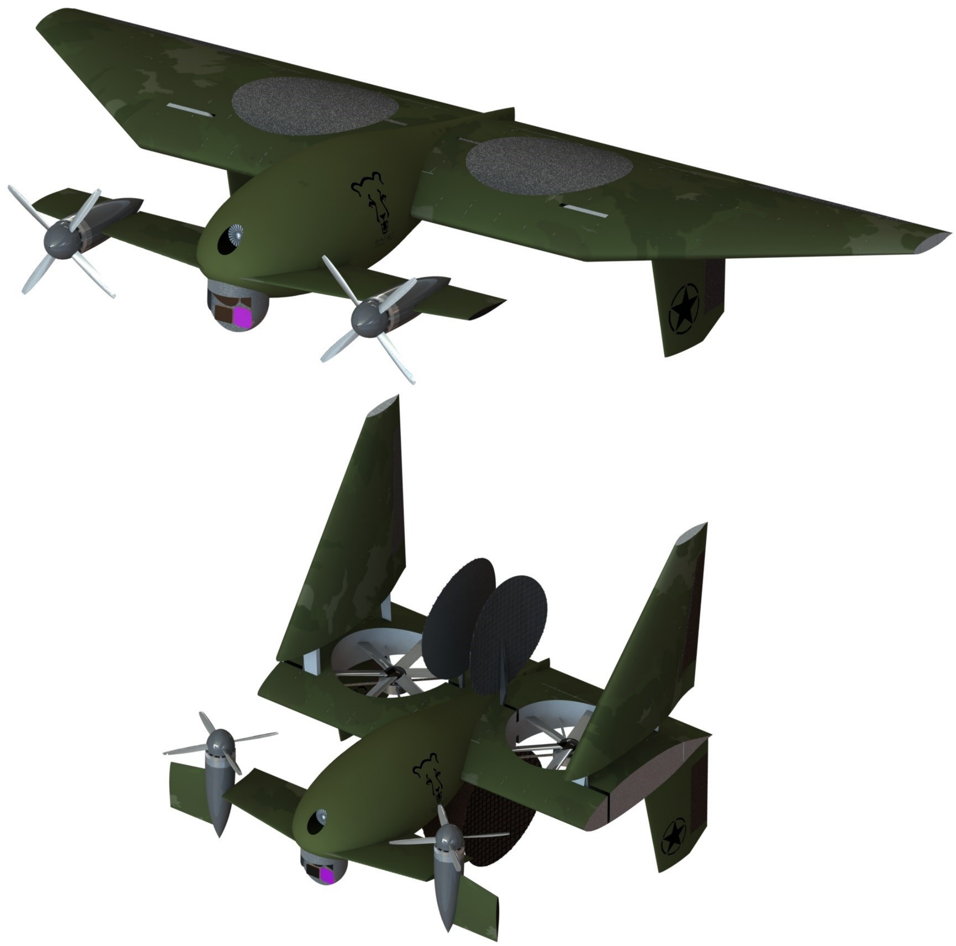
PennState College of Engineering

TOCHO



The Pennsylvania State University

May 8, 2018

Team Members

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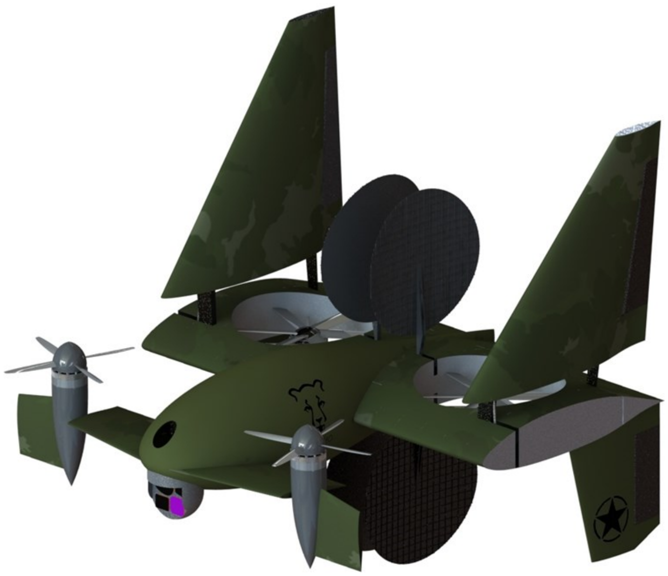
Introduction

In response to the American Helicopter Society's 35th annual Student Design Competition request for proposals, the Pennsylvania State Student Design team designed the Tocho aircraft. The word Tocho stems from the Hopi Native American Tribe's word for mountain lion which resembles to Penn State's mascot, the Nittany lion.



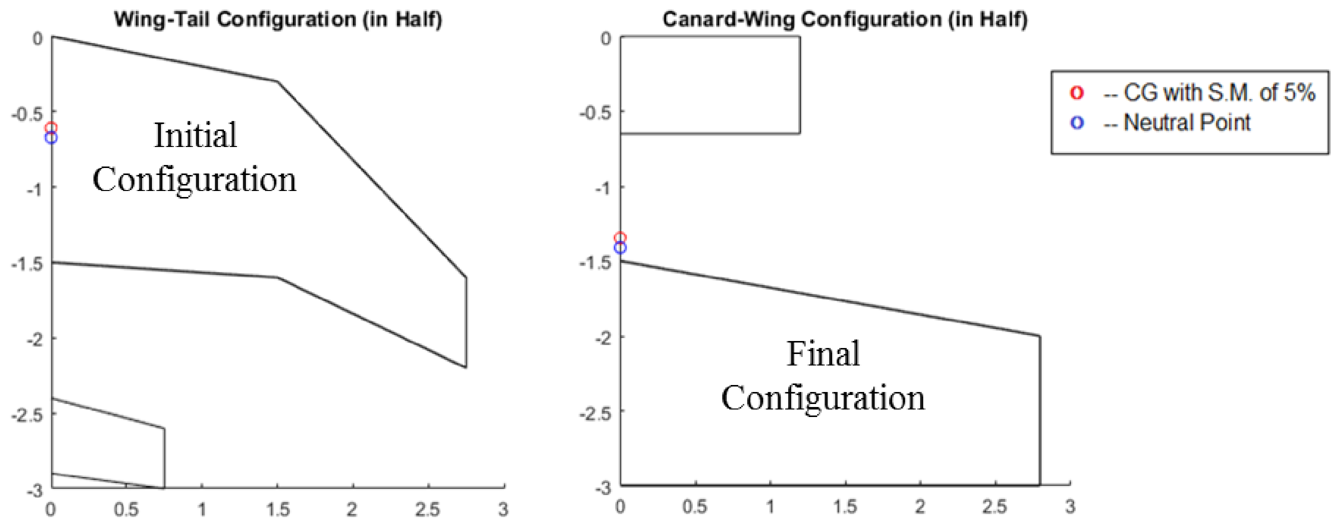
The Tocho aircraft is highly reconfigurable, possessing a set of unique reconfigurations to allow the aircraft to transition from hover to forward flight. Tocho is capable of carrying a 100 pound payload up to 764 km, and achieving a dash speed of 559 km/h (302 knots) at an altitude of 3000 meters. All of the components on the aircraft are based on current technologies and manufacturing methods.

Tocho possesses unique design features:

- Reconfigurable Ducted Rotors for efficient hover
- Hybrid electric propulsion system
- Folding wings to allow the aircraft to maneuver down city streets
- Reconfigurable-flow-path Recuperated Turbine Engine
- Four variable RPM electric motors

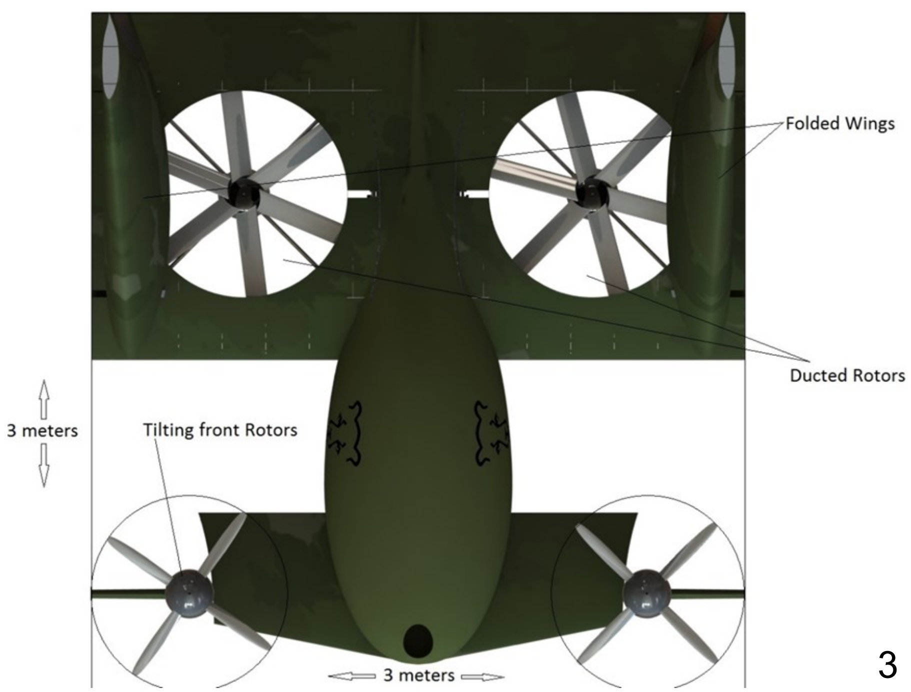
Design Drivers

One critical design feature is the use of a canard instead of a traditional aircraft with a wing and tail. This is for a more desirable static margin. Below is a figure that shows where the neutral point is located. With a front wing, the CG would be too far forward, so a canard design is selected.



