DESIGN, DEVELOPMENT AND ASSESSMENT OF A DUCTED RUAV

Frank Buysschaert
Royal Military Academy of Belgium
Brussels, Belgium

Patrick Hendrick
Université Libre de Bruxelles
Brussels, Belgium

Jean-François Aernouts (ULg), Raphaël Evariste (EMA), Alexandre Abadie (EMA),
Sébastien Roche (EMA), Pierre Slangen (EMA), Bruno Liévin (ISIB)

Abstract

The paper describes the design, development and assessment of a rotary wing uav, which has as primary mission the observation and registration of targets at close range and which is commanded by a one-man-portable, three person operated ground control system. The chosen system configuration, the mission profiles and the in accordance developed design protocol are explained. Different construction methods are elucidated as well, allowing complex structures to be made without having important detrimental influences on weight.

Symbols and Formulae

θ	Rotor blade pitch angle (°)
GL	Ground Level
HF	Horizontal Flight
ISA	International Standard Atmosphere
LiPo	Lithium Polymer
n	Load factor (g)
RPM	Rotational Speed (1/min)
T/O	Take-off
V_h	Horizontal speed
V_v	Vertical speed

Introduction

In September 2002, ONERA (Office National d'Etudes et de Recherches Aérospatiales), launched an interuniversity mini-UAV contest with the intention to evaluate the capabilities of different platforms, which have to fulfil observation missions in a (artificial) city, in which multiple targets and threats are positioned. The goal is to track and register hostile targets in the city via GPS, by deploying a system, dimensioned in such a way that only one person is needed to carry it and operated by maximally three individuals.

The contest is financed by the DGA (Délégation Générale de l'Armement), the French department of defence. From all the universities that sent a proposition, only 20 were selected for funding, of which l'Ecole des Mines d'Alès (EMA). In the beginning of 2004, EMA invited the Royal Military Academy of Belgium to cooperate on this project, involving the design, development and assessment of a prototype : the EMA'tador.

Design

The principal foundations for the EMA'tador's design incorporate safety and operational definitions. The most important are :

- A ducted rotor to reduce risk of injury during deployment ; to protect the rotor from hitting obstacles when approaching objects (e.g. when flying close to trees, improving camouflage) ; to improve power consumption ; to enhance hover qualities.
- Battery equipped, to reduce IR signature ; to avoid smoke production, which would be the case when using an internal combustion engine, making the UAV more detectable and possibly hindering camera sight (e.g. oil deposition on lens) ; to reduce acoustical footprint and vibrations.
- Deployable at 2500 m ISA / ISA +20°C
- A powerful camera with outstanding optical zoom, allowing to inspect a larger area when flying a fixed pattern ; permitting to inspect targets more carefully when observing a stakeout from a fixed altitude, i.e. during hover or when landed temporarily on a building or similar.
- Use of a classic swash plate to control the rotor, avoiding the need for a complex flight control system and still allowing upgrades with piezo-electrics, possibly reducing weight.

Mission profile

The mission flight profile during the contest is a priori unknown. However, in order to facilitate calculations, RMA and EMA agreed to use a mission profile as shown in Fig. 1 and Fig. 2.

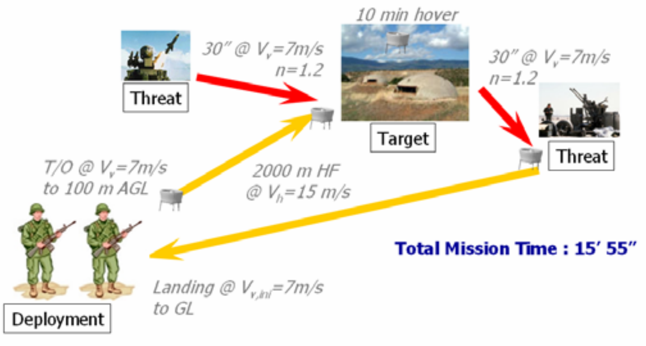

Fig. 1 : Military mission profile

5 different flight conditions are considered :

- Vertical take off (T/O) to 100 m AGL @7m/s
- Horizontal flight (HF), 2 km @ 15m/s
- Manoeuvres for 30s with vertical speed of 7m/s and load factor of 1.2 g
- Hover, 10min @ 100 m AGL
- Vertical landing

All flight conditions are examined during the aerodynamics assessment, which will give an output for the average energy consumption. This output allows then partially the correct amount of batteries to be installed. However, this calculation will require multiple iterations, since the correct mass of batteries is a priori unknown. Indeed, the mass has an influence on the helicopter blade dimensions and thus power consumption. This will be discussed in the next paragraph.

