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Flight tests for meteorological studies with MAV

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Abstract

The use of UASs (Unmanned Aerial Systems) in meteorological studies has been a growing interest in the recent years but several technical and legal issues have to be overcome in order to fly safely and efficiently within the civil airspace. This paper addresses the technical aspects of the VOLTIGE (Vecteur d'Observation de la Troposphère pour l'Investigation et la Gestion de l'Environnement) project where a fleet of UAVs will fly simultaneously in and out of fog. Several improvements have been made on the communication between the payload and the autopilot in order to have an efficient sensor-based navigation. The challenges regarding the integration into civilian airspace are also presented.

1 Introduction

The use of UAVs in meteorological studies has been a growing interest in the recent years [5, 1, 6]. Several types and sizes of platforms have already been used around the world with different technical and legal issues. Small UAVs have shown especially good results in observing the planetary boundary layer [4, 3]. When studying fogs, most of the measurements are currently constrained to ground-based observations or vertical soundings. The use of manned aircraft is too dangerous in this particular situation. Small and micro UAVs are probably the best tool to observe fog events since they can safely fly close to the ground, yet adapt their trajectory to the current meteorological conditions. Such a sample strategy has not been permitted before.

This paper will first introduce the main objectives of the VOLTIGE project. The initial and improved architecture of our autopilot and payload control are then described (including a justification of the tight integration between payload and navigation systems). Finally, the flight campaigns that have already been carried are presented with some preliminary scientific results. The regulatory aspects concerning those flights are addressed as well.

2 Objectives

One of the VOLTIGE project goals is to perform a coordinated flights of several UAVs equipped with meteorological sensors for the study of fogs. These flights have to be performed within the civil airspace while complying with the French airspace regulations. Another key aspect of this project is the improved integration of the communication between the payload and the autopilot in order to have an efficient sensor-based navigation.

The meteorological sensors include pressure, temperature, humidity, solar radiation, cloud and fog detection, and turbulence. Three types of flights' profiles will be performed simultaneously from different aircraft in order to gather the scientific data:

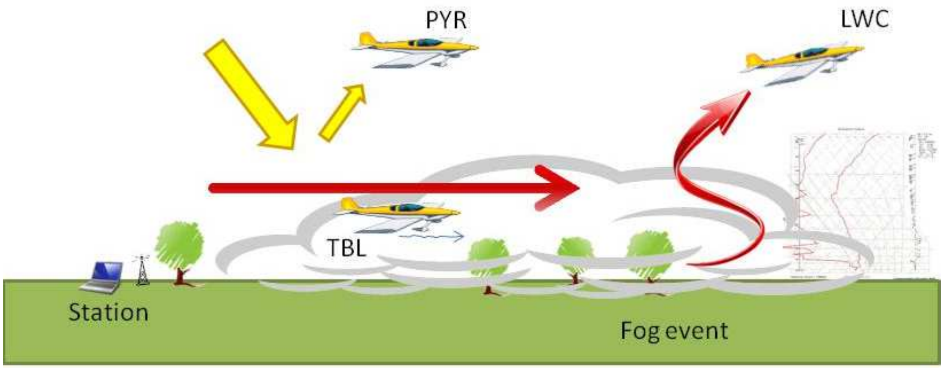

Figure 1: Principals of the VOLTIGE project fog study

- turbulence measurements from an horizontal flight inside the fog (TBL on Figure 1),
- vertical profiles from ground level to above the fog (LWC),
- radiation measurements above the fog (PYR), which implies detection of the fog boundaries.

Since the visibility will be reduced, it is important that the aircraft can perform automatic collision avoidance. This safety system is based on the same principals than the TCAS [2] used on commercial aircraft.

3 System architecture and integration

3.1 Initial setup

The autopilot system used in the project is the Open-Source UAV system *Paparazzi*[1]. The initial setup for this project includes two independent inboard electronics. The first part of the system consists of the flight control system, which is composed of the main autopilot board, a GPS, a radio modem, a RC receiver for the safety pilot, a motor and the actuators. The second part is the scientific payload (Fig. 2) including the sensors and specific electronic boards (usually two boards in each flights and a data logging system with its SD card. Each part has its own power supply.

While offering a fast and easy integration for the preliminary flight tests and sensor calibration, this solution has a lot of limitations and drawbacks, such as difficulties to fit all the components in a reduced space, redundant capabilities between the mission payload and UAS leading to an unnecessary increased weight, EMI issues,. . .

3.2 New autopilot development

In order to overcome the difficulties arising from separate electronics while offering required capabilities for atmospheric studies, a new autopilot hardware design has been initiated with the following constraints: payload management and sensor reading on the main autopilot board, data logging, and small size.

