# MODELLING AND STABILIZING CONTROL LAWS DESIGN BASED ON BACKSTEPPING FOR AN UAV TYPE-QUADROTOR

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Abstract: In this paper; we are interested principally in dynamic modelling of the four rotor mini aircraft named as a quadrotor while taking into account the high-order nonholonomic constraints as well as the various physical phenomena, which can influence the dynamics of a flying structure. These permit us to introduce a new state-space representation. We present also the development and the synthesis of a recursive control algorithm based on backstepping technique ensuring Lyapunov stability and desired tracking trajectories. Finally simulation results are also provided in order to illustrate the performances of the proposed controller.

Keywords: Dynamic modelling, High-order nonholonomic constraints, Backstepping.

## 1 INTRODUCTION

Unmanned aerial vehicles (UAV) have shown a growing interest thanks to recent technological projections, especially those related to instrumentation. They made possible the design of powerful systems (mini drones) endowed with real capacities of autonomous navigation at reasonable cost.

Despite the real progress made, researchers must still deal with serious difficulties, related to the control of such systems, particularly, in the presence of atmospheric turbulences. In addition, the navigation problem is complex and requires the perception of an often constrained and evolutionary environment, especially in the case of low-altitude flights.

Nowadays, the mini-drones invade several application domains (Hamel, et al., 2002): safety (monitoring of the airspace, urban and interurban traffic); natural risk management (monitoring of volcano activities); environmental protection (measurement of air pollution and forest monitoring); intervention in hostile sites (radioactive workspace and mine clearance), management of the large infrastructures (dams, high-tension lines and pipelines), agriculture and film production (aerial shooting).

In contrast to terrestrial mobile robots, for which it is often possible to limit the model to kinematics, the control of aerial robots (quadrotor) requires dynamics in order to account for gravity effects and aerodynamic forces (Guenard, et al., 2004).

In (Lozano, et al., 2004), authors propose a control-law based on the choice of a stabilizing Lyapunov function ensuring the desired tracking trajectories along (*X*, *Z*) axis and roll angle. However, they do not take into account nonholonomic constraints. In Bouabdallah and Siegwart, (2005); do not take into account frictions due to the aerodynamic torques nor drag forces or nonholonomic constraints. They propose a control-law based on backstepping in order to stabilize the complete system (i.e. translation and orientation). In (Tayebi and Mcgilvray, 2004), authors take into account the gyroscopic effects and show that the classical model-independent PD controller can stabilize asymptotically the attitude of the quadrotor aircraft. Moreover, they used a new Lyapunov function, which leads to an exponentially stabilizing controller based upon the $PD^2$ and the compensation of coriolis and gyroscopic torques. While in (Derafa, et al., 2006) the authors develop a PID controller in order to stabilize altitude.

In this paper, based on the vectorial model form presented in (Derafa, et al., 2006) we are interested principally in the modelling of quadrotor to account for various parameters which affect the dynamics of a flying structure such as frictions due to the aerodynamic torques, drag forces along (*X, Y, Z*) axis and gyroscopic effects which are identified in (Derafa, et al., 2006) for an experimental quadrotor and for high-order nonholonomic constraints (S. Yazir, et al., 2007). Consequently, all these parameters supported the setting of the system under more complete and more realistic new state-space representation, which cannot be found easily in the literature being interested in the control laws synthesis for such systems.

Then, we present a control technique based on the development and the synthesis of a recursive

algorithm by backstepping ensuring the Lyapunov stability and desired tracking trajectories expressed in term of the center of mass coordinates along *(X, Y, Z)* axis and yaw angle, while the desired roll and pitch angles are deduced from nonholonomic constraints unlike to (Bouabdallah and Siegwart, 2005).
Finally, all synthesized control laws are validated by simulations for the complete model.

# 2 MODELLING

## 2.1 Quadrotor Dynamic Modelling

Fig. 1: Typical example of a Quadrotor (OS4 of EPFL).

