Preliminary Design and Testing of a VTOL Light UAV Based on a Box-wing Configuration

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ABSTRACT

Since early 1950s convertiplanes have been studied for approaching to Vertical Take-Off Landing, but a lot of concern was about safety. Nowadays, these architectures are also starting to catch on in civil application thanks not only to the development of more reliable flight control systems but also to the possibility of integrating aircraft disruptive configurations. This paper aims to present a preliminary study on unconventional configuration based on the Best Wing System concept by L. Prandtl. The developed Unmanned Air Vehicle is called "TiltOne" because it can tilt its wings by 90 degrees, switching from multicopter configuration to box-wing configuration. The preliminary design has been addressed from several points of view: a conceptual design has been carried out thanks to in-house optimization tool; aerodynamic performances, propulsion design, and mechanical design have been addressed in order to make the prototype for preliminary vertical flight test. The aerodynamic configuration is helpful for endurance and payload performance; however, particular attention must be paid to the propeller choice to reduce current consumption during the mission.

1 INTRODUCTION

Convertiplane are vehicles initially developed in 1950s and 60s to investigate unconventional configurations capable of Vertical Take Off and Landing (VTOL). The first developed prototypes were the Hiller X-18 (tiltwing), the Vertol VZ-2A (tiltwing) and the Curtiss-Wright X-19A (tiltrotor), ancestor of the more "recent" Canadiar CL-84 and Bell-Boeing V-22 Osprey. The development of these projects, mainly under experimental military programs, highlighted how the conversion can be very critical, so the typical conversion corridor has to be deeply investigated.

Nowadays, these architectures are catching on in civil application, but a deep study has to be done for the development of more reliable flight control system and the integration of disruptive aircraft configurations. For example, Airbus [VI] and Uber [VII] are developing VTOL aircraft for the conception of Urban Air

Mobility (UAM). Nevertheless, the transition phase (from multicopter to fixed-wing configuration and vice-versa) is a hard challenge and a lot of control techniques have been developed to overcome the problem [12].

A promising disruptive configuration is the so-called “box-wing” which is based on the Best Wing System concept by L. Prandtl. This configuration, which in honour of Prandtl researchers at University of Pisa called “PrandtlPlane” ([4],[5]), shows several advantages: high efficiency, smooth post-stall behaviour, good damping in pitch dynamic, good structural stiffness, and the possibility to allocate surface controls in a different way (e.g., two counter-rotating elevator can be placed on the two wings in order to obtain a pure pitch control). For the previous reasons this configuration is very interesting for both military and civil [VIII] transportation.

The Unmanned Air Vehichle (UAV) presented in this work has been called “TiltOne” because of the capability of tilting its wings by 90 degrees and switching from multicopter to fixed-wing configuration. It is a tilt-wing, with PrandtlPlane configuration in forward flight, capable of taking off and landing vertically. This study focuses on the preliminary design of the UAV which involves several design areas. The conceptual design has been addressed with an in-house optimization code taking into account aerodynamic, propulsion, and flight mechanic. By the evaluation of the aerodynamic performance it was possible to define the constraints for the propulsion system. A proper mechanical design has been done in order to define the main components for the manufacturing. Thanks to its modularity, a preliminary flight test has been completed (without wings) defining the main parameters of the flight controller in multicopter configuration.

2 LAYOUT OF THE TILTONE

The TiltOne. is a tilt-wing, with four mounted propellers, capable of vertical take-off, vertical landing, and forward flight tilting both wings and propellers around the wing axes. Its configuration is relatively different respect to other convertiplanes (e.g. SUAVI [1] or QTW of Chiba University [11]); in fact it has two tilting wings (one forward and one backward) mounted on different heights: the forward wing is on the same level of the fuselage whereas the rear one is higher, so there is a vertical gap (h) between the two wings. Generally, for a box-wing configuration, the parameter indicating the vertical gap is the ratio h/b (where b is the span); the induced drag reduction is strongly dependent by the vertical gap and the lift distribution, as shown by Prandtl [13]. With a symmetrical lift distribution is possible to obtain the so-called “Best wing system”, the configuration with the lowest induced drag and the maximum lift-to-drag ratio (also referred as aerodynamic efficiency). This configuration can allow different advantages verified in previous works ([6], [7] and [8]), as:

- A smooth post-stall which promises a better aircraft behaviour near the transition phase.
- A higher aerodynamic efficiency hence an increase of flight endurance or payload capabilities.
- An enhancement of structural stiffness.
- A damped dynamic pitch due to the wing position along the longitudinal axis [14].

