Preliminary design of a box-wing VTOL UAV

Giuseppe Palaia and Vittorio Cipolla
Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy, and
Vincenzo Binante and Emanuele Rizzo
Skybox Engineering, Pisa, Italy

Abstract

Purpose – This paper aims to present a preliminary study on a disruptive vertical take-off and landing (VTOL) configuration based on the best wing system concept by L. Prandtl.

Design/methodology/approach – A preliminary design has been addressed from several points of views: a conceptual design has been carried out thanks to in-house optimization tool; aerodynamic performances, propulsion design and mechanical design have been addressed to make the first prototype for preliminary vertical flight tests.

Findings – The study shows the feasibility of box-wing configuration for VTOL aircraft.

Practical implications – The work shows a general design procedure for box-wing unmanned air vehicle (UAV) configuration. The study of this configuration can be easily adopted in wider range, from UAV to general aviation. In the last category, it can be a promising configuration for the future of urban air mobility.

Originality/value – This work lays the foundation for studying and testing box-wing configuration for unmanned VTOL aircraft. The design procedure can be scaled to manned aircraft belonging to general aviation aircraft.

Keywords UAV, Box-wing, VTOL, Optimization, Aircraft design, Prandtl-plane

Paper type Research paper

Introduction

Convertiplane are vehicles initially developed in 1950s and 1960s 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), ancestors of the more "recent" Canadiar CL-84 (tiltwing) and Bell-Boeing V-22 Osprey (tiltrotor). The development of this aircraft, under experimental military programs, highlighted the criticality and the deep investigation needed for the conversion corridor. Nowadays, these architectures are also starting to catch on in civil application thanks not only to the development of more reliable flight control system, but also to the possibility of integrating disruptive aircraft configuration. For example, Airbus[1] and Uber[2] are developing VTOL aircraft for improving urban air mobility. Nevertheless, the transition phase (from multicopter to fixed-wing configuration and vice-versa) is a hard challenge and a lot of control technique has been developed to overcome the problem (Zhong *et al.*, 2017). A promising configuration is the so-called "box-wing" which is based on the Best Wing System concept by Prandtl (1924), described in Prandtl 1924. Prandtl showed, starting with a biplane, that the total induced drag (D_b) is given by:

$$D_b = D_{11} + D_{22} + 2D_{12} = \frac{1}{\pi q}\left(\frac{L_1^2}{b_1^2} + \frac{L_2^2}{b_2^2} + \frac{2\sigma L_1 L_2}{b_1 b_2}\right)$$

where D_{11} is the induced drag of the first wing, D_{22} is the induced drag of the second wing, D_{12} is the mutual induced drag; L_1, b_1 and L_2, b_2 are respectively the lift and the span of each wing, and σ is the coefficient of mutual influence. For a biplane, the minimum occurs, in the case of the same wingspan ($b_1 = b_2$), when the lift is equally distributed. The minimum induced drag (D_{bmin}) is:

$$D_{bmin} = \frac{L^2}{\pi q b^2}\frac{1+\ \sigma}{2} = D_m\frac{1+\ \sigma}{2}$$

where D_m is the induced drag of a monoplane. The coefficient of mutual influence is lower than one, so the induced drag of best biplane is lower than a monoplane with the same span and lift. The analysis was extended to triplane and infinite plane, showing how higher the number of wings lower the induced drag. The minimum occurs with infinite wings, but also with a configuration made of two wings closed by lateral panels whit a proper lift distribution, as shown in Figure 1 and described in Frediani (2005). In the last case, the best efficiency is achieved, and this configuration is called "Best Wing System". The induced drag of the Best Wing System was approximated by Prandtl, but a more accurate formula can be found in Frediani *et al.* (1999).

