

Flying Autonomously to Corsica : A Long Endurance Mini-UAV System

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ABSTRACT

The paper presents the whole design steps of a 1.5 m UAV so called *Spirit of Corsica 2 (SPOC-2)* which is designed to fly over the Mediterranean sea from Menton to Corsica. Conceptual design is described following the decision taking for the mission constraints. Aerodynamics and windtunnel results of the design has been presented. A specific, mission based propulsion system matching methodology has been described. A compact and lightweight proposal has been made for one of the biggest difficulties for long range communication by using a GSM module. Finally the mission attempt has been described.

1 INTRODUCTION

Long endurance UAVs generally require a large airframe and a significant infrastructure. Although limited in energy density, electrically powered UAVs offer flexibility and robustness and can be combined with solar cell power supply. The present paper addresses the technical dilemma between

endurance and size with the objective of investigating long endurance mini-UAV systems. As an example of this effort, a specific over-the-sea mission has been designed to assess the feasibility of a long-endurance mini-UAS.

2 PROJECT DESCRIPTION & HISTORY

Fly to Corsica Project has started as a collaborative student project between ISAE and ENAC in 2009. The objective of the project is to fly autonomously from Menton to Calvi (approximately 185 km, figure 1) with the smallest possible electrically powered UAV. Figure 2 illustrates two successive versions of the Corsica mini-UAVs with their specifications. In 2009, the first year of the project, three prototypes have been manufactured and, more than 90 minutes of test flights have been accomplished in total. Unfortunately the final plane was not ready at the time of mission attempt so it has been decided to extend the project to 2010. New version of the mini-UAV (*SPOC-2*) has been redesigned and fine tuned in the light of the experiences gained from the initial prototypes. Following sections will cover all of the design and development phases of *SPOC-2*.

3 CONCEPTUAL DESIGN AND AERODYNAMIC ANALYSES

3.1 Aircraft Conceptual Design

Conceptual design has been done using a homemade tool[1, 2], sweeping over a range of wing spans and wing

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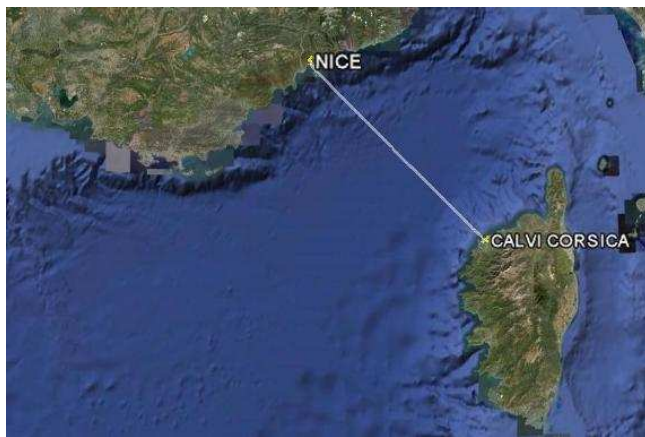


Figure 1: Planned mission map.

Design Restrictions		
Stall Speed	<11	(<i>m/s</i>)
Ground Distance	185	(<i>km</i>)
Head-Wind	2.5	(<i>m/s</i>)
Span	<2	(<i>m</i>)

Table 1: Constraints of the mission for the conceptual design.

surface areas in order to find the optimum design according to the mission definition.

The mission can be simply expressed as flying a straight line of 185 *km* ground distance. Without any restrictions, constraints and safety margins, conceptual design program shows that the mission is feasible even with an 40 *cm* sized plane. As it is known that there will never be perfect conditions and as the practical reasons should be taken into account such as safety piloting, landing approach, etc. more restrictions and constraints have been added to the mission definition. Table 1 shows the constraints.

Most of the constraints have been added in the light of last year's experience, especially the difficulties that have been seen while landing made us decide to have a limit on the wing loading. Also an average wind speed have been extracted from previous year's meteorological records which lead us to extend the distance in order to be able to deal with the additional head-wind.

