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Preliminary design of a Tiltwing UAV with a box wing configuration

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Abstract

In the last years, aircraft disruptive configurations have been studied on view to increase civil air transport and safety of flight and, also, to reduce air pollution and noise. One of the promising configurations is the so called box wing, based on the Best Wing System concept by L. Prandtl. This paper presents an application of the box wing to the case of an unconventional Unmanned Air Vehicle (UAV), called "TiltOne", because the two horizontal wings tilt together with the engine-propeller groups, so allowing us to take off and landing vertically and to fly as a fixed wing airplane during cruise. TiltOne is full electric, with distributed propulsion; the preliminary design has been carried out by using a home-made optimization code, where aerodynamics, controls and electric propulsion are taken into account. After defining the airframe configuration, aerodynamic analyses have been performed, electric motors and propellers and batteries are defined; finally, a detailed analysis of the mechanical components is presented and a prototype has been manufactured. Preliminary vertical test flight has been carried out successfully.

1. Introduction

The continuous growth of the aerospace civil market and the request of a more sustainable way of transportation is leading to study aircraft disruptive configurations [2] to improve the aircraft performances from efficiency, safety, noise, noxious emissions viewpoints, according to the report "Vision 2050" [17]. The change of air mobility regards all capacities and range, from the long-medium and the short range one. In the case of the short range air transport, new aircraft configurations with the capability of hovering and level flight are studied as, for example, Airbus with Vahana project [9] and Uber [10], in order to create a new concept of urban air taxi transportation. The air taxi is a Vertical Take Off Landing (VTOL) vehicle, capable of carrying a limited number of passengers (from two to four) along a short range and to reduce the traveling time. These new vehicles match the good properties of rotor-craft and fixed-wing configurations, allowing a transportation with a lower energy consumption compared to helicopter: nevertheless the transition from hovering condition to level flight and vice-versa is a challenge and numerous control techniques have been developed so far [16].

Some European projects are currently ongoing, like Parsifal project [18], to match the requests of "Vision 2050" report, thanks to the box wing aerodynamic configuration named PrandtlPlane (PrP). The PrP configuration is based on Prandtl's paper [1]; two horizontal wings as a biplane are connected each other at their tips with properly designed vertical wings, to minimize the induced drag. The PrP configuration exhibits several advantages [4–6]: smooth post-stall behaviour, higher aerodynamic efficiency, structural stiffness, damped dynamic pitch behaviour. These performances are valid among others also for small airplanes like Light Sport Aircraft (LSA), Ultra Lights (ULM) or Unmanned Air Vehicle (UAV); in line with these an innovative box wing convertiplane has been patented [19]. Two innovative aspects can be underlined: (a) the new aerodynamic configuration to reduce the total drag and, thus, enhancing the time flight, and (b) the adoption of the Distributed Electric Propulsion (DEP). DEP, according some works [20,21] and important companies [10], is a useful and strategic methodology for increasing efficiency and safety and for reducing noise and noxious emissions. The adoption of DEP architecture allows us to fulfill the new requirements and also to conceive the new urban air vehicles called "air taxi". The importance of the aerodynamic configuration stems not only for improving the endurance time but also for the smooth post-stall behaviour to improve the aircraft performance during the transition from hovering to level flight and vice-versa.

In this work a technological demonstrator of the patented air taxi, called TiltOne, is presented: TiltOne is a tilt-wing vehicle with PrP configuration capable to take off and landing vertically and to fly as a fixed wing aircraft during cruise. This UAV lays the foundation for a future air taxi however it can be used for surveillance or monitoring operation as well. A preliminary design has been addressed by means of: a home-made optimization code based on genetical algorithms or gradient based which takes us to account aerodynamic, controls and electric propulsion. The architecture has been defined with a proper aerodynamic design; propulsion and mechanical designs have been considered in order to define the components necessary for the manufacturing. A first prototype has been manufactured and a preliminary flight test has been accomplished in order to define the main parameters of the flight controller as a multicopter only.

