An Experimental Study on the Design of Ornithopter and Tiltrotor Configurations

Horácio Moreira
Instituto Superior Técnico, Universidade Técnica de Lisboa

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Abstract

The goal of this thesis was to develop a Micro Air Vehicle. Requirements were initially defined for the aircraft. These requirements formed the base of a comparative study for various configurations, which yielded two good candidate configurations, a lightweight ornithopter and a tiltrotor. Initial work was made on the ornithopter configuration. Eventually, it was deemed too difficult to achieve a degree of construction quality sufficient to ensure good performance. The aircraft weight and the wing performance were the major issues. Afterwards, the tiltrotor configuration was explored. This configuration allowed the choice of a wider variety of components and more standard building techniques. A preliminary design was made for a tandem wing tiltrotor aircraft with fixed pitch propellers as rotors. This design was implemented and built over several iterations. Two flying prototypes were built and tested, the second being an improved version of the first. This aircraft performed reasonably well in some flight conditions. Some issues remain unresolved, especially the need for a more sophisticated stability augmentation system but nonetheless, the aircraft created shows promise for further development as a low cost remote sensing platform capable of indoor and outdoor operation.

Keywords: Tiltrotor, Micro Air Vehicle, Aircraft Design, Ornithopter, Flight Testing

The present text is a brief summary of the work more thoroughly described in reference [1]. The reader should refer to that text for any additional clarifications or explanations found necessary.

Abbreviations

AUW	All Up Weight
BEC	Battery Eliminator Circuit
CG	Center of Gravity
CNC	Computer Numerical Control
EPS	Expanded PolyStyrene
ESC	Electronic Speed Controller
MAV	Micro Air Vehicle
POM	PolyOxyMethylene
RC	Remote Controlled
UAV	Uninhabited Aerial Vehicle
V/STOL	Vertical/Short Take-Off and Landing

1 Introduction

1.1 Micro air vehicles - overview

Micro Air Vehicles (MAVs) are a relatively recent branch of the UAV (Uninhabited Aerial Vehicle) family. They are characterized by their small size, and some have the ability to operate indoors and in confined spaces. For this purpose, they often employ rotors or other moving aerodynamic surfaces and take advantage of the unique phenomena that are found at the low Reynolds numbers they operate in. After about a decade since the first models, nowadays there are some established designs, while others are merely waiting for advances in other areas, such as electric motors, actuators and power sources to become feasible.

The application potential for such small aerial vehicles is great, especially in the area of remote sensing. This applies to combat operations contexts but civilian security, rescue and disaster relief operations can also benefit from small, easily deployable airborne drones. Another possible application would be maintenance of large structures, where a suitable drone can perform visual inspections easier, faster and safer than a human. The small size and lower cost of MAVs enable them to be integrated in larger quantities and smaller teams, bringing their advantages and capabilities to a larger number of operators.

1.2 Establishment of mission requirements

The initial premise for this work, (design, construction and testing of a Micro Air Vehicle) was somewhat ambiguous. Therefore, it was necessary to set some design requirements to guide the project. These requirements were thought up based on the available resources for construction, design and testing, and on the utility of the aircraft they aimed to produce.

The first decision made was relative to the normal operating environment of the aircraft. It was decided to set indoor operation as the main environment, since it would be easier and safer to test the aircraft inside one of campus' buildings instead of an adjacent outdoor space. However, another requirement set was that the aircraft should have some forward flight capability, in order to add to its ultimate usefulness and give it the ability to cope with light winds. These considerations resulted in three requirements for the aircraft:

- It should be capable of hovering (i.e. maintain altitude and climb even with zero airspeed);
- It should be able to hover for at least 4 [minutes] in no-wind conditions;
- It should be able to achieve a forward flight speed of at least 7[m/s] (approximately 25[km/h]).