This configuration, which in honor of Prandtl researchers at University of Pisa called "PrandtlPlane" (Frediani and Montanari, 2009; Cavallaro and Demasi, 2016), show several advantages: high efficiency, smooth post-stall behavior, good

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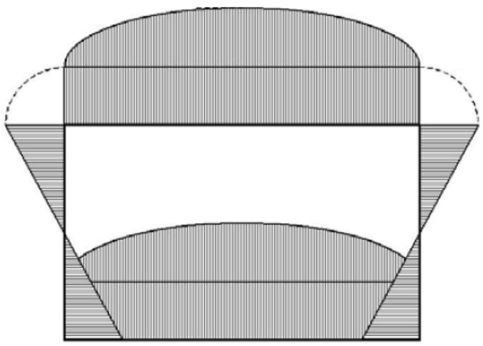
Figure 1 Lift distribution for the best wing system



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 to obtain a pure pitch control). For the previous reasons this configuration is very interesting for both military and civil[3] transportation. The unmanned air vehicle (UAV) presented in this work has been called "TiltOne" because it can tilt its wings by 90 degrees, switching from multicopter configuration to fixed-wing configuration. It is a tilt-wing, with PrandtlPlane configuration, capable of taking off and landing along a vertical direction. 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. First, the aerodynamic performance has been evaluated, then the constraints of the propulsion system have been defined; finally, a proper mechanical design has been done to define the main components for the manufacturing. Thanks to its modularity, preliminary flight test has been completed (without wings) defining the main parameters of the flight controller in multicopter configuration.

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 [like, for example, SUAVI described in Cetisnoy *et al.* (2012) or QTW of Chiba University described in Suzuki *et al.* (2010)]; 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; the rear one is higher, so there is a vertical gap (h) between the two wings. Generally, for 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 this parameter and the lift distribution, as shown by Prandtl (1924). The TiltOne, as said before, can change its configuration, so, during the fixed-wing phase (the most time consuming), it exhibits a box-wing configuration which, with a symmetrical lift distribution, defines the "Best wing system", the configuration with the lowest induced drag. The Best Wing System minimizes the drag; hence, it is possible to increase, respect to a competitor tiltrotor/tilt-wing with same wingspan and same weight, the flight time in recognition mission or increase the payload. This configuration can allow different advantages verified in previous works (Cipolla *et al.*, 2016; Frediani *et al.*, 2015; Oliviero *et al.*, 2016), as:

- a smooth post-stall which promises a better aircraft behavior near the transition phase;
- a higher aerodynamic efficiency and, hence, an increase of flight endurance and/or payload capabilities;
- an enhancement of structural stiffness; and
- a damped dynamic pitch due to the wing position along the longitudinal axes.

The PrandtlPlane, as shown in previous works (Cipolla *et al.*, 2016; Frediani *et al.*, 2015), is also capable of conventional take-off and landing (CTOL). This configuration should be helpful for the transition phase for the smooth post-stall behavior, and thanks to the higher aerodynamic efficiency an increase of the range capability is possible. Thanks to its features, it seems reasonable to assume that the PrandtlPlane can be used in both military and civil application, for improving safety in critical operations.

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; and
- maximizing the payload.

The optimization problem is complete if the constraints equations and the optimization variable range are defined. Several non-linear constraints equations have been defined (e.g. geometry, maximum current absorbed by the motors, or minimum available thrust); it implies that a proper algorithm has to be selected to solve the problem, so a Genetic or Non-Liner Programming (NLP) algorithm can be select. The optimization variables for this problem are defined in Table I.

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

Table I Description of the optimization variables

b [m]	Wingspan
c [m]	Wing chord
n_0 [rpm]	Motor speed in hovering
n [rpm]	Motor speed in cruse
α [deg]	Angle of attack
N	Number of propellers
t [min]	Flight time
C_{T0}	Propeller static thrust coefficient
J	Advance ratio
D [m]	Propeller diameter

chosen. The mission profile (depicted in Figure 2) is divided in three parts: in the first the UAV takes-off with a vertical speed (V_z); when the right altitude (z_{cruise}) is reached the speed gradually changes; the vertical speed goes to zero, in the meanwhile, the horizontal speed goes to the cruise speed ($V_{xcruise}$). In the third phase, the speeds mutually change again, and the aircraft lands. The time for take-off and landing is fixed; the altitude is 500 m, while the cruise time is the variable to be optimized.

