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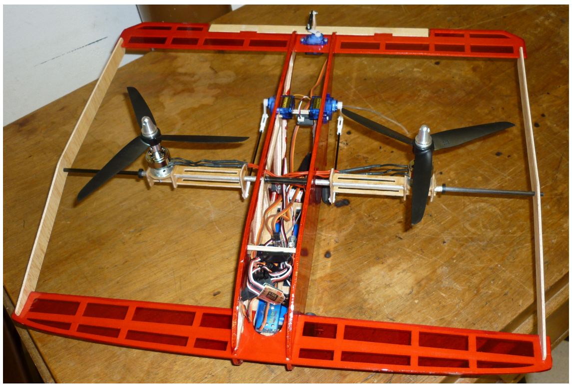

An Experimental Study on the Design of Ornithopter and Tiltrotor Configurations

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Dissertação para a Obtenção do Grau de Mestre em

Engenharia Aeroespacial

Júri

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Novembro de 2010

Acknowledgements

To my thesis advisors, professors Afzal Suleman and Agostinho Fonseca;

To Luís Cruz, for the continued support and friendship throughout so may years and so many projects, in academia and beyond;

To all the colleagues with whom I studied and worked, succeeded and failed with, learned from and passed along to whatever little I have to teach;

To all the good teachers I had over two decades, for the firm cornerstones they placed in my education, and the valuable lessons I learned from them;

And above all, to my family and friends, for their continued support and encouragement in all my endeavors and all my decisions, and for continually being there for me;

Thank you.

This work was funded by project IDT-05-S3T-FP012 (*SMORPH*) from FCT (Fundação para a Ciência e Tecnologia). An additional thanks, for making it possible.

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

Resumo

O objectivo deste trabalho foi o desenvolvimento de um pequeno veículo aéreo não tripulado. Foi definido um conjunto de requerimentos para a aeronave. Estes requerimentos originaram um estudo comparativo envolvendo várias configurações. Deste estudo emergiram dois bons candidatos, as configurações ornitóptero ligeiro e *tiltrotor*.

O trabalho inicial foi desenvolvido com a configuração ornitóptero. Fram encontradas dificuldades em obter um grau de qualidade de construção suficiente para garantir bom desempenho. O peso da estrutura e o desempenho da asa revelaram-se os maiores problemas.

Posteriormente, a configuração *tiltrotor* foi explorada. Esta configuração permitiu uma escolha de uma maior variedade de componentes e técnicas de construção mais convencionais. Um projecto preliminar foi feito para uma aeronave com duas asas em *tandem*, utilizando hélices de passo fixo como rotores. Este projecto foi implementado em várias iterações.

Dois protótipos foram construídos e testados, sendo o segundo uma versão melhorada do primeiro. A aeronave teve um desempenho razoável em algumas condições de vôo. Alguns problemas permanecem por resolver, nomeadamente a necessidade de um sistema de aumento de estabilidade mais sofisticado. Mesmo assim, a aeronave desenvolvida é promissora para desenvolvimento futuro como uma plataforma de detecção remota de baixo custo, para ambientes exteriores e interiores.

Palavras-chave: *Tiltrotor*, *Micro Air Vehicle*, Projecto de Aeronaves, Ornitóptero, Testes de Vôo

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Abbreviations

AUW	All Up Weight
BEC	Battery Eliminator Circuit
CAD/CAM	Computer Aided Design / Computer Aided Manufacturing
CG	Center of Gravity
CNC	Computer Numerical Control
EDF	Electric Ducted Fan
EPS	Expanded PolyStyrene
ESC	Electronic Speed Controller
MAV	Micro Air Vehicle
POM	PolyOxyMethylene
PVC	PolyVinyl Chloride
PWM	Pulse Width Modulation
RC	Remote Controlled
SAS	Stability Augmentation System
UAV	Uninhabited Aerial Vehicle
VTOL	Vertical Take-Off and Landing
VTOT	Vertical Take-Off Throttle

Symbols

E	Young's modulus
I	Second moment of area
I_T	Total current
I_M	Motor current
Kv	Speed to voltage ratio of an electric motor
l	Length of the beam
M	Bending moment
r_e, r_i	Exterior and interior radius of the annular cross-section
T	Thrust of one motor/propeller
x	longitudinal coordinate in the beam
y	vertical coordinate of the beam's neutral plane

Note On Unit Use

The choice of units used in this text was influenced both by the scale of the project it aims to describe and current industry standards for giving out product specifications. In several cases, multiples of SI units like the gram and millimeter will be used to convey a more intuitive notion of the values involved. In other cases, like describing the parameters of propellers or the torque developed by servo actuators, non-SI units will be used because they are the ones found on product specifications provided by manufacturers and sellers. The value in SI or SI multiple units may also be indicated. Also, and given the nature of the aircraft that will be described and its area of operation (near Earth's surface, where a constant gravity field is assumed), weights and vertical forces will be mostly indicated in kilograms-force or grams-force, for easier relation to the aircraft masses involved.

All the calculations however, were made in SI units for greater ease and more consistent results. The unit symbols are indicated in [] for clarity and better distinction from the rest of the text.

Chapter 1

Introduction

This work presents an experimental study into the design and construction of small size (MAV - Micro Air Vehicles) ornithopter and tiltrotor aircraft. The introductory chapter will present a brief overview on MAVs, the definition of mission requirements for the aircraft designed and the structure of the rest of the document.

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, which grants them a good degree of portability, 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.

However, there is not one single definition for an MAV. In the late 1990's DARPA (the United States of America's Defense Advanced Research Projects Agency) introduced a program to develop Micro Air Vehicles (see [1]). The main goal of this program was to developed small, man portable aircraft to provide reconnaissance and remote sensing on a localized level. A Micro Air Vehicle was defined as being smaller than 15[cm] in any direction. This size-based definition came from the projected use of Micro Air Vehicles at the time but over the years, larger aircraft have been given the designation of MAV. For example, the indoors scoring rules of the 2009 EMAV [1] defined a maximum dimension of 70[cm] in any direction for flapping and rotary wing MAVs and 80[cm] for fixed-wing ([2]). DARPA's program gave rise to several MAV designs, like the AeroVironment Black Widow (figure 1.1,

[1] European Micro Air Vehicle Conference and Flight Competition, held in Delft, The Netherlands

see [3]) or the CalTech/UCLA/Aerovironment MicroBat (figure 1.2, see [4]). Other research and development efforts followed throughout the decade. Nowadays this trend is still ongoing. 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.

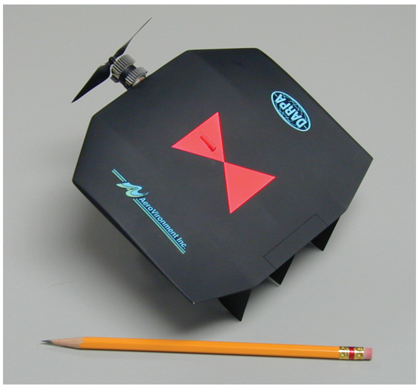

Figure 1.1: The AeroVironment Black Widow MAV.

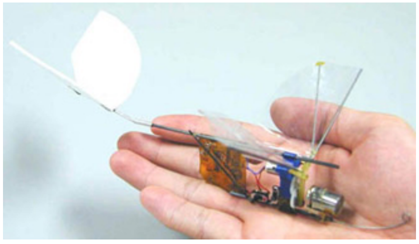

Figure 1.2: The MicroBat ornithopter MAV.

The application potential for such small aerial vehicles is great, especially in the area of remote sensing. Giving an individual the means to see and detect behind obstacles or in its near vicinity is an asset in most operational environments. This applies to combat operations contexts (which were one of the original concerns of the first DARPA effort), but is not limited to it. Civilian security, rescue and disaster relief operations can also benefit from information 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, given that MAVs can vary a lot in size, configuration and mission. 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. Aerial vehicles small and maneuverable enough to be able to fly indoors tend to be susceptible to wind gusts found outdoors, while aircraft built for covering long distances or operating in windy conditions are often too large and fast to fly in confined spaces. Blurring the line are intermediate sized aircraft in some specific configurations, that offer a solution of compromise. 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 close to sustainable as possible.

1.3 Thesis structure

The present thesis is divided into seven chapters, including this one. Chapter 2 will give an analysis and comparison of several aircraft configurations for the project. In chapter 3 the work done in a lightweight ornithopter and the lessons learned from it will be briefly described. From chapter 4 onwards, the tiltrotor will be the aircraft addressed, starting with the preliminary design, including dimensioning of the aircraft, choice of layout and selection of components for onboard systems, as well as stability and performance considerations. Chapter 5 will describe briefly the detailed design process,some of the design solutions adopted, the construction process of the prototype and the testing of individual components prior to integration on the airframe and also the cost analysis for the construction of one prototype. Chapter 6 will deal with the testing procedures of the integrated system, both on the ground and in flight, the results obtained and all the design changes and corrections made during that phase. Finally, chapter 7 will present the conclusions of the present work, as well as an assessment of goal satisfaction and guidelines for future development.

Chapter 2

Study of Possible Configurations

Chapter 1 set forth the requirements that the aircraft to be designed and built should follow and also referred to the wide variety of MAV configurations in existence. In this chapter, a qualitative and comparative analysis of some of those configurations will be described.

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 horizontal airspeed. Coupled with the requirement for fast forward flight, the number of possible configurations is reduced, since there are only three possible general solutions: the aircraft has a fixed (relative to the fuselage) force-generating device and pitches 90 to transition between hover and forward flight ("thrust hanging"); the aircraft has a swiveling force-generating device that pivots to redirect force between thrust and lift ("thrust vectoring"); or the aircraft has two force-generating devices, one for hover flight, one for forward flight ("orthogonal thrust").

2.2 Thrust hanging group

Not being an aircraft type *per se*, 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 is exploited in aerobatic aircraft for maneuvers like the torque roll.

Although conceptually and mechanically the simplest way to combine hover and fast forward flight, this configuration has important drawbacks. One is that any payload intended to operate in both conditions and that has direction dependent operation (i.e. a camera), must be either tilted or duplicated. The other one is that control in hover is limited, since the traditional flight control surfaces have very little airflow over them in this condition. One exception to this case is the ornithopter configuration, in which the flapping wings create a wake that is large enough (in terms of cross-section area) to provide effectiveness to the tail surfaces. This group includes conventional, fixed wing aircraft, as well as ornithopters. Figures 2.1 and 2.2 show examples of this type.

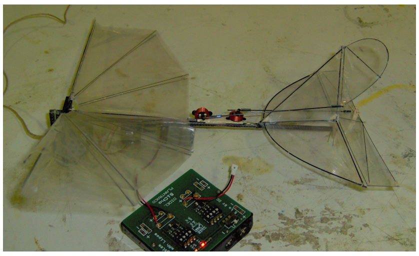

Figure 2.1: The DelFly 2, an ornithopter MAV.

Figure 2.2: A 3D aerobatic airplane performing a “prop hang”.

As a special case, the conventional helicopter configuration can be inserted into this section, although unlike the previous aircraft discussed, the helicopter's natural position is one for hover instead of forward flight. A conventional RC helicopter can achieve speeds of around 18[m/s](see reference [5]), which would be adequate to the mission requirements, and it can also hover very efficiently. This configuration however, was not considered for several reasons. On the one hand, a conventional helicopter is a machine of great mechanical complexity and the construction of an originally designed aircraft from the ground up would require great effort and an array of diverse precision tools. On the other hand, there is a very wide offer in the market for kits and readily assembled helicopters which, from a practical standpoint, would make development of a new and similar model quite redundant (i.e. nobody looking for a conventional helicopter would prefer developing a new model when an already made model is available that fulfills all the requirements).

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. This technique has been used successfully in the last decades in several full-scale military aircraft like the Hawker-Siddeley Harrier(figure 2.3), the Sukhoi Su-35BM or the Bell-Boeing V-22 Osprey, be it to achieve vertical flight capability or extend the maneuver envelope in combat situations. The advantages of this configuration lie in the potential to have a full featured flight both in hover and forward flight. This is to say that having one capability does not limit or hinder the other, although the performance in either mode is usually below that of aircraft specialized aircraft. In therms of weight penalty it is an intermediate solution, and the complexity varies with the design, although it's always above the mark for thrust hanging aircraft.
In terms of smaller scale applications, this type is not very common at present but there are successful examples, particularly scale replicas of the V-22 (such as in [6], depicted in figure 2.4).

Figure 2.3: An Hawker-Siddeley AV-8A Harrier, hovering.

Figure 2.4: A scale model of the V-22 Osprey, by Rotormast.

2.4 Orthogonal thrust group

The orthogonal thrust group includes aircraft configurations that are fully featured for both types of flight, and use different devices to produce the horizontal (thrust) and vertical (lift) forces, instead of a single device. This group includes compound helicopters as the most typical example, but other mixes of design features can be thought of (even if not practical) to achieve this end. 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. This often means powering down one system and powering up the other at the same time.

The main disadvantage is that, while design compromises must be made to accommodate both systems, generally a system used for one flight mode is of limited utility in the other. In a compound helicopter (like the gyrodyne in figure 2.5 for example), the main rotor only produces part of the lift in forward flight and the propellers serve only for yaw control in hover. Even if the same powerplant is shared by both systems, which is less feasible at the small scale being considered, there will still be important weight penalties. The best solution that could be implemented at small scale would be an autogyro/helicopter compound, but it would still would require the complex rotor head of a conventional helicopter for controlled hover flight, greatly increasing its complexity

Figure 2.5: The Fairey Rotodyne, a compound helicopter with VTOL capability.

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. The parameters were:

- Forward flight performance: covers agility and speed envelope in forward flight;
- Hover flight performance: covers ease of control in hover flight in all 6 degrees of freedom;
- Complexity: covers both mechanical and electronic systems complexity (higher score denotes less complexity);
- Scaling: covers how well the configuration scales within the size range defined;

- Forward flight efficiency: covers overall efficiency in forward flight in terms of both thrust and lift;
- Hover efficiency: covers efficiency and endurance in hover flight;
- Transition: covers ease and smoothness of transition between hover and forward flight modes;
- Payload: covers payload capability and any limitations imposed by the aircraft on the payload;
- Reference: covers the amount of reference work that was readily available at the time.

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 table 2.1.

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

Table 2.1: Scoring table for choice of configuration

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, although there was also a danger of the result becoming a clone of the existing aircraft. Eventually, work was developed in both the ornithopter and tiltrotor configurations, the latter producing better results. Chapter 3 will deal with all the work developed on the ornithopter, while chapters 4, 5 and 6 will deal with the work developed on the tiltrotor.

Chapter 3

Ornithopter - Work Developed

A large part of the total working time spent on this project was in developing an aircraft with an ornithopter configuration. Although this configuration was eventually abandoned, the work done brought important lessons to learn. This chapter will present a qualitative and brief description of the design, construction and testing work that was made with the ornithopter configuration.

3.1 Context

A similar and very successful project, the Delfly (see [7]), by students and professors of TU Delft and Wageningen University served as reference for the work developed on the ornithopter. There has been a large amount of research and development work done on and around that platform since its inception, as evidenced in references [8], [9], [10], [11], [12], [13], [14], [15], [16] and [17].

The initial goal was to match or surpass the performance of a Delfly 2 of late 2008 specification (figure 3.1), incorporating improvements as possible along the way. Although this reference was available from the start and provided valuable insight into the solutions of several technical problems, an effort was constantly maintained to give this project its own identity and making it more than just a Delfly clone.

