Dynamic modeling and intuitive control strategy for an "X4-flyer"

N. Guenard[†],T. Hamel[‡],V. Moreau[†]
[†], CEA/List, F92265 Fontenay-Aux-Roses, France, vincent.moreau@cea.fr, guenardn@zoe.cea.fr
[‡] I3S, UNSA-CNRS, 2000 route des Lucioles, 06903 Sophia Antipolis France, thamel@i3s.unice.fr,

June 6, 2005

Abstract

This paper describes an intuitive control strategy for a four rotors vertical take-off and landing (VTOL) remote-controlled vehicle known as the "X4-flyer". A quasi-stationary flight dynamic modeling including gyroscopic effects due to the rotors dynamics is proposed. A nonlinear controller simplifying the vehicle manipulation and insuring quasi-stationary flight conditions is developed. The approach considers that the rotor dynamics are negligible compared to the body dynamics and develops a control law based on saturating the linear dynamics for bounding the vehicle orientation and limiting it to very small values. Experimental results show the success of this approach.

1 Introduction

The interest for autonomous unmanned aerial vehicles has grown in the recent years, particularly for military purposes. Autonomous VTOL vehicles allowing stationary flight have a particular interest. Significant research effort has been directed towards the development of autonomous scale-model helicopters due to their high payload-to-power ratio [1, 3, 8]. Helicopters, however, are extremely dangerous in practice due to the exposed rotor blades. Very little has been done on the development of secure platforms [2]. Such platforms have a considerable potential for surveillance and inspection roles in dangerous or awkward environments. One can imagine the use of such vehicles in order to explore a contaminated area before a human intervention for example. However, contrary to a remote-controlled car, the manual control of a flying system such as an X4-flyer with a joystick needs several hours of training before being able to succeed. Consequently, we are interested in the assisted manual control of the X4-flyer in order to allow a neophyte to control it without difficulty. In this paper, we propose to design an embedded controller using velocity control-inputs issued from a remote and an inertial measurement unit to stabilize the displacement velocities through the roll and pitch correction. However, on board calculators, computing in real time the control algorithms, have nevertheless a limited processing power. Consequently, the control algorithms have to be simple and robust to achieve their successful implementation in a real system.

Figure 1: The X4-flyer

More precisely, we propose in this paper to elaborate a simple nonlinear control law of an "X4-flyer" unmanned aerial vehicle (cf. figure 1) insuring quasi-stationary flight by bounding the vehicle orientation and limiting it to very small values. In contrast to classical remote-control orders consisting in sending forces and torques to the vehicle, the proposed approach uses intuitive orders such translational velocities and yaw angle as desired inputs sent from the ground to the aerial vehicle.

The paper is arranged into five sections, including the present introduction. Section 2 presents the X4-flyer dynamics. Section 3 derives a Lyapunov control function of the vehicle and analyses the stability of the closed-loop system. Section 4 presents some experimental results and finally section 5 provides a short summary of conclusions.

2 Dynamic model

The X4-flyer is an omnidirectional VTOL (vertical take off and landing) vehicle ideally suited for stationary and quasi-stationary flight conditions. The control of an X4-flyer is achieved by the differential control of the thrust generated by each propeller. Up/down motion is controlled by collectively increasing or decreasing the thrust of all four motors. The thrust difference between the forward and the rear rotor creates a pitch torque inducing translation forward/rear motion. In the same way, the left/right translational motion is obtained by

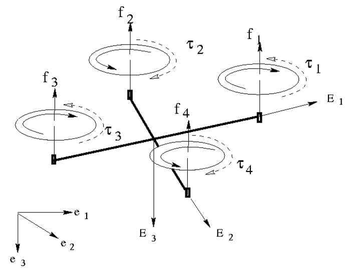

Figure 2: The four rotors generating the collective thrust

the differential thrust of the right and the left rotors. To finish, let's see the yaw control. When a propeller turns, it has to overcome air resistance. The reactive torque acts on the blades in the opposite direction to the rotation. In the X4-flyer, both sets of front-rear and left-right motors turn in opposite directions (cf Figure 2). Moreover, the reactive torque is essentially a function of the propeller rotational velocity. Consequently, controlling the X4-flyer yaw is equivalent to control the sum of reactive torques. As long as all rotors produce the same reactive torque (all rotors turn at the same speed), the sum of all reactive torques is zero and there is no yaw motion. If one set of rotors increase its speed, the induced torque will cause the X4-flyer to rotate in the direction of the induced torque. The X4-flyer modeling is inspired from [**?**, 4, 6]. In order to model the system dynamics, we define two frames shown figure 2,

