Vertical Flight Society

LEONARDO HELICOPTERS

SOLIDITYone

Executive Summary

Delft University of Technology Undergraduate Team
37th Vertical Flight Society
Annual Student Design Competition
Sponsored by Leonardo

TUDelft

Team members

Team SolidityONE:

SeoungHoun Han (Captain)

Kenny van Gaalen

Mark van den Ham

Thijs van Herwerden

Nick Pauly

Original Project Members:

SeoungHoun Han

Kenny van Gaalen

Mark van den Ham

Thijs van Herwerden

Nick Pauly

Ensar Asir

Hugo Kerckhoffs

Rembert Kortenhorst

Teun Vleming

Rowan de Voogt

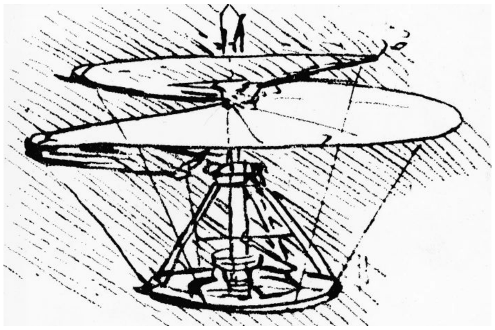
Supervised by:

Dr. Marilena Pavel
Assoc. Prof. Rotorcraft Flight Dynamics

Introduction

SolidityONE is the Delft University of Technology's undergraduate student answer to the 37th Vertical Flight Society Annual Student Design Competition request for proposal of a vehicle based on Leonardo da Vinci's aerial screw concept as proposed by the great inventor more than 500 years ago.

This competition challenged students to design a vehicle that could fly a 60 kg pilot at a minimum altitude of 1m, distance of 20 m and duration of 60 s, using only one or more aerial screws.

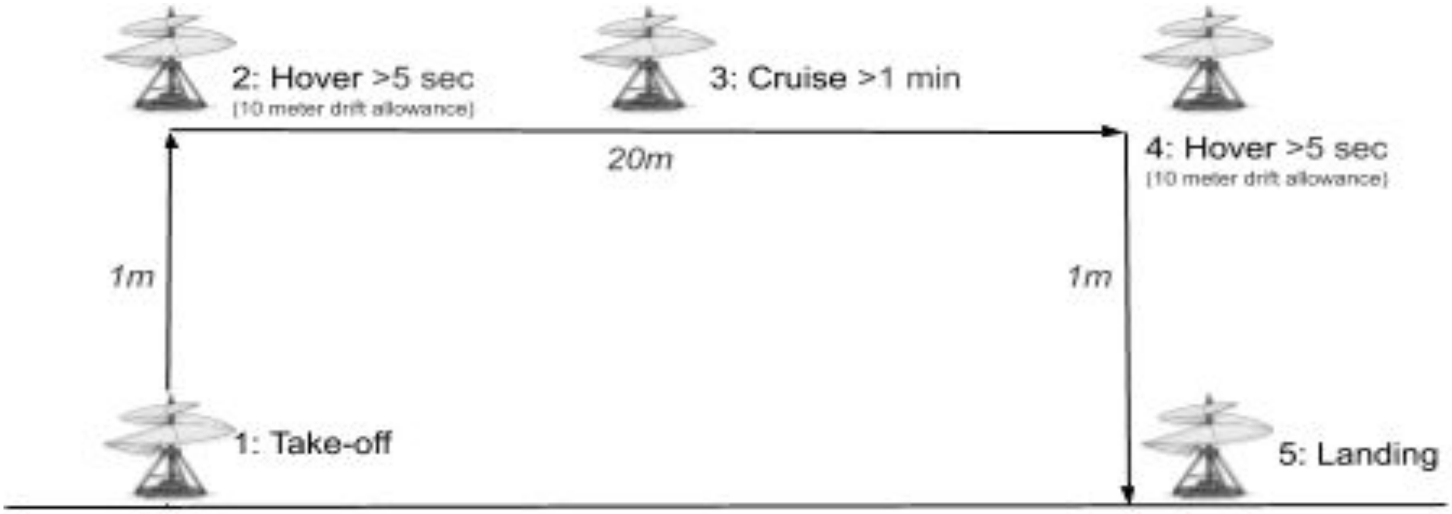


da Vinci's Aerial Screw

SolidityONE's rotor

SolidityONE is a tandem electric air vehicle with ducted aerial screw rotors, capable of carrying a single pilot, meeting and exceeding all competition mission profile specifications. It was designed with a focus on sustainability, with sustainable and lightweight materials and zero-emission propulsion. A low tip speed and electric propulsion contribute to low noise generation, making SolidityONE suitable for urban use.

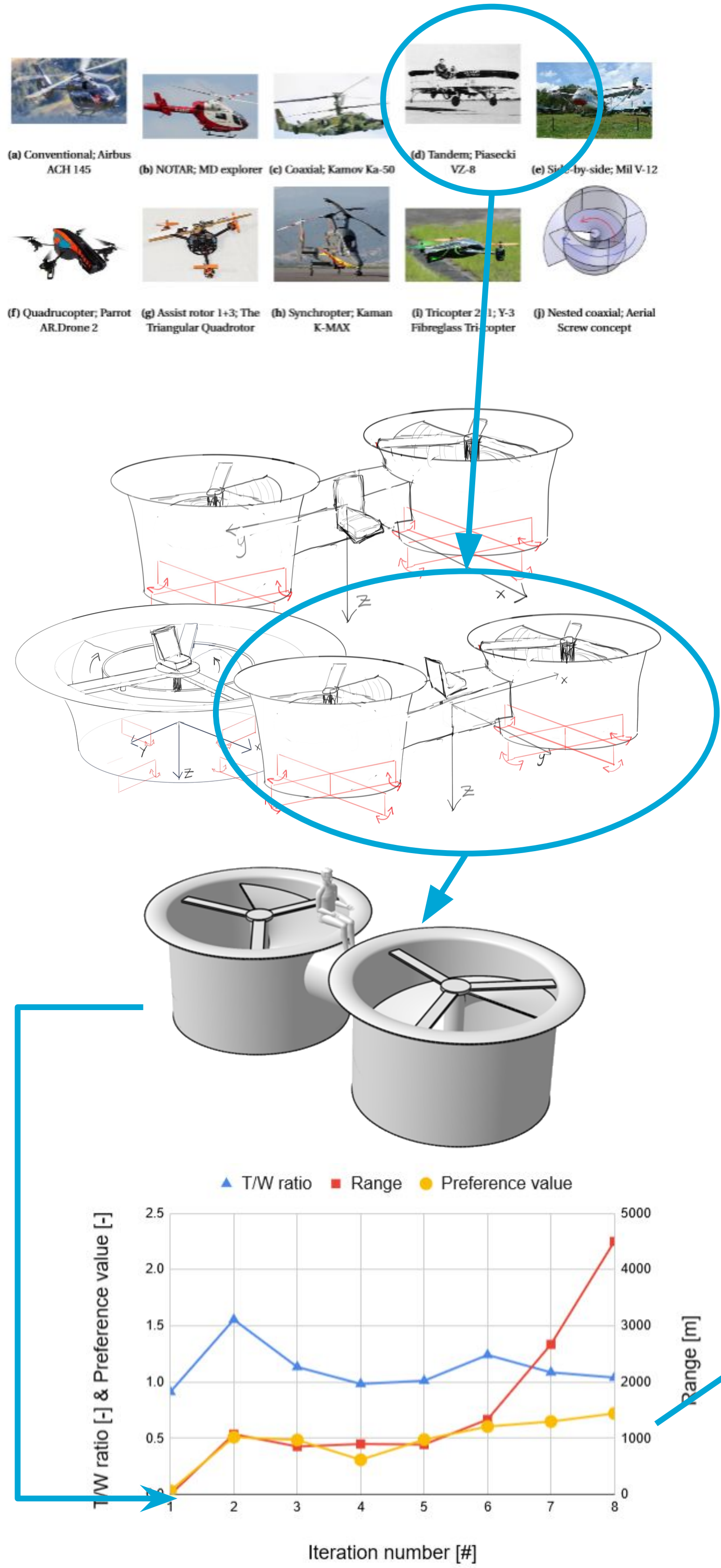
Mission Compliance



Visualization of the RFP mission

CODE	REQUIREMENT	VALUE	SolidityONE
RFP-1	The vehicle shall rely for lift and thrust on one or more "aerial screws"	True	True
RFP-2	The aerial screw shall have one continuous blade per rotor	1	1
RFP-3	The aerial screw shall have a blade solidity of at least 1	1	1.016
RFP-4	The rotor shall be capable of carrying a 60 kg pilot	60 kg (132.3 lbs)	68.4 kg (150.8 lbs)
RFP-5	The vehicle shall be capable of vertical take off and landing	True	True
RFP-6	The vehicle shall drift no more than 10m during hover	<10 m (32.8 ft)	True
RFP-7	The vehicle shall hover at an altitude of at least 1m	1 m (3.28 ft)	860 m (2,822 ft)
RFP-8	The vehicle shall cover a least 20m of distance	20 m (65.6 ft)	4500 m (14,800 ft)
RFP-9	The vehicle shall fly for at least 60 seconds	60 s	296 s