After careful review of the original aircraft, some details were selected as possible opportunities for improvement, namely the control actuators and 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 for the same

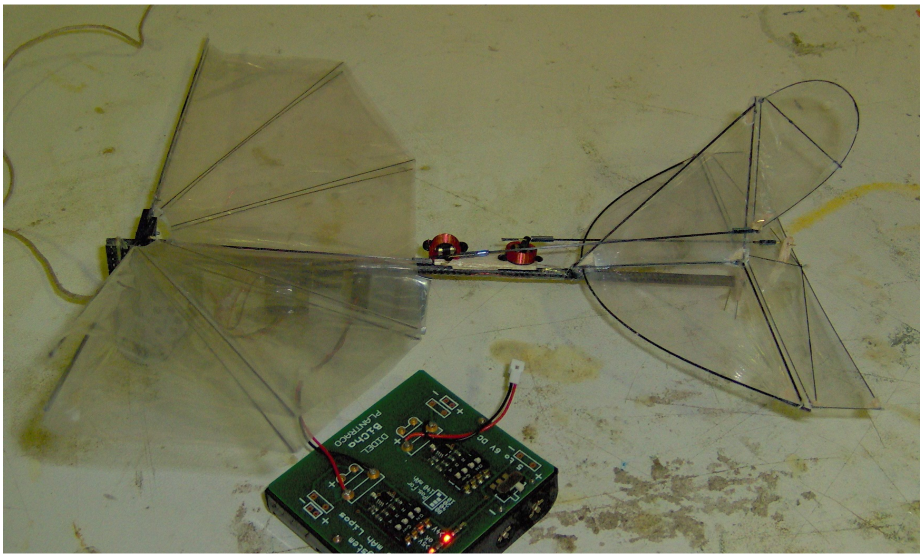

Figure 3.1: A DelFly 2 on the bench, recharging its battery.

fuselage.

The component availability also played a role in the design. Custom-made electronics, motors and actuators were excluded from the outset. The most suitable radio system found was that of Plantraco, especially designed for small, lightweight models. It uses an 868[MHz] radio link, which has shorter antennae and greater reliability than the old RC aircraft standard 35[MHz] system. For the propulsion there were two choices considered: a coreless (brushed) motor or a brushless motor. The coreless motor was the initial choice, mainly due to it's greater simplicity, low price and the fact that it does not require a separate ESC. However, a brushless motor has undeniable advantages when it comes to performance, durability and reliability (mainly because of the lack of friction from the brushes). Thus, it was decided to begin the project using a brushed motor and at a later stage, switch to a brushless motor, once the other features of the design had matured. However, to power the mechanism driving the wings, both types of motors had an unsuitable torque-speed characteristic, which forced the adoption of a gear train to increase the torque applied to the mechanism.

3.2 Sizing and layout

The basic dimensioning of the ornithopter was based on pre-existing flyers, both biological and man-made. The parameter for choice of scale was the all-up weight. It was decided that the aim would be to have a maximum AUW of 20[gf] with payload already included. From this number, an estimate was obtained for the wingspan and flapping frequency of the prototype, both from correlations pertaining to birds (from [18]). These correlations gave an estimate of the wing span, wing area and flapping frequency for a hovering hummingbird. The results and expressions used are presented in table 3.1

Parameter	Expression	Value
Mass [kg]	m	0.020
Wingspan [m]	$b = 2.24 \cdot m^{0.53}$	0.282
Wing area [m^2]	$S = 0.69 \cdot m^{1.04}$	0.012
Flapping frequency [Hz]	$f = 1.32 \cdot m^{-0.6}$	13.8

Table 3.1: Ornithopter sizing parameters

As for the layout, it has evolved over several iterations, although some features remained constant that are common to most ornithopter designs of the same category. These are the forward mounted flapping mechanism, the high wing, the tail at the rear and the flexible membrane wings with stiff, oscillating leading edges. Regarding the number of wings, a biplane configuration (two pairs of wings) was chosen over the monoplane. The advantages of this configuration are qualitatively described in reference [19] and the most important among them is the better low speed efficiency that allows a sustained hover.

3.3 Gearing and flapping mechanism

The gear train is always a necessity in electric powered ornithopters, since the electric motors available are designed for higher speed and lower torque than the requirements of the typical flapping mechanisms. The design of the geartrain must take into account the total reduction ratio, number of stages, the type of gears used and their spatial arrangement. After some trials, the gears selected were Didel's lightweight POM compound spur gears (they can be seen along with the rest of the mechanism in figure 3.3). They were found to be suitable for the intended task, available in a range of sizes wide enough to enable several different gear ratios and most importantly, available with precisely machined bushings and shafts that enabled a low friction setup without the need for modification during construction.

The spatial arrangement of the gears varied during the several iterations of the project but was always kept plane (bi-dimensional) in order to keep friction low and avoid the need for gears with more complex geometry (which weren't readily available anyway). The initial gear train was a single stage using a pinion and a standard spur gear, to which a single crankshaft was connected (see figure 3.2). This arrangement served the initial flapping mechanism, only requiring a single crank. As the flapping mechanism changed to require two cranks, the gear train evolved to a three stage arrangement, using one pinion and three compound spur gears.

The gear ratio calculation was made with estimates of the motor's torque-speed characteristic and the maximum expected torque (at the crank). Both these quantities vary with speed, and the gear ratio is subject to conflicting requirements: on one hand, too little reduction means there will not be enough torque to drive the wings at the desired speed (flapping frequency). On the other hand, too much reduction means the mechanism will remain limited to smaller flapping frequencies, even as the motor reaches its maximum speed. Unsurprisingly, the value calculated for as the optimal gearing ratio was very similar to the gearing ratio used in the DelFly 2.

The flapping mechanism was one of the targets for possible improvement regarding that of the Delfly. The original idea was to use a parallelogram linkage, with the wing hinge and a slider pin at opposing ends, being the slider pin driven by a single crank-rocker mechanism (see figure 3.2). The vertical groove over which the pin slid would at a later stage be actuated in order to tilt left and right and change the neutral line of the flapping wings. Given a fuselage with a large enough inertia, this should enable the aircraft to roll by changing the neutral position of the wings. This was left unverified however, since it was not possible at the time to produce the mechanism with sufficient quality (i.e. dimensional precision, low friction) to successfully use in the aircraft.

The flapping mechanism was changed to a more conventional design in which there are two cranks and each of them drives directly one pair of wings. This mechanism is simpler to dimension and build and has lower friction and lower weight than the previous. It is illustrated in figure 3.3. All the components shown except for the gears and their axles were originally manufactured.

Regarding the mechanism used in the Delfly, the two are comparable, although the Delfly uses a transverse shaft, enabling two cranks to be connected to the same output gear. This approach is lighter, since it saves one gear but usually presents greater friction in the joints, both at the crank and at the wing, as well as being slightly more difficult to build. It is illustrated in figure 3.4.

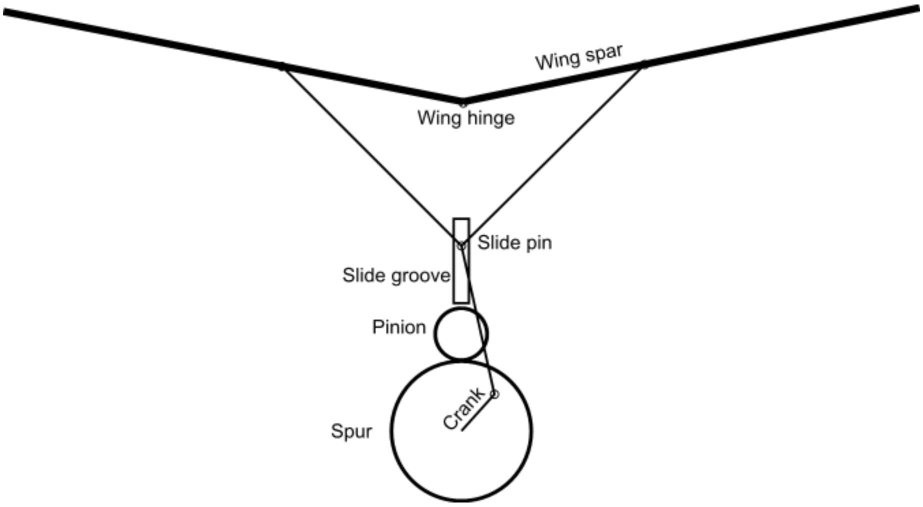

Figure 3.2: Diagram of the originally intended flapping mechanism

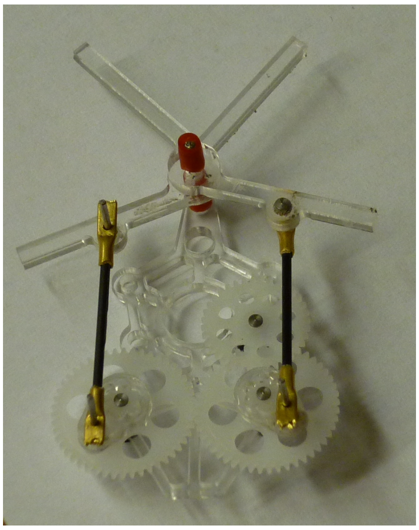

Figure 3.3: The flapping mechanism used in the final prototype (see also figure 3.6).

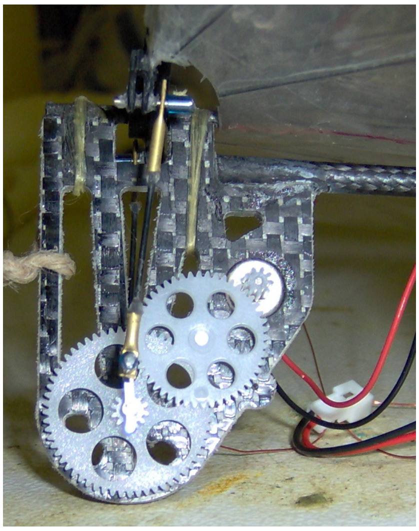

Figure 3.4: The flapping mechanism of the DelFly 2.

3.4 Wings

The wings used were of the same type as those found in nearly all small ornithopters. Each one consisted of a carbon fiber spar in the leading edge and a thin flexible membrane cut from mylar (bi-axial polyester film). The planform changed very slightly from iteration to iteration, mainly in dimension and proportion, with the shape remaining mostly that of a quarter ellipse. The wing was reinforced with thin carbon fiber rods acting as extra bracing.

The optimal wing form and bracing was intended to be determined experimentally, and a great effort was made to make the wing sets easily interchangeable. This brought severe limitations on wing design, particularly in the way to join the wings and the fuselage. Three approaches were attempted: in the first one there was a complete set of wings that included the membranes, spars and the arms of the flapping mechanism and was attached to the fuselage in two fixed points and two mechanism pivots; in the second one, the entire mechanism was part of the fuselage and the wing sets consisted of membranes glued to spars that were slid in sockets in the mechanism arms, while a carbon rod glued to the membranes' centerline and snap fit to the fuselage kept them centered; in the third approach, only the membranes were interchangeable, with the spars being part of the fuselage. The first was used in the first flying prototype while the second flying prototype used the second approach, in order to shorten the manufacturing time and material requirements for new pairs of wings. In this second aircraft, a pair of cellophane wings without extra bracing was also briefly tested, but no noticeable benefits were detected, other than the greater ease of construction and durability of the wing set. Eventually, the configuration was abandoned before any relevant conclusions regarding wing shape and structure could be made from the experiments.

3.5 Stability and control

The stability and control are fairly straightforward, since they are very similar to a conventional airplane. The two important differences are: the thrust line, which in the case of the ornithopter is at the same level as the wings above the CG, which causes an additional nose-down pitching moment that needs to be compensated, and the fact that even at zero forward flight velocity, the wake of the flapping wings exists throughout the wingspan, which means the tail has airflow over it, adding to its effectiveness in hover and slow flight.

As for the tail structure, both a conventional and a V-tail (butterfly tail) were considered and incorporated in the different iterations. The first prototype to take flight used a conventional tail, for simplicity. The following iteration, however employed an all-moving, bird-like tail in order to reduce weight further. This control surface consisted of a carbon fiber frame, covered in stretched film (like the previous stabilizers), only with a triangular planform and connected to the fuselage through a flexible hinge with two rotational degrees of freedom (implemented with a sleeve of silicon). This tail is illustrated in figure 3.5. Although flight testing was very limited on this prototype, no stability problems were detected, which indicates that this type of tail may be successful in other aircraft.

For the choice of actuators for the control surfaces, the were two basic options: electromagnetic actuators such as the ones used on the Delfy and servos (i.e. feedback controlled actuators). This aspect was one of those selected for improvement, since the Delfly's actuators had insufficient torque to hold the elevator properly at intermediate positions, losing much of the control resolution they would have on a less demanding application. Therefore, a servo would be better suited for the job. Conventional servos are typically heavier than equivalent electromagnetic actuators, a penalty that would be critical on this aircraft. However, in recent years a new type of servo was developed, that uses not a motor and a potentiometer to move and control the position of the arm, but a shape memory alloy, that acts as both an actuator and a position sensor (see [20]). The result is a lightweight servo with far better torque than an electromagnetic actuator. On the downside, these servos are about twice as costly as the electromagnetic actuators and and also lose some speed when actuated repeatedly over a short period of time. Nonetheless, they were chosen for the aircraft.

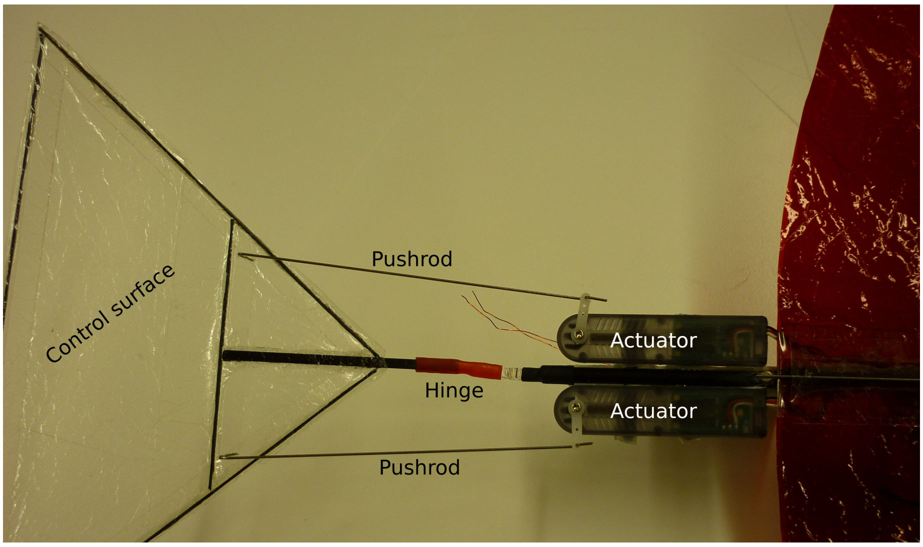

Figure 3.5: Image of the bird-like tail and actuators.

3.6 Structure

The structure suffered important changes throughout the design iterations. The conflicting requirements for lightweight and the protection of the components drove most of the changes, with a final compromise being reached in the last iteration by the addition to the main boom of a lightweight EPS part to shield the receiver, battery and flapping mechanism. The entire evolution, being far less relevant than the final result, will not be described here.