The aerial robot under consideration consists of a rigid cross frame equipped with four rotors (Tayebi and Mcgilvray, 2004) as shown in figure 1. The up-down motion is achieved by increasing or decreasing the total thrust while maintaining an equal individual thrust. The forward/ backward, left/ right and the yaw motions are achieved through a differential control strategy of the thrust generated by each rotor. In order to avoid the yaw drift due to the reactive torques, the quadrotor aircraft is configured such that the set of rotors (right-left) rotates clockwise and the set of rotors (front-rear) rotates counter-clockwise. There are no direction changes in the rotors rotation. If a yaw motion is desired, one has to reduce the thrust of one set of rotors and increase the thrust of the other set while maintaining the same total thrust to avoid an up-down motion. Hence, the yaw motion is then realized in the direction of the induced reactive torque. On the other hand, forward and backward motion are achieved by pitching in the desired direction by increasing the front (rear) rotor thrust and decreasing the rear (front) rotor thrust to maintain the total thrust. Finally, a sideways motion is achieved by rolling in the desired direction by increasing the left (right) rotor thrust and decreasing the right (left) rotor thrust to maintain the total thrust. Let $E(O,X,Y,Z)$ denote an inertial frame, and $B(o',x,y,z)$ denote a frame rigidly attached to the quadrotor as shown in figure 2.

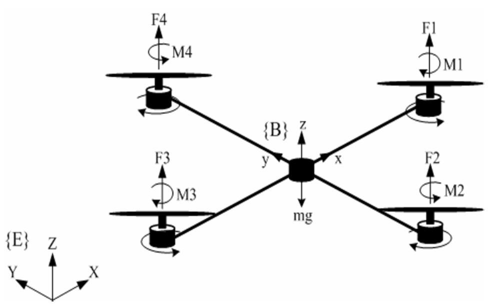



Fig. 2 : quadrotor configuration.

We will make the following assumptions:

- The quadrotor structure is rigid and symmetrical.
- The center of mass and *o'* coincides.
- The propellers are rigid.
- Thrust and drag are proportional to the square of the propellers speed.

Under these assumptions, it is possible to describe the fuselage dynamics as that of a rigid body in space to which come to be added the aerodynamic forces caused by the rotation of the rotors.
Using the formalism of Newton-Euler, the dynamic equations are written in the following form:

$$\begin{cases} \dot{\xi} = v \\ m\ddot{\xi} = F_f + F_t + F_g \\ \dot{R} = RS(\Omega) \\ J\dot{\Omega} = -\Omega \wedge J\Omega + \Gamma_f - \Gamma_a - \Gamma_g \end{cases} \tag{1}$$

$\xi = [x, y, z]^T$ is the position of the quadrotor center of mass with respect to the inertial frame. $m$ is the total mass of the structure and $J \in R^{3\times3}$ is a symmetric positive definite constant inertia matrix of the quadrotor with respect to $B$.

$$J = \begin{pmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{pmatrix} \tag{2}$$

$\Omega$ is the angular velocity of the airframe expressed in $B$:

$$\Omega = \begin{pmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\phi\cos\theta \end{pmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{3}$$

In the case where the quadrotor performs many angular motions of low amplitude $\Omega$ can be assimilated to $\left[\dot{\phi}\ \dot{\theta}\ \dot{\psi}\right]^T$.
$\phi$, $\theta$ and $\psi$ are roll, pitch and yaw angles respectively.
R is the homogenous matrix transformation (Khalil, Dombre, 2002).

$$R = \begin{pmatrix} C\theta C\psi & C\psi S\theta S\phi - S\psi C\phi & C\psi S\theta C\phi + S\psi S\phi \\ C\theta S\psi & S\psi S\theta S\phi + C\psi C\phi & S\psi S\theta C\phi - C\psi S\phi \\ -S\theta & S\phi C\theta & C\phi C\theta \end{pmatrix} \tag{4}$$

Where C and S indicate the trigonometrical functions **cos** and **sin** respectively. $S(\Omega)$ is a skew-symmetric matrix. For a given vector $\Omega = [\Omega_1\ \Omega_2\ \Omega_3]^T$ it is defined as follows:

$$S(\Omega)=\begin{pmatrix} 0 & -\Omega_3 & \Omega_2 \\ \Omega_3 & 0 & -\Omega_1 \\ -\Omega_2 & \Omega_1 & 0 \end{pmatrix}$$

$F_f$ is the resultant of the forces generated by the four rotors.

$$F_f=\begin{pmatrix} C\phi C\psi S\theta + S\phi S\psi \\ C\phi S\theta S\psi - S\phi C\psi \\ C\phi C\theta \end{pmatrix}\sum_{i=1}^{4} F_i \tag{5}$$

$$F_i = K_p \omega_i^2 \tag{6}$$

Where $K_p$ is the lift coefficient and $\omega_i$ is the angular rotor speed.