Concept Analysis

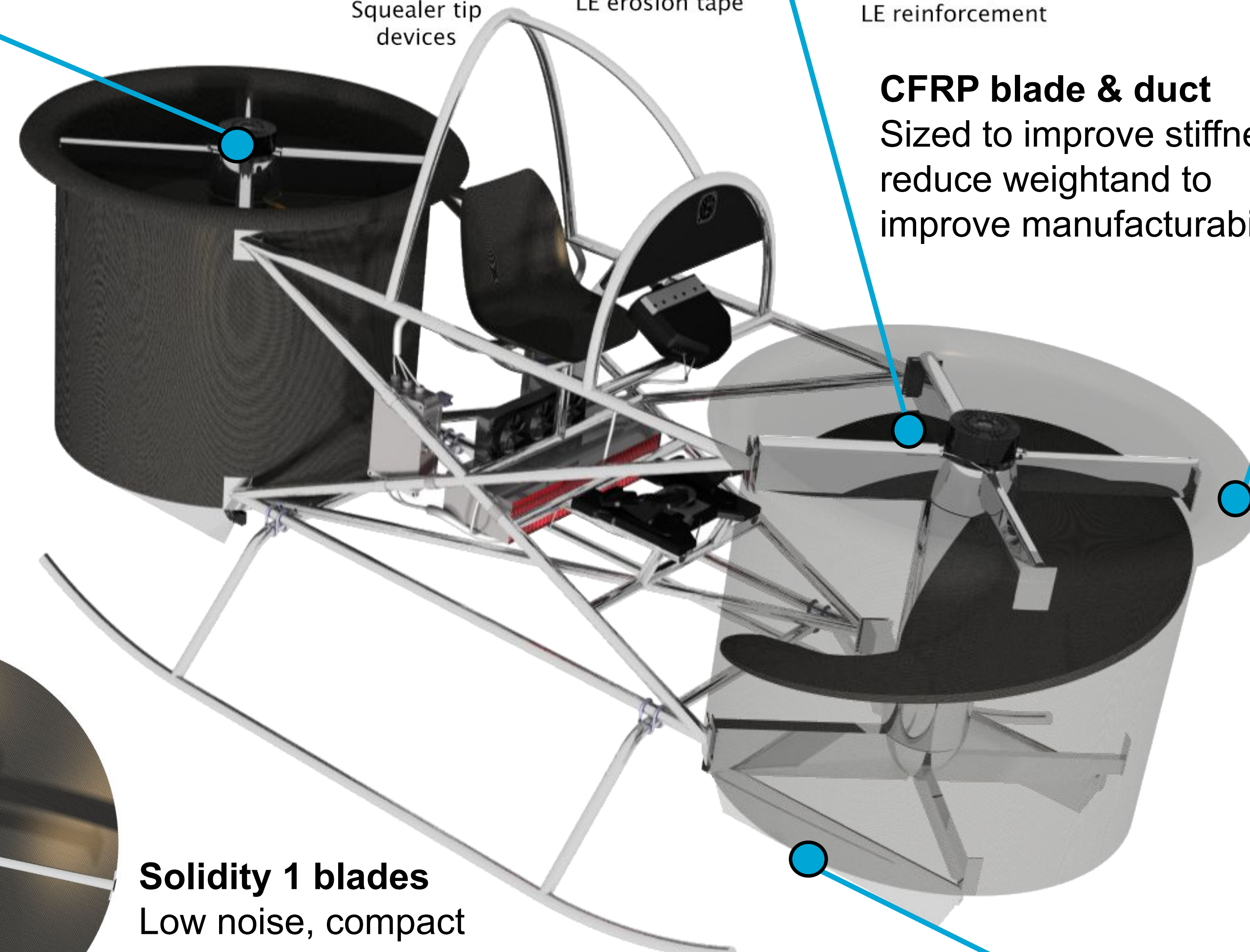


Eighteen concepts were initially considered and reduced to three promising options: tandem, side by side and nested coaxial configurations.

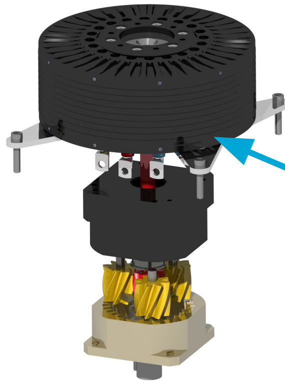
These were sized with structural, aerodynamic and performance calculations to predict their viability. Then through a multi objective design process a down selection was made for the tandem design with lateral vanes.

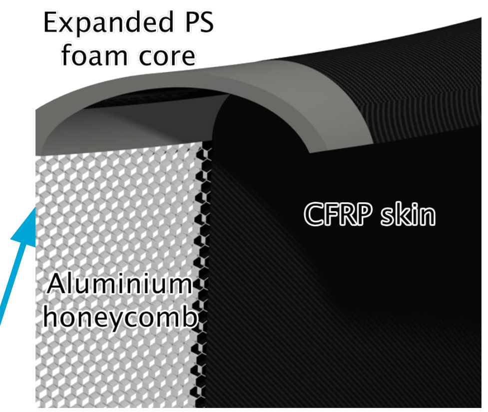
This concept was reiterated for further sizing and design, increasing in performance and range to evolve into SolidityONE.

Key Features



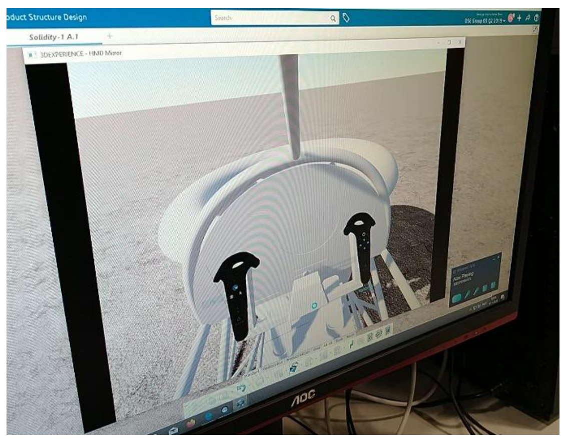
Electric propulsion
Sustainable, compact and lightweight motors mounted directly to the rotor shaft

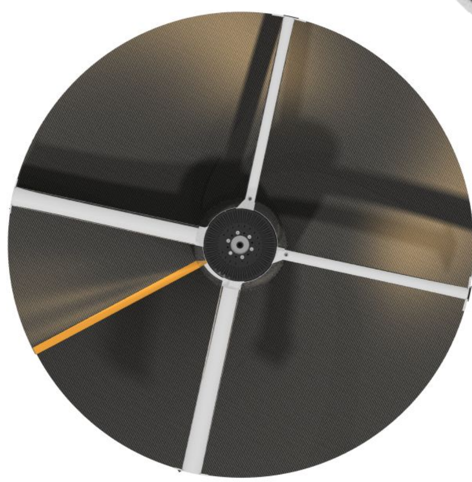


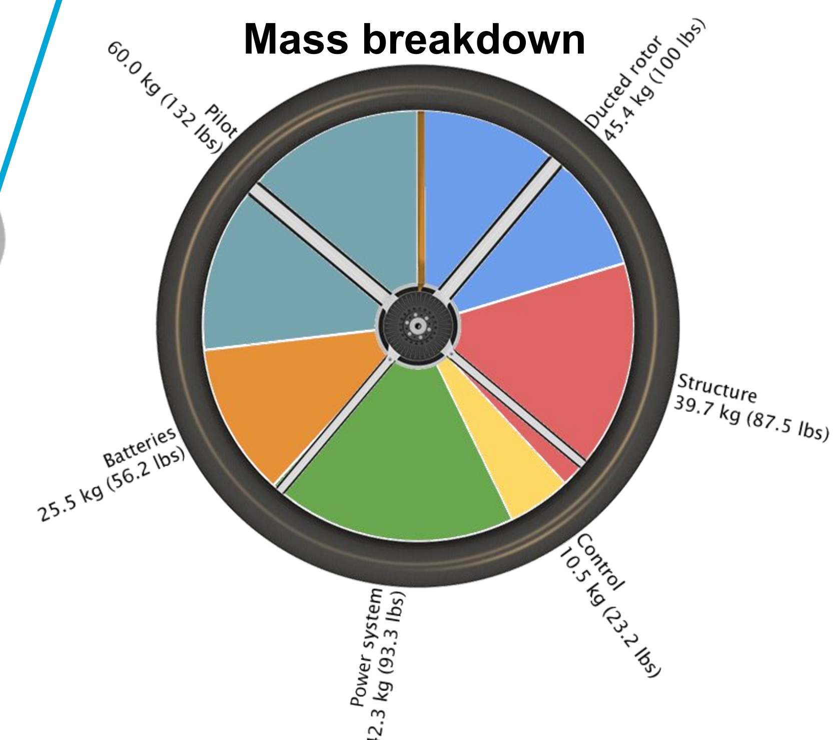


CFRP blade & duct
Sized to improve stiffness, reduce weightand to improve manufacturability