The following optimization problem has been defined:

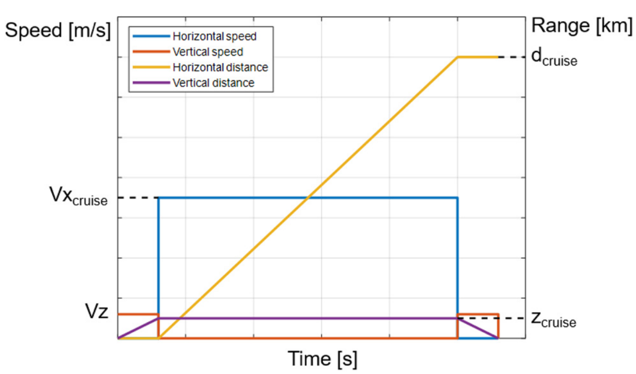
$$\begin{cases} \min -t^2 \\ T_0/MTOW \geq K_0 \\ F_x/Drag = 1 \\ F_y/MTOW = 1 \\ RPM_{required} \leq RPM_{allowed} \\ NK_{span}D \leq 2b \\ \mathcal{J}_{required} \leq \mathcal{J}_{max} \\ P_{motreq} \leq P_{motormax} \\ AR \leq AR_{max} \\ I_{required} \leq I_{max} \\ n \leq N_{parM} \\ l_b \leq x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

- $T_0/MTOW \geq K_0$ defines that the static thrust T_0 must be higher than the MTOW. An extra thrust of about 20 per cent is requested.
- MTOW is the maximum take-off weight. It is calculated according the following equations:

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

W_{pay} is the payload weight, and it is about 300 gr. W_{struct} is the structural weight, and it is composed by the wing (W_{wing}) and the fuselage (W_{fus}): the first is proportional to the wing surface

Figure 2 Mission profile for the TiltOne



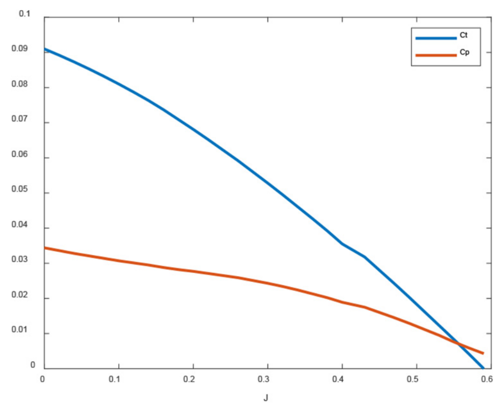
(measured in m^2) while the second is fixed. W_{batt} is the weight associated to battery; it depends on the total requested battery energy (E) and the specific battery energy (E_{spec} = 185 Wh/kg). W_{prop} is the propeller weight depending on the propeller diameter (D measured in inch). W_{mot} is the weight associated to the brushless motor; the relationship is based on the interpolation of data of the Hacker motors datasheet:

1. F_x/Drag = 1 and F_y/MTOW = 1 are the equilibrium equations along the horizontal and vertical direction. We assumed that:
   - The aircraft is approximated like a material point.
   - The aerodynamic drag coefficient is defined according the classic formula (Raymer, 2018):

$$C_D = C_{DO} + kC_L^2 = C_{D0} + \frac{\pi}{ARe}C_L^2$$

   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 (Nita and Scholz, 2012; Schirra *et al.*, 2014). The forces included in the equilibrium are the aerodynamic drag and lift, the propeller thrust, and weight:
2. $RPM_{required} \leq RPM_{allowed}$ 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[4]. 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.
3. NK_{span} D $\leq$ 2b avoids the overlapping of the propeller disk. N and D are respectively the number of the propellers and the diameter, b is the wingspan, and K_{span} is a real number bigger than one which guarantees a minimum clearance between the propeller tips.
4. $J_{required} \leq J_{max}$ states that the propeller advance ratio (J=V/(ΩD), V is the flight speed and Ω is the angular speed) cannot overcome the maximum advance ratio of the selected propeller (Jmax). An accurate database[1], where information on thrust coefficient (C_T) and power coefficient (C_P) are detailed, was created to select the right propeller. The procedure necessary for the calculation of the propeller is:
   - Calculate the minimum static thrust with T_0=1.2 MTOW/N.
   - Calculate the static thrust coefficient $C_{T0} = T_0/\rho n_0^2 D^4$.
   - 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). If more than one propeller is eligible, the most efficiency has to be chosen.
   - Calculate the cruise flight speed V=JnD.
   - By using the propeller curve, the coefficients C_T and C_P and the efficiency are extracted. The needed thrust in cruise and the power requested are evaluated as well.
5. $P_{motreq} \leq P_{motormax}$ limits the upper value ($P_{motormax}$, the maximum power available) of the absorbed motor power

