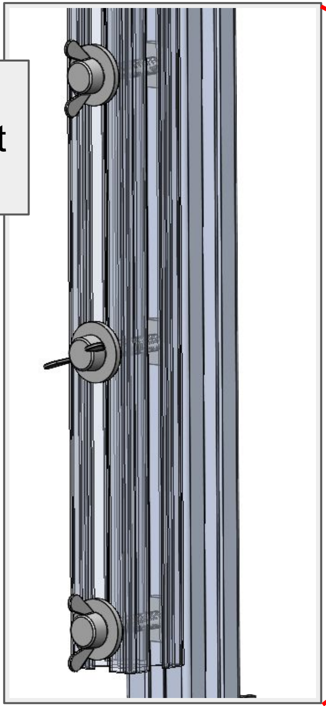
Requirement	Description
FR 2	1 Hour endurance, 2 Takeoffs and Landings
DR 2.7	Cruise speed shall be at least 18 m/s

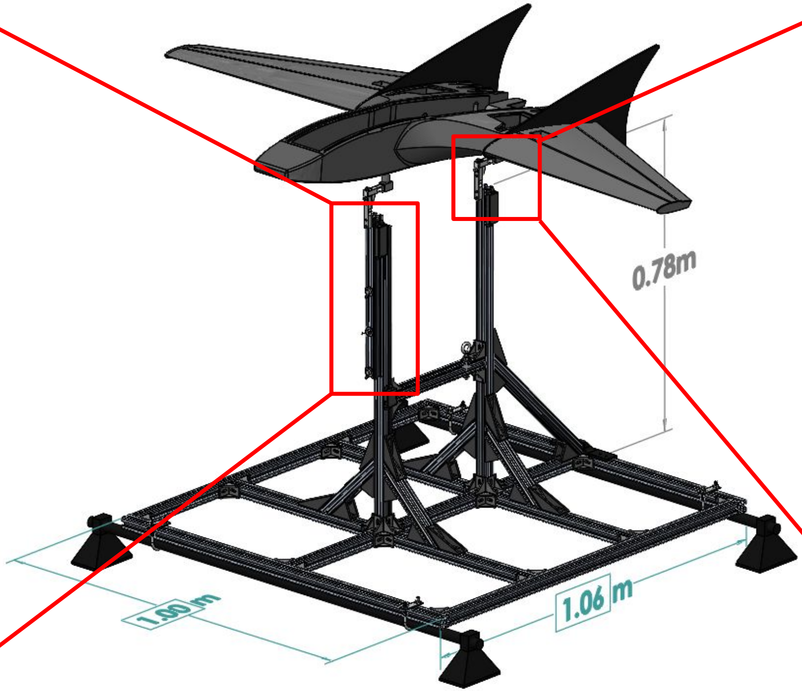


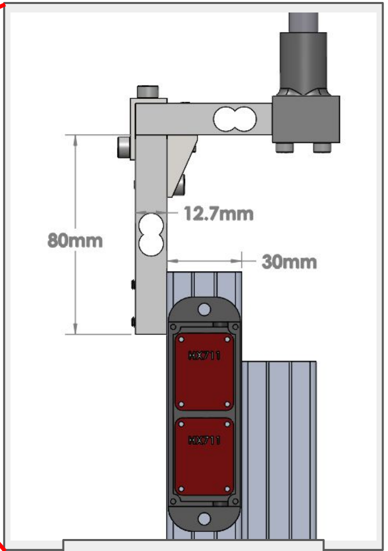
Electronics Package

Aerodynamic Test Stand Overview

AoA adjustment capability







Load cell & amplifier configuration

Aerodynamic Test Stand Overview

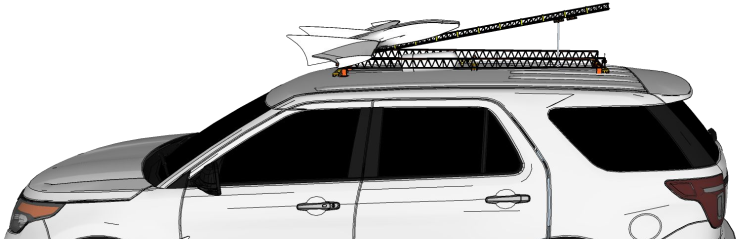
*Car behind test vehicle is designated chase car with additional team members

RAPCat Integration Overview

FR6	The aircraft shall be capable of taking off from existing RAPCat launch system

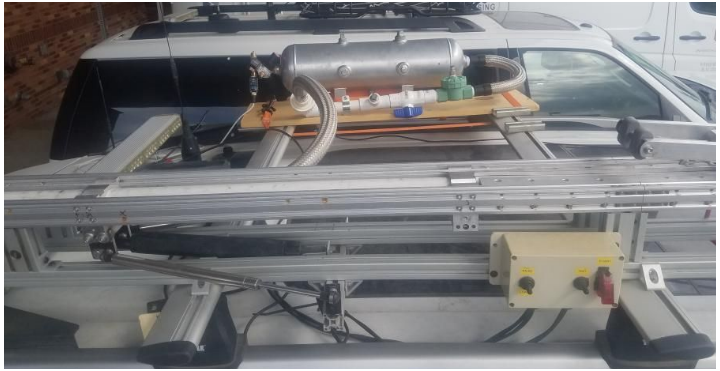
What and Why:

- Rapid Acceleration Pneumatic Catapult
- RAPCat hook incorporated into the bottom of the fuselage



Testing and Verification:

- Complete one RAPCat launch directly into horizontal flight
    - Alternate: Complete a bungee launch into horizontal flight



Hover Testing Overview

What and Why:

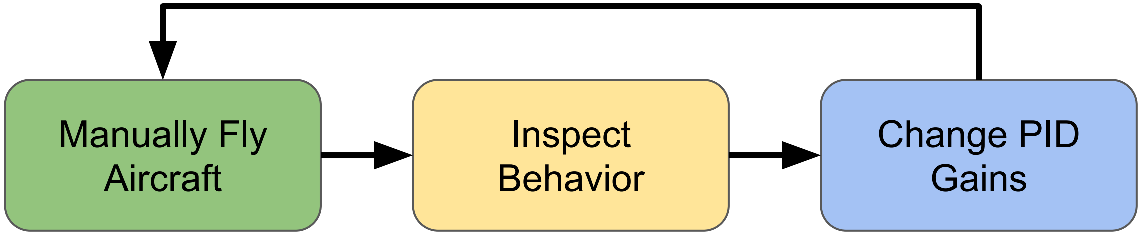
- Ensure stability in hover modes
- Show motors are capable of providing enough thrust
- Test various PID parameters to optimize hover stability

Verification Methods:

- Data logs saved by GCS
- Visual inspection, watch for oscillations
- Pilot input - How well does it respond?
- Demonstrate hover stability in QStabilize/QHover modes

Requirement	Description
DR 1.1	The aircraft shall be able to sustain hover using its own thrust system
DR 3.2	On-board flight controller shall control propulsion system and flight surfaces
DR 3.5	The aircraft shall autonomously hover without pilot input

Testing Process



Full Test Flight

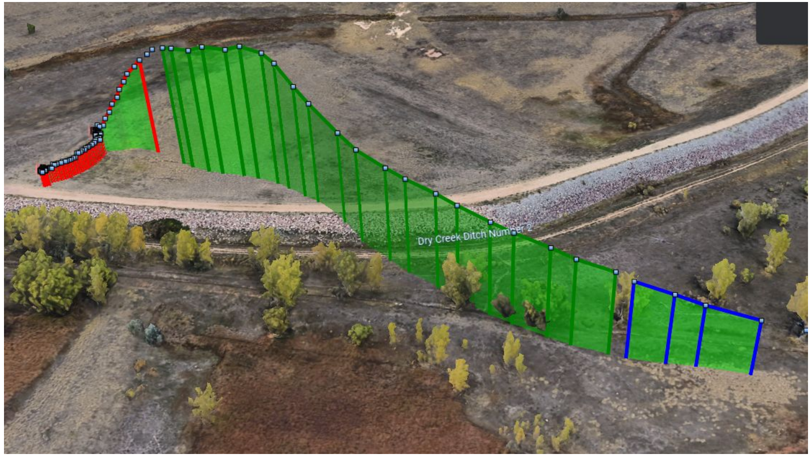
What and Why:

- Full Planned Mission
- Check Endurance/Autonomy Requirements
- Shortened Schedule due to Weather/Scheduling

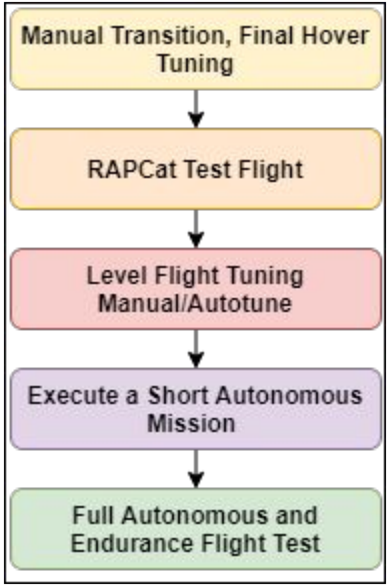
Requirement	Description
FR 2	The aircraft shall have an endurance of one hour in addition to two takeoffs and landings.
FR 3	Aircraft shall be able to autonomously execute all aspects of its mission from takeoff through landing.
DR 3.2	On-board flight controller shall control propulsion system and flight surfaces

Google Maps view of first full flight test

More on this later

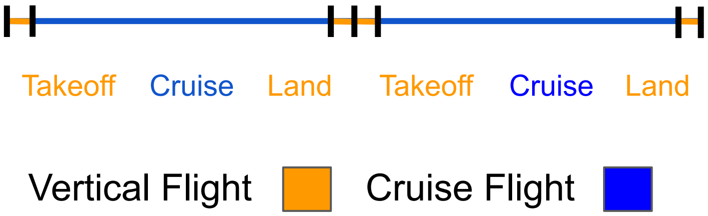


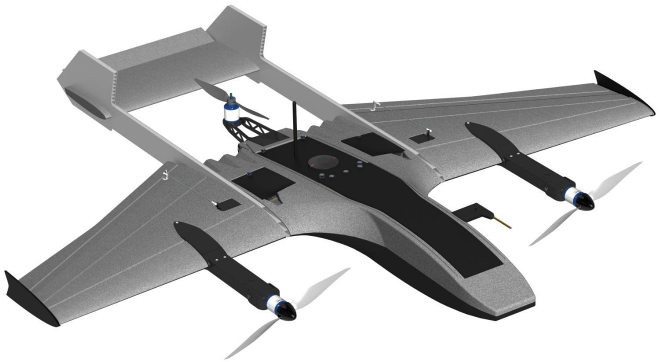
Test Schedule



Full Flight & Future Tests

Flight mission profile
60 minutes





RAPCat Integration
- Verify the connector fits correctly
- Execute launch procedure

Planned
4/19-4/23

Hover Test
- Execute static full mission profile
- Show stability in hover

Complete

Full Flight Test
- Execute realistic full mission profile similar to CONOPS

Planned
4/21-4/30

Test Results

Wing Stress Testing Results

Downward Stress (Landing):

- 10G requirement is 1.9kg (18.65N)
  - Tested to 2.1kg (20.5N)
  - No FOS calculation
- Small bending in arm and wing

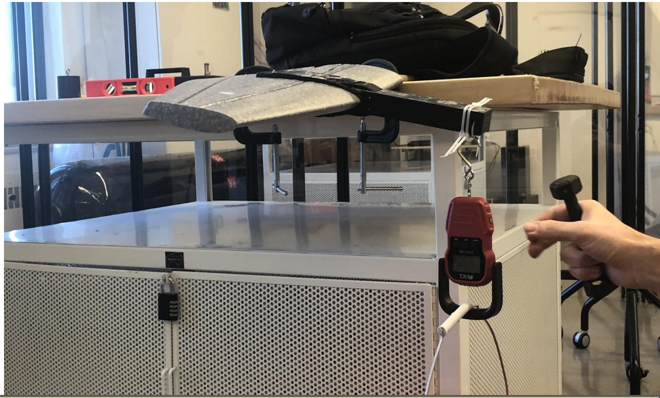
Upward Stress (Takeoff):

- Requirement of 2.5kg (24.5N)
  - Tested incrementally to 6.6kg (64.7N)
  - 2.6 FOS
- Extreme bending in arm and wing
- Only small (<1mm) plastic deformation after test