The materials used for the structure were mainly wood and composites, with some metallic pieces used in joints and linkages. The earlier structures were built from a laminate of wood (as a core) and fiberglass outer layers. This material showed good rigidity, machinability and adequate resistance for use in the fuselage. Pultruded carbon fiber tube and rod was used on the wing spars and reinforcement battens, in the frames for the stabilizers and control surfaces, in the mechanism and linkage rods and, in later iterations, as the main structure in the fuselage, which was effectively a carbon fiber tube from which all other components and parts were attached, along with a shaped part of EPS foam to protect them from damage in case of a crash. These are all shown in figure 3.6.

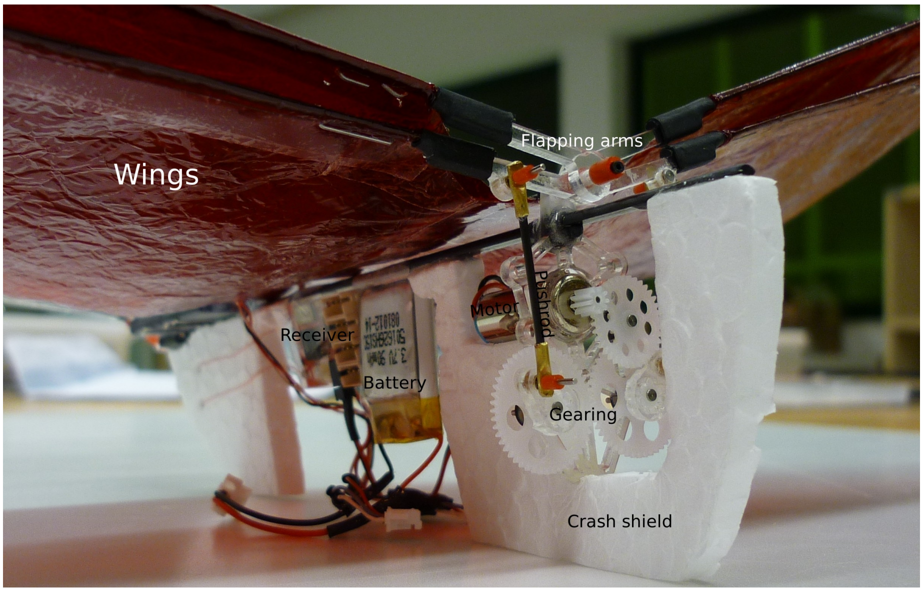

Figure 3.6: Flapping mechanism, basic structure and materials used

3.7 Construction and testing

Several prototypes were constructed, two of them flight-capable. The parts to be assembled were either bought, made by CNC cutting or handmade. The latter were the most time-consuming to get done and included mechanism connection rods and aerodynamic surfaces. Assembly was also done by hand, with several sub-assemblies being made first (wings, flapping mechanism, tail and fuselage), and then joined together. The electronic components (receiver, battery and actuators) were the last to be integrated.

The testing for either prototype consisted of two types of tests: the ground tests, to verify the correct systems integration and the effect of flapping vibration on the structure, and the flight tests. In both cases the prototype was unable to hover, due to insufficient thrust and excessive weight. The masses of the prototypes were 18.2[g] and 17.3[g] respectively for the first and second. Although these figures are below the sizing limits, the flapping frequency achieved in hover was also inferior to the intended. This meant that the only tests that could be made were in forward flight. These have shown that the prototype was capable of sustained and controllable flight, although the stall speed at the trim angle used was somewhat high. Further testing was not pursued, for the first prototype due to crash-related damage, and for the second due to the reassessment that ultimately lead to a change in configuration.

3.8 Conclusions

The main conclusion to be drawn from the work on the ornithopter is that, although the configuration is valid and an acceptable design is possible, the weight is a very critical factor (even more so than in other types of aircraft). At this scale, it takes a combination of refined construction techniques, building skill and precise tools to construct successful aircraft. Even then, this may come at a cost in terms of survivability, reliability, noise reduction, etc.... In order to keep weight down, most structures and components used are open and bare, which leaves them vulnerable. For example, bare electronic components are exposed to water in high humidity environments and bare flapping mechanisms can be fouled or seriously degraded by airborne solid particles or sand. This is a serious downside to be overcome if successful ornithopters are to be used in operational environments. Increasing the scale in order to have a weight allowance large enough to include component protection may not be an option, since it would require moving out of the range of Reynolds number in which several lift enhancement mechanisms are present (see [18]). A great degree of integration (as opposed to modularity) can be a good solution for this problem, along with different approaches to the wing's aerodynamics and control (see [21]). However, it requires more sophisticated tools and is best done by multidisciplinary development team.

Regarding theoretical study of the aircraft, it requires a precise coupled modeling of the flapping wings and flapping mechanism from the standpoint of dynamics, aerodynamics and aeroelasticity. Although there is interest in the area and advances have been made in recent years to a point where there are fairly good aerodynamic simulations for rigid flapping wings (see [22]) and some attempts at a coupled aeroelastic simulation (see [23]), there is not yet a definitive and comprehensive analysis tool that will allow design and manufacture of new ornithopters without a stage of experimental work (as described in [24]).

Chapter 4

Tiltrotor - Preliminary Design

In this chapter, the principal parts of the preliminary design of the tiltrotor aircraft will be elaborated upon. It will start with the general dimensioning, and include the traditional areas of aircraft design: layout, performance, propulsion, stability and control, structures, materials and electronic components.

4.1 General sizing

The basic sizing of the aircraft had two main constraints. One of them is the dimension of the off-the-shelf components for the aircraft. The other comes from the mission requirements. These state that the aircraft should be able to fly through the threshold of a standard door. Considering a clearance of 120[mm] to each side, to allow a safety margin, a maximum width of 460[mm] was decided for the aircraft. A minimum width was also established, since it is tied to the smaller diameter of opposite rotation propeller pairs that can be chosen to use as rotors. The smallest pair found was in the GWS 3-Blade series, at a diameter of 127[mm] (5[in]). Also the size of the electronic components to include in the fuselage must be taken into account. Based on the observed dimensions of several necessary components, a minimum fuselage width of 35[mm] was decided. This, along with fuselage wall thickness and necessary propeller clearances, lead to a minimum width of about 310[mm]. Note that this minimum corresponds to the lightest and smallest aircraft that could be built in this configuration. The width serves as reference to the length, which was to be close the same value in order to not increase the needed space for heading change maneuvers in hover. For height, it was decided to set a reference limit of 100[mm], this being the standard width of balsa wood plates that would become an integral part of fuselage construction.

These were the initially defined intervals for aircraft sizing. The final dimensions were set in the detailed design stage.

4.2 Layout evolution

The initial iteration drew some inspiration from the Bell-Boeing V22 Osprey (figure 4.1, see [25]) and the Bell-AgustaWestland BA609 (figure 4.2, see [26]) designs, with the motors and rotors at the tip of short thick wings mounted on top of the fuselage. This fuselage however, was more similar to a sea ship, with a superstructure and a deck fore and another aft. Further refinements saw the superstructure stretched forward to include all the forward deck, and, in a later iteration, the rear deck as well. The tilting mechanism, initially slated to operate inside the fuselage, was moved to the outside after it was noticed that the cables running inside the fuselage could disturb its free functioning. Thus the tilt servos, initially mounted vertically on the deck were transferred to the sides, in an horizontal position. This change also spelled a difference in the movement transmission, since now a rotating sleeve over the main beam tilted the motors, instead of a rotating shaft inside the beam. This arrangement also allows a quicker replacement of the sleeve and motor assembly if necessary. As a disadvantage, the tension-compression stresses on the top and bottom of the beam were transferred to the sleeve, which required an oversizing of both tubes in order to maintain deformations small enough to keep wear to a minimum. Figure 4.3 shows the evolution in layout through several fuselages built, either real-scale mockups (white PVC) or airframes ready for component integration (balsa wood). The second from the right is the stripped down airframe of the first flying prototype. Dihedral in the forward wing and the covering on the rear wing were added after the airframe was retired from use.

Figure 4.1: Bell-Boeing V-22 Osprey in flight.

Figure 4.2: Bell-AgustaWestland BA-609 civilian tiltrotor in flight.

When stability calculations and tail dimensioning began to take a more definitive

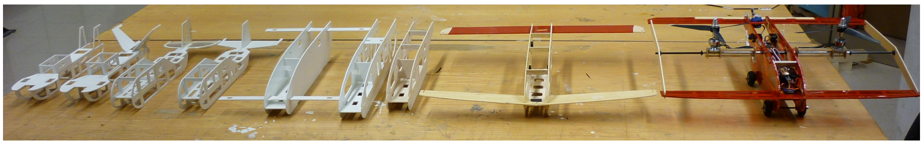

Figure 4.3: Several iterations of fuselage design.

form, a study was made for a tandem wing arrangement, for extra lift during forward flight. As such, an opportunity arose to increase the structural rigidity of the tilt arm assembly by bracing it with the wings. This layout has two advantages: structurally, all the lifting surfaces are connected at a point other than the fuselage, which allows the stress caused by the lift forces to be better distributed to all three members, regardless of whether the forces are being generated by the rotors or the wings, and the longitudinal bracing and the wings form a box around the rotors, preventing the spinning blades colliding with walls or other similar obstacles. This layout was used successfully in both flying prototypes and is illustrated in figure 4.4. Figure 4.5 shows a 3-view of the same airframe, with major dimensions shown.

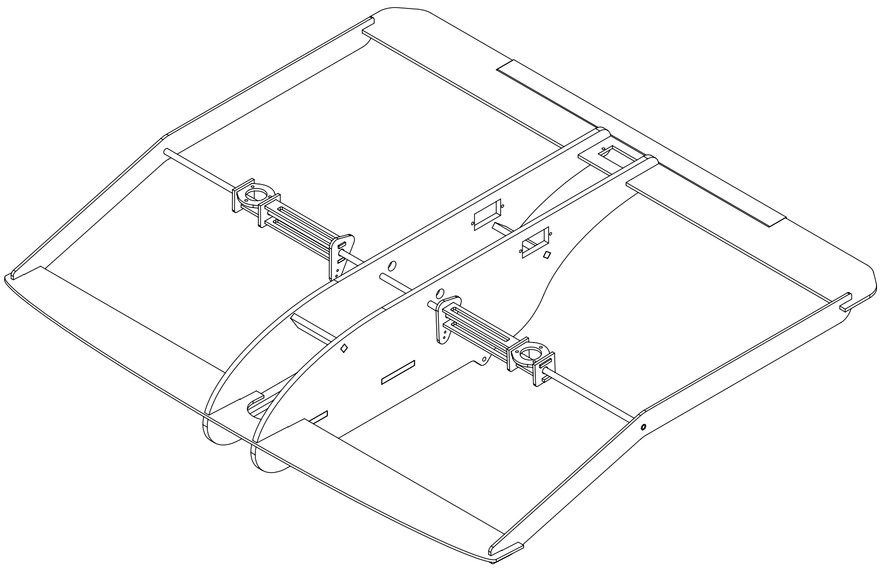

Figure 4.4: Isometric view CAD drawing of Flight Prototype Two airframe, showing the layout (not to scale).

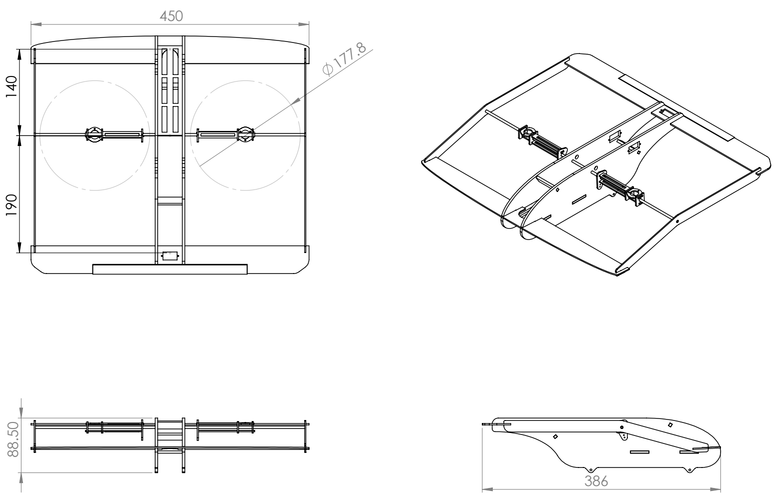

Figure 4.5: Three view CAD drawing of Flight Prototype Two airframe, with main dimensions shown in [mm] (not to scale).

4.3 Propulsion

4.3.1 Selection of rotor, motor and ESC

A distinctive and important feature of the tiltrotor configuration is obviously the rotor. At this scale there are two valid approaches to select a rotor type from off-the-shelf components: one is to use a regular RC airplane propeller (fixed or variable pitch); another one is to use an RC helicopter's rotor head and blades(with collective only or also with cyclic pitch control). The latter solution is used on full scale tiltrotors (the so called prop-rotors) or larger UAVs (as in reference [27]), but is not the best option for small scale versions. An articulated rotor is heavier than a similar sized propeller and requires extra servos to move the blade pitch controls. These controls enable a simple, helicopter-like way of controlling the aircraft's translation in hover mode. However, because there is also a tilt control and differential throttle for both propellers is possible, there is no absolute need to have rotor heads and all the associated weight and complexity.

Other VTOL-capable small aircraft, both tiltrotors and quadrotors, even as large as the recent Israel Aerospace Industries Mini-Panther (see [28]), have used airplane-like propellers to provide vertical thrust. Among these, the best suited for this application are propellers tailored for slow flight, as well as multi-blade propellers. The driving requirement for propeller selection is static thrust, since in the most demanding flight condition (hover), there will be little airflow perpendicular to the rotor disk. The corresponding lack of efficiency in forward flight (versus a high speed propeller) is offset by the existence of two propellers instead of one in the aircraft.

Variable pitch airplane propellers have also been considered. These would allow changing pitch to optimize the propeller performance for both hover and forward flight conditions. However, these propellers are often commercialized as integrated systems (propeller, motor and blade pitch servo) and in a very narrow range of sizes, the smallest of them being too large for the intended aircraft size. Other drawbacks include the mechanical complexity and overall smaller efficiency of the system in either of the flight regimes, versus a specialized propeller.

There were four main parameters important to the selection of the propeller: the diameter, pitch, direction of rotation and number of blades. The diameter was constrained to a maximum defined by the general dimensioning described above. Considering the selected layout, the largest (standard) diameter that could fit the size was 178[mm] (7[in]). As for the minimal diameter, opposite rotation pairs were available also for 5[in] and 6[in] diameters. The final decision fell to the largest diameter in order to have a greater propulsive efficiency for the same thrust (i.e. accelerating a greater mass of air by a smaller amount). The pitch in the commercial propellers considered varied little in the same diameter. Since a pair of propellers with opposite direction of rotation was needed, a market search was conducted. Two propeller types matching the already defined conditions were found: the GWS 7x3.5x3 (figure 4.6) and the Master Airscrew 7x4x2[1]. The three bladed propeller would seem like the obvious choice for greater static thrust. However the deciding parameter as thrust *per current* drawn by the motor. The two propellers were pre-selected and at a later stage, a static thrust test was conducted with them (see 5.3.2). The three blade propeller was found to perform better, for which it was adopted.

Regarding motors, there is a wide variety of suitable electric motors on the market. The type most common and most suited for directly driving a propeller is the brushless outrunner type. Brushless motors have a static arrangement of windings that are excited in such a way as to create a rotating magnetic field. This field drives a rotor that has permanent magnets attached to it. The outrunner arrangement has the windings in the center of the motor and the permanent magnets in a rotating can around the center. The opposing arrangement (windings on the

[1] Diameter x Pitch x Number of blades

Figure 4.6: GWS 7x3.5x3 nylon propeller (left handed).

outside and magnets on the inside) is called inrunner. The outrunner motors are more suited to directly driving a propeller because they typically exhibit lower values of the speed-over-voltage (Kv) ratio (which translates to greater torque and lower speed) than inrunners, making them suitable to drive relatively large propellers, as opposed to the small diameter electric ducted fan (EDF) impellers that inrunners are typically used for.

