Università degli Studi di Padova – Dipartimento di Ingegneria Industriale

Corso di Laurea in Ingegneria Aerospaziale

Relazione per la prova finale

«DESIGN AND PROTOTYPING OF A QUADCOPTER DRONE AND MULTIPARAMETER OPTIMIZATION OF A DUCTED PROPELLER»

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The HIGHRISE Project

Objective: High definition 3D scanning of monuments, buildings and infrastructures via Photogrammetry

↓

Technology : Drone capable of panning around large structures while carrying a remotely actuated high resolution camera

Rendering: Francesco Zanotti

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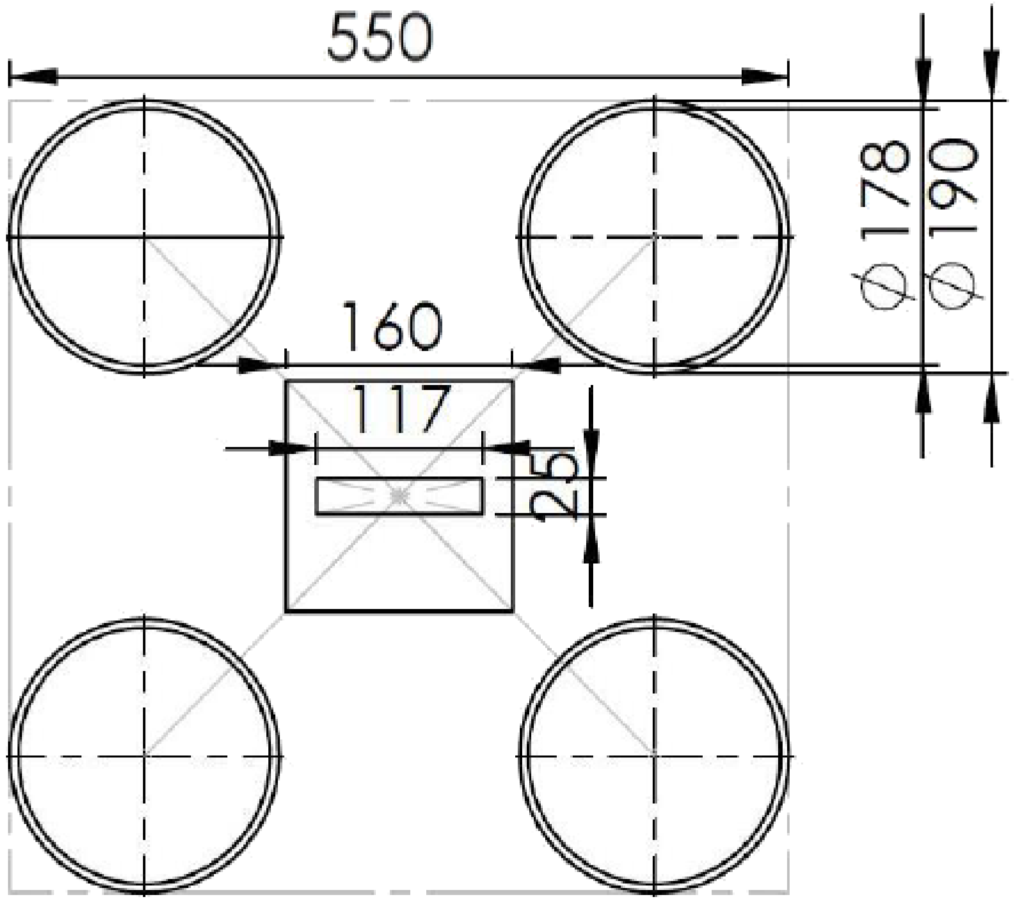
Preliminary design



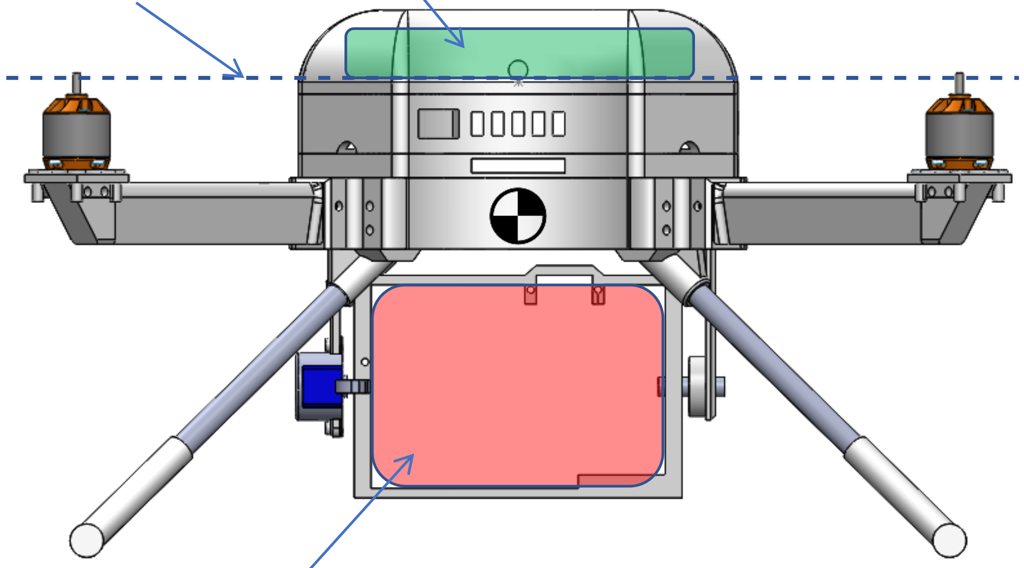
Design goals:

- Load capacity of approximately 500g
- Flight time of approximately 10 minutes
- Reliability
- Stability and maneuverability

Constraints:

- Limited size
- Low cost

Preliminary design



Main design drivers : payload shape and weight

→ Gimbal and drone core-body design

→ motor-propeller selection and placement

Gimbal and drone core-body design

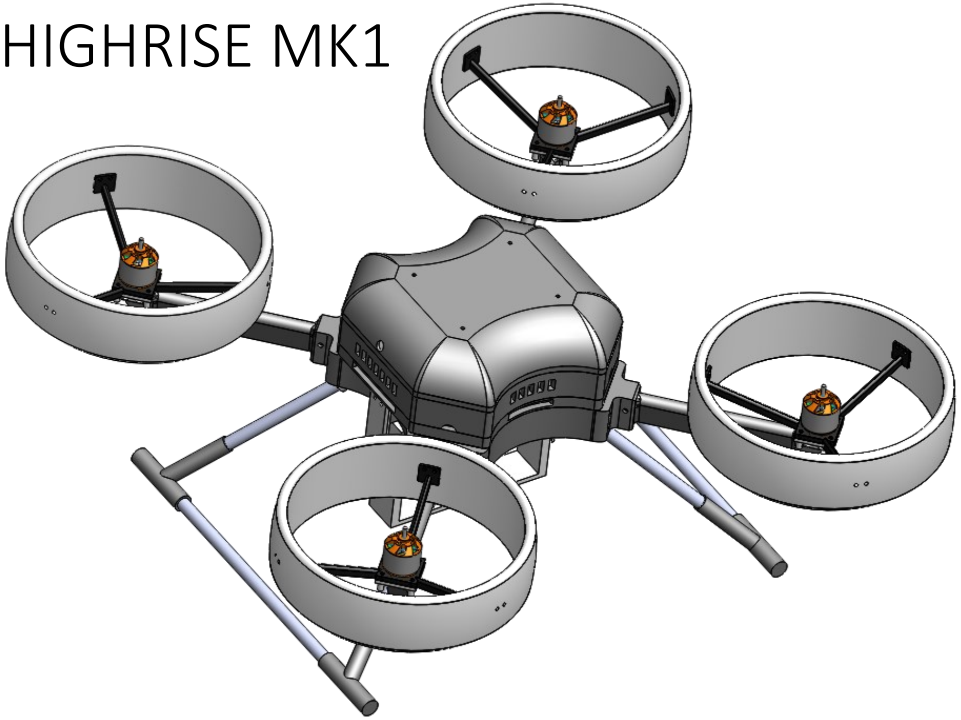
The core-body assembly was designed to keep the CG within the drone's body in order to minimize the vertical distance between the CG and the center of thrust located on the propeller's plane in favour of stability[1]

Motor-propeller selection and placement

after comparing the design to similar configurations on the market and estimating an adequate power to weight ratio the total thrust requirement as well as the motor selection was determined.