Iterative Platform Determination

Fig. 3 represents simplified the iteration scheme that was used to mainly determine the platform weight, battery choice and gearbox reduction.

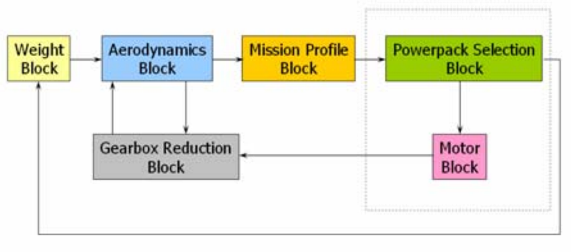

Fig. 3 : Simplified iterative design process

The iteration starts with an estimation of the platform's weight. This will allow an optimum rotor blade to be calculated in the aerodynamics block, releasing figures of power required in function of the flight conditions for a minimum blade RPM. The data is then applied in the mission profile block, which calculates an average power consumption. The power pack selection block takes this data into account as well as the maximum power required during the mission. This data, along with ambient conditions and several losses serve to determine the required engine power, thus also the engine, as well as the engine RPM. The RPM serves to determine the gearbox reduction. Unfortunately, the theoretical gearbox reduction is not always feasible. Since we are to use off the shelf gears, we have to look for a safe reduction (to verify in the aerodynamics block and this for the most critical flight condition, taking the several atmospheric conditions into consideration), which differs usually from the theoretical figure. Therefrom, a new average energy consumption can be calculated from

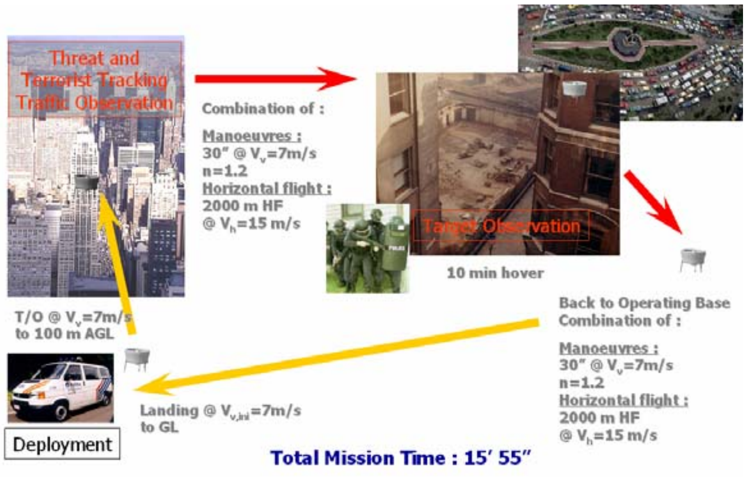

Fig. 2 : Civil application, anti-terror, traffic observation

the mission profile block, etc.. Once this inner loop has converged, a new estimation of the weight can be performed. The outer loop iteration is run through again until converged.

Weight

The approximate mass of the EMA'tador amounts to 6kg. The mass breakdown is shown in Fig. 4.

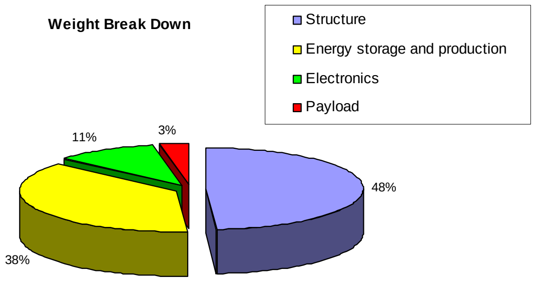

Fig. 4 : Platform weight breakdown

As one can see, the largest mass contribution comes from the structure and the energy storage and production.

Aerodynamics (Fig. 5)

The rotor blades were iteratively designed using a modified blade element momentum theory completed with data obtained from X-foil© (Ref.1 & 2). The blades are non symmetric and have a washout. Depending on the flight and atmospheric conditions, the rotor RPM can go up to 5000 RPM.