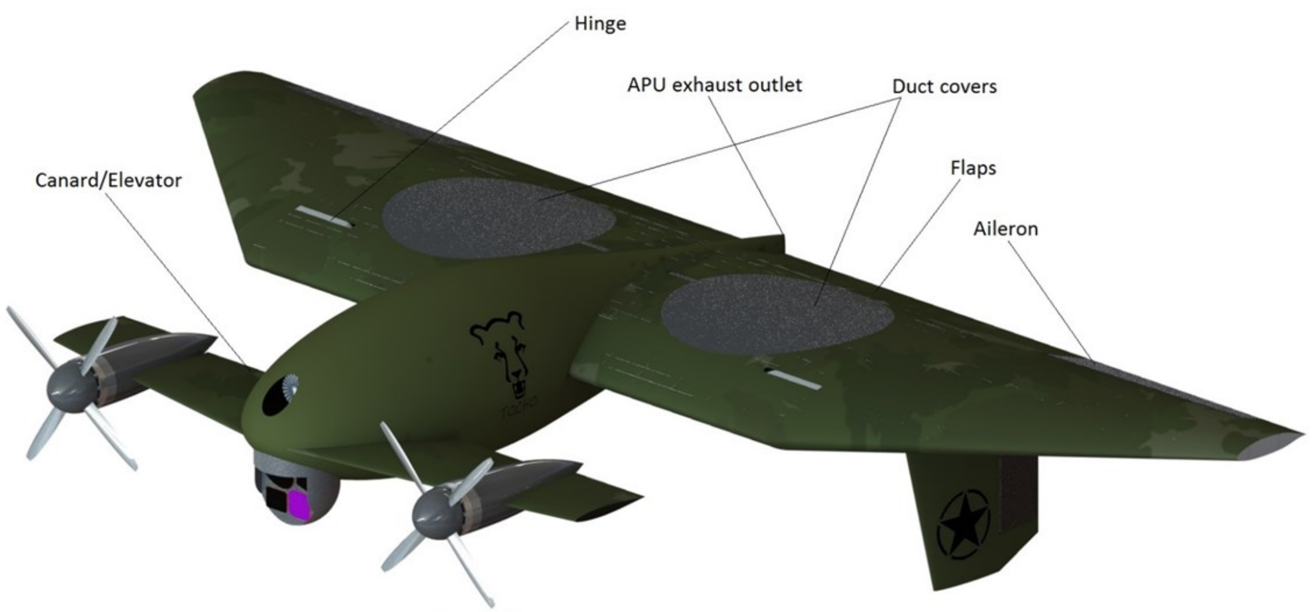
Another design driver is the capability to fly down city streets while being able to fly well above 180 knots in forward flight. To accomplish this, folding wings are used.

To fit down a city street all horizontal dimensions are limited to 3 meters, so the propeller and ducted rotor dimensions are to limited to the 3 meter box.