HIGHRISE iterations

HIGHRISE MK1



MK1 main issues :

- Low motor reliability
- Low maneuverability and attitude stability
- Low impact resistance of the landing structure

MK2 addressed these problems thanks to:

- More robust electric motors
- New arm design to improve structural efficiency and maneuverability that also acts as landing structure

HIGHRISE MK2

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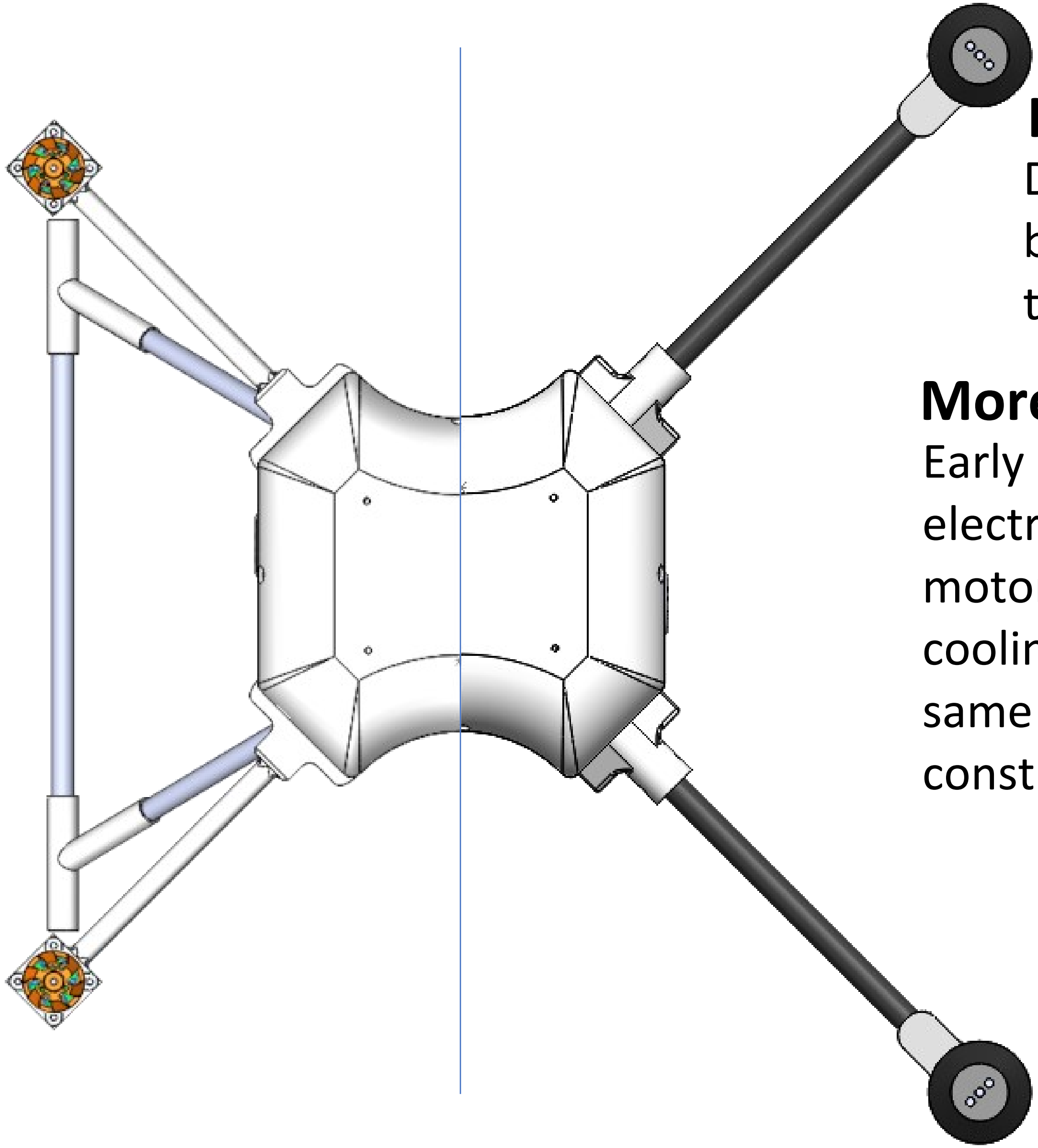
From MK1 to MK2 : arms comparison



Improved maneuverability

During pitch and roll maneuvers longer arms provide a bigger moment about the CG for the same amount of thrust thus improving maneuverability and efficiency.

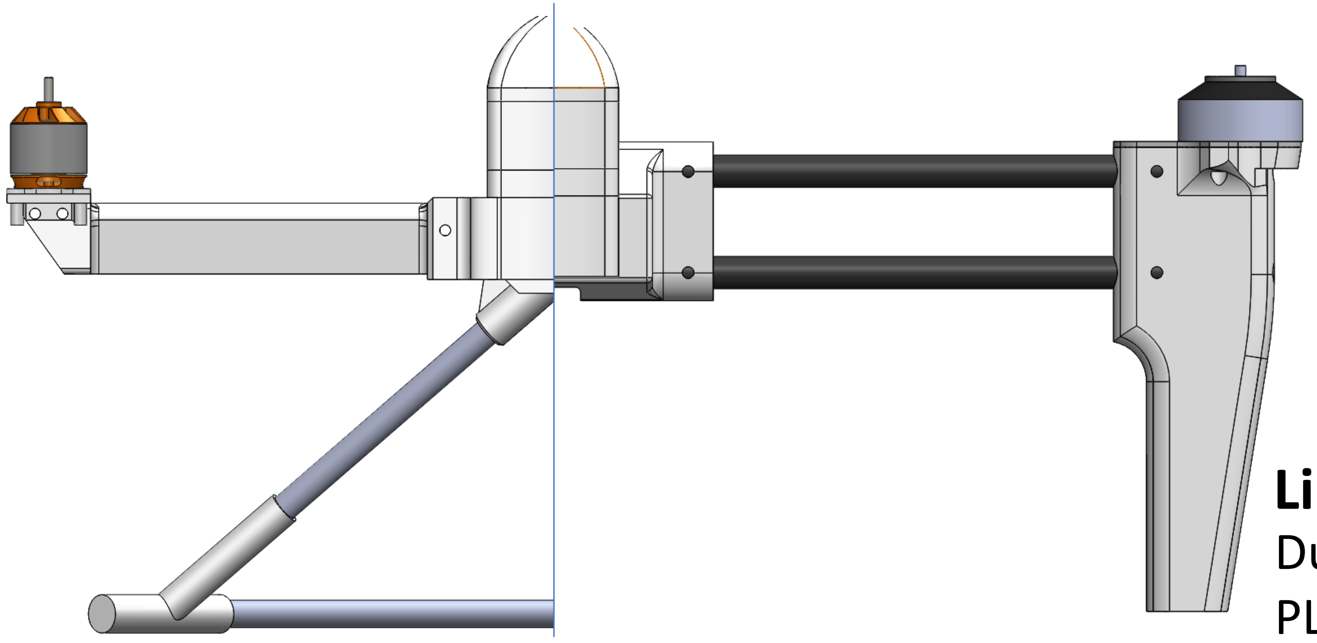
More robust motors

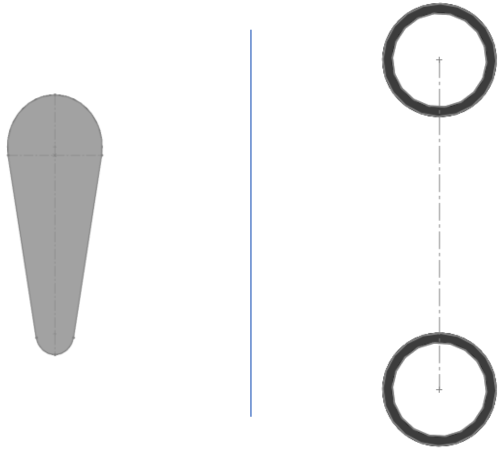
Early MK1 flight test showed the need for more robust electric motors. In fact prolonged hovering can put the motors under thermal stress due to high loads and poor cooling. The MK2 motors were selected to produce the same amount of thrust as MK1 but with a stronger construction.

