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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Aerodynamics, propulsion and testing of an eVTOL drone

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

Unmanned Aerial Vehicles (UAVs) have undergone a transformative evolution, transcending the conventional perception of small quadrotors. Ranging from compact drones to large-scale vehicles, UAVs play pivotal roles in diverse sectors. Overcoming the limitations of multicopters' short flight times and fixed-wing UAVs' spatial demands, the Vertical Take-Off and Landing (VTOL) configuration emerges as a groundbreaking solution. VTOL UAVs combine the flexibility of vertical take-off and landing with the efficiency of covering extensive distances using wings, making them ideal for applications spanning infrastructure monitoring, agriculture, environmental protection, emergency response, police operations, and logistics. This innovative design opens up new possibilities of UAV utilization across sectors.

1.1. Background

This thesis constitutes the fourth phase of a project dedicated to the development of an electric Vertical Takeoff and Landing (eVTOL) Unmanned Aerial Vehicle (UAV) designed and built at the *Politecnico di Milano, Department of Aerospace Science and Technology* (DAER). The first thesis involved the conceptual and preliminary design; then, the drone has been built and integrated in conjuction to the development of a simulator; lastly, a custom control system has been designed in Simulink, installed onboard, and tested within the *Aerospace System and Control Laboratory* (ASCL). This current work builds upon the foundation laid in the preceding theses with the objective of conducting a complete flight test campaign to provide key performance metric for comparison with the predictions of previous work, and to gain significant insight for improved future design development.

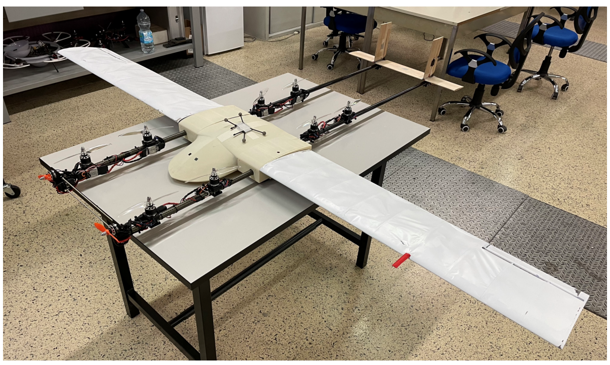

Figure 1: eVTOL UAV developed at *Politecnico di Milano.*

2. Wing and tail redesign

Upon beginning of the flight test campaign, aerodynamic limitations were immediately met:

- the wing's structure, composed by a carbon-fiber tube as spar, 3D printed ribs and a Mylar sheet as outer skin, was not able to maintain the design airfoil's shape causing it to perform as a flat plate;
- while the aircraft take-off mass (W_{TO}) increased significantly, from 4.4 kg by design to 6.4 kg during subsequent work upgrades, the wing surface remained the same and was not sufficient to provide the required lift to sustain level flight.

These issues caused a crash and prompted the resizing and redesign of the wing and tail. The results of the resizing are reported in Table 1: the wing's surface increased significantly with the span increasing from 2.25 m to 3 m. Concurrently, also the control surfaces underwent a resizing process followed by an assessment of the servomotors ability to provide the new higher torques.

	Initial value	Updated value
$\mathbf{S}_w$ [m^2]	0.562	0.780
$\mathbf{b}_w$ [m]	2.25	3
$\mathbf{S}_h$ [m^2]	0.0610	0.0939
$\mathbf{W}_{TO}$ [kg]	6.4	5.6

Table 1: Wing and tail resizing results.

To address the airfoil shape issue, both the wing and the tail have been redesigned to include the same carbon-fiber tube as spar but with hot-wire cut foam for aerodynamic shape, retaining the same airfoil as the original design, Selig 2046 for the wing and NACA 0008 for the tail. Taking the opportunity, further modification have been applied during the redesign process:

- cable's disposition from ESCs to motors optimized;
- ESCs position moved from below the vertical motors to inside the fuselage, allowing better aerodynamic performance;
- removed additional non-structural material from the fuselage.