In order to reduce parasite rotor drag and to protect the rotor from dust and filth, the rotor is equipped with a rotor hub fairing.

The duct and fuselage dimensions are fixed by the limits imposed by ONERA : the platform should fit in a sphere with a diameter inferior to 0,70m. Ref.2 derived the outer duct diameter to be 0,69m. The fuselage has an external diameter of approximately 0,16m. The duct and fuselage are designed in such a way to profit most of the power reduction invoked by the use of a ducted rotor, without to much risk of flow separation at the trailing edge during hover.

Unconventionally, the EMA'tador uses anti-torque vanes and blades to compensate for the rotor torque. 3 fixed (stators) and 3 (blades) movable "wings" are installed in the downwash of the rotor. The stators are asymmetric, the blades are symmetric.

Battery selection

Two different types of batteries are used aboard :

- High power density Lithium-Polymer Polyquest PQ 2200-2S batteries to drive the engine (Fig. 6)
- NiMH high current batteries to drive the electronics and servos.

Fig. 6 : Weight and power leading to the selection of the PQ2200-2S

During the power pack selection block (Fig. 3), 80 different batteries are evaluated for optimum weight and power.

20 LiPo batteries are installed aboard, able to deliver up to 37V and 30-40A.

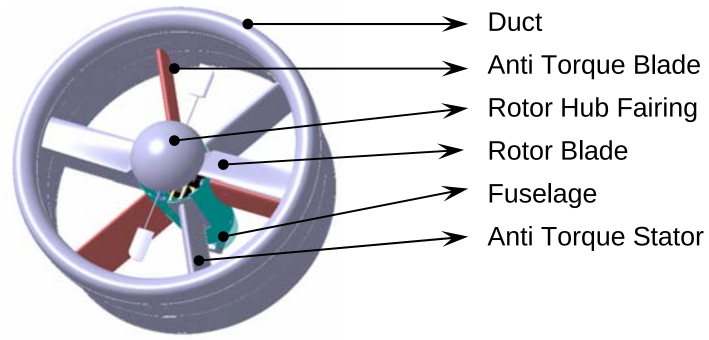

Fig. 5 : Component designation

The NiMH batteries however are much more forgivable when high currents are drained, necessary for the multi-servo commands. LiPo batteries have a very bad reputation regarding this issue. Every abuse results in permanent damage : the battery blows itself up and risks to catch fire. It is therefore of utmost importance that the LiPo batteries are never discharged beyond their limits, because this would lead to loss of power and in the worst case fire aboard the platform, with possible disastrous consequences e.g. when flying observation missions above dry land, houses and other “inflammable regions”.

Engine selection

Calculations show that the Twister® Brushless .90 brushless motor is suitable for the EMA’tador. The brushless engine is very compact, develops a sustained power up to approximately 1kW and allows a 1,5kW peak performance for 30 seconds (4° timing). The brushless engine is controlled with a Flash-Pro® Air 60 variator, which protects the motor e.g. against excess of temperature, produced by the Joule losses in the copper windings.

The engine is shown in Fig. 7. The estimated rotational speed is 10kRPM.

Fig. 7 : Twister® Brushless .90 Motor

Gearbox reduction selection

The gearbox reduction closest to the theoretical value amounts to 3. The issue here is to find as light as possible gears, that withstand the torque, that can fit in the fuselage, that can work under high rotational velocities and observe high efficiency. It appeared that only a combination of a Delrin® gear and a stainless steel gear (35NCD) could satisfy most requirements. An important remark is that no conventional lubrication can be foreseen. Indeed, grease might increase the friction and thus temperature production at high rotational velocities. On the other hand, a less viscous lubrication might be catapulted away due to centrifugal forces. Fortunately, Delrin® has self-lubricating qualities, which overcomes the problem partially. Moreover, the application of a Klüber solid lubricant coating on the steel gear is expected to decrease friction appreciably.

Structure

The structure of the EMA’tador can mainly be subdivided into :

- Rotor head
- Aluminum chassis
- Fuselage in advanced materials
- Duct in advanced materials
- Anti-torque devices
- Landing gear

Rotor head : The rotor head developed for the EMA’tador is made completely of titanium Ti6Al4V, except for the Hiller flap holder, which is made of Aluminium (Fig. 8). This way, the highest strength to weight ratio could be obtained. FEM calculations in Catia© helped to find weak spots and to dimension properly (Fig. 9). The power from the engine is transmitted via a titanium rod to the rotor hub.