2. DROPT

DROPT(DRone OPTimization) is a toll developed by Skybox Engineering to select the best parameter combination in the design of a box wing tilting drone. The main design parameters for this problem are: wingspan (b); wing chord (c); motor speed in hovering (RPM_{hov}); motor speed in cruise (RPM_{cr}); cruise angle of attack (α); number of motors/propellers (N); endurance (t); propeller static thrust coefficient (C_{T0}); propeller advance ratio (J); propeller diameter (D). Several objective functions can be defined useful for the drone sizing, namely:

- maximizing the endurance given the mission profile;
- minimizing the energy consumption in the mission;
- maximizing the cruise speed;
- maximizing the payload;

The different variables are in some relationships each other; some examples are the following: geometry constraints, maximum electric current absorbed by the motors, minimum static thrust to accelerate the drone, etc. All these relationships constitute the set of problem constraints which are non-linear and, thus, a suitable algorithm is needed to deal with these functions. Genetic algorithms or NLP (Non Linear Programming) algorithms like SQP (Sequential Quadratic Programming) can be selected to solve the problem. The overall hovering time is fixed in 10min whereas the cruise endurance is the variable to be maximized. A greater flight time is possible with higher aerodynamic efficiency and with batteries with larger capacity (heavier). In the present model, the aerodynamic efficiency is calculated with a parabolic polar assumption and with the well-known relationships for the induced drag

$$CD = C_{D0} + KCL^2 = C_{D0} + \frac{\pi}{ARe} CL^2 \tag{1}$$

AR is the wing aspect ratio, e is the Oswaldâs coefficient. $0 < e < 1$ for planar wing systems, $e \geq 1$ for non-planar wing systems [12, 13]. Moreover the drone is approximated as a material point moving on a plane where the equilibrium equations are expressed in the two coordinates of a Cartesian reference system (X,Y). Within this framework, the following optimization problem has been defined:

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

The above constraints have the following meaning:

- $min - t^2$ defines the objective function, in particular the maximization of the endurance. The TiltOne can afford to do conventional mission (like a CTOL) or unconventional mission (like a VTOL). In DROPT an unconventional mission has been considered and defined in the following parts:

  1. Take off (hovering maneuver)
  2. Cruise (transition from hovering to level flight)
  3. Landing (hovering maneuver)

  The time for take off and landing is fixed, the cruise time is the optimization variable.

- $T_0/MTOW \geq K_0$ states that the static thrust (T_0) shall be K_0 greater than the Maximum Take Off Weight (MTOW); in the present case, $K_0 = 1.2$ so that a 20% of extra thrust respect to MTOW shall be available for the vertical take off.

- $F_Y/MTOW = 1$ and $F_X/MTOW = 1$ are the two equilibrium equations along the horizontal (X) and vertical (Y) axes. Forces F_X and F_Y include propeller thrust and aerodynamic lift and drag.

- $RPM_{required} \leq RPM_{allowable}$ limits the maximum speed required ($RPM_{required}$) to the maximum allowable spinning speed ($RPM_{allowable}$). The maximum allowable speed is related to structural integrity of the propellers or to the maximum available speed of the motor given the

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feeding voltage; the maximum propeller speed is given by the propeller manufacturer ([7], in the present application). An important parameter of brushless motors is the $K_V(rpm/V)$ factor which gives the no-loading speed of the motor[1]; the voltage (V), in turn, is determined by the number of batteries in a series arrangement. For the present case the 6S configuration with a maximum available voltage of 22,2V has been fixed in advance as preferred solution.

- $ND/2K_{span} \geq b$ is a geometrical constraint aiming at avoiding the overlapping of two adjacent propeller disks, where N is the number of propellers, D is their diameter, and $K_{span} \geq 1$ is a factor to keep some clearance between the propellers

- $J_{required} \leq J_{\max}$ limits the propeller advance ratio to the maximum value of the selected propeller. The propeller advance ratio is defined as J=V/(Ω D), where V is the flight speed, Ω is the propeller speed in rps (rotation per second), D is the propeller diameter. From the propeller charts, once the advance ratio is known, it is possible to obtain the thrust and power coefficients and, in turn, the thrust coefficient C_T and the power coefficient C_P, being:

$$C_T = T/(\rho n^2 D^4)$$
$$C_P = P/(\rho n^3 D^5)$$

  A propeller database built from the data of the manufacturer ([7]) has been implemented in the DROPT program. The program selects the propeller with the closest thrust coefficient at the given advance ratio among the available propellers in the database. A more general approach to define the propeller could be applied by using a general propeller performance solver, with the optimization of the airfoil camber and the chord distribution along the span as design parameters.

