Development of a Mini Unmanned Aerial Vehicle

From Telemetry to Teleoperation

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Abstract: A Mini Unmanned (and/or Uninhabited) Aerial Vehicle, developed at ENSICA, has been modeled and equipped with an embedded system in order to achieve manual and autonomous flight. First, we present the embedded system we have developed to acquire flight parameters. Then we introduce attitude estimation algorithms and control law designed from a linear model of the plane. Later on, we present some teleoperation aspects approached in the project. Finally we show some results obtained from real flight experiments.

Keywords: Mini Unmanned Aerial Vehicle, telemetry, teleoperation

1. Introduction

Research using flying robots has begun to progress in recent years due to a number of emerging technologies like computers, machine vision or sensors' miniaturization. While the unmanned (and/or uninhabited) aerial vehicle (UAV) has already been significantly used in military context (e.g., Hunter or DragonEye), most civilian uses of UAVs fall into movie filming, fire fighting, remote surveying or traffic surveillance [1].

Since 2001 the Ecole Nationale Supérieure d'Ingénieurs de Constructions Aéronautiques has been operating a small fixed wing MUAV (Mini UAV) as part of a program of basic research to develop capabilities for UAVs. We focused on demonstrating the feasibility of using gyrometers, accelerometer and magnetometer data fusion with a Kalman filter as a global sensor system for attitude and position control as well as navigation with the aid of a GPS [2]. Furthermore this system can be seen as a tool to evaluate the quality, in the sense of improving performance of the Human/MUAV control-loop, of perception and control interfaces.

This paper will first review the telemetry system we have conceived and developed. Then we will introduce the data fusion algorithm implemented in this system to estimate in real time the MUAV attitude. Then we will focus on the control law design based on a simplified MUAV attitude model. This automation aspect will then be replaced in a teleoperation context and we will consider the MUAV's human operator immersion through an embedded micro camera. Finally we will present some results validating the telemetry system and the attitude estimation (emphasizing the remote viewing system efficiency).

2. Flight Parameters Acquisition

2.1 Telemetry system

We have conceived and manufactured a compact embedded system that is able to acquire several flight parameters, such as acceleration, angular speed, magnetic field coordinates, position, speed and altitude. The system is shown in Figure 1.

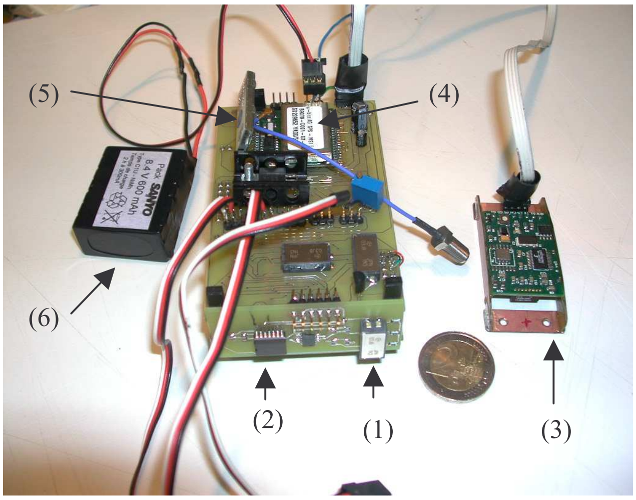

Figure 1: The embedded avionic system

The processing power of our platform is provided by a micro-controller Motorola 68332 which has been mounted on a pseudo-BBC board including 32 Kb of ROM and RAM and serial interfaces. This controller allows us to connect easily all our sensors and make future expansion of the system possible.
To evaluate the angular velocity of the MUAV we used 3 piezoelectric Murata gyrometers (1) following the 3 axes of the plane (for the roll, pitch and yaw). They are connected to the calculator through a 4-channel 12-bit ADC which gives us a measure (+-300°/s<->0-5V) at 50Hz (linked to the bandwidth of the sensor).
To acquire the acceleration of the MUAV we have used two Analog Devices ADXL210 (2) placed, as for the gyrometers, following the 3 axes of the plane. They are working at 125 Hz. Furthermore, in order to compensate a