Being that the outrunner type is more suitable to the task, it was necessary to decide on a particular model. The main parameters within the type are the size and the Kv ratio.

Typically manufacturers and suppliers recommend a limited number of propellers for best use with a particular motor. The battery pack also influences the choice, since the battery voltage will directly control the speed curve of the motor. Each motor has a maximum of current it can handle, due to cooling issues. The tradeoff lies in using a smaller propeller at higher rotation speed (with a higher voltage battery) or a larger propeller at a smaller rotation speed (with a lower voltage battery). The batteries considered were two and three cell lythium-polymer batteries. Since for the same capacity a two cell battery weighs about two thirds of the three cell battery (and also costs less), it was decided to choose a motor that had a 7[in] propeller as its largest recommended propeller, and use the two cell battery. Within that range however, the largest available Kv ratio was chosen, in order to get the greatest possible thrust off the arrangement. Based on this, the motor selected as the AX1806N. Although no test data for the specific propeller/motor/battery combination was given by the motor's supplier, tests for a similar propeller suggested good performance. This was later confirmed in the static thrust tests (section 5.3.2).

Figure 4.7: AX 1806N brushless motor.

The criteria for ESC selection was simply the lightest ESC rated for the same current than the motor or more, and including a BEC capable of supplying enough current for all the onboard electronics. The selected model was the Turnigy Plush 10A, rated at 10[A] maximum continuous current and 12[A] burst current, and with a BEC rated at 2[A] continuous.

4.3.2 Battery

The choice of battery is closely linked to the dimensioning of the propulsion system, since this will be the greatest drain on available power. Also, the number of battery cells influences directly the motor's maximum speed, as explained before.

The main parameters to consider in selecting the battery were its capacity (in terms of stored energy) and its discharge rate. The number of cells was previously chosen to be two. The discharge rate is closely linked to its capacity and it is often given as a function of it, despite actually being an electrical current. Thus a battery with a capacity of 1000[mAh] (1[Ah]) and a discharge rate labeled as "10C" (ten times the capacity, per hour) can deliver a maximum current of $1 \cdot 10 = 10[A]$.

First, a brand and model line of batteries was selected. Battery model lines differ in price and performance. The more expensive models have less voltage degradation and usually have higher discharge rates and lower internal resistance. However, these higher end batteries are expensive. As a means of compromise, the Hyperion LVX was chosen, being rated for 3D and aerobatic RC aircraft (thus delivering good performance), but with prices still within an acceptable range.

The next step was to list all the batteries of that model and to filter out the ones that couldn't deliver the necessary maximum discharge current, which was majored by the sum of the maximum (continuous) currents that the two ESC and one BEC could withstand ($2 \cdot 10 + 2 = 22[A]$). This established a lower threshold. The upper threshold is then defined by weight constraints. At the time, the propulsion system's thrust vs. current curve had not yet been determined and the choice was made by estimating a fraction of the total mass to belong to the battery (20[%] to 25[%]). Based on this, two batteries were chosen for the flight testing, with capacities of 1200 and 1500 [mAh].

4.4 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. While in forward flight it is possible to control the aircraft in a way very similar to a conventional airplane using conventional tail surfaces, in hover mode the control must be made using only the rotors.

As a convention, whenever tilt angle is referred to, it is considered to be 0[°] when the rotor axes are vertical and 90[°] when they are horizontal.

4.4.1 Pitch stability and control

Hover

For pitch stability, it is important to consider the longitudinal and vertical locations of the center of gravity. In an ideal hover situation, when no aerodynamic surfaces are creating significant forces, the center of gravity should be in the same longitudinal coordinate as the tilting pivot and the only applied forces will be aircraft weight and rotor lift. In terms of vertical location, the aircraft will exhibit neutral stability with the center of gravity either above or below the pivot. In order to improve this situation, an artificial stability augmentation needed to be added to the aircraft. This consisted of rate gyro set to input feedback control on the pitch control channel. The implementation can be made with off-the-shelf components that are usually known only as "gyros".

Regarding pitch control, there were three mechanisms known at start to implement it. One of them is to use an articulated rotor with (forward-aft) cyclic pitch control. Since a fixed-pitch propeller was chosen for reasons outlined before, this option was not considered. Another option was to use gyroscopic precession caused by a tilt of the spinning propellers about the aircraft roll axis to induce a pitching moment on the aircraft. This method has been used successfully on the designs by Gary Gress and is described in [29]. However, it was considered that from a cost/benefit point of view, the added weight and complexity of the systems (both the mechanical tilting and its electronic control) would not justify the advantages.

Finally, the rotors can be tilted symmetrically, changing the orientation of the thrust vector to produce an horizontal component. This component, multiplied by vertical the distance between the tilting pivot and the center of gravity the center of gravity creates a pitching moment. This method is the simplest and uses the same actuator and mechanism for the tilt control and it was chosen for the aircraft.

Forward Flight

In this condition there is a forward airspeed that enables the use of aerodynamic surfaces. These surfaces were chosen as a tandem wing, so that in cruise, both surfaces would produce lift, rather than having a main wing interfering with the rotors and a conventional tail producing downforce. For the wings a flat plate airfoil was chosen, mostly due to its greater construction simplicity. Both wings have approximately the same area, which means that for positive pitch stability, the rear wing must have zero incidence and be farther away from the center of gravity (thus having greater authority) than the forward wing. The distances and forward wing incidence were chosen so as to have the forward wing stalling before the rear wing, and producing nearly its maximum lift in trimmed conditions. The span was limited by the maximum width of the aircraft. Table 4.1 shows the wing data.

	Front Wing	Rear Wing
Airfoil	Flat Plate (t/c=5%)	Flat Plate (t/c=5%)
Incidence [°]	3	0
Chord [m]	0.045	0.045
Span [m]	0.386	0.386
Area [m^2]	0.193	0.193
Dist. to CG [m]	0.140	0.190

Table 4.1: Wing Data

In order to assess the aerodynamic performance in forward flight, some approximate calculations were made. The Scilab code used to perform them is listed on appendix B . For several different speeds, a steady condition was considered, with tilt angle and throttle setting adjusted for level, unaccelerated flight. A trim angle of attack was calculated. This angle of attack was found to be quite similar for all velocities considered. The airfoil lift curve was modeled as linear between -7[°] and 7[°] of angle of attack, with a slope adapted of 2π [/rad] (0.11[/°]). This was used due to the relatively large aspect ratio (8.6) of either wing. These theoretical values were obtained from [31] and [32] . The drag coefficients were estimated from quick analyses in XFLR5 (fuselage, using panel method) and JavaFoil (airfoil, also using panel method). An extreme accuracy on the calculations was not a primary concern at the time, though later testing showed the results obtained to be relatively close to the observed (see section 5.3.3). The trim angle calculated varied between 0[°] and 4[°], the latter value being common to all velocities above 5[m/s]. Figures 4.8 and 4.9 show respectively the variations of calculated trim thrust and trim tilt angle with velocity. Figure 4.10 shows the thrust-tilt curve.

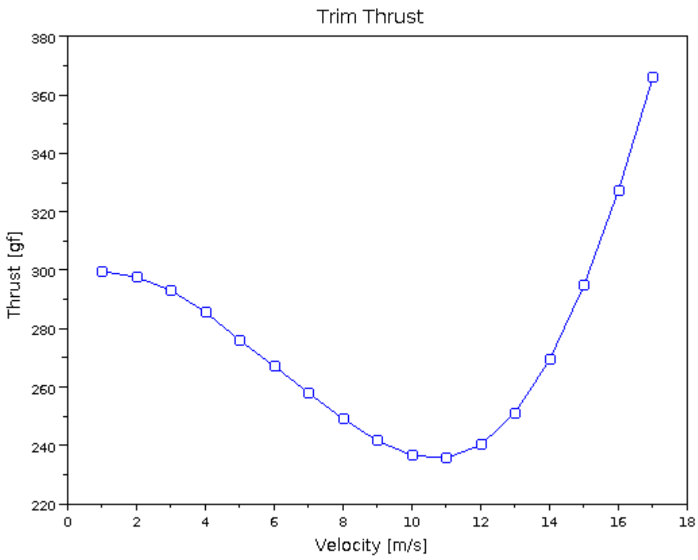

Figure 4.8: Trim thrust (both motors) versus forward velocity.

The trim thrust curve shows a minimum for a velocity of approximately 11 [m/s]. This should be the most efficient velocity for forward flight. At lower velocities a greater throttle setting is necessary to produce additional lift and at higher velocities the increase in drag requires an increase in thrust to compensate.

The trim tilt angle curve shows that as speed increases, so should the tilt angle. This is due to two factors: firstly, as speed increases the amount of required rotor lift decreases with the increase in lift from the wings; secondly, as speed increases

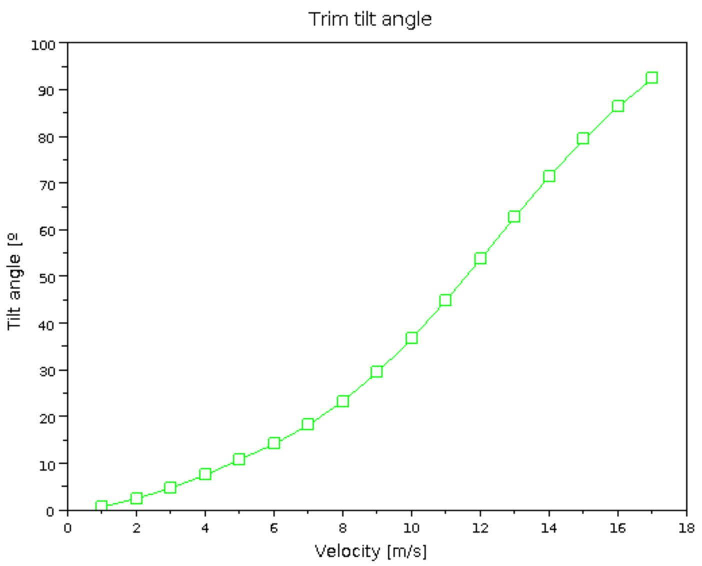

Figure 4.9: Trim tilt angle (common) versus forward velocity.

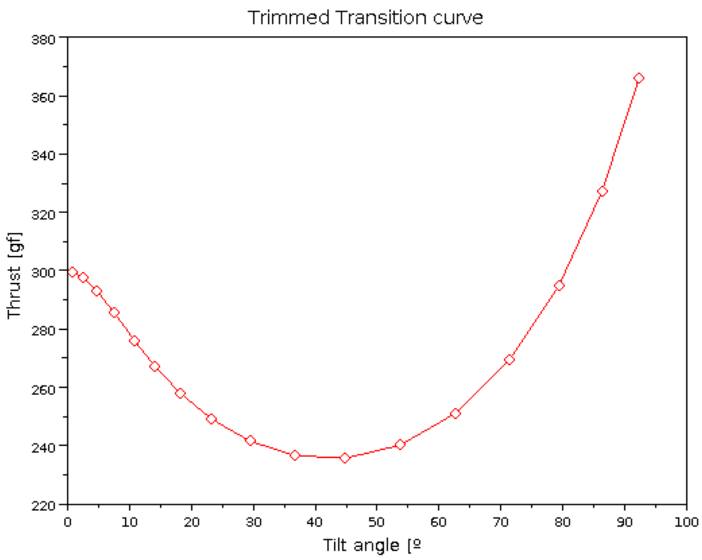

Figure 4.10: Trim combinations for thrust and tilt angle at a fixed angle of attack for several velocities.

drag also increases, which requires more forward thrust to compensate. It should be noticed that the tilt angle will not exceed (approximately) 45°, due to lateral control issues (see section 4.4.2). Thus this curve also indicates a maximum forward speed of approximately 11 [m/s] will be established for the aircraft.

Plotting these two curves against each other, it is possible to obtain an indicative curve of how the tilt angle and thrust should relate in order to keep the aircraft trimmed during a transition to forward flight.

In order to have greater pitch control, a conventional elevator was added to the rear wing of the aircraft. This should allow the pilot a more conventional control during transition and forward flight.

4.4.2 Roll-Yaw stability and control

Hover

For roll stability the important directions regarding center of gravity location are the transverse direction and the vertical direction. Since the aircraft is symmetrical, the transverse coordinate will naturally lie in the symmetry plane of the aircraft. Vertically, a situation similar to the pitch case applies, also requiring gyro correction on the roll axis. This gyro will also help correct asymmetries in the functioning of the motors.

The simplest manner of obtaining lateral-directional control in hover is through the use of asymmetric thrust for the roll and differential tilting for the yaw. However, this rotor-based control leads inevitably to a coupled output on both axes when only one of them is actuated, even with a null common tilting angle (rotor disks horizontal). The choice of which propeller (right handed or left handed) is put on which side affects this coupling. For nomenclature, let it be considered that the configuration in which the right handed propeller is on the right side and the left handed propeller is on the left side will be called configuration A, while the opposite arrangement will be called the configuration B.

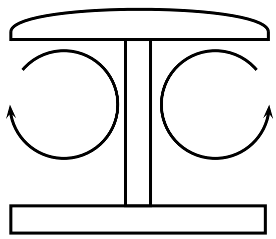

Figure 4.11: Spinning directions in configuration A

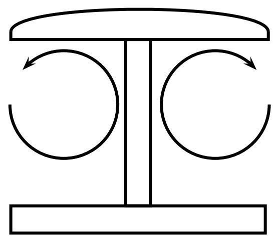

Figure 4.12: Spinning directions in configuration B

The two phenomena that lead to this coupling and how the propeller arrange-

ment affects them will now be described:
When differential thrust is applied, the rotational speed of both propellers becomes mismatched. Therefore, a net reaction torque appears. For configuration A, a roll to the right will cause the left propeller to spin faster than the right one, resulting in a net torque to the left side, i.e. adverse yaw. For configuration B this is opposite. This torque will be applied for as long as the asymmetric thrust is maintained.

When differential tilting is applied, the gyroscopic precession of the propellers acts in the same direction, adding up instead of canceling each other. This results in a net rolling moment. In configuration A, when a yaw to the right is applied, the right propeller is tilted back, while the left propeller is tilted forward. The roll induced by precession is towards the left side, therefore adverse. In configuration B, this situation is reversed. Also, and unlike the previous coupling, this one is only effective while the rotors are being tilted (i.e. it's a transient phenomenon).

Since it is better, from an aircraft control standpoint, to have favorable instead of adverse coupling, configuration B chosen for the aircraft.

In the forward flight condition, and because of the common tilting, there is also a direct coupling resultant from the orientation of the thrust vectors. Therefore, an input in one of the channels will have an impact on the other channel, which grows with the common tilting angle. Past the 45° threshold, the channels will be effectively swapped from the hover condition, with the roll control mainly causing yaw and the yaw control mainly causing roll. Furthermore, although the direction is maintained for the asymmetric thrust channel (commanding a roll to the right causes roll and yaw to the right) , the same is not valid for the differential tilt channel (commanding a yaw to the right causes roll to the left and yaw to the right). Also, the fact that the gyro on the roll channel is connected to the asymmetric thrust control will cause both a yaw and roll response to a roll disturbance. Two factors mitigate the problem. One, is that the forward flight capability is intended to allow the prototype to make short (straight line) dashes between target areas, and not much maneuvering should be expected in this mode. The other is that this coupling is favorable, thus making it easier for the pilot to correct any deviations intuitively. At any rate, the aircraft was not meant to fly with the rotors completely tilted forward (i.e. vertical rotor disk). That would require a more advanced control scheme, with the roll and yaw gyro and control channels swapping at 45° and the gyro gains varying with tilt angle. In the implementation of the design, the tilt travel was mechanically limited.

