BOEING

Vertical Flight Society

ALBATROSS

Executive Summary

April 28, 2021

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Introduction

Out in the remote costal cliffs of the North Pacific Ocean, the Great Albatross can soar at sea for days and even weeks at a time. With a wingspan of more than 10 feet, this magnificent bird can stay aloft for free by utilizing dynamic soaring. Its maneuverability and flight longevity allow it to be unrivaled by any other sea bird.

Inspired by this bird, the aerospace engineering undergraduate team from Penn State University designed the *UQ-9 Albatross*: an autonomous medical supply delivery VTOL aircraft in response to the 2020-2021 VFS Student Design Competition sponsored by Boeing.

Albatross is a **hybrid 4-bladed quad rotor** VTOL aircraft with **folding wing capabilities**, designed to deliver packages at **high speed** to local delivery centers and logistics sites. Its **variable geometry** and autonomous, **compact package unloading system** makes it an effective delivery vehicle. It was also designed to be multiply **redundant to maximize safety**. These features allow *Albatross* to operate in environments that are void of conventional runways with the advantages of a fixed wing aircraft.

Vehicle Overview

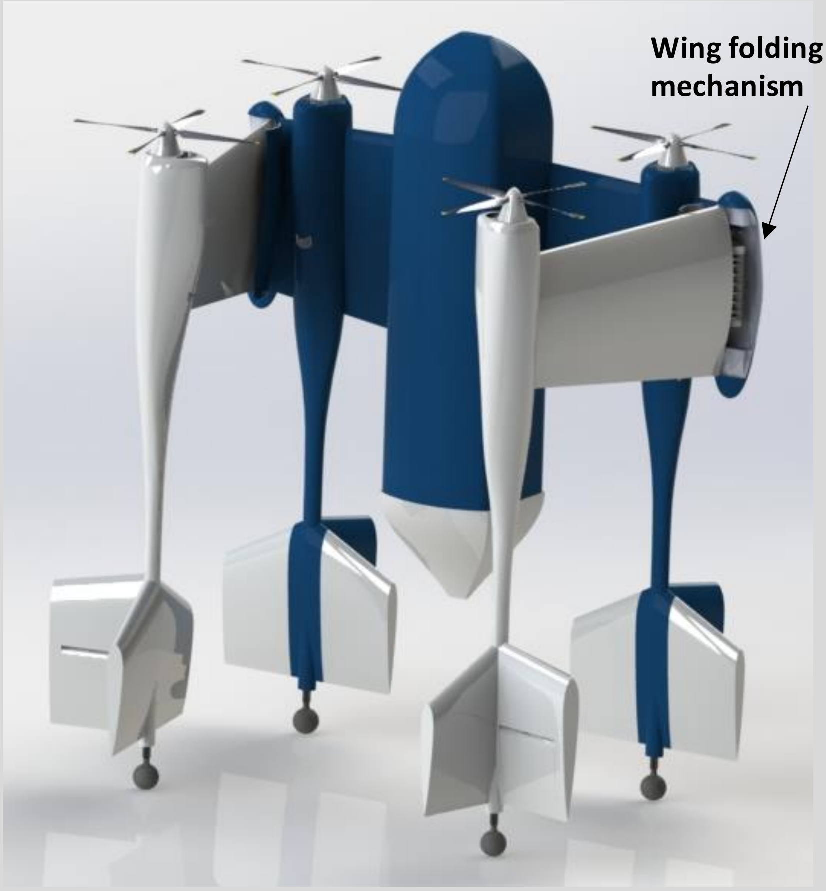
The Albatross is a cargo aircraft that is capable of vertical takeoff and landing during the Fall semester. Our group decided upon a vehicle that changes the configuration of its wings between vertical and horizontal flight. The folding wing concept is a design that attempts to trade-off the advantages and disadvantages of a conventional vertical take-off and landing vehicle with a conventional fixed-wing aircraft configuration. The RFP outlines that the vehicle needs to take-off and land vertically: however, the cruise portion of the mission is ambiguous.

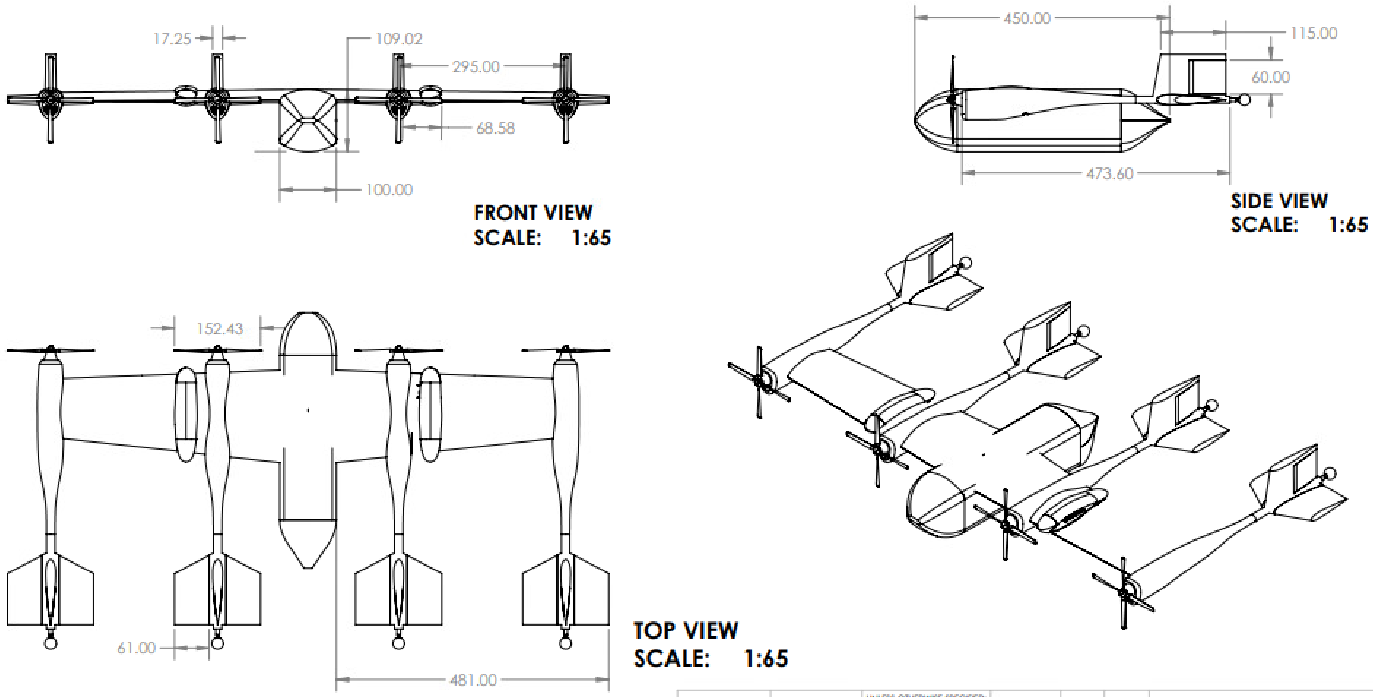
Based on the RFP outlines, this design we chose optimizes the given parameters for VTOL and cruise configurations. The horizontal configuration shown above takes advantage of the flight characteristics of a fixed-wing airplane, which can fly faster and more efficiently than a helicopter-characteristic aircraft at cruise. The vehicle is very light, so each rotor is small but has low enough disk loading. Allows for efficient cruise and space limitations.