Finally after all of these constraints, one final limitation is added with the selection of battery. As it is decided to place all of the batteries inside the wing instead of fuselage in order to have more sleek design, the wing geometry and the airfoil became dependent on the battery choice. The previous year's experiences showed us that using several individual battery cells in parallel creates a lot of troubles during the building and operating the plane. So in order to reduce the number of cells used in the design, 21 *Ah* Lithium Polymer batteries



Version 2009		
Total Power	(<i>W</i>)	100
Battery Capacity	(<i>Wh</i>)	310
Structural Weight	(<i>N</i>)	5.35
Total Weight	(<i>N</i>)	29.45
Wing-Loading	(<i>N/m</i> ²)	124
Lift Coefficient		0.50
Span	(<i>m</i>)	1.5
Chord	(<i>m</i>)	0.158
Drag	(<i>N</i>)	2.36



Version 2010		
Total Power	(<i>W</i>)	45
Battery Capacity	(<i>Wh</i>)	210
Structural Weight	(<i>N</i>)	4.50
Total Weight	(<i>N</i>)	19
Wing-Loading	(<i>N/m</i> ²)	91
Lift Coefficient		0.65
Span	(<i>m</i>)	1.5
Chord	(<i>m</i>)	0.140
Drag	(<i>N</i>)	1.3

Figure 2: 2009 and 2010 versions of Corsica mini-UAV.

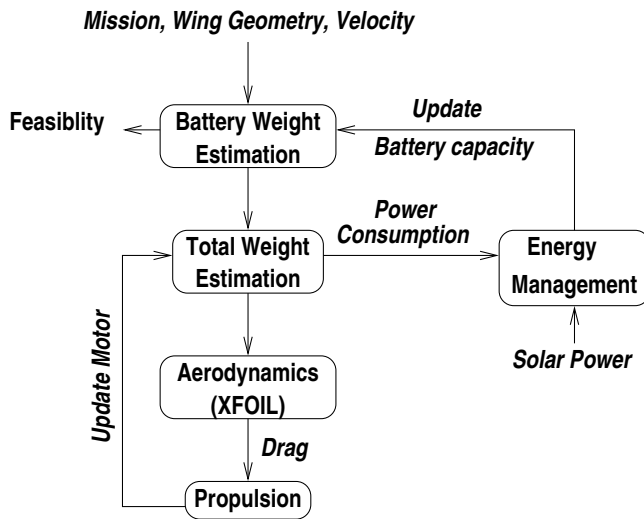


Figure 3: Flow chart of Conceptual Design program

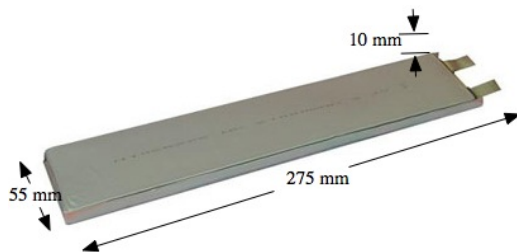


Figure 4: Selected 21 Ah Lithium Polymer Battery

have been selected (Figure 4). The decision of the battery has limited the chord length to 14 – 15 cm for a suitable airfoil for the mission. Analyses carried out on Xfoil¹ and finally a modified SB96 Airfoil (5) has been chosen for the plane mostly because of its advantageous volume and high Cl_{max} .

3.2 Aerodynamic Analyses

As a result from the conceptual design program, we obtain the wing area, span, airfoil, tail surfaces and the moment arm of the tail surfaces. After, preliminary sizing has been evaluated with analytical methods and numerical methods (AVL² and XFLR5³) using a classical vortex lattice method (Figure 5). The wing planform shape has been designed to have almost elliptical lift loading along the span so as to have a higher span efficiency. It has been also taking into account for the low Reynolds problems near the small tip chords, avoiding tip stalls for favourable flight characteristics and integration of the batteries. Figure 5 shows the lift and lift coefficient distribution along the span for total equilibrium