Stronger landing structure

In MK2 the arm also acts as a landing structure. Reinforced arm-core joints make this design simpler and stronger than MK1 tubular structure.

From MK1 to MK2 : arms comparison





Main load on arms: Bending moment

The drone will operate mostly in hovering thus vertical loads will be dominant. High moment of inertia relative to the longitudinal direction of the arm is needed thus the vertical separation between the 2 tubes

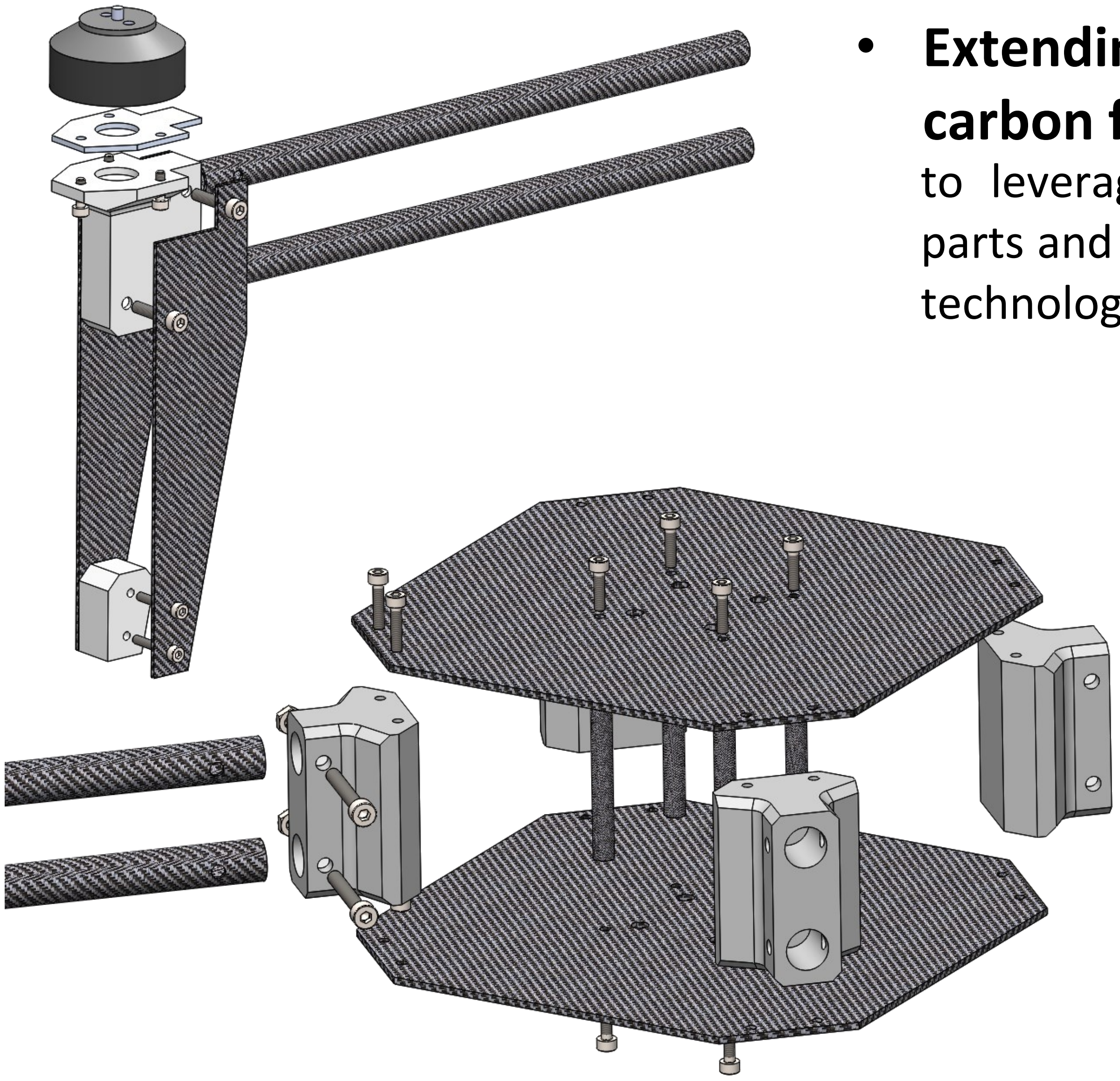
Limitations of PLA as a structural material

Due to the mechanical properties of 3D printed PLA a larger cross sectional area is needed to reach the required stiffness and strength, the problem gets worse the longer the arm is

Carbon fiber tubes and 3D printed PLA connectors

This new design leverages the high stiffness of carbon fiber and the manufacturing flexibility offered by 3D printed PLA. Moreover with a smaller cross sectional area the tubes produce less disruption to the downstream airflow

Future development: HIGHRISE MK3



- **Extending the concept of 3d printed parts joining carbon fiber composite tubes or plates**
  to leverage the mechanical properties of carbon fiber parts and the geometrical flexibility offered by 3D printing technology to manufacture complex connectors.

- **Sensors and GPS**
  adding obstacle detecting sensors and GPS localization would make operations safer and GPS localization could make pre-planned autonomous missions possible.

- **Hexacopter configuration**
  such configuration would increase reliability and payload safety in the event of a motor failure while also increasing overall thrust

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Ducted propeller evaluation

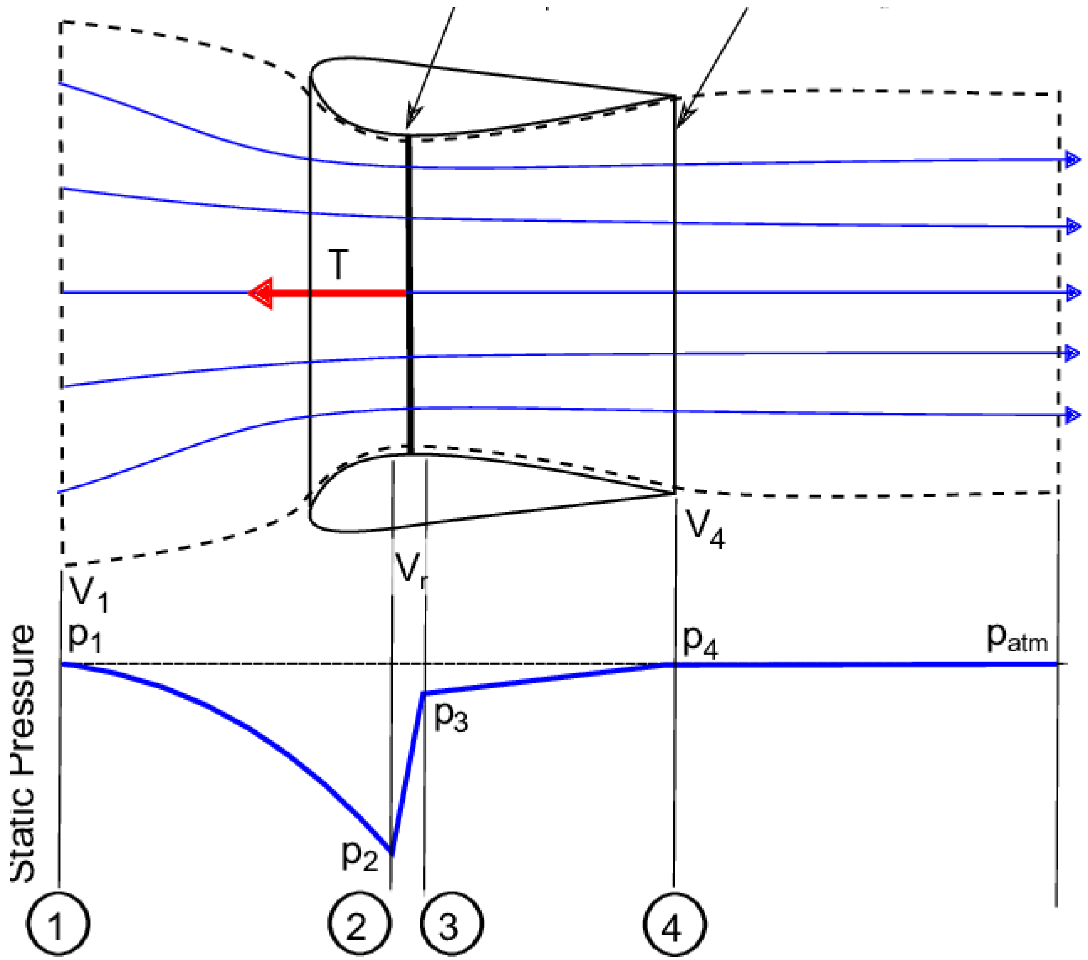


image source [4]