- $P_{motreq} \leq P_{motmax}$ limits the absorbed motor power (P_{motreq}) by the maximum available power of the motor (P_{motmax}). In analogy with the propellers, a surrogate database of motors (in this case from [8]) has been implemented as well. Starting from the raw data, different models have been constructed wit the motor torque as input, taking weight, K_V factor, max current, max power, max rotating speed into account.

- $I_{required} \leq I_{\max}$ 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:

$$\begin{aligned} I_{required} &= P_{motor}/V_{motor} \\ &= (P_{motor}K_V)/RPM \\ &= (P_{propeller}K_V/\eta_{mot})/RPM \end{aligned}$$

  where η_{mot} is the motor efficiency during the operating condition.

- $n \leq N_{parM}$ limits the maximum number of batteries in parallel. This number is related to the capacity required to accomplish the mission which, in turn, is related to the absorbed power and to the mission duration (i.e. the energy consumption). The limit has been selected on a basis of the battery commercial availability (typical batteries arrangements are 1P/6S or 2P/6S).

- $AR \leq AR_{max}$: wing aspect ratio (AR) is limited by the maximum allowable one (AR_{max}). Indeed, the maximization of the flight time implies the minimization of the consumed energy and, therefore, the maximization of the wing aspect ratio (in order to minimize the induced drag). In a complete aerodynamic model, where the wing weight would be correlated with the wing aspect ratio, this constraint would be automatically embedded in the process, because solutions with high aspect ratios would be weight penalized. In the present release of DROPT code, the wing weight model is prescribed on the basis of weight/m^2 of the wings and a given weight of the fuselage (coming from the manufacturing of a prototype; no other reference data are available from the literature); these values are known with high accuracy. In the present work, based on the experience gained on similar airplanes, a density of 5 kg/m^2 for the wing and a fixed weight of 1.3 kg for the fuselage have been assumed. In the optimization process of the aerodynamic performances, the wing chords tend to be minimized to reduce the drag, independently from the structural constrains; for this reason, the maximum aspect ratio has been limited to $AR_{max} = 10$.

- The MTOW is given by the following equations:

$$\begin{cases} MTOW = W_{pay} + W_{struct} + W_{elect} \\ W_{elect} = W_{batt} + W_{prop} + W_{mot} \\ W_{struct} = W_{wing} + W_{fus} \\ W_{batt} = E/E_{spec} \\ W_{prop} = 0.0005D^2 \\ W_{mot} = I^2/10^4 + I/10^3 \qquad ifI \leq 90A \end{cases}$$

  W_{pay} is the payload fixed to 300gr; W_{struct} is the weight composed by the wings (W_{wing})

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[1] the no-loading speed means the angular velocity of the shaft of the brushless motor for a given feeding voltage if no propeller is attached to it

and fuselage(W_{fus}), in particular the weight of the fuselage is fixed and weight of the wings is proportional to the wing surface (measured in m^2);W$_{batt}$ is the battery weight given by the ratio between battery energy (E) and the battery specific energy (E_{spec}): E_{spec} has been set to 185 Wh/kg and E has been calculated by the sum of the power required during the hovering and cruise phases; W_{prop} is the propeller weight and D is the propeller diameter in inch; W_{mot} is the weight associated to the brushless motors, it is based on interpolation of Hacker motor datasheets.

- l_b, u_b are lower and upper boundaries respectively, to limit the research space of the solution. For the present calculations, the following values have been fixed:

$$\begin{cases} 0.1m \leq b \leq 1m \\ 0.15m \leq c \leq Inf \\ 100 \leq RPM_{hovering} \leq 30000 \\ 100 \leq RPM_{cruise} \leq 30000 \\ 10 \leq \alpha \leq 85 \\ 2 \leq N_{mot} \leq 8 \\ 30min \leq t \\ min(database) \leq C_{T0} \leq max(database) \\ 0.1 \leq J \leq 1 \\ 0.05m \leq D \leq 1m \end{cases}$$

Note that the boundary on the J here is defined in different way from the constraint in equation (2). More specifically, J_{max} in the constraint equation, is a function of the selected propeller and, therefore, is a general non-linear constraint changing during the optimization process, whereas the boundary is fixed in order to initialize the optimization problem.