Regarding size and mass, it was opted not to severely limit the prototype from the onset. However, the choice of operating environment and the prospect of a further use for the aircraft (should the type be successful) dictated two more requirements:

- It should be able to fly through a threshold of 0.7[m] in width and 2[m] in height (the approximate dimensions of a standard door)
- It should have enough capability to lift a payload comprising at least 5[%] of its empty AUW;

Finally, some general guidelines were also laid out:

- It should use as much off-the-shelf components as possible;
- Overall cost and time of manufacture should be kept as low as practical;
- Materials to be used should have a life-cycle as sustainable as possible.

Based on these parameters, a study of possible configurations for the aircraft was made.

2 Study of Possible Configurations

2.1 Configurations considered for the aircraft

The requirement to be able to hover is the most defining one of the set. It means that the aircraft must be able to generate a force greater than its weight and that can be directed upwards (counteracting gravity), while maintaining zero airspeed. Coupled with the requirement for fast forward flight, the number of possible configurations is reduced, since there are only three possible general solutions, corresponding to three distinct groups of aircraft.

2.2 Thrust hanging group

An air vehicle capable of producing more thrust than its weight will naturally be able to hover, when its thrust line is directed vertically. This group includes conventional, fixed wing aircraft, as well as ornithopters. The main advantage of this configuration is its simplicity. The main disadvantages are the need to move or duplicate any payload with a direction dependent operation (i.e. a camera), and the limited control in hover for the fixed wing aircraft, due to the reduced airflow over the control surfaces in this mode. Ornithopters however, have a large wake from the flapping wings and don't suffer as greatly from this problem.

2.3 Thrust vectoring group

The thrust vectoring group includes aircraft types that can vary the direction of their thrust vectors over a relatively large angle. Examples include several V/STOL aircraft, as well as tiltrotors. The main advantage of this configuration is the potential for good flight characteristics in both hover and forward flight. This comes at a cost in added weight, complexity and possible inefficiency from the thrust vectoring system.

2.4 Orthogonal thrust group

The orthogonal thrust group includes aircraft configurations that use separate devices to produce the horizontal (thrust) and vertical (lift) forces. Compound helicopters are the most typical example. The main advantage of this kind of aircraft is a potentially simpler and smoother transition between flight regimes, while retaining full control in both of them. The main disadvantage is that generally a system used for one flight mode is of limited utility in the other.

2.5 Configuration selection

In order to aid the choice of configuration, a scoring table was made. Four particular configurations were chosen: a conventional fixed wing airplane and an ornithopter from the thrust hanging group, a tiltrotor from the thrust vectoring group and a compound helicopter (gyroplane) from the orthogonal thrust group. A qualitative assessment of several parameters was made.

These parameters were evaluated for each of the configurations. For each a score from 1 (very bad) to 5 (very good) was attributed. It was decided to give the same weight to all of the parameters. The results are presented in tables 1 and 2.

From the scores presented, the two best contenders were the ornithopter and the tiltrotor configurations. In order to decide which configuration to choose, a greater weight was given to the last parameter. The availability of a DelFly 2 specimen for analysis enabled the degree of uncertainty in exploring a new configuration to be greatly reduced. Eventually, work was developed in both the ornithopter and tiltrotor configurations, the latter producing better results.

Feature	Conventional	Ornithopter
Forward performance	5	5
Hover performance	1	2
Simplicity	5	3
Scaling	3	2
Forward efficiency	5	4
Hover efficiency	1	4
Transition	2	2
Payload	1	2
Reference	4	5
Total	**27**	**29**

Table 1: Scoring table for choice of configuration - ornithopter and conventional fixed wing airplane

Feature	Tiltrotor	Gyroplane
Forward performance	4	3
Hover performance	3	4
Simplicity	2	1
Scaling	4	3
Forward efficiency	4	3
Hover efficiency	4	3
Transition	3	4
Payload	4	4
Reference	1	1
Total	**29**	**27**

Table 2: Scoring table for choice of configuration - tiltrotor and gyroplane

3 Ornithopter - Work Developed

3.1 Context

The work developed on the ornithopter configuration was based on the Delfly (see [2]). The goal was to match or surpass the performance of a Delfly 2 (figure 1), incorporating improvements as possible along the way. The aspects selected for improvement were the inclusion of more precise actuators, the flapping mechanism for a better flight control and efficiency, and the connection between wings and fuselage, in order to allow the use of different sets of wings with the same airframe.