- Since hovering performance is the main requirement a ducted propeller configuration could be beneficial
- Literature[2] proves that performance gains are to be expected compared to the non ducted case especially in hovering efficiency[3], but their magnitude depends on the specific flow conditions.
- Ducted propellers configuration may perform better in the right conditions due to the pressure difference between the duct inlet(2) and the diffuser(4) even if the performance of propeller itself inside the duct may be slightly impaired
- Ducted propellers potential benefits: higher thrust, higher efficiency, less noise, propeller protection

Multiparameter Optimization in Solidworks Flowsimulation

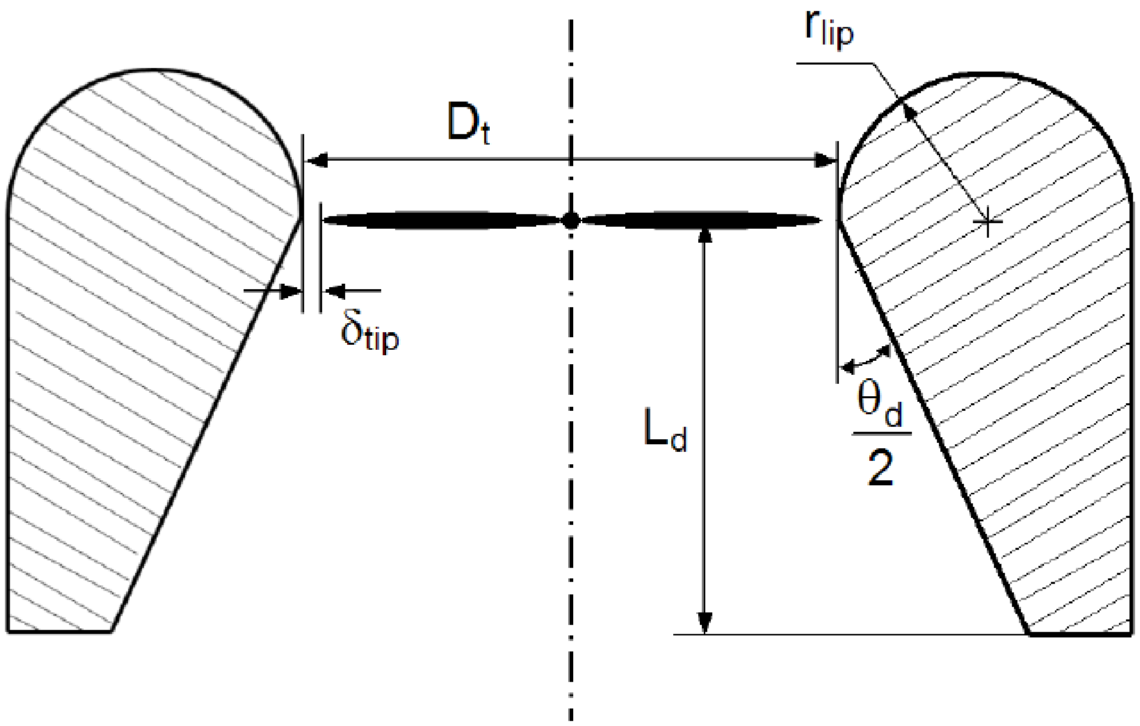


image source [4]

- Solidworks Flowsimulation was used to verify and size an optimal duct for the given flow conditions.
- The literature[2] identifies the most relevant geometrical variables in sizing a duct:
  - Inlet radius r_{lip}
  - Diffuser height L_d
  - Diffuser camber angle $\frac{\theta_d}{2}$
  - Propeller clearance δ_{tip}
- The first 3 variables were optimized through a *Design of Experiment and Optimization* while the propeller clearance was optimized indipendently via an *optimization* study

Multiparameter Optimization in Solidworks Flowsimulation

The *Design of Experiments and Optimization* produced 20 experiments (one discarded) based on which the software was able to extrapolate an optimum set of values which maximized the desired output (thrust).

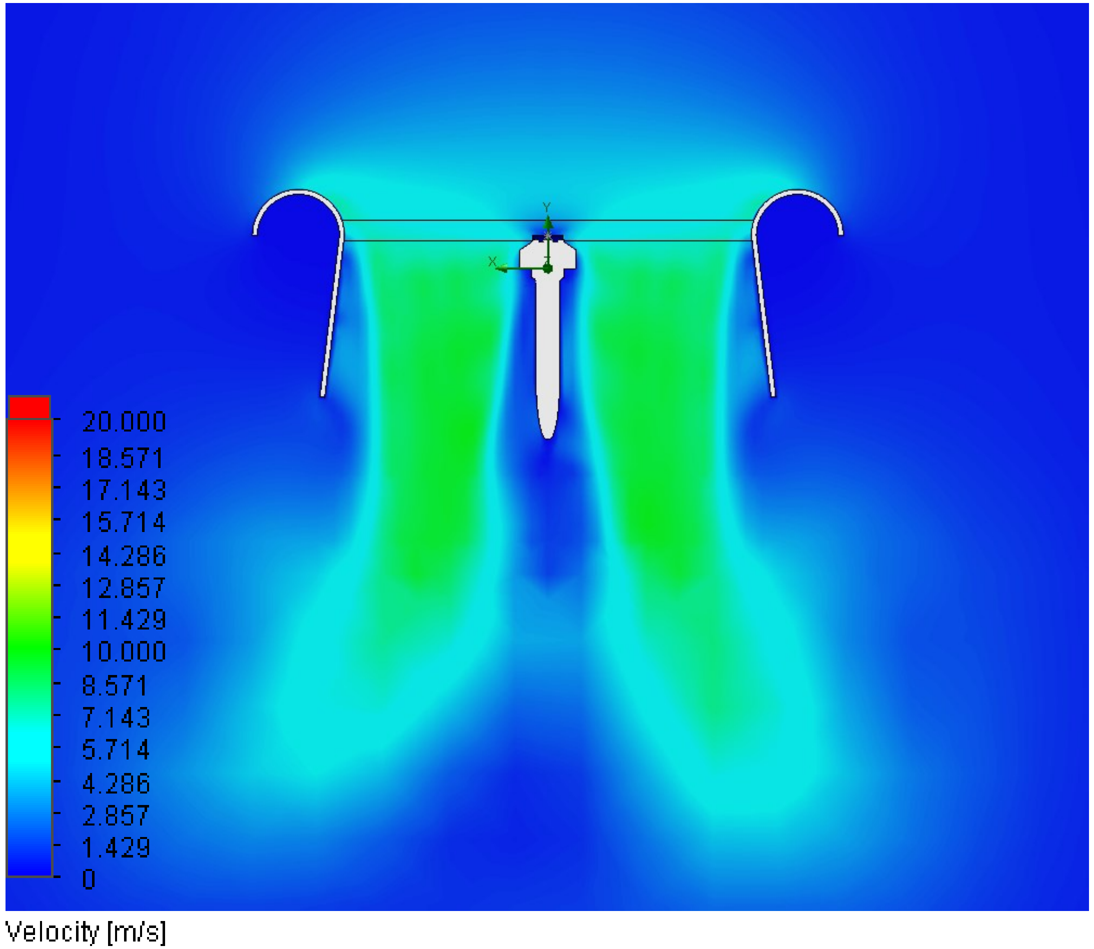
One experiment produced more thrust than the Optimum. This suggests that a higher number of experiments is necessary in order to better weigh the impact of the geometrical variables in relation to the desired output