$F_t=\left[F_{tx}, F_{ty}, F_{tz}\right]^T$ is the resultant of the drag forces along ( $X, Y, Z$ ) axis.

$$F_t=\begin{pmatrix} -K_{ftx} & 0 & 0 \\ 0 & -K_{fty} & 0 \\ 0 & 0 & -K_{ftz} \end{pmatrix}\dot{\xi} \tag{7}$$

Where $K_{ftx}, K_{fty}$ and $K_{ftz}$ are the translation drag coefficients.

$F_g$ is the gravity force.

$$F_g=\left[0\ 0\ \text{-}mg\right]^T \tag{8}$$

$\Gamma_f$ is the moment developed by the quadrotor according to the body fixed frame. It is expressed as follows:

$$\Gamma_f=\begin{bmatrix} d\left(F_3-F_1\right) \\ d\left(F_4-F_2\right) \\ K_d\left(\omega_1^2-\omega_2^2+\omega_3^2-\omega_4^2\right) \end{bmatrix} \tag{9}$$

$d$ is the distance between the quadrotor center of mass and the rotation axis of propeller and $K_d$ is the drag coefficient.

$\Gamma_a$ is the resultant of aerodynamics frictions torques.

$$\Gamma_a=\begin{bmatrix} K_{fax} & 0 & 0 \\ 0 & K_{fax} & 0 \\ 0 & 0 & K_{fax} \end{bmatrix}\begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \end{bmatrix} \tag{10}$$

$K_{fax}, K_{fay}$ and $K_{faz}$ are the aerodynamic friction coefficients around ( $X, Y, Z$ ).

$\Gamma_g$ is the resultant of torques due to the gyroscopic effects.

$$\Gamma_g=\sum_{i=1}^{4}\Omega\wedge J_r\begin{bmatrix} 0 \\ 0 \\ (-1)^{i+1}\omega_i \end{bmatrix} \tag{11}$$

Where $J_r$ is the rotor inertia.

Consequently, the complete dynamics is as follows:

$$\begin{cases} \ddot{\phi}=\frac{1}{I_x}\left\{\dot{\theta}\dot{\psi}\left(I_y-I_z\right)-K_{fax}\dot{\phi}^2-J_r\overline{\Omega}\dot{\theta}+dU_2\right\} \\ \ddot{\theta}=\frac{1}{I_y}\left\{\dot{\phi}\dot{\psi}\left(I_z-I_x\right)-K_{fay}\dot{\theta}^2+J_r\overline{\Omega}\dot{\phi}+dU_3\right\} \\ \ddot{\psi}=\frac{1}{I_z}\left\{\dot{\theta}\dot{\phi}\left(I_x-I_y\right)-K_{faz}\dot{\psi}^2+K_dU_4\right\} \\ \ddot{x}=\frac{1}{m}\left\{\left(C\phi S\theta C\psi+S\phi S\psi\right)U_1-K_{ftx}\dot{x}\right\} \\ \ddot{y}=\frac{1}{m}\left\{\left(C\phi S\theta S\psi-S\phi C\psi\right)U_1-K_{fty}\dot{y}\right\} \\ \ddot{z}=\frac{1}{m}\left\{\left(C\phi C\theta\right)U_1-K_{ftz}\dot{z}\right\}-g \end{cases} \tag{12}$$

$U_1, U_2, U_3$ and $U_4$ are the control inputs of the system which are written according to the angular velocities of the four rotors as follows:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix}=\begin{pmatrix} K_p & K_p & K_p & K_p \\ -K_p & 0 & K_p & 0 \\ 0 & -K_p & 0 & K_p \\ K_d & -K_d & K_d & -K_d \end{pmatrix}\begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{13}$$

and $\overline{\Omega}=\left(\omega_1-\omega_2+\omega_3-\omega_4\right)$

### 2.2 Nonholonomic Constraints

Taking into account nonholonomic constraints for our system is of major importance as are in compliance with physical laws and define the coupling between various states of the system.