The PrandtlPlane, as shown in previous works ([6],[7]), is also capable of Conventional Take-Off and Landing (CTOL). We believe that this configuration can have some advantage in the transition phase for the smooth post-stall behaviour, and it can be adopted for improving range or payload capability (for the higher aerodynamic efficiency). Thanks to its features, it seems reasonable to assume that the PrandtlPlane can be used in both military and civil application, in particular for improving safety in critical military operations.

3 CONCEPTUAL DESIGN

DROPT (DRone OPtimization) is an in-house optimization tool developed to select the best parameter combination for the design of an aircraft with box-wing configuration. DROPT can be applied to the design of different aircraft categories: from small UAV to general aviation. The optimization runs one variable at time, so it is possible to choose for each simulation one of the following objective functions:

- Maximizing the endurance for a given mission profile.
- Minimizing the energy consumption in the mission.
- Maximizing the cruise speed.
- Maximizing the payload.

The optimization problem is complete if the constraints equations and the range of optimization variables are defined. Several non-linear constraints equations have been defined (e.g. geometry, maximum current absorbed by the motors, and minimum available thrust); it implies that a proper algorithm has to be selected in order to solve the problem, so a Genetic or Non-Liner Programming (NLP) algorithm can be selected. The optimization variables for this problem are defined as follow: number of motors or propellers (N), propeller diameter (D), propeller advance ratio (J), propeller static thrustcoefficient (CT_0), wingspan (b), wing chord (c), motor speed in hovering and cruise (n_0 and n), and the angle of attack (α). The TiltOne can afford both conventional and unconventional mission; it can take-off like a "fixed-wing" aircraft or like a rotorcraft. In this work an unconventional mission has been chosen. The mission profile (depicted in Figure 3-1) is divided into three parts: in the first one the UAV takes-off with a vertical speed (Vz); when the right altitude (z_{cruise}) is reached the velocity gradually changes; the vertical speed goes to zero, in the meanwhile, the horizontal speed goes to the cruise speed (Vx_{cruise}). In the third phase, the horizontal and vertical speeds mutually change again, and the aircraft lands. The time for take-off and landing is fixed while the cruise time is the variable to be optimized.

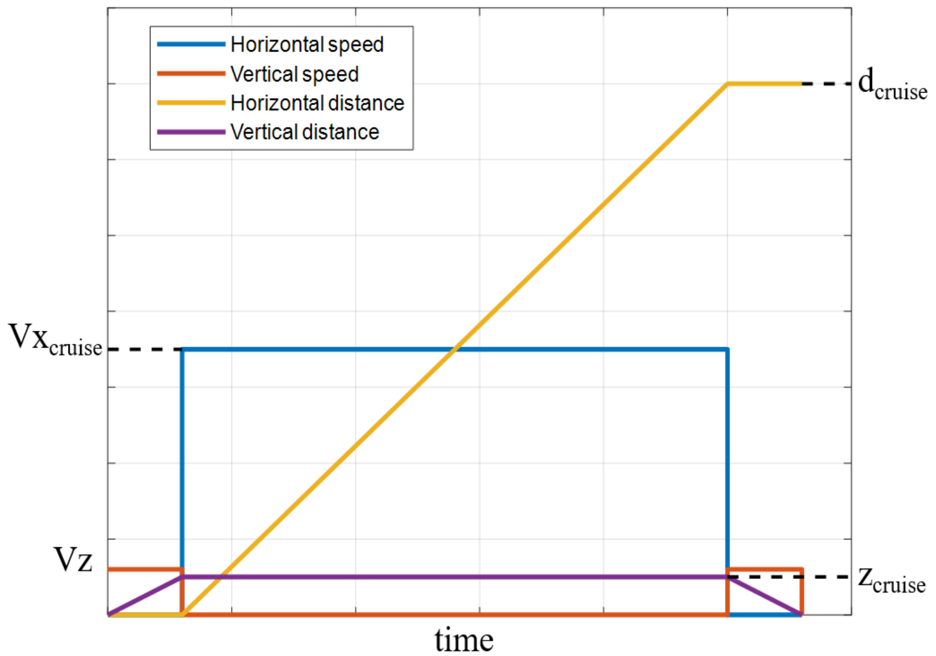

Figure 3-1: Mission profile for the TiltOne

The following optimization problem has been formulated:

$$
\begin{cases}
min - t^2 \\
T_0 / MTOW \geq K_0 \\
F_x / Drag = 1 \\
F_y / MTOW = 1 \\
RPM_{required} \leq RPM_{allowed} \\
NK_{span} D \leq 2b \\
J_{required} \leq J_{max} \\
P_{motreq} \leq P_{motormax} \\
AR \leq AR_{max} \\
I_{required} \leq I_{max} \\
n \leq N_{parM} \\
l_b \leq x \leq u_b
\end{cases}
$$

- $T_0/MTOW \geq K_0$ defines that the static thrust T_0 must be higher than the MTOW. An extra thrust of about 20% is requested.

- MTOW is the maximum take-off weight. It is calculated according the following equations

$$
\begin{cases}
MTOW = W_{pay} + W_{struct} + W_{elect} \\
W_{elect} = W_{bay} + W_{props} + W_{mot} \\
W_{struct} = W_{wing} + W_{fus} \\
W_{batt} = E / E_{spec} \\
W_{props} = 0.0005 D^2 \\
W_{mot} = 0.0001 I^2 + 0.001 I \; if \; I \leq 90\,A
\end{cases}
$$

W_{pay} is the payload weight and is about 300g. W_{struct} is the structural weight and is composed by the wing (W_{wing}) and the fuselage (W_{fus}): the first is proportional to the wing surface (measured in m^2) while the second is fixed. W_{batt} is the weight associated to battery; it depends on the total requested battery energy (E) and the specific battery energy (assumed as E_{spec} = 185 Wh/kg). W_{props} is the propeller weight depending on the propeller diameter (D measured in inch). W_{mot} is the weight associated to the brushless motor; the relationship is based on the interpolation of data of the Hacker motors datasheet [IX].

- $F_x/Drag = 1$ and $F_y/MTOW = 1$ are the equilibrium equations along the horizontal and vertical direction. We assumed that:

    1. The aircraft is approximated like a material point

    2. The aerodynamic drag coefficient is defined according the classic formula [2]

$$CD = CD_0 + KC_L^2 = CD_0 + \pi C_L^2/(AR\,e)$$

AR is the aspect ratio, and e is the Oswald coefficient; it is lower than unit for classic planar configuration and is bigger than one for non-planar wing system ([9],[10]). The forces included in the equilibrium are the aerodynamic drag and lift, the propeller thrust, and the aircraft weight.

- $RPM_{required} \leq RPM_{allowed}$ defines the maximum required angular rate ($RPM_{required}$) limited by the allowed angular rate ($RPM_{allowed}$). Generally, this value is defined by the manufacturer (APC in this case), so the limit was defined [I]. The maximum angular speed reached depends on the propeller-motor coupling and on the general feeding voltage; for this application a 6s configuration (22.2V) was chosen.

- $NK_{span} \leq 2b$ avoids the overlapping of the propeller disk. N and D are the number of the propellers and the diameter, respectively; b is the wingspan, and K_{span} is a real number bigger than one which guarantees a minimum clearance between the propeller tips.

- $J_{required} \leq J_{max}$ states that the propeller advance ratio ($J=V/(\Omega D)$ where V is the flight speed and Ω the angular speed) cannot overcome the maximum advance ratio of the selected propeller (J_{max}). An accurate database , where information on thrust coefficient (C_T) and power coefficient (C_P) are detailed, was created in order to select the right propeller. The procedure necessary for the calculation of the propeller is:

    1. Calculate the minimum static thrust with $T_0=K_0MTOW/N$.

    2. Calculate the static thrust coefficient $C_{T0} = T_0/(\rho n_0^2 D^4)$.

    3. From the database find the propeller with the closest static thrust coefficient and record the C_T-J and C_P-J curves (an example is depicted in Figure 3-2). If more than one propeller is eligible, the most efficiency has to be chosen.