¹raphael.mit.edu/xfoil

²raphael.mit.edu/avl

³xflr5.sourceforge.net

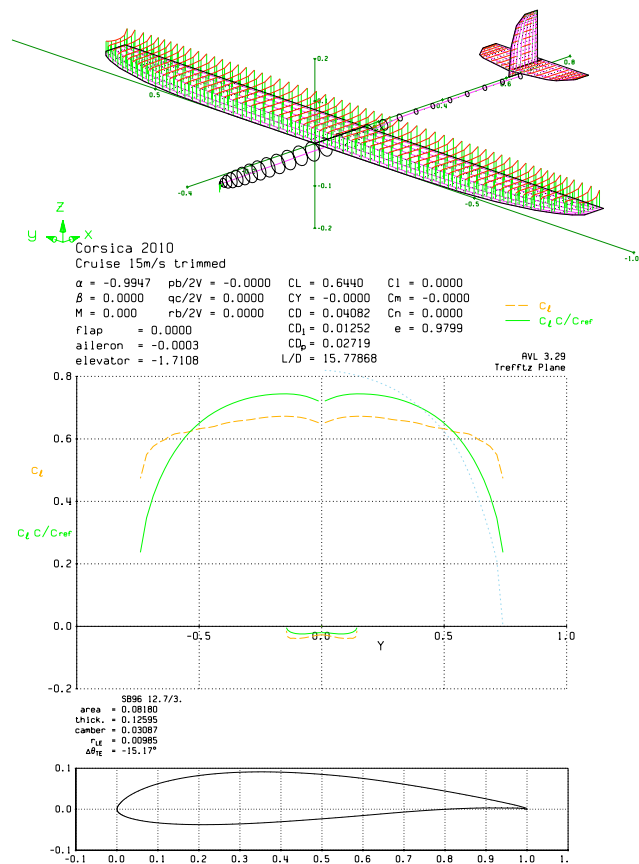


Figure 5: Analysis of SPOC-2 in AVL, with the wingloading visible on the top, lift force and lift coefficient visible along the span in the middle and the airfoil chosen on the bottom.

librium cruise condition at 15 m/s. Finally, the horizontal tail sizing have been done by using Naylor-Prandtl Theorem in order to calculate the downwash of the wing over horizontal tail. The horizontal tail has been designed as a zero lifting surface while satisfying %5 longitudinal static margin. In figure 5, it can be easily seen that the horizontal tail is almost at zero lift condition.

A specific wind tunnel campaign has been carried out as well in order to compare the theoretical and experimental results. Figure 7 shows the typical lift coefficient versus angle of attack and drag coefficient of SPOC-2 for different speeds. The effect of increased flight speed over lift to drag ratio is clearly visible in figure 8.

4 PROPULSION ANALYSIS

As expected, the importance of propulsion efficiency has been enlightened by the conceptual design program. Therefore, special effort has been given to experimentally and numerically analyse various electric motors and propellers. Both motors and propellers have been separately charac-

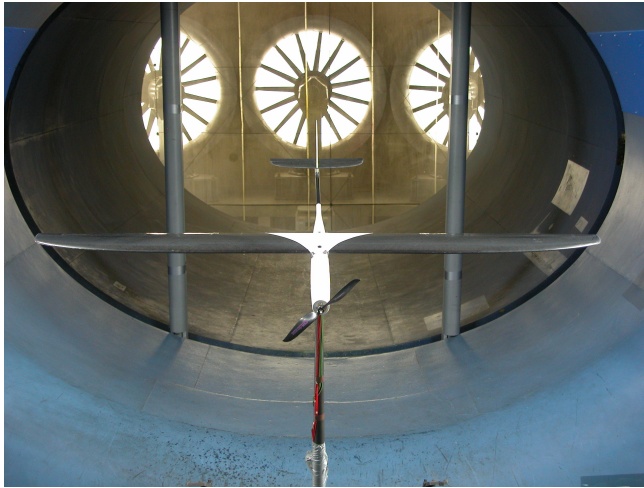


Figure 6: SPOC-2 in the S4 Windtunnel.

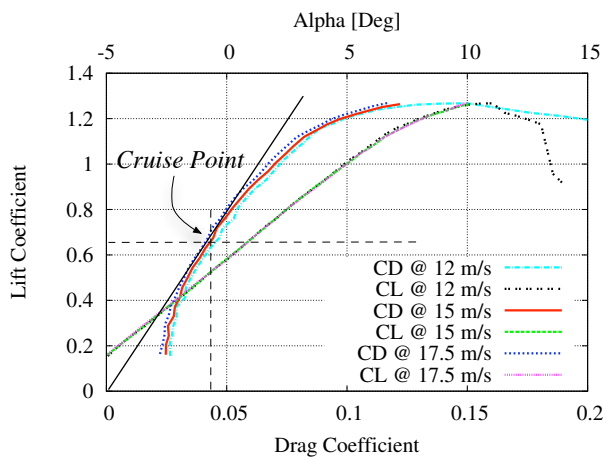


Figure 7: CL versus alpha and CL versus CD plots.