4.4.3 Radio control

The driving requirements for the selection the radio control system, constituted by a hand-held transmitter and an onboard receiver are: a sufficient number of control channels, signal reliability, range, overall system price and programming ability. This latter requirement is very important in an unconventional aircraft such as this. As for the number of channels, there is usually a minimum of two for aircraft. In a two channel configuration, the roll and yaw are normally coupled, as well as pitch and throttle control. This configuration is normally only used in lightweight toy-grade ornithopters ans slow-flyers, given that it requires all modes to be stable and well damped, leading to reduced performance. Faster or slightly larger aircraft tend to include a decoupled pitch control using an elevator. This arrangement is common in small foam fixed wing aircraft and most larger ornithopters. The standard, however is to have four channels, one for the throttle and one for each of the three (decoupled) attitude controls. For this aircraft an extra channel is required for control of the helicopter/airplane transition, meaning at least five channels were necessary. Furthermore, in a standard radio transmitter there are three types of controls: continuous with position hold (as a regular stick or a knob, commonly used for throttle), continuous with return-to-neutral (as a spring-loaded stick, commonly used for roll, pitch and yaw channels) and discrete position (as a switch of usually two or three positions, commonly used for flaps, retractable landing gear, etc...). For this aircraft it was necessary that the transition control could be held at fixed positions. This required either a switch or a knob control (as per rule, there is only one non-spring-loaded stick on most transmitters, reserved for the throttle). A switch would present a limitation in the number of options available for transition, allowing only two or three positions, with a very rapid change between them (unless an external servo response modulator was used).

Therefore, it was necessary to have a radio with at least five channels, where the fifth could be controlled by a knob, have sufficient range and signal reliability and be affordable. The radio selected was the HK-T6A sold by United Hobbies (the same basic model has been sold under other brand names in the past). This radio, although inexpensive, provides some features that made it desirable for this particular project:

- six channels, being the the fifth and sixth assignable to knobs;
- operating frequency band of 2.4[GHz] with spread spectrum technology, which is less susceptible to environmental interference than the standard 35 MHz band;
- a range of programming features including variable sensitivity, exponential

and linear variation of the control signal, three control mixes between any pair of channels and endpoint adjustment, all graphically set using a computer software and uploaded to the radio in real time (including mid-flight, if necessary);

- low price of the transmitter and the extra receivers.

Figure 4.13: HKT6Av1 radio transmitter.

4.4.4 Actuator selection

The actuators of choice for almost all remote controlled small and medium scale aircraft are commonly called servos (shortened from servomechanism, the feedback control scheme they use to control position). They consist of an electric motor, usually a coreless brushed motor, a drive train with a large reduction ratio connected to an arm, and a control circuit that reads a PWM signal and, together with a potentiometer, controls the motor to hold a given arm position. The most important parameters to choose a servo are their weight and their maximum torque. Other parameters include the control type (digital or analog), actuation speed and the materials used in the drive train. Digital servos use a different, microprocessor-based control circuit that enables higher pulse frequencies to be sent to the motor. This allows a faster response time to both a control input or an unwanted disturbance to the arm position, resulting in a smoother, more precise operation and a greater holding torque. For the gearing, there are several materials available, although they fall into one of two categories, metal and polymer. Both materials can withstand normal operating loads but metal gears are more resistant to shock loads, which are usually imposed by collisions or more abrupt maneuvers.

Since the servo specifications in terms of torque are usually only given for the maximum, a large safety margin was given, in order to allow the servo to operate away from it's maximum limits, prolonging operational life and reducing current consumption. The servos initially chosen for the tilt mechanism were the Hextronik HXT900 analog servos, with a mass of 10[g] and a maximum rated torque of 1.6 [kgf·cm]. At later stage of the design it was decided to determine what gain in performance was there by installing a higher quality digital servo. The choice fell on a servo with slightly higher specifications, the Ino-Lab D202MG, rated at 2.0[kgf·cm] and also with a mass of 10 [g]. This servo was used on Flight Prototype Two and onwards, with noticeable gains in flight performance, as will be described in chapter 6.

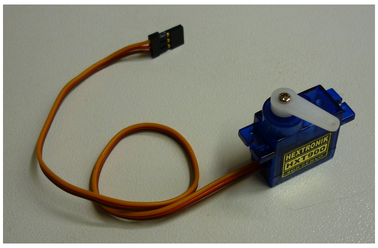

Figure 4.14: Hextronik HXT900 analog servo.

Figure 4.15: INO-LAB D202MG digital servo.

For the actuation of the elevator, a smaller servo was chosen. The selection was based on the servos used in the elevator of similar sized RC aircraft. An analog servo, the Hextronik HXT500, with a mass of 5[g] and a maximum rated torque of 0.6[kgf cm] was chosen for this role.

4.4.5 Gyros

The necessity for gyros has been discussed in sections 4.4.2 and 4.4.1. There are two types of gyros in the market: standard "rate gyros" and attitude-hold gyros. Although both have a rate gyro as the primary sensor, the standard gyros input a correction to the system that is proportional to the perturbation being measured, while the attitude-hold gyros can also input a correction proportional to the deviation from a reference. The latter are almost always marketed (and used) as heading-hold gyros in RC helicopters. They tend to be heavier and more expensive than the standard gyros and may require the use of an extra channel for remote control of the gain and alternating between standard and attitude-hold working modes.

Although an attitude-hold could have definite advantages on this aircraft, their price, weight and need for an extra channel were counted as important drawbacks. Three gyro models were tested, two standard and one attitude hold. Of the three, only one of the standards gyros showed to be compatible with the rest of the components (particularly the signal mixers) and thus was selected for the aircraft.

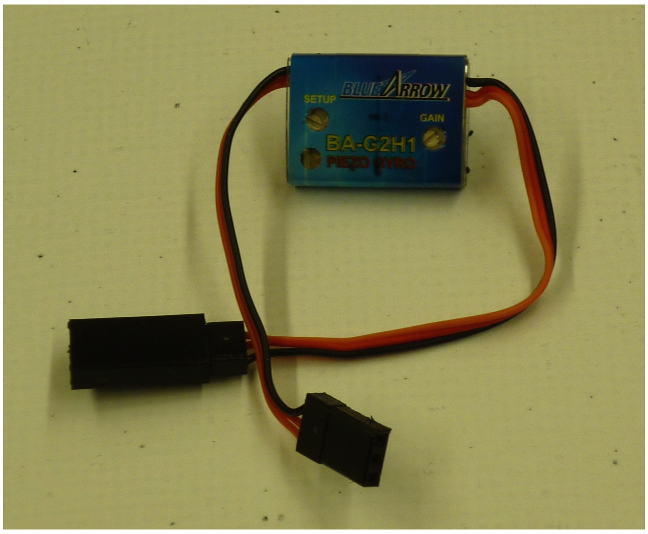

Figure 4.16: BA-G2H1 gyro selected for the project.

4.5 Structural considerations

4.5.1 Material selection

There were several materials considered for use in the aircraft, including woods (balsa wood and birch/mahogany plywood laminate), laminate composites (fiberglass and carbon fiber in epoxy matrix), polymers (acrylic and PVC) and metals (aluminum, and also brass and steel for small fittings and parts).

For the main structure several materials in sheet form were considered. The most important consideration was strength-to-weight ratio. Balsa wood is a material widely used in model aircraft construction for its good strength-to-weight ratio, and for this reason it formed the basis of the main structure. However, balsa alone would not be strong enough to handle impact loads or even some careless handling, both of which may cause across-grain and shear stresses. The solution used was to laminate the balsa, either as a plywood with differently oriented plies glued to each other, or with fibreglass for reinforcement. The traditional model aircraft plywood made from birch and mahogany is too heavy to be widely used. A structure made from carbon and glass fiber reinforced polymer was also considered and discarded as being difficult to construct and more expensive. The same reasoning applies to the wings.

For the booms, pultruded carbon fiber tubes were an attractive option, since they are readily available and have a good strength-to-weight ration. Smaller parts in the tilt arm were made of a plywood core fiberglass sandwich that, although heavy for more extensive use, is very appropriate for small parts that are subject to relatively high stresses or are part of linkages and need to withstand the bearing stresses caused by a loaded pin-hole joint. Metalic materials, aside from off-the-shelf parts (nuts, bolts the propeller adapters, etc.. . .) were only used on the tilt tube.

4.5.2 Structural design and dimensioning

Since one of the goals of the aircraft is to be easy and quick to build, the airframe structure reflects this philosophy. From early on there were several features that were deemed as necessary and were found in all the iterations of design: a three-dimensional structure based on a snap assembly of CNC-cut two- dimensional parts; a main deck that mounted the principal components on the top part and the battery on the bottom, being the battery's position changeable fore and aft to adjust the location of the center of gravity; motor mounts supported on one of two concentric tubes that rotated around one another to create the tilt movement (activated by a servo in the fuselage).

The largest suitable (affordable, modeling grade alloy with slide-fit tolerance) aluminum tube found commercially had a nominal interior diameter of 4[mm], which would be compatible with carbon fiber tubes or rods with an equal outer diameter. Linear beam theory (as described in [33]) was used to assess the suitability of such arrangement with respect to deformation. The tilt shaft was assumed as a cantilever beam from the fuselage to the thrust line of one propeller, plus clearance. For simplicity, this distance was considered as 100[mm] (the actual distance will be slightly smaller). The rest of the beam and the bracing were considered a margin of safety and were not accounted for. The load imposed on one boom was slightly above 250[gf], the expected maximum thrust for one rotor. From Euler-Bernoulli beam theory we have:

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI} \tag{4.1}$$

where y is the vertical coordinate of the beam's neutral plane, x is the longitudinal coordinate, M is the bending moment, E is the material's Young's modulus (for carbon fiber a value of 200[GPa] was assumed[2]) and I is the second moment of area of the cross section. For an annulus with inner radius r_i and outer radius r_e, this is given by:

$$I = \frac{\pi(r_e^4 - r_i^4)}{4} \tag{4.2}$$

The bending moment caused by a point load T at the tip of the beam (of length l) is given in this case by:

$$M = T \cdot l - T \cdot x \tag{4.3}$$

Solving for the deformation, we have:

$$y = \frac{-2 \cdot x^2 \cdot (x - 3l) \cdot T}{3 \cdot E \cdot \pi \cdot (r_e^4 - r_i^4)} \tag{4.4}$$

which yields, for the 4x2.5[mm][3] tube and the assumed conditions, a deformation at the tip of 0.38[mm]. The greatest concern with the deformation of the boom is the contact it causes with the outer aluminum sleeve. This contact will always be present, since the sleeve is transmitting loads from the rotor to the boom, but large deformations of the latter might severely increase the contact area and thus the wear on the carbon boom. The calculated value indicates an acceptable deformation. Nonetheless, this was one of the aspects to monitor in subsequent phases of the project.

In terms of stress, a simple test was performed with static weights hanging from the tip of a length of tube. The tube successfully held the weights and suffered no visually detectable damage.

Regarding the rest of the structure, it was deemed too costly in terms of both time and effort to make a comprehensive theoretical structural analysis. The structure's final geometry and material was determined in the detailed design stage, mostly through experimentation and using insight from the observation of the structures of similar sized aircraft.

4.6 Weight forecast

In order to do some of the calculations outlined before, an estimate of the total mass of the aircraft was necessary. Table 4.2 shows a breakdown by components of the respective weights. For the case of off-the-shelf components, relatively accurate figures were available. In the case of manufactured components however, before

[2]The beam was made from a high-grade pultruded carbon fiber tube with a hight fiber content, which makes this assumption feasible.

[3]Outer Diameter x Inner Diameter

their actual construction, only estimates could be made. The values presented were rounded to the nearest gram.

Item	Quantity	Unit mass [g]	Subtotal [g]
Motor	2	21	42
ESC	2	10	20
1200mAh Battery	1	67	67
Receiver	1	12	12
Tilt servo	2	10	10
Elevator servo	1	5	5
Propeller and adapter	2	10	20
Gyro	2	3	6
Signal Mixer	2	5	10
Linkages	1	6	6
Airframe	1	80	80
Extra connectors and cables	1	10	10
		Total	293

Table 4.2: Estimated mass breakdown and total.

Chapter 5

Tiltrotor - Detailed Design and Construction

This chapter is dedicated to the implementation (detail design and construction) of the preliminary design described in chapter 4. Some features that were added after some flight testing will be described instead in chapter 6. The construction process and the techniques used will be briefly explained. The tests made on the individual electronic components and their integration will also be explained. Finally, there will be a section detailing the costs involved in constructing one aircraft.

5.1 Detailed design

5.1.1 Tool and material availabity

In order to construct the aircraft, some tools are necessary, along with the raw materials in a suitable form and other components (like covering film or fasteners). The availability, cost and ease of use of these is one of the concerns conditioning detailed design. The Aeronautical Project Laboratory at IST, although not an industrial-grade workshop, has some very useful machine tools, especially a CNC miller capable of cutting two-dimensional parts on sheets and flat plates of several materials. The current miller mounted on the machine offers good precision and high rotation speeds, allowing the cut of soft and medium materials in short time frames. This machine was chosen as the main tool for airframe parts fabrication. Since its software lacks the capability to easily mill three-dimensional parts, the structure was kept as an assembly of two-dimensional parts whenever possible. This influenced the fuselage, wing and tilt arms detailed design.

All the sheet materials used for part fabrication were laminates produced for this project from off-the-shelf raw materials: plywood, balsa wood and fiberglass cloth, bonded with epoxy resin. Other necessary operations that were possible in the Laboratory were soldering of electronic components, carbon and metal tube cutting (small diameters) and sanding and griding operations on wood, composites and metal.

5.1.2 Airframe design

In order to design a lightweight, yet structurally capable airframe made of two-dimensional parts, an approach similar to that used in classical wooden RC aircraft was taken. This consists of a covered structure, in which the internal structure supports all the stresses and the covering is only used for aerodynamic streamlining and shape. This contrasts with real scale aircraft, that often employ monocoque (skin bears all loads) or semi-monocoque (skin bears shear loads) structures. The approach used provides a structure that is geometrically simple, with few parts and easy and fast to build.

The structure as mentioned, is an assembly of flat panels. These panels are made from a balsa laminate [1] and their dimension was conditioned by the standard size of commercial balsa sheets. Commonly available balsa wood sheets are 100 [mm] in width and 1000 [mm] in length (nominal dimensions). Fuselage length was ultimately determined by the distance between both wings and the center of gravity, which is compatible with the standard sizes. There was no specific limitation to fuselage height from the preliminary design, other than the fuselage having to have capacity to contain all the components and have enough room for them to be mounted and accessed for adjustment and replacement by hand. The fuselage height was initially sized as 80[mm]. A true scale fuselage mock-up was built to verify component mounting and cable routing and it also demonstrated that the height chosen was adequate.