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[1] http://paparazzi.enac.fr

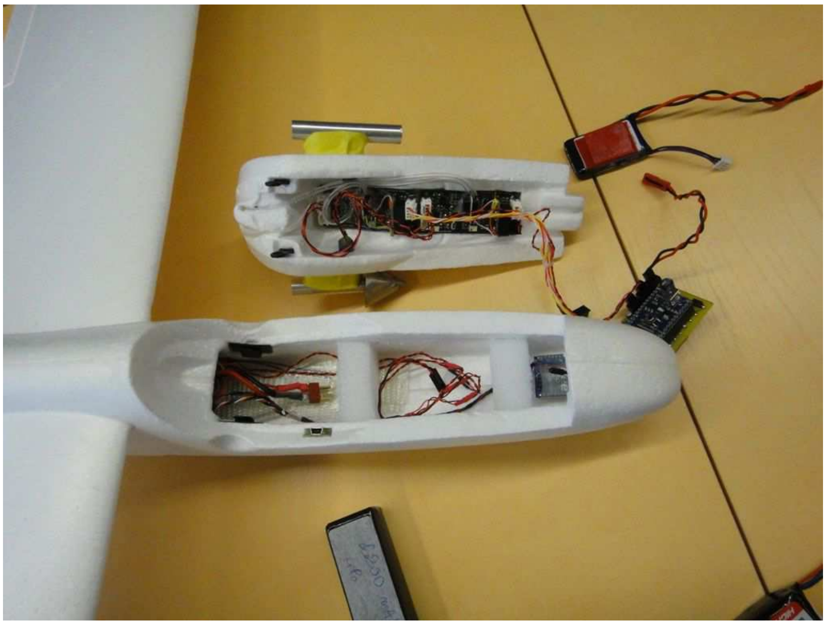

Figure 2: Payload electronics for the initial setup

The result is an autopilot, named *Apogee* (Fig. 3, right), with the same size as the previous generation, with a micro-SD card slot and more powerful micro-controller unit capable of handling the autonomous navigation of the MAV, a wider range of payload with more inputs/outputs, and high speed data logging (see characteristics in table 3.2).

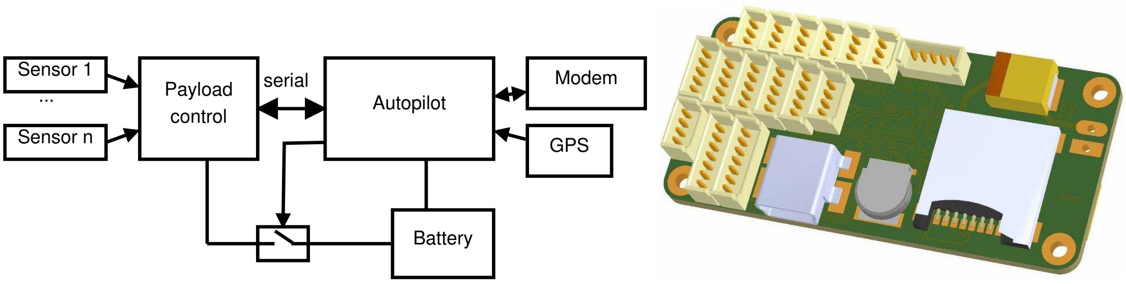

Figure 3: Integrated architecture and new autopilot design

This integrated architecture (Fig. 3, left) will allow to easily exploit the scientific data from the payload sensors in order to optimize the flight plan. Since the goal is to scan a wide and unknown volume, the trajectory of the aircraft has to be dynamically adapted to the meteorological conditions to gather a maximum of useful data. In order to optimize the battery consumption, the autopilot can control the power supply of all the payload and activate them only during the measurement phase of the flight.

With this architecture, the payload controller is able to either send commands to the autopilot, such as navigation commands or meteorological information (e.g. fog's boundary detection), or send

Processor	STM32F405
IMU	MPU-6050
Barometer	MPL3115A2
Logging	MicroSD slot over SDIO interface
Connectivity	6 PWM, 3 UART, 2 I2C, 1 SPI, 1 SWD, 1 USB, 4 AUX (PWM, ADC, GPIO)
Remote control	1 PPM input, 1 serial input
Power	1.5A switching power supply, 1 5V/500mA power switch
Size x weight	53x25 mm, 10.4 grams, 4 layers PCB

Table 1: *Apogee* autopilot characteristics

telemetry data that are relayed to the ground for real-time monitoring of the mission. It is also possible to store the scientific data on the autopilot SD card if the payload controller doesn't offer this functionality. An important benefit of the autopilot embedded data logger is to reduce the number of data sent to the ground compared to previous setup. The reason is that most of the bandwidth is used to send debugging information needed to investigated cases of failures after navigation errors or even crashes. With on-board data logging, all these information will be available after the flight for analysis with much more details than when using the datalink system.