temperature drift, present on this component and on the gyrometers, we have mounted a temperature sensor connected to the ADC's 4th channel.
We also use a Honeywell three axes magnetic field sensor (3) which lets us have an absolute reference for navigation. This sensor uses an asynchronous serial interface (RS232 19200 Bds) available on the calculator board.
To determine the position, altitude and speed of our plane we used a µ-Blox GPS (4). This component transmits those parameters through another serial interface with a 1Hz acquisition frequency.
The human-in-control system is provided by a standard eight-channel R/C radio system and standard R/C servos (PWM control signals). Three channels are used for control of the MUAV – aileron, elevator and propulsion. A fourth channel, which is a toggle switch, is used to switch between human and computer control of the aircraft. The embedded circuit is independent of the calculator systems. So that, in the event of a computer failure, the pilot can still assume the control of the MUAV.
So as to record and control actuators, we have connected the micro-controller to the R/C system, using a module of the 68332 which manages PWM signals, and keeping the two systems electrically independent.
We transmit all the flight parameters, with a 9600Bds digital HF transmitter Radiometrix (5), to a ground station which allows us to record and analyze the MAV comportment.
Finally we validated our complete system, which only weights 190g with an 8.4V/500mA NiMh battery (6), in the laboratory. Flight parameters acquisition was successfully performed as discussed in section 5.

2.2 Attitude Estimation

In order to control the attitude of the aircraft, three different angles (roll, pitch and yaw) must be determined. These angles are estimated from the fusion of sensors' measurements into an Extended Kalman Filter. We only consider two frames: the Earth frame, supposed to be Galilean, and the body frame. As we make no assumption on the aircraft dynamics, the system dynamic model is, in the discrete case:

$$\begin{cases} Q_{k+1} = Q_k + \frac{1}{2} T_e \Omega_k Q_k + T_e w_Q \\ \omega_{k+1} = \omega_k + T_e w_\omega \\ \varepsilon_{k+1} = \varepsilon_k + T_e w_\varepsilon \end{cases} \quad (1)$$

with:

$$\Omega_k = \begin{bmatrix} 0 & -p_k & -q_k & -r_k \\ p_k & 0 & r_k & -q_k \\ q_k & -r_k & 0 & p_k \\ r_k & q_k & -p_k & 0 \end{bmatrix}$$

If we consider X_k the complete state $X_k = [Q_k, \omega_k, \varepsilon_k]^T$ the equation above becomes :

$$X_{k+1} = f(X_k) + T_e w_k \quad (2)$$

T_e is the sample time. Q_k is the attitude (attitude of body frame relative to fixed frame, expressed in fixed frame) of the aircraft expressed as a quaternion. $Q_k = [a_k, b_k, c_k, d_k]^T$ is therefore a 4-dimension vector. Transformation from quaternion to Euler angles, used for the attitude control, is straightforward and is not described here. $\omega_k = [p_k, q_k, r_k]^T$ is the 3-dimension vector of angular rates for turning maneuver (rate of turn of body frame relative to fixed frame, expressed in body frame). The state vector is augmented with an additional state ε which is the drift of the gyrometers. For designing the Kalman filter we must take into account a set of disturbance w (with subscript corresponding to each state) supposed to be Gaussian white noise with covariance Q.
The measurement model is as follows:

$$\begin{cases} A_k = C_e^b \left(\ddot{x}_k + g \right) + v_A \\ G_k = \Omega_k + \varepsilon_k + v_G \\ M_k = C_e^b M_s + v_M \end{cases} \quad (3)$$

where:

$$C_e^b = C_b^{e^T} =$$

$$\begin{bmatrix} a^2+b^2-c^2-d^2 & 2(bc+ad) & 2(bd-ac) \\ 2(bc-ad) & a^2-b^2+c^2-d^2 & 2(cd+ab) \\ 2(bd+ac) & 2(cd-ab) & a^2-b^2-c^2+d^2 \end{bmatrix}$$

C_e^b is the transformation matrix (from fixed frame to body frame) and is related to the quaternion as the equation above states. A_k is the vector of three accelerometer outputs. As seen in the equation above, this measurement is related to the earth gravity $g = [0, 0, 9.81]^T$ and to the actual acceleration $\ddot{x}$ of the plane's center of gravity. We make here the assumption that this acceleration is mean null[1] and all derivatives fall into v_A. G_k is the vector of three angular rates measurement. The technology of this gyrometers (see section 2.1) makes them very sensitive to temperature: the drift ε is quite important and must be estimated online. The last measurement vector is M_k, the three components of Earth's magnetic field. M_s is the vector of Earth's magnetic field in Earth frame. v (with appropriate subscript) is the measurement noise supposed to be Gaussian white noise.
If we consider Y_k the complete measurement vector $Y_k = [A_k, G_k, M_k]^T$ the equation above becomes :

$$Y_{k+1} = h(X_k) + v_k \quad (4)$$

Let us just give the Extended Kalman Filter equations that makes the best estimate of X. (The subscripts $_k$ and $_{k+1}$ are