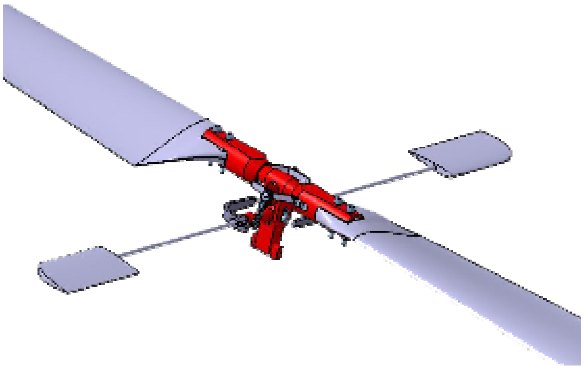

Fig. 8 : The EMA’tador rotor head

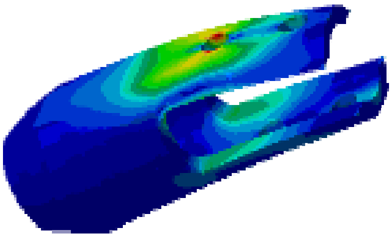

Fig. 9 : FEM calculations helped to find the weak spots

Inside the rotor head, special SKF roller and sliding bearings provide smooth movement of extremely highly loaded parts, such that cyclic and collective control are always guaranteed. A special Klüber lubricant assures safe bearing operations under high pressures and at the same time prevents the false Brinelling phenomenon to occur. False Brinelling happens when very small movements of the bearing balls or rollers, caused by e.g. vibrations, push grease away between their surface and the race, without allowing the grease to flow back in place. In fact, the ball or roller is penetrating the grease. At a certain point, no lubricant will be left and a metal – metal contact will occur, producing dents, similar to the Brinell hardness test.

Aluminium chassis : In order to have a stiff structure on which the servos, the motor, the gearbox, the anti-torque control system, … are mounted, an aluminium chassis was developed, without harming weight to much. The aluminium chassis is screwed into the fuselage and fixed on reinforcements of the latter (Fig. 10).

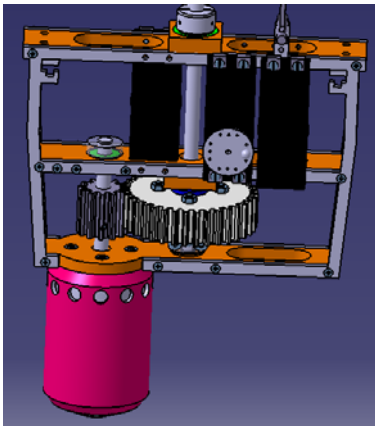

Fig. 10 : The aluminium chassis

Fuselage in advanced materials : The fuselage (Fig. 11) contains the aluminium chassis on which all vital parts are installed. It serves several purposes. First of all, it has to guarantee a smooth passage of the air flow beneath the rotor. Secondly, it protects the sensitive equipment inside, such as the flight stabilisation electronics, servos and gearbox. Thirdly, it is the anchor for the anti-torque stators and blades and it carries the duct.
The structure thickness is important since it has a non negligible impact on structure weight because of the fuselages rather large dimensions. Different materials have been evaluated. However, this discussion is the subject of the paragraph *development and assessment*.

Duct in advanced materials :

The slightly divergent duct (Fig. 12) was dimensioned such that the performance losses in hover, forward and vertical flight, or a combination of the last two due to flow separation was minimised (see development paragraph). The duct houses the LiPo batteries, which are placed as high as possible to position the centre of gravity as high as one can. This keeps the pitching and or rolling moments necessary for a sustained platform attitude, low, resulting in a more efficient use of power.
Reinforcements at the trailing edge provide a secure suspension for the landing gear.

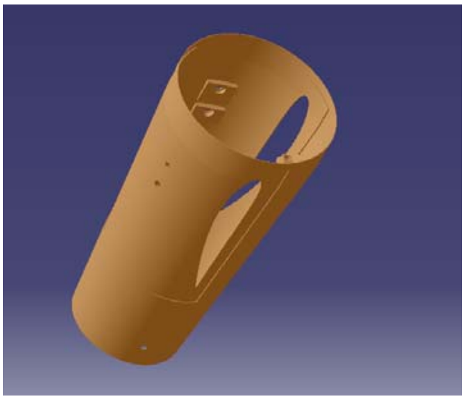

Fig. 11 : The fuselage has a maximum diameter of approximately 0,16 m and is designed to be as thin as possible to meet low weight requirements.