Vehicle Overview (cont.)

To mitigate challenges involved with flight controllability when in the vertical configuration, four propellers were found to be optimal and could balance the two different flight configurations. The vehicle is more optimized for cruise but is not an efficient hovering vehicle. The portions of vertical configuration must be carried out swiftly as to not waste fuel. When the wings are folded for vertical configuration, the vehicle can fly like a quadcopter, varying each of the motor thrust outputs accordingly to maintain control. In order to switch from the VTOL configuration to the Cruise configuration, the vehicle will perform an in-flight maneuver. It will begin in a “U” shape with quadcopter controls and hover out of ground effect. It will climb to the cruise altitude while executing the transition maneuver. The vehicle’s wings will fold out, as it uses variable thrust and mechanical advantage from the increasing lift on the wings to pitch the aircraft to horizontal flight. Once the wings are in the cruise position, they will lock into place and the aircraft will assume full horizontal flight in fixed-wing configuration.

The disk loading of the vehicle is 14 lb/ft^2, and the vehicle has a lift capacity of 500 kg.





Total Dimensions: 10.62 x 5.69 x 1.72 [m]

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
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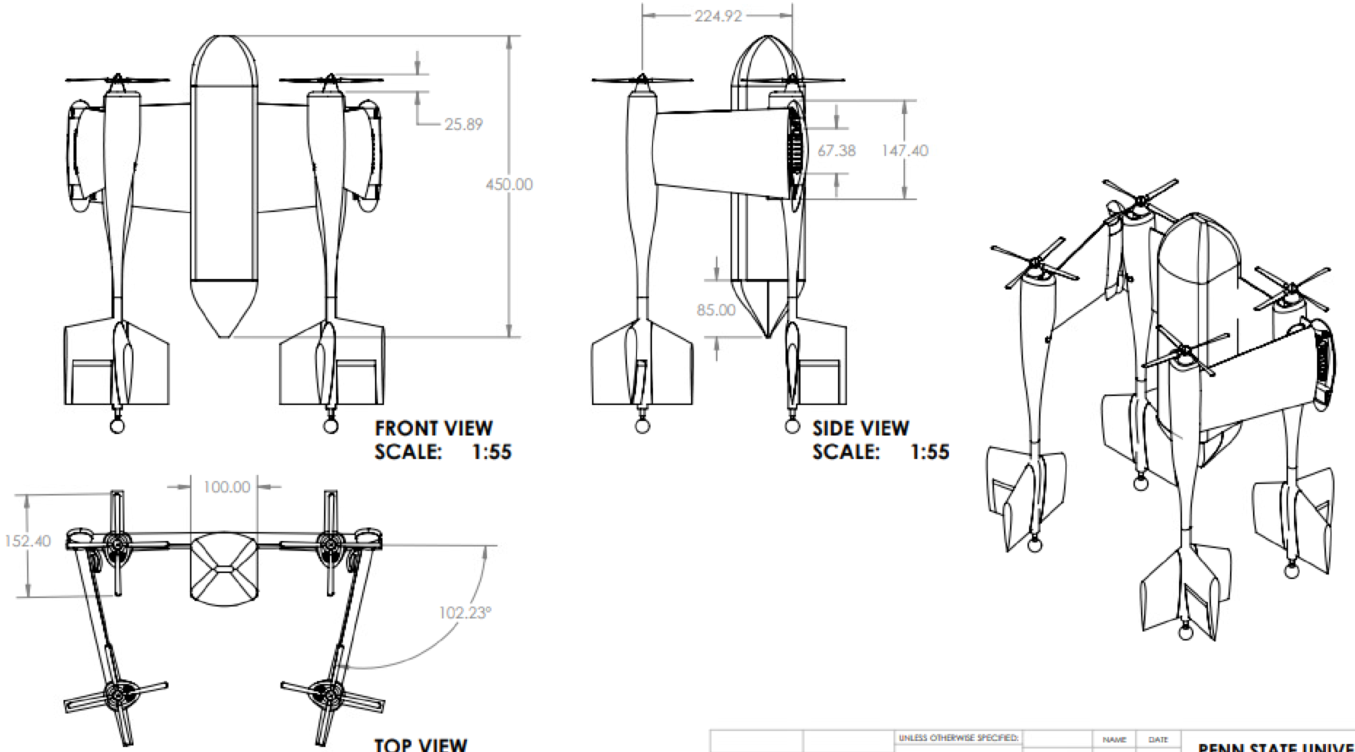
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY
USED ON
APPLICATION

PENN STATE UNIVERSITY
TITLE:
CRUISE MODE CONFIGURATION
SIZE **B** DWG. NO. Cruise Mode REV
SCALE: 1:150 WEIGHT: SHEET 1 OF 1



Total Dimensions: 4.73 x 3.78 x 5.69 [m]

UNLESS OTHERWISE SPECIFIED:
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FRACTIONAL ±
ANGULAR: MACH ± BEND ±
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Q.A.		