[1] This assumption leads to a good estimation of the attitude as long as the hypothesis is true. It is not true for circling flight.

now omitted as we describe here the algorithm, the equation $X_{k+1} = f(X_k)$ is written $X = f(X)$)

Step 1: compute the predicted state estimate:

$$\hat{X} = f(\hat{X}) \tag{5}$$

Step 2: compute the covariance matrix extrapolation:

$$P = F.P.F^T + Q \tag{6}$$

Step 3i: compute the Kalman gain, corresponding to the arrival of measurement n°i

$$K = P.C_i^T.(C_i.P.C_i^T + R_i)^{-1} \tag{7}$$

C_i is the i-th line of matrix C. R_i is the i-th element of matrix R. The strong assumption is that R is diagonal i.e. that measurement noises are uncorrelated; we can note that this step is not a matrix inversion but a scalar inversion, and the measurement can be asynchronous.

Step 4i: compute the covariance matrix update:

$$P = P - K.C_i.P \tag{8}$$

Step 5i: compute the state estimate update with measurement Y_i:

$$\hat{X} = \hat{X} + K.(Y_i - h(\hat{X})) \tag{9}$$

where Y_i is the i-th measurement.
F and C are respectively the jacobian matrixes of f and h.

The algorithm that we actually use is described in Figure 2 and derived from [3] and [4]:

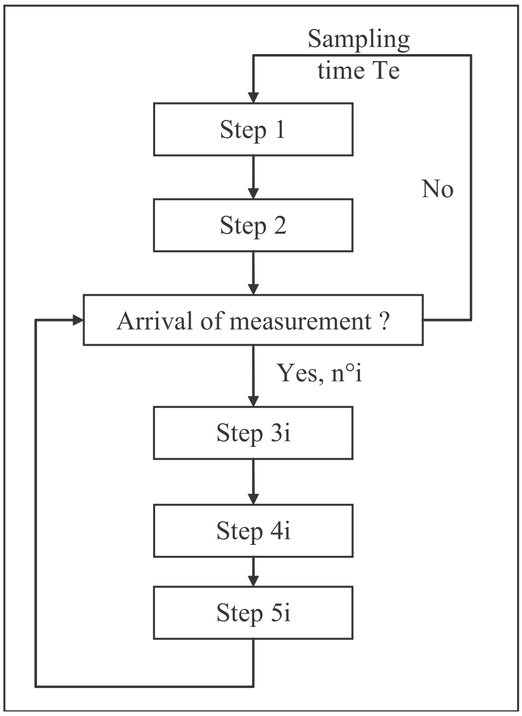

Figure 2: Kalman filter algorithm

3. Modelling and Control

3.1 Equation of the MUAV

Considering a straight level flight condition, the linear equations of this flight state have been identified restraining the model to a second order system:

$$\begin{bmatrix}\dot{q}\\ \dot{x}_q\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -161.7 & -15.66 & 0\\ 1 & 0 & 0\end{bmatrix}.\begin{bmatrix}q\\ x_q\\ \theta\end{bmatrix} + \begin{bmatrix}36.2\\ 114.6\\ 0\end{bmatrix}.\delta_e$$

$$\begin{bmatrix}\dot{p}\\ \dot{x}_p\\ \dot{\varphi}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -81.28 & -18.61 & 0\\ 1 & 0 & 0\end{bmatrix}.\begin{bmatrix}p\\ x_p\\ \varphi\end{bmatrix} + \begin{bmatrix}-138.9\\ 2212\\ 0\end{bmatrix}.\delta_a \tag{10}$$

where p is rolling angular rate, q is pitch angular rate, x_p and x_q are intermediate identified states, θ, ψ, φ are pitch angle, heading angle and rolling angle. The yaw angle can only be adjusted by the control of rolling angle because only two control variables are available.

3.2 Control law design

Therefore a very simple attitude control law can be obtained by applying the idea of dynamic inversion:

$$\begin{cases}\delta_e = k_{11}[k_{12}(\theta_d - \theta) - q]\\ \delta_a = k_{21}[k_{22}(\varphi_d - \varphi) - p]\end{cases} \tag{11}$$

where $k_{11}, k_{12}, k_{21}, k_{22}$ are control parameters to guarantee enough bandwidth and θ_d, φ_d are desired attitude of the MUAV

3.3 2-D guidance

The aim of the guidance system is to control the heading of the MUAV and to control the lateral position between actual trajectory and desired trajectory when the MUAV keeps a certain height. Thus, the guidance system includes *altitude holding loop*, *lateral position control* and *heading.*

Altitude holding control

The error of desired and actual height is introduced to the pitch angle control loop to constitute the altitude holding control loop. A saturation function is needed to limit the maximum value of feedback terms. Therefore the deflection command of elevator won't exceed its position limit. The altitude holding control law is:

$$\delta_e = k_{11}[k_{12}(\theta_d - \theta) - q] + k_h sat(H - H_0) \tag{12}$$

where H denotes the actual height of the MAV; H_0 is the desired height; $sat(\bullet)$ denotes saturation function.