Fig. 12 : The duct assures that a low perturbed air flow can be directed towards the rotor.

Anti-torque devices : 3 stators and 3 movable blades comprise the anti-torque system (Fig. 13). The lift created by the downwash around the airfoils, is in this case used to provide a torque. The stators deliver a continuous torque, while the blades allow a variable torque component for varying flight conditions and to obtain yaw control. Through the hollow stators, the electrical wiring passes from the batteries towards the variator of the motor.
A gyro placed inside the fuselage measures yaw position and the gyro system corrects for unwanted changes. A high speed servo, connected to the gyro system, rectifies

consequently any yaw anomalies via blade angle of attack regulation, in order to maintain stability.

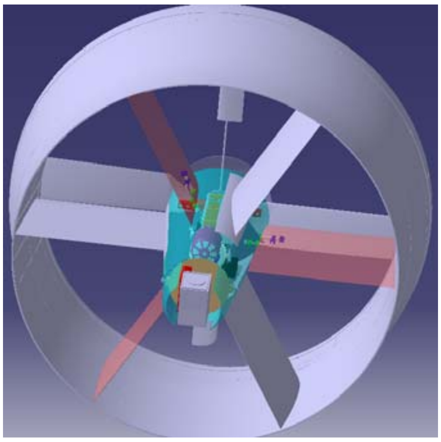

Fig. 13 : The blades from the anti-torque system are controlled via a high speed servo placed inside the fuselage.

Landing gear : The landing gear consists of carbon rods connected to the duct at one side and attached to a plastic ring at the opposite side. At the time of writing, no additional information can be released about this topic.

On board electronics

Servos : 5 servos are used, 3 servos for the rotor control (cyclic and collective, mixed electronically, also called H3), 1 servo for yaw control and 1 servo for camera pitch positioning.

Platform stabilisation : 4 gyros with accelerometers provide platform stabilisation.

GPS : The EMA'tador is equipped with a Globalsat BR305 GPS, working with the NMEA 0183 V2.2 protocol. The refresh rate amounts to 10 Hz.

Data transmission : Two 2,4 GHz channels are foreseen. One channel transmits the video data, the other sends position and flight data and receives flight commands. The channels are coded to avoid interference.

Camera : One of the basic requirements in the operational definitions emphasizes the need for a powerful camera. The camera that performs best at an acceptable weight is the SONY FCB-IX11AP (Fig. 14). The camera has a 10x optical zoom and a 4x digital zoom. The combination allows thus to zoom 40x in on objects.

The camera is installed at the bottom of the fuselage, in a fibre glass box. Left and right of the camera, a shield provides protection against dust and unwanted incident rays of sunlight. A servo offers the possibility to rotate the device around a horizontal axis, allowing one to observe forward as well as downward. A plastic bulkhead separates the camera compartment from the "engine and gearbox" compartment (Fig. 13).

Fig. 14

Development and Assessment

The following paragraphs will quote and assess some of the aerodynamical metrics obtained via wind tunnel tests. Also, the construction methods to become the platform's structure, which is specially designed to pursue an as low as possible weight, will be explained.

Aerodynamics

Thanks to the Free University of Liège (ULg), we were able to perform full scale wind tunnel tests. The wind tunnel has a cross section of 2m by 1,5m. The air flow can be accelerated up to 60m/s.

Rotor blade assessment : Before making moulds to produce the rotor blades, which is costly, one should verify the characteristics of the blade. Making a mould for an asymmetric evolutive blade requires many man-hours and is labour-intensive. Any modification on the blade that is pushed forward after examination of the wind tunnel results, requires the mould to be reconstructed or to be adjusted if possible, draining your budget and possibly endangering the project. Therefore, one decided to construct the first blade prototypes via stereo-lithography, using Optoform B material. Because of safety reasons, the blades of this brittle, stiff and strong material could not turn at RPM values higher than approximately 2500. Fig. 15 reflects the results obtained with the rotor blades installed in the duct, in hover. At 300 rad/s and a pitch angle of 20°, the ducted rotor seems to produce enough thrust to lift the platform. The calculated blade profile was accepted and released for production. The *structure* paragraph will give a more elaborate discussion about the final construction method.