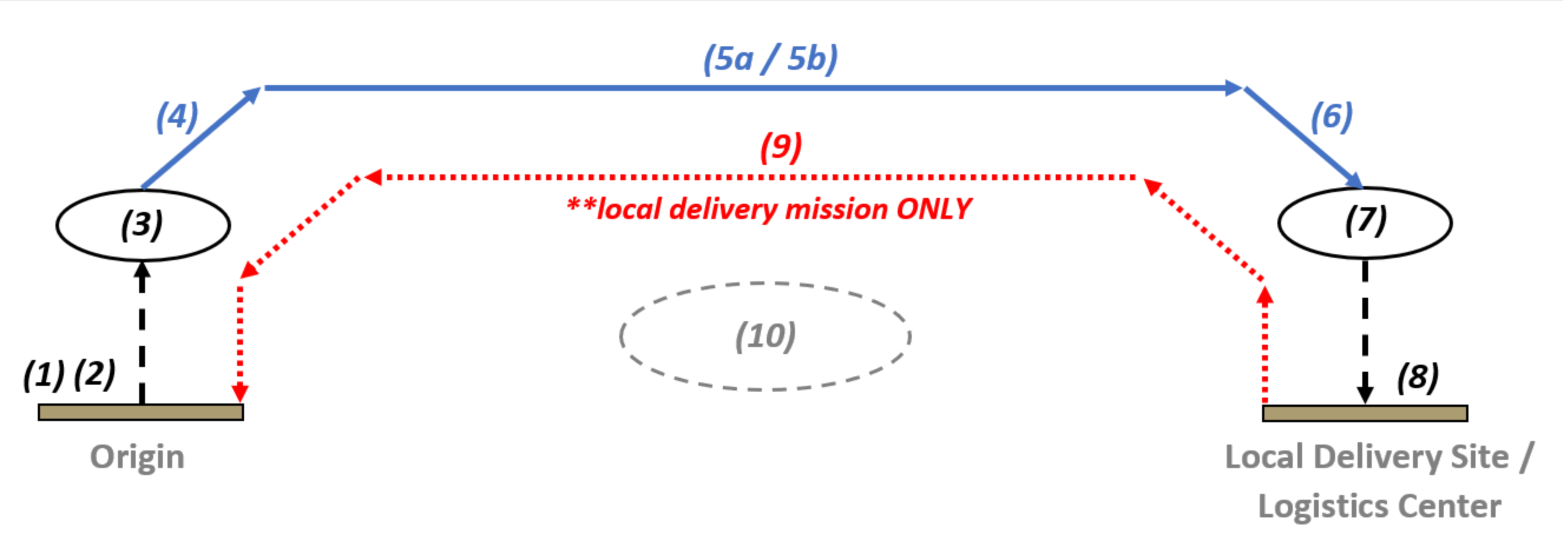
COMMENTS:

NEXT ASSY
USED ON
APPLICATION

PENN STATE UNIVERSITY
TITLE:
VTOL MODE CONFIGURATION
SIZE **B** DWG. NO. VTOL Mode REV
SCALE: 1:75 WEIGHT: SHEET 1 OF 1

Mission Profile

Local Delivery Mission / Logistics Mission:



Segment	Description	Details	Time
1	Loading	Ground crew package handling	4 m
2	Warmup	Vehicle warmup & pre-flight	4 m
3	Take-off	Vertical take-off HOGE	15 s
4	Climb	↑150 m AGL, transition to cruise	1 m 15 s
5a	Cruise	50 km @ 222 km/h (120 kts)	13 m 30 s
5b	Cruise	200 km @ 222 km/h (120 kts)	54 m
6	Descent	↓150 m AGL, transition to VTOL	1 m 25 s
7	Land	Vertical land HIGE	15 s
8	Unloading	Autonomous package delivery	2 min
9	Return	Repeat segments 3, 4, 5a, 6, 7	17 m 30 s
10	Reserve	Reserve fuel @ 80 km/h (43 kts)	20 m

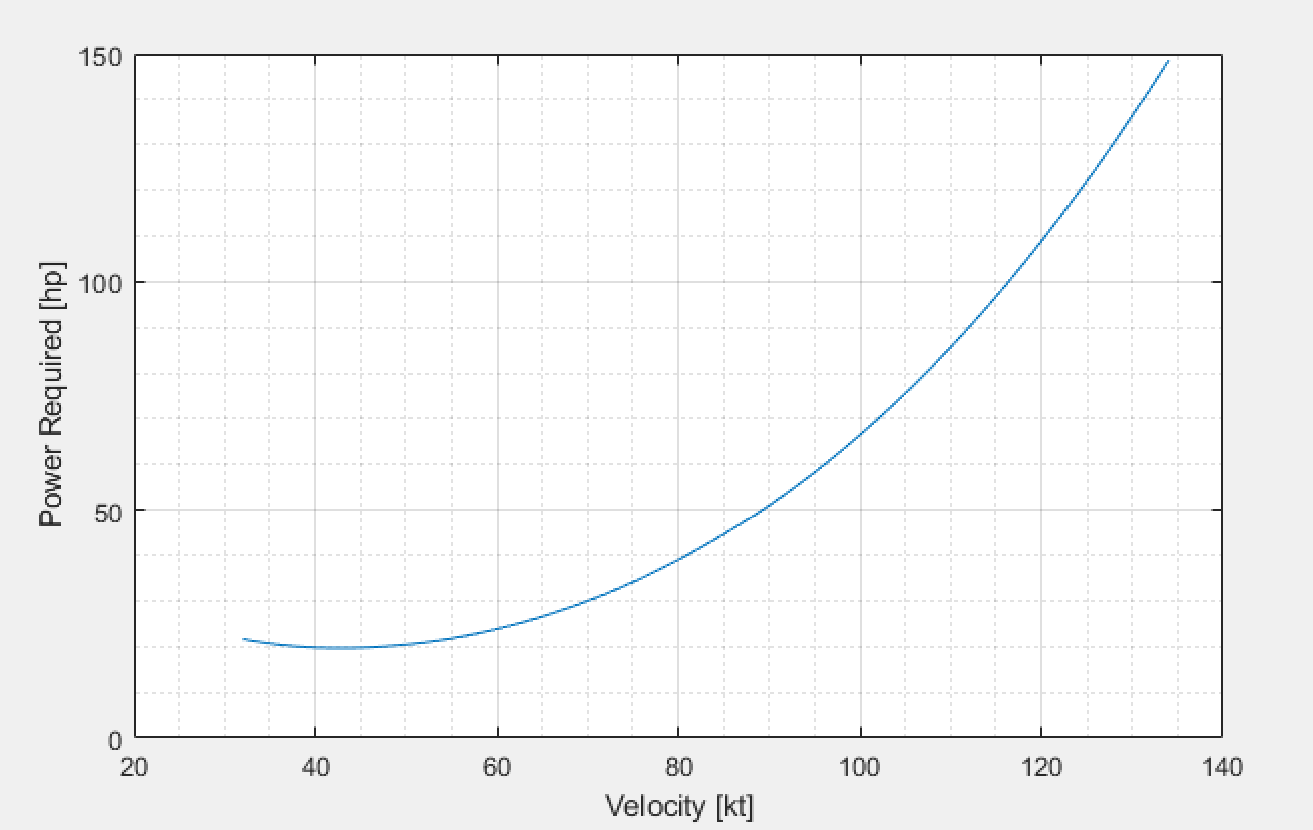
Configuration Selection

The Penn State team initially developed three prototype aircraft to meet the demands of the given RFP. These designs included a tilting wing aircraft, a folding wing aircraft and a compound helicopter. The matrix below shows the breakdown of each individual score that these prototypes were graded upon.