3.2 Aircraft produced

The basic dimensioning and layout of the ornithopter was similar to the Delfly. The main differ-

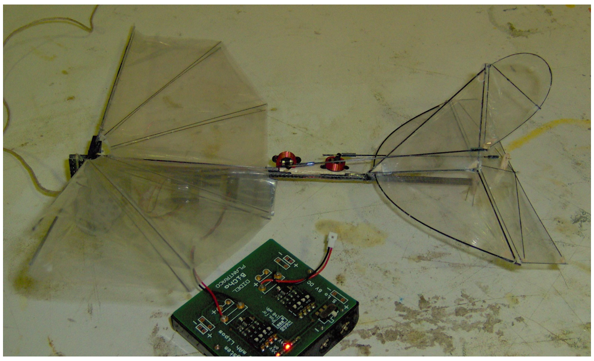

Figure 1: A DelFly 2 on the bench, recharging its battery.

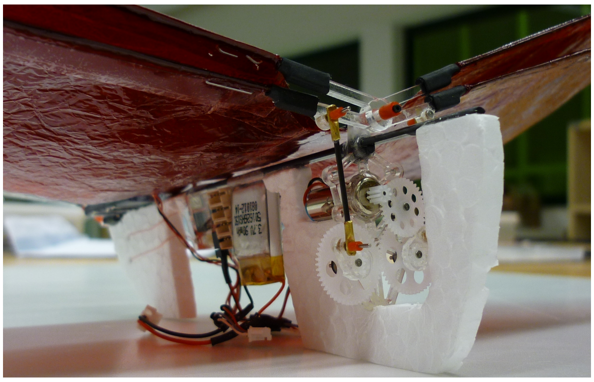

Figure 2: Flapping mechanism, basic structure and materials used

ences were the addition of a foam part to help protect the exposed components in case of a crash, the detachable wing set, the gear train and flapping mechanism (these are all shown in figure 2) and the bird-like tail (figure 3).

The wing set consisted of a pair of thin membranes glued to four spars (at the leading edge) and reinforced with carbon fiber battens. The spars were connected to the arms of the flapping mechanism by specially formed polymer pieces. This system allowed an easy replacement of the wing set.

The gear train used two reduction stages and two cranks, each connected to a pair of wings. Unlike the Delfly, the arrangement was in a transversal plane, which allowed for joints with decreased friction, although at the cost of an extra gear. The flapping mechanism was a scissor-like set of four flapping arms made of acrylic. Each pair of arms was connected to one crank by a carbon fiber rod and a specially made brass fitting.

The tail consisted of a thin mylar membrane glued to a triangular carbon frame. This frame was connected to the fuselage by a flexible sleeve and to the actuator arms by rods. The actuators were shape memory alloy servos (see reference [3]) and used common movement to change the incidence of the control surface (controlling pitch) and differential movement to change the sideways inclination (controlling yaw-roll). The tail is illustrated in figure 3.

3.3 Testing and conclusions

This ornithopter was flight tested and revealed itself to be unable to hover. This was due to excessive weight and a lower than expected efficiency from the wings. The main conclusion to draw is that, although the configuration is valid for this kind of use, a successful aircraft requires a great construction quality to have an efficient wing and a lightweight airframe. Such degree of quality was not attained in this work.