Complete

RAPCat Launch/Compatibility

- Upcoming



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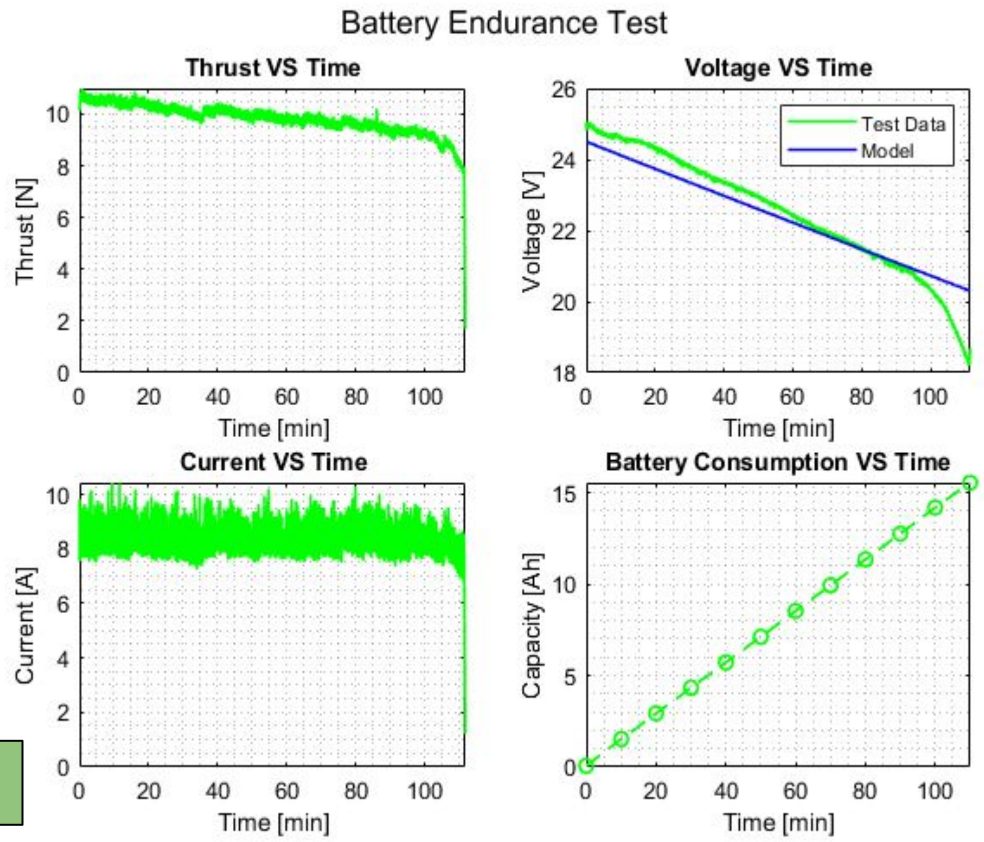
Battery Endurance Testing Results

- **Endurance Test:**
  - Manually maintained expected cruise current draw of ~8A
  - Run time of 110 minutes
  - Capacity of 15Ah compared to ideal 16Ah
- **Conclusion:**
  - Battery capacity meets expected performance for 1 hour cruise flight and the manufacturing data are satisfactory

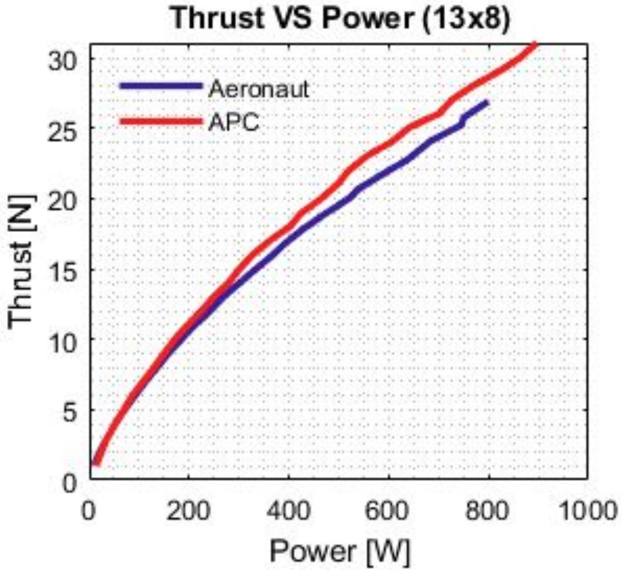
Requirement	Description
FR 2	Endurance of one hour with two takeoffs and landings

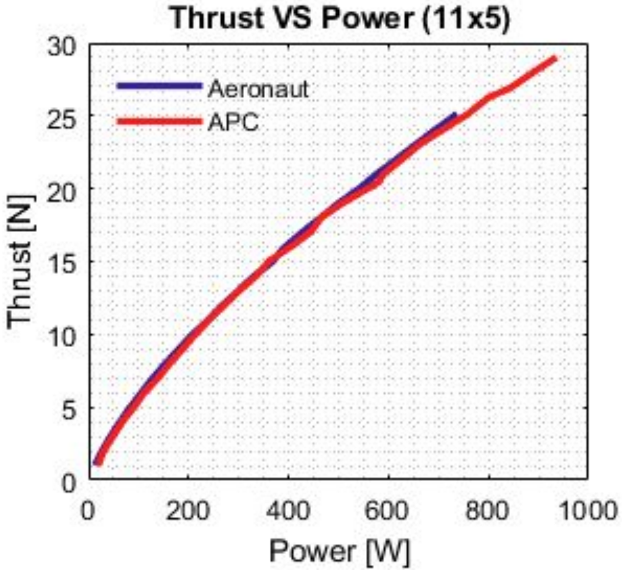
Complete



APC & Aeronaut

Propeller Comparison





Conclusion: *For our selected design size and conditions, the APC props offer more thrust for the same power as well as lower cost and lead time*

Static Propulsion Test Stand Results

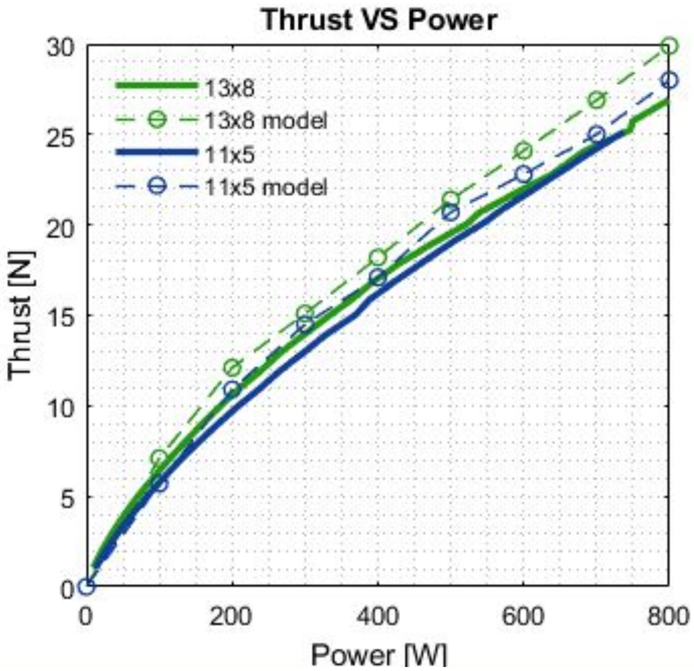
Propeller Style	Tested Sizes [Diameter x Pitch]
Aeronaut Electric Carbon Light	9x5 9x6 10x5 10x6 10x7 11x5 11x7 12x5 12x7 13x7 13x8
APC Thin Electric	11x4.5 11x5.5 13x8

Complete

Measured variables:

(limited by max motor power)

- Torque
- Thrust
- Voltage
- Current
- RPM (optical sensor)
- Power
- Prop Efficiency
- ESC input



Final Design:

Front Props: 13x8 APC Electric [2820 550KV motor]

Rear Prop: 11x5.5 APC Electric [2820 860KV motor]*new*

Controls Test Results

Control Input	RC Response	Autonomous Response
Ailerons	✓	✓
Elevator	✓	✓
Tilt-Servos	✓	✓
ESCs	✓	Planned

Requirement	Description
DR 3.3	Verify that control surfaces actuate properly

Complete

Successful servo RC communication

- Servo's stop at correct angles: preventing servo burnout
  - PWM calculations were correct
- Servo's are all actuating correct directions
- Control surfaces are trimmed with airfoil

Telemetry Verification

Complete

Telemetry Results

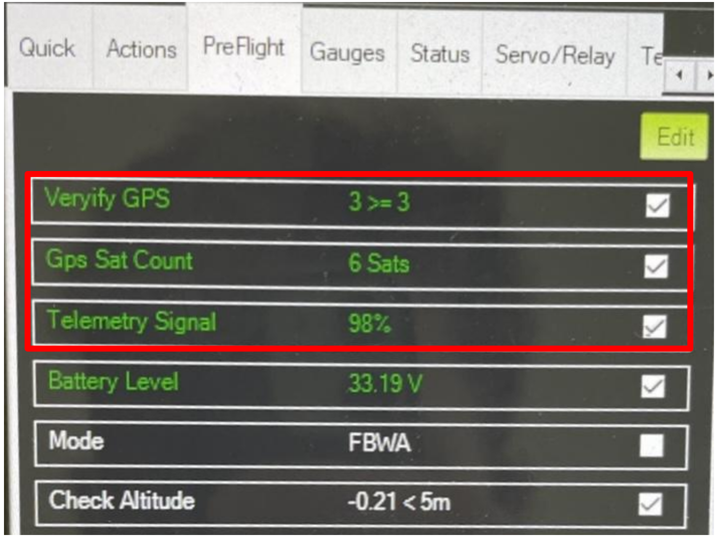
FR4	The aircraft shall maintain communication with the ground station up to a distance of 2km with less than 50% packet loss

Design Aspects:

- Radio package with receiver and transmitter
- One end interfaces directly with avionics package
- Connects directly to a laptop for real time data gathering and control

Requirement Satisfaction:

- Successful communication with less than 3% packet loss



Complete

LiDAR Test Results

Concrete Surface, Daylight

Trial #	Set Height(cm)	LiDAR Reading(cm)
1	180.3	183.489 **+/-**0.25
2	175.3	174.981 **+/-**0.25
3	132.1	135.509 **+/-** 0.35
4	81.3	84.074 **+/-** 0.20
5	10.0	13.183 **+/-** 0.20

Over Aluminum Foil

Trial #	Set Height(cm)	LiDAR Reading(cm)
1	160.0	166.294 **+/-** 0.25
2	109.2	114.776 **+/-** 0.25
3	88.9	94.742 **+/-** 0.15
4	27.94	33.274 **+/-** 0.20
5	11	13.732 **+/-** 0.10

Mimicking High Reflective Surfaces

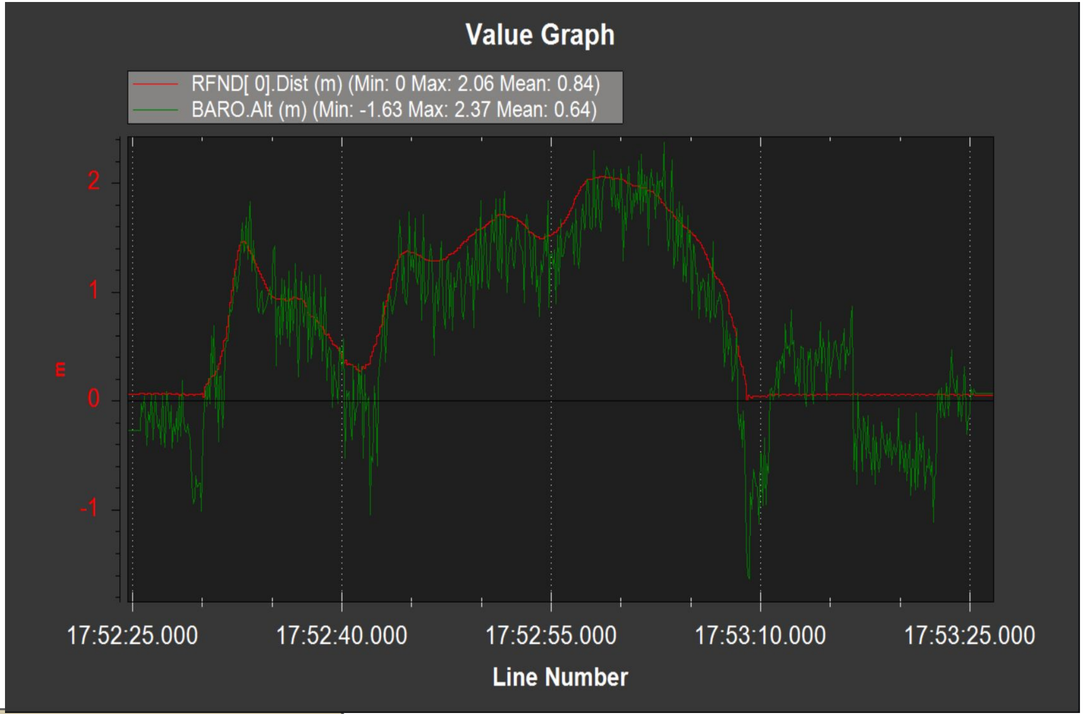
- Maintains a maximum difference of about 7.5 cm from set height
- Meets requirement of 10cm accuracy
- Ready to be used for landing, will add to accuracy of firmware