Criterion	Weight	Folding Wing	Tilt-Wing	Compound Helicopter
Size	5	95	88	92
Productivity	20	93	70	50
Feasibility	20	67	70	90
Maintenance	10	61	57	77
Cost	10	87	82	62
Safety	35	72	72	92
Total	100	79.0	71.3	78.5

Due to the extreme productivity of the folding wing that would come to be known as the Albatross, the Penn State engineering team settled on this design in order to satisfy the requirements outlined in the RFP provided for the 2021 challenge.

Vehicle Performance



Power Required vs Airspeed in Level Flight

- **Total Power Required for Hover**: 155 hp (116 kW)
  - Installed power of 130 hp (97 kW)
  - Extra power supplied by battery for faster climb, heavier payload, or operation at higher altitudes

- **Total Power Required for Level Flight:**

Airspeed	Velocity [kt]	Power Required [hp]
Best Endurance	43	18
Best Range	57	21
Design Cruise	120	102
Maximum	130	128

Transition Maneuver

Overview

Being a combination of both tilt rotor configuration and folding wing configuration aircraft, the transition maneuver is extremely critical to the aircraft. The transition maneuver makes sure that the aircraft will transition from vertical configuration to horizontal configuration safely. The transition maneuver is divided into three phases.

Phase One

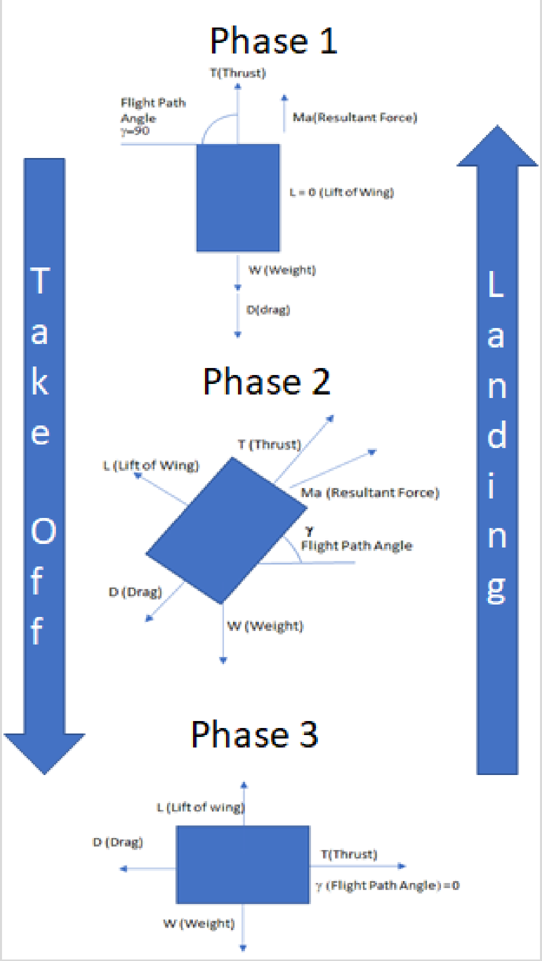
phase one transition maneuver is a pure vertical flight.

Phase Two

Phase two transition maneuver will bring the aircraft from vertical configuration to horizontal configuration that flies with inboard wing only.

Phase Three

Phase three trim the final state of phase two so that all forces and all moments are balanced.



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Propulsion System

The powerplant chosen for the Albatross is the Stuttgart Engineering STV 130. This lightweight and economical diesel-powered engine has already seen success in modified light aircraft such as the Cessna 150 and 172 and has the performance necessary to let the Albatross take flight.

	English Units	Standard Units
Power Produced	130 Horsepower	95.6 Kilowatts
Specific Fuel Consumption	0.554 lb/hp/hr	.0345 kg/kW/hr
Length	22 Inches	555 Millimeters
Width (Diameter)	11 Inches	280 Millimeters
Weight (Empty)	66 Pounds	33 Kilograms
Time Between Overhaul (TBO)	2000 hours/10 years	2000 hours/10 years
Engine Overhaul Cost	15,774 USD	13,000 Euro

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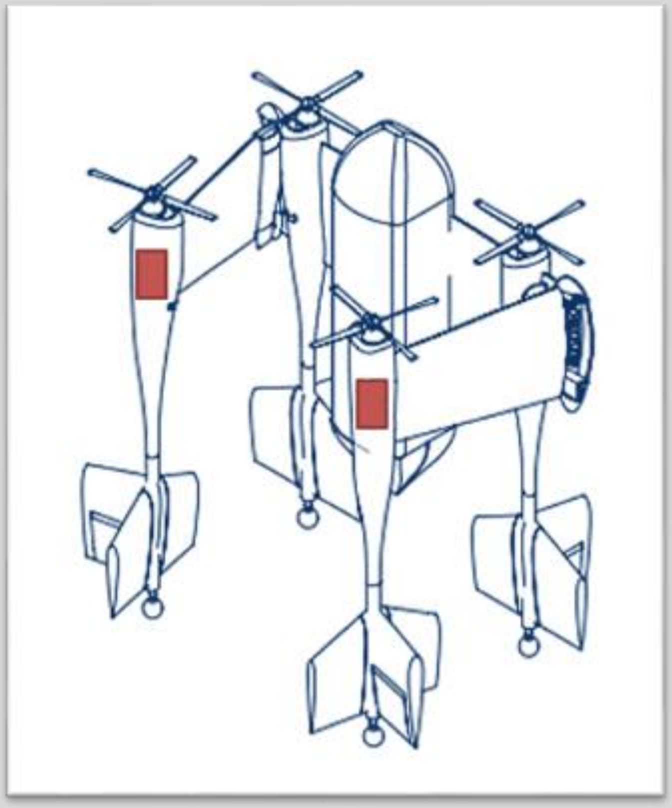
Hybrid System



Battery Locations (shown in red)

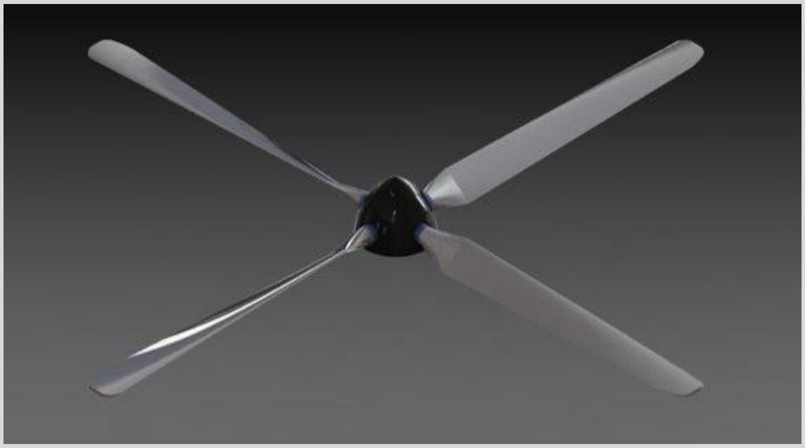
- **Battery Purpose:**
  - Provide excess power needed for takeoff, climb, and manuevering at top speed
  - Provide enough power and energy to perform a safe landing in case of engine or generator failure
  - Alter the weight distribution of the vehicle to make CG location more favorable for vertical flight.