3. Layout of the TiltOne

The UAV TiltOne is a quad-tilt-wing capable of vertical take-off and landing as a drone, and capable of forward flight as a fixed wings aircraft; this is possible by rotating both wings together with propellers around the wing axes. This configuration is different from other convertiplanes (like, for example, SUAVI [11] or QTW of Chiba University [3]). The front and rear wings are not positioned on the same plane; the front wing crosses the fuselage and the rear one is shifted upward in order to have a non-dimensional vertical gap, h/b, where b is the span. The induced drag reduction depends on h/b and, also, by the presence of the vertical wings connecting the front and rear wing tips. Thus, from an aerodynamic point of view, we can achieve the so-called “Best wing system”, the architecture proposed by Prandtl with the maximum possible efficiency among any other conventional configuration. This configuration can allow different advantages, as:

- a smooth post-stall [4] allowing a better aircraft behavior near the transition phase;
- a higher efficiency and, hence, higher time of flight;
- an enhancement of structural stiffness;
- damped dynamic pitch due to the high moment of inertia along the pitch axis [6] due to the wing positions along the longitudinal axes.

Another advantage of the TiltOne is its capability to be a conventional take-off landing (CTOL) aircraft, as shown in previous works [4,5]. It is worth to stress how this configuration is helpful for the transition phase not only for the smooth post-stall behavior but also for the low stall speed due the higher aerodynamic efficiency.

4. Aerodynamic performances evaluation

The aerodynamyc performances of the TiltOne has been evaluated during the level flight as well as the low stall speed. The main dimensions of the TiltOne are defined in table 1.

Table 1
Main dimensions of the UAV TiltOne

Wing airfoil	Convex airfoil
Vertical stabilizer airfoil	NACA 0012
Wingspan	1 m
Length	1 m
Wings surface	0.5 m^2
MAC	0.25 m
Fuselage section	150x97 mm^2

The evaluation of aerodynamic performances in terms of lift distribution, efficiency and flight stability has been analyzed by using the software AVL. The airfoil $C_L - \alpha$ curve has been obtained with software XFOIL; by using the drag polar curve, it was possible to evaluate the profile drag in order to add this contribution on AVL. The effects of the propeller streams on the wings was not taken into account so far and the cruise speed for the analysis was settled to 19.5 m/s whereas the cruise height was settled to 500m so the Mach is about 0.06 and Reynolds number is about 322000. The induced propeller velocity has been evaluated “a posteriori” and, in accordance with the assumption, its value was verified to be negligible. The time of flight depends strongly on the aerodynamic efficiency. Other

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important factors are motors, propellers and aerodynamic airfoil. Propellers with a variable pitch would be the best solution; high pitch propellers allow to achieve higher speed in forward flight, while in hovering flight a low pitch is more suitable. A variable pitch introduces a high complexity from a mechanical point of view, so a constant pitch is suitable for an unmanned air vehicle application; the propellers are the best compromise between hovering and forward flight. Wing airfoil also influences the time of the cruise flight; the best choice would be a convex airfoil due to the high $C_{L\alpha}$ coefficient and, thus, the aircraft is trimmed at lower flight speed and the electric energy consumption is reduced. The drag polar has been obtained by evaluating the induced drag by means of AVL code and by taking also the drag generated by the fuselage and the landing gears into account. The drag given of the fuselage has been evaluated on the basis of NASA experimental data [14]; the drag generated by the landing gears is based on the procedures by Roskam [15]. The maximum efficiency, resulting from the polar depicted in figure 1, corresponds to a trim angle of 10°, which defines the trim configuration which maximizes the time of flight.

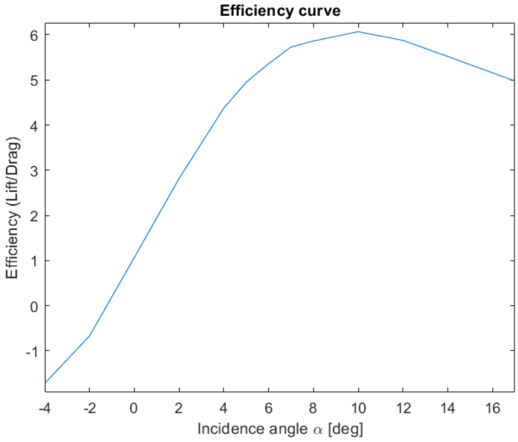

Figure 1. Drag polar curve of the TiltOne

A preliminary low speed analysis has been performed in order to evaluate the stall speed of TiltOne as well. The stall condition is assumed to occur when the first airfoil reaches the maximum value of the lift coefficient; this condition is conservative because, when the single airfoil reaches stall, the wing is not stalled yet. The analysis performed with AVL showed a stall speed of 15.6 m/s with an angle of attack of 17°. Figure 2 shows the lift distribution in an incipient stall condition which occurs on the front wing (it is more loaded than the rear one).