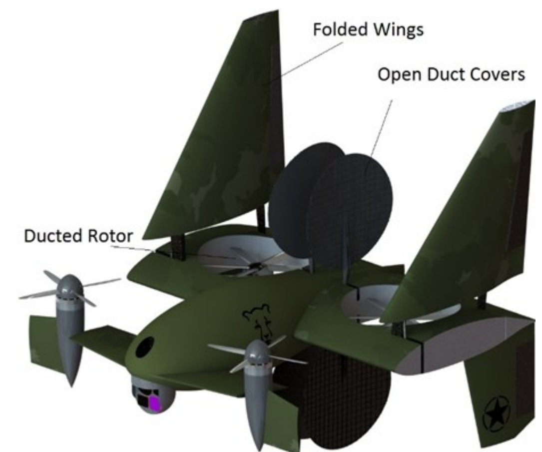


Vehicle Overview

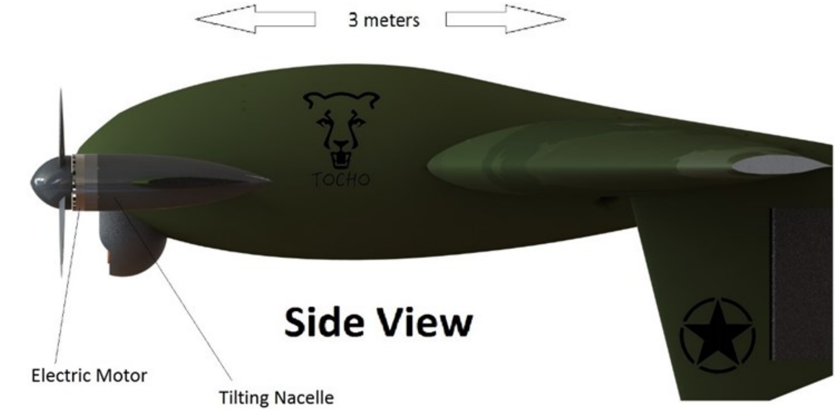
TOCHO



Isometric View

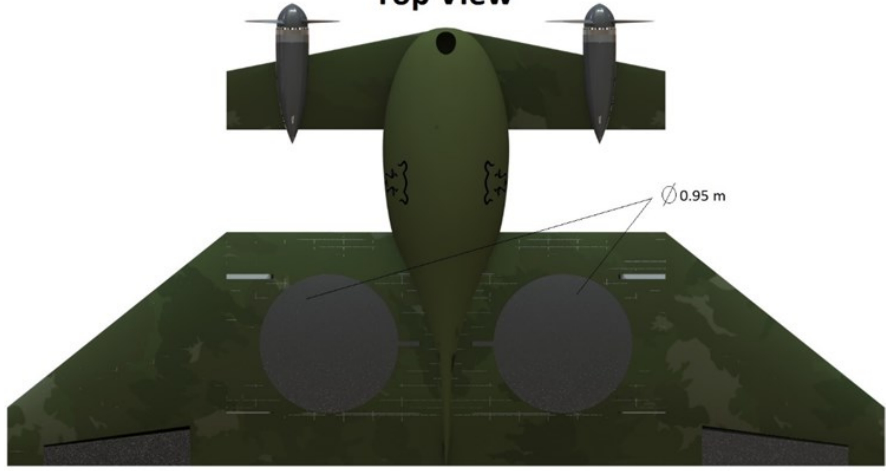


Hover

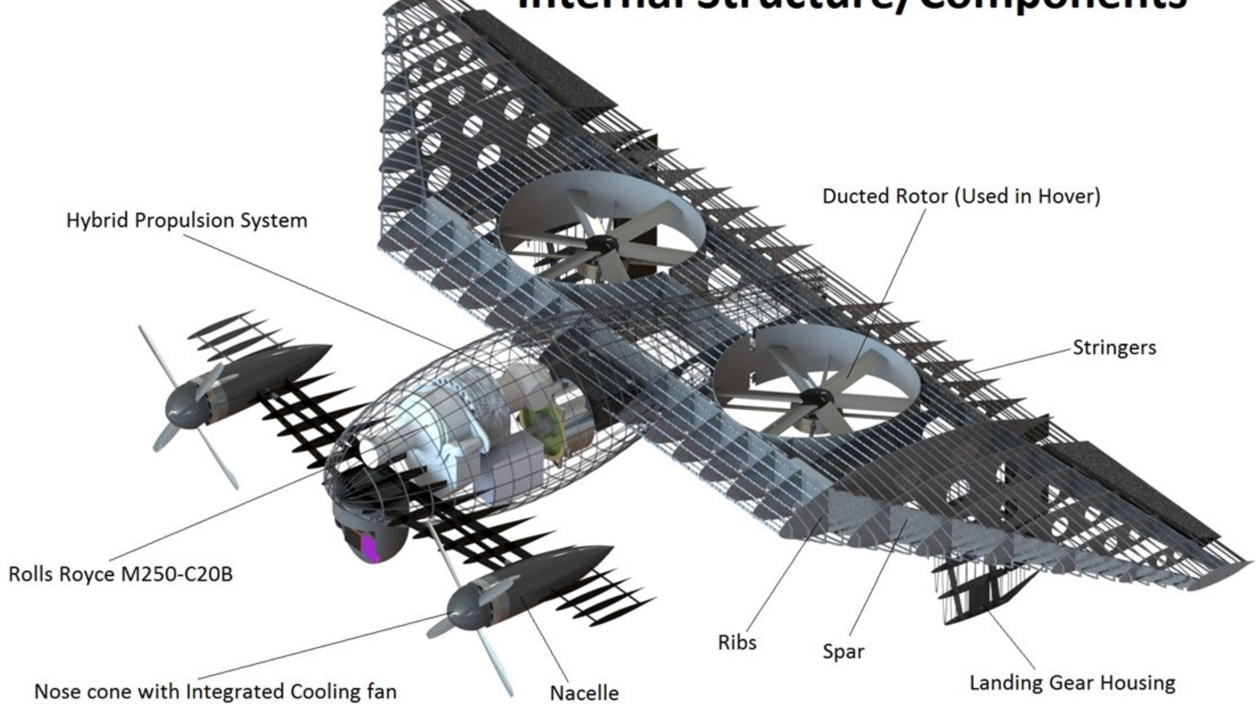


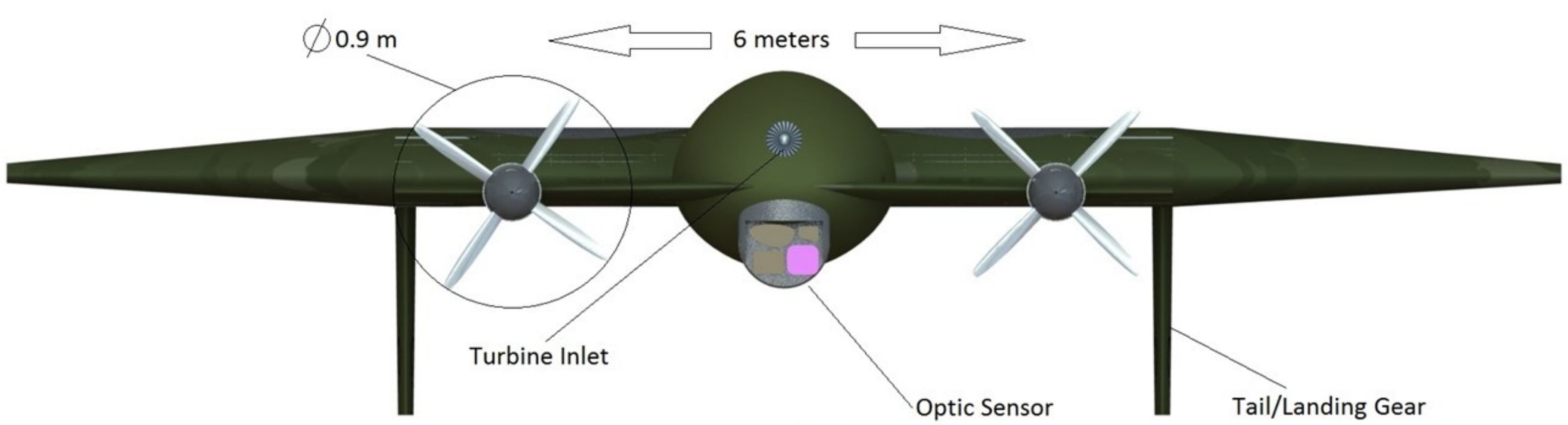
Side View

Top View



Internal Structure/Components





Front View

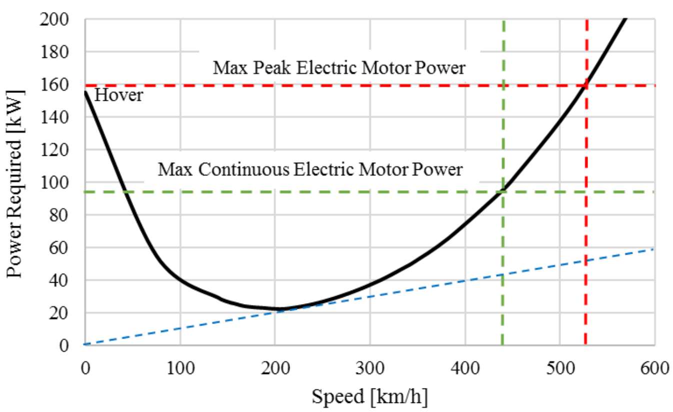
Vehicle Performance

Performance Metrics

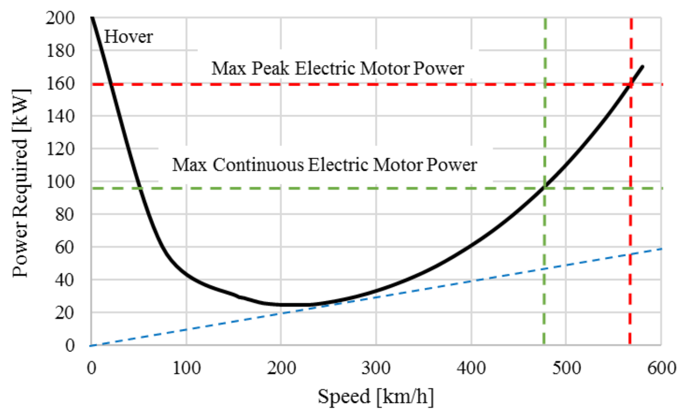
	SLS	3000 meters
Hover Time ***(50% energy)*** [hr]	1.17	1.28
Best Range ***(50% energy)*** [km]	316	382
Dash Speed [km/h]	519 (280 knots)	559 (302 knots)
Drag Area [m^2]	0.15	

The power required versus airspeed yields the best range, endurance speeds, and dash speed for a given altitude. The maximum peak power that the front electric motors can supply to the propellers is 160 kW. The maximum continuous power that the motors can supply is 95 kW.

SLS Conditions



3000 Meters

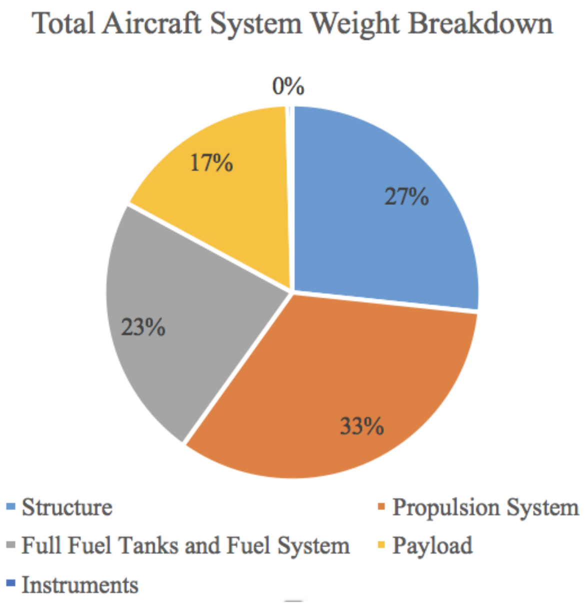


Best Range Speed	Max Endurance Speed	Altitude
234 km/hr	216 km/hr	SLS
256 km/hr	234 km/hr	3000 m

Weight and Balance

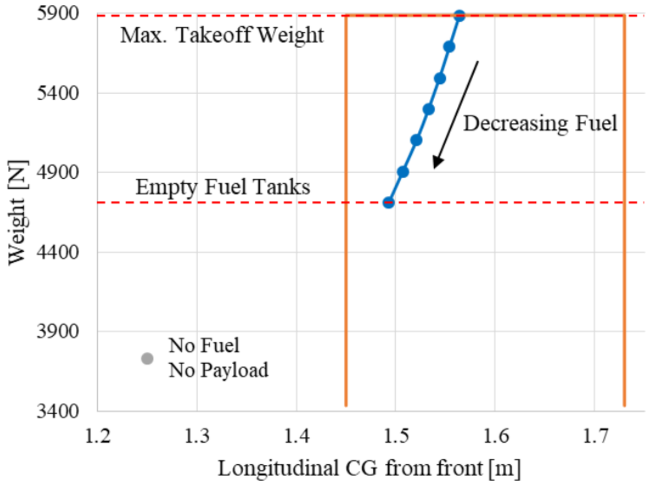
The Weight and Balance analysis was continuously modified throughout the design process to ensure 3 main objectives were met:

1. In forward flight, a positive static margin was necessary throughout the duration of any flight to ensure proper stability
2. In hover, the required thrust of the front propellers needed to be less than that of the rear lifting fans due to the design of each
3. The total vehicle mass needed to adhere to the RFP requirement of 600 kg maximum and 100 kg payload

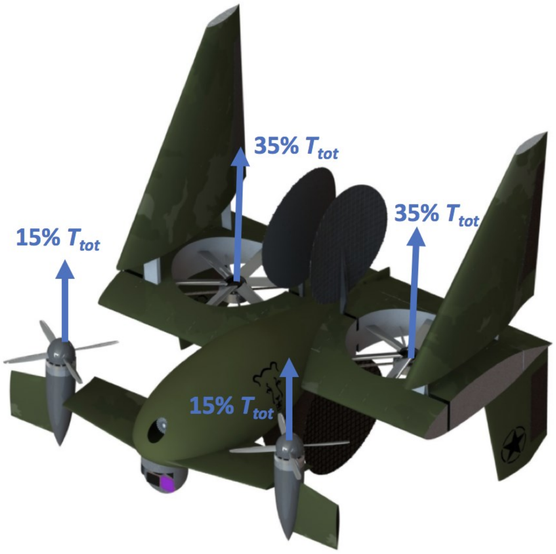


The pie chart on the right displays the weight distribution of all aircraft systems. The total mass of the aircraft is 600 kg, the payload is 100 kg, and there is 130 kg of fuel onboard.

The below figure shows the fuel burn curve for this aircraft, which proves that the CG will remain within its operational bounds throughout a flight. When a payload is not carried a balance weight should be used to keep the aircraft within CG limits



The below figure shows the thrust distribution between the rear fans and front propellers while the aircraft is hovering.