From the equations of the translation dynamics (12) we can extract the expressions of the high-order nonholonomic constraints:

$$\begin{cases} \tan\theta=\dfrac{\left(\ddot{x}-\frac{K_{ftx}}{m}\dot{x}\right)C\psi+\left(\ddot{y}-\frac{K_{fty}}{m}\dot{y}\right)S\psi}{\ddot{z}+g-\frac{K_{ftz}}{m}\dot{z}} \\ S\phi=\dfrac{-\left(\ddot{x}-\frac{K_{ftx}}{m}\dot{x}\right)S\psi+\left(\ddot{y}-\frac{K_{fty}}{m}\dot{y}\right)C\psi}{\sqrt{\left(\ddot{x}-\frac{K_{ftx}}{m}\dot{x}\right)^2+\left(\ddot{y}-\frac{K_{fty}}{m}\dot{y}\right)^2+\left(\ddot{z}+g-\frac{K_{ftz}}{m}\dot{z}\right)^2}} \end{cases} \tag{14}$$

### 2.3 Rotor Dynamic

The rotor is a unit constituted by D.C-motor actuating a propeller via a reducer. The D.C-motor is governed by the following dynamic equations:

$$\begin{cases} V=ri+L\frac{di}{dt}+k_e\omega \\ k_mi=J_r\frac{d\omega}{dt}+C_s+k_r\omega^2 \end{cases} \tag{15}$$

The different parameters of the motor are defined as follows:

$V$ : motor input.

$k_e, k_m$ : electrical and mechanical torque constants, respectively.

$k_r$ : load constant torque.

$r$ : motor internal resistance.

$J_r$ : rotor inertia.

$C_s$ : solid friction.

Then, the model chosen for the rotor is as follows:

$$\dot{\omega}_i = bV_i - \beta_0 - \beta_1\omega_i - \beta_2\omega_i^2 \qquad (16)$$

$$i \in [1,4]$$

with:

$$\beta_0 = \frac{C_s}{J_r}, \beta_1 = \frac{k_e k_m}{rJ_r}, \beta_2 = \frac{k_r}{J_r} \text{ and } b = \frac{k_m}{rJ_r}$$

## 3 BACKSTEPPING CONTROL OF THE QUADROTOR

In this section the backstepping technique will be applied to the Quadrotor model developed in the previous section. The choice of this method is not fortuitous considering the major advantages it presents:

- It ensures Lyapunov stability.
- It ensures the robustness and all properties of the desired dynamics.
- It ensures the handling of all system nonlinearities.

The model (12) developed in the first part of this paper can be rewritten in the state-space form: $\dot{X} = f(X) + g(X,U) + \delta$ and $X = [x_1 ... x_{12}]^T$ is the state vector of the system such as:

$$X = \left[\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, z, \dot{z}\right]^{\mathrm{T}} \qquad (17)$$

From (12) and (17) we obtain the following state representation:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 x_4 x_6 + a_2 x_2^2 + a_3 \overline{\Omega} x_4 + b_1 U_2 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a_4 x_2 x_6 + a_5 x_4^2 + a_6 \overline{\Omega} x_2 + b_2 U_3 \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = a_7 x_2 x_4 + a_8 x_6^2 + b_3 U_4 \\ \dot{x}_7 = x_8 \\ \dot{x}_8 = a_9 x_8 + U_x \dfrac{U_1}{m} \\ \dot{x}_9 = x_{10} \\ \dot{x}_{10} = a_{10} x_{10} + U_y \dfrac{U_1}{m} \\ \dot{x}_{11} = x_{12} \\ \dot{x}_{12} = a_{11} x_{12} + \dfrac{Cx_1 Cx_3}{m} U_1 - g \end{cases} \qquad (18)$$

$$\begin{cases} a_1 = \left(\dfrac{I_y - I_z}{I_x}\right), a_2 = \dfrac{-K_{fax}}{I_x}, a_3 = \dfrac{-J_r}{I_x} \\ a_4 = \left(\dfrac{I_z - I_x}{I_y}\right), a_5 = \dfrac{-K_{fay}}{I_y}, a_6 = \dfrac{J_r}{I_y} \\ a_7 = \left(\dfrac{I_x - I_y}{I_z}\right), a_8 = \dfrac{-K_{faz}}{I_z}, a_9 = \dfrac{-K_{ftx}}{m} \\ a_{10} = \dfrac{-K_{fty}}{m}, a_{11} = \dfrac{-K_{ftz}}{m} \\ b_1 = \dfrac{d}{I_x}, b_2 = \dfrac{d}{I_y}, b_3 = \dfrac{1}{I_z} \end{cases} \qquad (19)$$