- $\mathcal{R}_i(e_1, e_2, e_3)$ is an inertial frame attached to the earth, relative to a fixed origin. It is assumed to be Galilean.
- $\mathcal{R}_a(E_1, E_2, E_3)$ is a body fixed frame attached to the center of mass of the vehicle.

Define the attitude R of the body fixed frame with respect to the inertial frame by means of Euler angles ξ =(yaw(ϕ),pitch (θ) and roll (ψ)).

$$R = \begin{pmatrix} c_\theta c_\phi & s_\psi s_\theta c_\phi - c_\psi s_\phi & c_\psi s_\theta c_\phi + s_\psi s_\phi \\ c_\theta s_\phi & s_\psi s_\theta s_\phi + c_\psi c_\phi & c_\psi s_\theta s_\phi - s_\psi c_\phi \\ -s_\theta & s_\psi c_\theta & c_\psi c_\theta \end{pmatrix} \quad (1)$$

where the following shorthand notations for trigonometric functions are used: c_α=cos(α), s_α=sin(α), t_α=tan(α).

The position of the center of mass of the vehicle with respect to the inertial frame $\mathcal{R}_i$ is denoted x. Let v (resp. Ω) denotes the linear (resp. angular) velocity of center of mass expressed in the inertial frame $\mathcal{R}_i$ (resp. body fixed frame $\mathcal{R}_a$). Let W_ξ the matrix such that: $\dot{\xi} = W_\xi \Omega$,

$$W_\xi := \begin{pmatrix} -s_\theta & 0 & 1 \\ c_\theta s_\psi & c_\psi & 0 \\ c_\theta c_\psi & -s_\psi & 0 \end{pmatrix}. \quad (2)$$

Newton's equations of motion yield to the following dynamic model for the motion of the airframe.

$$m\dot{v} = mge_3 + F \quad (3)$$

$$\mathbf{I}\dot{\Omega} = -\Omega \times \mathbf{I}\Omega + C \quad (4)$$

where m is the mass of the airframe and $\mathbf{I}$ its inertia matrix expressed in $\mathcal{R}_a$. Let F represents the sum of the thrust provided by the four propellers, defined in $\mathcal{R}_i$. Let C represents torques acting on the rigid body, expressed in $\mathcal{R}_a$. In this approach, we consider that C is composed of the gyroscopic torque called Γ_g and the control torque Γ derived from differential thrusts. Let us write

$$C = \Gamma_g + \Gamma \quad (5)$$

The lift f_i generated by the rotor i turning at the speed ω_i in free air may be expressed as

$$f_i = -b\omega_i^2 E_3 \quad (6)$$

where b is a positive constant depending on air density, rotor blades collective pitch and geometric blade characteristics. The reactive torque due to the rotor drag generated by a rotor in free air may be modeled as

$$\tau_i = -\kappa\omega_i|\omega_i|E_3 \quad (7)$$

The positive constant κ depends on air density, rotor blades collective pitch and geometric blade characteristics. Define now the rotation dynamic of a rotor.

$$\mathbf{I}_r\omega_i = u_i - \tau_i \quad (8)$$

where $\mathbf{I}_r$ represents the inertia of the rotor i around its rotation axis and $\mathbf{u}_i$ the rotor torque.

With the above consideration and considering that propellers have a symmetrical disposition around the gravity center G with d as offset of each propeller from the center of mass, we can write

$$\begin{pmatrix} T \\ \Gamma_1^1 \\ \Gamma_1^2 \\ \Gamma_1^3 \end{pmatrix} = \begin{pmatrix} b & b & b & b \\ 0 & db & 0 & -db \\ db & 0 & -db & 0 \\ -\kappa & \kappa & -\kappa & \kappa \end{pmatrix} \begin{pmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{pmatrix} = A \begin{pmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{pmatrix} \quad (9)$$

Consequently, the expression of F in $\mathcal{R}_i$ is

$$F = -TRE_3 \quad (10)$$

Each rotor may be considered as a rigid disk rotating around the axis E_3 in the body fixed frame with angular velocity ω_i. The axis of rotation of the rotor is itself moving with the angular velocity of the airframe.