Complete

Requirement	Description
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

Lidar vs Barometer

Data Logs, LiDAR(red) and Barometer(green) data



Field Testing the LiDAR

- Much less noisy and accurate compared to barometer
- Redundant altitude sensing for landings and takeoffs
- Barometer starts to fail due to ground effect/prop wash

Requirement	Description
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

3.4 Complete, 3.5 in progress

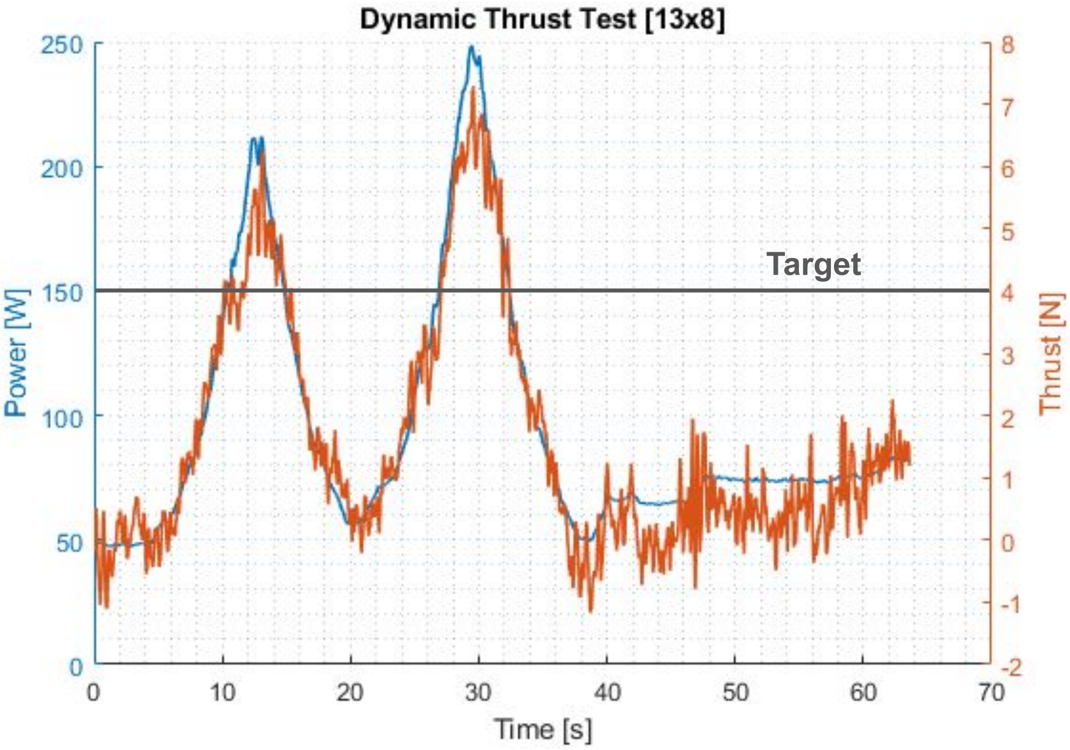
Dynamic Motor Test Results

Summary of Results:

- Our propulsion model (Based on aerodynamic data) estimated a cruise flight Thrust of 4N
- Approximate Power value for Cruise flight
  - Model: 77.5W
  - Experiment: 150W

Requirement	Description
FR 2	1 Hour endurance, 2 Takeoffs and Landings
DR 2.7	Cruise speed shall be at least 18 m/s

Partially Complete



Conclusion: *The test results hold several large sources of error such as wind and vibration, but give us ballpark estimates of power requirements. This 150W requirement*

Aerodynamic Test Stand Results

Summary of Results:

- Weather conditions significantly affected data
- AoA fluctuations from angle of road changed data
- Drag was much higher than expected
  - Load cells not isolated from moving air
  - Airspeed measurement not precise enough

Reasons for Moving to Hover:

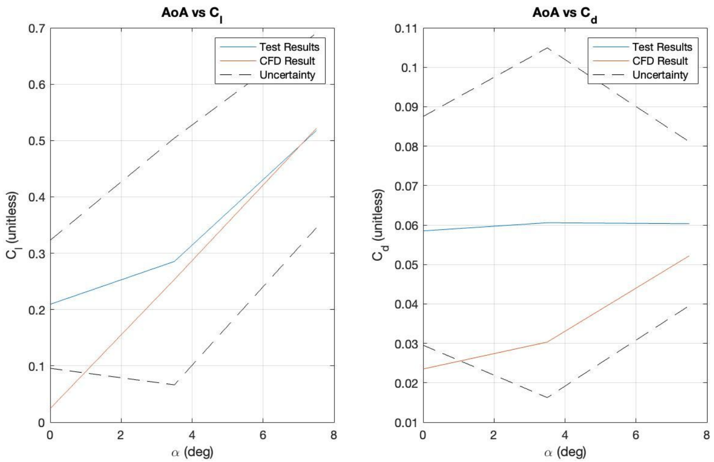
- Schedule and cost impacts in mitigating conditions
- Cost/Benefit - additional testing not worth pursuing

Mitigation Strategies:

- Large FOS in propulsion system
  - Ardupilot allows for VTOL assisted level flight
- Flight speed can be increased -> Increased lift

Partially Completed

Requirement	Description
FR 2	1 Hour endurance, 2 Takeoffs and Landings
DR 2.7	Cruise speed shall be at least 18 m/s



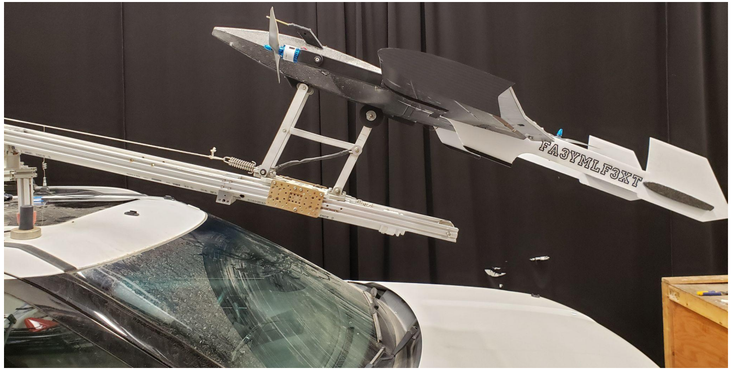
Vortex modified Drak with RAAVEN Tail

RAPCat Integration Status

FR6	The aircraft shall be capable of taking off from existing RAPCat launch system

Status:

- RAPCat hook incorporated into the bottom of the fuselage
- Printed part fits on the RAPCat



Plans for Requirement Satisfaction:

- Obtain flight approval from CU flight director
- Launch off bungee or RAPCat with IRISS

Partially Complete

IRISS
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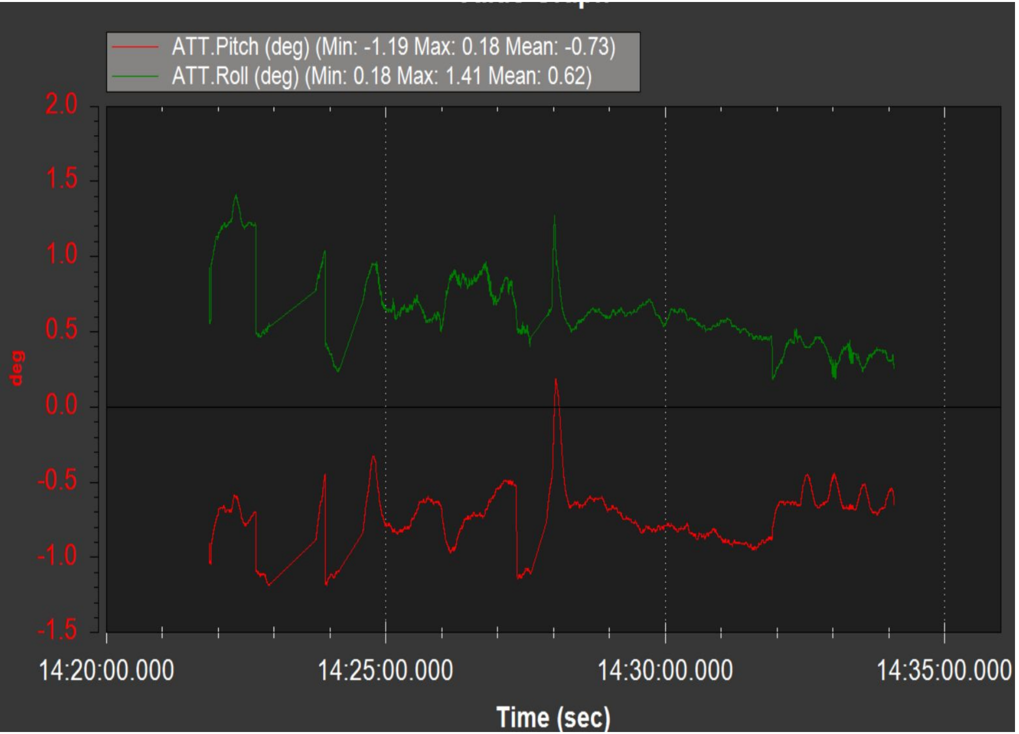
Hover Test Results



Analyzing data from Ground Station Data Logs

- Results from Qhover,(pilot input only to adjust position in case of emergency)
- Pitch/Roll Maintaining Position with Slight Error
- Yaw Oscillations Still Prevalent, but will be damped out with more tuning

Requirement	Description
DR 3.2	On-board flight controller shall control propulsion system and flight surfaces.
DR 3.5	The aircraft shall be capable of completing the mission profile without pilot input after initial flight configuration.

3.2 Verified, 3.5 in progress

*More GCS Data Logs in Backup Slides

Hover Thrusting

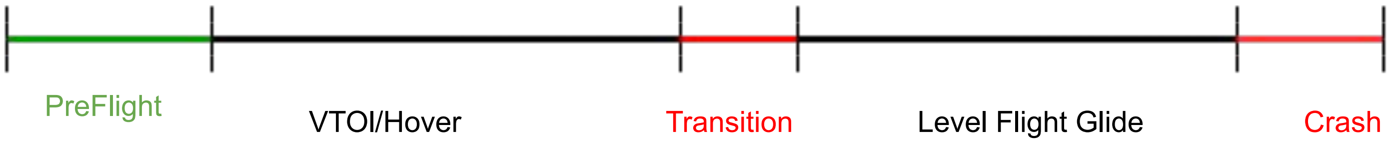
- Tests show that aircraft can produce enough thrust
- Capable of handling hard inputs
- Motor/Propeller Combinations are successful
- Note Yaw Oscillations but steady behavior

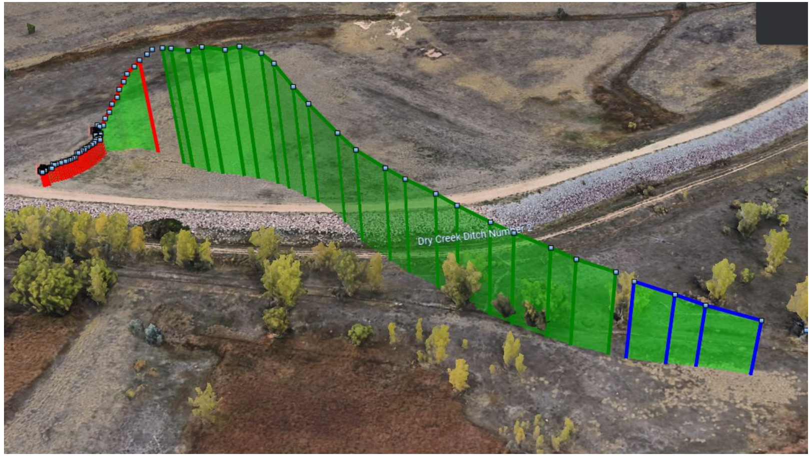
Requirement	Description
DR 1.1	The aircraft shall be able to sustain hover using its own thrust system

Complete

Test Flight Analysis

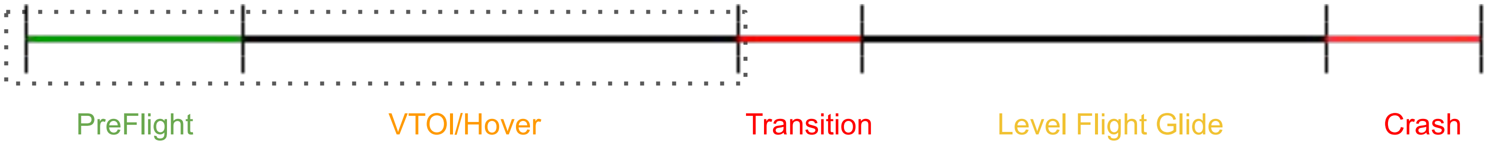
First Test Flight Mission Profile





- First flight test ended in tragedy
- Flight logs are a huge source of information
- Detailed Crash Analysis followed by major takeaways
- Ready to fly again!