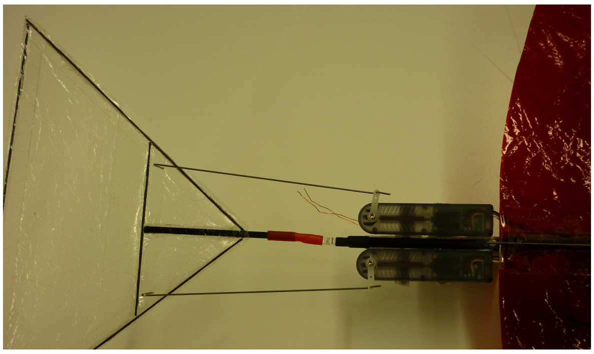

Figure 3: Image of the bird-like tail and actuators.

4 Tiltrotor - Preliminary Design

4.1 Dimensioning and layout

The layout chosen for the tiltrotor aircraft was a tandem wing with the rotors between the forward and rear wings. This choice decreases the aerodynamic interference between rotors and wings and allows both wings to produce lift in a cruise condition. It also allows the wings to be braced with the tilt shaft for added structural strength and protection of the spinning rotors against collision with vertical obstacles. The layout and the principal dimensions are shown in figure 4. These dimensions were based on the mission requirements and the rotor sizes available.

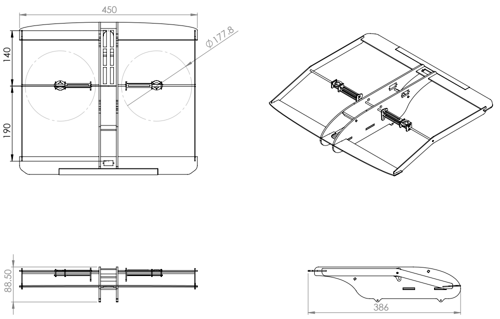

Figure 4: Isometric and three-view CAD drawing of Flight Prototype Two airframe, showing the layout and principal dimensions (not to scale).

4.2 Propulsion

The propulsive system is constituted by the rotors, motors, ESC and battery. For the rotor it was decided to use a fixed pitch propeller, for its simplicity and lighter weight. The propellers chosen were counter rotating (one right handed and one left handed propeller) so that the reaction torque from both motors would cancel each other. The largest available (considering aircraft dimensions) three blade propeller was chosen, with a diameter of 178[mm] (7[in]). The three blades were chosen for a greater static thrust, given the that the rotors will mostly operate with a small airflow perpendicular to them (near-static conditions). The motor, ESC and battery were chosen to match this propeller to its best performance in terms of thrust per electric current consumed. A lower voltage battery (two cells lithium-polymer type of 7.4[V] nominal voltage) and a motor with a higher speed-to-voltage ratio were used for lower weight. The battery capacities chosen for testing were 1500[mAh] and 1200[mAh]. The ESC chosen also included a BEC that provides electrical power to the remaining aircraft's systems.

4.3 Stability and control

4.3.1 Pitch stability and control

The two flight regimes, hover and forward flight present a fundamental difference: the forward speed that enables forces and moments to be created by aerodynamic surfaces. In forward flight it is possible to control the aircraft in a way very similar to a conventional airplane using conventional tail surfaces, while in hover mode the control must be made using only the rotors.

In terms of pitch stability in hover, there were two important aspects to consider: the longitudinal location of the aircraft's center of gravity and the need for a feedback loop on the pitch axis to stabilize it. The center of gravity must be in the same longitudinal coordinate as the pivot about which the rotors are tilted. This ensures that the fuselage maintains an horizontal attitude. However, pitch stability is still negative, thus the need for a stability augmentation control loop. This is implemented using an off-the-shelf aircraft gyro in the common tilt channel. Pitch control is made by tilting the rotors.

For forward flight, the aerodynamic characteristics of the wings play a crucial role in pitch stability. Although the feedback control loop is still active in this mode, the wings were calculated to have positive stability. For construction simplicity, the wings have thin flat plate airfoils and approximately the same area. According to studies presented in reference [4], these should have good performance in the Reynolds number range they are supposed to operate in. The rear wing has a greater distance to the center of gravity (thus stabilizing the system) and is also fitted with an elevator. Aerodynamic calculations were made for the trim parameters in forward flight: rotor thrust, rotor tilt angle and forward velocity. Figure 5 shows the thrust-tilt curve for longitudinally trimmed flight at several velocities. This curve was obtained from a calculation of the trim angle of attack for each velocity. Overall wing lift coefficients were estimated from flat plate theory (see references [5] and [6]) and fuselage drag from a simplified panel method analysis.