Figure 3 CT-J(blue) and CP-J(red) curve of an APC propeller



(P_{motreq}). A motor database, like the propeller one, has been created to extract the main motor informations: weight, motor voltage constant (K_v), absorbed current, maximum speed, and maximum current.

6 $AR \leq AR_{max}$ limits the maximum aspect ratio (AR). In this DROP release there is no relationship between aspect ratio and weight, so the optimization, reducing the chord dimension (because the drag has to be minimized), increases the AR without a weight penalization. To avoid this problem a maximum aspect ratio has been fixed.

7 $I_{required} \leq I_{max}$ 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:

$$I_{required} = \frac{P_{motor}}{V_{motor}} = \frac{P_{prop}Kv}{\eta_{mot}}RPM$$

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

$$\begin{cases} 0.1\text{m} \leq \text{b} \leq 1\text{m} \\ 0.15\text{m} \leq \text{c} \leq \text{Inf} \\ 100 \quad \text{rpm} \leq \text{n}_0 \leq 30000 \quad \text{rpm} \\ 100 \quad \text{rpm} \leq \text{n} \leq 30000 \quad \text{rom} \\ 10^\circ \leq \ \alpha \leq 85^\circ \\ 2 \leq \text{N} \leq 8 \\ 30\text{min} \leq \text{t} \\ \min(\text{database}) \leq \text{C}_{\text{T0}} \leq \max(\text{database}) \\ 0.1 \leq \text{J} \leq 1 \\ 0.5\text{m} \leq \text{D} \leq 1\text{m} \end{cases}$$

9 $n \leq N_{parM}$ limits the maximum number of batteries in parallel. The calculation passes through an energetic balance:

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

P_{hov} and t_{hov} are respectively the required power and the time spent during take-off and landing; 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), the number of batteries is given by:

$$N = \frac{E}{\eta_{batt}C}$$

10 $min\ -t^2$ 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).

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:

1 to verify its longitudinal stability at forward flight; and
2 to give an estimation of the stall speed, necessary as starting point for the transition phase.

Transition phase was not considered 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 (its value was verified to be negligible in cruise), the cruise speed was defined to 19.5 m/s, and the cruise height was settled to 500 meters. The main dimensions of the TiltOne are defined in Table II.

The lift induced drag was evaluated with AVL (Athena Vortex Lattice), a free potential flow solver[5]. 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[6], the drag of the fuselage, evaluated on NASA experimental data[7], and the drag of the landing gears, calculated with Roskam procedure (Roskam, 1997). The efficiency curve resulting from the polar drag procedure estimation is depicted in Figure 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 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 4 is depicted the lift distribution relating to this condition. It is worth to outline that this calculation is very conservative; in fact, when the first airfoil reaches the maximum C_L, in the front wing, the other airfoils have a lower lifting 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