Battery Specifications		
Discharge (Charge) Rate		10 C (2C)
Battery Chemistry		Lithium NMC or LCO w/ silicon nanowire anode
Specific Energy (Wh/kg)	Cell	230
	Module	195
Specific Energy (Wh/L)	Cell	780
Specific Power (W/kg)	Cell	2300
	Module	1950
Average Voltage (V)		3.15
Cell Capacity (Ah)		2.05
Cell Mass (g)		27.8
Cell Dimensions		4.2 x 50 x 55 mm

Rotor System

REB 50 Electric Motor

Parameter	Value
Torque	200 N-m
RPM	1500-4000 RPM
Power	53.6 HP
Weight	26.5 lb
Diameter	5 in

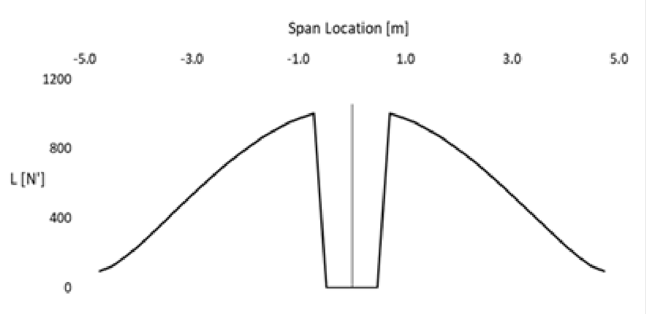


Parameter	Value
Area of the Disk	78.1 ft^2
Disk Loading	14.08 lbs/ft^2
Solidity	0.12
Figure of Merit	0.84
Coeffic. Of Thrust/solidity	0.12
Thrust per Rotor	275 lbs

Rotors designed for the Albatross are 1.52 m (5 ft) in diameter and utilize a NACA 2410 airfoil, chosen due to the high coefficient of lift at angles of attack necessary due to this design without a large need for a high lift airfoil meant for hovering.

A large angle of twist of 40° was incorporated along the blade length to optimize performance in both vertical and horizontal flight.

Wings and Tails



Lift Distribution Over Wingspan

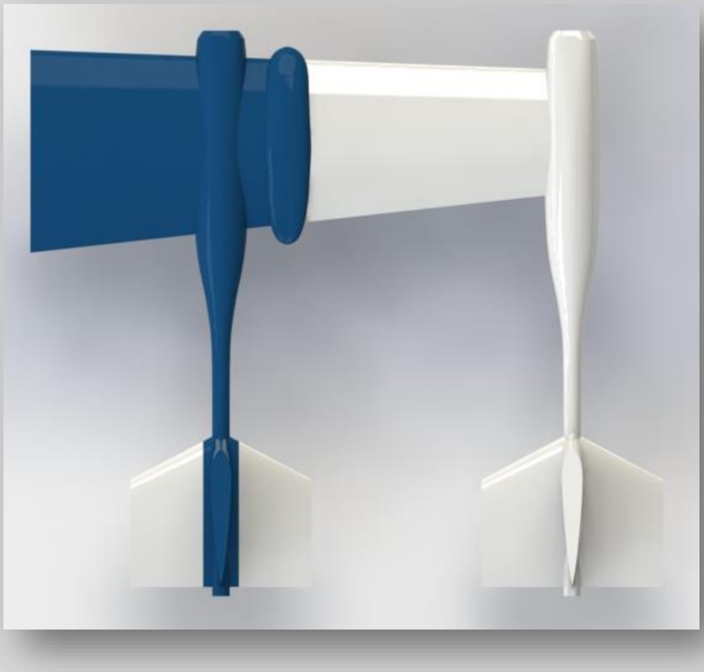
Tails

Tail surfaces are mounted on and extended with landing pylons. There are three tail surfaces mounted on each pylon, which are two horizontal tail surfaces and one vertical tail surface. Every vertical tail surface is being able to pitch and functions like rudder. Every pair of horizontal tail surface is being able to pitch collectively and functions like elevator. With all tail surfaces being able to pitch, there will not be rudders and elevators install on tail surfaces.

All surfaces are using Eppler 475 airfoil.

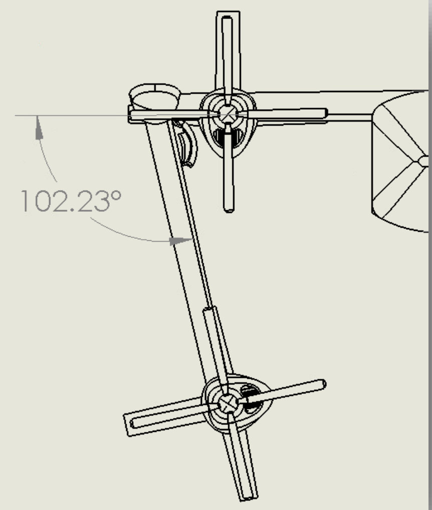
Wing

The wing of the aircraft will have a total span of 9.46 m (31.0 ft), including fuselage in between. Due to the folding capability, the wing will be divided into three parts, which are two outboard wing parts and one inboard wing part, separated by folding wing mechanism. The wing will have a total twist of 2.40° . Lift distribution of the wing is going to bell shaped, assuming no lift contribution from fuselage. The whole wing is using Eppler 668 airfoil.