Test Flight Analysis, Continued



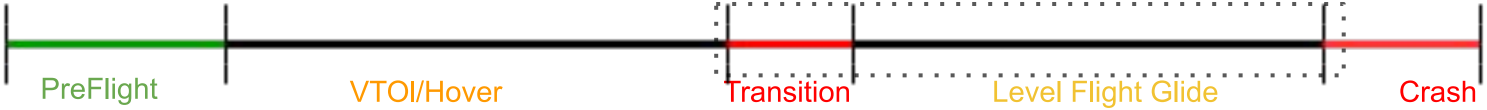
Analysis

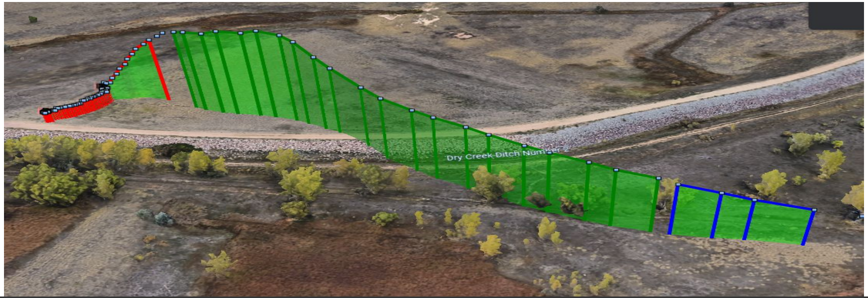
- Steady wind and takeoff location too close to boundary
- Transitioned too quickly, not enough altitude,airspeed
- Ignored pilot input to reach transition state
- Seen in thrust curves from data logs

Pilot inputted thrust, jagged lines

Rapid transition between QHOVER and FBWA modes

Test Flight Analysis, Continued





Analysis

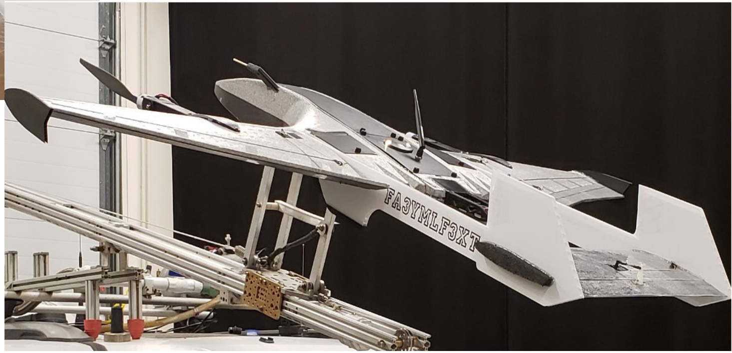
- Slow motor tilt rate caused a stall
- Recovered and glided
- Initial EKF error yielded a 15 degree roll bias
- Led to aircraft only achieving a 10 degree bank

Test Flight Analysis, Takeaways

Major Takeaways

- Configure Pitot Probe as digital sensor
- Alter transition parameters (transition time & servo transition tilt-rate)
- Additional pre-flight checklist procedures
  - Calibrate the airspeed sensor
  - Let plane rest for >15s after arming (Settles EKF)
- Improve hover tune - reduce yaw oscillation
- Include LiDAR for precise altitude information
- Improve battery restraint system

- R.I.P. Discordia [Left]
- (Currently Unnamed) VORTEX ready to go [Below]



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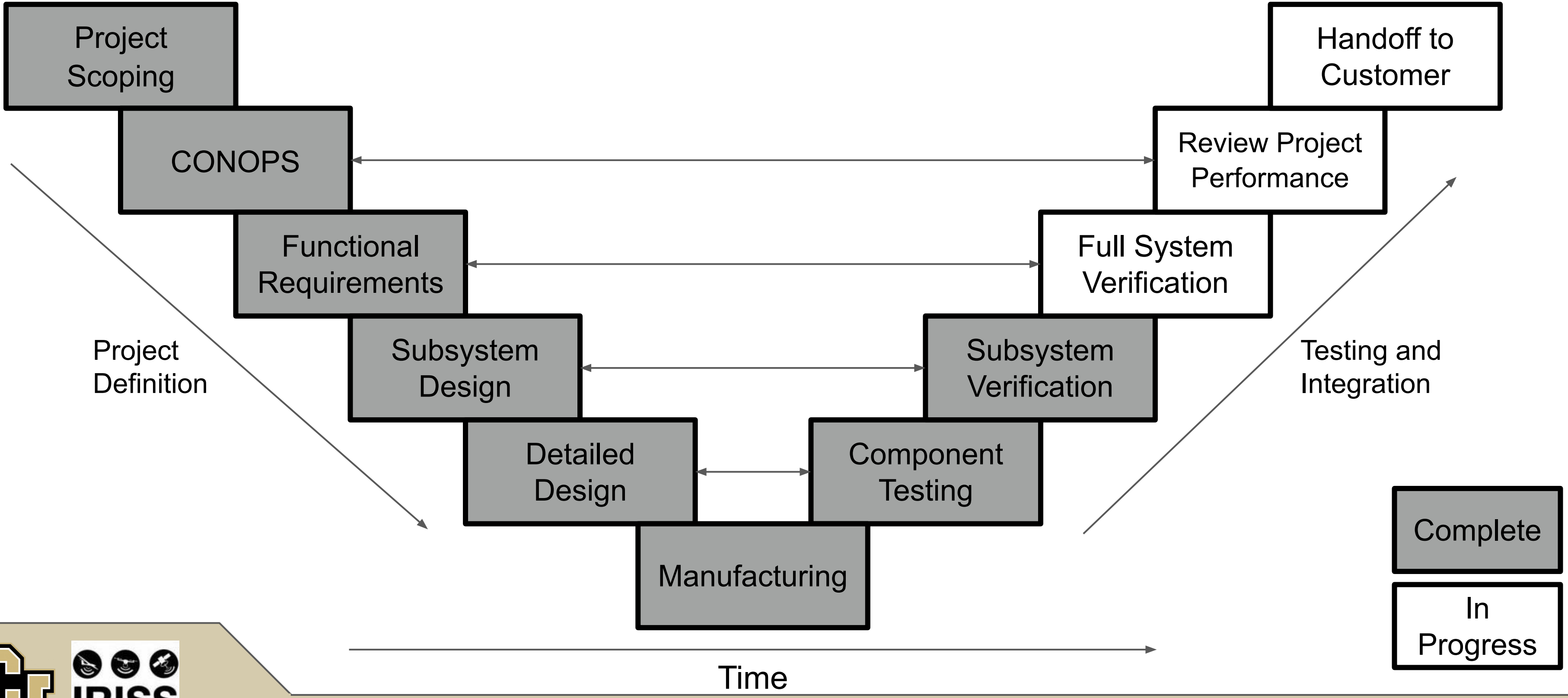
Systems Engineering

Systems Engineering Overview



Scope Refinement /Functional Requirements

Original Project Scope

- Must be based on Standard DRAK wingset
- Modified Propulsion for VTOL
- 1 Hour Endurance at Cruise
- 2 take-off, 2 landing - must be autonomous
- ~~Nose mounted probe to be protected~~
- 0.5 kg payload
- ~~IRISS Avionics Package~~
- Must maintain Catapult launch capability
- Goal: Build Cost less than $1000 (not inc. avionics)
- Goal: automated landing to a target/beacon
- ~~Land and takeoff from water~~
- ~~Deployment of a submersible sensor~~

Functional Requirements

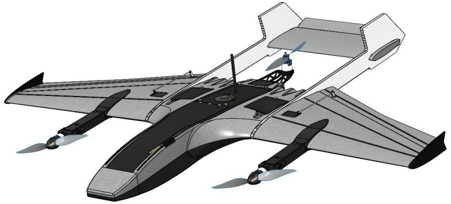
- The aircraft shall be a VTOL conversion of the COTS Ritewing RC “Drak” airplane kit
- The aircraft shall have an endurance of 1 hour with 2 takeoffs and landings
- The aircraft shall be capable of carrying a 0.5kg payload
- The aircraft shall be capable of taking off from existing RAPCat launch system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

* original project scope taken directly from customer proposal presentation

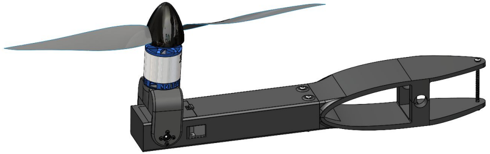
Requirements Breakdown

Functional Requirements → Design Requirements → Subsystem Requirements → Component Requirements

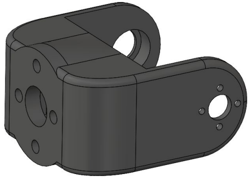
Design Requirements from FR1	
FR1	The aircraft must be a VTOL conversion of the COTS RiteWing RC "Drak" airplane kit
DR1.1	The aircraft shall be able to sustain hover using its own thrust system
DR1.2	The aircraft shall be able to transition between vertical and horizontal flight
DR1.3	All components shall mount to a modified Drak airplane kit
DR1.4	Modified kit shall require fewer than 20 person-hours to assemble a full unit



Front Motor Assembly	
SSR 1	The structure shall be constructed of 3D printed PET-G
SSR 2	The assembly shall withstand 10g downward in the body frame while in vertical flight mode
SSR 3	The assembly shall withstand 5g downward in the body frame while in horizontal flight mode
SSR 4	The assembly shall withstand 5g axially in both flight modes



Front Motor Rotating Bracket	
CR 1	The component shall be capable of attaching the front tilt motors to the motor arms
CR 2	The component shall integrate with the tilt servo and attached rotation arm
CR 3	The component shall house the bearing that attaches to motor arm pin
CR 4	The component shall withstand 1 Nm of torque from the motor



Trade Studies

Configuration Trade Study

		Tilt Rotor			Tail Sitter				Hybrid		Tilt Wing	
Option	Weight	Tri	Quad	Quint	Quad	Double Push	Double Pull	Single Push	4L1C	3L1C	Inboard Motors	Wingtip Motors
Risk	0.2	2.5	2.5	2	2	1.5	4	1	4	4	1	1
Manufacturing/ Complexity	0.15	4	3	2	1.5	1	4	5	2	3	1	1
Weight	0.1	4	3	1	2.5	2.5	4	5	1	2	3	2.5
Hover Controllability	0.2	5	5	4	3.5	1	2	1	5	5	2.5	3
Cruise Efficiency	0.3	4	3	2	2.5	4	4.5	5	1	2	5	5
Cost	0.05	3	2	1	2	4	4	3	1	2	2	2
Total	1	3.85	3.25	2.25	2.43	2.30	3.75	3.30	2.55	3.15	2.75	2.80

Material Trade Study

Option	Weight	3D Printing	Aluminum	Carbon Fiber Rods
Weight	0.35	3	1	5
Strength	0.2	3	4	5
Cost	0.3	5	2	1
Manufacturability	0.15	5	2	1
Total	1	3.9	2.05	3.2