Ergonomics
High seating position for large field of view

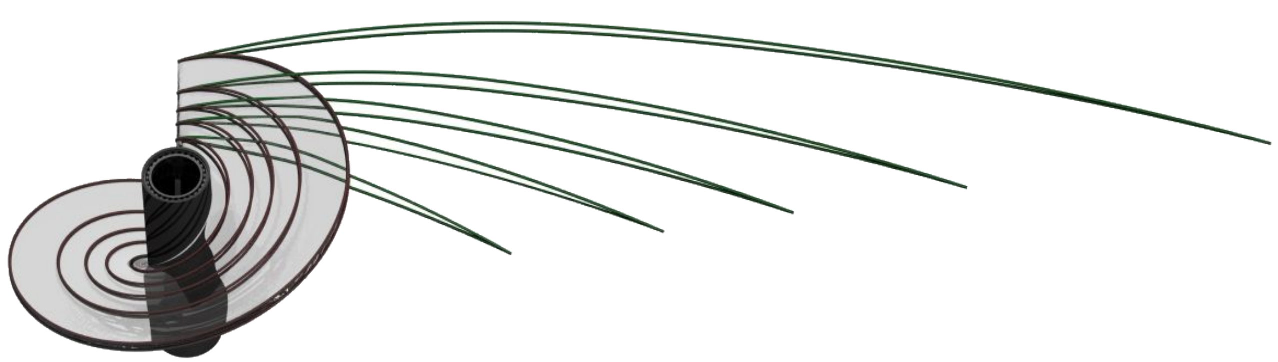




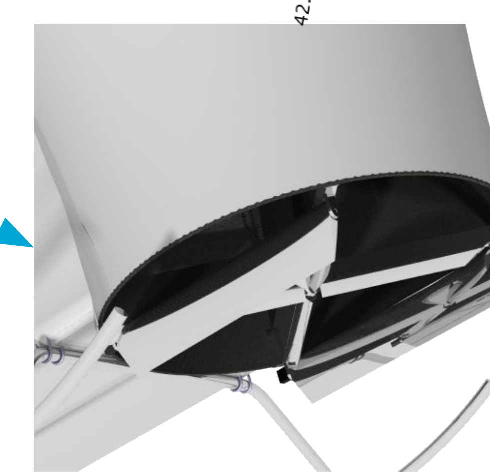


Unique rotor properties

Rotor diameter	1.2 m (4 ft)
Figure of merit	0.68
Blade solidity	1.016
Taper ratio	3.8
Aspect ratio	0.3
Airfoil root	NACA8508
Airfoil tip	NACA8501



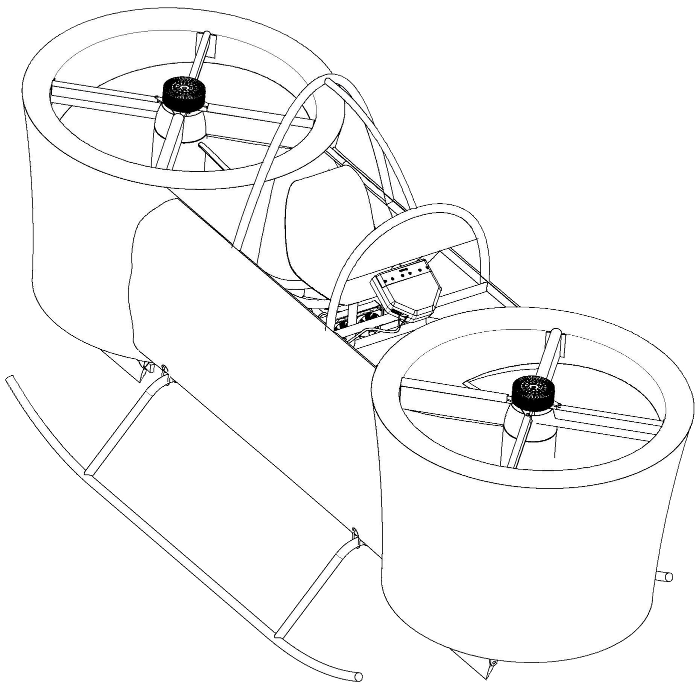
Solidity 1 blades
Low noise, compact aerial screws based on da Vinci's design



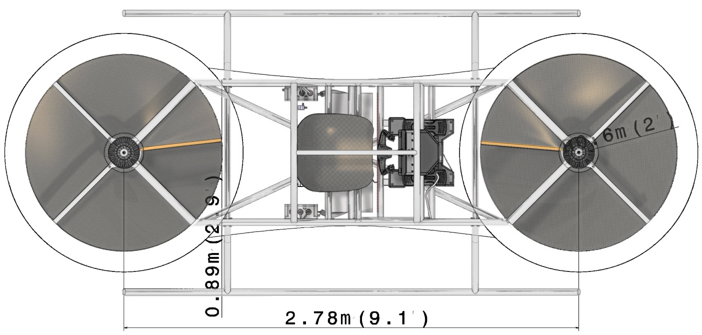
Custom controls
Efficient, low complexity control by differential RPM and adjusting control vanes

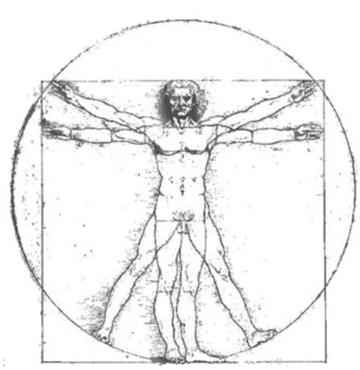
SOLIDITYone

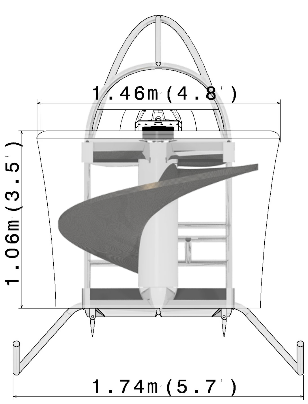
Specifications

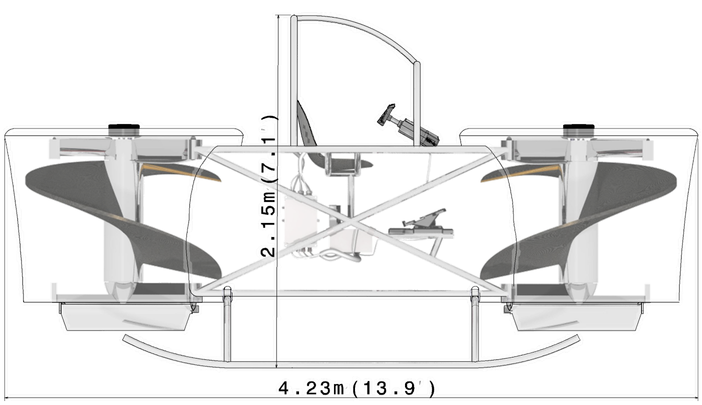


Parameter	Metric	Imperial
Length:	4.23 m	(13.9 ft)
Width:	1.74 m	(5.7 ft)
Height:	2.21 m	(7.3 ft)
Takeoff weight:	223.4 kg	(492.5 lbs)
Max pilot weight:	68.4 kg	(150.8 lb)
Rotor radius:	0.6 m	(2 ft)
Rotor RPM:	1516	1516
Figure of merit:	0.68	0.68
Blade solidity:	1.016	1.016
Tip speed:	95.3 m/s	(312.7 ft/s)
Power:	2x23 kW	(2x30.8 hp)
Top speed:	51.48 km/h	(32 mph)
Range:	4500 m	(14763.8 ft)
Hover ceiling:	860 m	(2821.5 ft)
Rate of climb:	1.9 m/s	(6.2 ft/s)
Disc loading:	98.8 kg/m²	(10.1 lb/sqft)
Power loading:	0.21 kW/kg	(0.13 hp/lb)
Endurance:	4.97 min	4.97 min