4 Experiments

4.1 Regulation, permit to fly

All the flights for the VOLTIGE have been performed with respect of the latest French regulation concerning MAV operation (since April 11, 2012). Two documents are needed in order to fly out of sight of the ground operator and safety pilot and at an altitude higher than 150 m: a *permit to fly* and the creation of a temporary regulated area (ZRT, Zone Reglementée Temporaire).

The *permit to fly* is a document sent to the French civil aviation authority (DGAC) that presents the aircraft, the autopilot system and all the safety procedures that will be activated in case of flying out of the zone, loss of GPS, data link or safety link,... Several categories exist with different requirements depending of the possible damages that can be caused by the aircraft. All MAV involved in the VOLTIGE project are in the smallest class category (less than 2 kg), which has relatively fewer restrictions compared to other categories.

Flying in a regulated area means that the airspace for the experiments is separated from the general airspace and no human-piloted aircraft can enter this airspace during the activated period. The request for the creation of such an area must be done several weeks in advance, which impacts the experiments since meteorological conditions are difficult to forecast more that a few days in advance. If accepted, a NOTAM is published to inform the pilots that a temporary zone has been created. The flight zone is activated the day of the flight by calling the air traffic controllers in charge of the area.

4.2 Flight campaigns

Three fields campaigns have been performed for the VOLTIGE project. The goal was to validate the capacity of the MAV for sampling the atmosphere.

Figure 4: The two types of MAV used in the VOLTIGE project

First campaign The first campaign was held in Lannemezan (November 2012). The purpose of these flights was to do the initial testing and validates the choice of the airframes (Figure 4). A comparison was made between the two platforms: a glider (Multiplex Easystar) and a flying wing (Multiplex Funjet). The first plane ends up to be easier to handled, launch and land with a low flight speed, but is limited in terms of vertical climb speed and maximum wind speed for operation. The result is that the maximum altitude that can be reached is usually lower than with the other plane. For horizontal flights, it is a sane and reliable aircraft. The second flight has an higher flight speed (horizontal and vertical) with a comparable endurance. It allows to reach higher altitude (usually 50% more with similar payload).

During this first campaign, some meteorological sensors have been evaluated (temperature, pressure, humidity) by flying with two measurement units on the same aircraft (as seen Figure 4 right) and close to fixed poles (60 meters high) equipped with calibrated sensors for reference (as seen Figure 4 left).

Finally, the conditions during the campaign was pretty harsh with a lot of wind and rain. Tape have been used in order to keep the electronic dry. The selected aircraft are normal hobby planes not designed for this kind of weather. Even if the planes have satisfactory performances for the mission, it has been decide to evaluate the possibility to build a custom aircraft with an adapted payload bay if not found out of the box.

Second campaign Second campaign was at Lit-et-Mixe (French west coast) in February 2013 (Figure 5). It was the first attempt to fly within fogs since the area as the highest probability. Finally, out had no luck out of three days of flights. But other interesting meteorological phenomenon have been observed during the day with a flight almost every hours. This campaign also allowed to test all our procedures and highlight some of the limits of our system. In particular, it appears that the autonomous landing on a narrow field (short runway between trees) has to be improved in order to safely fly with reduced visibility.

Some of the preliminary scientific results are presented in section 4.3

Third campaign The third campaign was again held at Lannemezan in May 2013, with the main goal of integrating and testing a cloud sensor (Figure 6, left) under development at Reading University (UK). This was done successfully despite the difficulties to carry this extra sensor and its dedicated electronic board. From the operational point of view demonstrate once again that an integrated on-

Figure 5: Second campaign at Lit-et-Mixe. Left: sensor calibration with a reference sensor on the ground. Right: base camp of the campaign with the planes and antennas.

board electronic and an aircraft with a waterproof, easily accessible payload bay is the key point for this kind of mission.

Figure 6: Third campaign at Lannemezan. Left: base camp. Right: Easystar equipped with a cloud sensor (right wing), a video recorder (left wing) and a static electricity sensor (noise).

4.3 Preliminary scientific results

In order to validate the data measured during VOLTIGE fields campaigns, a comparison have been made with the forecasts of the AROME fine scale operational forecasting numerical model of Météo-France. Those plots (Fig.7) show the good agreement between the two types of data on some of the parameters measured.