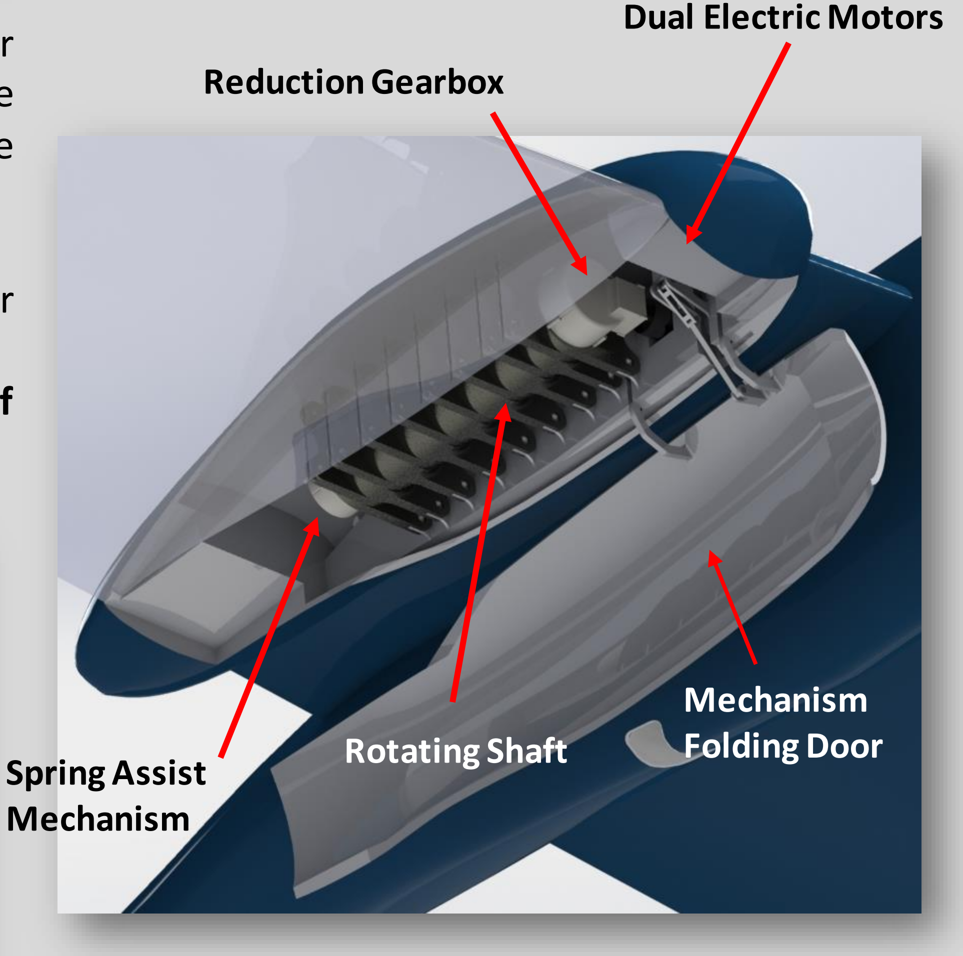


Folding Wing Mechanism

- **Transition Time** – 20 seconds
- System can operate under one of the dual motors in the event of a single motor failure to ensure smooth transition
- **Hinge Angle** – 102°
    - Will ensure all four rotors are equally aligned
- **Force Required at top of transition**
    - 2600 N or 585 lbs



The folding wing mechanism incorporated into each wing box allows the Albatross to function as both as a VTOL and a fixed wing aircraft. Taking inspiration from the McDonnell Douglas F-18 Hornet which is fitted with a folding wing design meant to fold the wing tips in for use on an aircraft carrier. Each wing is connected to a single shaft that is driven by a reduction gearbox of 3:1 at the front of the assembly, driven by dual electric motors. A coiled spring located in the rear of the assembly will ensure an added measure to assist the transition as it transitions into a fixed wing aircraft.



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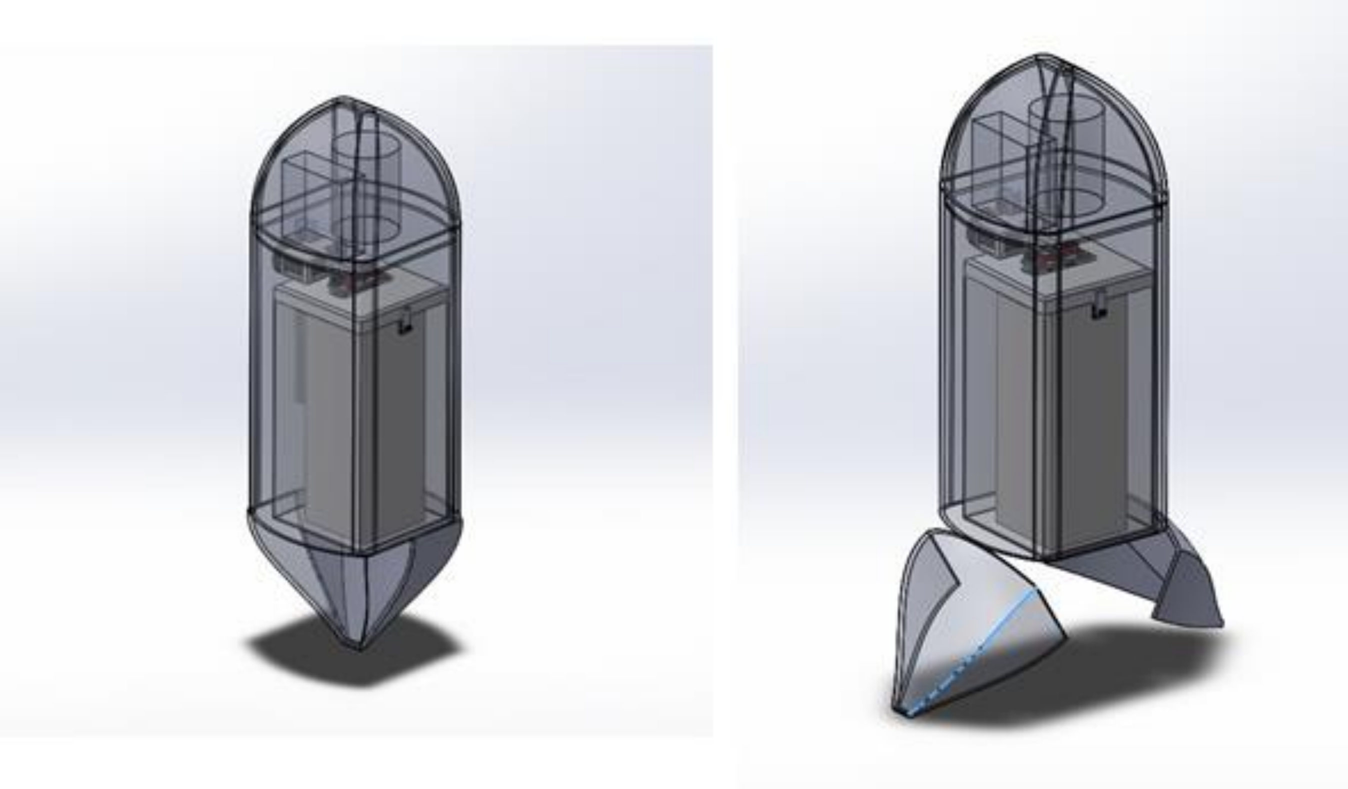
Payload System

For the unloading system, we chose to handle one package at a time in a container that can either handle the 140x50x50 cm package, or the 70x70x70 cm package. As shown in the figure below, the container is oriented lengthwise to minimize frontal surface area of the fuselage when in level horizontal flight.