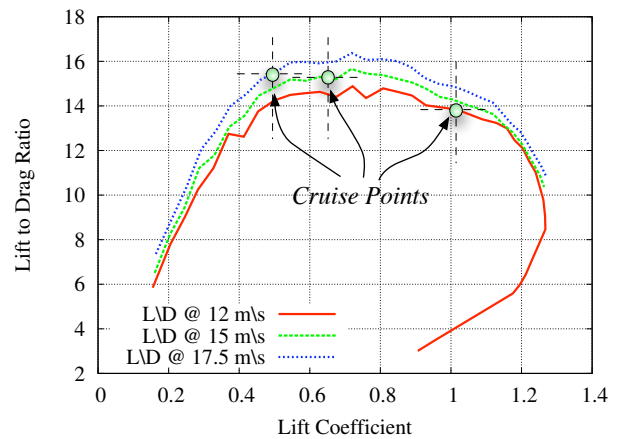


Figure 8: Lift to drag ratio of SPOC-2 for different flight speeds with the equilibrium points marked for each corresponding flight speed.

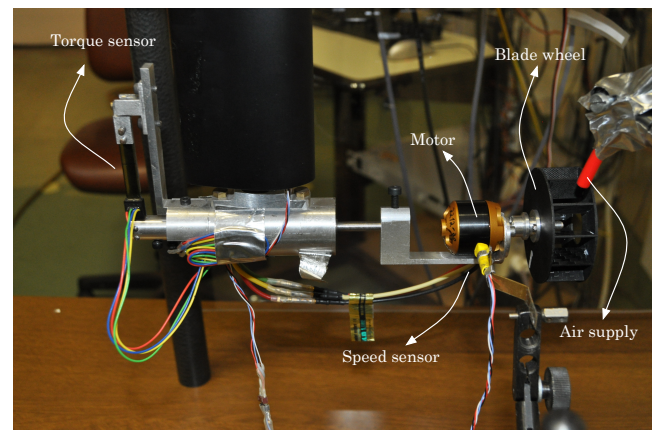


Figure 9: Characterisation of Motors

terised in order to determine the best matching couple for maximising performances.

4.1 Motor, Propeller & Battery Characterisation

A custom designed specific test bench has been used to measure the torque, rpm, volt and current required while continuously changing the resistance applied to the motor (Figure 9). Pressurised air has been blown on to a small fan in order to change the resistance. By this method, it is possible to characterise the motor solely. The efficiency of the motor is simply given by the following formula :

$$\eta_{motor} = \frac{Q \cdot \omega}{U \cdot I}$$

where Q is the torque (Nm), ω is the rotation speed (rad/s), U is the tension (V) and I the current consumed (A).

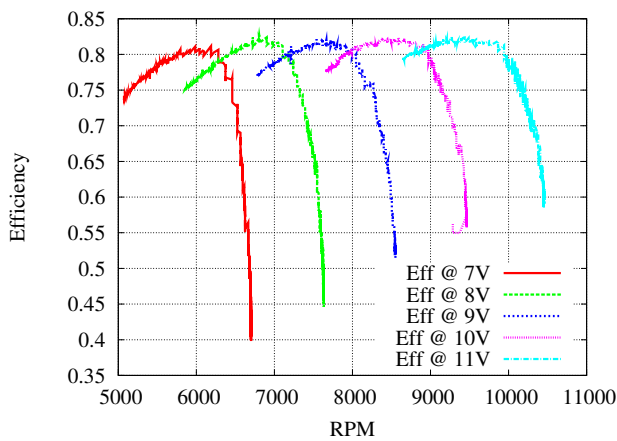


Figure 10: Efficiency graph of AXI 2212/26 brushless motor at various Voltages.