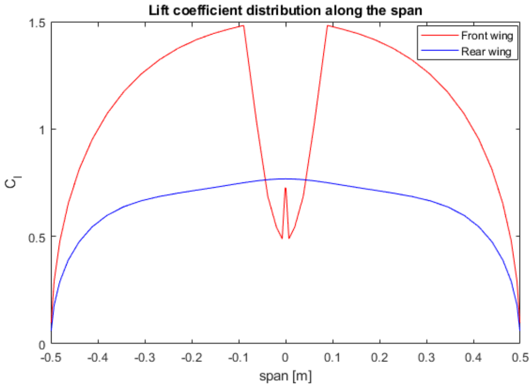

Figure 2. Lift coefficient distribution of the front(red) and rear(blue) wings for the TiltOne

5. Motors and propellers

The choice of motors and propellers depends on the mission to be performed; a typical mission of the present aircraft has different phases, namely: lifting and hovering; cruise; hovering and descending. TiltOne has a multi-copter configuration during the vertical flight and a fixed-wing configuration during cruise flight. The best possible propellers should be able to adapt the pitch according to the flight phases; these variable pitch propellers are well known. Nevertheless, as said before, it was preferred to simplify the solution by adopting a constant pitch. The design of these propellers should be based on a compromise between the multi-copter and the fixed wing configurations; pitch should be small during the multicopter phases of take off and landing in order to minimize the required current, and high during cruise. The best compromise is the propeller from [7] with a diameter of 13 inch and pitch of 6.5 inch: this propeller was chosen because it exhibits the maximum efficiency in level flight (a typical efficiency curve is shown in figure 3), allowing to enhance the time spent during this phase. The performances in hovering and cruise are presented in table 2.

Table 2
Performances of propeller APC 13x6,5

	Hovering	Cruise
Angular velocity [rpm]	7584	6700
Coefficient of thrust (C_t)	0,0948	0,033
Coefficient of power (C_p)	0,0358	0,024
Total power [W]	1418	569
Advance ratio (J)	0	0,53

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The motor coupled with the propellers is the T-motor U7-V2.0 KV490. The brushless motor coupled with the propeller 13x6.5 was tested on a test bench in order to evaluate the maximum thrust and the relative current consumption. The experimental maximum thrust of a single motor is 3.35 kgf and the relative current consumption is 35A. This test gave the following two important informations:

1. Li-Po batteries 6s with 10000mAh 15C capacity (supplying a maximum continuos current of 150A);
2. Assuming a weight of 8 kg, the minimum ratio between the maximum thrust and the weight is about 1.7.

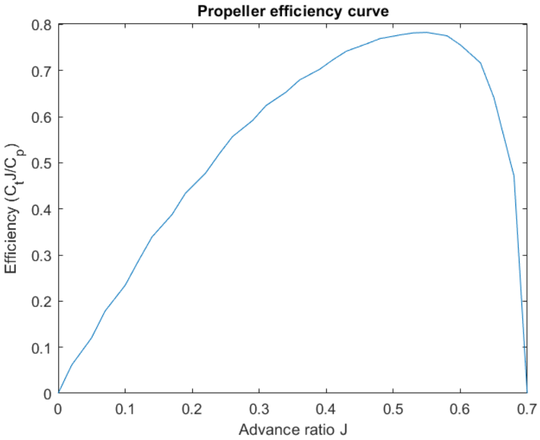

Figure 3. Propeller efficiency curve

In this configuration TiltOne has a current consumption of 64A in hovering flight and 19A in forward flight, where the consumptions are calculated by using the values in table 2 as follows: starting from the angular velocity, the advance ratio, J, can be calculated and, hence, the thrust and power coefficients can be evaluated on the typical propeller curve; once the coefficients are known, the total power, P, can be evaluated as:

$$P = C_p \rho n^3 D^5.$$

The ratio between P and the potential of the batteries gives the total current absorbed by the motors. As an example, by assuming a typical mission of 5 minute in hovering flight and using the 80% of the entire capacity, the cruise time is about 34 min, so that TiltOne can cover a maximum distance of 40km.