The combination of all of these upgrades led to the reduction in aircraft weight from 6.4 kg to 5.6 kg.

2.1. OpenVSP analysis

To validate the resizing, the numerical software OpenVSP (vortex lattice method) has been employed to predict the aerodynamic performance of the aircraft. Additionally, a correction method to account for the interaction between fuselage and wing has been investigated but did not yield significant result. The simulation's results will be used for comparison in Section 5.

2.2. Aeroelasticity and glass-fiber cladding

The resizing and the upgrade from 3D printed ribs and Mylar to hot-wire-cut foam allowed the successful transition to fixed-wing flight, validating the design. However, after prolonged flight, the foam exhibited significant torsion at the wingtips caused by its low rigidity. Further investigation, prompted by a subsequent crash, found proof of control reversal events, highlighting the necessity to further enhance the design. The problem has been solved by cladding the foam wing with a glass-fiber cloth weighing 100 g/m^2. Subsequently the foam wing and the glass-fiber cladded wing have been tested to obtain their bending stiffness K_h and torsional stiffness K_θ. Lastly, a two-degree-of-freedom model has been employed to assess the divergence and control reversal airspeeds and confirm the solution of the aeroelastic issues. Table 2 summarizes the results of the tests and of the aeroelastic analysis.

	Foam	Glass-fiber
$\mathbf{K}_h$	145.6	170.3
$\mathbf{K}_\theta$	9.7	47.8
$\mathbf{V}_{rev}$	13 m/s	29 m/s
$\mathbf{W}_{TO}$	5.6 kg	6 kg

Table 2: Comparison between foam ad glass-fiber cladded wings; K_h [N/m] and K_θ [Nm/rad].

3. Propulsive system

Concurrently to the aerodynamic and structural limitations discussed in Section 2, the propulsive system immediately proved critical. The initially mounted propellers, the GF 6x4.5, were not capable of producing enough trust to accelerate the aircraft over 10 m/s, rendering completion of the transition and fixed-wing flight impossible. Given the immediate availability in the laboratory of the larger GF 9x4.3, they have been substituted. The new propellers performed better, allowing transition to fixed-wing flight. However, their performance was quickly decreasing with airspeed forcing flight with throttle nearly always at 100%, even for airspeeds below cruise. After a market research for new propellers, a new alternative was selected among the candidates: the APC 10x55MR.

3.1. Wind tunnel tests

Before mounting, the APC 10x55MR underwent wind tunnel tests to assess their performance and obtain an accurate in-flight thrust estimation model. The tests, conducted in the "Galleria Sergio De Ponte" of *Politecnico di Milano*, required the adaptation of the already available motors test bench to fit in the test chamber and minimize airflow disturbance. The setup for the test of the forward flight system comprised:

- motor: KDE2315XF-965;
- ESC: KDEXF-UAS35;
- propeller: APC 10x55MR;

and is shown in Figure 2.

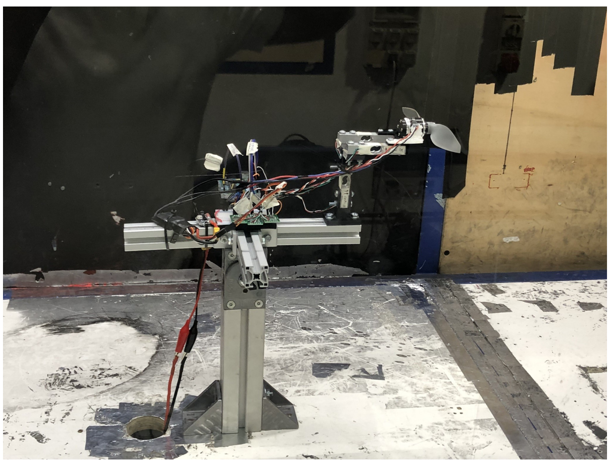

Figure 2: Test bench configuration with the APC 10x55MR mounted for wind tunnel testing.