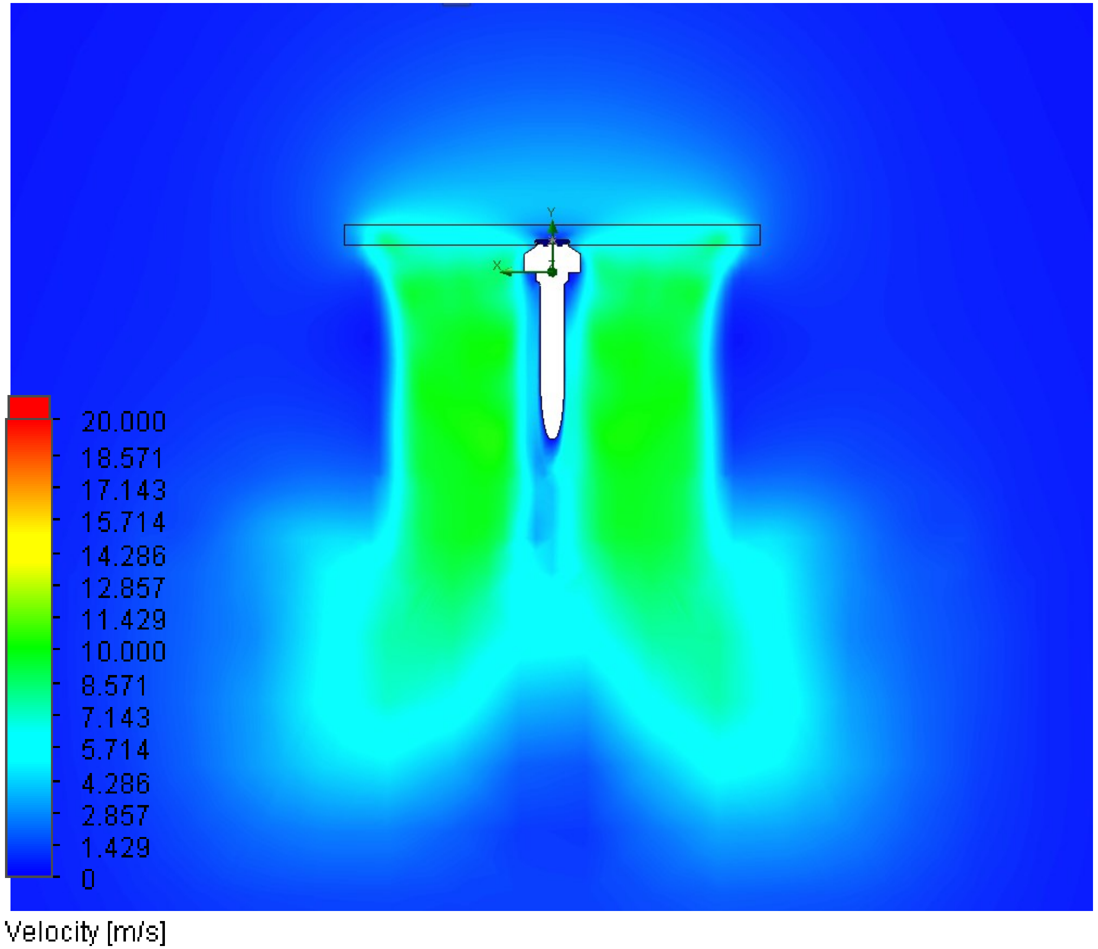
	Optimum	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Exp 10
Duct Camber Angle [rad]	0,077	0,077	0,119	0,049	0,063	0,175	0,133	0,147	0,161	0,091
Duct Height [m]	0,144	0,144	0,106	0,098	0,129	0,113	0,090	0,152	0,137	0,160
Duct Inlet Radius [m]	0,050	0,028	0,025	0,036	0,050	0,033	0,044	0,031	0,047	0,042
Force on Propeller [N]	2,986	2,709	2,892	2,666	2,821	2,805	2,943	2,872	2,665	2,924
Force on Duct [N]	0,712	0,462	0,442	0,558	0,718	0,472	0,621	0,528	0,694	0,625
Total Force (vertical comp.) [N]	3,700	3,173	3,337	3,226	3,541	3,280	3,565	3,402	3,361	3,550

Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	Exp 19	Exp 20
0,105	0,141	0,095	0,055	0,128	0,155	0,069	0,082	0,108	0,168
0,121	0,127	0,123	0,149	0,116	0,156	0,108	0,101	0,094	0,134
0,039	0,029	0,032	0,037	0,049	0,041	0,026	0,046	0,034	0,038
2,935	2,842	2,869	2,796	2,932	2,857	2,958	2,850	2,953	3,587
0,627	0,491	0,519	0,574	0,732	0,664	0,458	0,678	0,590	0,841
3,563	3,336	3,390	3,372	3,667	3,523	3,418	3,530	3,544	4,431

Optimal duct CFD results: velocity plot

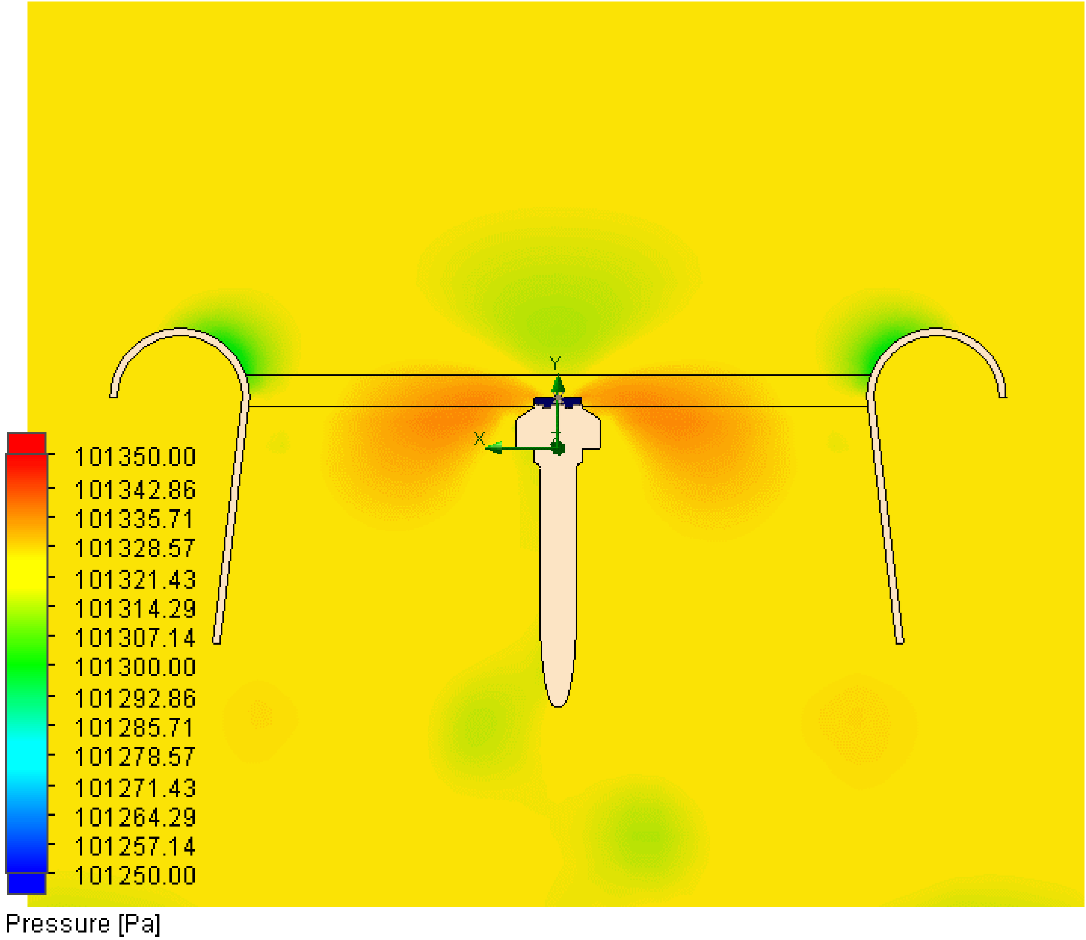
From the velocity plots of the maximum thrust case it's clear that the upstream flow relative to the propeller is the most affected by the duct geometry while downstream flow is less affected