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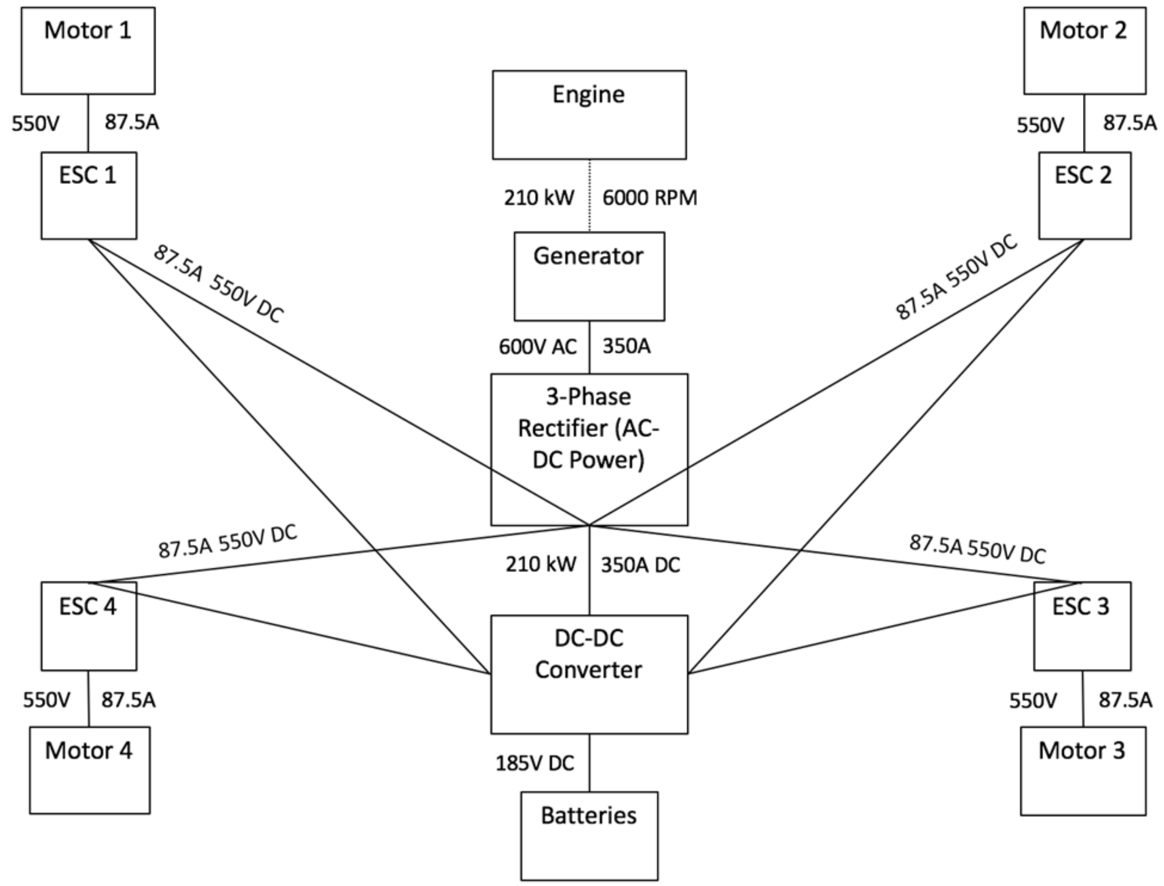
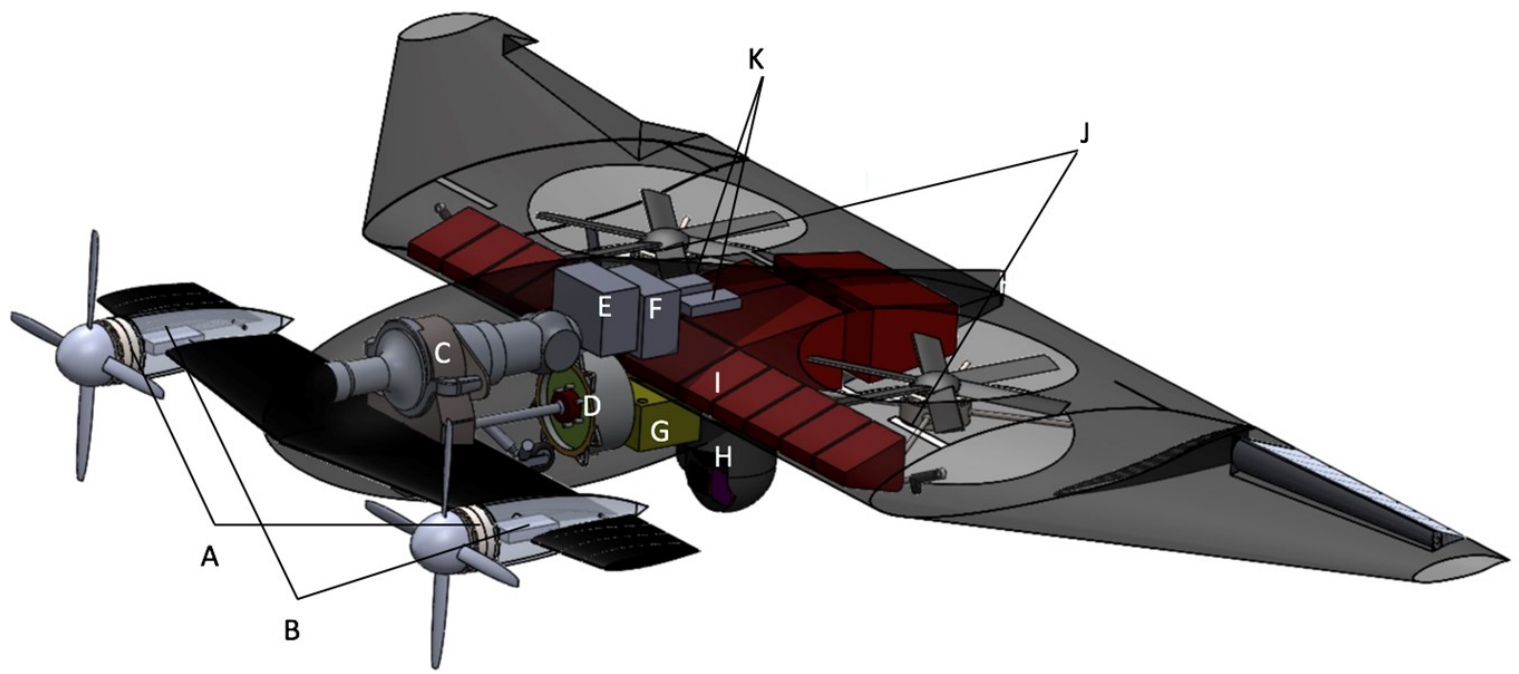
Internal Layout

The following layout was developed for the hybrid propulsion system of the aircraft. This layout ensured all electric components were operating at consistent voltages and currents. The engine drives the generator, which produces AC power for the 3-phase rectifier which converts it to DC power for each of the motors. The batteries are used when a surplus of power is needed for a maneuver, and use a DC-DC converter to provide the appropriate voltage.

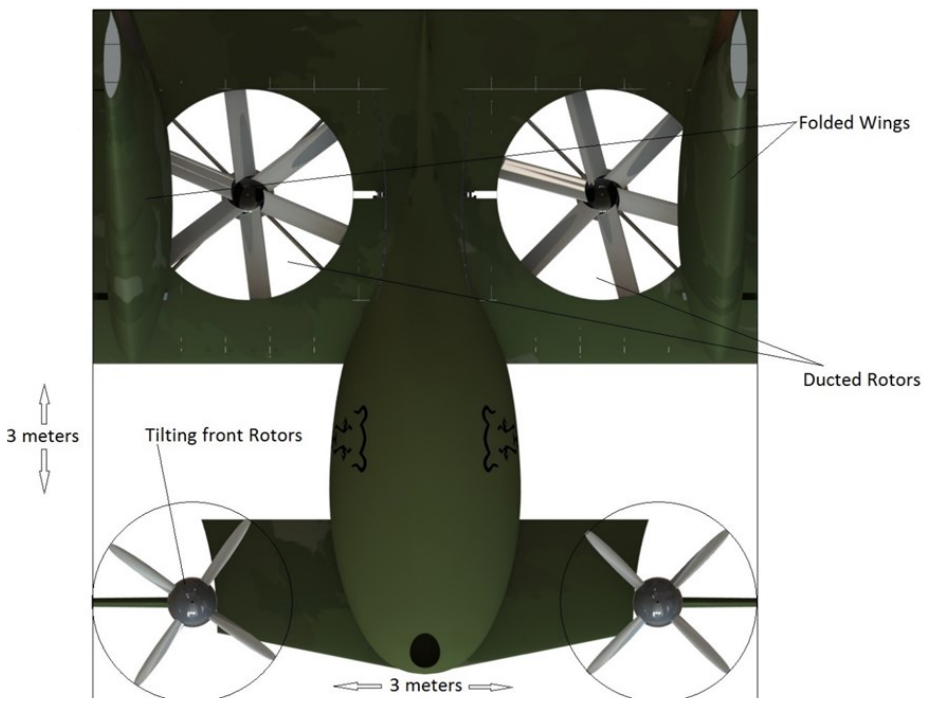


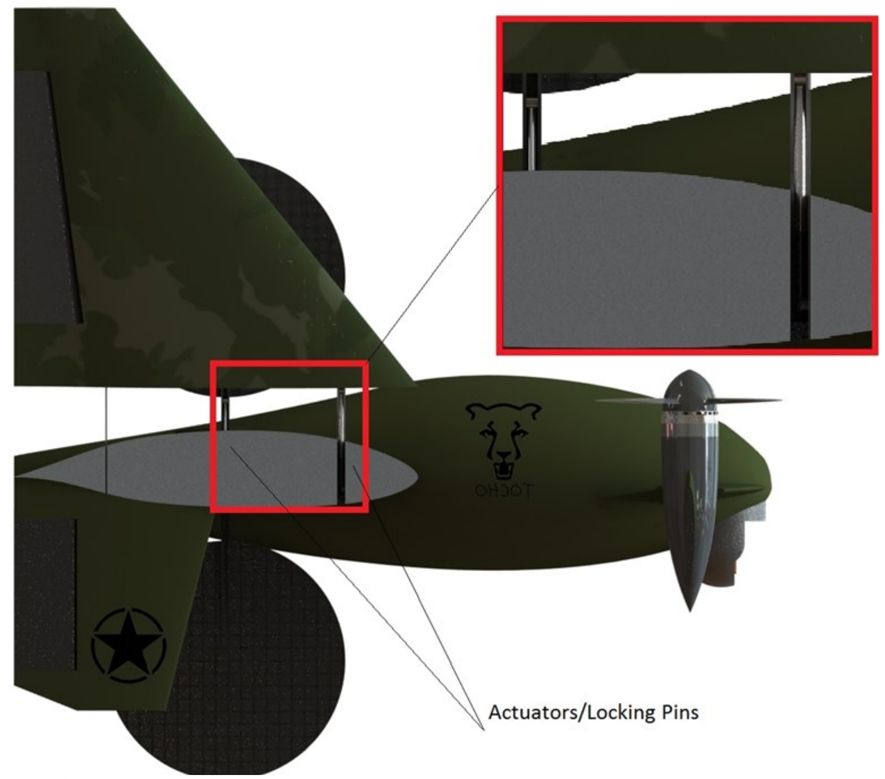
The below figure displays the internal layout in the 3-dimenional model of the aircraft. All components are referenced in the table below the figure. It should be noted that although the EO ball is not seen at the nose of the aircraft in this figure, that is where it is located and can be seen in all other photos of the aircraft.