The procedure of the test involved collecting data at all throttle values from 0% to 100%, with increments of 10%; for each of these throttle setting, all the airspeeds ranging from 0 m/s to 24 m/s have been tested with increments of 3 m/s. Given the availability of the wind tunnel, the test has been performed also on the vertical flight system with non-axial inflow, meaning that the wind reaches the propeller parallel to its plane of rotation. This setup was composed of:

- motor: KDE2315XF-2050;
- ESC: KDEXF-UAS55;
- propeller: GF 7x4.2.

This additional data allowed refinement of the VTOL model in the simulator developed during previous work, by providing accurate trend of the thrust generated by the vertical motors with variations of throttle and non-axial inflow, which is a characteristic scenario of all multirotor configurations.

3.2. Results

First, the wind tunnel test data have been fitted with a polynomial model resulting in an estimation of thrust as a function of airspeed and throttle. Through a trial-and-error approach, the polynomial has been selected to be of third-degree both with respect to airspeed and throttle. This approximation has been applied also to both the forward flight configuration with the APC 10x55MR and the vertical flight configuration with the GF 7x4.2. The graphical result of this procedure on the forward flight case, which is the case of interest of this work, is illustrated in Figure 3;

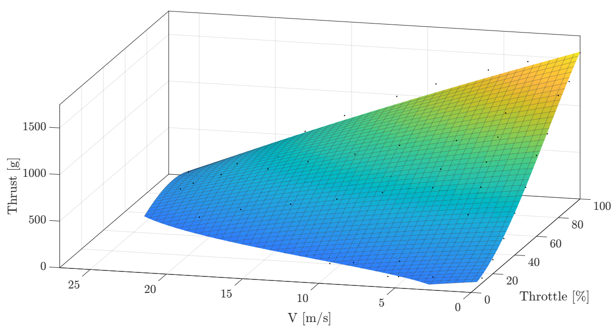

Figure 3: APC 10x55MR wind tunnel data fit carpet plot.

Given the great performance exhibited during wind tunnel testing, the new propellers have been mounted and tested in flight. Their performance was satisfactory; they addressed the poor thrust performance of the previous propellers by successfully bringing the VTOL into fixed-wing mode and allowing flight with as low as 35% of throttle. Consideration has been given to upgrading the forward flight motors too; this option has been discarded for an other limitations encountered: the eight vertical motors could not be powered by 6S batteries, while there were no available more powerful front motors compatible with 4S batteries, as the ones currently mounted. For future development, the substitution of the entire propulsive system is advised to allow a better overall thrust generation both in multirotor flight and in fixed-wing flight, and additionally, improve battery consumption by increasing battery voltage.

4. Multirotor flight testing

The multirotor phase of a VTOL drone is the most power-intensive. In the specific case of the VTOL under study, the voltage drop caused by the significant amount of electrical current drawn during operation by the eight vertical motors, aggravates the situation; this issue has been highlighted also by the latest thesis and relates to the previously mentioned upgrade of batteries from 4S to the higher voltage version 6S. Moving from an indoor environment to outdoor testing, the added variable of wind and gusts posed a challenge. The yaw control depending on the differential RPM of the motors, thus having reduced authority compared to control over the other angles, causes surges in throttle when the controller attempts to counteract wind. These surges, in turn cause high current absorption further limiting the aircraft endurance.

4.1. VTOL Weathervane feature

PX4's software offers a feature specifically designed for VTOL hybrid vehicles flying in multirotor mode: the VTOL Weathervane. This feature works by actively orienting the drone's nose into the estimated wind direction, thus improving aerodynamic efficiency, control and flight safety.

After testing in strong wind condition, significant improvement has been noticed both in motors commanded throttle and battery consumption. The motors went from saturation and shutdown to smooth operation around the hover throttle value and drawn current decreased from approximately 100 A during gusts without the feature enabled to 70 A. The only notable downside of the feature is the lack of yaw angle control during hover, which causes the aircraft to spin depending on wind condition, behaviour that might not be acceptable for certain applications.