6. Aircraft configuration

The configuration of TiltOne is depicted in figure 4. The main components are: fuselage and vertical fin; vertical structures connecting wing tips; wings; motors and propellers. The motors and propellers are mounted at the midspan of the wings which is provided with a flight control surface (the aileron), along the entire span. The front wing is connected to the rear one by vertical structures connecting the wing tips; the rear wing is connected to the fuselage with the vertical fin; the vertical fin is provided with a rudder. A mechanism allows to move the two wings in order to change configuration (more details are provided later on).

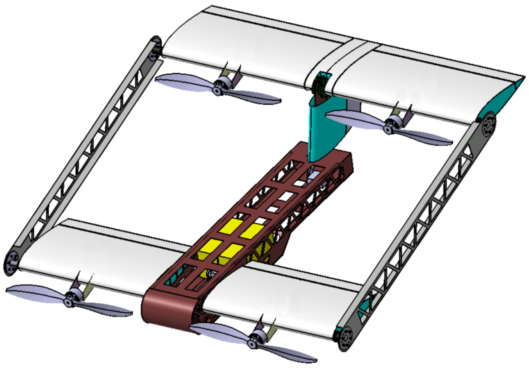

Figure 4. Axonometric view of the TiltOne

The load-bearing structure, depicted in figure 5, is composed by the fuselage, two concentric pipes and the vertical structures connecting wings' tips also called "bulkheads".

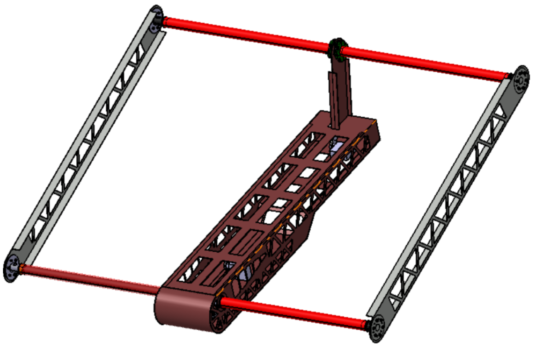

Figure 5. Axonometric view of load-bearing structure

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6.1. Fuselage

The fuselage, depicted in figure 6, is made with very thin aluminum 2024-T3 plate (0,8 mm thick) and stiffened by ribs; this structure is light and stiff at the same time. The shape of the fuselage has been chosen in order to allocate all the electronic components inside and, in particular, the front part is more voluminous in order to allocate the Li-Po batteries.

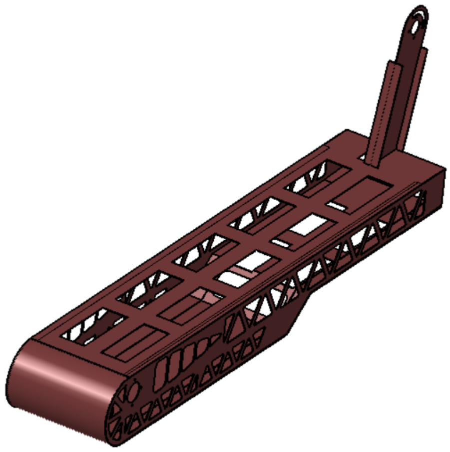

Figure 6. Axonometric view of the fuselage

6.2. Tip wings connections

The connection of the tip wings or "bulkheads" enhances the global stiffness and, after being suited with an aerodynamic covering, the bulkheads become the wings of the Prandtl's Best Wing System to minimize the induced drag. The skeleton in Figure 7 is made with a 0.8mm plate manufactured with a water jet machine.

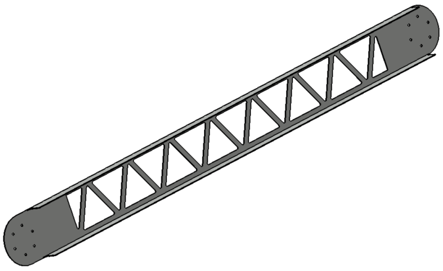

Figure 7. Axonometric view of the tip wings connections

6.3. The tilting mechanism

As said before, TiltOne has the two possibile configurations: multi-copter and fixed-wing. In the multi-copter configuration, depicted in figure 8, the wings are rotated by 90° respect to the fuselage. This configuration is used for landing, take-off and hovering.