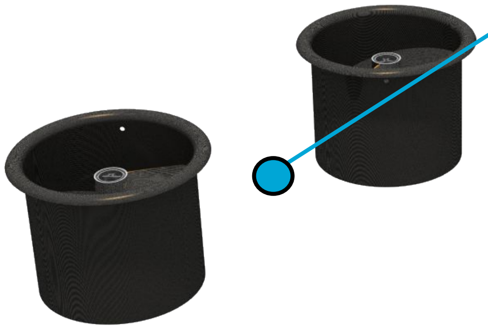


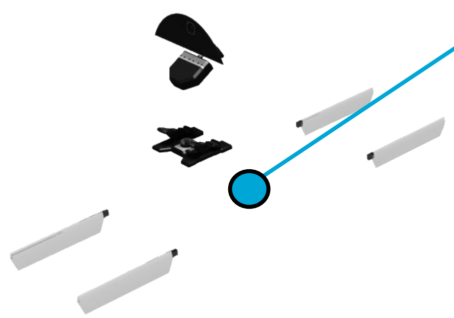


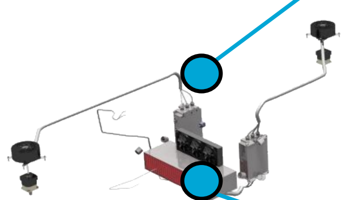




Mass Breakdown



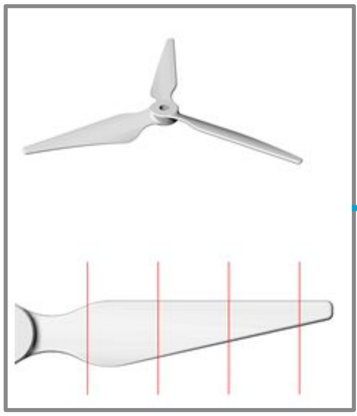




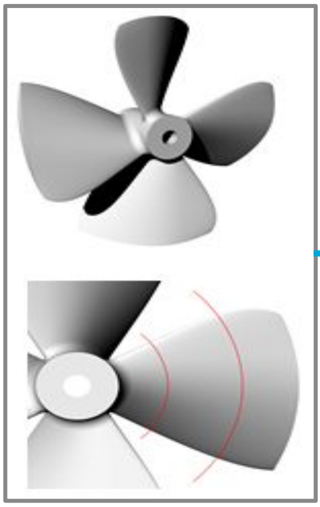
Part	Material	Weight total
Ducted rotor		45.4kg (100.1lbs)
Rotor hub	Low alloy steel, AISI 4340	5.3kg (11.7lbs)
Rotor blade skin	Epoxy/HS carbon fiber weave	2.2kg (4.9lbs)
Rotor blade core	Expanded PS foam	4.8kg (10.6lbs)
Duct skin	Epoxy/HS carbon fiber weave	11kg (24.3lbs)
Duct core	Aluminum 5056 honeycomb	6kg (13.2lbs)
Rotor LE tape	3M Polyurethane Protective Tape	0kg (0.0lbs)
Rotor LE reinforcement	PPS/E-glass fiber 3 mm	0.1kg (0.3lbs)
Bearing	Steel	16kg (35.3lbs)
Structure		39.7kg (87.6lbs)
Duct struts	Aluminum, 7068, T6511	4.5kg (9.9lbs)
Duct struts sec.	Aluminum, 7068, T6511	1.6kg (3.5lbs)
Duct strut fairing	Expanded PS foam	0.6kg (1.4lbs)
Duct strut fairing sec	Expanded PS foam	0.1kg (0.2lbs)
Duct struts attachment	Aluminum, 7068, T6511	0.9kg (2.0lbs)
Airframe	Aluminum, 7068, T6511	13.4kg (29.5lbs)
Roll cage	Aluminum, 7068, T6511	5kg (11.0lbs)
Aerodynamic fairing	Phenolic/E-glass fiber weave	5kg (11.0lbs)
Landing gear	Aluminum, 7068, T6511	6.6kg (14.6lbs)
Seat	plastic	2kg (4.4lbs)
Control & Avionics		10.5kg (23.1lbs)
Control vanes	Aluminum, 7068, T6511 Expanded PS foam	3.2kg (7.0lbs)
Sticks	HC 615-200	2kg (4.4lbs)
Pedals	HC 300-111	4kg (8.8lbs)
Control computer	Pixhawk 4	0.3kg (0.6lbs)
Dashboard		1kg (2.2lbs)
Power		42.3 kg (93.3 lbs)
Engine	Emrax 188	14.0 kg (30.9 lbs)
Gearbox	ANAHEIM GBPS-0901-NM-003	7.0 kg (15.4 lbs)
Cooling	Approximation	6.2 kg (13.7 lbs)
Engine bracket	Aluminium 7068 T6511	0.3kg (0.6 lbs)
Gearbox bracket	Aluminium 7068 T6512	0.3kg (0.6 lbs)
Controller	emDrive 500	9.8kg (21.6 lbs)
Fire casing	Aluminium, 7068, T6511, aramid paper	3.4 kg (7.5 lbs)
Cabling	Aluminium conductor	2.5 kg (5.5 lbs)
Battery	GensAce 5000mAh 18.5V 60C 5S1P LiPo	25.5 kg (56.2 lbs)
Pilot		60kg (132.3lbs)
Total		224.6kg (495.2lbs)

Aerial screw

SolidityONE is propelled by two da Vinci Aerial Screw inspired rotors. They were designed with a modified Blade Element Theory model incorporating elements from marine propellor design to accommodate the aerial screw's high blade solidity. BET was applied by dividing the blade in curved sectional blade elements as is done in propeller design, then unwrapping them and treating them as flat elements.



a) BET Helicopter



b) BET Marine propeller

Unique rotor properties

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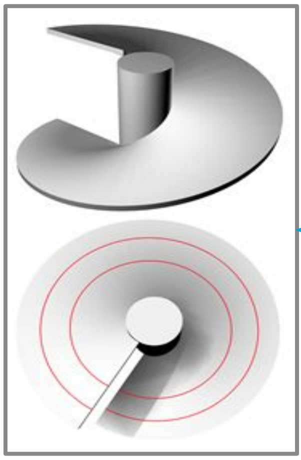
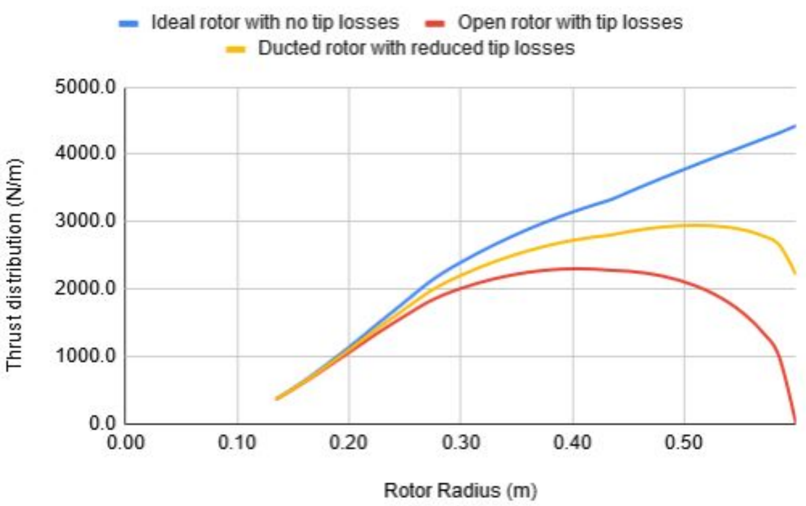


c) BET Aerial screw

Visualization of unwrapped sectional blade elements

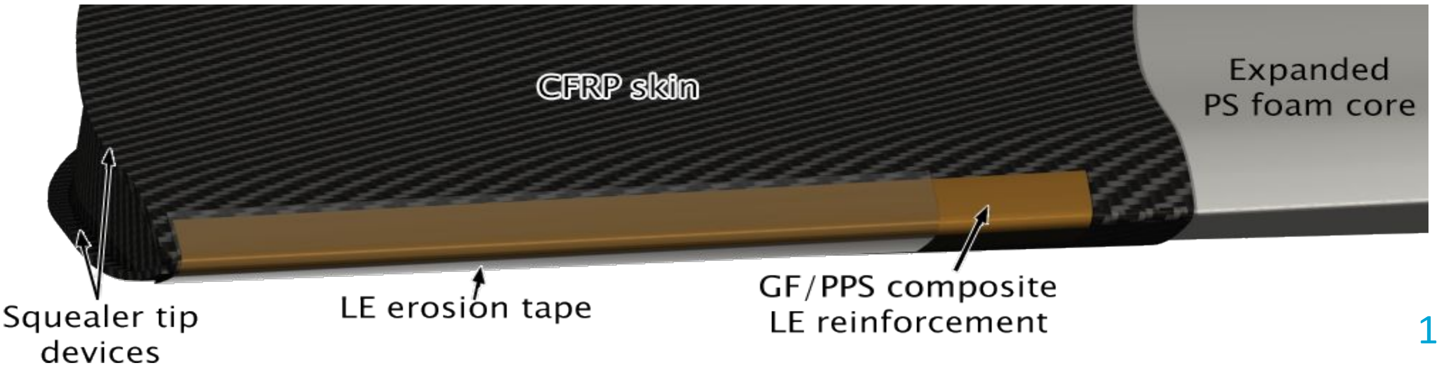
Aerial screw

The aerial screw has high lift generation in a compact format due to its high blade surface area. However the inverse taper ratio results in more surface area towards the tip, aggravating tip-losses. This was solved by ducting the screw and adding squealer tips, which in combination with a low tip-speed results in an overall low noise level of 64.8 dB.