If the inertia of the rotor is defined by $\mathbf{I}_r$, the behavior of this torque is defined by

$$\Gamma_g = \sum_{i=0}^{4} \sigma \times \Omega \tag{11}$$

where $\sigma_i = \mathbf{I}_r \omega_i E_3$ being the kinetic torque of the rotor i. Knowing that $E_3 \times \Omega = -\Omega \times E_3$, one can rewrite the expression of Γ_g as follows:

$$\Gamma_g = -\sum_{i=1}^{4} I_r(\Omega \times E_3)\omega_i.$$

As a conclusion, the dynamic model of the "X4-flyer" is

$$\dot{\xi} = v \tag{12}$$

$$\dot{v} = ge_3 - \frac{1}{m}TRE_3 \tag{13}$$

$$\dot{R} = R\text{sk}(\Omega), \tag{14}$$

$$\mathbf{I}\dot{\Omega} = -\Omega \times \mathbf{I}\Omega + \Gamma_g + \Gamma. \tag{15}$$

$$\mathbf{I}_r \omega_i = u_i - \tau_i \tag{16}$$

where the notation $\text{sk}(\Omega)$ denotes the skew-antisymetric matrix such that $sk(\Omega)v = \Omega \times v$ for the vector cross-product $\times$ and any vector v.

In the control section (Sec. 3) we will suppose that the rotor dynamics are negligible compared to air frame dynamics. Consequently, we will consider the components of the vector $\varpi = (\omega_1^2 ... \omega_4^2)$ as control inputs instead of torques of propellers.

3 Control law

In this section, we propose to develop a nonlinear controller for the above dynamics based on saturating the linear dynamics for bounding the vehicle orientation and limiting it to very small values. The control strategy is based on Lyapunov function conception using backstepping techniques [5].

The control problem considered consists in finding a control action $\varpi = (\omega_1^2 ... \omega_4^2)$ from equation (9) depending only on the state measurements (v, R, Ω, ϖ) and parameters of the desired trajectory (v_d, ϕ_d). In order to pilot the X4- flyer, we will separate the control design into two parts: translational and rotational dynamics control designs.

- For the translational dynamics the thrust will be assigned and the full desired orientation will be defined.

- For the rotational dynamics the control torques are assigned.

From the assigned thrust and torques, the speed (ω_i) of each propeller is obtained using equation 9, the desired orientation speed (ω_i) of the propeller 'i'. Each propeller speed will be then controlled with fast transient to obtain the desired orientation speed (ω_i).

3.1 T and R_d compute

Firstly, we would like to have the velocity of the X4-flyer converging to the desired velocity. Let define the error function

$$\varepsilon = v - v_d \tag{17}$$

At this point of the study, let S_1 be the first storage function in order to stabilize the translation dynamics.

$$S_1 = \frac{1}{2}m||\varepsilon||^2 \tag{18}$$

Differentiating S_1 and substituting for (Eq 13), it yields

$$\dot{S}_1 = \varepsilon^T(mge_3 - TRE_3 - m\dot{v}_d) \tag{19}$$

If TRE_3 is considered as a control vector for the translational dynamics, it is possible to propose a control vector assignment allowing an exponential convergence of the error ε towards zero. However this type of convergence is not recommended when the error ε is important. This is due to the fact that the proposed model is no more realistic. In this case, small gain control technique must be employed [9]. This approach seems particulary well adapted to our problem. Indeed, if the translation dynamics are saturated, the tilting angle of the vehicle is also saturated. Therefore, we define the continuous saturation function $\text{sat}(\epsilon)$ as:

- $x^T \text{sat}(x) > 0$, for all $x \neq 0$,
- $\text{sat}(x) = \text{vect}(\text{sat}(x_i))$,
- $\text{sat}(x_i) < M_i$ for all $x_i \in \mathbb{R}$ and $\text{sat}(x_i) = x_i$ for all components $|x_i| \leq M_i$.