4.2. GPS module and position accuracy

In the indoor context the VTOL relied on a *Motion Capture System* for position data. Moving to outdoor tests forced the use of the GPS module for that purpose. The initial position of the GPS module, inside the fuselage close to the power cables, caused position drift due to electromagnetic disturbance. This issue has been solved by temporarily placing the GPS module out on the right semi-wing, far from any disturbance. This helped reduce the initial position error that reached up to 3 m, and characterized by a divergent spiraling motion, to an error contained within 0.6 m from the hovering position, as depicted in Figure 4.

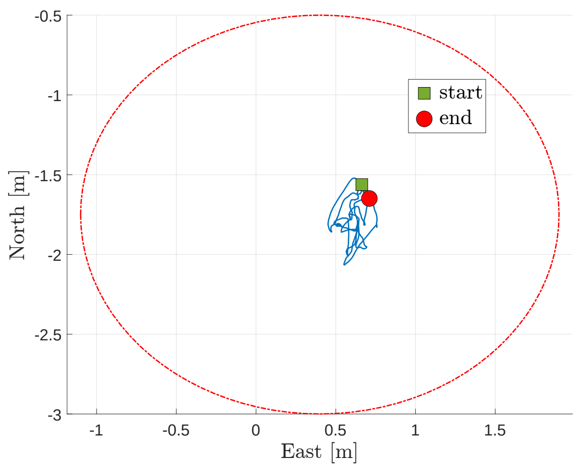

Figure 4: Trajectory during hover with GPS module on the right wing, red dash-dot curve represents position drift before the modification.

Additionally, the hover endurance and the hover throttle have been assessed and compared to the indoor condition but no difference has emerged. The VTOL sustains 2 minutes and 40 seconds of hover flight with a throttle value ranging from 52% to 59%, assuming that it is not subject to wind, that would cause a reduction of the time for the reasons previously mentioned.

4.3. Transition phase testing

The transition phase testing posed many challenges. Given its complex logic and dynamic, it has been tested progressively and analysed from two different points of view: the performance point of view, assessing metrics such as maximum achieved airspeed, distance required to achieve it or to complete the transition, altitude variation, and duration; the behaviour point of view, in which the dynamics is observed to gain insights.
The primary encountered difficulties, anticipated in Sections 2 and 3, were the limited acceleration capabilities of the initially mounted propellers and the inability of the Mylar wings to produce enough lift. Once these two issues have been addressed through the resizing, redesigning and cladding of the wing accompanied by the substitution of the propeller with better performing ones, comparison has been made between the different configurations that the transition has been tested with.

Performance results

From a performance point of view three main results can be discussed:

- neglecting the first APC 6x4.5 that were completely unsuitable for the aircraft, upgrading the propellers, not only allowed completion of the maneuver, but drastically reduced the requested distance from 120 m to less than 80 m; depending on wind condition, an absolute minimum of 34 m has been recorded to complete the transition;
- the duration too decreased from approximately 12 seconds to within the range of 7 to 9 seconds.
- the recorded altitude loss was bound to 3 m over the entire tests database; with the upgraded propellers and with the cladded wing, this altitude variation assumed positive value, meaning that after a first acceleration phase, altitude was gained thanks to the pitch-up behaviour of the aircraft.

Behaviour results

At the beginning of the campaign, the aircraft exhibited two distinct but related behaviours. The first one, a pitch-up attitude at the beginning of the acceleration; the causes of this have not been pinpointed but assumptions were maid and concerned the interaction between the non-axial inflow generated by the front propellers on the vertical propellers positioned right behind. The second dynamic, induced by the pitch-up behaviour, was the build-up of elevator deflection during a phase in which it was not expected to move. Furthermore, the deflection accumulated during the pitch-up was not annulled once the aircraft was level again, pointing towards an integral gain tuning issue. One last dynamic that occurred during the transitions was the pitch divergent oscillations starting right after the blending phase was reached; dynamic later associated with the pitch rate proportional gain.
In conclusion, the pitch-up attitude remained throughout the entire campaign and is presumed to be caused by the specific configuration of the VTOL and the interaction between forward flight and the front vertical flight propellers. The elevator deflection build-up and the pitch oscillations have been addressed by tuning the fixed wing pitch rate controller, specifically the pitch rate integral gain has been reduced from 0.1 to 0.01, and the pitch rate proportional gain has been reduced from 0.08 to 0.04. These changed proved effective and allowed flawless execution of the maneuver.
Further testing is suggested to investigate the activity of the elevator during the initial phases of the transition when, being below the blending speed, the fixed-wing controller is expected to have no control authority.