    4. Calculate the cruise flight speed V=JnD.

    5. By using the propeller curve, the thrust and power coefficients, and the efficiency are extracted. The needed thrust in cruise and the power requested are evaluated as well.

- $P_{motoreq} \leq P_{motormax}$ limits the upper value ($P_{motormax}$, the maximum power available) of the absorbed motor power ($P_{motoreq}$). A motor database, like the propeller one, has been created in order to extract

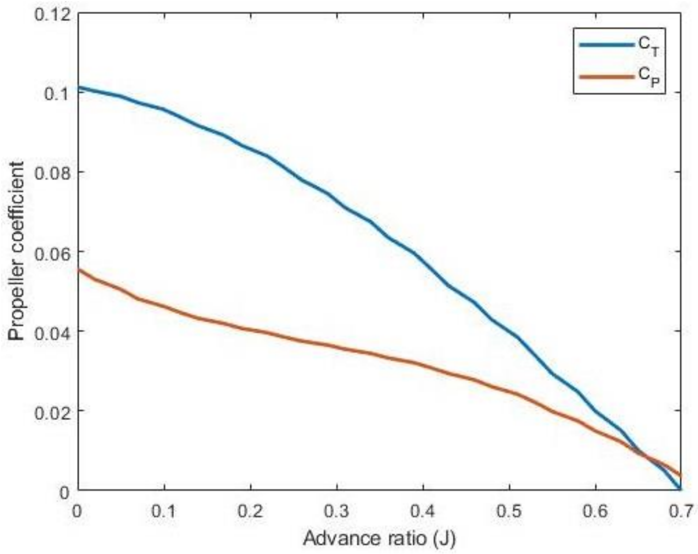

Figure 3-2: Thrust coefficient-advance ratio (blue) and power coefficient-advance ratio (red) curves

the main motor information: weight, motor voltage constant (K_v), absorbed current, maximum speed, and maximum current.

- $AR \leq AR_{max}$ limits the maximum aspect ratio (AR). In this DROP release there is no relationship between aspect ratio and weight, so the optimization reduces the chord dimension (because the drag has to be minimized) and increases the AR without a weight penalization. To avoid this problem a maximum aspect ratio has been fixed.

- $I_{required} \leq I_{max}$ limits the required current ($I_{required}$) to the maximum allowable current (I_{max}) of the motor. The required current is calculated once the required motor power has been determined:

$$I_{required} = P_{motor} / V_{motor} = P_{rops} K_v RPM / \eta_{motor}$$

- $N \leq N_{parM}$ limits the maximum number of batteries in parallel. The calculation passes through an energetic balance

$$E = P_{hov} t_{hov} + P_{cruise} t_{crusie}$$

P_{hov} and t_{hov} are the required power and the time spent during take-off and landing, respectively; P_{cruise} and t_{cruise} are the required power in cruise and the time spent in cruise. Knowing the capacity of a single battery (C) and the battery efficiency (η_{batt}), the number of batteries (n) is given by

$$N = E / (\eta_{batt} C)$$

- $\min - t^2$ is the objective function; it maximizes the flight time of the mission which, as said before, is divided in three parts: take-off (multicopter configuration), cruise (fixed-wing configuration), landing (multicopter configuration)

- x is the optimization variable vector which is low and upper bounded. For this application the following boundaries are defined:

$$\begin{cases} 0.1\,m \leq b \leq 1\,m \\ 0.15\,m \leq c \\ 100 \leq n_0 \leq 30000 \\ 100 \leq n \leq 30000 \\ 10° \leq \alpha \leq 85° \\ 2 \leq N \leq 8 \\ 30\,min \leq t \\ min(database) \leq C_{T0} \leq max(database) \\ 0.1 \leq J \leq 1 \\ 0.5\,m \leq D \leq 1\,m \end{cases}$$

3.1 Aerodynamic performance evaluation

The aerodynamic performances of the TiltOne have been evaluated at two different speeds: in particular, the lift distribution on the two main wings, the total drag, and the longitudinal stability are the main parameters. The performance evaluation in forward flight was conducted for two reasons:

- To verify its longitudinal stability at forward flight.