Considering TRE_3 as a virtual control input, stabilize S_1 consists in choosing an expression of TRE_3 in order to have $\dot{S}_1$ negative. To this end, we define TRE_3 desired as

$$(TRE_3)_d = -m\dot{v}_d + mge_3 + k_1\text{sat}(\varepsilon) \tag{20}$$

where k_1 is a positive gain.

Remark 3.1 *The saturation on ε allows us to limit the tilting angle of the "X4-flyer". The tilting angle limit can be regulated by exploiting the saturation parameter M_i and the control gain k_1.*

Assuming that the rotor dynamics are negligible compared to the airframe dynamics, we assume that the thrust T is immediately reached and therefore:

$$(TRE_3)_d = T(RE_3)_d, \tag{21}$$

At this step of the approach, we can dissociate the translation dynamics from the rotation dynamics. Indeed, $(RE_3)_d$ provides the tilting angle of the body. By adding the desired yaw one can compute the full desired rotation matrix R_d.

Introducing Eq. 21 in Eq. 19, it yields

$$\dot{S}_1 = -k_1 \varepsilon^T \mathrm{sat}(\varepsilon) + \varepsilon^T (T R_d E_3 - T R E_3) \tag{22}$$

Moreover, knowing that R is an orthogonal matrix ($R^{-1} = R^T$), the derivative of the first storage function S_1 becomes:

$$\dot{S}_1 = -k_1 \varepsilon^T \mathrm{sat}(\varepsilon) - T \varepsilon^T (R R_d^T - I_3) R_d E_3 \tag{23}$$

Let define $\tilde{R} = R R_d^T$ as the deviation between the current and desired orientations.

As $||R_d E_3|| = 1$ and consequently $||T R_d E_3|| = T$, it yields

$$T = || - m(\dot{v}_d - g e_3) + k_1 \mathrm{sat}(\varepsilon)|| \tag{24}$$

$$R_d e_3 = \frac{-m(\dot{v}_d - g e_3) + k_1 \mathrm{sat}(\varepsilon)}{T} \tag{25}$$

As T (Eq. (24)) is bounded, we can establish the asymptotic convergence of S_1 to zero if an exponential convergence of $\tilde{R}$ to zero is guaranteed (cf. theorem 3.2).

3.2 Stabilization of the rotation dynamics

The next stage of the control design involves controlling the attitude dynamics such that the error $(\tilde{R} - I_3)$ is minimized. Designing a controller to stabilize the above term is a difficult problem. Note however that the Frobinus norm of the rotation error [7, 4] is:

$$||\tilde{R} - I_3||_F = 2\sqrt{2}||\tilde{\eta}||,$$

where $\tilde{\eta}$ is the quaternion vector of the angular deviation $\tilde{R}$.

Based on the above development, the attitude control objective is achieved when $\tilde{\eta}$ converges to 0. Consequently, we are going to employ quaternions in order to represent the angular deviation instead of Euler angles (yaw (ϕ),pitch (θ) and roll (ψ)). Quaternions will be written with their geometric form. As a consequence, a rotation matrix R defined by a rotation α around the unit vector u is represented by the quaternion Q of which the real part is $\tilde{\eta}_0 = \cos\frac{\alpha}{2}$ and the imaginary part is $\tilde{\eta} = \sin\frac{\alpha}{2}u$. If $\tilde{\eta}$ is associated to the angular deviation $\tilde{R}$, we obtain

$$\tilde{R} = (\tilde{\eta}_0^2 - ||\tilde{\eta}||^2) I + 2\tilde{\eta}\tilde{\eta}^T + 2\tilde{\eta}_0 \mathrm{sk}(\tilde{\eta}) \tag{26}$$
$$\text{avec } ||\tilde{\eta}|| + \tilde{\eta}_0^2 = 1$$