Battery Chemistry Trade Study

Option	Weight	Li-Po	Li-ion	NiMH	NiCd	LiFePO4
Discharge Rate	0.2	5	2	2	3	3
Energy Density	0.25	2	5	2	1	2
Cost	0.2	3	2	4	3	2
Lifespan	0.2	1	4	3	4	5
Safety	0.15	2	3	4	3	4
Total	1	2.6	3.3	2.9	2.7	3.1

Altitude Sensor Trade Study

Option	Weight	LiDAR	Micro Radar	Sonar
Complexity	0.25	3	3	3
Accuracy and Consistency	0.25	4	5	2
Size & Weight	0.2	5	3	5
Resiliency	0.15	4	5	2
Cost	0.15	5	3	5
Total	1	4.1	3.8	3.3

Firmware Trade Study

Option	Weight	Ardupilot	PX4	iNAV	Paparazzi UAV
Functionality	0.30	4	5	3	5
Resources and User Interface	0.3	5	5	3	3
Customer Preference	0.25	5	3	1	1
Hardware / Software Interface	0.15	5	4	3	3
Total	1	4.7	4.1	3.2	3.1

Risk Assessment - Key Risks Identified from CDR

#	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 - Mitigation Summary

Before mitigation

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

Consequence

Mitigation

After mitigation

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

Consequence

Risk Assessment - Update

Risk	Description	Encountered?	Result
Supply	Backorder of Drak and other components	Yes - Drak was obtainable but some other components required obtaining replacements	Project proceeded according to schedule with no significant delays due to component sourcing
Propulsion	Risk of injury during battery use/manufacture	No - Safety protocols were followed and no dangerous situations were encountered	Battery and propulsion system safely performed to expectations
Testing	Car-top testing safety considerations	No - Safety protocols were followed and no dangerous situations were encountered	Dynamic testing was performed safely and data was obtained
Structures	Material failure during operation	No - components proved stronger than expected under normal loading	Components only required replacement when subjected to abnormal forces

Systems Engineering - Key Challenges and Lessons Learned

Challenges	Lessons Learned
Clear requirement breakdown	Clear requirements would help individuals work on components with less guidance from other team members
Cross system requirements	Would help individuals understand better how individual subsystems and components affect the project as a whole
Subsystem testing dependances	Parallel subsystem testing could help reduce the risk of schedule creep when a subsystem test runs long
Biased assumptions	Greater care should be taken when making assumptions early on the project.

Project Management

Project Management Summary

Key concepts/guidelines:

- Morale
  - Lead by example and stick to your word
  - Set achievable short-term goals to maintain the sense of progress moving forward
  - Don’t take things *too* seriously
- Minimize micromanagement
  - Trust in team members’ skills and competence
  - Assign reasonable tasks and ensure support is available where needed
- Organization
  - Ensure team members are aware of schedules, assignments, deadlines, etc.
  - Prepare resources/plans for meetings ahead of time whenever possible

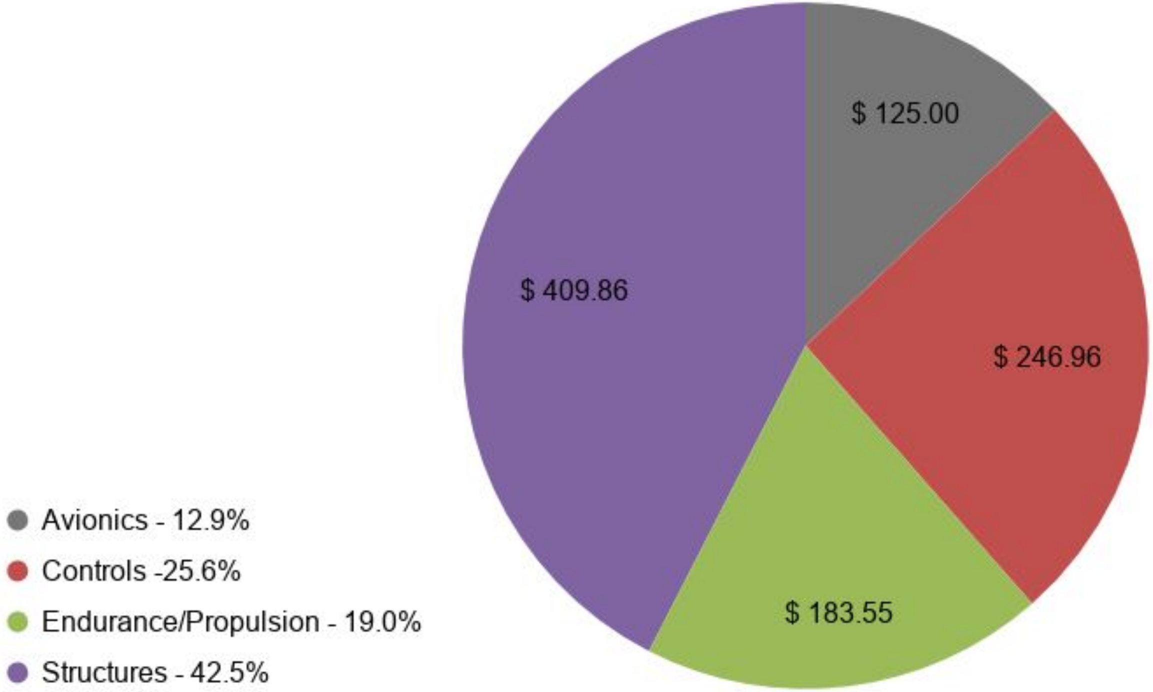
Per Unit Budget

Unit Budget Breakdown:

Target Budget: $1,000.00

Avionics: $125.00
Controls: $246.96
Endurance/Propulsion: $183.55
Structures: $409.86

Final Cost Per Unit: $965.37



Financial Status/ Budget

VORTEX Budget Breakdown:

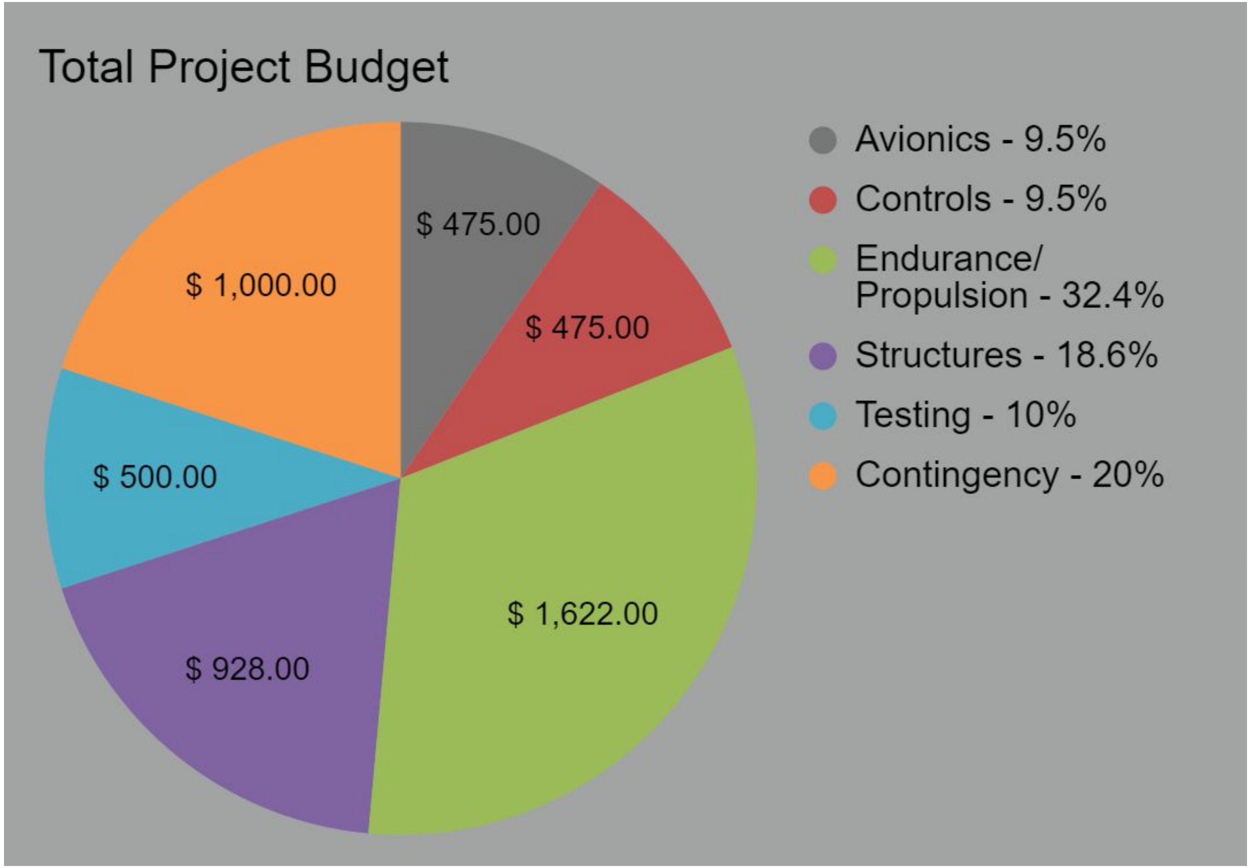
Total Budget: $5,000.00

Confirmed Purchases: $4,683.58
Pilot Lab Deposit: -$200.00
(assuming is returned)

Initially Planned Budget

Total Expenses: $4,483.58

Remaining Balance: $516.42



Industry Cost

Total Hours Worked	Cost Per Hr ($65k Salary)	Total Salary Cost	Materials	Overhead	Total Cost
4822	$31.25	$150,687.50	$4,483.58	$301,375	$456,546.08

Acknowledgements

Dr. Donna Gerren - Advising, Guidance, and Moral Support

Steve Borenstein, Michael Rhode, Chris Choate -
General guidance and answers to numerous questions

Devesh Sharma - Autonomy, Piloting, PCB Soldering, Component Troubleshooting, and being an all-around champion

Thank You

Questions?

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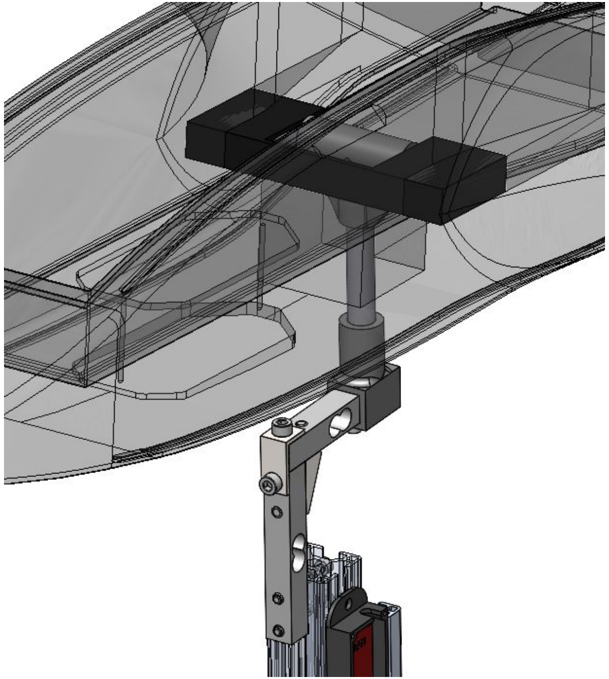
Backup Slides

Aerodynamic Test Stand Adjustable Angle Bracket

- Internal bracket allows spar to slide forwards and backwards to change angle
- Horizontal carbon fiber rod slides inside internal bracket
- Internal bracket will be 3D printed out of PETG



More Hover Test Results

Overview and Scope

The purpose of the early manufacturing stages with regards to the VORTEX project is to both build and test individual subsystems.

1. Assemble basic functioning subsystems
2. Assemble testing apparatuses
3. Test and simulate realistic performance against modeled performance

Moving forward, each subsystem will be iteratively improved to meet desired performance. Full system testing can begin.