As for the structure itself, it is comprised of two equal 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. The lateral panels were to be covered with heatshrink adhesive covering film, although this only materialized in the second prototype. The top, bottom, rear and front ends of the fuselage were to be covered with a thin sheet of fiberglass and also covered with film. The fiberglass backing will give the covering rigidity enough to be pulled back for easy access to the interior, an then put back into place. This covering was not

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

added in the flight tests made, for a conveniently faster access to the interior of the aircraft.

To fit the flat parts, two types of joints were used: for the two lateral panels and the horizontal panel a mortise and tenon joint was used, reinforced with epoxy resin; for the fitting of the wings on the fuselage, halved joints were used. These types of joints were selected by their simplicity (they could be seamlessly incorporated in the cutting process with no further operations required) and fitness to the structure's geometry. This also allowed the assembly of the airframe to a near-complete state before any glue was added, which enabled additional checks on cable routing and component fitting to be made before the final assembly.

5.1.3 Wing design

The wing design was intended to be simple and straight forward. The preliminary 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 cloth on both sides (increasing total thickness to 2.3[mm]).

The wing bracing is anchored on the tips of both wings (by a halved joint) and slid into the main boom. The material used is fiberglass reinforced balsa. This part was conceived to be easily replaced, since it is prone to damage by sideways collisions with objects.

5.1.4 Tilt arm design

The tilt arm is one of the critical components of the aircraft, since it transmits, along with the tilt servo, loads from the motor to the rest of the aircraft. Additionally, it must also rotate the motors with the least possible friction, and be resistant to wear. Since the main transverse boom (which is also a beam) has to run the full span of the aircraft, the portion that rotates was built around its outside, in the form of an aluminum tube in which ends are the motor mount and an arm connected to the tilt servo. This arm is a flat part to which a clevis and pushrod are attached. It is slid in and glued to the tilt tube. The motor mount is an assembly of three flat parts, forming a shelf with two supports that are slid in and glued to the tube.

The contact area between the tilt tube and the boom has been lubricated with oil to reduce the wear on the carbon fiber caused by friction with the aluminum while under load. Figure 5.1 shows the tilt arm of Flight Prototype two and its components.

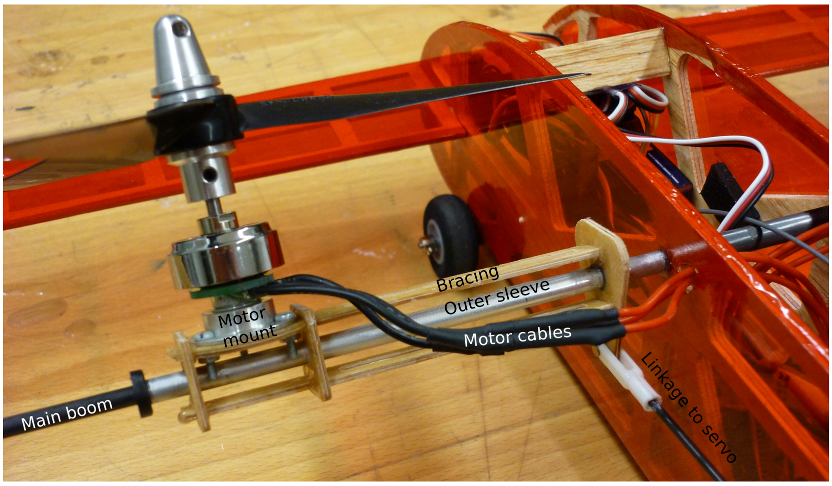

Figure 5.1: Tilt arm, with the various components named.

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. The tilt horn was designed with another hole with a smaller arm to be used if a greater angular motion were required at some point along the testing. Using this hole will increase the tilting range to about 21° rear tilt and 61° forward tilt.

5.2 Construction

The construction process consisted of three stages: fabrication of airframe parts, airframe assembly and component integration. The two following section will cover the former stages, while the latter will be described further along the text.

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 in sandwiched materials. 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 veneer).

The layup was made entirely by hand. The bonding agent used was a slow curing epoxy resin, which was left to set at room temperature and without vacuum or pressure applied. The curing was made between two boards of PVC to ensure a straight surface and ease of removal of the laminate. To give a rough texture (ideal for later application of adhesives) on the surface and to absorb some excess resin, a layer of peel ply was used between the outer layers of the laminates and the PVC boards.

After the cure was completed the aircraft parts were cut from the laminates on the milling machine. The nature and thickness of the materials allowed a clean and precise cut in all of the parts, with few sanding and grinding operations needed afterwards.

The covering of parts prior to assembly was only applied to the wings of the second prototype. Nevertheless, the procedure is the same for covering operations post-assembly: the film is stretched over the surface and heat is applied by means of an iron to melt the adhesive and glue it to the structure. After all the film is glued, a greater heat setting is applied to shrink the film and make a smooth, taut covering. Care should be applied in the case of thin panels so that a shrunk covering in only one side won't warp the panel. In the case of the wings, the covering was on both sides. The fuselage lateral panels were already fully assembled with their transverse reinforcements and showed no noticeable bending or warping.

5.2.2 Assembly

The airframe assembly stage was fairly straightforward, given the simple design of the parts. After cutting, all the joints were rectified for proper fitting and then assembled with fast curing epoxy resin, attaching first all transverse parts (the horizontal panels and reinforcement bars) to one of the side panels and then the other side panel onto those parts. The lateral panels were then covered externally with the covering film. Finally, the tilt shaft and tilt arms, the landing gear axes and wheels (in the second prototype) and the finished wings (with their lateral bracing) are mounted on the fuselage.

The wings only needed to be covered in film after cutting and prior to fitting in the fuselage. The bracing does not require further operations either.

The tilt arms however, 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 lateral angles on each part were designed to make the intended alignment in this way, without need for added 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. Some problems were found and solved during this stage. Of particular importance was the propulsive system test, which allowed to set working limits on the motor. The components tested were: all servos, radio system, signal mixers, gyros, ESCs, motors and batteries.

5.3.1 Control and actuation components

Servos were tested for movement range, torque and centering. Movement range was tested by measuring the maximum angle the servo arm could move. Torque was tested by hanging an object of known mass, in the servo arm at a know distance (adjusted to the servo specification) and verifying that the servo could lift it with no damage or overheating. Centering was tested by measuring the correlation between the PWM signal (read with a dedicated servo testing device) and the arm position. All servos performed to their respective specifications.

The radio system was tested for range, function and reliability. Range testing was made only indoor, with the radio link operating satisfactorily through two consecutive walls and a total distance of about 30 [m], with interference in the 2.4 [GHz] band present (from wireless network devices). Function was tested by operating all the radio's inputs (control sticks and knobs) throughout their range and verifying the intended movement on the devices connected to the receiver. Radio programming was also tested at this stage. As for reliability, the same radio system was operated through all bench and ground trials phases without any noticeable glitch or failure.

The signal mixers were tested simply for the output they produced on servos. Two models were tested, with one of them producing a slight jitter servo movements. This model, the "Turnigy V-tail Mixer" was shelved in favor of the other, the "GWS V-tail Mixer". The lag introduced by the mixers in the control circuit was not quantified.

The gyros were tested for function and sensitivity (qualitatively only, since no device to accurately measure angular rates was available). Both types of gyros acquired performed as specified on the bench, although it was not possible to measure the actual angular rates at which they operated, specifically, the minimum rate that would set off the compensation feedback. Function was found satisfactory, with the rate gyros (BA G2H1) but not so much with the HK-401B, which added a large amount of jitter to the system when connected to the signal mixer. Since the BA gyro was initially selected for its lighter weight, this test only confirmed the selection.

5.3.2 Propulsive system

The propulsive system (battery, ESCs, motors and propellers) were the components subject to the most extensive tests. A test setup was assembled in which it was possible to measure: battery voltage and current supplied (via a wattmeter with those functions available), PWM pulse width of the throttle control signal (with a servo testing device), and propeller static thrust (with a precision scale and a purposefully made motor stand). These tests had two goals: one was to assert the difference in terms of static thrust (per current consumed) between two propellers (two and three blades) of the same diameter and similar pitch, and confirm the choice of propeller; the other was to determine approximately the relation between the propeller's thrust with the chosen motor and ESC, and the current drawn, and verify that it was sufficient for its intended use.

The tests included a motor run from start up to a high throttle setting with two different propellers. The test setup is shown in figure 5.2.

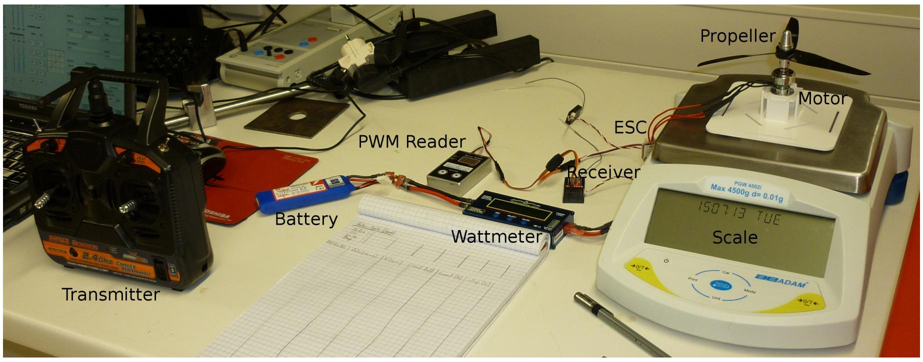

Figure 5.2: Setup for motor/propeller tests.

The test results are summarized in tables 5.1 and 5.2. The I_T value corresponds to the maximum current drawn from the battery, while the I_M corresponds to the current drawn by the motor. The difference in current is mainly due to the wattmeter used. Although both the ESC and the motor are rated for higher currents than the

maximum achieved, the motor was also designed to have a cooling airflow over it from the wake of the propeller. The propeller was turned upside down on this test, with the wake directed up and away from the motor, so the motor was not pushed to its limit.
Regarding the precision of the values obtained, although the scale was quite accurate, the oscillations in the readings lead to an error of about ± 1[gf], which is more than acceptable in this case, since it is much smaller than the difference between the two propellers (at the relevant throttle settings). Also, it was not possible to use a constant voltage power supply for the test and the flight battery was used instead. This meant that there was a slightly decrease in voltage between the tests. However, this would never cause a performance gap as large as the one verified and thus, the results remain conclusive.

Pulse [ms]	Thrust [gf]	I_T [A]	I_M [A]	T/blade [gf]
1.10	0	2.1	0	0
1.17	11	2.3	0.2	5
1.21	22	2.5	0.4	7
1.31	57	3.2	1.1	19
1.40	89	3.9	1.8	30
1.51	124	4.8	2.7	41
1.62	163	6.1	4.0	54
1.73	205	7.8	5.7	68
1.77	222	8.5	6.4	74

Table 5.1: Test results for the motor runs with the GWS 7x3.5x3 propeller.

Pulse [ms]	Thrust [gf]	I_T [A]	I_M [A]	T/blade [gf]
1.10	0	2.1	0	0
1.29	9	2.3	0.2	5
1.39	39	3.1	1.0	20
1.50	64	4.1	2	32
1.60	92	5.3	3.2	46
1.69	118	6.8	4.7	59
1.75	133	7.9	5.8	67

Table 5.2: Test results for the motor runs with the Master Airscrew 7x4x2 propeller.

From the results, there were two important conclusions to draw. The first is that both propellers exhibit roughly the same static thrust *per blade* for the same

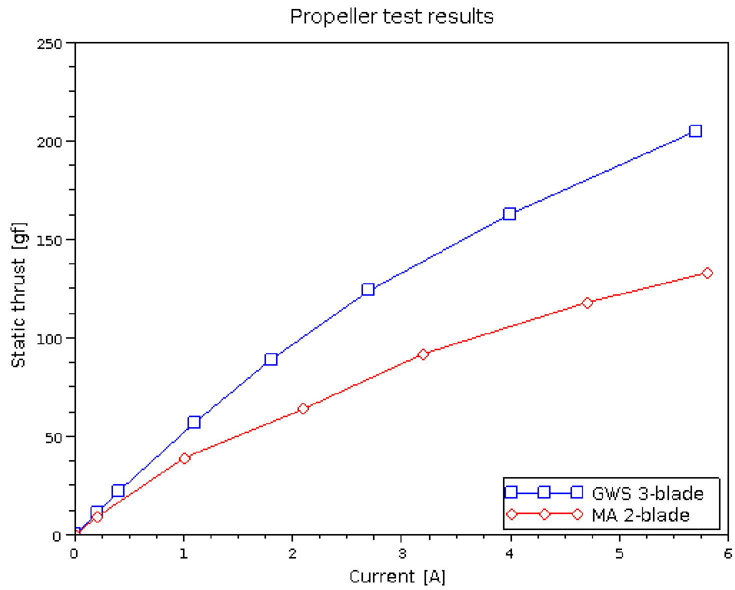

Figure 5.3: Comparison plot for both propellers.

current consumed. This has obvious implications on the choice of propeller for this particular aircraft configuration, giving three blade propellers a definite advantage over the two bladed ones. The second conclusion was that the propulsive system can provide enough thrust to perform vertical climbs without exceeding the maximum rated current for the ESC (10[A]) and the motor, since the maximum measured thrust (multiplied by the two motors) was well above the projected aircraft weight (293[gf]). These two conclusions fulfill completely the goals of the test.

5.3.3 Airframe

Additionally to component testing, some tests were performed on the airframe before the component integration in order to confirm its aerodynamic performance. These consisted of adding ballast to the bare airframe in order to place the center of gravity in its design position and then launching it in free flight. The airframe maintained a slight pitch up attitude in all flights, which agrees with the design calculations made, although the observed incidence appeared to be higher than the calculated value of 3[°]. This is possibly due to the absence of the pitch-down moment caused by the forward-tilted propellers. In all throws the airframe sunk slowly (at an average rate estimated of 0.7 [m/s]) and landed without suffering damage. No important rolling, yawing or pitching tendencies were detected at this stage. This test was not repeated after component integration since the (then heavier) aircraft was designed to be at all times at least partially hung on the propellers and thus would likely have a too high sink rate and suffer damage upon the landing.

5.3.4 Component integration and flight controls

The components were installed on the aircraft using one of three fixation methods. The batteries are attached with velcro strips, so they can be easily removed and replaced. The electronic components like the gyros, the radio receiver and the ESC were attached in a more permanent fashion by using foam-padded double-sided tape. The foam padding will isolate the electronic components from the vibrations caused by the motors and transmitted through the airframe, which will reduce the probability of failure of the soldered joints due to fatigue and, in the case of the gyros, it will also prevent the vibrations from being picked up by the sensor and amplified at the gyro output. The adhesive is strong enough to keep the components in place during flight but also allows relatively easy removing, if necessary. Finally, the force-creating components (motors and servos) are bolted to their respective mounting places in the fuselage. These connections used either locknuts or threadlock glue so that they do not loosen with vibration.
The component wiring is shown in figure 5.4 and part of the radio programming in figure 5.5. Dashed lines show transmitter channel mixes.