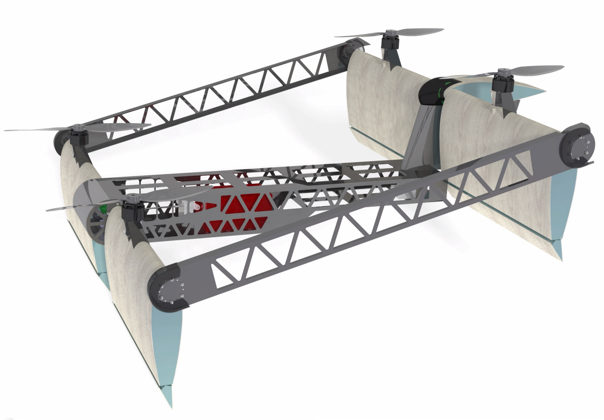

Figure 8. Rendering of the TiltOne in multi-copter configuration

In the fixed wing configuration, depicted in Figure 9, the wings are parallel to the fuselage and TiltOne can operate in forward flight with a high aerodynamic efficiency.

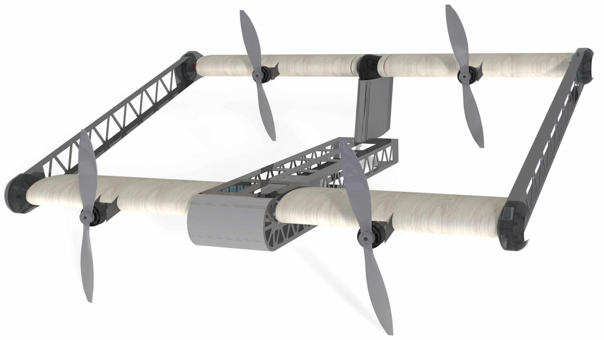

Figure 9. Rendering of the TiltOne in fixed-wing configuration

The configurations are changed by means of two servo motors, one for each wing. A fork joined with a rod connects servomotors and wings; the entire mechanism is depicted in Figure 10. The servo motor moves the fork, the fork rotates a custom flange (composed by

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two parts which wrap the external pipe by bolts) which rotates the external pipe thanks to the friction force generated by the bolts. The external pipe can rotate around the internal pipe thanks to the bushings located between the two pipes and allowing a low friction dynamics.

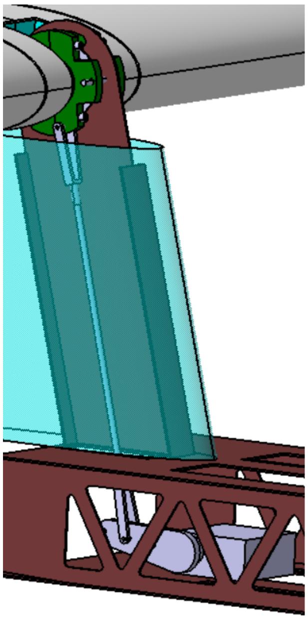

Figure 10. Tilting mechanism for the rear wing

7. Structural analysis

Structural analysis was conducted under aerodynamic and loads on the entire structure. The load-bearing structure used for the FEM analysis and depicted in figure 11, showed the need to introduce ribs inside the fuselage. The ribs, made of birch with thickness of 1 mm, were positioned with a constant distance of 75 mm in the forward zone and 150 mm in the backward one. The two pipes are made of carbon fiber. The birch is an orthotropic material while the carbon fiber is a transversely isotropic material; their properties[2] are showed in table 3. The carbon fiber orientation is 0°-90°, so the pipes are modeled with a sequence of piled sheet (thickness of 0,25mm) of 0°-90°-90°-0°. The model and the load distribution (the distribution load comes from AVL) are symmetric so a half model has been used in order to reduce time calculation. The result (Figure 12) show that the maximum stress is 12,3MPa near the battery zone. A compression stress acts on the upper surface of the fuselage so the maximum load factor without any buckling of the upper plate was evaluated as well. The simulation showed a maximum load factor of the load-bearing structure of 24,6.

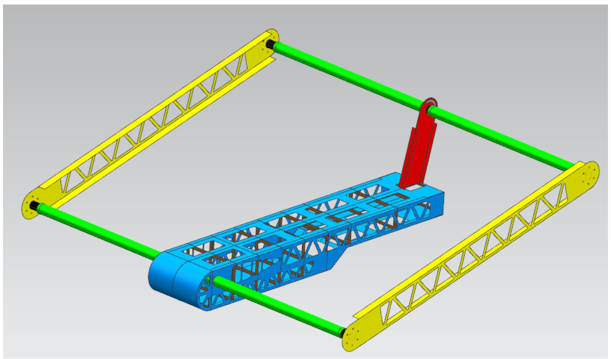

Figure 11. Load-bearing structure CAD model for FEM analysis

Table 3
Material properties of birch and carbon fiber

	Birch	Carbon fiber
E_x	16300 MPa	7646 MPa
E_y	1110 MPa	7646 MPa
E_z	620 MPa	142000 MPa
ν_{xy}	0,42	0,0368
ν_{yz}	0,43	0,0146
ν_{xz}	0,68	0,0146
G_{xy}	1180 MPa	2770 MPa
G_{yz}	190 MPa	2776 MPa
G_{zx}	910 MPa	2776 MPa