- To give an estimation of the stall speed, necessary as starting point for the transition phase.

Transition phase was not taken into account while take-off and landing performances were evaluated only from an energetic point of view. The effects of the propeller streams on the wings were not considered (it was verified to be negligible), the cruise speed was defined as 19.5 m/s, and the cruise height was settled to 500 meters. The main dimensions of the TiltOne are defined in Table 3.1-1.

Table 3.1-1: Main geometric dimension of the TiltOne

Main dimensions of the TiltOne	
Wing airfoil	Convex airfoil
Vertical stabilizer airfoil	NACA 0012
Wingspan [m]	1
Length [m]	1
Wing surface [m^2]	0.5
Mean aerodynamic chord [m]	0.25
Fuselage section [mm^2]	150×97

The lift induced drag was evaluated with AVL (Athena Vortex Lattice), a free potential flow solver [II]. In order to obtain a proper value of the total drag other contributes were considered: the drag polar of the profile (evaluated with the free software XFOIL [III]), the drag of the fuselage (evaluated on NASA experimental data [IV]), and the drag of the landing gears, calculated with Roskam procedure [3]. The efficiency curve resulting from the polar drag procedure estimation is depicted in Figure 3.1-4. It defines an optimum trim angle of ten degrees with a maximum efficiency of about six. The minimum speed allowable during cruise has been evaluated as well. The analysis, performed with AVL, was conducted with a trial and error procedure in order to define the speed such that the first airfoil reached the maximum lift coefficient (C_L). The calculated stall speed is about 15.6 m/s and, in Figure 3.1-3, the lift distribution relating to this condition is depicted. It is worth to outline that this calculation is very conservative. When the first airfoil reaches the maximum C_L (in the front wing) the other airfoils have a lower lift coefficient, so the front wing is not yet stalled, and the rear one is very far to this condition. It is reasonable assuming that the minimum speed is lower than the value calculated in this preliminary analysis and further analyses with high fidelity tools must be done.