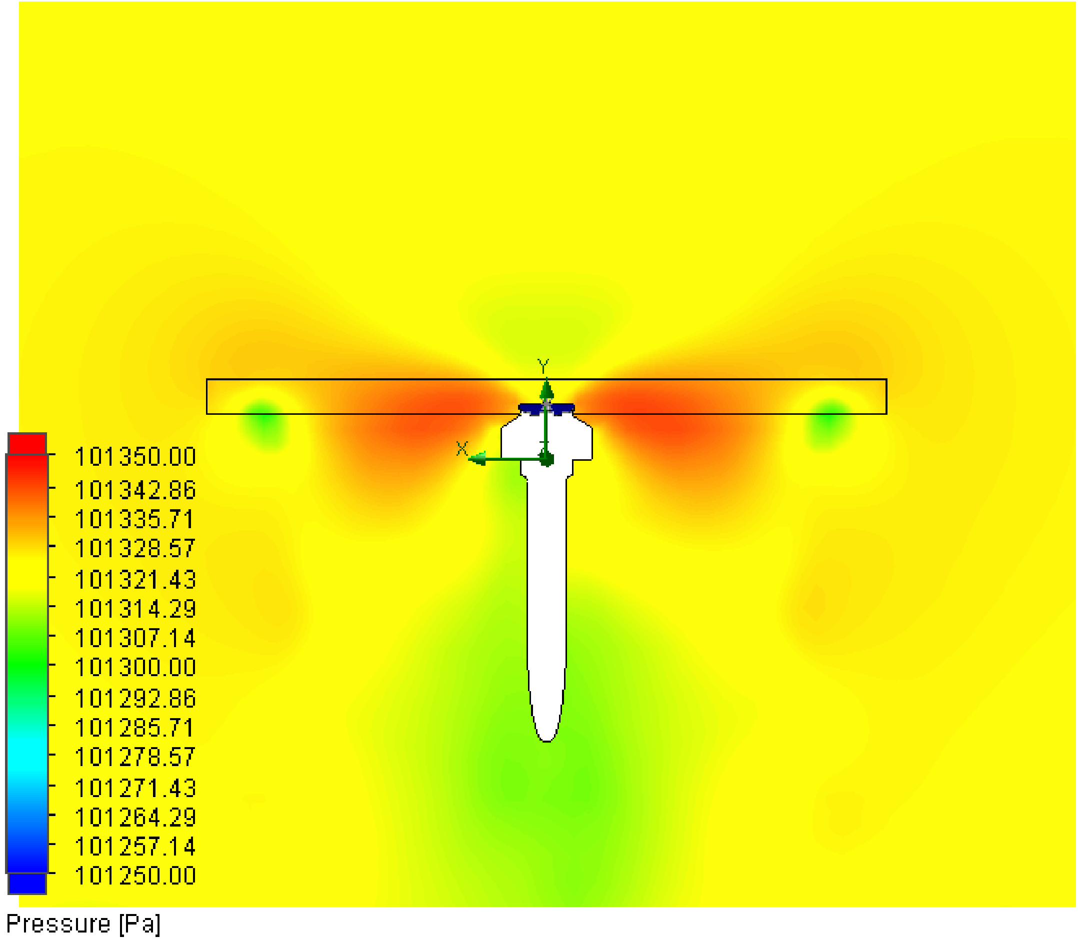




Optimal duct CFD results: pressure plot

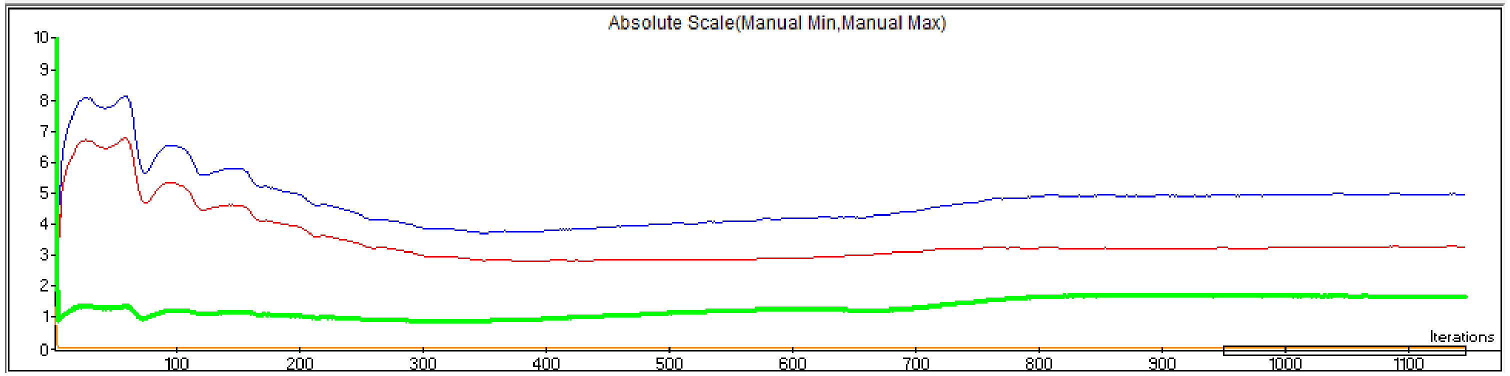
increased velocity near duct inlet → Decrease in duct inlet pressure → Pressure gradient between diffuser and inlet surfaces → Thrust on duct



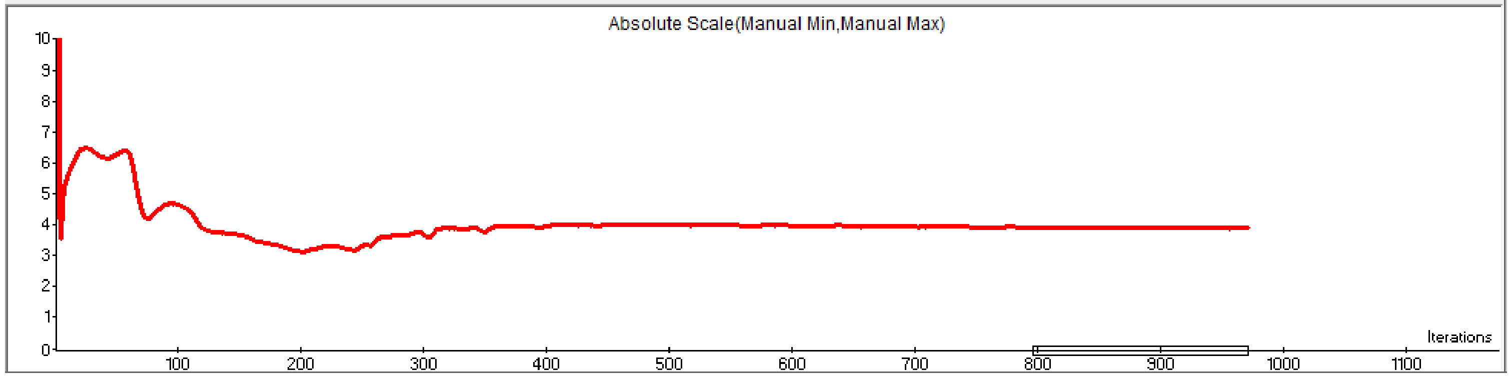


Optimal duct CFD results: thrust values

Name	Current Value	Progress	Criterion	Averaged Value
SG Force - Duct	1.66774 N	Achieved (IT = 1146)	0.0247257 N	1.68946 N
SG Force - Motor	0.00751576 N	Achieved (IT = 774)	0.00144322 N	0.00878888 N
SG Force -Propeller	3.26946 N	Achieved (IT = 898)	0.13673 N	3.25697 N
SG Total Force(prop+duct+motor)	4.94471 N	Achieved (IT = 968)	0.133531 N	4.95522 N



Name	Current Value	Progress	Criterion	Averaged Value
SG Force -Propeller	3.90395 N	Achieved (IT = 529)	0.139353 N	3.89853 N