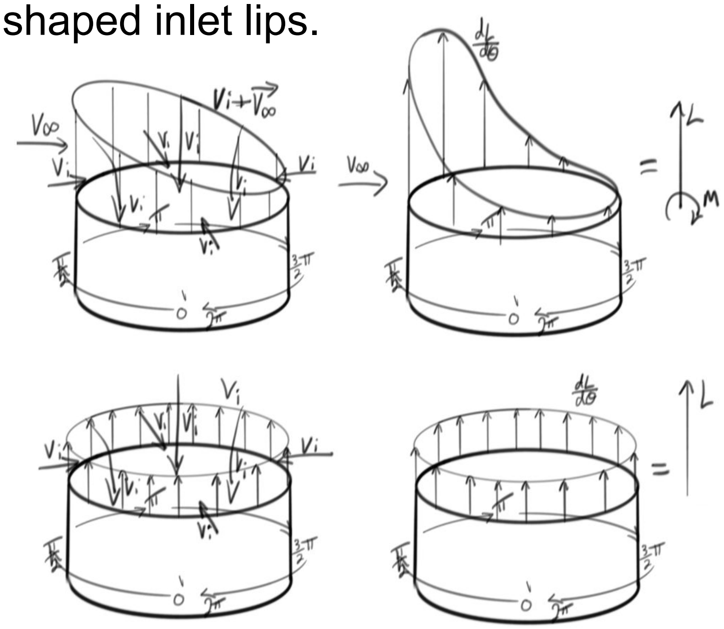
The rotor blade has a solidity of one, its uninterrupted surface and solidity results in a blade with no gaps visible when seen from above.

The blade is made of a high stiffness and lightweight sandwich structure composing of a foam core and carbon fiber reinforced skin. The blade features a glass fiber thermoplastic composite leading edge reinforcement for impact protection and leading edge erosion tape for abrasion resistance. Squealer tips augment the duct wall in further reducing leakage losses at the blade tip.



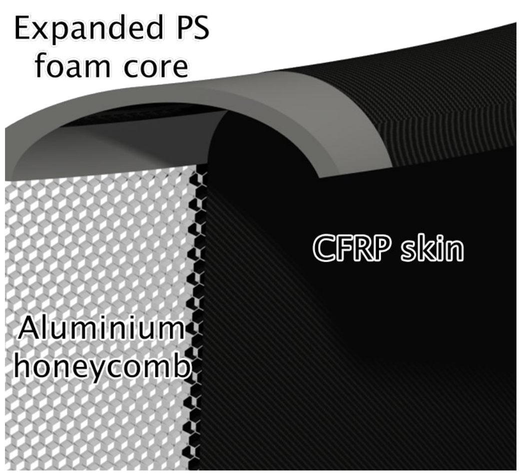
Duct

A duct was designed to reduce tip-losses of the aerial screw and protect the pilot. The duct inlet lips enhance lift generation as the upper surface experiences a pressure drop due to air accelerating around the wing shaped inlet lips.



The lift distribution on the duct lip has a stabilizing effect on the whole vehicle due to horizontal airflow skewing the lift resulting in a restorative moment.

Lightweight materials were chosen for the duct. The inlet lips are made of foam core and carbon fiber composite skin sandwich structure. Foam was chosen for manufacturability of the double curved surface.



The duct walls are made of an aluminium honeycomb core and carbon fiber composite skin sandwich structure. This had to be stiff enough to prevent contact between the duct and rotor tip, which are only 1.2 mm apart.

Airframe

In order to properly design an airframe and pick the right structure and materials for it, first an overview needs to be made of the requirements and constraints. The airframe has the function to protect the pilot and other critical system components. This also make the ergonomics for the pilot and the packaging is of importance. Since the vehicle also needs to fly and be manufacturable, a few requirements were set on the structural and material selection.

Pilot safety

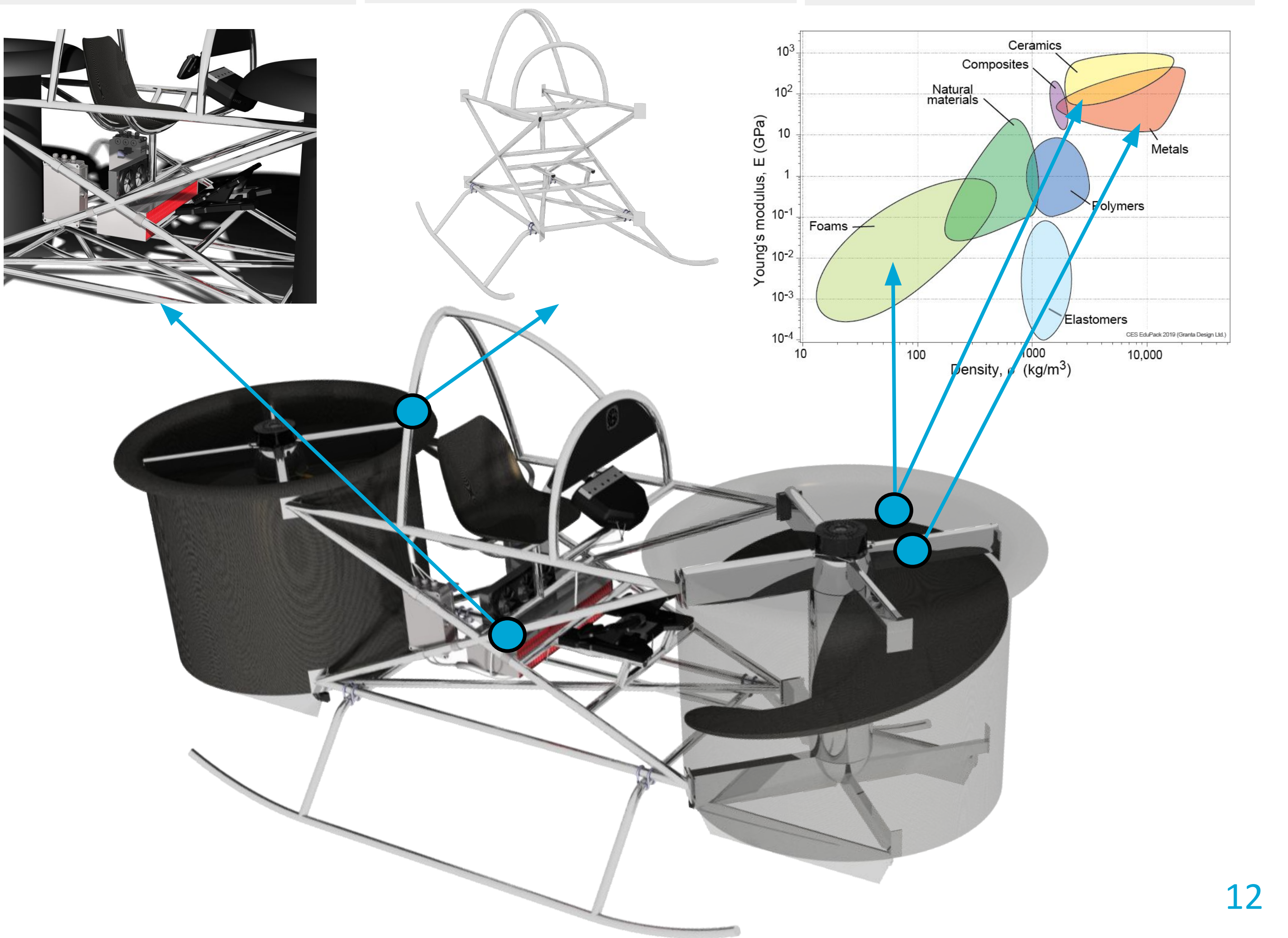
- Roll hoop
- Ducted screw
- Firewall

Shape

- Ergonomics
- Manufacturability
- Packaging

Structures & Materials

- Specific stiffness
- Specific strength
- Manufacturability



Airframe

For the airframe and the secondary components a structures and material selection has been made based on the different, most critical loadcases, size and component complexity.