When standing upright on the ground, the fuselage and package container shall be oriented longest side upwards. A clam-shell door on the bottom/back of the fuselage opens for the vertical gear rack crawler to lower the container and set it on the ground. Once the container is set on the ground and released, the vehicle lifts off in vertical configuration, while closing the rear clamshell door and raising the crawler mechanism.

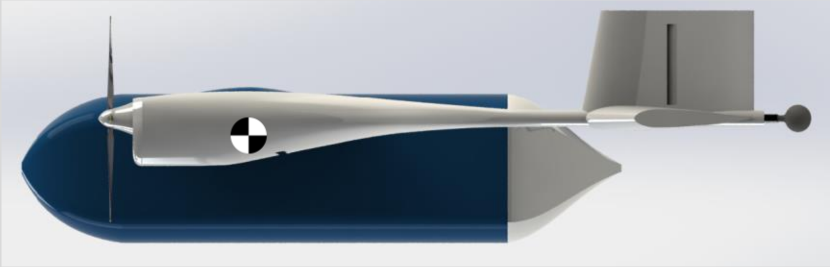
Weight & CG Analysis

Component	Weight (kg / lbs)
Aircraft Structure	79/ 174
Engine	30 / 66
Generator	10 / 22
Electric Motors (4x)	61 / 134
Fuel Tank	10 / 22
Batteries	59.5/ 131
Rotors (4x)	27 / 60
Geartrains (4x)	32 / 71
Cooling Systems (4x)	4 / 9
Payload System	18 / 40
Wing Folding Mechanism (2x)	55 / 121
Landing Gears (4x)	23 / 51
Avionics	4 / 9
Payload	50 / 110
Fuel	36 / 79

Total	Weight
Operating Empty Weight (OEW)	**412.5 kg (909 lbs)**
Zero-Fuel Weight (ZFW)	**462.5 kg (1020 lbs)**
Aircraft Gross Weight (AGW)	**498.5 kg (1099 lbs)**

CG Location (VTOL)		
X_{CG}	Y_{CG}	Z_{CG}
1.87 m	0.00 m	0.11 m

CG Location (Cruise)		
X_{CG}	Y_{CG}	Z_{CG}
1.87 m	0.00 m	0.83 m



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Trim Analysis

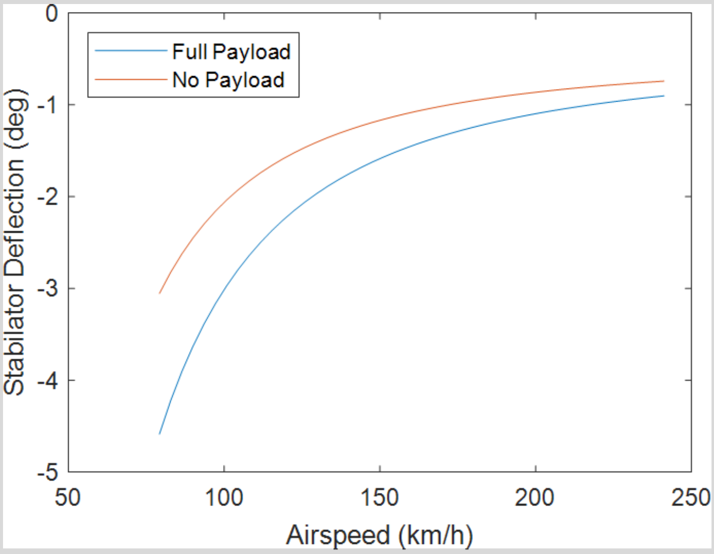
Overview:

Static Margin (h_n-h): 0.10 to 0.15

Yaw Stiffness ($C_{n\beta}$): 0.3936

Longitudinal Static Stability:

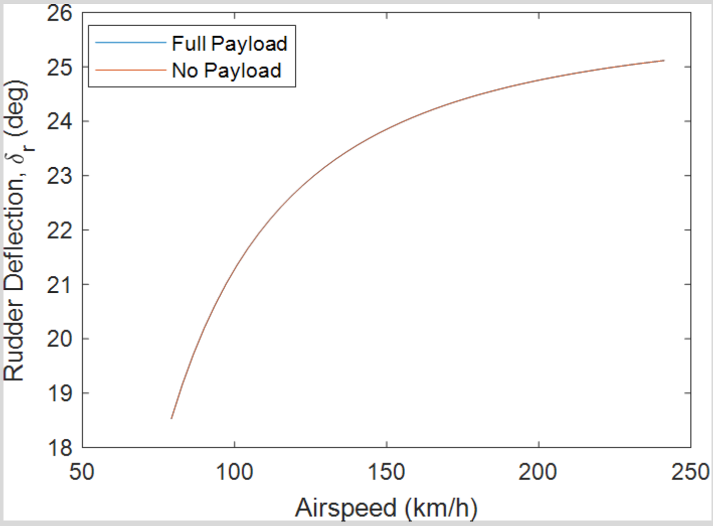
The configuration features four tails, all of which deflect as stabilators for longitudinal static stability. The large tail surface and stabilator effectiveness contributes to a positive static margin and minimal stabilator deflection in horizontal flight. The tail surfaces experience a positive angle of attack for all airspeeds and always contribute to lift.



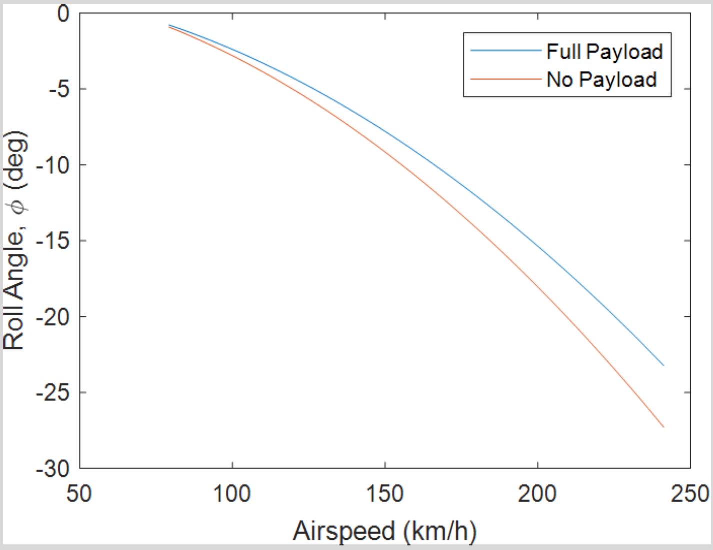
Stabilator Deflection in cruise

Lateral Static Stability

The aircraft has positive yaw stiffness, a key stability parameter for lateral stability. Without variable thrust from the rotors, the aircraft can withstand an 8.3-degree sideslip angle for all airspeeds. The aircraft can withstand higher sideslip angles at lower airspeeds. Additionally, the aircraft has excess power in cruise and can use variable thrust to achieve lateral stability trim.