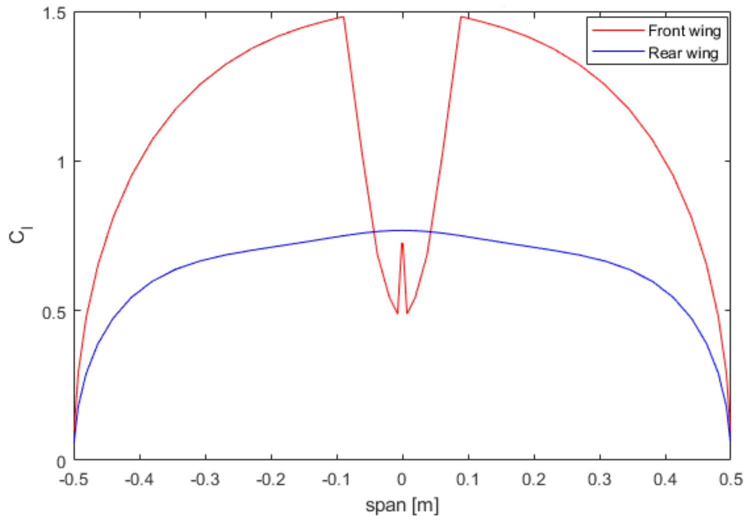

Figure 3.1-3: Lift coefficient distribution along the wingspan

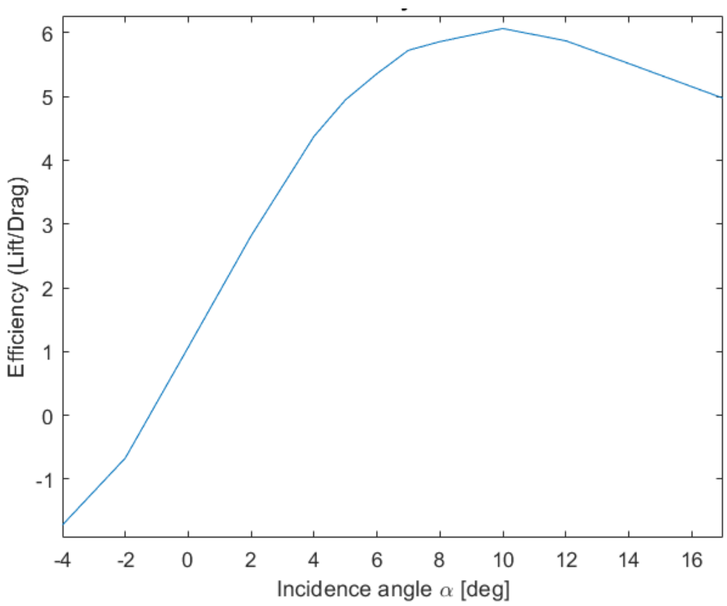

Figure 3.1-4: Polar curve of the TIltOne with respect to incidence angle α

3.2 Motors and propellers

The right choice of motors and propellers influences the performance of the UAV, and it depends also on the mission to be accomplished. As shown in Figure 3-1, the typical mission is divided in three main phases: take-off, cruise, and landing. In order to minimize the current consumption in each phase the right propeller pitch should be used: in cruise high pitch propellers while in take-off and landing low pitch propellers. Nevertheless, the adoption of a propeller pitch mechanism gets less safe the UAV and harder the construction, so a constant pitch propeller was adopted as best solution. The best propeller has been selected from the database of APC [I] according the following procedure:

1. Choice of a set of propellers

2. Calculation of the requested thrust for each propeller in cruise

3. Calculation of the propeller angular speed from the C_T-J and C_P-J curve

4. Calculation of the propeller efficiency

5. Choice of the propeller with maximum efficiency

The chosen propeller maximizes the overall efficiency because the energetic consumption in cruise (the longest phase of the entire mission) is minimized. The result of this strategy is a propeller of 13×6. The performances in hovering and cruise are presented in Table 3.2-2.

Table 3.2-2: Propulsion system performance at hovering and cruise

	Hovering	**Cruise**
Angular velocity [rpm]	7584	6700
Thrust coefficient (C_T)	0.0948	0.033
Power coefficient (C_P)	0.0358	0.024
Total power [W]	1417	569
Advance ratio (J)	0	0.53

A brushless motor with Kv of 490 has been tested with the selected propeller on a test bench in order to evaluate the maximum thrust and the relative current consumption. The experimental tests have provided as result a maximum thrust of 3.35 kgf and a relative current consumption of about 35A. Consequently, we decided to:

1. Choice two Li-Po battery 6s with 10000mAh and 15C (it can supply a maximum continuous current of 150A)

2. To not overcome the mass of 11 kg, in order to satisfy the minimum ratio between the maximum thrust and the weight

We evaluated the current consumption during each phase: it is of about 64A in hovering flight and 19A in forward flight. These two values have been calculated dividing the requested power at the electric motor by the tension of the battery (22.2V). As an example, by assuming two Li-Po battery 6s of 10000mAh and a typical mission of 5 minute in hovering flight the cruise time is about 34 min (using the 80% of the entire capacity). The TiltOne, flying at 19.56m/s, can cover a maximum distance of 40km.

3.3 Main Aircraft Components

The final configuration is depicted in the left of the Figure 3.3-5. Fuselage, vertical fin, structures connecting wing-tips, wings, motors, and propellers are the main components. The control surfaces are the ailerons, located in both wings and along the entire span, and the rudder located behind the vertical fin fairing. Motors and propellers are located at the midspan of the wings in order to avoid contact between propellers and the wing-tip surfaces. The connection between rear wing and fuselage is through the vertical fin. Two servomechanisms, located in the front and rear part, allow moving the two wings in order to change configuration. The two wings rotate along two fixed pipes (one for each wing) which together with fuselage and bulkheads make the load-bearing structure, depicted in the right of the Figure 3.3-5.