Table II Main geometric dimension of the TiltOne

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

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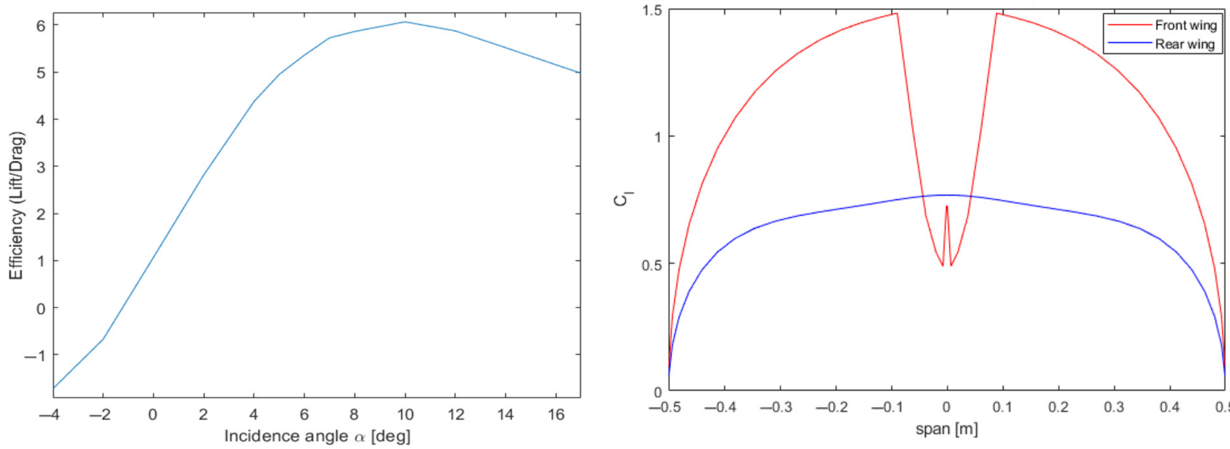
Figure 4 Efficiency curve of the TiltOne (left) and lift coefficient distribution along the span at stall speed (right)



preliminary analysis and further analyses with high fidelity tools must be done.

Motors and propellers

The right choice of motors and propellers influences the performance of the UAV, and it depends also on the mission has to be accomplished. As shown in Figure 2, the typical mission is divided in three main phases: take-off, cruise, landing. To minimize the current consumption in each phase the right propeller should be used: in cruise high pitch propellers while in take-off and landing low pitch propellers. Nevertheless, the adoption of the change of the propeller pitch 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[5] according the following procedure:

- choice of a set of propellers;
- calculation of the requested thrust for each propeller in cruise;
- calculation of the propeller angular speed from the C_T-J and C_P-J curve (Figure 3);
- calculation of the efficiency (an example of efficiency curve is depicted in Figure 5); and
- choice of the propeller with maximum efficiency.

The chosen propeller maximizes the overall efficiency because the energetic consumption in cruise (the longer phase of the entire mission) is minimized. The result of this strategy is a propeller 13 × 6, where the fist number indicates the diameter and the second the pitch both measured in inch. The performances in hovering and cruise are presented in Table III.

A brushless motor with Kv of 490 has been tested with the selected propeller on a test bench 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 35 A. Through this test we decided to:

- choice two Li-Po battery 6s with 10000mAh and 15C (it can supply a maximum continuous current of 150A); and
- to not overcome the mass of 11 kg, to satisfy the minimum ratio between the maximum thrust and the weight.

By using the test bench data, we evaluated the current consumption during each phase: the consumption is of about 64 A in hovering flight and 19 A in forward flight. These two values have been calculated dividing the requested power at the electric motor by the tension of the battery (22.2 V). As an example, by assuming two Li-Po battery 6 s of 10,000mAh and a typical mission of 5 minute in hovering flight the cruise time is about 34 min (using the 80 per cent of the entire capacity). The TiltOne, flying at 19.56 m/s, can cover a maximum distance of 40 km.

Figure 5 Efficiency-advance ratio (J) curve

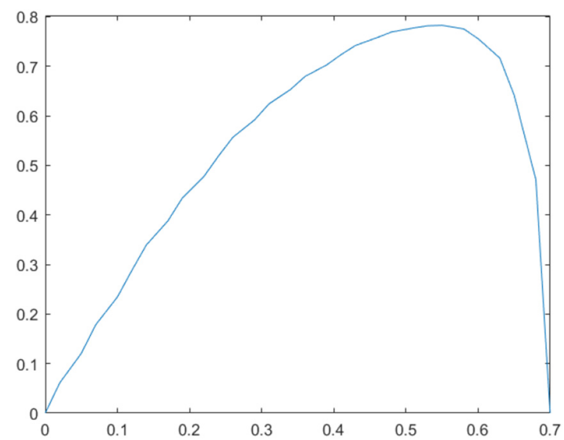


Table III Performances of the propulsion system

Main parameters	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]	1417	569
Advance ratio (J)	0	0.53

Main aircraft components

The final configuration is depicted in the left of the Figure 6. Fuselage, vertical fin, structures connecting wing tips, wings, motors, and propellers are the main components. The control

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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 mid-span of the wings to avoid contact between propellers and the wingtip surfacese. 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 to change configuration, so 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 6.