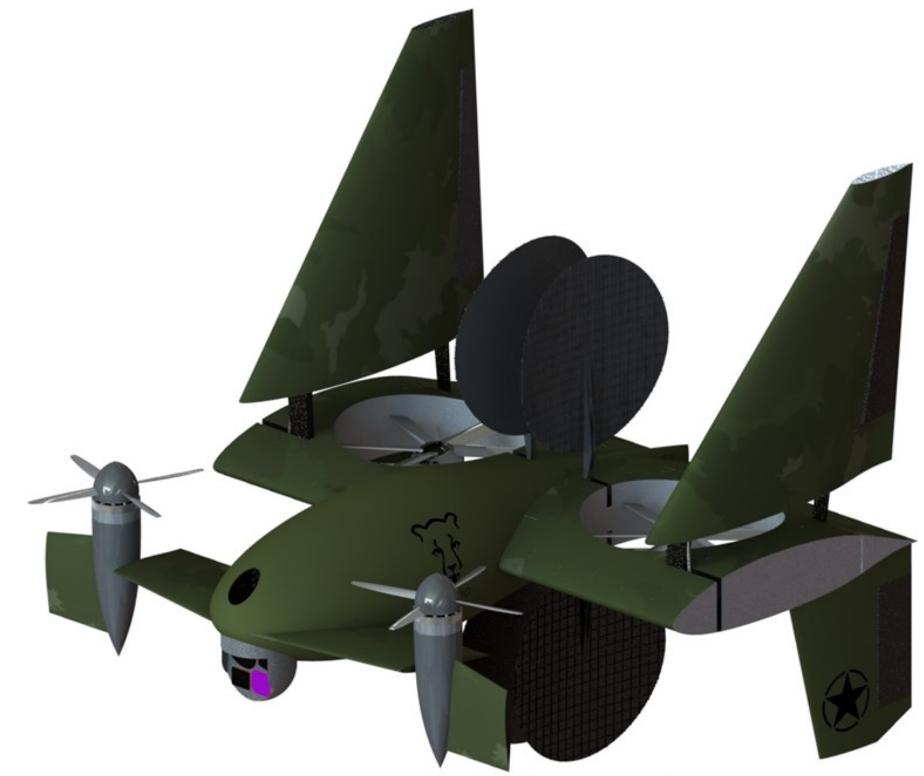


Label	Component	Label	Component
A	Front Motors	G	Battery Pack (yellow)
B	Front Motor's ESCs	H	Payload Bay
C	Variable Flow-Path Recuperated RRM250	I	Fuel Tanks (red)
D	Generator	J	Rear Motors
E	DC-DC Converter	K	Rear Motor's ESCs
F	3-Phase Rectifier (AC-DC Converter)		

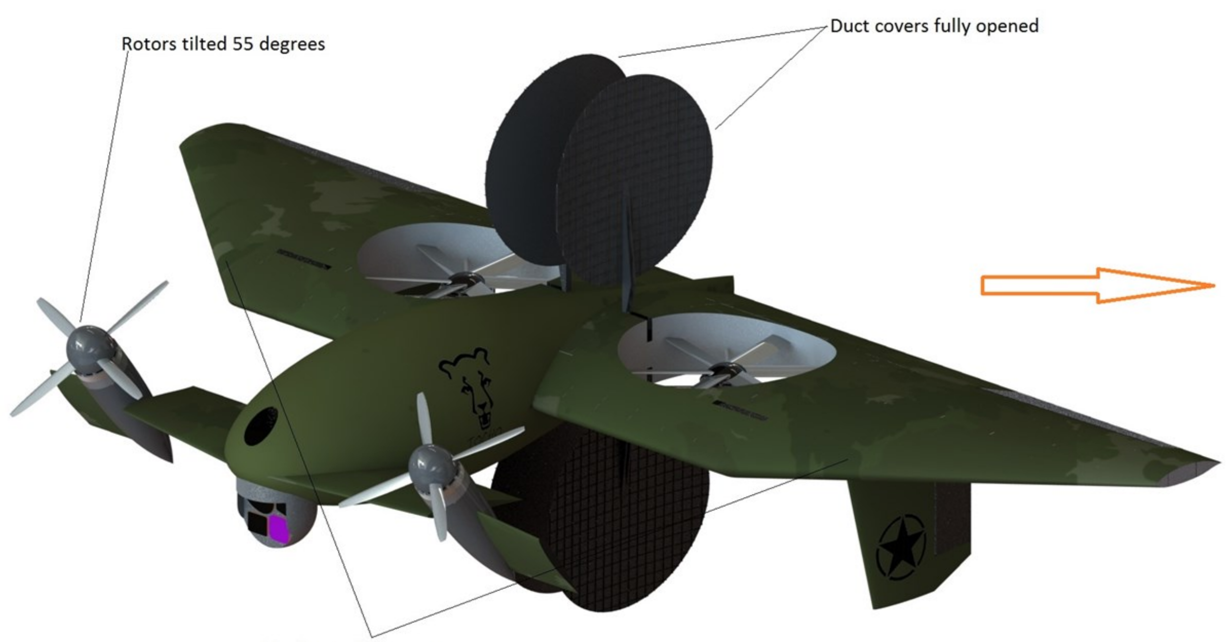
Vehicle Reconfiguration



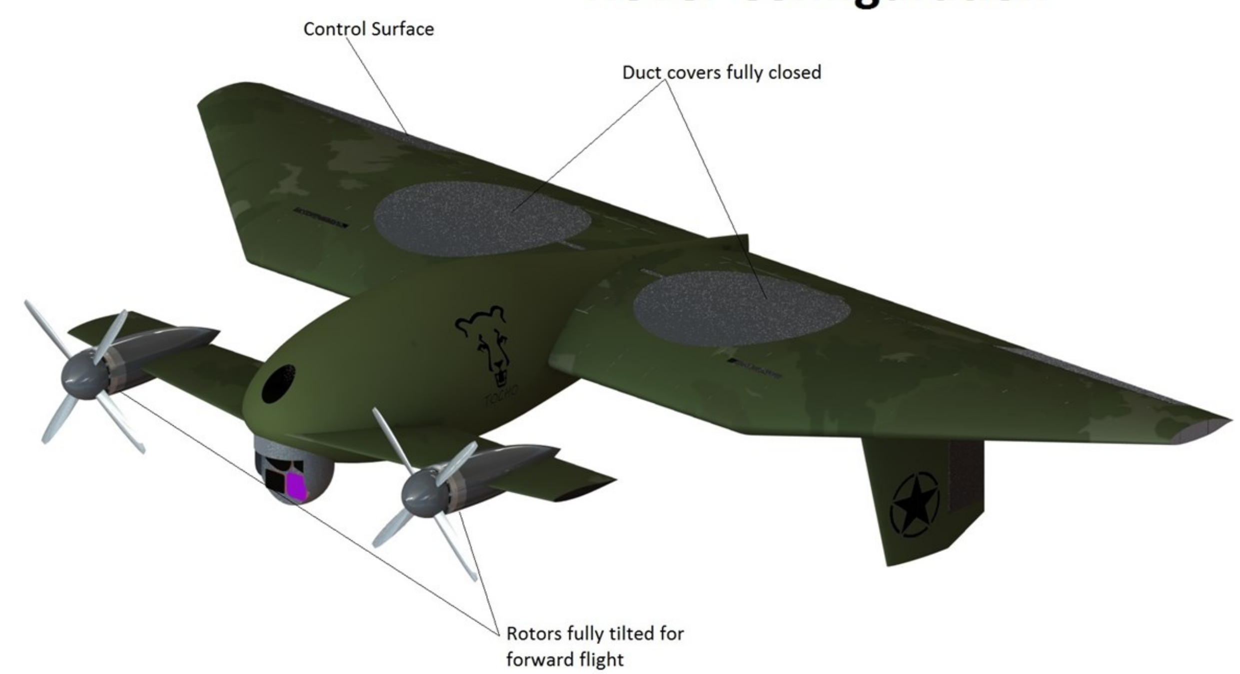




Hover Configuration



Transition to airplane mode



Forward Flight Configuration

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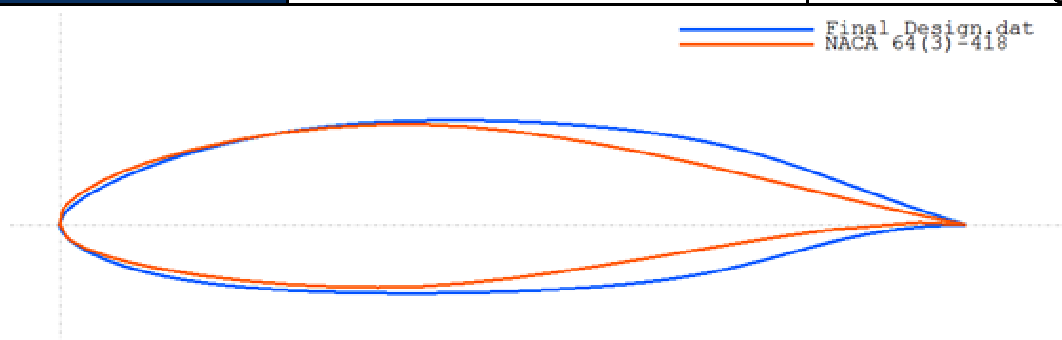
Wing Design

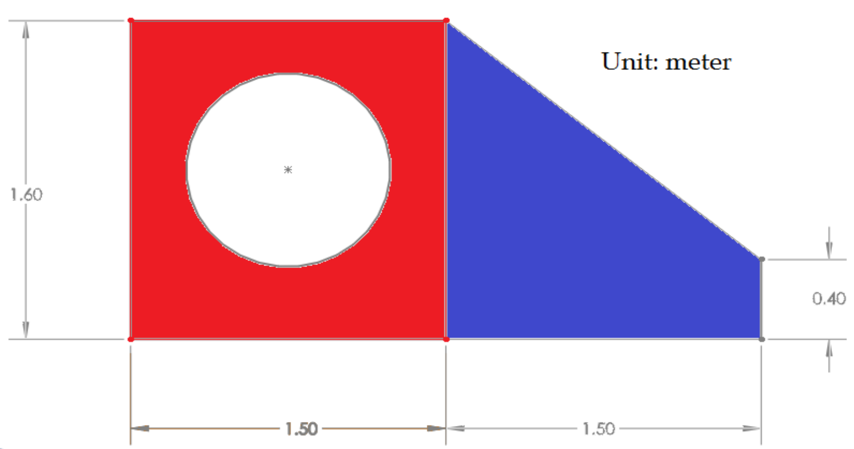
A customized airfoil is designed to accomplish mission requirement with lowest drag possible. The final designed airfoil a modification of NACA 64(3)418 using XFoil inverse design tool. The drag coefficient at low drag region is 0.0036 at operating Reynolds number.