Heading control

Heading angle and the lateral distance between airplane and desired flight trajectory can be controlled by adjusting the rolling angle. Based on this idea, lateral guidance law can be obtained. Saturation function is used here for the same reason as in altitude holding control loop. The heading control law is:

$$\delta_a = k_{21}[k_{22}(\varphi_d - \varphi) - p] + k_\psi sat(\psi - \psi_d) + k_{\Delta y} sat(\Delta y) \tag{13}$$

where Δy denotes the lateral distance error.

4. Teleoperation

The control of a MUAV can be apprehended in a general teleoperation context involving telesupervision and telepresence. The first aspect was introduced in the

precedent section through the control laws (designed and being implemented) which will allow the operator to give high level orders (altitude and heading) and to supervise the flight. The second aspect deals with the idea that the more the operator is immersed in the distant teleoperator environment the more complex can be the distant task for a fixed teleoperator automation degree [6].
The effect of those elements on task execution can be qualitatively represented by the following Figure 3

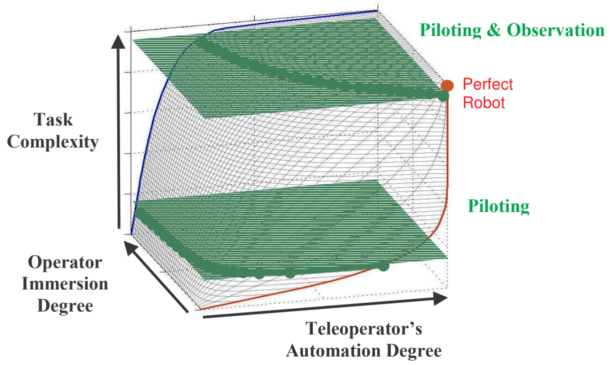

Figure 3: Qualitative link between operator immersion, teleoperator automation and task complexity

Considering the teleoperator can now perform part of the tasks (i.e. straightforward level flight) more or less autonomously (attitude, 2D guidance), human operator can be immersed in order to execute more sophisticated tasks such as observation.
As a human being gets more than 90% of his perception information via vision [5], the telepresence part of our study focuses on the several viewing means which can be used with the modified fixed wing model aircraft:

-classical direct viewing: the pilot is standing on the ground looking directly at the MUAV.

-embedded monoscopic camera viewing: the pilot sees the distant environment through an embedded camera which can be placed in several locations on the MUAV (on or under the aircraft, in front of (see Figure 4) or back of the propeller…). At the ground, the display can be a classical color screen or a 2D head mounted display.

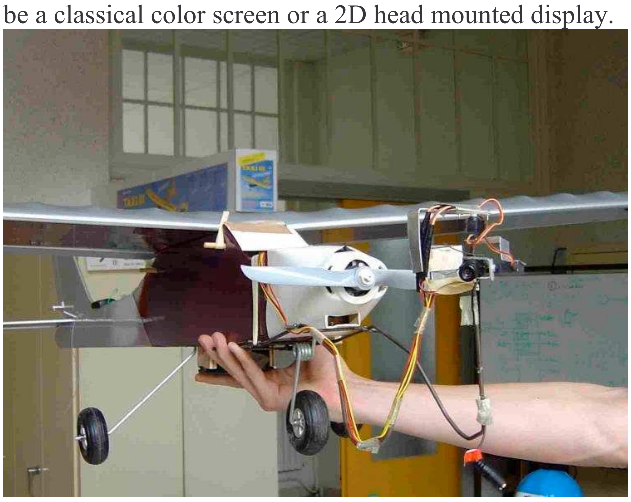

Figure 4: The 2 DOF monoscopic video camera embedded in the front of the propeller.

-embedded stereoscopic camera viewing: the pilot has now a three dimensional perception of the distant environment threw a 3D head mounted display.

The two first means, direct viewing, monoscopic embedded camera on video screen and immersive glasses, were tested in flight, 3D viewing has been tested in the laboratory and is being implemented. An experiment involving several pilots with different trainings is being conducted in order to evaluate objectively and subjectively different teleoperation configurations.