4.4. Backtransition phase

Similar to the transition phase, the backtransition has been gradually explored with the aim of understanding its dynamics and tuning the parameters to obtain a smooth and safe maneuver. The criticality of this phase has been its double-purpose: it initially served as an emergency recovery maneuver, where speed of execution had priority over smoothness, encouraging the setting of shorter duration of the maneuver; while gaining confidence and perfecting each flight, the emergency purpose dropped and smoothness of execution became the main focus. A smoother maneuver allowed to lower the structural loads sustained by the aircraft and by the wings while decelerating and to minimize the attitude angles assumed in order to stop the aircraft in place.
For these reasons, the two parameters that tune

the backtransition phase (specifically, the total duration of the maneuver and the tamp-up time to turn on the vertical motors) have evolved going from a 2 seconds duration and 1 second ramp-up time to the default values of 4 seconds duration and 3 seconds ramp-up.

Results

The 2 seconds duration and 1 seconds ramp-up time set up for emergency recoveries exhibited extreme structural load, with visible bending of the wings during deceleration; moreover, while stopping, the aircraft reached an undesirable pitch angle of 43.8 deg. Relaxing the ramp-up time to 2 seconds, allowed a smoother execution of the maneuver by decelerating more gradually; the maximum pitch angle achieved with this setting was of 16 deg. Lastly, the default settings exhibited the most uniform motors' PWM trend but did not yield improvements in terms of attitude compared to the 2 seconds duration and 2 seconds ramp-up combination.
The horizontal distance required to go from the activation of the maneuver to a complete stop has been of approximately 50 m, consistent with all the different configurations.
A noteworthy observation related to the descent phase, rather than the backtransition, is that the large wings render the aircraft extremely susceptible to the vertical velocity in multirotor flight; descending at a rate exceeding 2 m/s caused loss of control and a "falling-leaf" behaviour of the aircraft. Extreme bank angles up to 48 deg, pitch angles of up to 40 deg and constantly saturated motors' PWM have been experienced during such a descent. Through experience, the optimal rate of descent to maintain perfect control and land safely has been determined to be of maximum 1.5 m/s.

5. Fixed-wing flight testing

5.1. Stall speed determination

One of the most critical performance to be determined as early as possible in a flight test campaign is the stall speed. Difficulties have been encountered in the execution of the test because of the impossibility during the current work to implement custom control modes for the automatic execution of the tests. The pilot had to manually manage the aircraft, with the only aid of permanent stabilization.
Analysing the executed tests, two main results have been obtained:

- the stall speed has been determined to be 9.9 m/s, with a maximum lift coefficient of 1.255; these values have been considered satisfactory considering that the resizing of Section 2 aimed at a stall speed of 12 m/s associated to a maximum lift coefficient of 1.10;
- given the single-configuration of the VTOL, the only stalling behaviour exhibited has been a break in pitch angle followed by a rolling maneuver; recovering from the stall did not present challenges.

5.2. Drag polar estimation

The estimation of the drag polar curve is of paramount importance during a flight test campaign of a fixed-wing aircraft. During this work, given the limitations posed by the reduced dimensions of the available airspace that prevented the aircraft from properly stabilizing during the tests, an effort has been made to take into consideration all of the variability experienced during the tests. This effort translated in the commonly used equations for lift and drag coefficient determination being augmented with terms to account for:

- altitude variations, through the flight path angle γ;
- misalignment between the thrust vector and the airspeed vector, through the angle of attack α;
- airspeed variations and normal accelerations, through the associated acceleration terms.