Fuselage and tip wing connections

Fuselage and "bulkhead" are depicted in Figure 7. Both structures are made of aluminum 2024-T3 of 0.8 mm of thickness and the lightening holes, made with water jet cutting machine, allow to save weight. The shape of the fuselage has been chosen to locate in the front part two Li-Po batteries of 10,000 mAh, so to have a rigid structure the fuselage is stiffened with wood ribs. 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" as described in the Introduction).

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 at a higher aerodynamic efficiency than the multicopter configuration. The switch from a configuration to another 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 8.

Figure 6 Final configuration of the TiltOne (left) and its load-bearing structure (right)

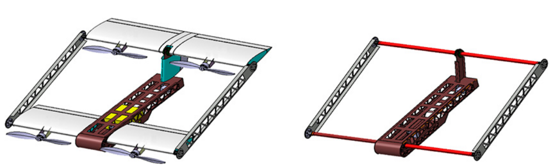
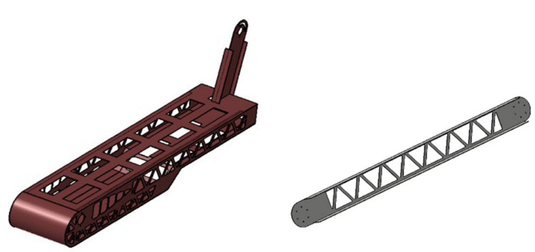


Figure 7 Fuselage of the TiltOne (left) and "bulkhead" (right)



Prototype and flight test

Before starting with the prototyping phase, a structural analysis has been performed on the entire structure to verify it. The simulation showed a maximum load factor of the load-bearing structure of 24.6. The Aluminum 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. This manufactured prototype is depicted in Figure 9.

Manually and autonomous flight tests (shown in Figure 10) of the TiltOne in multi-copter configuration (without wings) have been accomplished to set-up the flight controller which is a commercial autopilot (Pixhawk 2.1[8]). A PID tuning has been accomplished and an automatic flight has been performed to obtain a better response of the UAV.

Conclusion

A preliminary study on a disruptive unconventional configuration based on the Best Wing System Concept has been accomplished. The flying machine, called TiltOne, can rotate both wings propulsion group affording 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 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; and

Figure 8 Rendering of the TiltOne in forward flight (top left) and hovering (bottom left), A schematic view of the tilting mechanism of the rear wing (right)

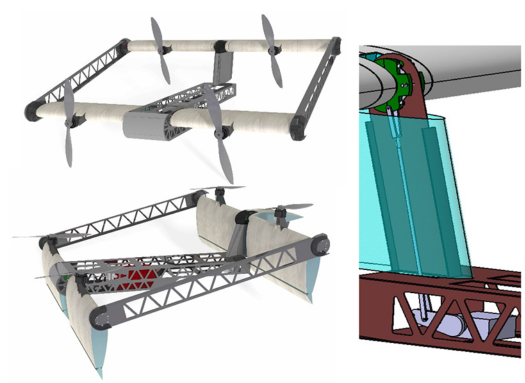


Figure 9 First prototype of the TiltOne

Figure 10 Maiden flight of the TiltOne

- 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.

Further work

A dynamical model of the TiltOne both in cruise and take-off phase will be investigated. It will be defined to develop the flight control system for the transition phase. The TiltOne will be tested also in real environment to verify the efficacy of the control system in two different conditions: completely autonomous and manually piloted.

Notes

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Corresponding author

Giuseppe Palaia can be contacted at: giuseppe.palaia@phd.unipi.it