Wing Section Requirements

Low drag region	C_L = 0.35+- 0.07	0 to 3000 m altitude
Cruise Reynolds number	6.0e6	
Thickness Ratio	>18% @ x/c = 0.16 to 0.80	To house the Ducted fan
C_L max	>1.1 @ Re = 3.0e6	Minimum speed for fixed wing

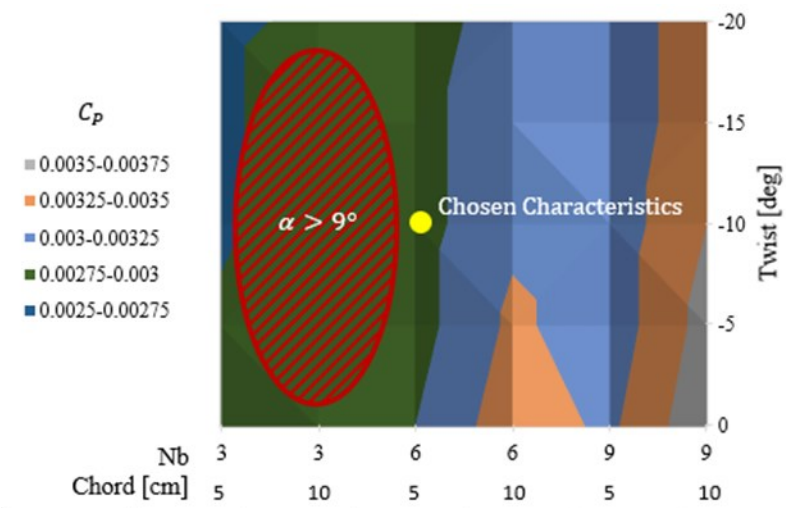


Wing planform consists inner section (red) and outer section (blue). The inner section has span of 3 m, laying inside the 3 m square limit. It has a chord of 1.6 m to house the ducted fan. The outer section is extended during fixed wing mode to reduce induced drag with minor increase



Rotor Design

The ducted rotor is designed using BEMT methods. Rotor blade characteristics are varied to minimize the power required to hover while ensuring the blade is not stalled. The below figure illustrates how the power coefficient changes with blade characteristics. Above 9 degrees angle of attack, the section is considered stalled. The rotor is ducted to fit in the wing, but to also reduce tip losses.



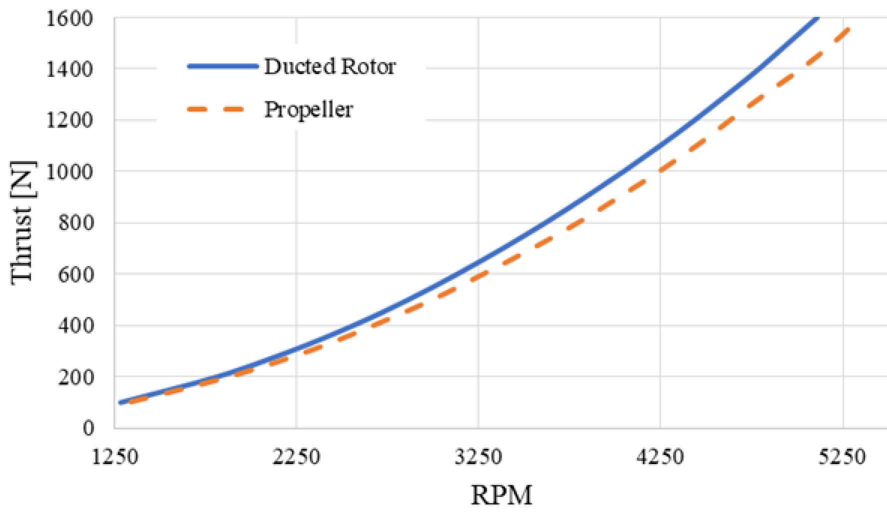
Ducted Rotor Characteristics	
Chord	5 cm
Twist	10 degrees
Number of Blades	6

The front propellers are designed for both hover and high speed forward flight. Due to the wide range of flight conditions, pitch actuators have to be implemented. The optimal propeller characteristics are determined again using BEMT with tip losses and modified inflow.

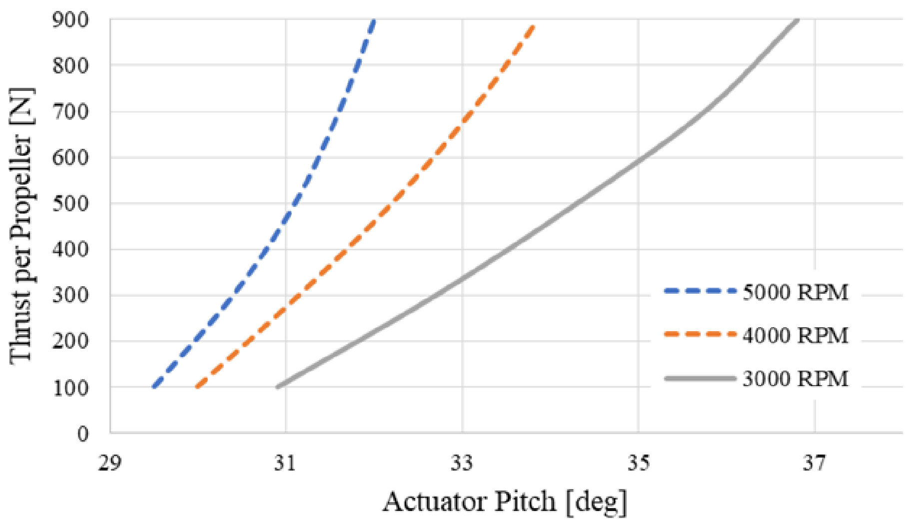
Propeller Characteristics	
Chord	5 cm
Twist	35 degrees
Number of Blades	4

Rotor Control

In hover and slow forward flight, both the ducted rotors and front propeller's thrust is achieved by varying the RPM of the electric motors. The below figure illustrates the required RPM for a desired thrust. At maximum RPM, the tip Mach number is 0.8.



In forward flight, the propeller can vary pitch and RPM; therefore, there is a range of operating conditions to achieve a desired thrust. Three RPMs are shown in the below control plot. At maximum RPM, the tip Mach number is 0.8.



Vehicle Transition Control

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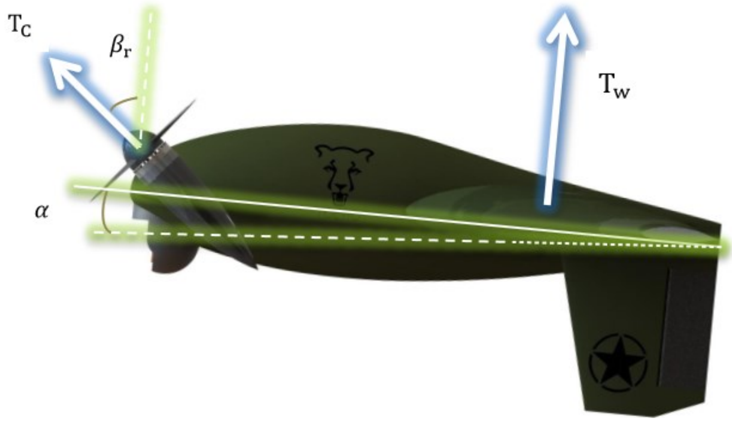
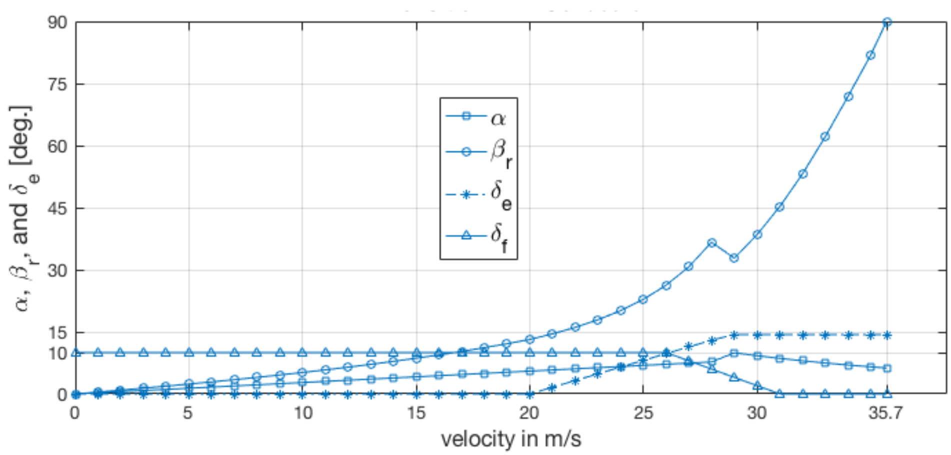
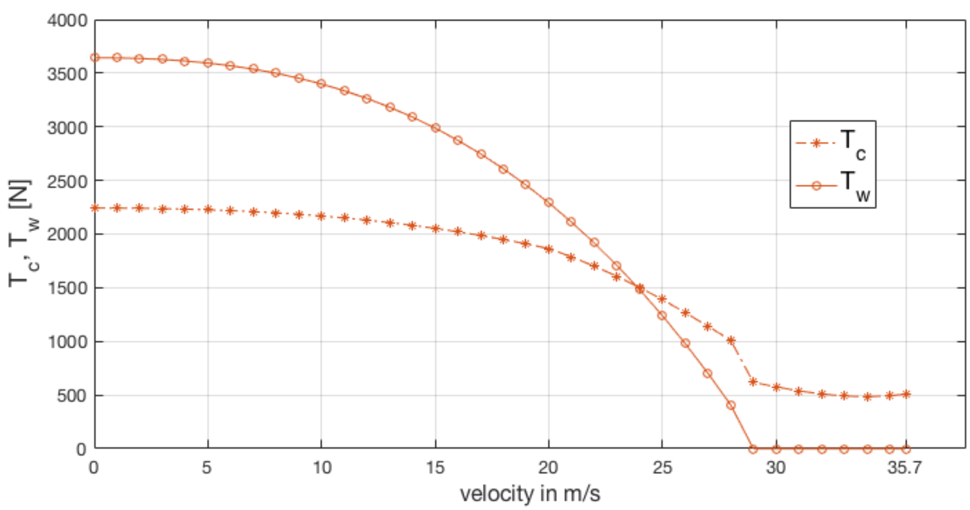
A Dynamic model is developed for transition from hover to fixed wing mode. Trim points, including, angle of attack, defections of elevators and flaperons, front propeller thrust and tilt angle, and thrust from the ducted rotors, are found as a function of air speed. The below figures show the control surface deflections, propeller tilt, angle of attack, and ducted rotor and propeller thrust.