The result of such study led to the coefficient being calculated as:

$$C_L = \frac{2}{\rho V^2 S}\left(Mg\cos\gamma - T\sin\alpha - Ma_z^{\mathcal{S}}\right), \quad (1)$$

$$C_D = \frac{2}{\rho V^2 S}\left(T\cos\alpha - Mg\sin\gamma - Ma_x^{\mathcal{S}}\right). \quad (2)$$

Additionally, from each test point, the whole set of collected data has been plotted instead of averaging, to allow direct observation of the variability of the parameters and the associated uncertainty. The result of this procedure is illustrated in Figure 5.

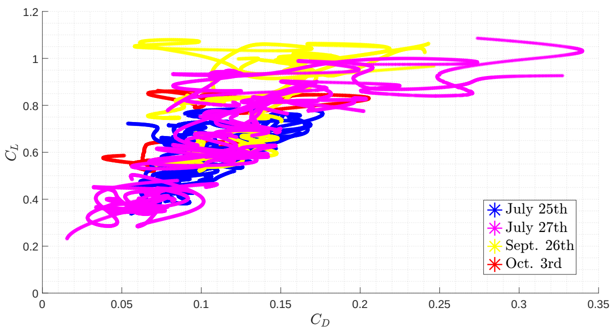

Figure 5: All drag polar points color-mapped by the day of execution.

Notably, September and October flights have been put in place specifically to populate the higher part of the curve (lower airspeeds). Given the stabilization issue, coupled with the lower airspeeds accentuating the aircraft's susceptibility to disturbancies, these points resulted in a lower drag coefficient estimation than the July counterpart at similar lift coefficients.
This discrepancy has been investigated by analysing the outside air temperature difference from the wind tunnel effect on thrust estimation and the stabilization issues' effect on the aircraft attitude. None of the above provided answers to the phenomenon, which has been addressed by studying two separate datasets: July dataset, and a dataset composed by all the valid test points available. Figure 6 shows a comparison between the second order fits of the datasets and the OpenVSP prediction discussed in Section 2.1.

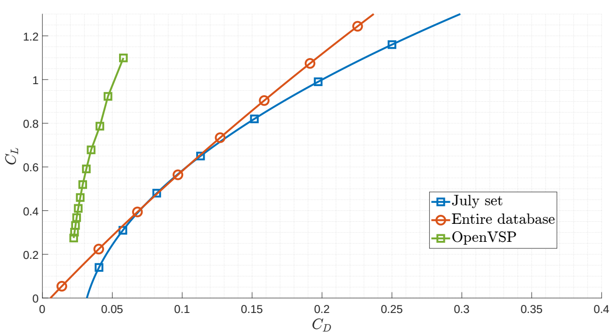

Figure 6: Drag polar comparison: fitting of the datasets vs. OpenVSP prediction.

Notably, the datasets estimation exhibits substantial deviation compared to the numerical prediction. Despite the OpenVSP C_{D_0} prediction of 0.0283, which is close to July's set estimation of 0.03182, the two curves have extremely different curvatures, which are representative of the lift-induced component's contribution to drag. This divergence between the curves is presumed to be caused partially by the omission of the eight vertical motors and their propellers in the OpenVSP model, and partially by the aerodynamically inefficient design of the fuselage's shape.
The dataset composed of all the points available can be observed having a nearly linear trend; this is caused by the previously discussed discrepancy between the high lift coefficients and led to its invalidation.
In conclusion, further testing in a larger field and with the aid of custom control modes for test execution is suggested to obtain better data, mainly in the low speed region of the flight regime.