Differentiating $\tilde{\eta}$, [7](pg. 74), it comes:

$$\dot{\tilde{\eta}} = \frac{1}{2}(\tilde{\eta}_0 I + \mathrm{sk}(\tilde{\eta}))\tilde{\Omega}, \qquad \dot{\tilde{\eta}}_0 = -\frac{1}{2}\tilde{\eta}^T \tilde{\Omega} \tag{27}$$

where

$$\tilde{\Omega} = R_d(\Omega - \Omega_d) \tag{28}$$

Based on this result, the attitude control objective consists now to drive $\tilde{\eta}$ to zero. We introduce at this stage of the study, the backstepping procedure. Let W be a storage function

$$W = \frac{1}{2}||\tilde{\eta}||^2 \tag{29}$$

Differentiating W and introducing Eq. 27, we obtain

$$\dot{W} = \frac{1}{2}\tilde{\eta}_0 \tilde{\eta}^T \tilde{\Omega} \tag{30}$$

In order to exponentially stabilize $\tilde{\eta}$ to zero, we consider the following virtual input:

$$\tilde{\Omega}^v = -2k_\eta \tilde{\eta}_0 \tilde{\eta}, \quad k_\eta > 0$$

Let define $\sigma = \tilde{\Omega} - \tilde{\Omega}^v$ and consider the following storage function

$$S_2 = W + \frac{\gamma}{2}||\sigma||^2, \quad \gamma > 0 \tag{31}$$

Knowing that $\dot{R}_d = R_d \mathrm{sk}(\Omega_d)$ and introducing Eq. 27 and Eq. 28 it yields:

$$\dot{S}_2 = -k_\eta \tilde{\eta}_0^2 ||\tilde{\eta}||^2 + \frac{1}{2}\tilde{\eta}_0 \tilde{\eta}^T \sigma + \gamma\sigma^T \Big(R_d(\dot{\Omega} - \dot{\Omega}_d) + R_d \mathrm{sk}(\Omega_d) R_d^T \tilde{\Omega} + k_\eta \Big((\mathrm{sk}(\tilde{\eta}) + \tilde{\eta}_0 I_3)\, \tilde{\Omega}\tilde{\eta}_0 - \tilde{\eta}^T \tilde{\Omega}\tilde{\eta} \Big) \Big). \tag{32}$$

At this step of the approach, we can remark that the relation between $\dot{\Omega}$ and the torque control Γ is algebraic (cf. Eq. 15). Choosing Γ as follow:

$$\Gamma = \mathrm{sk}(\Omega)\mathbf{I}\Omega - \Gamma_g + \frac{\mathbf{I}}{\gamma}(\dot{\Omega}_d + R_d^T(-k_\sigma \sigma - \frac{1}{2}\tilde{\eta}_0 \tilde{\eta} + k_\eta \tilde{\eta}^T \tilde{\Omega}\tilde{\eta} - (R_d \mathrm{sk}(\Omega_d) R_d^T + k_\eta \tilde{\eta}_0^2 I_3 + k_\eta \tilde{\eta}_0 \mathrm{sk}(\tilde{\eta}))\tilde{\Omega})), \quad k_\sigma > 0 \tag{33}$$

it comes,

$$\dot{S}_2 = -k_\eta \tilde{\eta}_0^2 ||\tilde{\eta}||^2 - k_\sigma ||\sigma||^2 \tag{34}$$

Knowing the global thrust T and the vector of torques Γ to apply, we have now to control the motors. Since the relationship between (T, Γ) and ϖ is algebraic, a proportional corrector can be used. However, to simplify, the analysis, we assume that a high gain is used in order to consider that the computed thrust T and the torque Γ as inputs of the controller.

Theorem 3.2 *Consider the dynamic system defined by Eq. 12 - Eq. 15, the thrust control T Eq. 24, the torque vector Γ Eq. 33. Let v_d be a bounded desired* *velocity. Let $\delta << 1$ be a positive constant. Then for all initial conditions $(\varepsilon(0), \tilde{\eta}(0), \sigma(0))$ such that:*

$$\tilde{\eta}_0 > \delta, \ \gamma \leq \frac{\delta^2}{\sigma(0)^2} \tag{35}$$

The exponential stability of $\tilde{R}$ and the asymptotical convergence of ε to zero are guaranteed.