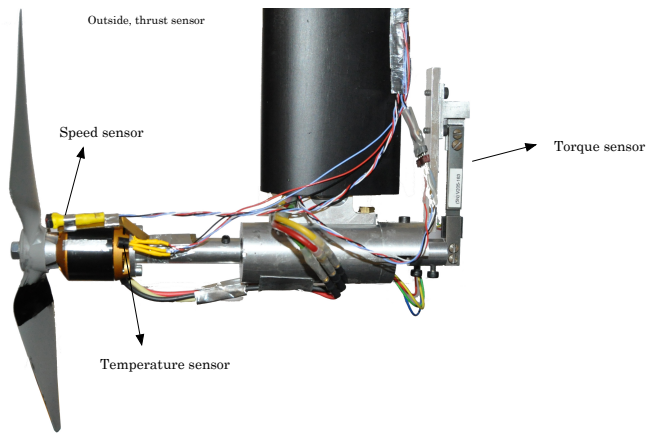


Figure 11: Characterisation of propellers

The same test bench (Figure 11) is placed into the S6 closed circuit wind tunnel of ISAE in order to characterise various propellers at different forward speed conditions. Mechanical input power of the propeller is measured with the built in torque and rpm sensor, and out put power is recorded from the thrust generated times the forward speed. The propeller efficiency given by:

$$\eta_{prop} = \frac{T \cdot V_w}{Q \cdot \omega},$$

where T is the thrust (N) and V_w is the forward wind speed (m/s).

Finally, as the batteries need to be characterised as well, they have been discharged at various power output conditions in order to see the real capacity corresponding to each discharge output and their efficiency.

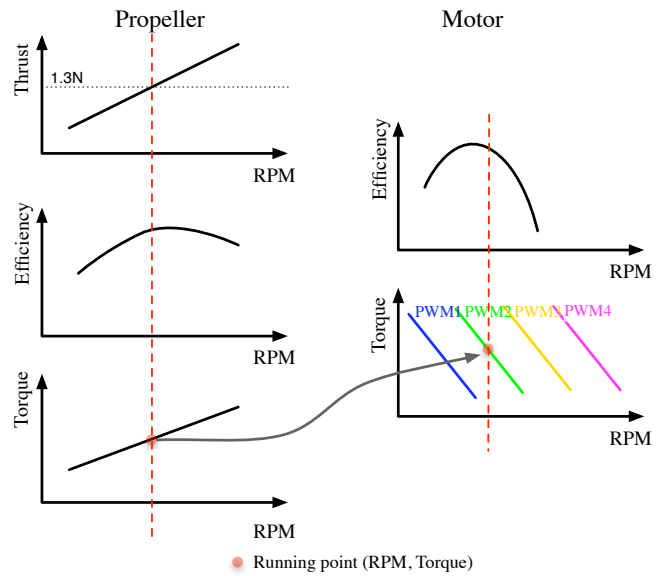


Figure 12: Motor and propeller matching methodology

4.2 Matching of System

Knowing the real performance of the motors and propellers at our disposal, the best propeller-motor couple have been determined following the scheme pictured in figure 12[3].

Starting by finding the rotation speed of the propeller giving 1.3 N of thrust, the efficiency η_{prop} and torque for that point are also known (thanks to the data recorded during the tests). The [torque, RPM] point required for the cruise is then searched for the motor used and its efficiency η_{motor} is also obtained. Finally, the global efficiency is found by $\eta = \eta_{prop} \cdot \eta_{motor}$.

Finally, experiments showed that it is possible to achieve an efficiency as high as %83 for the motor and %74 for the propeller. With a proper matching of motor and propeller with in some additional practical constrains like a certain thrust at static condition or a certain thrust at a given forward speed, it is feasible to have an total efficiency of %50 for the propulsion system at cruise conditions.

4.3 Endurance Tests

A crucial test before trying the actual mission was to ensure that the batteries actually held enough energy to allow such a long trip (185 km). For this experiment, the propeller test bench (placed in the S6 wind tunnel) has been used; unlike the propeller characterisation test, the power supply was the battery. The wind tunnel was set to have a 15 m/s wind while the propeller was providing 1.3 N of thrust which are the cruise condition values. As the voltage of the batteries decreased during the course of each test, the throttle command (PWM) had to be corrected. The cut-off voltage for each cell

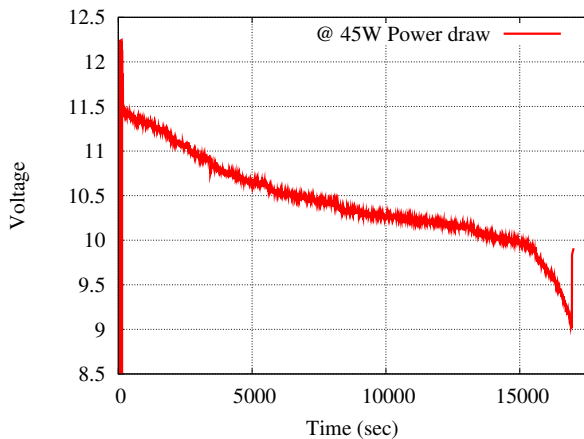


Figure 13: 4 hours and 40 minutes of discharge graph of the batteries.

has been set at 3 V to avoid any irreparable damage. Figure 13 shows the discharge graph of the batteries inside the wind tunnel at the cruise condition power consumption rate (45 W). Finally it was only possible to extract 18.6 Ah of capacity out of 21 Ah but as the batteries happened to be lighter than their specifications, they still satisfied their 191 Wh/kg specific energy.