Duct struts

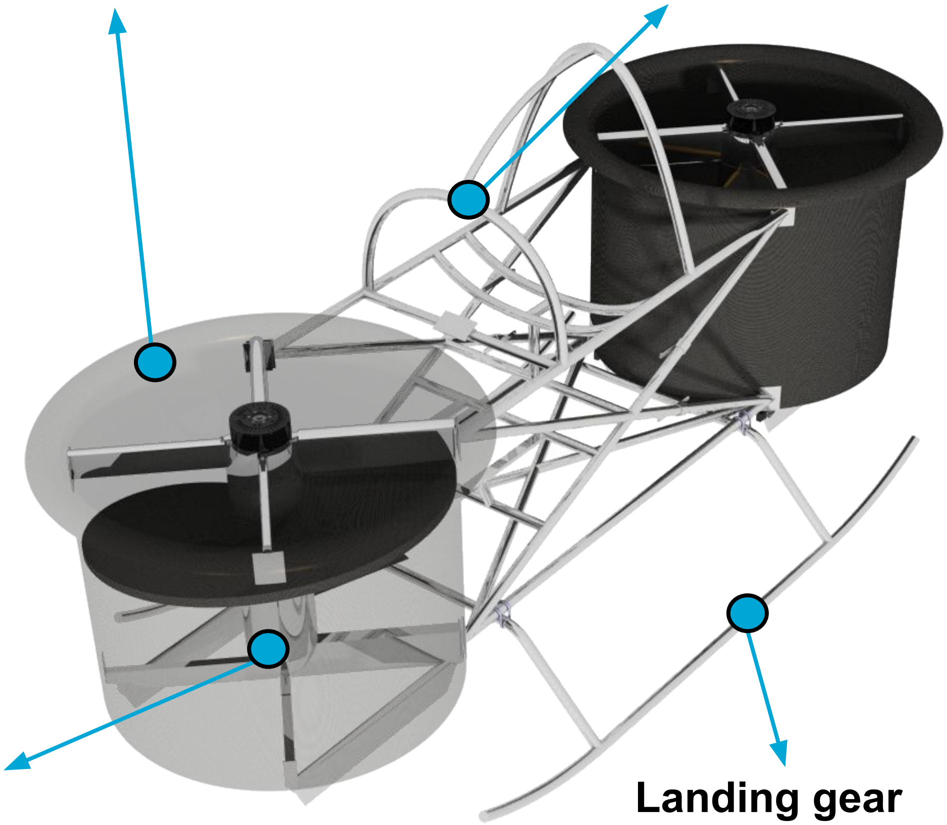
Thin-walled aluminium beam with fairing

- \+ Bending stiffness
- \+ Torsional stiffness
- \+ Torsional strength
- \+ Aerodynamic shape

Airframe

Thin-walled aluminium truss structure

- \+ Functional integration
- \+ Specific stiffness
- \+ Specific strength
- \+ Torsional rigidity
- \- Labor intensive



Rotorhub

Thin-walled steel tube

- \+ Torsional stiffness
- \+ Torsional strength
- \+ Toughness
- \- Weight

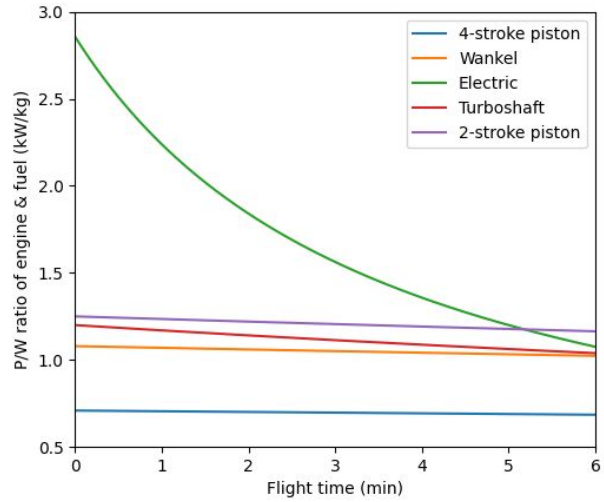
Landing gear

Thin-walled aluminium skids

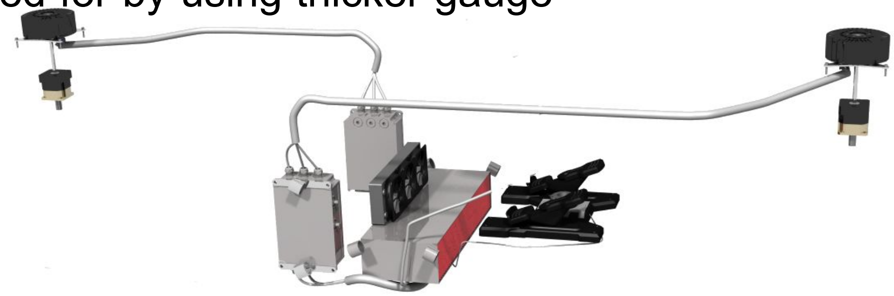
- \+ Weight
- \+ Stability

Power

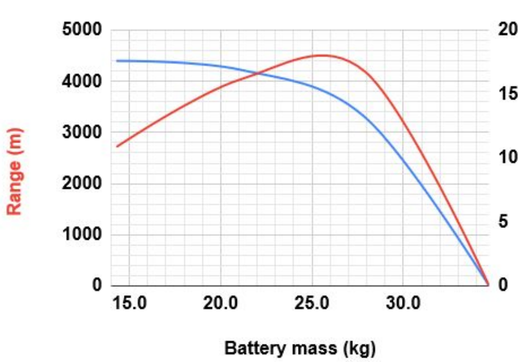
SolidityONE is fully electric, powered by two electric Emrax 188 motors, each mounted directly to the hub. Electric propulsion was found to be the most lightweight option for flight durations of less than 5 minutes.

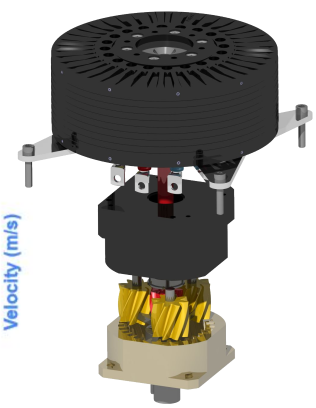


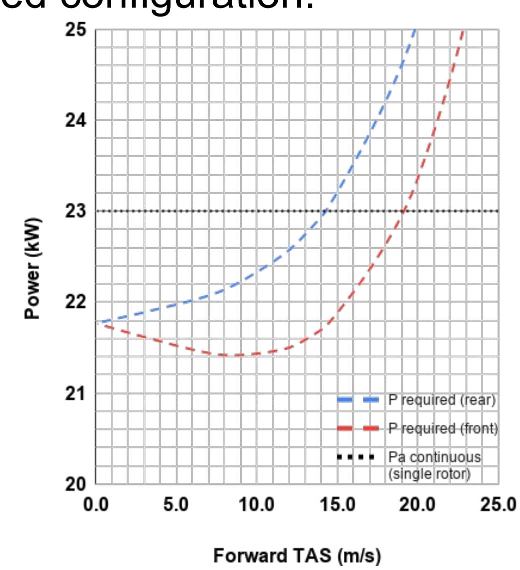
Aluminium cables were selected because it resulted in a lighter cabling solution over copper. The higher resistance of aluminium was compensated for by using thicker gauge wiring.



Due to the use of LiPo batteries, the power output of the battery pack is far greater than the limit of the motors, therefore the power available curve represents continuous power the motors can utilize before beginning to overheat, which is 23 kW per motor in air-cooled configuration.