Although this curve was drawn from approximate calculations, several conclusions may still be inferred, like the tilt angle for minimum needed thrust (around 40[°]) and the most efficient forward speed (which not

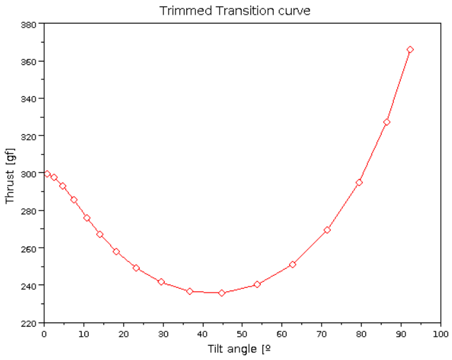

Figure 5: Trim combinations for thrust and tilt angle at a fixed angle of attack for several velocities.

explicit in the plot but was calculated to be around 11 [m/s]).

4.3.2 Roll-Yaw stability and control

In terms of roll and yaw stability, the greatest difficulty to overcome is the control coupling. In hover mode, roll can be controlled by differential rotor thrust, while yaw can be controlled by differential rotor tilt, with a minimal coupling that results from the spinning of the rotors. The rotation direction for each rotor (right rotor spins clockwise and left rotor spins counter-clockwise) was chosen in order to make this coupling favorable. As the common tilt angle increases, these controls become more strongly coupled. This coupling is resolved by the pilot, who must operate both controls to produce the required attitude on the aircraft. Past 45° common tilt angle, the roll and yaw controls become effectively swapped. For this reason, in the implementation of the design, the tilt travel was mechanically limited. This limitation may be lifted when a more advanced stability augmentation system is implemented.

A gyro sensor in the roll axis with feedback control on the differential thrust channel was also added to the stability augmentation system. This helps dampen unwanted disturbances and correct rotor asymmetries. With the rotors tilted, the gyro response affects both the roll and yaw axes. This is not problematic because the coupling between them is favorable.

4.4 Airframe structure

The critical structural component in the aircraft is the tilt shaft. It consists of a cylindrical boom over which a sleeve rotates. This boom must support bending from several directions (as the tilt angle changes) with minimal deformation, in order to minimize wear. Calculations and tests showed that a carbon fiber tube with an outer diameter of 4 [mm] has a suitable resistance and rigidity to serve as the main boom. The remaining structure of the aircraft was not calculated, but was built and tested further along the project.

4.5 Weight forecast

In order to do some of the calculations outlined before, an estimate of the total mass of the aircraft was necessary. For the case of off-the-shelf components, relatively accurate figures were available. In the case of manufactured components however, before their actual construction only estimates could be made. The total estimated value for aircraft mass was about 293[g].

5 Tiltrotor - Detailed Design and Construction

5.1 Detailed design

5.1.1 Tools and materials used

The principal tool used for creating the airframe parts was a CNC milling machine that allowed cutting bi-dimensional parts from sheet materials. Hand tools were also used for grinding, sanding and cutting. As for materials, the most extensively used were balsa wood and fiberglass cloth. Model aircraft plywood, aluminum, carbon fiber and steel were also used.

5.1.2 Airframe design

In order to design a lightweight, structurally capable airframe made of two-dimensional parts, a covered structure was designed. This structure was an assembly of flat panels made from a balsa laminate [1]. The

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[1] The particular laminate was different in each one of the flight prototypes

structure was comprised of two identical lateral panels (vertical), one longitudinal horizontal panel and several transverse reinforcement bars. The wings, that are fit in the forward and rear ends of the fuselage, also add to the overall structural rigidity. All the panels have holes cut out for weight reduction, resulting in a truss-like structure. The lateral panels were covered with heatshrink adhesive covering film.