$$\begin{cases} U_x = Cx_1 Sx_3 Cx_5 + Sx_1 Sx_5 \\ U_y = Cx_1 Sx_3 Sx_5 - Sx_1 Cx_5 \end{cases} \qquad (20)$$

The state representation of the system under this form has never been developed before.

From the high-order nonholonomic constraints developed in (14), $\phi$ and $\theta$ angles depend not only on the $\psi$ but also on the motions along ($X, Y, Z$) axis and their dynamics. However, the adopted control strategy is summarized in the control of two subsystems: the first relates to the position control while the second is that of the attitude control, as shown in figure 3.

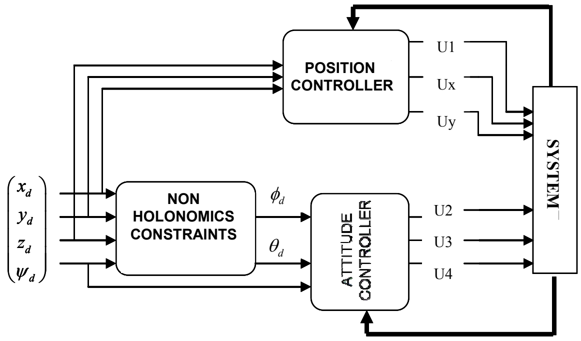



Fig. 3: Synoptic scheme of the proposed controller

### 3.1 Stabilizing Control Laws Synthesis

Using the backstepping approach as a recursive algorithm for the control-laws synthesis, we simplify all the stages of calculation concerning the tracking errors and Lyapunov functions in the following way:

$$z_i = \begin{cases} x_{id} - x_i & / \quad i \in \{1,3,5,7,9,11\} \\ x_i - \dot{x}_{(i-1)d} - \alpha_{(i-1)} z_{(i-1)} & / \quad i \in \{2,4,6,8,10,12\} \end{cases} \qquad (21)$$

with $\alpha_i > 0 \quad \forall i \in [1,12]$

and:

$$V_i = \begin{cases} \dfrac{1}{2} z_i^2 & / \quad i \in \{1,3,5,7,9,11\} \\ \dfrac{1}{2}\left(V_{i-1} + z_i^2\right) & / \quad i \in \{2,4,6,8,10,12\} \end{cases} \qquad (22)$$

Proof

For $i = 1$:

$$\begin{cases} z_1 = x_{1d} - x_1 \\ V_1 = \dfrac{1}{2} z_1^2 \end{cases} \qquad (23)$$

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1 \left(\dot{x}_{1d} - x_2\right) \qquad (24)$$

According to Lyapunov's theorem and especially, $\dot{V}_i \le 0$, the stabilization of $z_1$ can be obtained by introducing a virtual control input $x_2$:

$$x_2 = \dot{x}_{1d} + \alpha_1 z_1 \qquad \text{with} : \alpha_1 > 0 \qquad (25)$$

The equation (24) is then:

$$\dot{V}_1(z_1) = -\alpha_1 z_1^2 \qquad (26)$$

Let us proceed to a variable change by making:

$$z_2 = x_2 - \dot{x}_{1d} - \alpha_1 z_1 \tag{27}$$

For $i = 2$:

$$\begin{cases} z_2 = x_2 - \dot{x}_{1d} - \alpha_1 z_1 \\ V_2 = \dfrac{1}{2} z_1^2 + \dfrac{1}{2} z_2^2 \end{cases} \tag{28}$$

$$\dot{V}_2 = z_1 \dot{z}_1 + z_2 \dot{z}_2 \tag{29}$$

Such as:

$$\dot{z}_2 = a_1 x_4 x_6 + a_2 x_2^{\,2} + a_3 x_4 \overline{\Omega} + b_1 U_2 - \ddot{x}_{1d} - \alpha_1 \dot{z}_1$$

The control input $U_2$ is then extracted, satisfying $\dot{V}_2 < 0$:

$$U_2 = \frac{1}{b_1}\left\{-a_1 x_4 x_6 - a_2 x_2^{\,2} - a_3 \overline{\Omega} x_4 + \ddot{\phi}_d + \alpha_1\left(\dot{\phi}_d - x_2\right) - \alpha_2 z_2 + z_1\right\}$$

The term $\alpha_2 z_2$ ($\alpha_2 > 0$) is added to stabilize $z_1$.