Proof 3.3 *Firstly, recall the expression of the storage function S_2 (Eq. 31) and its derivative (Eq. 34):*

$$\begin{aligned} S_2 =& \frac{1}{2}||\tilde{\eta}||^2 + \frac{\gamma}{2}||\sigma||^2 \\ \dot{S}_2 =& -k_\eta \tilde{\eta}_0^2 ||\tilde{\eta}||^2 - k_\sigma ||\sigma||^2 \end{aligned}$$

It is obvious that an exponential stabilization of S_2, guarantees an exponential stabilization of $\tilde{\eta}$ to zero and $\tilde{\eta}_0$ to ± 1 (cf. Eq. 26). In order to show that $\tilde{\eta}_0$ converges to $+1$ to avoid the ambiguity, we are going to introduce the condition Eq. 35 of the theorem in the expression of S_2 (Eq. 31). It comes,

$$S_2(0) < \frac{1}{2}$$

This ensures that $\tilde{\eta}_0$ is never equal to zero and converges to $+1$.

Let us bound the expression of the derivative of S_1 Eq. (23),

$$\dot{S}_1 \leq -k_1 \varepsilon \text{sat}(\varepsilon) + 2\sqrt{2}T||\varepsilon||||\tilde{\eta}|| \tag{36}$$

Knowing that T is bounded and that $\tilde{\eta}$ is bounded by an exponential function, it comes

$$\dot{S}_1 \leq -k_1 \varepsilon \text{sat}(\varepsilon) + ||\varepsilon||\sqrt{2}\beta e^{-\alpha t}, \ \ \beta = 2T \tag{37}$$

From this relation, we note that there is a finite time t_s from which $\text{sat}(\varepsilon) = \varepsilon$. i. e., for all $t \geq t_s$:

$$\begin{aligned} \dot{S}_1 &\leq -k_1||\varepsilon||^2 + \sqrt{2}\beta||\varepsilon||e^{-\alpha t}, \ \ \forall t \geq t_s && (38) \\ &\leq -2k_1 S_1 + 2\beta\sqrt{S_1}e^{-\alpha t} && (39) \end{aligned}$$

In order to simplify this relation, we introduce a new variable $S = \sqrt{S_1}$ and rewrite Eq. 39 as follows:

$$\dot{S} = \frac{\dot{S}_1}{2\sqrt{S_1}} \leq -k_1 S + \beta e^{-\alpha t}, \ \forall t \geq t_s,$$

or

$$\dot{S} \leq -k_1 S + \frac{\beta}{\sqrt{2}} e^{-\alpha t}, \ \ \forall t \geq t_s$$

Now we can show that

$$S(t) \leq e^{-k_1(t-t_s)} S_1(t_s) + \beta \int_{t_s}^{t} e^{-k_1(t-\mu)} e^{-\alpha\mu} d\mu, \ \forall t \geq t_s$$

converges to zero and ensures the convergence of ε.

Figure 3: The X4-flyer in flight

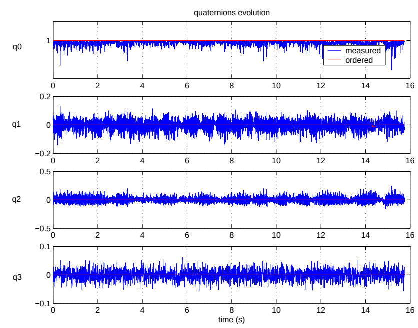

Figure 4: Evolution of the quaternion representing the attitude of the vehicle in stationary flight

4 Experimentation results

In order to validate the controller elaborated above, we have implemented it on the experimental X4-flyer built in our laboratory (fig 1). The vehicle is equipped with an inertial measurement unit (IMU) which is constituted of 3 MEMS accelerometers and 3 angular rate sensors to provide the components of the gravity in the body frame. A Digital Signal Processing is embeded and performs all the computations to stabilize the system from the IMU data. The 4 propellers are controlled in velocity loops.

To show the experimental behaviour of the system, we present two types of experimentation. In both of them, flight parameters are stored in the DSP board.

In the first experimentation, the behaviour during stationary flight conditions (the operator doesn't move the joystick) is presented. On figure 4 we have plotted the set point (horizontal attitude) and the recorded estimated attitude during flight computed from the row IMU data. We can see that the raw measured quaternion agrees well with the set point attitude; however, the remaining noise is essencialy caused by the mechanical vibrations of the body frame during the flight. Nevertheless, the results show the very good behaviour of the attitude stabilization in stationary flight conditions.