Subsystem	Testing Equipment
Autonomy	• Ardupilot • Pixhawk • LIDAR Test Stand
Structures	• Dynamic Test Stand
Propulsion	• Static Test Stand • Construction Battery • Dynamic Test Stand

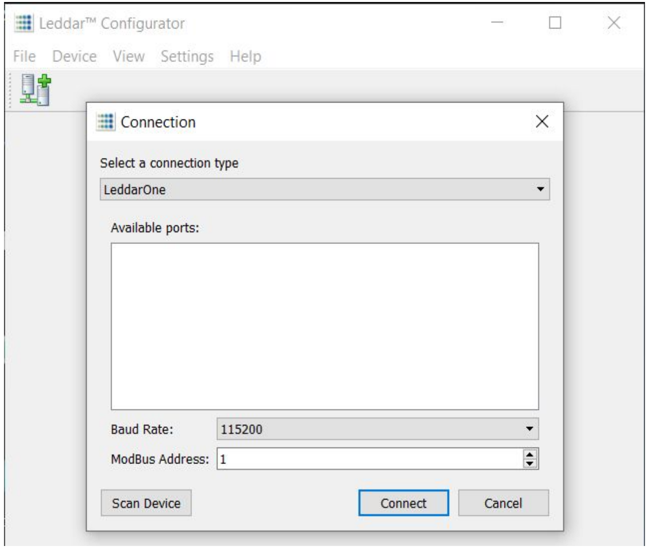
Key
Software (in-house)
Custom Hardware (in-house)
Borrowed Hardware

LiDAR Data

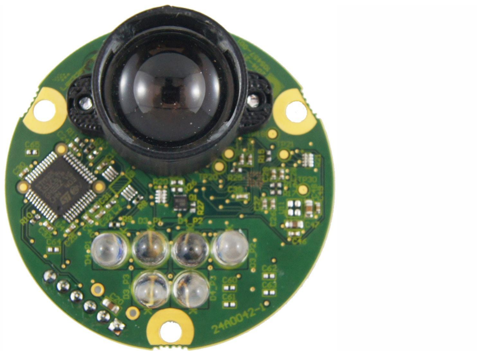
Testing the purchased LiDAR sensor to verify 10cm accuracy

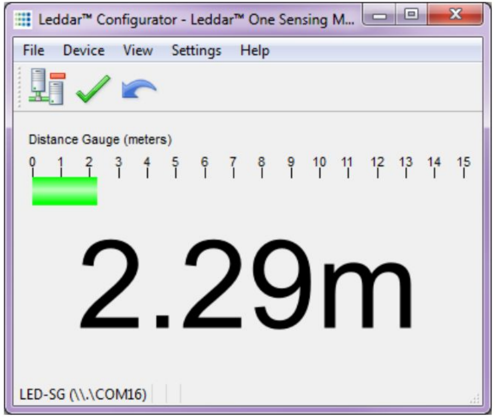
LeddarTech Configurator
- Exports data to .txt file
- USB to UART cable to laptop

LeddarTech Configurator



LeddarOne Sensor





Empennage Design

Static Equilibrium of Forces

$$\sum F = C_{L_c} q_\infty S_c + C_{L_{wb}} q_\infty S - W$$

Static Equilibrium of Moments
(about wing/body neutral point)

$$\sum M = C_{m_c} q_\infty S_c \bar{c}_c + C_{L_c} q_\infty S_c (d_{wb} - d_c) + C_{m_{wbac}} q_\infty S \bar{c} - W(d_{wb} - d)$$

Static Stability

$$K = \frac{1}{\bar{c}} \left[\frac{C_{L_{c\alpha}} \frac{S_c}{S} d_c + C_{L_{wb_\alpha}} d_{wb}}{C_{L_{c\alpha}} \frac{S_c}{S} + C_{L_{wb_\alpha}}} \right]$$

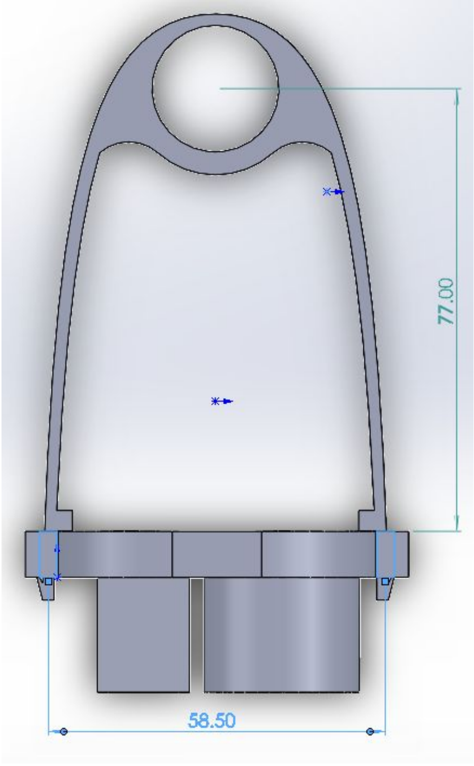
Canard vs Tail Trade Study

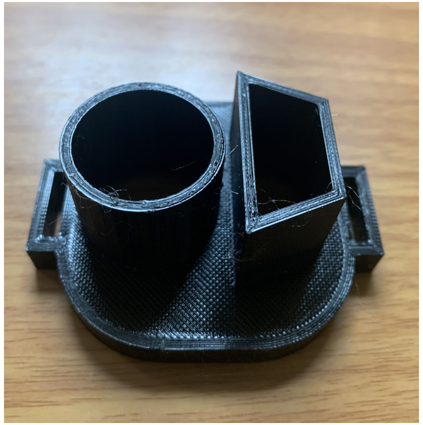
Options Considered
- Static Canard
- Static Tail
- Tail with Elevator

Tail with Elevator won out
- Reduces elevon deflection
- Used by IRISS
- Heavier than Canard though
- Easy to manufacture

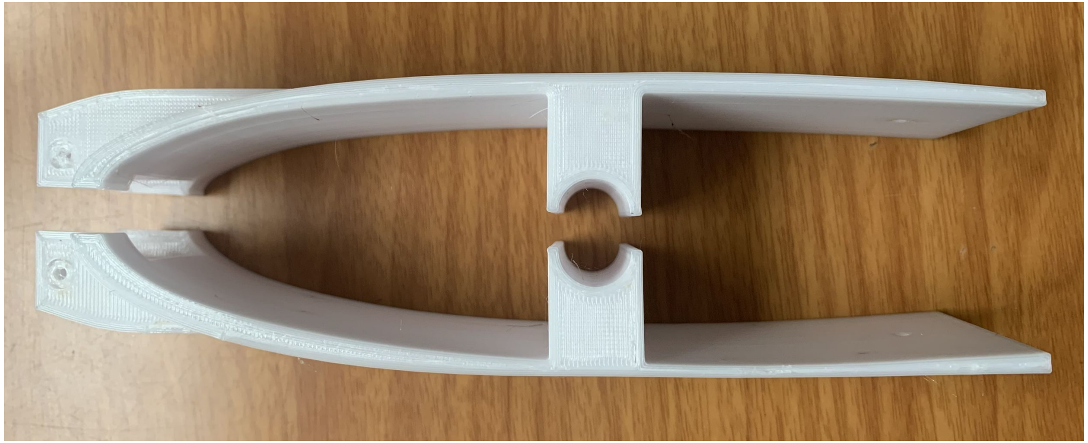
Criteria	Things to Consider	Criteria Weight
LIft and Drag Performance	• Trim Lift Deficit Calculations • Estimate Drag, NACA airfoil, Parasite, Induced, etc. • Effect on Elevon deflection at trim	25%
Stability	• Static Margin Calculations • Trim Moment Deficit Calculations • Stall performance • Static, dynamic stability	30%
Weight	• Weight of supplementary components ○ Servos, Spars, Foam • Shift in center of gravity	15%
Complexity	• Supplementary Components • Electronics • Structure required • Manufacturability ○ Materials and Methods • Design Optimization ○ Expected effort to optimize the design	30%

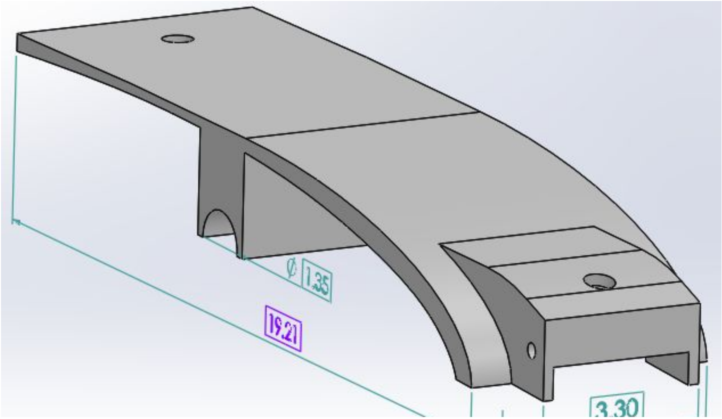
LiDAR Test Stand

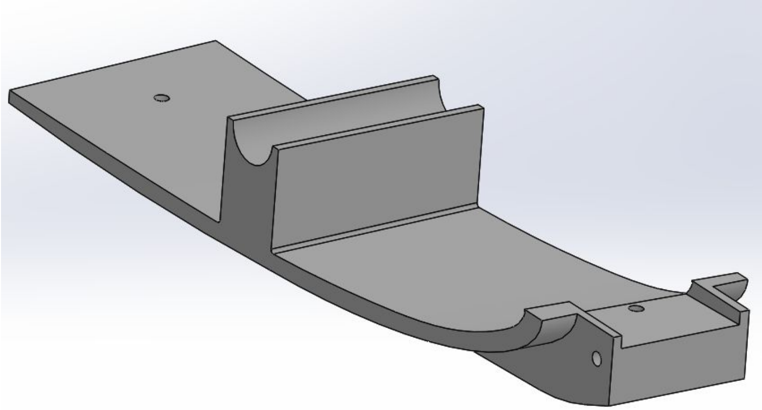




LiDAR Test Stand







Aerodynamic Test Stand - 3D Printed

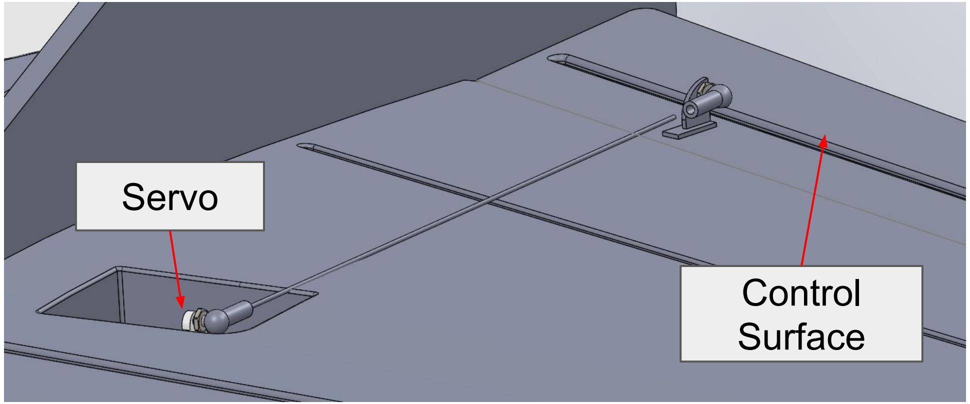
Custom Battery Progress

- On Hand:
  - Insulator rings
  - XT90 connectors
  - XT60 connectors
  - MT60 connectors
  - 10 AWG Wire
  - Wire Kapton tape
  - 100x LiPo battery cells
- Barriers to Progress
  - Balancing cable not delivered
  - Waiting on R2R
  - Spot welding to connect cells
  - Spot welder supplied by IRISS

Waiting on R2R approval and balancing cable to begin manufacturing

Manufacturing Extra Control Surfaces

- Control Surface
  - Same material and manufacturing method as horizontal tail
  - Mounted using Z-Tape
- Servo
  - Mounted inset into the horizontal tail
  - Connected to control surface same as wing
- Foam and servo still need to be purchased



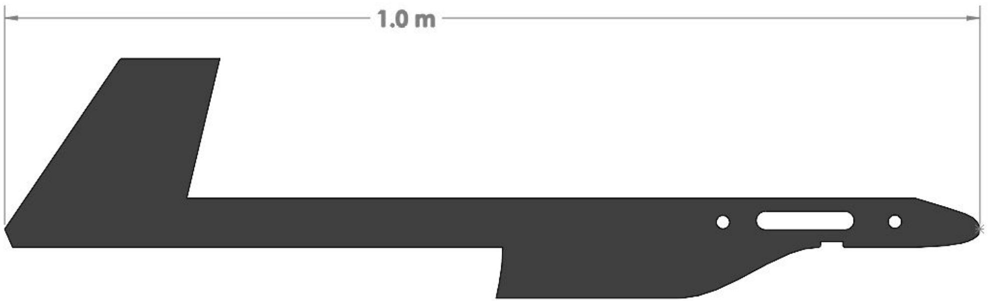
Mounting example from the wing

Manufacturing of horizontal tail and control surfaces is scheduled to be completed by Feb 11th