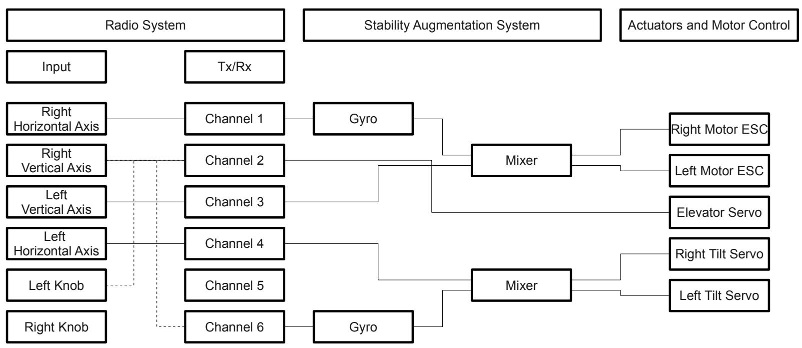

Figure 5.4: Wiring diagram for the aircraft controls

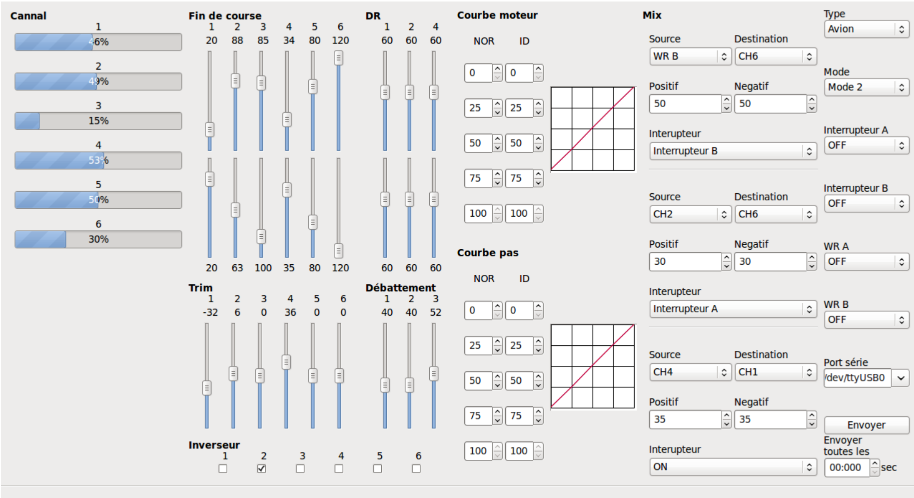

Figure 5.5: Radio programming interface showing trim and programming (FP2) (software UI in French).

5.4 Cost analysis

The project bugdet was limited from the beginning. This section will estimate the total cost of constructing one aircraft, using the tools and methods used for the prototype.

The costs can be divided in two sections: The cost of components and raw materials and the cost of transforming the raw materials and assembling the aircraft, both in terms of and man-hours and machine hours. The former is fairly easy to quantify and is described in table 5.3. This table includes the purchase costs of the several items required to build one aircraft to the specification of Flight Prototype 2. These items were obtained from various suppliers, both domestically and abroad. The values indicated are only a reference, since there is a large number of factors that could affect the exact cost of buying materials to construct another aircraft. Not included are import duties, postage costs or additional taxes and fees, since these depend highly in how the purchases are conducted and where. Also, and because some raw materials are only sold in quantities larger than those necessary for a single aircraft, the actual value to spend may be higher, with the excess being converted in leftover materials.

Regarding the labor costs, these are not as easy to estimate. Based on the experience gathered throughout the several months of the project, it was determined that, for a sufficiently qualified worker (i.e. one that is no longer learning during the construction process), approximately 14 man-hours would be required to build one aircraft. The only machine time required was on the CNC miller and is approximately 2 to 3 hours, depending on the specification of the particular machine. This does not include any time necessary for the CAD/CAM data generation. Lacking a more accurate estimate, a man-hour rate of 7[€] and a machine-hour rate of 1.50 [€] can be assumed, leaving a cost of 102.50[€] to be added and bringing the total to 320.84[€], approximately.

Item	Quantity	Unit cost [€]	Subtotal [€]
AX 1806N Motor	2 [un]	6.25	12.50
Turnigy Plush 10A ESC	2 [un]	5.70	11.40
Hyperion LVC 2S 1200mAh Battery	1 [un]	9.38	9.38
HobbyKing 6ch Radio System	1 [un]	24.69	24.69
Ino-Lab D202MG Servo	2 [un]	27.56	55.12
Hextronik HXT500 Servo	1 [un]	2.55	2.55
GWS 7x3.5x3 Propeller	2 [un]	2.34	4.68
Turnigy 3S 1450mAh Radio Battery	1 [un]	5.68	5.68
BA G2H1 Gyro	2 [un]	19.60	39.20
GWS V-Tail Signal Mixer	2 [un]	2.21	4.42
Alum. Prop. Adapter 3-5mm	2 [un]	1.48	2.96
Clevis 2mm	4 [un]	0.30	1.20
Ball link 2mm	2 [un]	1.00	2.00
Flexible hinge	2 [un]	0.80	1.60
Foam wheel 30mm	4 [un]	0.44	1.76
"Deans" electric connectors	1 pair	0.53	0.53
Bullet connectors 2mm	8 pairs	0.59	4.72
Covering film	0.36[m^2]	3.53	1.27
Aluminium tube ⌀5x4mm	0.3 [m]	5.00	1.50
Carbon tube ⌀6x4mm	0.1 [m]	8.00	0.80
Carbon tube ⌀4x2.5mm	0.5 [m]	4.60	2.30
Carbon tube ⌀3x2mm	0.1 [m]	4.06	0.41
Carbon rod ⌀2mm	0.26 [m]	2.48	0.62
Steel rod ⌀2mm	0.1 [m]	0.50	0.05
Heatshrink sleeve 4mm	0.5 [m]	1.18	0.59
Double side adhesive padded tape	0.1 [un]	0.98	0.10
Fiberglass cloth 80g/m^2	0.2 [m^2]	12.00	2.40
Balsa wood sheet 1000x100x1mm	3 [un]	1.50	4.50
Balsa wood sheet 1000x100x2mm	2 [un]	1.90	1.90
Aircraft grade plywood 1200x200x1mm	0.1 [un]	17.00	1.70
Laminating epoxy resin	0.25 [kg]	36.00	9.00
Peel ply	0.3 [m^2]	4.00	1.20
		Total cost	218.34

Table 5.3: Estimation for component and raw material costs of constructing one prototype

Chapter 6

Tiltrotor - Flight Testing

This chapter will describe the tests made on the completed prototypes, their goal, how they were planned and executed, and what conclusions were drawn from them. The flight tests were conducted on two different prototypes, designated as Flight Prototype One and Flight Prototype Two (FP1 and FP2). These consisted of two different implementations of the design outlined in chapters 4 and 5, with FP2 incorporating some improvements made on the detailed design of FP1.

6.1 Flight testing: goals and planning

The third initial premise of this work was that the aircraft designed and built would be tested. 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 on the present or following iteration;
- 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.

The plan for the testing of each prototype generally follows a procedure described in detail in appendix A, for which a brief summary is given below as a numbered list of steps:

1. Designate a suitable indoor testing area;
2. Verify on the ground the location of the center of gravity and the correct operation of all subsystems;

3. Use brief, low height flights to determine tendencies and trim the prototype;
4. Test hover and maneuvering capability at low height(still in ground effect);
5. Test hover and maneuvering capability outside ground effect;
6. Follow a circuit (indoors) that resembles a real remote sensing mission and includes a standard door threshold;
7. Measure hovering time;
8. Designate a suitable outdoor testing area;
9. Test hover and maneuvering capability outdoors in a light steady wind;
10. Test hover and maneuvering capability outdoors in a light changing wind;
11. Estimate maximum forward speed in linear flight at constant altitude;
12. Follow a small circuit (outdoors) that resembles a real remote sensing mission;
13. Follow a large circuit (outdoors) that resembles a real remote sensing mission;

Each step is dependent on the successful completion of the previous. If any of the tests resulted in damage beyond repair to the prototype or it systematically failed to successfully complete one of the tests, a new iteration would be built with any improvements deemed necessary and the flight testing program would be reassessed. The following sections describing the test results are a qualitative description and analysis of what happened during them.

For the entire testing program there was no experienced RC pilot available to fly the aircraft. This constituted a hindrance to the tests, especially since it was noticed that, even with proper trimming and adjustment, the aircraft's handling was not docile enough to be properly controlled by unexperienced pilots.

6.2 Testing results for FP1

The testing of FP1 (figure 6.1) successfully completed the first three steps of the plan outlined before. Trimming of the aircraft revealed itself difficult and it was noticed that the proper aircraft trim would vary with the motor throttle setting. The best gyro setting for roll was successfully determined but there remained some ambiguity regarding which pitch gyro setting gave better handling. The main issues that prevented a successful continuation of the tests were:

- Necessary roll and yaw trim seemed to vary with throttle setting, requiring almost constant re-trimming;

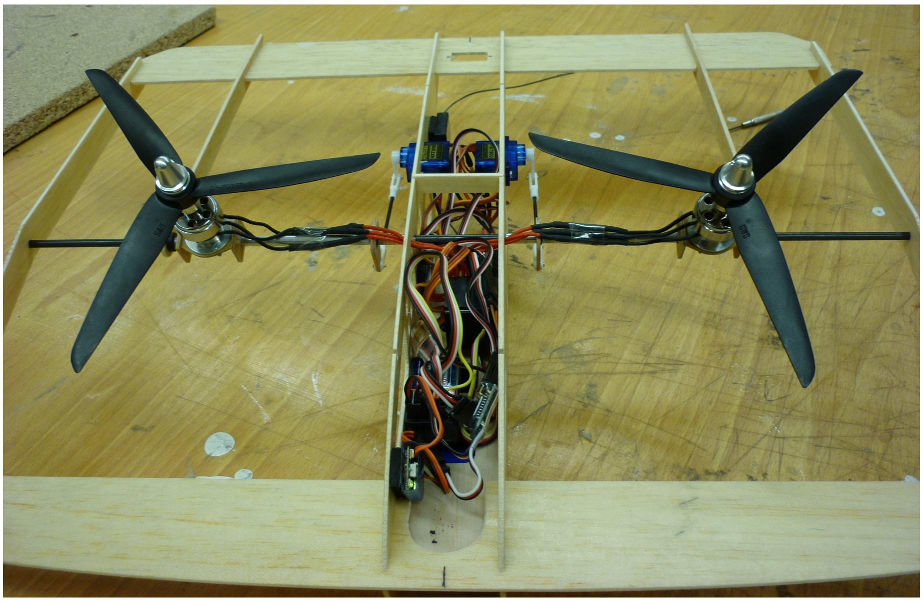

Figure 6.1: Flight Prototype 1.

- 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.

This last phenomena was considered serious enough to ground FP1. This pitch oscillation was similar to a pendulum swing: the aircraft would move backwards and adopt a pitch down attitude, or forwards, adopting a pitch up attitude. Since the pilot would be trying to hover the aircraft over a given position, the pendulum swing, which caused both a pitch-down attitude and a translation to the rear (or the opposite), would induce the pilot to try and correct the position deviation, rather than the attitude deviation. However, since the "forward" control (common tilt forward) was also the "pitch-down" control, this correction caused the aircraft to exacerbate the pitch deviation and quickly flip over. These pitch oscillations were relatively fast, but not fast enough to be corrected by the pitch gyro. There were three possible solutions to counter this event:

- Transfer authority in the common tilt axis from the pitch/forward control to the transition control, thus diminishing the mis-correction the pilot could make;

- Train the pilot to identify and correctly handle the phenomenon, by correcting first the attitude and afterwards the position;
- Use an attitude hold gyro for the pitch axis.

The latter solution seemed to be the best, from a technical standpoint. However, one model of attitude hold gyro was tested with the other electronic components and revealed itself to induce unacceptable oscillations in the output. Further tests evidenced this to be related to the inclusion of the signal mixer in the control circuit. Since there was no data available to correlate which makes and models of attitude hold gyros and signal mixers were compatible with each other, and no budget or time available to do testing to gather this data, this solution was not adopted. Instead, emphasis was given to the former two measures.

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

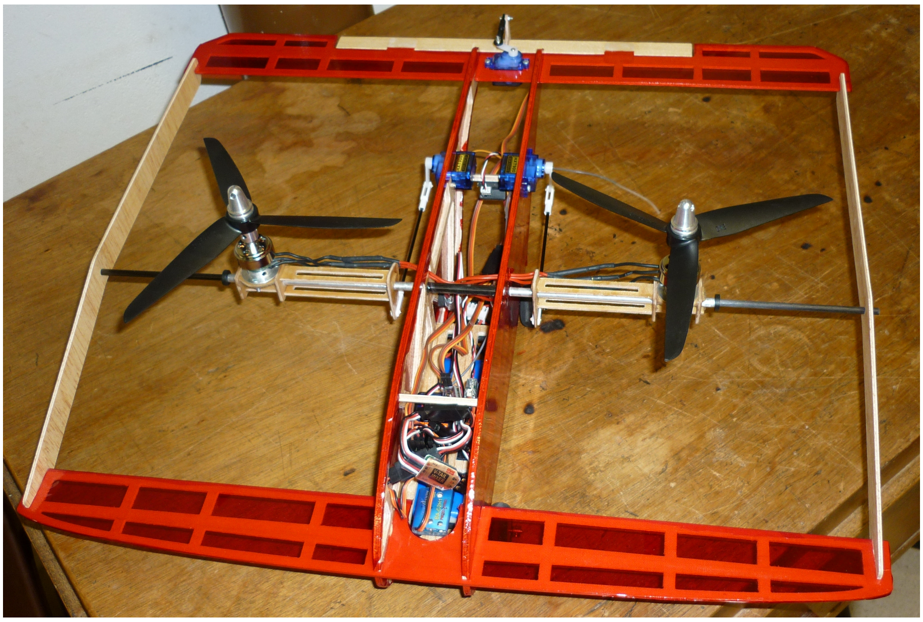

Figure 6.2: Flight Prototype 2.

The flight testing of FP2 (figure 6.2) took the same form as that of the previous aircraft, but progressed faster. In general, the FP2 had a gentler handling than

FP1, although it still required pilot skill to fly in hover. One of the signal mixers (the "GWS" model) was replaced for a "Turnigy" model, since it would glitch upon impact, locking the tilt servos in a given position. This time the jitter noticed in the individual component tests was not detected. After the first few tests using analog servos to control tilt, these were replaced with digital servos and the improvement in handling was noticeable. Regarding the test program, FP2 completed the first four steps successfully. However, it was decided after a few tries not to risk further testing outside of ground effect without an experienced pilot. The pendulum oscillations were still observed in this aircraft, although slower (and easier to correct) than in the previous. The correction on the pitch control circuit also proved itself effective, and only in two extreme situations did the actual flip-over occur.

It was noticed that general handling, both in the pitch and roll axis is both qualitatively different and worse outside of ground effect. In the roll case, when a control input causes roll to one side, the fact that one of the rotors is lowered and the other rises should cause a difference in the extra thrust due to ground effect added to each of the rotors, resulting in a net moment that counters the input. In practical terms, for a fixed, non-zero stick position in the roll axis, there is in ground effect a corresponding roll angle in which the roll moments are balanced and the net movement of the aircraft (provided pitch an yaw axis are properly corrected) is only a sideways translation. This means that in ground effect, the roll control is a translation control. Outside of ground effect, however, the compensating moment does not appear, as there is no added thrust in either of the rotors. Thus, a fixed, non-zero stick position will cause a roll rate, rather than a roll angle, making the control similar to an helicopter's lateral cyclic control, and also more sensitive.

For the case of the pitch, it was experimentally determined that the pendulum oscillations do not occur in ground effect. This alone represents a significant difference between the two flight states. In ground effect the forward/backward in hover movement is easily made with the pitch control, which allowed the completion of the corresponding step in the flight test program. Outside of ground effect however, more or less severe pitch oscillation occurs in almost every occasion. It is yet to be determined for certain whether this is caused by the transition away from ground effect, or from the non-existence of it. Also, it was observed that the rearward/pitch-down oscillations are more frequent and severe than the forward/pitch up oscillations. This may be related to the wing arrangement, which causes pitch instability in fast backwards flight.