In the second experimentation, we present the behaviour of the system when the set points are modified by the pilot. On figure 5 and 6, we can see that the or-

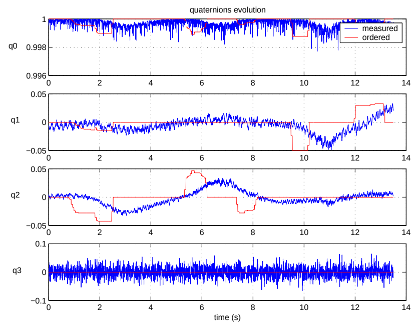

Figure 5: Evolution of the quaternion representing the attitude of the vehicle in ordered flight

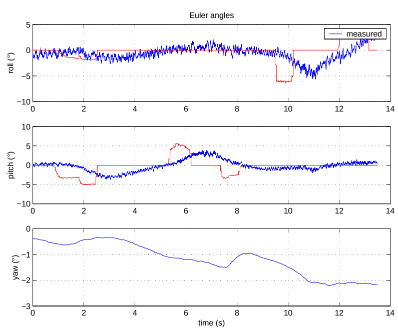

Figure 6: Evolution of the Euler angles during the second experimentation

dered quaternion is modified in roll and pitch. The measured quaternion follows the changes with some reasonable delay caused by the dynamic properties of the airframe and the timing of our controller which is limited by the reasonance modes of the mechanical structure. It is remarquable that the changes in roll and pitch attitude affect very little the yaw of the system.

5 Conclusion

In this paper, we have proposed a dynamic modeling and a stabilization control algorithm for a mini-rotorcraft vehicle having four vertical rotors known as an "X4-flyer". The purpose of this controller is to control the translational velocities of the vehicle as well as the yaw angle. The simplicity of the proposed control law and the use of quaternions have allowed us to implement the proposed controller in an embedded calculator for which the computing power is limited. Flight experimentations show the efficiency of the proposed controller for the flight stability of such a vehicle.

6 Acknowledgements

This work has been realised with the support of the french company "WANY Robotics www.wanyrobotics.com " in the frame of a CEA-WANY Phd grant. The authors also thank the French robotic research program ROBEA - CNRS for its support in the project.

References

[1] O. Amidi, T. Kanade, and R. Miller. Vision-based autonomous helicopter research at Carnegie Mellon robotics institute (1991-1998). In M. Vincze and G. D. Hager, editors, *Robust vision for vision-based control of motion*, chapter 15, pages 221–232. IEEE press and SPIE Optical Engineering press, New York, USA, 1999.

[2] J. Fleming and Troy Jones. Improving control system effectiveness for ducted fan vtol uavs operation in crosswinds. In *2nd AIAA "Unmanned Unlimited" Systems, Technologies and Operations-Aerospace*, San Diego, California, 2003.

[3] E. Frazzoli, M. A. Dahleh, and E. Feron. Real-time motion planning for agile autonomous vehicles. *AIAA Journal of Guidance, Control, and Dynamics*, 5(1):116–129, 2002.

[4] T. Hamel, R. Mahony, R. Lozano, and J. Ostrowski. Dynamic modelling and configuration stabilization for an X4-flyer. In *International Federation of Automatic Control Symposium, IFAC 2002*, Barcelona, Spain, 2002.

[5] M. Krstic, I. Kanellakopoulos, and P. V. Kokotoviv. *Nonlinear and adaptive control design*. American Mathematical Society, Rhode Islande, USA, 1995.

[6] R. Mahony and T. Hamel. Robust trajectory tracking for a scale model autonomous helicopter. *To appear in the International Journal of Non-linear and Robust Control*, 2003.

[7] R. M. Murray, Z. Li, and S. S. Sastry. *A Mathematical Introduction to Robotic Manipulation*. CRC Press, Inc., Florida, U.S.A., 1994.

[8] S. Saripalli, J.F. Montgomery, and G.S. Sakhatme. Vision based autonomous landing of an unmanned aerial vehicle. In *Proceedings of International Conference of Robotics and Automation, ICRA2002*, Wahsington DC, Virginia, USA, 2002.

[9] A. R. Teel. A nonlinear small gain theorem for the analysis of control systems with saturation. *IEEE Transactions on Automatic Control*, 41(9):1256–1270, 1996.