Also a cooling test has been carried out in the wind tunnel. As the selected motor is very optimized for the cruise conditions, whenever more power is needed it gets extremely hot. Figure 14 shows the temperature of the motor while the cruise condition, while simulating a climb with maximum throttle at 15 m/s and while simulating a fast straight flight at maximum throttle at 20 m/s. The effect of additional speed on cooling can be easily seen.

5 EMBEDDED SYSTEMS & COMMUNICATION

5.1 Autopilot System

For the autonomous navigation and stabilisation system, the well proved and worldwide well known Paparazzi System⁴ is integrated [4, 5]. Primary attitude stabilisation is established by the help of infrared thermopiles. Additionally, for the roll rate correction, the UAV is equipped with a gyro.

5.2 GSM Module

As expected, typical low power radio-modem ranges are not sufficient to keep contact during the whole flight (mid-point range is approximately 90 km from the two GCS). It was also not possible to use a high power radio-modem because of power emitting regulations in France. A GSM module was planned to be used for the telecommand and telecontrol communications. This would enable us to keep track of the extremely important information such as GPS location, power

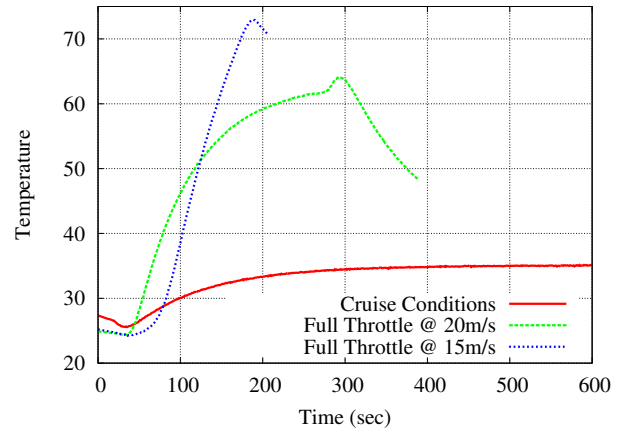


Figure 14: Motor temperature during three different conditions.

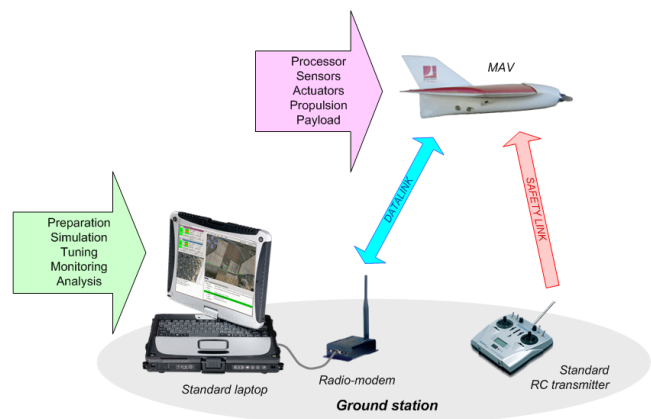


Figure 15: Paparazzi System overview and Autopilot board

⁴paparazzi.enac.fr

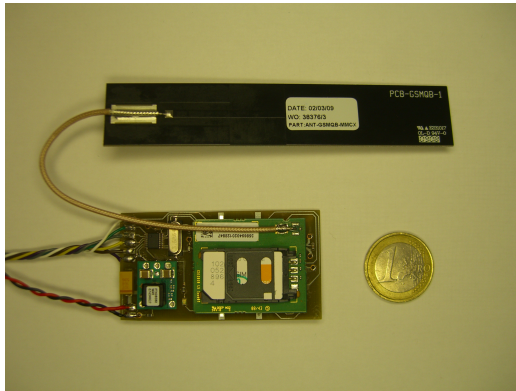


Figure 16: Telit GC864 GSM/GPRS Module with antenna

consumption and the remained energy on-board during the flight. It would also allow us to abort the flight if an unexpected and unrecoverable situation happens. These communications were also required for a periodic reporting of the position of the aircraft to the air traffic control.