Rudder deflection in 8.3-degree sideslip



Roll angle in 8.3-degree sideslip

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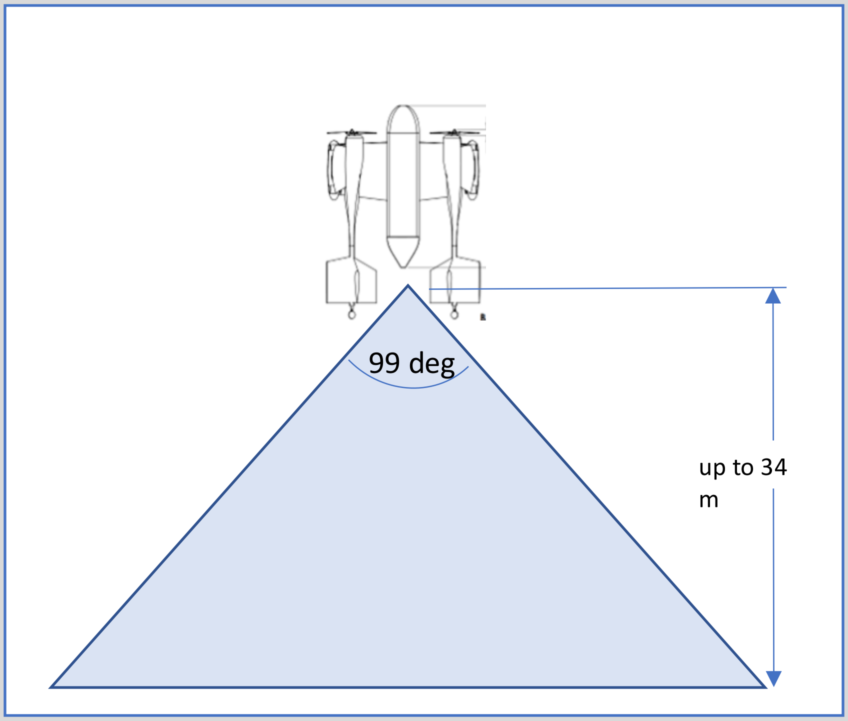
Obstacle Avoidance



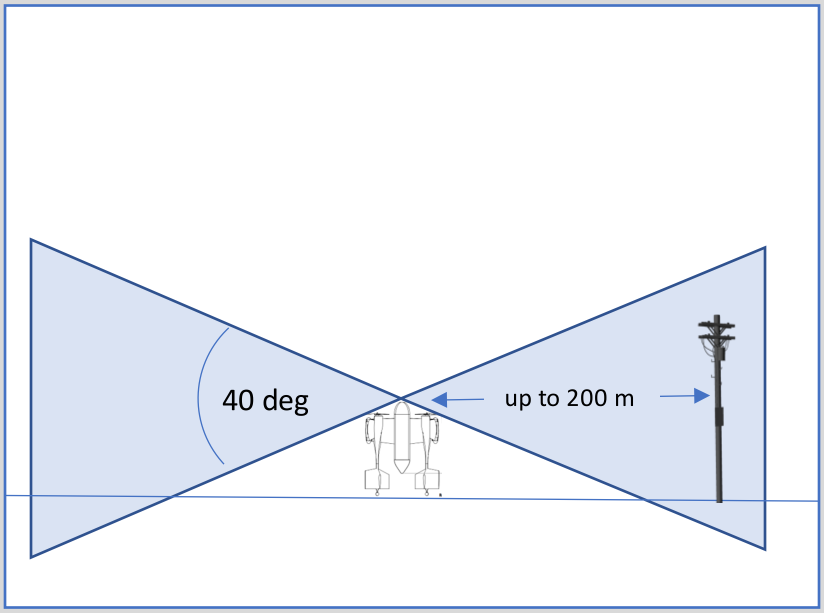
Field of view cross section of downward facing LiDAR

Landing:

- Pair of Leddar Vu8 LiDAR sensors provides a 3D representation of the landing site prior to landing.
- Radar altimeter provides redundancy
  and ensures LiDAR range finding is accurate
- Albatross will detect obstacles and terrain underneath to ensure landing is safe for the vehicle and personnel.

Situational Awareness:

- Velodyne "Ultra Puck" LiDAR allows the aircraft to detect power poles and lines, buildings, personnel and other obstacles in a 360° view around the aircraft.
- Additional radar distance sensors are placed in key locations for overlapping coverage and a complete field of view
- Onboard transponder can communicate with other aircraft and ground control



Field of view cross section of lateral LiDAR

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Safety Analysis

Vehicle safety assessed through **Functional Hazard Assessment**

Identify Vehicle Functions

Assess Failure Modes

Determine Failure Severity

Prevent Failure Mode

FHA discovered potential catastrophic failures that led to design changes

Engine Failure

- Leads to: Vehicle crash and hull loss
- Prevention: Back-up battery power packs with enough power to return-to-base or complete mission

Electric Motor Failure

- Leads to: Vehicle instability and loss of control
- Prevention: Variation of rotor RPM and gimbaled motors to balance vehicle moments

Folding Wing Mechanism Failure

- Leads to: Emergency horizontal landing and extensive vehicle damage
- Prevention: Double-redundancy in actuators and casing to prevent debris

Control Surface Failure

- Leads to: Loss of vehicle control
- Prevention: Redundancy through four horizontal stabilizers and four vertical stabilizers

Summary

The **UQ-9 Albatross** is Penn State's unique approach to the 2025 Unmanned Vertical Lift for Medical Equipment Distribution Design Competition. As a tail-sitting, VTOL design, the Albatross can complete long distance missions as a fixed wing aircraft while also taking off and landing vertically with folded wings.

RFP Requirements Fulfilled

- Size (folded on ground): 3.28 x 4.72 m (10.8 x 15.5 ft)
- Block Time
    - Local Delivery: 26.5 min (28 min maximum)
    - Logistics Mission: 67 min (75 min maximum)
- Safety: Vehicle can suffer the failure of any single component while still maintaining safe flight and landing at launch site or destination

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