5.1.3 Wing design

The preliminary wing design called for rectangular, flat plate wings. For better streamlining and to avoid having rectangular corners outside the wing box, the leading edge of the of the front wing was modified to a shallow semi-ellipse and the trailing tips of the rear wing were rounded. The wings were cut from a 2[mm] balsawood sheet reinforced with fiberglass on both sides.

The wing bracing is anchored on the tips of both wings and slid into the main boom. The material used is fiberglass reinforced balsa.

5.1.4 Tilt arm design

Figure 6 shows the tilt arm of Flight Prototype Two and its components.

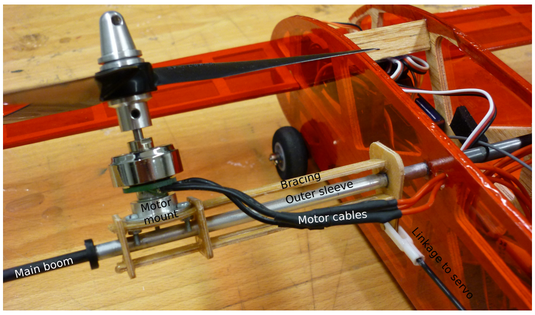

Figure 6: Tilt arm, with the various components named.

The tilting mechanism was designed to have a small mechanical advantage. The servo travel range of 90° (45° each way) is converted by the mechanism to 60° and an offset is added by the angle at which the motor is mounted on the tilt arm (20°). The effective travel range of the tilt arm then becomes between 10° rear tilt and 50° forward tilt.

5.2 Construction

The construction process consisted of three stages: fabrication of airframe parts, airframe assembly and component integration.

5.2.1 Part fabrication

There were three main operations for part fabrication: lamination, cutting and covering.

Lamination is the layup of the balsa wood, plywood and fiberglass. The laminates used were:

- plywood core with three layers of fiberglass cloth on either side;
- balsa wood core with one layer of fiberglass on each side
- balsa plywood that consist of three layers of thin balsa wood sheet arranged with their main directions perpendicular to those of the adjacent layers (similar to regular plywood, but using balsa sheet instead of other wood veneer).

The layup was made by hand using an adequate epoxy resin. The curing process was at ambient temperature and pressure. After the cure was completed the aircraft parts were cut from the laminates on the milling machine.

5.2.2 Assembly

After cutting, all the joints were rectified for proper fitting and then assembled with fast curing epoxy resin. The wings only needed to be covered in film after cutting and prior to fitting in the fuselage. The bracing did not require further operations either. The tilt arms needed to be assembled from their parts. These components have been designed to fit together and be glued with epoxy resin. The exact angle between the arm at the root and the motor mount is achieved by pressing the two parts, once slid into place, against a flat surface. The side angle on each part were designed to make the intended alignment in this manner, without need for further measuring and adjustment.

5.3 Component testing and integration

All the components were tested prior to integration to verify proper function and correlation to specified performance. The propulsion system test was of particular importance, since it allowed to set the working limits for the motor. This test was conducted on a scale and measured static thrust and current drawn as a function of the ESC control input.

The component connections are shown in figure 7. Dashed lines show transmitter channel mixes.

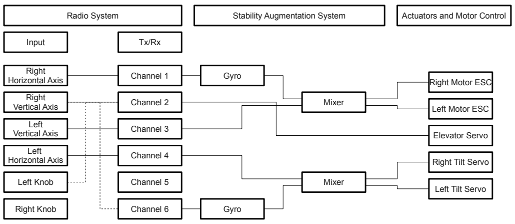

Figure 7: Wiring diagram for the aircraft controls

5.4 Cost

The costs of constructing one aircraft were analyzed. They amounted to approximately 218.34[€] in components and raw materials and 102.50[€] in manpower and machine time, totaling 320.84[€]. The factors affecting these costs can vary greatly though, and these figures are approximate.