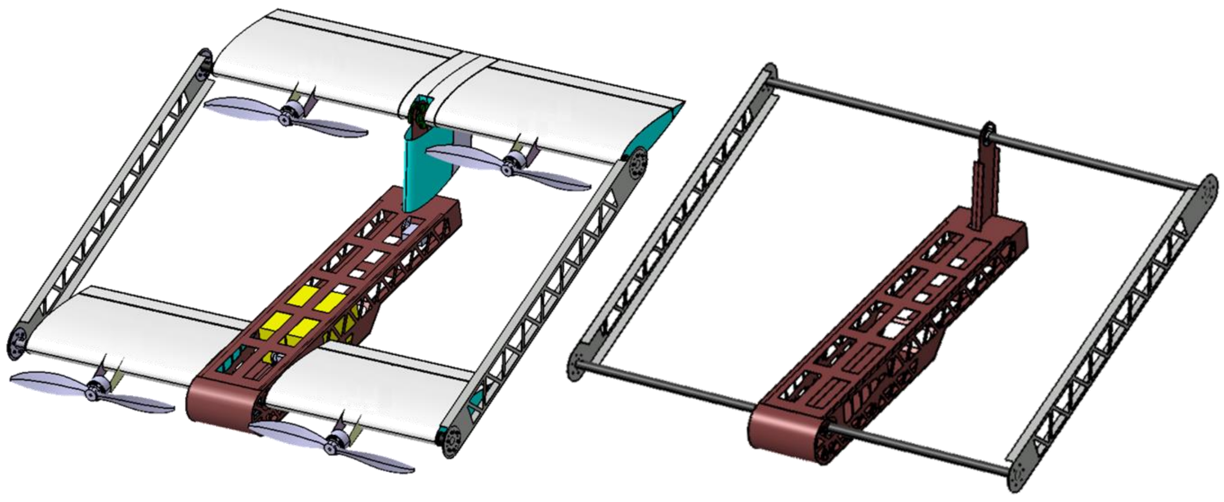

Figure 3.3-5: Final configuration of the TiltOne (left) and the load-bearing structure (right)

3.3.1 Fuselage and wing-tip connection

Fuselage and "bulkhead" are depicted in Figure 3.3.1-6. Both structures are made of aluminium 2024-T3 of 0.8mm of thickness and the lightening holes, made with water jet cutting machine, allow to save weight. The shape of the fuselage has been chosen in order to locate in the front part two Li-Po batteries of 10000 mAh, so in order to have a rigid structure the fuselage is stiffened with wood ribs (not depicted). The wing-tip connections create a closed box enhancing the global stiffness and, if properly careened, the reduction of the induced drag (making the "Best Wing System").

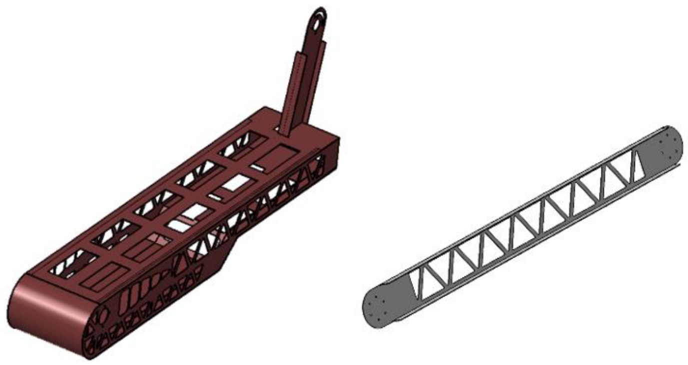

Figure 3.3.1-6: Fuselage of the TiltOne (left) and "bulkhead" (right)

3.3.2 The tilting mechanism

The TiltOne can switch between two configurations: multi-copter and fixed wing. In the first configuration the wings are rotated by about 90° respect to the fuselage, so landing, take-off, and hovering are possible. In the second configuration the wings are parallel to the fuselage, and TiltOne can fly with a high aerodynamic efficiency. The switch from a configuration to another one is through two servo motors, one for each wing. The mechanism is composed by a fork which, joined with a rod, connects servomotors and wings. The rotation of the servomotor is transmitted by friction (thorough a custom flange) to the rotating pipe of the wing. The bushing between the rotating and the fixed pipe allow a low friction dynamic (with less work for the servomotor). The TiltOne in the two configurations and the tilting mechanism are depicted in Figure 3.3.2-7.