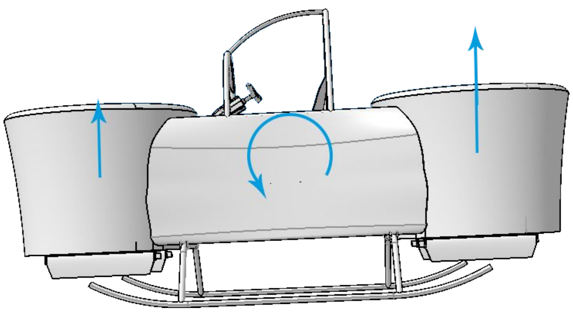




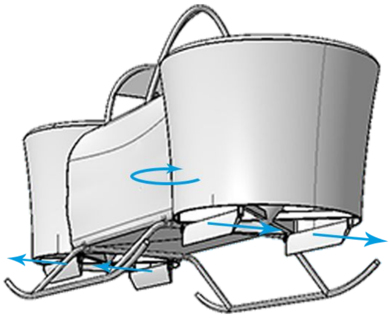
Control & Stability

Stability without stability augmentation system	
Longitudinal	Dynamically unstable due to overcompensation of ground effect, induced velocity difference and duct.
Lateral	Dynamically stable due to duct

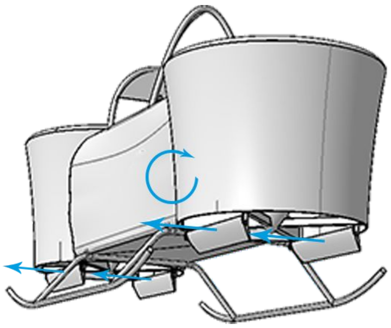
SolidityONE has the following control mechanisms:



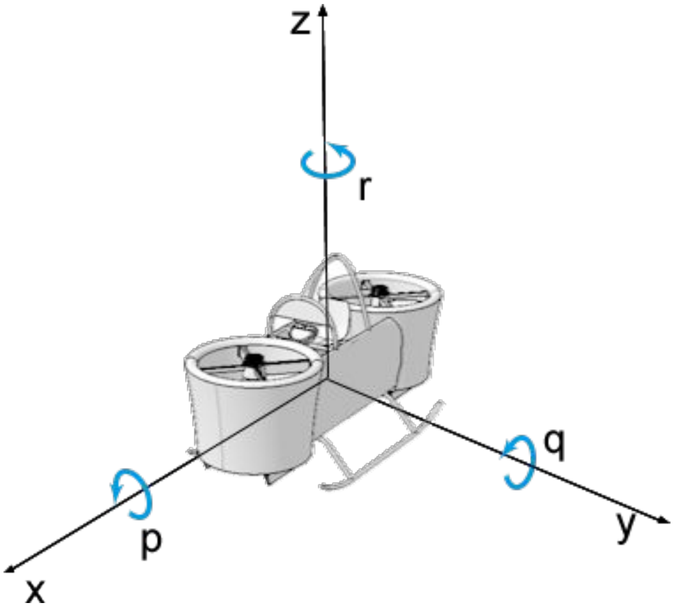
Pitch control by differential RPM (1520 RPM ±4%)



Yaw control by duct exit vane deflection (±12°)

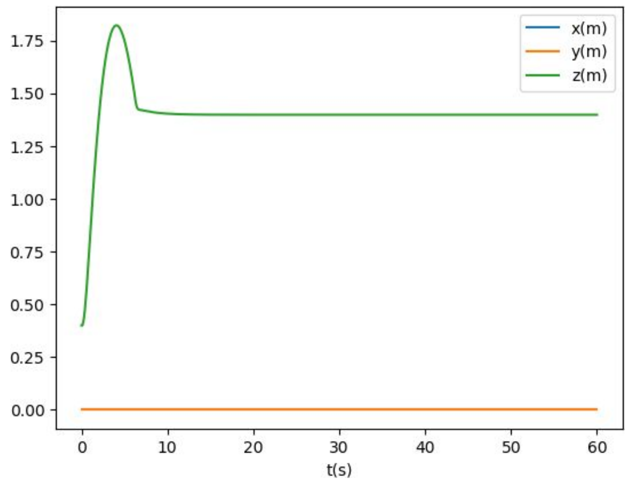


Roll control by duct exit vane deflection (±12°)

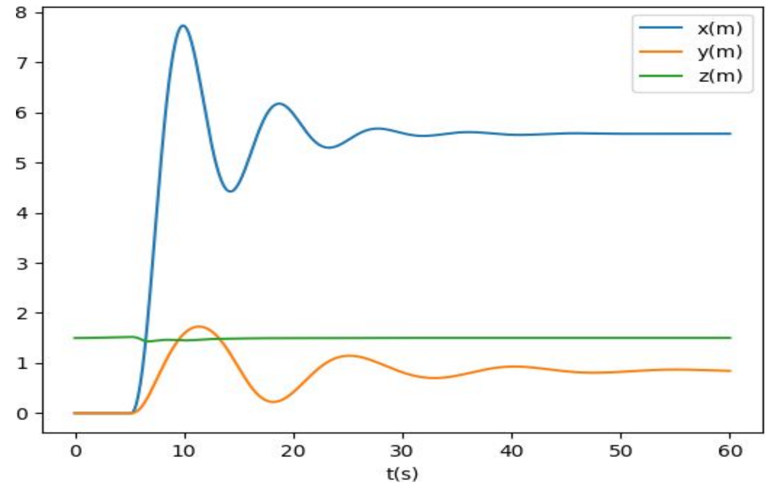


Control & Stability

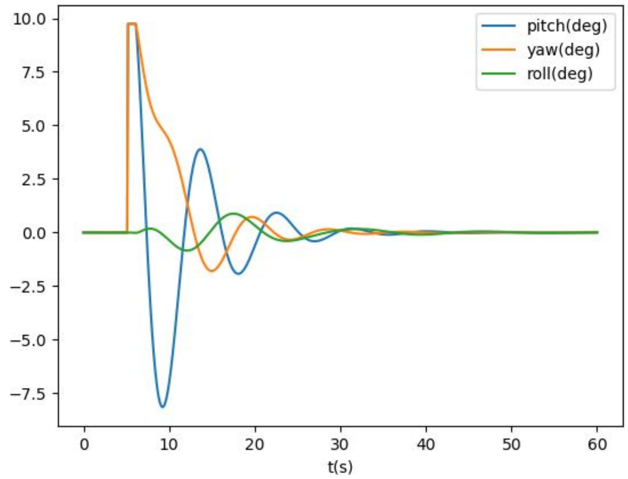
A six degree of freedom simulation of SolidityONE was developed and a PD controller was implemented to improve stability.



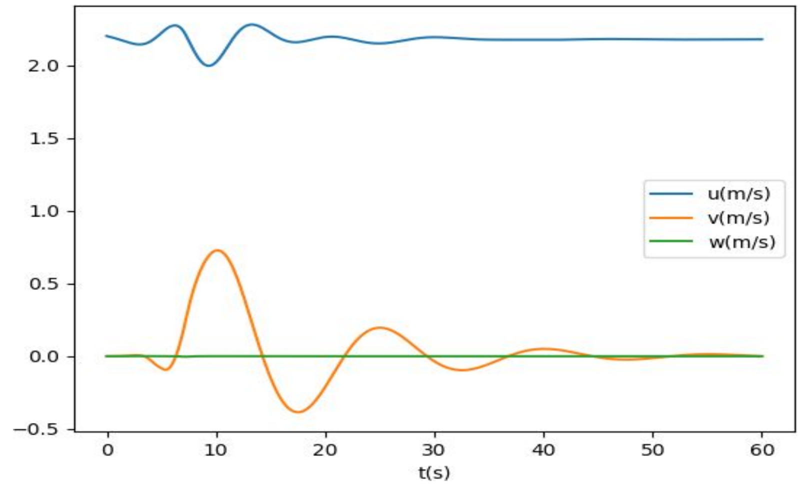
Takeoff



Forward flight



Stability from disturbance

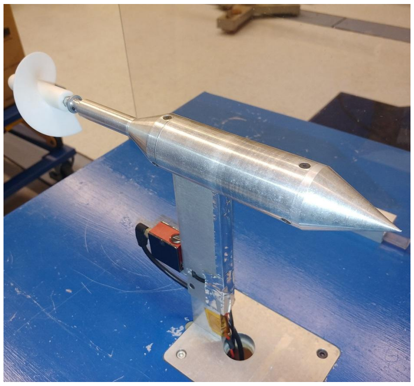


Dutch-roll

Stability with stability augmentation system	
Longitudinal	Stable
Lateral	Stable

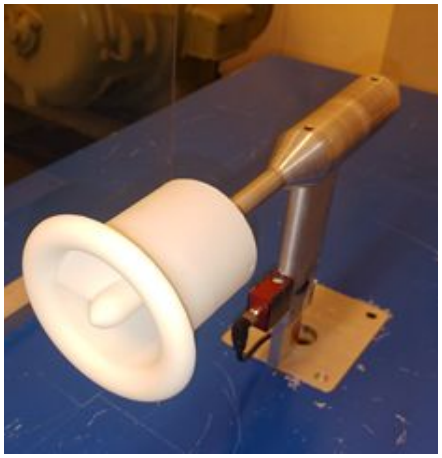
SOLIDITYone

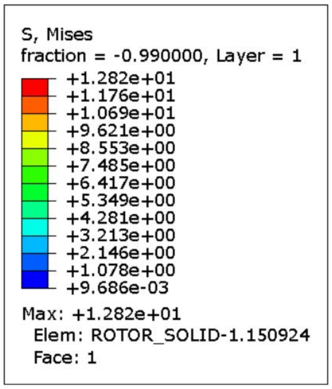
Validation

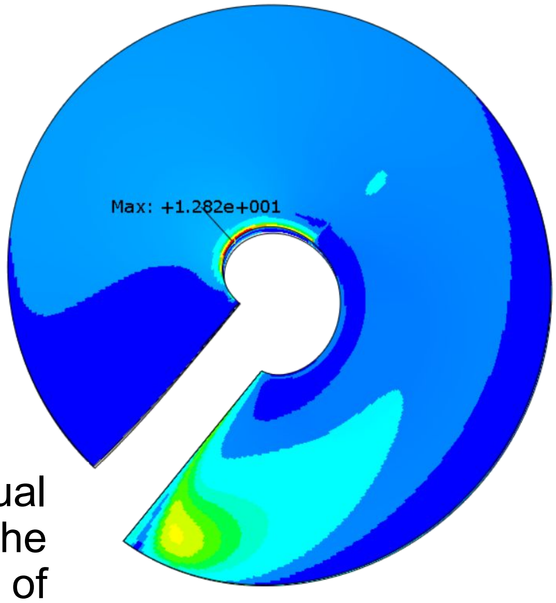


The BET calculations were validated by an scaled experiment performed at the High Speed Lab facility from the TU Delft.