The same steps are followed to extract $U_3$, $U_4$, $U_x$, $U_y$ and $U_1$

$$\begin{cases} U_3 = \dfrac{1}{b_2}\left\{-a_4 x_2 x_6 - a_5 x_4^{\,2} - a_6 \overline{\Omega} x_2 + \ddot{\theta}_d + \alpha_3\left(\dot{\theta}_d - x_4\right) - \alpha_4 z_4 + z_3\right\} \\ U_4 = \dfrac{1}{b_3}\left\{-a_7 x_2 x_4 - a_8 x_6^{\,2} + \ddot{\psi}_d + \alpha_5\left(\dot{\psi}_d - x_6\right) - \alpha_6 z_6 + z_5\right\} \\ U_x = \dfrac{m}{U_1}\left\{-a_9 x_8 + \ddot{x}_d + \alpha_7\left(\dot{x}_d - x_8\right) - \alpha_8 z_8 + z_7\right\} \quad / U_1 \neq 0 \\ U_y = \dfrac{m}{U_1}\left\{-a_{10} x_{10} + \ddot{y}_d + \alpha_9\left(\dot{y}_d - x_{10}\right) - \alpha_{10} z_{10} + z_9\right\} \quad / U_1 \neq 0 \\ U_1 = \dfrac{m}{\cos\phi \cos\theta}\left\{g - a_{11} x_{12} + \ddot{z}_d + \alpha_{11}\left(\dot{z}_d - x_{12}\right) - \alpha_{12} z_{12} + z_{11}\right\} \end{cases} \tag{30}$$

### 3.2 Simulation Results

The simulation results are obtained based on the following real parameters (Bouadi, et al., 2007):