6 Tiltrotor - Flight Testing

6.1 Flight testing: goals and planning

The objectives of the flight testing program were:

- to verify that the aircraft built was capable of sustained and controlled flight;
- to identify flaws in the design and construction of the prototype, so that they could be corrected;
- to establish the ease of piloting and the guidelines to be followed by anyone controlling the aircraft;
- to assess whether the mission requirements (section 1.2) were fulfilled.

6.2 Testing results for FP1

The testing of Flight Prototype (FP1, shown in figure 8) successfully completed only the first steps of the test plan, which corresponded to basic take off and hovering in ground effect. The main issues that prevented a successful continuation of the tests were:

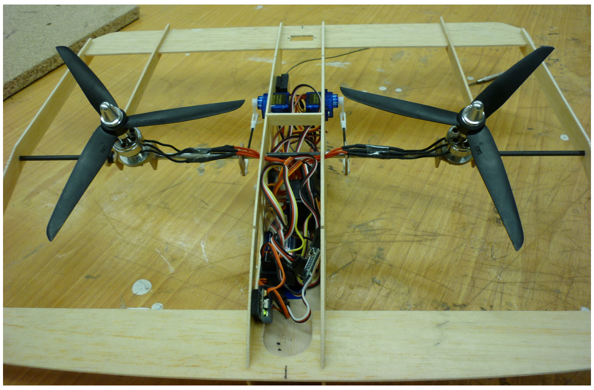

Figure 8: Flight Prototype 1.

- Necessary roll and yaw trim seemed to vary with throttle setting, requiring almost constant re-trimming;
- The impact of sudden landings (i.e., when the throttle was suddenly cut off to avoid collision with an obstacle) was entirely absorbed by the structure and not softened in any way;
- Outside of ground effect, a pitch oscillation would occur that would quickly flip-over the aircraft and cause it to fall to the ground, upside down.

6.2.1 Changes introduced for FP2

During the tests on FP1 various other observations were made that were translated in improvements for the second flight prototype:

- The flip-over crashes caused deviations in the angle at which the motor mounts were glued to the tilt arm (i.e. they rotated on the aluminum sleeve). The tilt arms were reinforced for the second prototype, relying on additional bracing rather than just the glue to maintain the correct angle;
- The wings showed good resistance to damage, so were selected for lightening, by using a drilled structure covered in film instead of a solid plate;

- The wing-boom bracing near the motor was discarded, since it introduced warping on the wing and was deemed unnecessary from a structural standpoint;
- The elevator, although predicted in the design, was not added for Flight Prototype One since most of the testing was to be in the hover condition, where the elevator was ineffective. However, the behavior of the prototype and its encounters with obstacles have indicated that a more safeguarded design for the elevator would be better than the originally intended;
- The fuselage revealed a certain lack of rigidity in some points, even with the transverse bars used for reinforcement. To correct that, the material was changed from glass-reinforced balsa (about 2.3[mm] thick) to balsa plywood (about 4[mm] thick). The structure designed was also changed to maintain the weight low, despite the thicker material. This trade-off allowed and increase in fuselage rigidity with marginal weight gain. Also, for the second prototype, the fuselage was already covered in film;
- The tests on Flight Prototype One often ended with a drop, in which motor throttle would suddenly be cut off and the aircraft would drop to the ground. To limit the (cumulative) damage that these drops could have been causing in the fuselage and electronic components, a set of four foam wheels was added.
- In order to mitigate the flip-over phenomenon changes were made to the radio programming. These consisted of transferring authority from the pitch control (the stick) to the transition control (the knob), so that an incorrect pilot action had a slower effect and could be corrected in time. As a consequence, the wiring diagram was also changed. The elevator became connected directly to the pitch control and a splice of this signal goes to the “common” entrance of the signal mixer connected to the tilt servos.