Because of its small size and weight, Telit GC864 GSM/GPRS module is chosen. It requires an UART connection to exchange data, but as there were no UART connections left available on the Paparazzi module, the remaining SPI ports are used. And an all-in-one embedded GSM module is developed for Corsica mission, including a switching power supply (SMPS), a Maxim MAX3100 SPI/UART converter, and the GSM/GPRS module. The Telit GC864 is connected to a standard patch antenna which is located in the tail. For the ground stations, two of the same module is used one at Menton, one at Lozari/Calvi with an additional FTDI serial-to-USB cable which allows us to connect these ground stations directly to laptops.

With regard to the software, two additional pieces of code have been developed. The embedded code is designed to initialize the Telit GC864 settings, then to send a text message every minute. These messages contain the position of the plane, its altitude, its speed, the battery voltage and the strength of the GSM signal. The code for the ground stations reads messages as soon as they are received, and parse them in order to get the data in a readable form.

6 MANUFACTURING & INTEGRATION

In order to achieve the required surface quality and the accuracy in the integration, CNC-machined molds have been used in the manufacturing of the UAV (Figure 17).

Manufacturing process has been accomplished by the professionals of the composite laboratory of ISAE, which resulted in a high quality airframe as required. *SPOC2* is made out of fully composite materials with wet layup and vacuum bag technique. One of the particular property of the UAV is to carry large capacity of lithium polymer batteries, which are embedded inside the hollow molded wing. The integra-



Figure 17: Composite molds of SPOC-2.

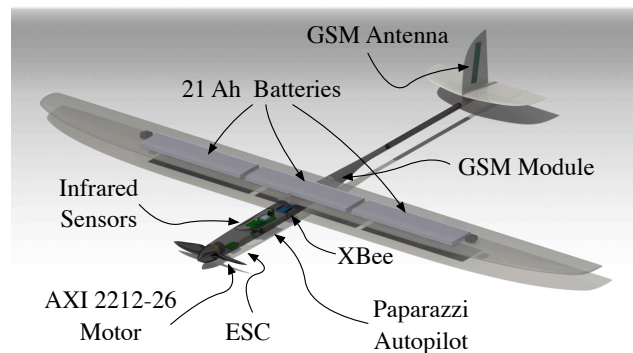


Figure 18: Integration of the components.

tion of the batteries is done in the mold before combining the top and bottom wing skins together. Through out the whole project in 2010, four wings, four tail group and six fuselages have been manufactured in five months. Figure 18 shows the final integration of main components.

7 FLIGHT TO CORSICA

7.1 Certification

In order to operate UAVs in a legal way, several authorizations from the DGAC (Direction Générale de l'Aviation Civile, French Civil Aviation Authority) needs to be obtained dealing with different aspects of the system. For the platform (plane or helicopter), it is needed to have a "Permit to Fly" which will allow to use the platform with in the conditions mentioned in the permit. The DSAC department of DGAC has been contacted in order to obtain Permit to Fly which is only given after a certification visit composed by a technological analysis and a flight demonstration.

When a "Laisser-passer" type permit to fly obtained, the restricted area in which the UAV will fly needs to be determined. Therefore, a file including all GPS coordinates which

describe the area and flight altitude, has been provided to DGAC. Then the DSR department has been contacted in order to "build" the area for the mission. Finally the last point to fly legally was to obtain the a matriculation number for SPOC-2 (*F-WZSC*) has been taken from DGAC in order to fly legally.

7.2 The Mission

A good knowledge of the weather conditions was a key parameter for the success of the mission. That's why AROME and ALADIN forecasts models from Météo France were used, in order to choose the best day for the launching. A few minutes before the launching, the weather was checked one final time with the current data of the local Météo France centers.

At 6.30 AM the 23rd June 2010 the weather conditions were favourable. Unfortunately, just after the take off, the pilot lost the RC link, probably due to a considerable electromagnetic pollution, and the mode of the plane changed to HOME (meaning that the plane should go directly to Calvi). The plane intended to climb to reach its cruise altitude too rapidly and a stall happened resulting with a crash on the rocks near the harbor. Immediately, preparations have been started for the next attempt, starting by finding the reason of failure.