Manufacturing the Tail

- Cut Foam Horizontal Tail
  - CNC Hot Wire Foam Cutter
  - XPS foam

- Tail Booms
  - Laser Cut Coroplast
  - 8 mm thick



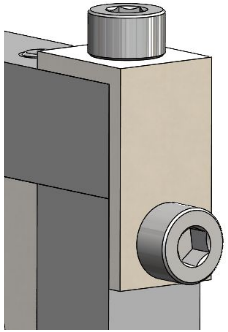
- Preliminary Dimensions (Subject to Change)
  - 1 m length
  - $V_h = 0.6$
  - $S = 0.089\ m^2$
  - $c = 0.22$ m

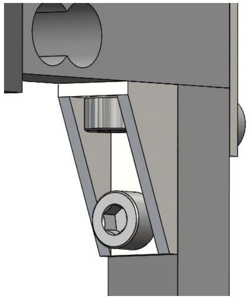
Aerodynamic Test Stand: Load Cells

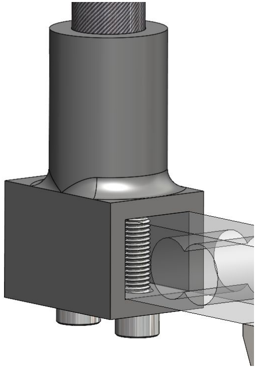
Manufacturing Sufficient Brackets

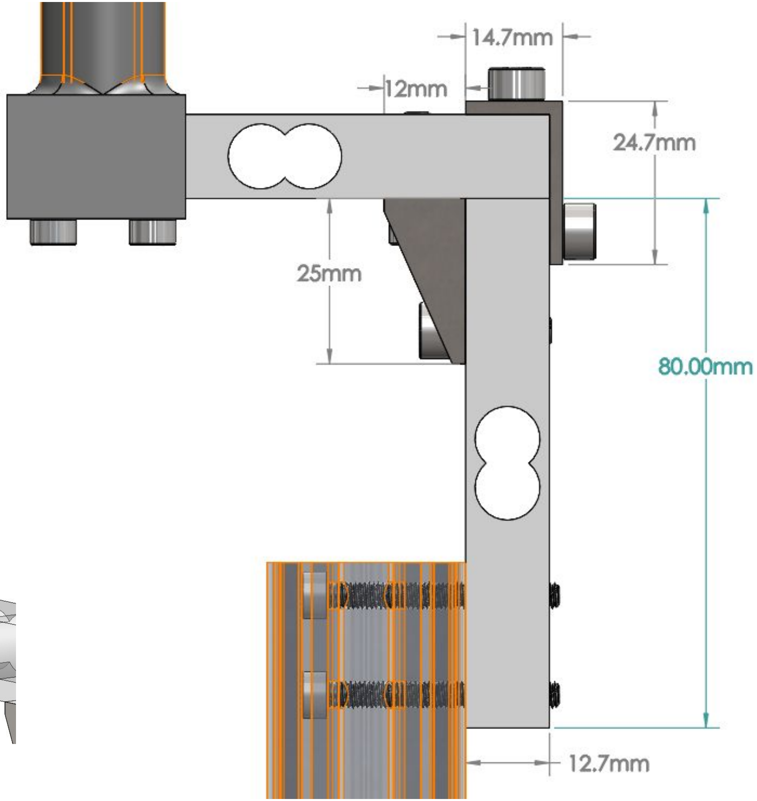
Solution:

- Nylon Alloy 3D print bracket for cell to carbon fiber rod
- 90° inner and outer brackets milled from a low carbon ste







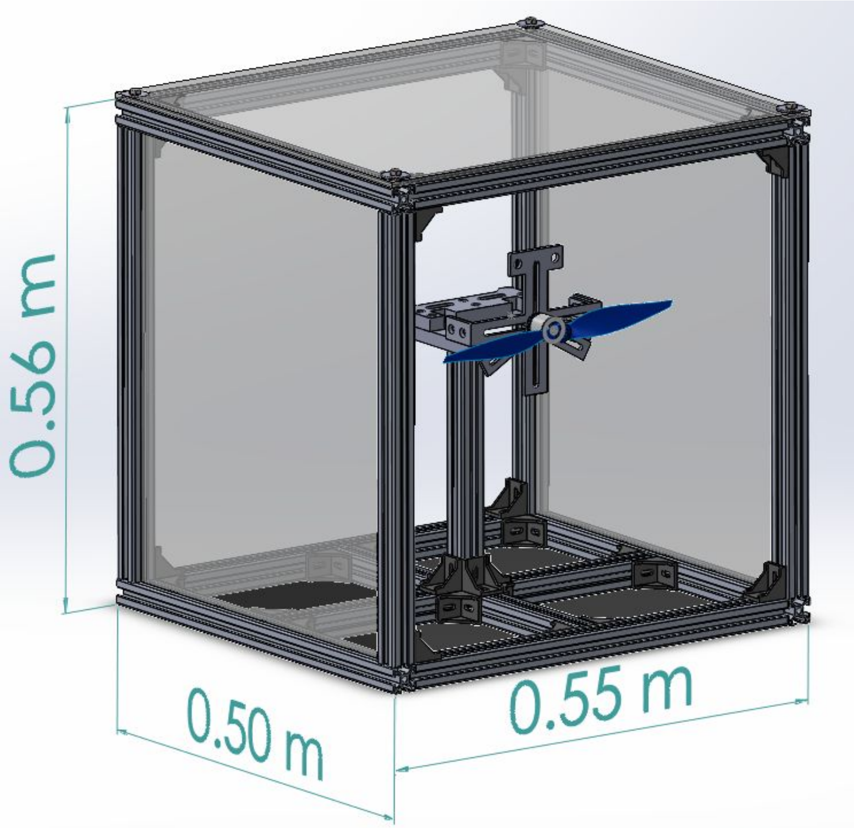


Aerodynamic Test Stand

Static Propulsion Test Stand

- Will be assembled by us
- Main Parts
  - Aluminum Extrusion
    - Cut to length/thread ourselves
  - 3 ¼” Acrylic Panels on sides
    - Cut to size ourselves
  - 1” wire screen for front/rear
  - Load Cell/Motor Mount Assembly
    - Lent by DBF

Cutting aluminum extrusion and assembling this week



Custom Battery Progress

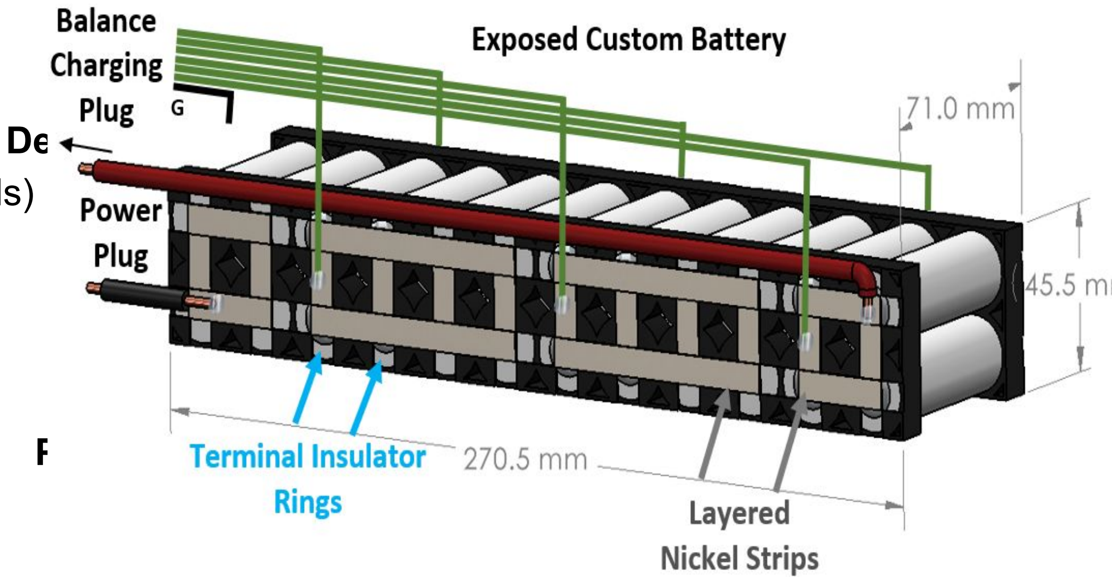
Still waiting for procurement on 1 major part

- Charging pin (delivery eta: **unknown**)

1. Single simple parallel cell testing (4 cells)
   Estimated time (1 hour)
2. 1st iteration full battery pack (24 cells)
   Estimated time (1 day)

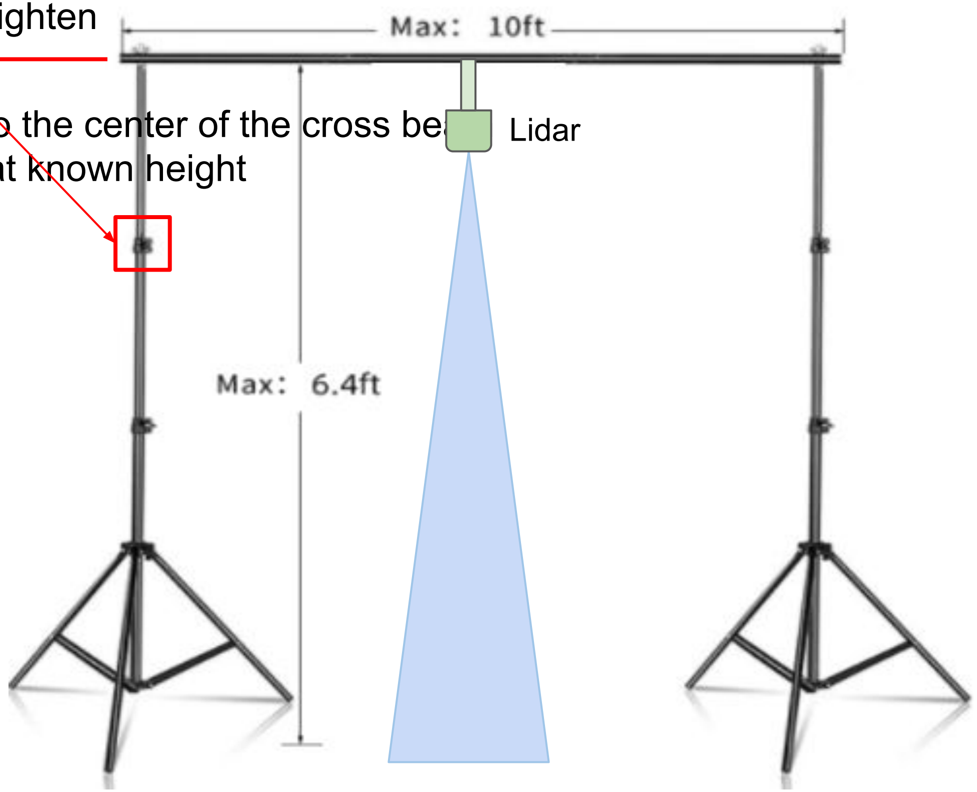
Waiting on R2R approval to begin manufacturing

Inventory



LiDAR Test Stand

- Test stand has been purchased
  - Waiting on delivery
- Lidar Mount printed out of PETG and mounts to the center of the cross be
  - Holds lidar sensor in vertical orientation at known height