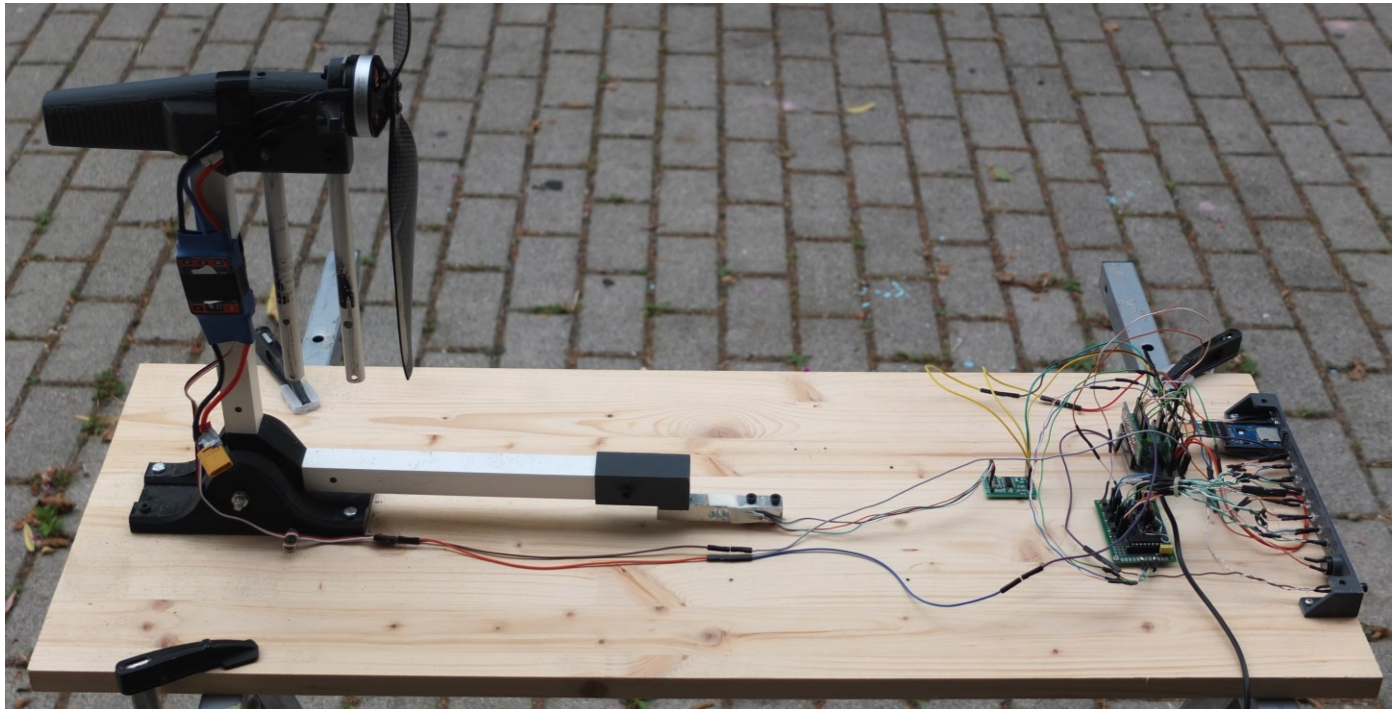


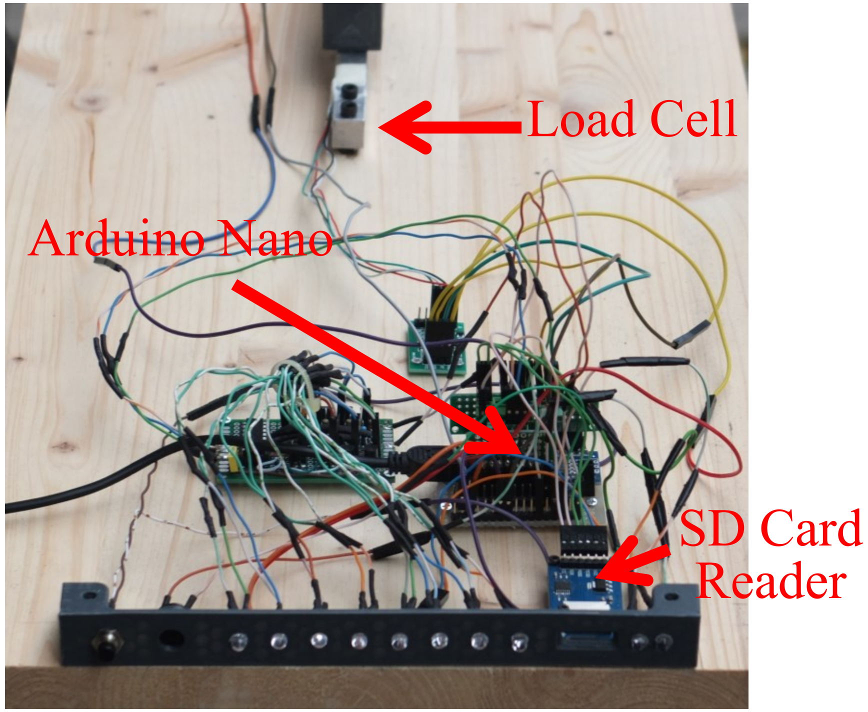
- Due to geometrical differences between the propeller's CAD model and the real propeller the CFD thrust values were not representative of the real world thrust. These values were used to measure the ducted case relative improvement.
- In the Ducted case the propellers performance are poorer than the non-ducted case but overall thrust is higher

Thrust benchmark

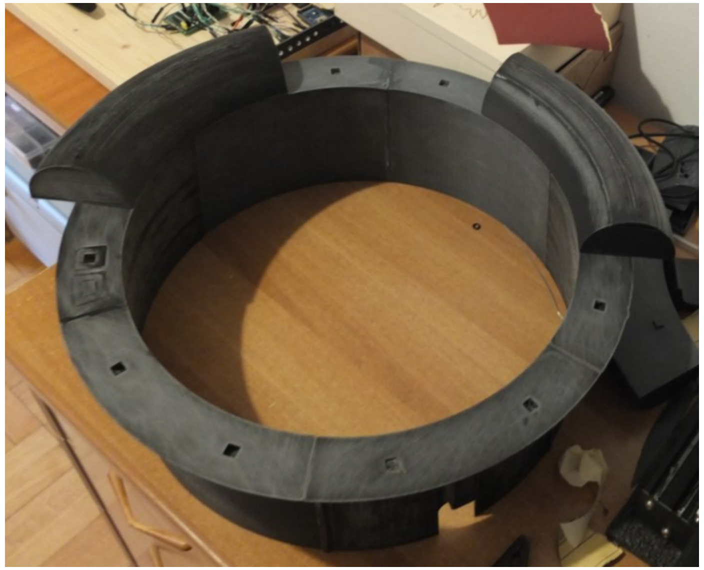
- In order to validate the CFD results and to verify the absolute thrust increase between the non ducted and the ducted case a thrust benchmark was set up

Automated and repeatable motor throttling sequence via Arduino → **L-Shape conveys thrust to load cell** → **Load cell readings are stored in SD card**