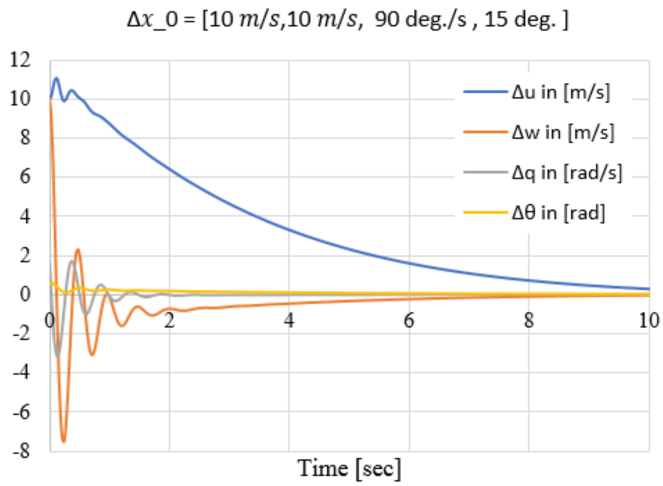






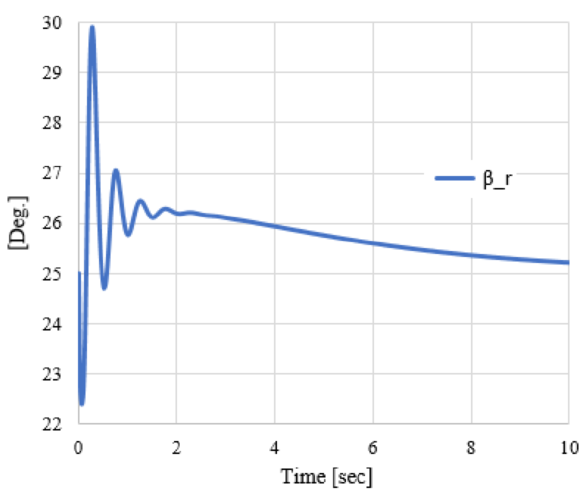
H∞ Controller for Transition

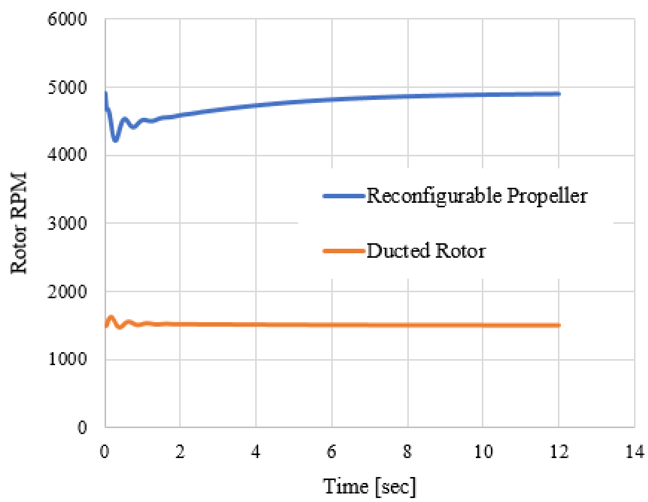
A H∞ controller method is utilized during transition for its robustness over unmolded dynamics. After linearizing about a trim point, the associated gain can be calculated. The figure below illustrates how the system responds to a perturbation.



It can be seen that the system is stable using the H∞ controller since the change in states are approaching zero. After given an initial perturbation.

The control effect is obtained by inversion and is shown below. The nonlinear system is stable under a large perturbation with H∞ controller.





The left figure illustrates how the reconfigurable propeller angle changes during the transition period. The right figure shows how the RPM of the ducted fan and reconfigurable propellers change during the transition period.

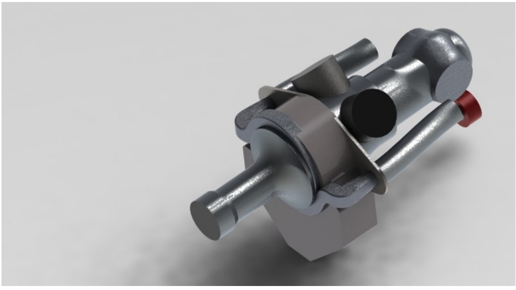
Propulsion

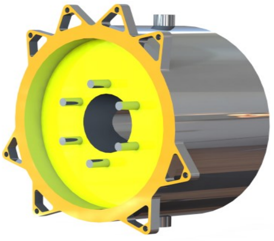
A hybrid propulsion system was chosen for this aircraft for two reasons:

1. Quad-rotor control in hover is more easily controllable with electric motors that can change RPM instantaneously
2. Current day batteries have poor specific energy storage and are heavy, in which case an all electric aircraft would not have as good performance metrics

The design uses a turboshaft engine to spin an electric generator which generates the power for the 4-electric motors. The specifications of each of these components can be seen below.

Recuperated Engine
Variable Flow-Path Recuperated RRM250Turboshaft Engine
Mass: 83.1 kg
Power: 250.6 KW (336 HP)
Output Shaft: 6000 RPM





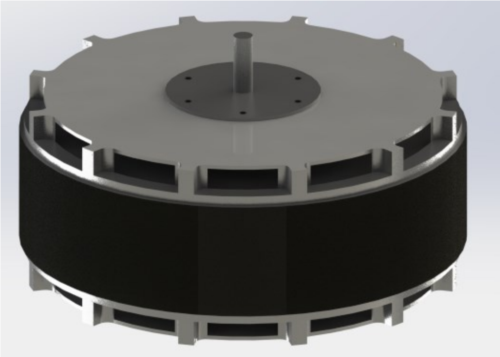
Generator
Siemens High Power Density Generator
Mass: 27.3 kg
Max Continuous Power: 210kW
Max Continuous Voltage: 650V
Max Continuous Current: 323A

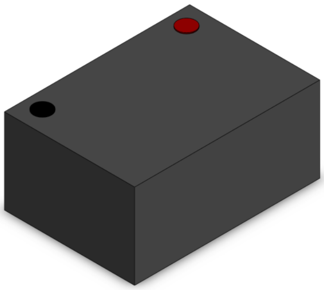
3-Phase Rectifier
Parker SSD 590P
Mass: 32 kg
Current Rating: 380A
Voltage Rating: 500V

Electronic Speed Controllers
Alien Power Systems ESC
Mass: 1.42 kg each
Max Current: 500A

Propulsion Continued

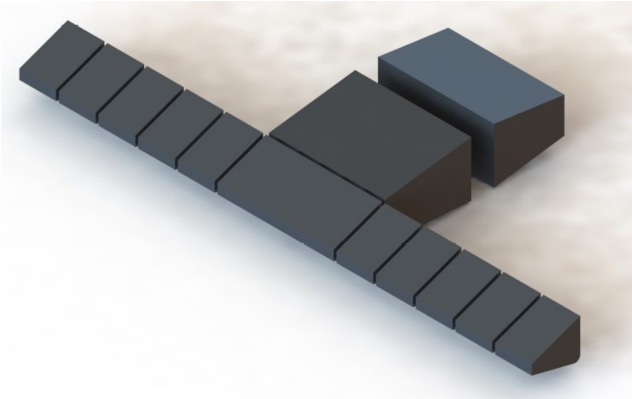
Motors
Alien Power Systems Motors
Mass: 5.08 kg each
Power Density: 9.4 kW/kg continuous
Maximum Current: 603A
Maximum Voltage: 190V
Maximum RPM: 6000 RPM





Battery Pack
Alien Power Systems
Mass: 25.6 kg
Nominal Voltage: 185V
Current Hours: 44Ah

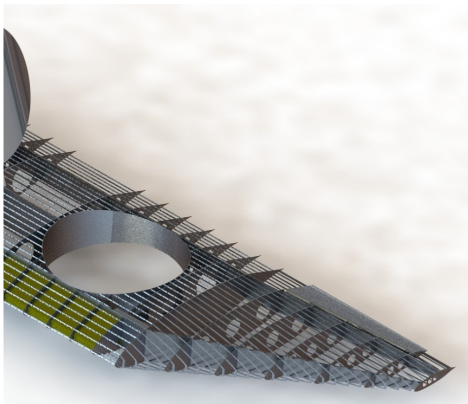
DC-DC Converter
YellowBee
Mass: 7.5 kg
Battery Voltage: 185V
Battery Current: 270A
Output Voltage: 550V
Output Current: 90A

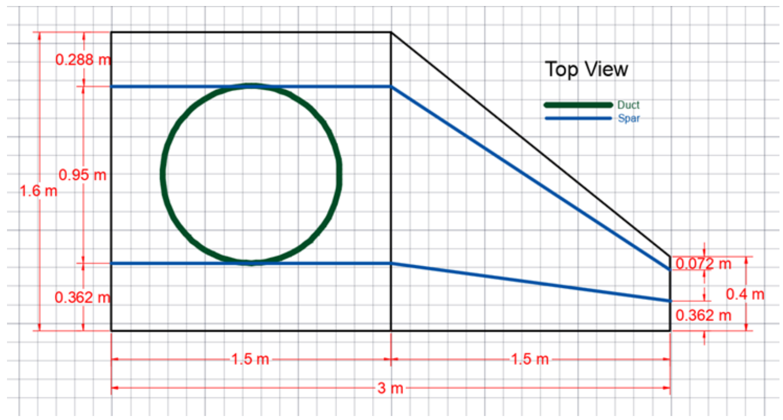


Fuel Tanks
Fuel Tank Mass: 7.7 kg
Available Fuel Volume: 0.17m^3
Available Fuel Mass: 130 kg

Wing Material and Structure

There are two I-beam spars running along the wingspan in order to hold the duct in the inboard part of the wing while allowing for a consistent structure in the outboard part of the wing. Stiffeners and ribs were employed along the whole wingspan to prevent buckling of the skin.