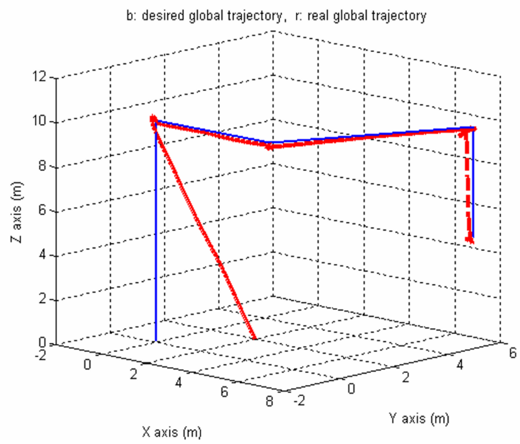



Fig. 4: Global trajectory of the quadrotor in 3D

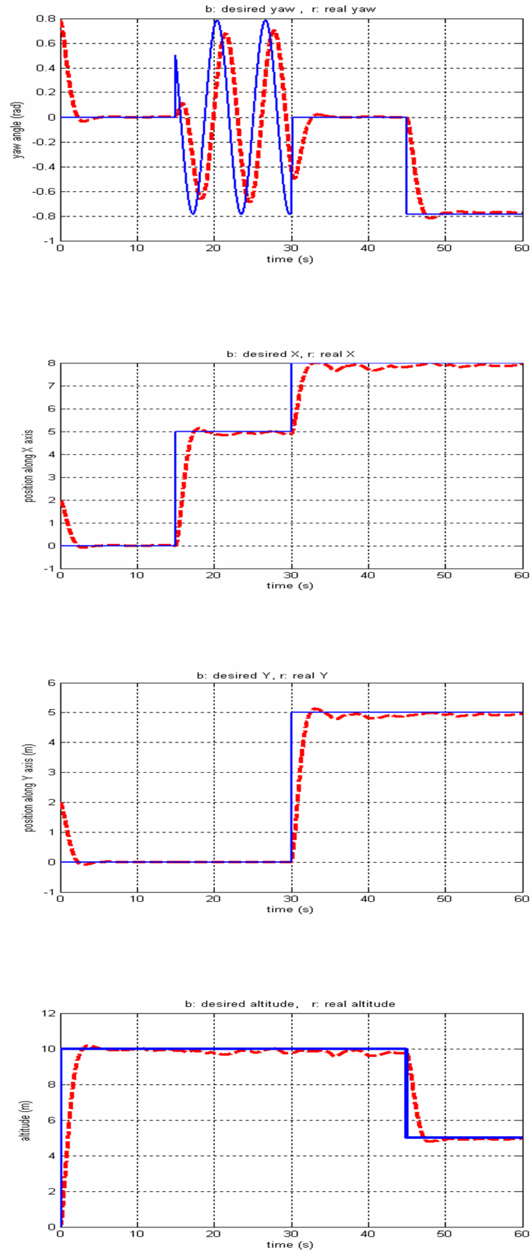
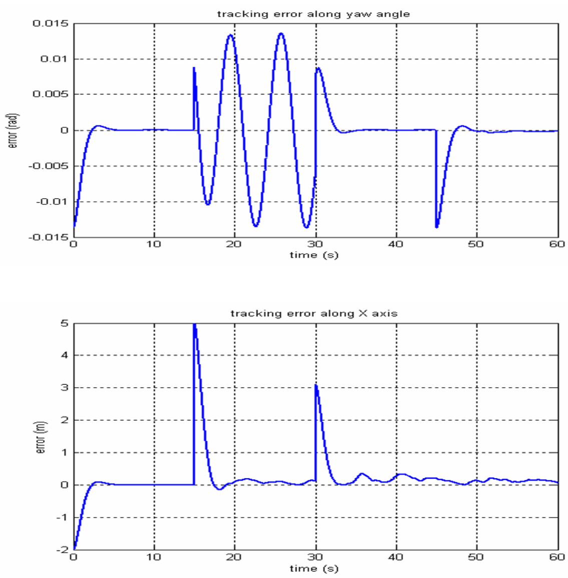
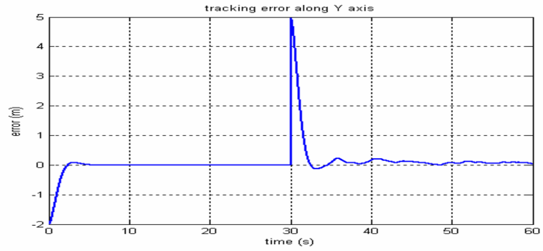



Fig. 5: Tracking simulation results of the desired trajectories along yaw angle ($\psi$) and $(X, Y, Z)$ axis.





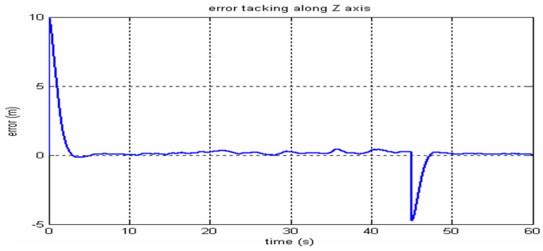




Fig. 6: Tracking errors along yaw ($\psi$) angle and $(X, Y, Z)$ respectively.

Figure (4) shows the tracking of the desired trajectories by the real one and the evolution of the quadrotor in space and its stabilization.

Figure (5) highlights the tracking of the desired trajectories according to the yaw angle ($\psi$) and the three axis (X, Y, Z) respectively. The response time of the system is about 3s and the tracking in altitude presents a rather weak permanent error.

Figure (6) represents the errors made on the desired trajectory tracking and shows well the presence of a permanent error of tracking along (z) about 0.2m.

## 4 CONCLUSION

In this paper, we presented a stabilizing control laws synthesis by Backstepping based firstly, on the development of the dynamic model of the quadrotor taking into account the different physical phenomena which can influence the evolution of our system in the space and secondly on the development of the high-order nonholonomic constraints imposed on the system motions. These control laws allowed the tracking of the various desired trajectories expressed in terms of the center of mass coordinates of the system in spite of the complexity of the proposed model. As prospects we plan to develop other control techniques in order to improve the performances and to implement them on a real system.

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