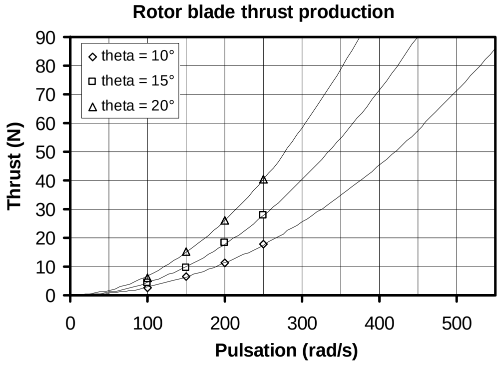

Fig. 15 : Thrust characteristics of ducted rotor

Anti-torque production assessment : The system (Fig. 13) could not really be evaluated on beforehand. This because of the hard-to-predict downwash velocities. Stators and blades were dimensioned from an estimated velocity field below the rotor.

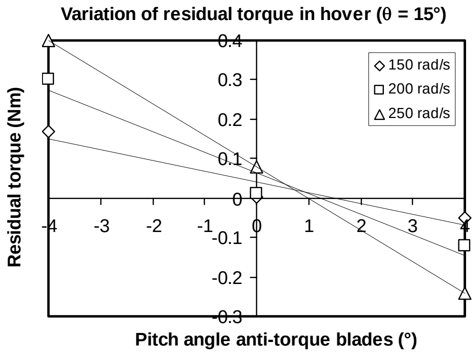

Fig. 16 : Anti-torque governing

The airfoils for the wind tunnel application, were made from polystyrene foam wrapped in a glass fibre skin.

Fig. 16 shows that the blades need to deflect by approximately 1° in order to counteract all torque produced by the rotor. In fact, the stators absorb the biggest part of the torque, while the blades take only what is left (residual torque). If the residual torque were 0Nm at 0° pitch angle, then, the optimum would be obtained. However, since the error of the measured blade pitch angle amounts to 1°, no changes were made to the configuration.

The "excess" of torque is used for yaw control. Remark that the slope of the curves steepens with rotor pulsation, meaning that the directional responsiveness of the platform increases with rotor RPM.

Duct and fuselage aerodynamics : Five duct shapes were examined. The ducts differed from each other by length, lip radius and divergence angle. During the tests, smoke helped to identify flow behaviour around the inlet.

Fig. 17a shows, for the examined configuration, that the airflow remains attached to the lips, when accelerating. Even downstream the rotor, the divergent does not invoke flow separation. However, in forward flight (Fig. 17b), the airflow changes direction dramatically, whereby the air is encouraged to separate much more easily. Still, at 7m/s, the lip radius seems to be adequately dimensioned, minimising losses.

The fuselage dimensions in the wind tunnel set-up were slightly smaller than those of the real fuselage, needing the motor to be installed outside. The effects of installing a slightly larger fuselage, thus invoking a smaller stream tube cross-section, are believed to be negligible.

Fig. 17a : V_V = 7m/s

Fig. 17b : V_H = 7 m/s

Remark : future research might still improve the duct characteristics, using a synergy of additional wind tunnel tests and CFD simulations.

Structure

Rotor blade construction : The rotor blades should be as stiff as possible in order to avoid all kind of vibratory and instability problems as well as to keep the gap between the blade and the duct minimized. Moreover, a lower weight of the blade produces lower centrifugal forces, thus, smaller and consequently lighter bearings can be installed. Also, this allows to implement weight reductions on the rotor hub, since it absorbs less forces too. Therefore, the choice of material fell on carbon fibre. This material allows much more damage and shocks than the Optoform B material, which is brittle.The mould consists of an upper part and a lower part (Fig. 18), made of Ureol®.