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[2] E is the elastic modulus, ν is the poisson coefficient, G is the shear modulus

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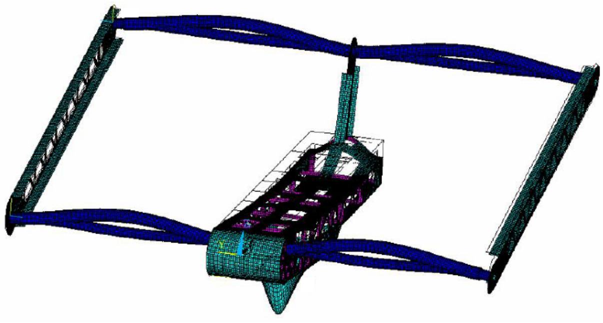

Figure 12. Deformation of the structure increased of a factor of 500

8. Prototyping and testing

The structure of the fuselage is made of Aluminum sheets, with thickness of 0,8mm joined by riveted stiffeners. The internal wings are made of polyurethane covered by Obece wood while the ailerons are made of balsa wood. This type of structure has a good strength/weight ratio and feasible for the manufacturing of TiltOne, depicted in figure 13. The main components like wing tips and fuselage has been cut by a water-jet machine.

Figure 13. Prototyping of the TiltOne

Flight tests of TiltOne in multi-copter configuration (without wings) have been performed in order to set-up the flight controller and define speed range and endurance performances, as shown in figure 14. The flight controller is a commercial autopilot (Pixhawk 2.1 [22]). In order to obtain a better response of the UAV a PID tuning has been accomplished and an automatic flight has been performed.

Figure 14. Maiden flight of the TiltOne

9. Conclusion and future work

An optimization code, DROPT, for the preliminary design of UAVs with tiltable wings of a box wing configuration has been set up; different objective functions can be chosen as, e.g.: maximum payload, maximum flight duration, etc. The aerodynamic analyses have been carried out by AVL code in the two conditions of multi-copter and fixed wings configurations. The flying machine studied in this work is a box wing aircraft with front wing connected to the fuselage and the rear wing mounted upward over a fin; the tip wings are connected by a structure to be covered with proper profile to create the best wing system. Both wings can rotate together with the engine/propeller groups in such a way that the same flying vehicle could become, when designed with a larger scale, a helicopter to take off and landing vertically, or a Short Take Off and Landing (STOL) or an aircraft (this configuration is patented as a "personal aircraft"). In fact, code DROPT can be used to design different scale vehicles, from small to general aviation; in this work it has been used to design a UAV, named TiltOne. A prototype of TiltOne has been designed and manufactured and preliminary flight test have been conducted in the case

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of drone configuration; the test results have been totally satisfactory both manually and, with a Pixhawk autopilot, automatically. The next steps regard the automatic control of the transition phases (from vertical to horizontal flights and vice-versa). In this work the design of a VTOL unmanned aerial vehicle called TiltOne was presented. This design has been developed under several points of view:

- the aerodynamic analysis allowed to evaluate efficiency and lift distribution. This analysis was necessary in order to set the motors and propellers suitable for the application;
- the mechanical design allowed to evaluate the dimensions (1m x 1m), the weight and the design of the tilting wing mechanism;
- the structural design allowed to evaluate stress and deformation of the entire structure, under the lifting load distribution. The maximum load factor beared by the load-bearing structure without any buckling of the upper surface plate of the fuselage was evaluated too.

The choice of the propellers was the best compromise between the hovering and the forward flight, consequently the motors were chosen. A prototype was realized in order to perform flights in hovering and in forward flight. As a future work, a full dynamical model of the TiltOne by using Newton-Euler formulation will be defined in order to develope the flight control system for the transition phase. The TiltOne will be tested in real environment in order to verify the efficacy of the control system.

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