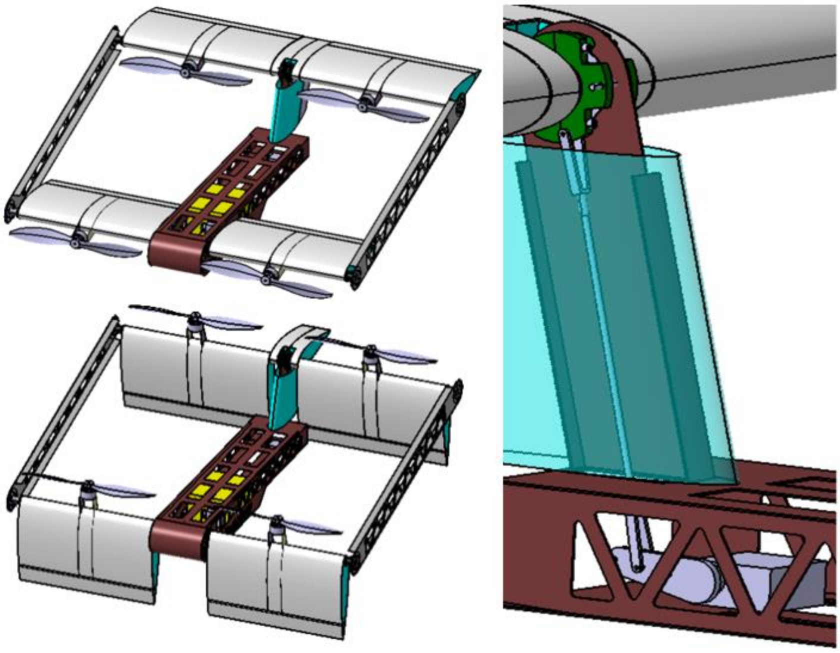

Figure 3.3.2-7: TiltOne in forward flight (top left) and hovering (bottom left). A schematic view of the tilting mechanism of the rear wing (right).

4 PROTOTYPE AND FLIGHT TEST

Before starting with the prototyping phase, a structural analysis has been performed on the entire structure in order to verify it. The simulation showed a maximum load factor of the load-bearing structure of 24.6. The Aluminium sheets of the fuselage are joined by riveted stiffeners. The internal wings are made of polyurethane covered by Obece wood while the ailerons are made of Balsa wood. The manufactured prototype is depicted in Figure 4-8. Manually and autonomous flight tests (shown in Figure 4-9) of the TiltOne in multi-copter configuration (without wings) have been accomplished in order to set-up the flight controller which is a commercial autopilot (Pixhawk 2.1 [V]). A PID tuning has been accomplished and an automatic flight has been performed in order to obtain a better response of the UAV.

Figure 4-8: Rendering (top) and first prototype of the TiltOne (bottom)

Figure 4-9: Maiden flight of the TiltOne

5 CONCLUSIONS AND FUTURE WORK

A preliminary study on a disruptive configuration based on the Best Wing System Concept have been accomplished. The flying machine, called TiltOne, can rotate both wings propulsion group and afford to do unconventional missions (like VTOL). The preliminary design has been developed under several points of view:

- the optimization code has allowed to deal with a preliminary conceptual design. Several objective functions can be defined according the Top-Level Aircraft Requirements (TLAR).
- the aerodynamic analysis allowed to evaluate efficiency and lift distribution. This analysis was necessary in order to choose the best motors and propellers (a compromise between the hovering and the forward flight).
- the mechanical design allowed to define all the component for the prototype.
- flight tests have been conducted in the case of drone configuration; the test results have been totally satisfactory both manually and, with a commercial autopilot, automatically.

This prototype represents the first step for further studies for manned and unmanned application; in fact, DROPT can be used for small aircraft (UAV) as well as general aviation category.
A dynamical model of the TiltOne both in cruise and take-off phase will be investigated. It will be defined in order to develop the flight control system for the transition phase. The TiltOne will be tested also in real environment in order to verify the efficacy of the control system in two different conditions: completely autonomous and manually piloted.

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