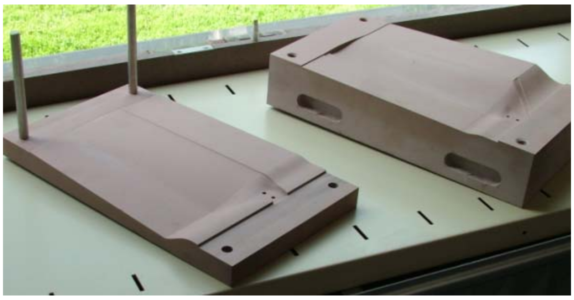

Fig. 18 : The blade mould in Ureol®

Fig. 19 : The carbon fibre composite blade (Ets. Poncelet, Belgium)

This material has a high form consistency and is easy to machine. In the mould, one places plastic sheets to prevent the composite from sticking on the Ureol®. The blade is made hollow to reduce weight. After sanding the surface and applying a protective layer, which enhances surface smoothness as well, de blade is balanced. The weight of the blade after all operations amounts to a bit less than 50g (Fig. 19).

Rotor head construction : The rotor head parts made of titanium were obtained via various machining techniques such as turning, milling and electro-erosion. The difficulty with this material is machinebility, especially the threading.

Duct, fuselage and anti-torque airfoil construction : The duct, fuselage and anti-torque airfoils consist of complex to very exotic shapes that require lots of machining skills to obtain them via traditional tooling. Weight reduction is of paramount importance. A healthy choice would be the use of light weight composites such as carbon fibre and honeycomb materials. Unfortunately, these materials require moulds and or special cutting techniques to obtain the specifications. Since we deal with a prototype, thus likely subject to

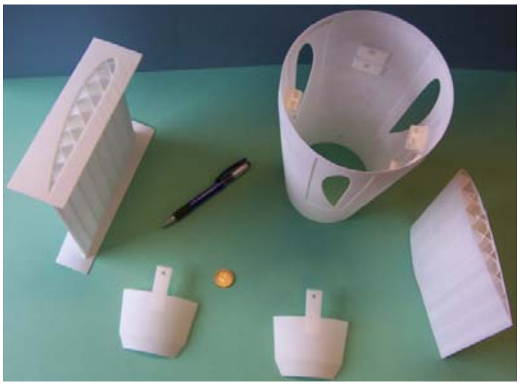

Fig. 20a : Sintered polyamide parts

Fig. 20b : Duct and fuselage covered with polyurethane paint future modifications, the decision to make the parts via rapid prototyping, seems acceptable and affordable in time and cost. Here a polyamide polymer powder is put forward as the most appropriate material. A laser fixes the polyamide layer by layer, it becomes sintered polyamide (Fig. 20a & Fig. 20b).

The duct breaks up into two main parts, each composed from several similar subparts in sintered polyamide. The main parts consist of an upper part and a lower part. The upper part covers the batteries. Removal of this part allows the batteries to be replaced after discharge. The lower subparts (Fig. 21) support the batteries and are made as light as possible through avoiding the use of excess of material. Between the walls, a lattice stands in for rigidity.

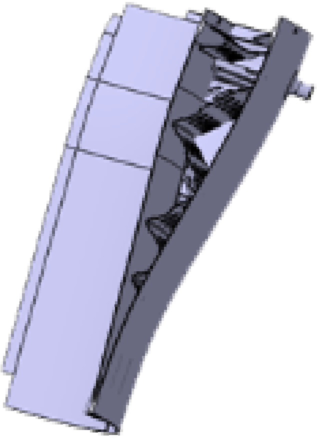

Fig. 21 : Duct lower main part

Fig. 22 : Lattice must allow excess of powder to be removed

The same technology applies on the anti-torque blades and stators. The lattice ensures airfoil rigidity and separates electrical cables from one another. As seen on Fig. 22, excess of powder must be removed from the part. This shows that every part must be engineered such that it allows the powder to be removed from "hidden" cavities.

Conclusions

The development of the Ematador RUAV relies on basic foundations defined by RMA and EMA. The mission profile, together with an iterative design process and a detailed study of rotor blade and duct aerodynamics allowed to enhance performance and to reduce weight.

Wind tunnel tests are fundamental in order to assess aerodynamic behaviour of the rotor blades and the duct at different flight conditions. Also, they were indispensable to study the feasibility of the anti-torque system.

Since the platform experiences high loads, special materials and lubricating agents are pushed forward in order to decrease its weight.

Future test flights will determine the Ematadors' performance and its ability to comply with the postulated mission profile.

References

1. Liévin, B.: *"Dimensionnement aérodynamique du rotor principal d'un hélicoptère de type drone"*, ISIB, Bruxelles, June 2004.

2. Aernouts, J.F.: *"Conception et développement d'un mini-drone de type hélicoptère"*, ULg, Liège, June 2005.