The parameter virtual potential temperature dayly evolution (Fig. 8) permits to detect the temperature inversion level and how the boundary layer is mixed during the day. On this exemple, in the morning the boundary layer is divided in three layers. A mixing layer can be seen from the ground to 100m above it. The relative low level of humidity explains partly why fog didn't occure on this morning despite the favorable atmospheric conditions. Above this layer (around 100m a.g.l.) the strong gradient of virtual potential temperature is the marker of the inversion separating the mixing layer

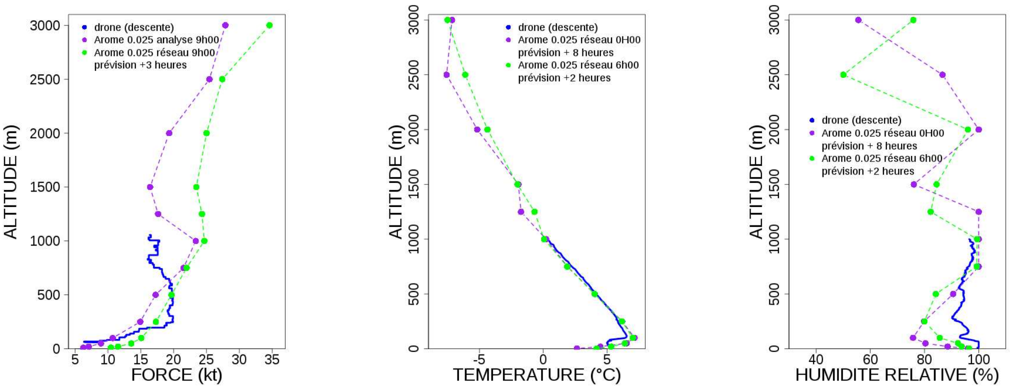

Figure 7: VOLTIGE project wind, temperature and relative humidity observations vs model forecasts

and the residual layer which is neutral with few turbulences. This is the remaining of the previous day's mixing layer. While the surface is warming during the day, the surface layer is becoming thicker and even convective (negative gradient) in the afternoon. The mixing layer is becoming thicker and overtake the residual one. At the end of the day this layer is up to 600m a.g.l. where an inversion is visible on flight n°13. This inversion seems to be the entrainment zone separating boundary layer from free atmosphere. In this case virtual potential temperature warming is probably due to the arriving of a warm front.

The measurements of the boundary layer height dayly evolution and meteorological parameters are important for the understanding of fog life cycles. The comparison to the model will be helpful to judge its ability to reproduce and forecast this phenomenon. This information will help the modelisation community to improve fog forecasting.

5 Conclusion

The VOLTIGE project is offering a good opportunity to develop new capabilities in the *Paparazzi* autopilot family, with newer processor, integrated data logger, better overall connectivity and payload management. While still at the early phase of the project, valuable experiences have been gain with three field campaigns and more than fifty flights. Among them, the constraints of operating small UAVs under bad weather conditions are leading us towards a custom payload bay with an appropriate design for easy and safe operation. The scientific results already gathered are promising, with accurate measurements and fast response time.

The next step will consists in flying multiple UAVs at the same time as a preparation for the field campaign during winter 2014 where we expect to fly in foggy conditions.

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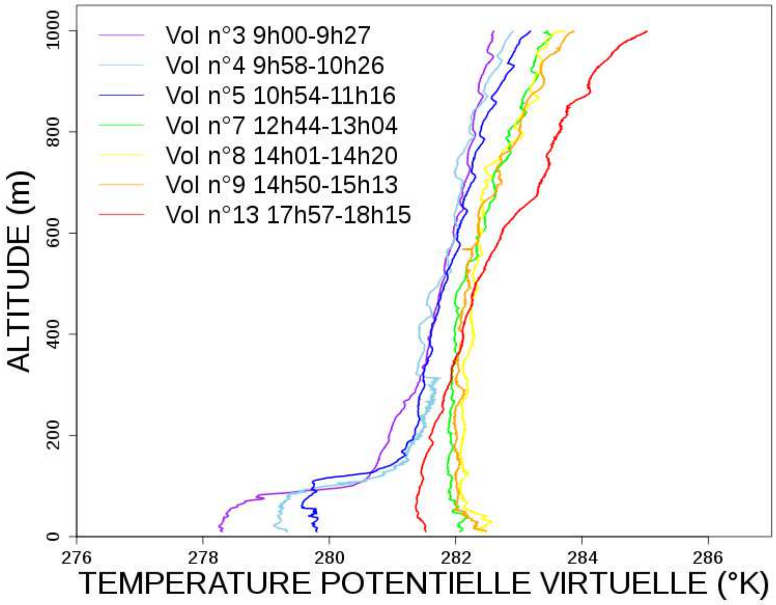

Figure 8: Virtual potential temperature evolution during the VOLTIGE project second field campaign (Lit-et-Mixe, 13/02/2013, local time).

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