- The HOME mode has been replaced by the AUTO2 mode with a low altitude reference, to avoid any stall in case of RC loss.
- After several tests in different environments, we concluded that there was too much electro-magnetic influence on the coast. We took the decision to pilot the plane directly through the Xbee (2.4GHz Datalink) with a remote control plugged on the ground station.
- In order to avoid the risk related to the proximity with the boats, we changed the take off place, using a large free beach.

On the second day of attempt, at 6.10 AM the 24th June 2010, the take off happened without any problems, final trimming and the tuning occurred quickly and without difficulties. After 6 minutes, it is decided to stop circling for testing and send the plane to Corsica for its real mission. Finally, when the plane was in direction to Calvi, the altitude, the speed, and the direction(19) were perfect during the first eight minutes. We have lost the contact with the plane after flying 5 km as expected. GSM module was not in operation as we had some problems in the first attempt. Finally, we couldn't have had any more information from SPOC-2. Without data, we are not able to give the real failure reason. Of course, some hypotheses can be imagined like path through low clouds (Figure 20), wind gust,... but without certitudes.

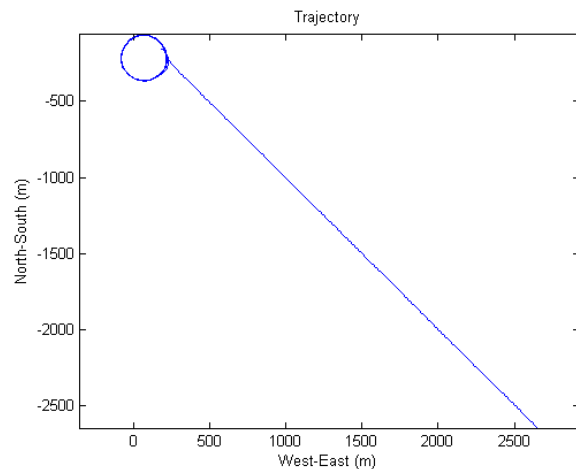


Figure 19: Trajectory of SPOC-2 before losing communication.

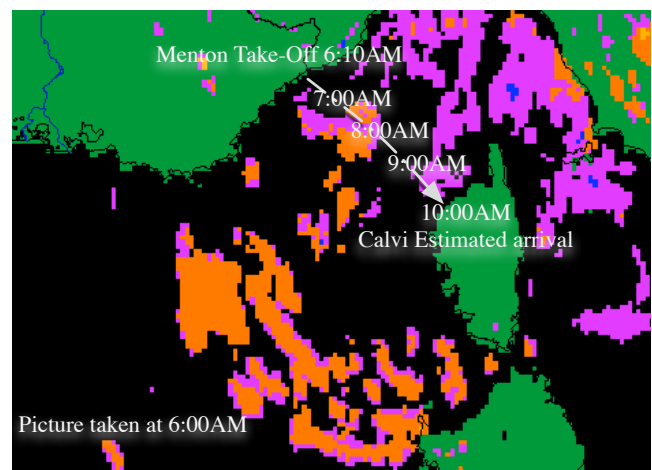


Figure 20: Satellite picture of the clouds taken at 6:00 AM, orange colour shows very low altitude clouds which could cause the failure of the infrared sensors.

8 CONCLUSION

The design of a long-range mini UAV so called *SPOC-2* has been described with all of its development phases. A specific wind tunnel campaign has been accomplished in order to verify the real specifications of the design. As a result of this wind tunnel campaign, it has been proven that for 1.5 m span UAV, a lift to drag ratio of 16 is feasible to obtain. A specific method for matching the propeller and motor according to the mission requirements has been briefly described, and shown that at least %50 of total efficiency for the propulsion system is feasible to achieve at this scale. Also a solution found for a lightweight long range communication by using a GSM modem. Although not being able to accomplish the mission, the attempt is done with a perfect take-off and start phase. *SPOC-2* has left the coast of Menton/Nice and flew towards Calvi/Corsica smoothly before disappearing in the sky. For the future of the project it has been decided to concentrate more on the test flights. Also some minor modifications to both hardware and autopilot software have been planned. As an additional to this year's attempt, it is planned to use an IMU and a pitot-static tube on the next year's plane.

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We will never forget you Pascal...

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