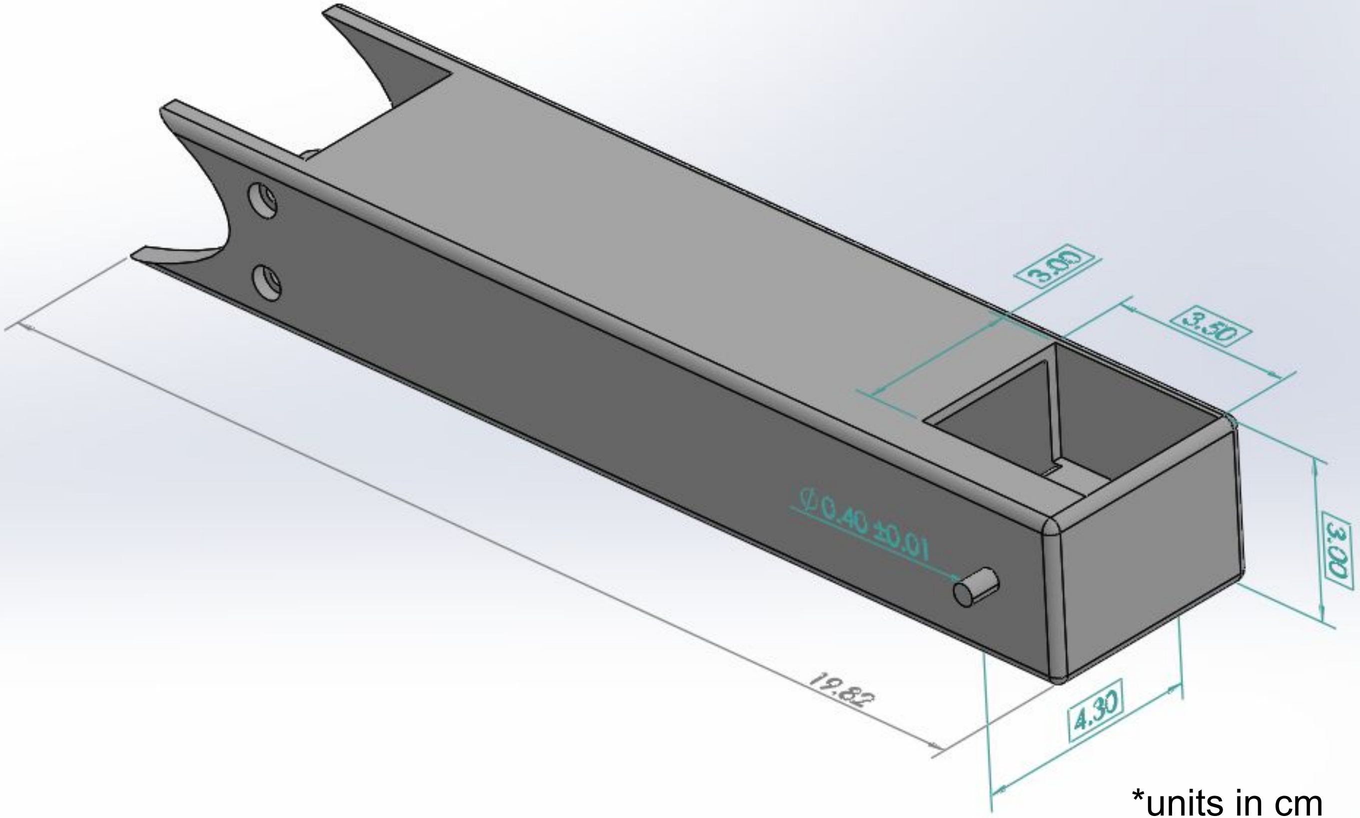
*Dimensions in mm

Waiting on Test stand to be delivered
LiDAR mount printed
Assembled by Feb 5th

Motor Arm

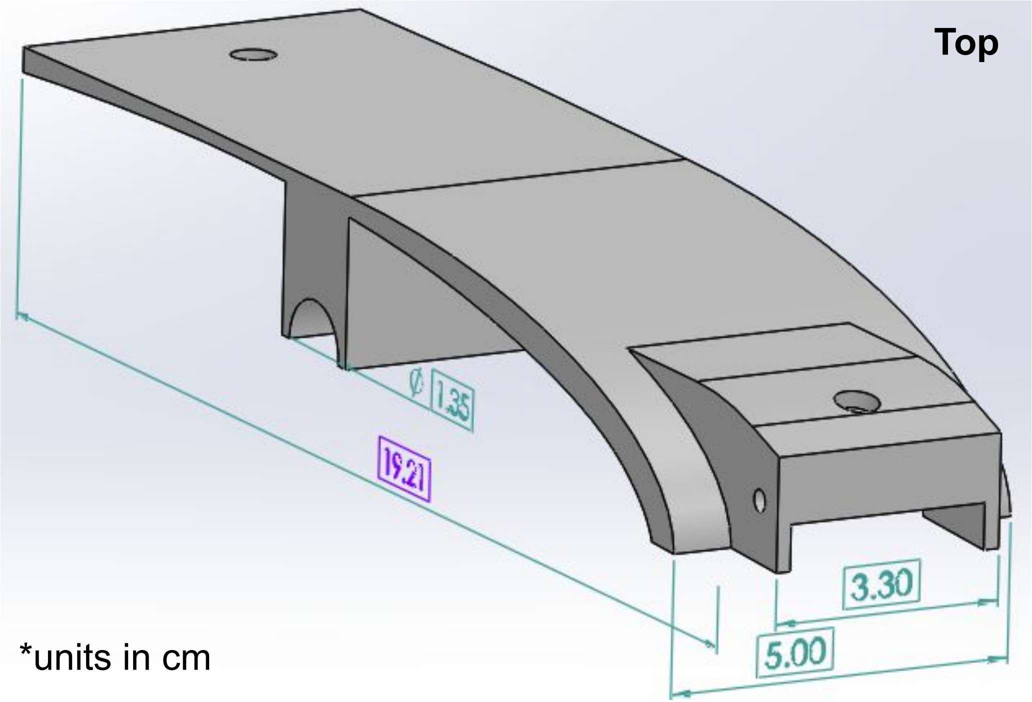
- Arm mounts printed out of PETG
  - ~10 hours each
  - Hollow to allow for wire channeling
- Motor arm attaches to wing mount by two horizontal 3mm bolts

To be 3D printed by Feb 5th



*units in cm

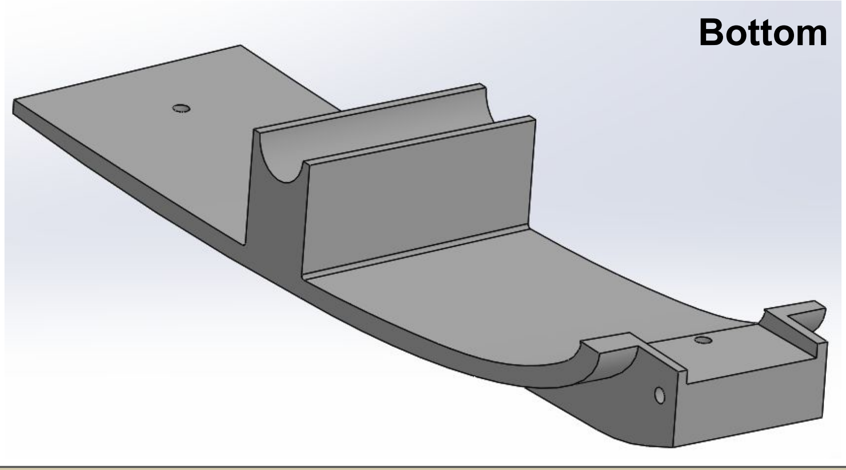
Wing Mounting



*units in cm

- Wing mounts printed out of PETG
  - ~12 hours total
- Wing mounts held together by glue and forward & rear 3mm bolts in the wing

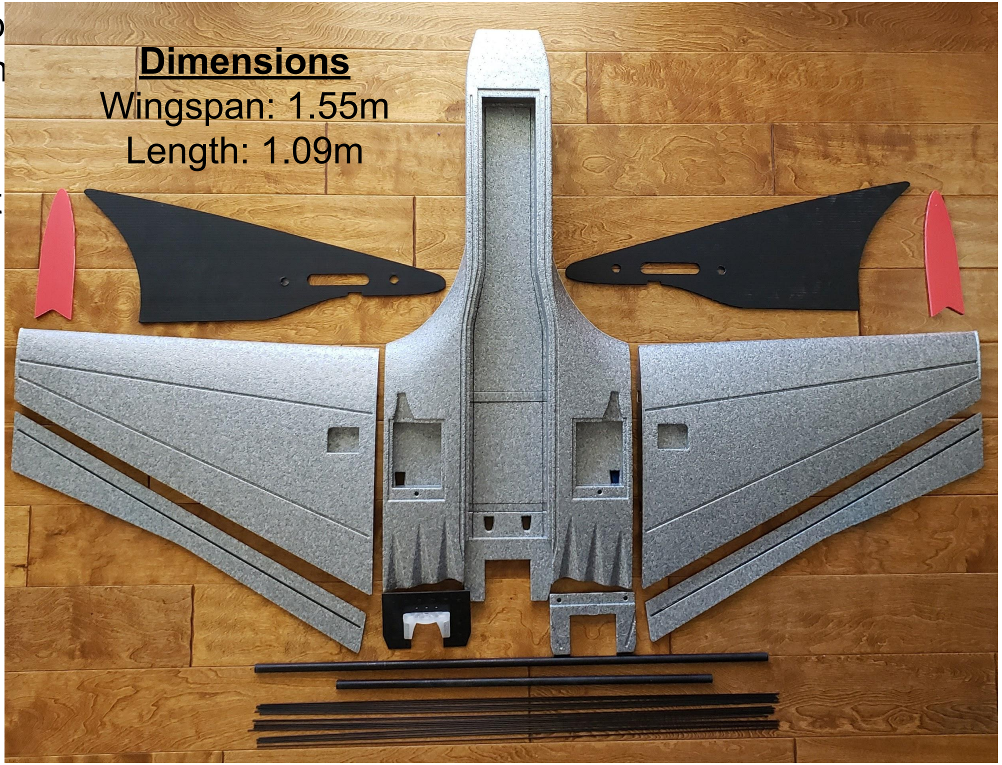
One set is printed and ready to begin wing load testing



Overview and Scope

Component	Purchased or Manufactured	Manufacture Time	Completion Date	Status
Drak Wing Kit	Purchased/Assembled	~ 3 days	Feb 5th-8th	Waiting on Adhesive
Wing & Motor Mounts	Manufactured/Printed	12 hours	Jan 30th	Printed
Lidar Test Stand	Purchased/Printed	1 hour	Feb 5th	Printed, Waiting on Delivery
Custom Battery	Manufactured	6 hours	Feb 3rd	Waiting on R2R
Static Test Stand	Manufactured	3 hours	Feb 4th	Waiting on R2R
Dynamic Test Stand	Manufactured	4 hours	Feb 3rd	Waiting on Delivery

- Three Drak kits purchased and in our p
  - Backups in case of damage durin
- Extra wing set
  - Test wing mount loading
- Kit includes EPP foam body, coro-plast
- Additional assembly tools
  - Adhesive
  - Tape for control surfaces



All Drak kits procured, waiting on adhesive to be delivered
To be assembled by Feb 5th-8th

Manufacturing/Testing Concerns

Category	Concern	Notes
Dynamic Test Stand	High	Primarily safety, Milling and cutting metal, Organizing testing space, Intense data processing
Static Test Stand	Medium	Safety, Experience with DBF propulsion testing, Shop work
Custom Battery Packs	Medium	Shipping parts. Battery pack performance after manufacturing. Safety
Motor Mounts, and Loading Test	Low	Uncertainty in FEM causing failure before the required loading.
Extra Control Surface	Low	Tail booms approx. 40 in, Hot wire foam cutting, Optimization Sizing, Ardupilot parameters

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

Interface Control Overview

Hardware	Software	Electronics
Tilt Servo must lift motor Design tail around existing structure RAPCat interfacing	LiDAR RS-232 to Avionics Servo Rail PWM to Servos & ESC's Digital Pitot Probe measurement	Battery to Power Module Power Module to Avionics Power Module to 3 - ESC's Avionics Servo Rail to Servo/ESC Avionics to Pitot-Probe

Interface Control Overview

Battery, Power Module, & ESC

- Battery must provide enough burst current to ESC's
  - Below continuous 100A limit of Power Module
  - Wires must sufficiently carry large current
- Power module output must be split to 3 ESC's
  - Special wiring harness created
- Battery and ESC must interface to Power Module

Avionics Board, Servo's, & ESC's

- Servo and ESC PWM signal must run off 5V
- Avionics Servo Rail must match physical wiring
  - Servo Rail output set in Mission Planner
  - Aircraft wiring is labeled for rail outputs 1-8

Avionics Board & LiDAR

- LiDAR Required RS-232 Communication W/ 5V
  - Designate COM-5 in MissionPlanner Setup