Other smaller handling issues were detected.The battery status seems to affect roll trim. This may be caused by the wiring and connectors between the battery and either ESC [1]. It does not pose a problem, since the battery voltage decay is much slower than any aircraft maneuver, and this is is easy to compensate by any pilot aware of the phenomenon. Also the connections may be re-made, although it is not obvious at present which exact part or feature (the soldering, the wires used, the connectors used etc. . .) is causing the issue.

On takeoff, the asymmetries in the landing gear can induce rolling and yawing moments. The foam wheels used in FP2 have slight irregularities that cause them not to be perfectly round and perfectly aligned. Thus a slow take off may cause the roll gyro to induce erratic behavior if it detects oscillations caused between sporadic contact between the some of the wheels and the ground. The correct take off procedure laid out during the flight tests is to first raise the throttle to below VTOT, to spin up the motors (it takes about 1[s] to start the motors from a stop to any throttle setting), and then accelerate them to above VTOT, causing the aircraft to quickly jump to a height of about 5[cm] above ground, at which the landing gear is distanced enough and the roll gyro performs its functions normally.

Finally, the aircraft was overweight by about 17%. A malfunction in the laboratory's scale that went undetected for several weeks (including those during which the bulk of the flight testing was conducted) caused the initial mass value of FP2, (303[g]) to be later corrected to 356[g]. This variation is significant and helps explain the difference between actual and expected performance. Also, it was not easy to correct, given not only its magnitude, but also its discovery, almost at the end of the project. Shaving off the excessive mass would require a further structural optimization of the airframe but especially, a reduction in component weight. Proposals for achieving this are outlined in section 7.1.

6.4 Conclusions of the flight testing program

This chapter explained the planning, execution and results of the flight testing program. The original planning was unfinished, due to a few issues, mainly the lack of a more capable and experienced pilot or, alternatively, a more advanced stability augmentation system. 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 minor improvements in the platform may be necessary.

[1] Possibly one of the ESCs was receiving a slightly different voltage, doe to different electrical resistances on the branching connector

Chapter 7

Conclusions and Future Work

This chapter will list the final conclusions of the work described, regarding goal completion, the aircraft produced and the project execution in general. Based on these, some proposals for future work will also be listed.

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.

In terms of the work performed, it can be said that both the time and effort necessary were grossly underestimated at the beginning.

Several deadlines ended up having to be postponed. One of the reasons for the delay was the long lead times in the acquisition of components. As an example, the gyros took almost two months between the moment of ordering and their final delivery. This lead time might have been reduced by using faster courier services, but the increased cost of this option would have been an unacceptable burden on the budget available. Alternative local suppliers were used in a comparatively small proportion for two reasons: the higher prices and the reduced variety of available components. Long term planning revealed itself hard to follow, given the dynamic nature of the project and the comparatively long period in which a minor change in the design would require different components or raw materials to be purchased.

The previous experience with designing and building small scale aircraft was crucial to success, but still insufficient. There were learning processes that had to be completed regarding the workings and operation of radio equipment, aircraft construction techniques and other practical matters. It was however a very enriching experience, and one recommended for all students to undertake at some point in their academic career. It allowed not only development of practical skills in several disciples, but also a sense of autonomy and independent problem solving.

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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Appendix A

Detailed testing procedures

The following list details to a greater extent the procedures to use in the flight testing. Notice that the basic ground checks and similar procedures are only explicitly described in the initial steps, but should be performed before all flights.

1. Define, clear and secure an indoor testing area;
2. Verify on the ground the location of the center of gravity and the correct operation of all subsystems;
   - 2.1. Verify the longitudinal location of center of gravity and move that battery to correct if necessary;
   - 2.2. Connect and turn on all the radio control equipment;
   - 2.3. Connect and turn on all the electronic components on the aircraft;
   - 2.4. Verify and correct the direction and movement range of all the servos. Adjust and trim as necessary;
   - 2.5. Verify the startup setting of each motor. Trim until both motors are starting up simultaneously;
3. Use brief, low height flights to determine tendencies and trim the prototype;
   - 3.1. With the rotors pointing up, increase throttle until lift off is achieved. Take note of the VTOT stick position;
   - 3.2. Set the roll gyro gain to the maximum. Spin up the motors to below VTOT and check for oscillations on the roll axis. If detected, gradually lower the gain and re-test until oscillations are gone.
   - 3.3. Take off with a setting just above VTOT and pitch gyro gain at maximum. If pitch oscillations detected, gradually lower the gain and re-test until they are gone;

3.4. Take off briefly and check for systematic tendencies in yaw and roll. Trim and repeat until a controlled hover is achieved in a reasonable amount of space, with the least possible pilot input.

4. Test hover and maneuvering capability at low height(still in ground effect);

   4.1. Take off (still in ground effect) and attempt controlled maneuvers in one axis at a time: heading change, sliding sideways and moving forward and aft;

   4.2. Take off and land in a predetermined target on the ground, a short distance away;

   4.3. Elevate the target a small amount and repeat test;

5. Test hover and maneuvering capability outside ground effect;

   5.1. Take off and climb out of ground effect. Register tendencies in yaw, pitch and roll. Trim as possible, without worsening performance in ground effect;

   5.2. Take off and attempt landing on a target at the height of a standard table (about 1[m]);

6. Follow a circuit (indoors) that resembles a real remote sensing mission and includes a standard door threshold;

   6.1. Setup a circuit that includes take offs and landings at three different heights and a door threshold;

   6.2. Fly each step of the circuit individually;

   6.3. Fly the entire circuit sequentially in one direction;

   6.4. Fly the entire circuit sequentially in the reverse direction;

7. Measure hovering time;

   7.1. Delimit a circular target space with a diameter of 2[m];

   7.2. Install a fully charged 1200[mAh] battery in the aircraft;

   7.3. Take off from the center of the target space and measure the time until either the battery pack runs out or the pilot fails to keep the aircraft within the circle;

   7.4. Repeat until three tests end in depletion of the battery. Always use a fully charged battery at the start of each attempt;

   7.5. Repeat tests with the diameter of the circle reducing to 1.5, 1 and 0.7[m].

8. Define, clear and secure a large enough outdoor testing area;
9. Test hover and maneuvering capability outdoors in a light steady wind;
   9.1. Assure that tests are conducted with a light wind, blowing with near constant velocity and direction;
   9.2. Take off into ground effect with headwind and observe wind effect in roll, pitch and yaw;
   9.3. Take off into ground effect with tailwind and observe wind effect in roll, pitch and yaw;
   9.4. Take off into ground effect with lateral wind and observe wind effect in roll, pitch and yaw;
   9.5. Verify need for changes in aircraft trim;
   9.6. Repeat the first three steps out of ground effect;
   9.7. Verify need for changes in aircraft trim or gyro gain;
10. Test hover and maneuvering capability outdoors in a light changing wind;
    10.1. Assure that tests are conducted with a light wind, blowing with near constant velocity and changing direction;
    10.2. Delimit a circular target space with a diameter of 2[m];
    10.3. Take off and hover the aircraft within the target circle in the changing wind;
    10.4. Repeat tests with the diameter of the circle reducing to 1.5, 1 and 0.7[m].
11. Estimate maximum forward speed in linear flight at constant altitude;
    11.1. Delimit a straight lane with a known length (greater than 10[m]) and no wind;
    11.2. Set up instrumentation to measure the time the prototype takes to fly from one end of the lane to another;
    11.3. Hover the aircraft next to one end of the lane, then use the transition control to slowly move the aircraft to the other end of the lane;
    11.4. Repeat with increasingly abrupt transitions from and to forward flight configuration and record the shortest time to for from one end of the lane to the other;
12. Follow a small circuit (outdoors) that resembles a real remote sensing mission;

12.1. Setup a circuit that includes take offs and landings at three different heights and also vertical obstacles;

12.2. Fly each step of the circuit individually;

12.3. Fly the entire circuit sequentially in one direction;

12.4. Fly the entire circuit sequentially in the reverse direction;

13. Follow a large circuit (outdoors) that resembles a real remote sensing mission;

    13.1. Setup a large circuit that includes take offs and landings at three different heights, two targets for hovering and also vertical obstacles. Assure at least one part of the circuit has wind;

    13.2. Fly each step of the circuit individually, but with the pilot always in the same position;

    13.3. Fly the entire circuit sequentially in one direction;

    13.4. Fly the entire circuit sequentially in the reverse direction;

Appendix B

Code Listing for Aerodynamic Calculations

The following Scilab code was used for the aerodynamic, transition and pitch stability calculations described in section 4.4.1.

```
///////////////////////////////////////////////////
//Calculation script for stability and transition//
//       flight of an MAV tiltrotor              //
//       Horacio Moreira, July 2010              //
///////////////////////////////////////////////////

clear
//Constants
ro=1.225;
//Geometry
mass=0.300;
prop.arm=0.01;
fw.inc=3;
rw.inc=0;
fw.arm=0.14;
rw.arm=0.19;
fw.span=0.386;
rw.span=0.386;
fw.chord=0.045;
rw.chord=0.045;
fw.area=fw.span*fw.chord;
```

```
rw.area=rw.span*rw.chord;
fu.area=0.025;
//aerodynamics
fu.cd0=0.027;
for i=1:25
  alpha=(i-10);
  if abs(alpha)>7 then
    FPWing(i,:)=[alpha,abs(alpha)*0.01,0.1,0];
  else
    FPWing(i,:)=[alpha,(alpha)*0.087,0.3+abs((alpha)
        *0.05),0];
  end
end

Vmax=18; //integer
Vmin=1; //integer
alphamax=7;  //integer
alphamin=-3; //integer

for i=1:Vmax-Vmin
  V=Vmin+(i-1)
  for j=1:alphamax-alphamin
    alpha=alphamin+(j-1)
    fw.alpha=fw.inc+alpha;
    rw.alpha=rw.inc+alpha;
    fw.CL=interp1(FPWing(:,1),FPWing(:,2),fw.alpha);
    fw.CD=interp1(FPWing(:,1),FPWing(:,3),fw.alpha);
    fw.CM=interp1(FPWing(:,1),FPWing(:,4),fw.alpha);
    rw.CL=interp1(FPWing(:,1),FPWing(:,2),rw.alpha);
    rw.CD=interp1(FPWing(:,1),FPWing(:,3),rw.alpha);
    rw.CM=interp1(FPWing(:,1),FPWing(:,4),rw.alpha);
    fw.lift=0.5*ro*V^2*fw.CL*fw.area
    rw.lift=0.5*ro*V^2*rw.CL*rw.area
    drag=0.5*ro*V^2*(fu.area*fu.cd0+fw.area*(fw.CD+fw.CL
        ^2/(%pi*(fw.span/fw.chord)*0.85))+rw.area*(rw.CD+
        rw.CL^2/(%pi*(rw.span/rw.chord)*0.85)))
    theta=atand(drag/(mass*9.81-fw.lift-rw.lift))+alpha;
    thrust=drag/sind(theta-alpha)
```

```
      fw.mom=-0.5*ro*V^2*fw.CM*fw.area*fw.chord+fw.lift*fw.
          arm;
      rw.mom=-0.5*ro*V^2*rw.CM*rw.area*rw.chord-rw.lift*rw.
          arm;
      prop.mom=-thrust*prop.arm*sind((theta));
      //prop.mom=-thrust*prop.arm*sind((theta-alpha));
      total_mom=fw.mom+rw.mom+prop.mom;
      mom(j)=total_mom;
      tempalpha(j)=alpha;
   end
   alphatrim(i)=interp1(mom,tempalpha,0);
   fw.alpha=fw.inc+alphatrim(i);
   rw.alpha=rw.inc+alphatrim(i);
   fw.CL=interp1(FPWing(:,1),FPWing(:,2),fw.alpha);
   fw.CD=interp1(FPWing(:,1),FPWing(:,3),fw.alpha);
   fw.CM=interp1(FPWing(:,1),FPWing(:,4),fw.alpha);
   rw.CL=interp1(FPWing(:,1),FPWing(:,2),rw.alpha);
   rw.CD=interp1(FPWing(:,1),FPWing(:,3),rw.alpha);
   rw.CM=interp1(FPWing(:,1),FPWing(:,4),rw.alpha);
   fw.lift=0.5*ro*V^2*fw.CL*fw.area
   rw.lift=0.5*ro*V^2*rw.CL*rw.area
   drag=0.5*ro*V^2*(fu.area*fu.cd0+fw.area*(fw.CD+fw.CL
       ^2/(%pi*(fw.span/fw.chord)*0.85))+rw.area*(rw.CD+rw.
       CL^2/(%pi*(rw.span/rw.chord)*0.85)))
   theta=atand(drag/(mass*9.81-fw.lift-rw.lift))+alphatrim
       (i);
   thrust=drag/sind(theta-alphatrim(i))
   fw.mom=0.5*ro*V^2*fw.CM*fw.area*fw.chord+fw.lift*fw.arm
       ;
   rw.mom=0.5*ro*V^2*rw.CM*rw.area*rw.chord-rw.lift*rw.arm
       ;
   prop.mom=-thrust*prop.arm*sind(theta);
   //prop.mom=-thrust*prop.arm*sind(theta-alphatrim(i));
   momtrim(i)=fw.mom+rw.mom+prop.mom;
   thrusttrim(i)=thrust;
   thetatrim(i)=theta;
   tempV(i)=V;
end
```

```
//plot relevant quantities
cfh=gcf;
cfh=scf(0);
plot(tempV,alphatrim,'m');
xtitle( 'Trim angle of attack with velocity', 'Velocity [
   m/s]', 'Angle of Attack [ ]');
a=get("current_axes");
a.x_label.font_size=2;
a.y_label.font_size=2;
a.title.font_size=3;
a=sca(a);
cfh=scf(1);
plot(tempV,thetatrim,'gs-');
xtitle( 'Trim tilt angle', 'Velocity [m/s]', 'Tilt angle
   [ ]');
a=get("current_axes");
a.x_label.font_size=2;
a.y_label.font_size=2;
a.title.font_size=3;
a=sca(a);
cfh=scf(2);
plot(tempV,thrusttrim*1000/9.81,'bo-');
xtitle( 'Trim Thrust', 'Velocity [m/s]', 'Thrust [gf]');
a=get("current_axes");
a.x_label.font_size=2;
a.y_label.font_size=2;
a.title.font_size=3;
a=sca(a);
cfh=scf(3);
plot(tempV,momtrim,'y');
xtitle( 'Pitching moment at trim angle of attack (i.e.
   calculation error)',  'Velocity [m/s]', 'Pitching
   moment [Nm]');
a=get("current_axes");
a.x_label.font_size=2;
a.y_label.font_size=2;
a.title.font_size=3;
a=sca(a);
```

```
cfh=scf(4);
plot(thetatrim,thrusttrim*1000/9.81,'rd-');
xtitle( 'Trimmed Transition curve', 'Tilt angle [ ]', '
    Thrust [gf]');
//set up figure properties
a=get("current_axes");
a.x_label.font_size=2;
a.y_label.font_size=2;
a.title.font_size=3;
a=sca(a);
//export to png
xs2png(1,'/home/horacio/tiltrotor/thesis writing/images/
    ThetaTrim.png');
xs2png(2,'/home/horacio/tiltrotor/thesis writing/images/
    ThrustTrim.png');
xs2png(4,'/home/horacio/tiltrotor/thesis writing/images/
    TransCurve.png');
```