5.3. Climb performance

To obtain the aircraft climb performance, an energy approach has been chosen, by the name of Rutowski energy method, which leads to the level acceleration test, an efficient alternative to the sawtooth climbs method. Several test points have been performed and after filtering out the invalid ones, five have been analysed.
The maximum airspeed achieved has been of 21.7 m/s, in accordance with the original design value of 22 m/s. Additionally, the specific excess power (SEP) curve has been obtained and fitted with a rational polynomial model, yielding the curve depicted in Figure 7

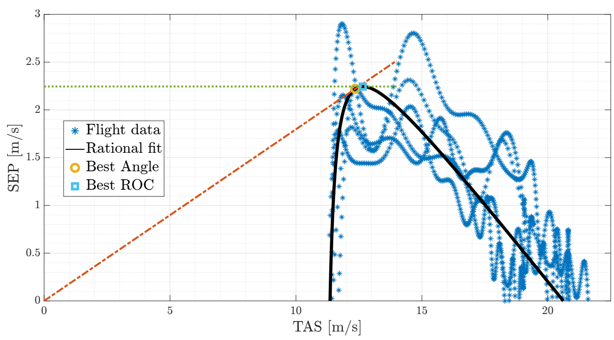

Figure 7: SEP fitting curve and associated performance.

One last significant finding from the SEP curves is the noticeable reduction after the initial peak, followed by an increase and a subsequent gradual decrease to zero. This phenomenon has been attributed to the mounting position of the forward flight motors: slightly above the horizontal plane of the aircraft's CG. The interaction between the pitch-down moment caused by the full-throttle acceleration and the controller's stabilized mode counteracting it leads to the oscillation that reflects in the acceleration performance. Modifications to the mounting supports can be explored to align the thrust vector with the CG, mitigating this oscillatory behavior.

6. Conclusions

In this thesis, hardware upgrades and a flight testing campaign have been carried out on an eVTOL drone entirely designed and built at *Politecnico di Milano*. Several limitations, some of which were highlighted in previous theses, necessitated the enhancement of the drone's systems. From an aerodynamic perspective, both the wing and tail have been resized to match the increased maximum take-off mass of the aircraft. In this process, a structural redesign was also performed, resulting in a much stiffer wing and a lighter tail. This allowed to overcome aeroelastic issues faced during the experimental campaign.

Simultaneously, the limits of forward propulsion was evident: the propellers initially mounted for forward flight were unable to provide sufficient thrust for acceleration. Through research and wind tunnel testing, these propellers were substituted with better performing ones. The wind tunnel data has been utilized to develop a model for accurate thrust estimation, which has been used in the data analysis of the following flight test campaign.

The next step undertaken is a specific flight test campaign outdoor, conducted both in multirotor and in fixed-wing modes. The tests performed encompassed transition and backtransition tests, outdoor hover endurance tests, stall speed determination, drag polar estimation, and specific excess power performance determination.

The transition and backtransition phases have been progressively explored and deep understanding of the aircraft's dynamic during these maneuvers has been achieved. Further exploration of the controller blending, *i.e.,* the airspeed at which both multicopter and fixed-wing controllers output start to blend together, and its effect on the transition is advised given the unexpected action of the elevator that has been encountered.

The fixed wing testing allowed to identify the stall speed of the aircraft, its aerodynamic characteristics and the excess power performance; these key aspects have been compared with the preliminary design values and the numerical predictions obtained in the first stages of the thesis. Among the results, the most critical one was the parabolic drag polar of the aircraft: data obtained in two different periods of flight testing (namely, July and September) presented some discrepancies in the drag coefficient; at the moment these discrepancies are attributed to difficulties in the stabilization of the aircraft in the near stall airspeed region. Further testing and comparison are recommended for future work.

Key considerations for future developments include:

- enhancement of the currently employed model for numerical aerodynamic simulation in OpenVSP to achieve a better estimation of the drag characteristics of the aircraft. Optionally, the adoption of more advanced software should be explored;
- upgrading the batteries to 6S models, with a consequent upgrade of the propulsive system, to reduce consumption and enhance overall performance (mainly in multicopter mode);
- improving the flight testing procedure with the addition of custom flight modes in PX4 autopilot to automate the execution of test maneuvers and performing the experiments at a larger airfield to allow for better stabilization during the tests.