5. Results

Our avionic system, introduced in section 2.1, has been successfully tested as a telemetry tool during real flight tests. A GPS trajectory example of a manual flight is given in the Figure 5.

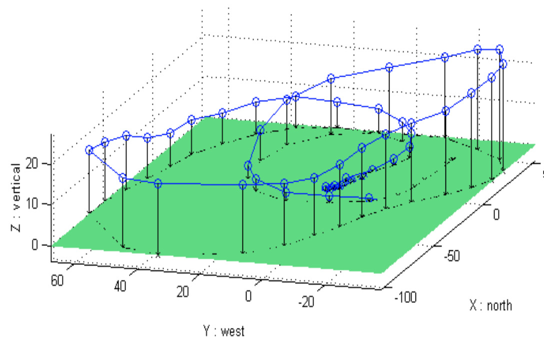

Figure 5: GPS flight trajectory

The implementation of the attitude estimation algorithm, presented in section 2.2, was validated. The attitude was visualized in real time with a 7Hz refreshment rate (see Figure 6) in the laboratory.

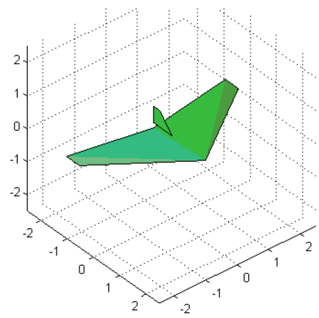

Figure 6: Real Time 3D attitude visualization

On the other hand, Figure 7 shows the convergence of the algorithm. Only the gyrometers output (scale °/sec) is drawn but accelerometers and magnetosensors are included into the algorithm. One can see that the gyro output is not centered at 0.

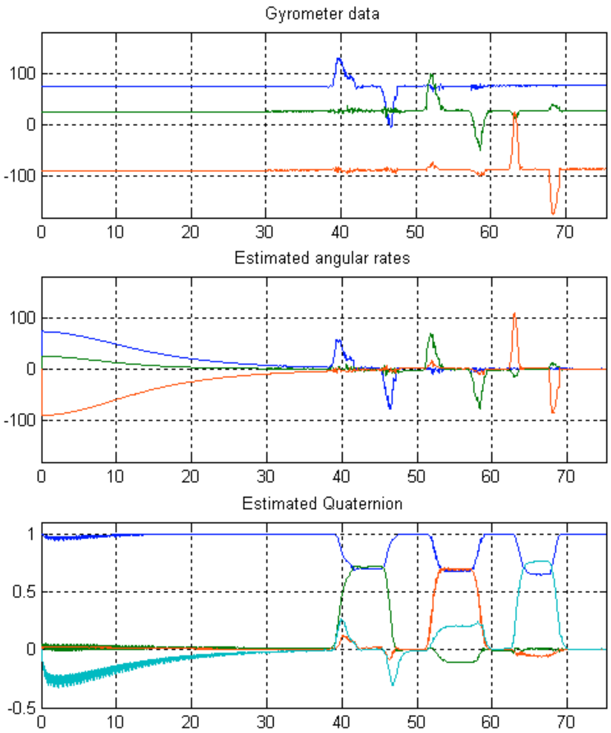

Figure 7: Attitude estimation algorithm convergence

About 30s of convergence is necessary to estimate the gyro drift. One can see the estimated angular rates that converge to 0 °/s after 30s. At 38s a few +/–90° rotations are made along the three axes and the attitude quaternion is estimated.

Figure 8: Embedded camera view

The remote control through an embedded camera was conducted and validated. Figure 8 illustrates the pilot view of the distant environment. Several flights were realized using the remote viewing configuration and validated the remote viewing system. Straight levelled flight, turn and landing were correctly executed.

6. Conclusion

This paper first described the avionics developed for a Miniature Unmanned (and/or Uninhabited) Aerial Vehicle and some applications for such a system from telemetry to teleoperation. Acquisition of the flight parameters was used to estimate the aircraft's attitude through an Extended Kalman Filter. We then introduced a simplified model of the aircraft used to design the attitude and navigation control laws. This automation potentiality was later included in a general teleoperation consideration where we presented the human operator immersion in the distant environment through embedded camera.

The telemetry avionic system was tested in real flight and provided good results. It has been used to implement and validate the attitude estimation algorithm. Finally we confirmed that it is possible to control the MUAV in the situation that the operator can not see it directly using an embedded camera.

The future work on this project will emphasize the implementation of autonomous navigation and operator immersion through experiments involving several MUAV pilots with different training levels, in order to evaluate objectively and subjectively different teleoperation configurations.

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