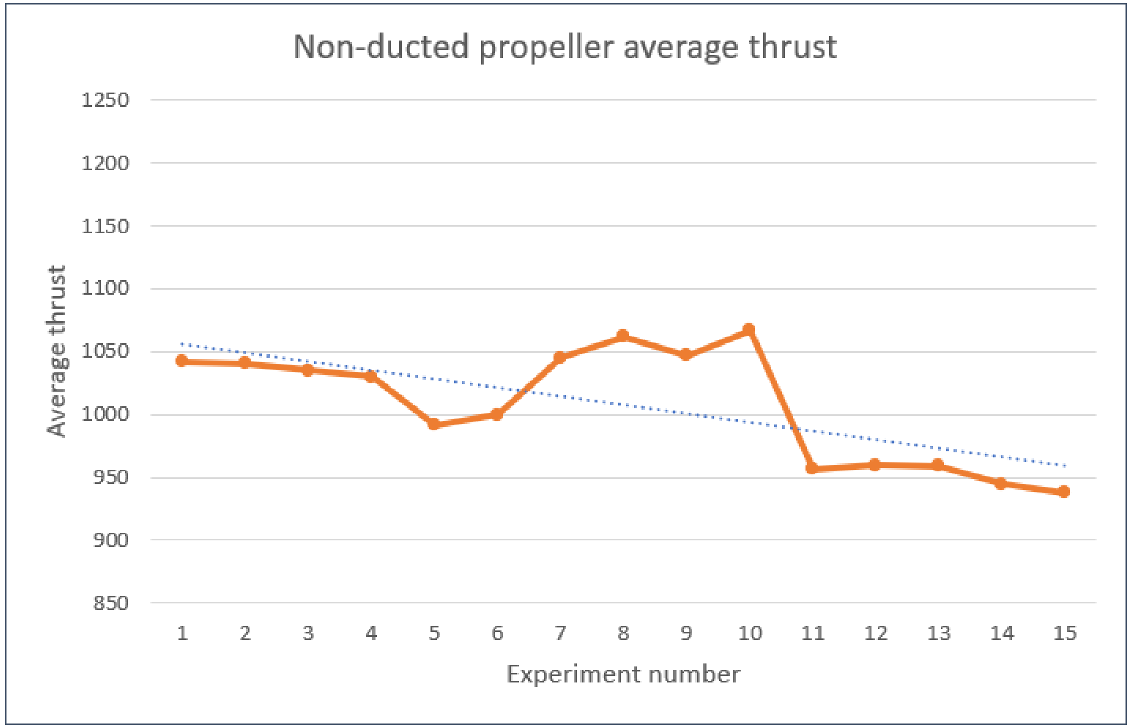


Duct 3D printed prototype

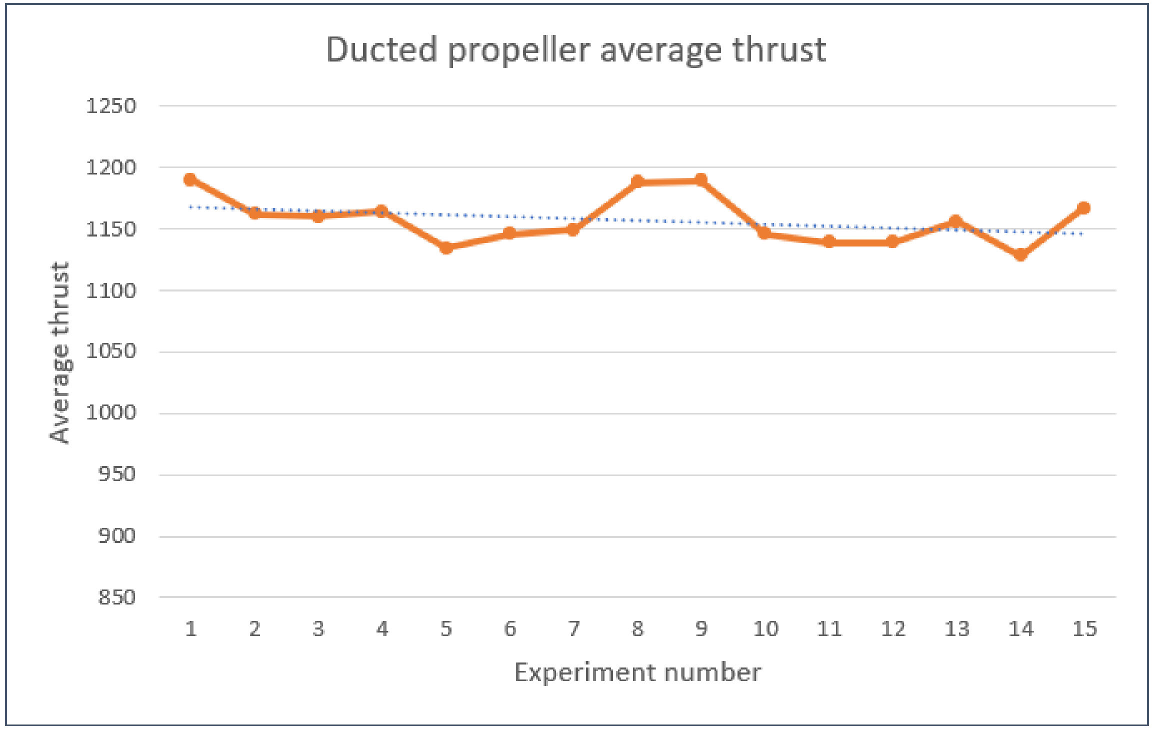


- To test the ducted propeller performance a 3D printed prototype of the duct producing the most thrust was manufactured.
- Due to the size of the duct relative to the maximum printing volume available a modular design was chosen.

Thrust benchmark experimental results



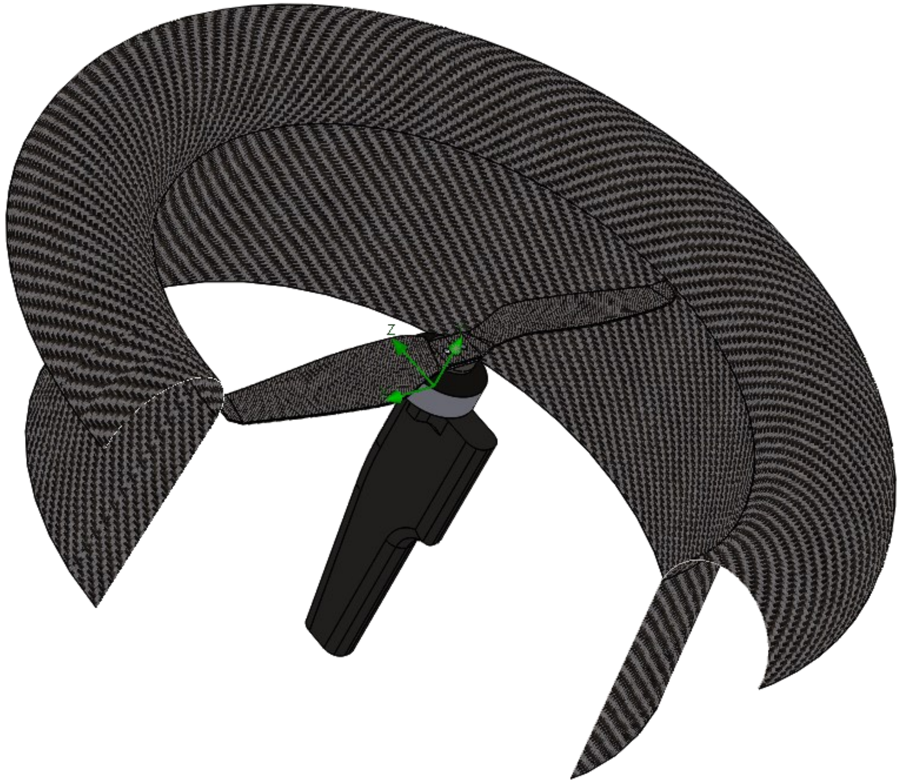
Thrust global average : 1008 g



Thrust global average : 1157 g

- The real-world relative Thrust gain was 14,7% while the CFD one was 26,67%
- Absolute average thrust gain was 149g
- In the ducted case thrust decreased less with the number of experiments, since the experiments were conducted using the same battery as power source this is an indication of higher efficiency

Weight Penalty



- Although performance gains were proved for the specific flow conditions the drone will operate in, the net gain depends on the duct weight, which represents the cost of such performance improvement.
- Due to the size of the proposed duct a 3D printed load-bearing duct would lead to an excessive weight penalty.
- Therefore a carbon fiber-epoxy construction is advised
- The estimated weight of a composite duct would be between 175g and 340g depending on the number of composite material layers [5]

Conclusions

Drone design

Through flight testing HIGHRISE MK2 proved to be the first mature iteration of the project: capable of stable flight, improved reliability, payload carrying capacity of around 500g such as a camera or lidar device. However the one objective missed was the flight time which was 4 times inferior than the 10 minute goal. Therefore a further iteration of the project would be needed with a focus on structural efficiency to make the drone lighter and ultimately improve flight autonomy.

Ducted propeller evaluation and optimization

Given the flow conditions in which the drone will operate and the estimated duct weight, the net thrust gain is negligible. However the higher efficiency(reduced absorbed power for the same amount of thrust) plus the protection and structural benefits the duct offer may be sufficient reasons to implement a ducted propeller configuration.

References

[1] Bristeau, Pierre-Jean & Martin, Philippe & Salaün, Erwan & Petit, N.. (2009). The Role of Propeller Aerodynamics in the Model of a Quadrotor UAV. 2009 European Control Conference, ECC 2009.

[2] Jason L. Pereira. 2008. HOVER AND WIND-TUNNEL TESTING OF SHROUDED ROTORS FOR IMPROVED MICRO AIR VEHICLE DESIGN.

[3] Vikram Hrishikeshavan, James Black, Inderjit Chopra. 2014. Design and Performance of a Quad-Shrouded Rotor Micro Air Vehicle. JOURNAL OF AIRCRAFT 51(3):1812–1817.

[4] Michael Speck, Jörg Buchholz, Mathieu Sellier. 2013. A Mathematical Model of a Twin Ducted-Fan VTOL Jetpack. Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace January 2015

[5] Matweb, 2022, *Overview of materials for Epoxy/Carbon Fiber Composite* , accessed 13 July 2022, < https://www.matweb.com/search/datasheet_print.aspx?matguid=39e40851fc164b6c9bda29d798bf3726>.