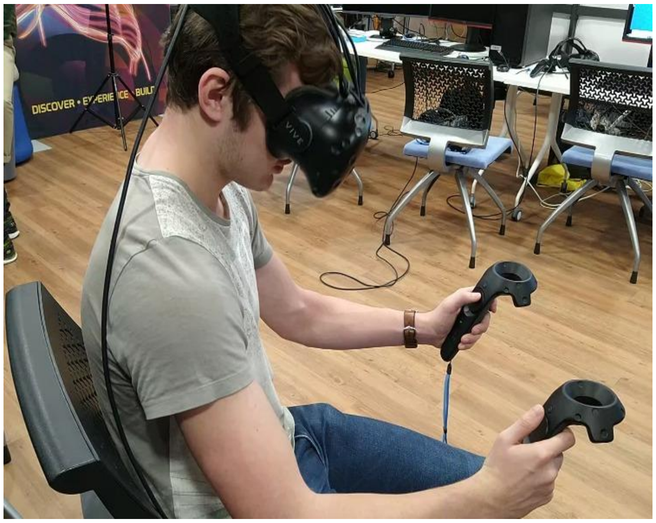
To ensure that the structural models accurately represent the physical problem, the models were validated using Finite Element Analysis.

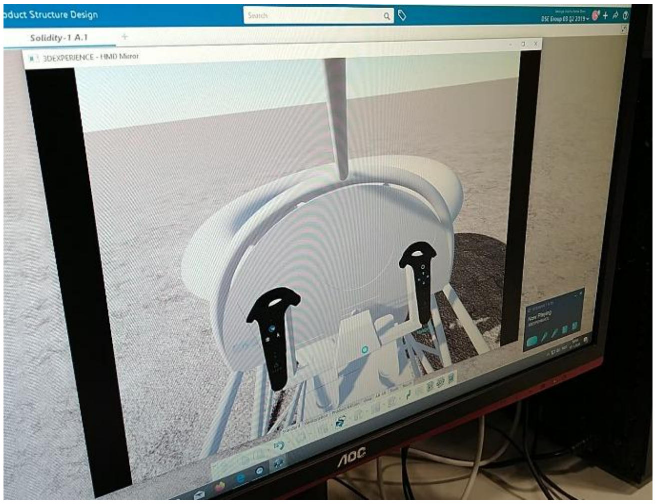




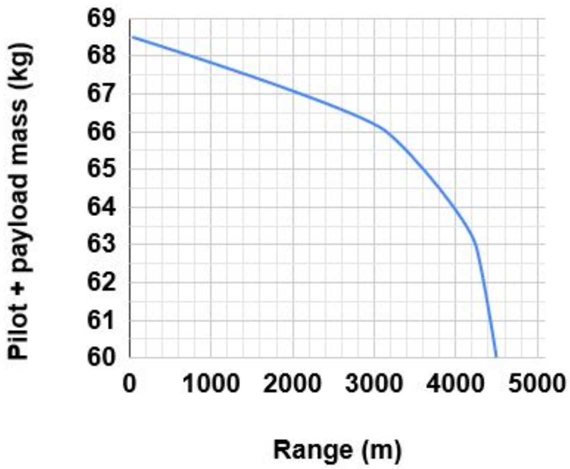


Design features were checked in Virtual Reality during the ergonomics test such as the aesthetics, visibility and overall ergonomics of the vehicle

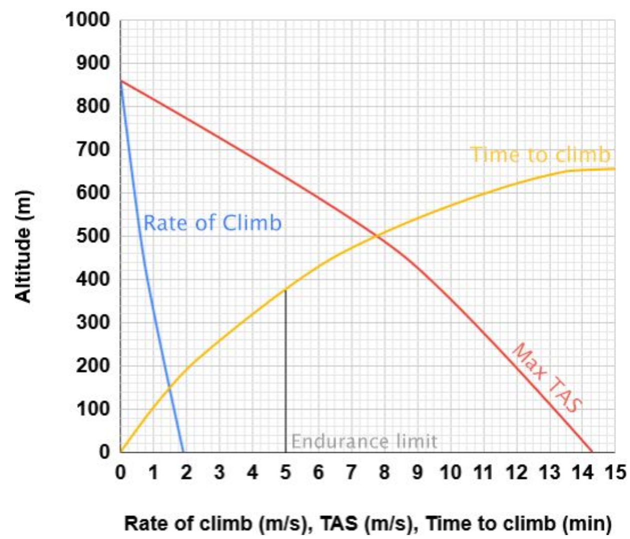




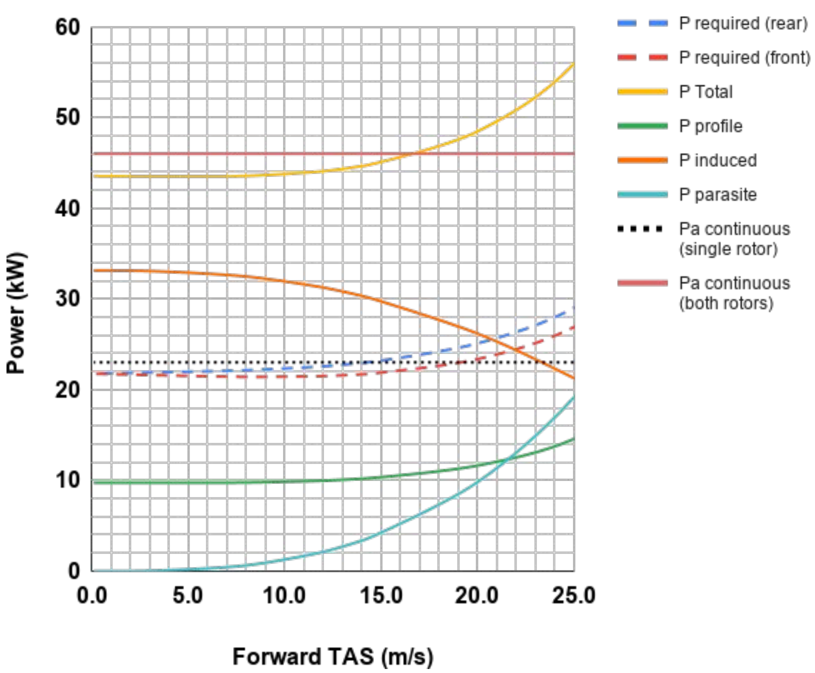
Performance



SolidityONE achieves a range of 4,500 m (14,800 ft) with the specified 60 kg (132 lbs) pilot weight and 1 m (3.28 ft) flight altitude. It is also capable of completing the RFP mission with a 68.4 kg (151 lbs) pilot at 1 m (3.3 ft) or hover at altitudes of up to 860 m (2821 ft) with a 60 kg (132 lb) pilot.



While the vehicle is capable of hovering at an altitude of 860 m (2,822 ft) it lacks the endurance to climb to that altitude from sea level, the altitude obtainable (without considering the power required for controlled descent) is 375m.



The speed and altitude are limited by the power ratings of the individual motors and the capacity of the batteries as they were sized for the RFP requirements. If required, performance could be increased by using more powerful motors with improved cooling and increased the battery capacity.

Conclusion/Summary

The peculiarities of the aerial screw posed some interesting design challenges to this project. The geometry of the screw rigidly defined the blade parameters so a new control scheme had to be designed and camber was used to tweak the airfoils.

Analyzing the high solidity blades had to be solved with inspiration from marine propeller blade element theory. The low blade aspect ratio of 0.3 and inverse taper ratio of 3.8 caused high tip-losses which were solved by ducting the aerial screw.

SolidityONE is a fully electric vehicle capable of meeting and exceeding the competition requirements.Producing low noise and zero-emissions, with ducts enhancing the safety, stability and efficiency of the vehicle, it has the potential to become a viable personal air mobility vehicle for urban environments.

Kind regards, team of SolidityONE