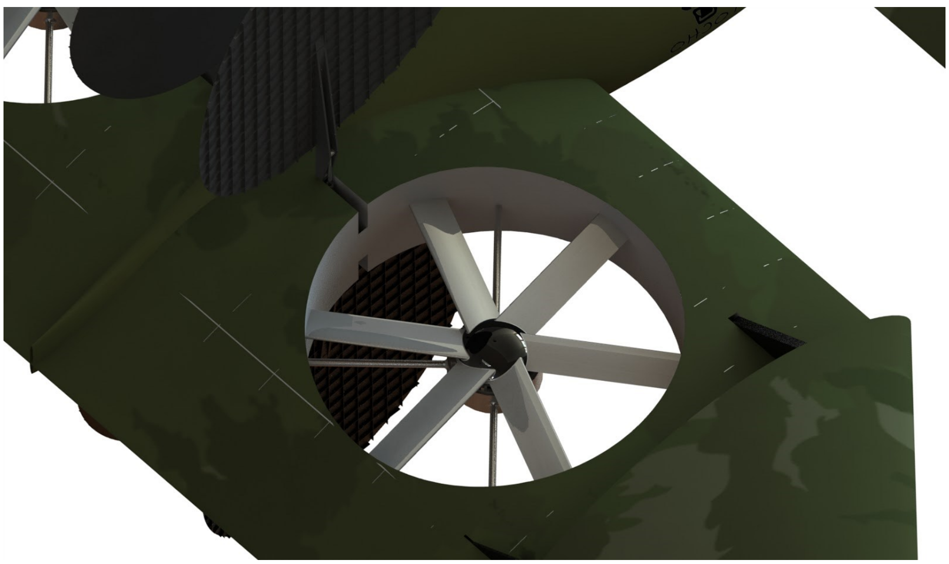
The whole wing structure is manufactured by graphite/epoxy composite material with the lay-up type of [m=50%, 2n=50%, p=0%], where m, 2n, p are the percentages of laminate plies laid in 0-degree, ±45-degree, and 90-degree respectively. The weight of the wing box is reduced to 11.4 kg, taking only small portion of the wing structure weight.

WING STRUCTURE DESIGN DATA	
Leading Edge Spar Depth (m)	0.248
Trailing Edge Spar Depth (m)	0.188
Spar Thickness (mm)	1.02
Skin Thickness (mm)	0.508
Max Bending Deflection (mm)	0.132 horizontally, 33.4 vertically at wing tip
Critical Load Factor	3.5
Max twist (deg)	0.19 deg at wing tip

Material Lay-up $[0_m/\pm45_n/90_p]_s$	Density (kg/m^3)	E (GPa)	G (GPa)	Tensile $\sigma_{ultimate}$ (MPa)	Compressive $\sigma_{ultimate}$ (MPa)	$\tau_{ultimate}$ (MPa)
[m=90%, 2n=10%, p=0%]	1660	132	7.93	1150	1150	103
[m=50%, 2n=50%, p=0%]	1660	82.7	21.4	703	703	255

Duct Material and Structure

There are four solid cylinder-shaped struts mounted to the duct to hold the motor house, each with a length of 0.375 m and radius of 0.019 m. They are designed to hold the loads generated by the motor operation during hovering with a deflection smaller than 2 mm at the tip that is mounted to the motor house. The total weight of all the struts are only 2.83 kg.



Duct Struts Design Data

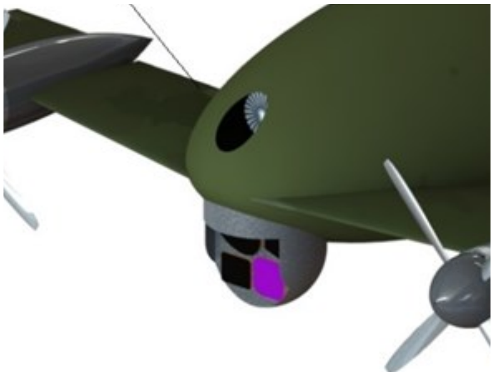
Max Horizontal Deflection (mm)	1.82 at tip
Max Vertical Deflection (mm)	0.574

The duct struts are made of graphite/ epoxy composite material with the lay-up type of [m=90%, 2n=10%, p=0%].

Graphite Solid Rods

CONOPS & Avionics

Tocho is capable of carrying various payload systems in its payload bay. The aircraft is always has a retractable electro-optical sensor in the nose of the aircraft.



The sensor of choice is the explosive detection system which is used in the detailed mission profile on the following page.

The Tocho aircraft is a fully autonomous fly by wire vehicle. The complexity comes when navigating down narrow city streets where the vehicle uses camera vison and LiDAR.

RPLIDAR A2M6 360° Laser Scanner

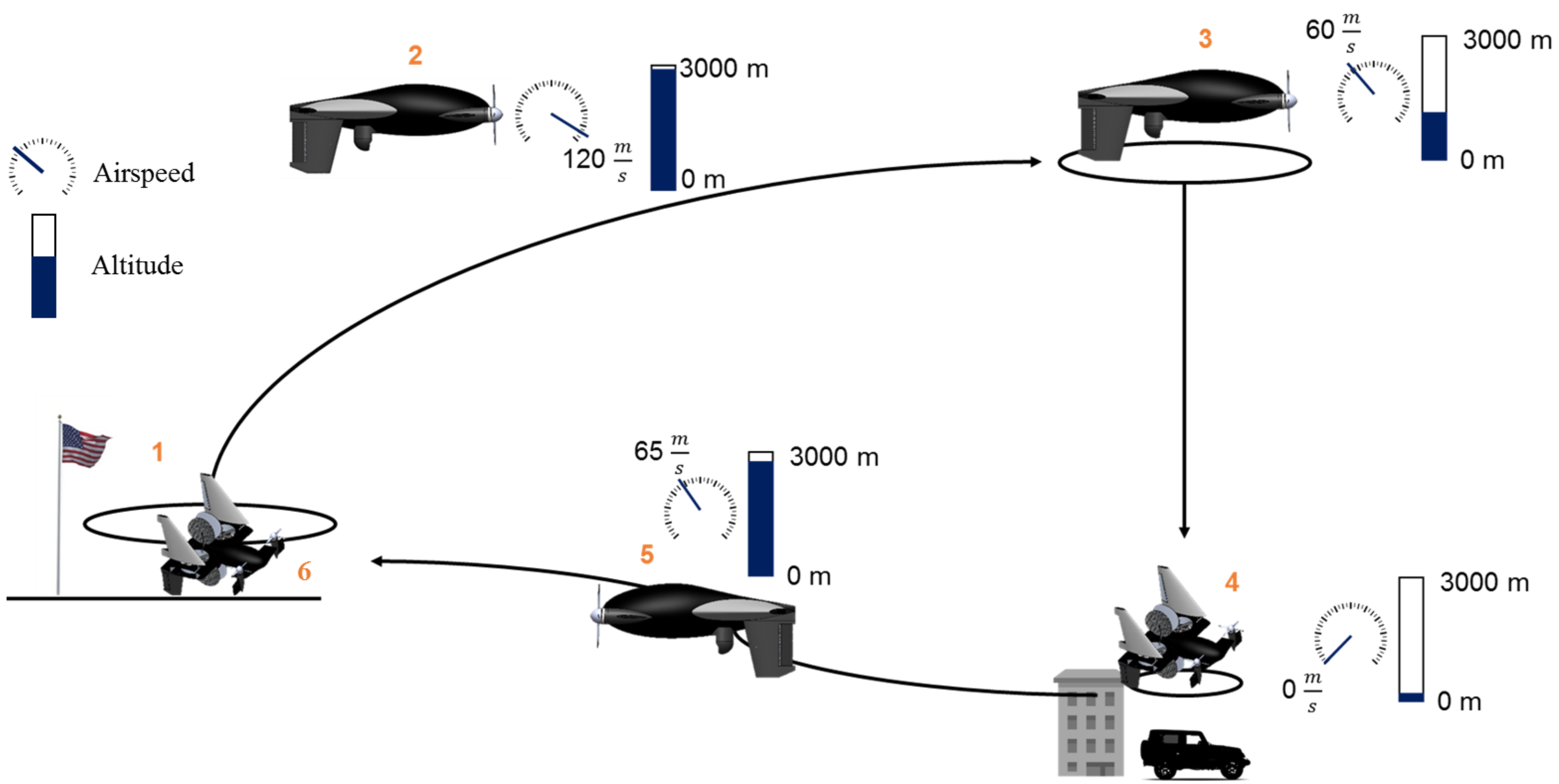
AP04 Autopilor

mvBlueLYNX-X Cameras

Detailed CONOPS

TOCHO

A Detailed mission profile for the Tocho aircraft is presented below.



1 Aircraft performs pre-flight checks, power up and takes off

2 Travels towards the target at dash speed

3 Enters a loitering pattern above the target at maximum endurance speed. The target is tracked using the electro-optical payload.

4 Explosive detection system is used to scan the target while the aircraft hovers out of ground effect above the target.

5 Traveling back to deployment site at best range speed.

6 Aircraft lands with fuel reserve for at least 20 minutes of cruise.

Phase	Power Required [kW]	Speed [km/hr]	Elapsed Time [hr]	Energy Consumed [MJ]	Distance Traveled [km]	Aircraft Mass [kg]
1	155	-	0.1	55.8	-	600-582
2	95	432	0.22	752	97	582-561
3	20	216	0.5	36	108	561-537.3
4	155	-	0.05	28	-	537.3-533.1
5	24	234	0.42	36	97	533.1-512.6

Summary

The Tocho aircraft offers a highly reconfigurable aircraft capable of flying down tight city streets while flying at 556 km/h in forward flight mode carrying 100 pounds of payload. The vastly different flight regimes are achieved through innovative features such as ducted rotors, folding wings, and a hybrid electric propulsion system.

The Tocho aircraft uses common manufacturing methods and commercial products. Maintenance on the aircraft can be done with ease since the aircraft can full transition on the ground.

Due to the many controls, the aircraft can safely fly in all flight regimes ranging from hover to dashing at 3000 meters using a fly by wire autonomous system. The versatility of the Tocho aircraft enables the use of the vehicle in multifarious missions.