6.3 Testing results for FP2

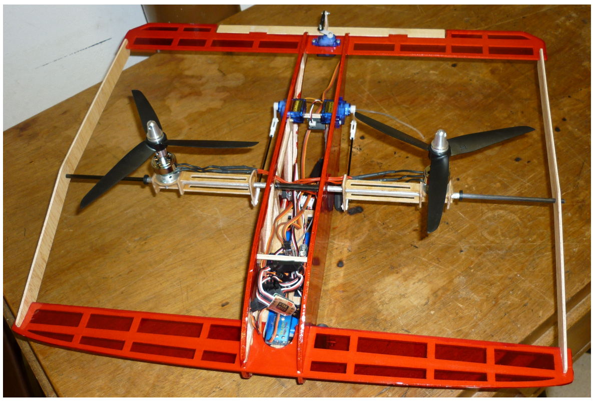

Figure 9: Flight Prototype 2.

The flight testing of FP2 (figure 9) took the same form as that of the previous aircraft, but progressed faster. In general, the FP2 had a gentler handling than FP1. However, it was discovered after the first tests that this second prototype was severely overweight. This severely degrades performance out of ground effect. In ground effect, however the prototype has good performance and flight characteristics.

6.4 Conclusions of the flight testing program

The original planning was unfinished, due to a few issues. Nevertheless, the performance of the final prototype, FP2 was partially assessed and it shows promise, if the problems that arose are properly solved. Up to this point, no data was found that may hint at crippling issues in the untested flight conditions, although some improvements in the platform are still necessary.

7 Conclusions and Future Work

7.1 Conclusions

Several aircraft prototypes were designed and built during this project. Two configurations were explored, one after the other proved unable to achieve the objectives. It can be said that goal completion was partial. Although an MAV was effectively designed, built and tested (the initial premise of the thesis), not all of the additional goals were achieved. Nonetheless, the end result was overall satisfactory.

Regarding the final aircraft developed (Flight Prototype Two), it shows promise as a platform for close range, indoor/outdoor remote sensing. However, the testing plan should be finalized in order to fully confirm performance. If outdoor flight reveals itself to be unfeasible, it may still be possible to make good use of it inside buildings, since it was dimensioned both in terms of size and operating speed to be able to perform indoors. Without payload, it may also be used for leisure as a regular RC model, although it is not currently appropriate for inexperienced pilots. In the short term, are a number of small details that can be improved on the current iteration. These include:

- Reducing the amount of aluminum tube on the tilt arm and rely on only the bracing to transmit the loads;
- Reducing weight on the propeller adapters and motor mounts;
- Re-doing the wing bracing in balsa plywood and use bolted joints to connect them to the wings;
- Reducing receiver weight by removing plastic case;
- Adding leading and trailing edge carbon reinforcements;
- Replacing the wheels for a lighter skid landing gear with the same shock absorption capability;
- Re-doing all the wiring to reduce the weight and dissipated power in all the cables and connectors;

The overall mass reduction necessary should be close to 50[g], in order to bring the aircraft mass to the design value and the performance to the degree expected.

7.2 Proposals for future work

Regarding future work, there are some general proposals. The minor ones are related to the platform itself, while the most extensive are related to payload and the avionics and flight control systems.

The proposals for improvement on the platform include:

- Adding one or two dedicated payload mounts to the airframe, that could later be used to install sensors;
- Improving the aerodynamic performance of wings, through a more detailed experimental and theoretical study. Using very thin low-Reynolds wings could be one of the options to investigate;

The proposals for improvement on the avionics include:

- Implementing a layer of control between the radio receiver and the actuators, that would provide stability augmentation in all three axis and handle transition flight and roll-yaw coupling, reducing needed pilot skill. This would need to be a custom-built electronics package, to replace the current solution using off-the-shelf components;
- Integrating a camera and transmitter payload and setting up a ground station. This would allow for remote control without visual contact and be the first step towards developing the system into a fully autonomous solution.

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