Robust Control Algorithm Considering the Actuator Faults for Attitude Tracking of an UAV Quadrotor Aircraft

Hicham Khebbache

Department of Electrical Engineering,
University of Ferhat Abbes, Setif-19000, Algeria
khebbachehicham@yahoo.fr

Abstract

The work proposed in this paper aims to design a robust control algorithm for the attitude tracking of a quadrotor UAV system in presence of actuator faults. The attitude dynamic modeling of quadrotor while taking into account various physical phenomena, which can influence the dynamics of a flying structure is presented. Subsequently, a control algorithm which based on robust integral backstepping taking into account the actuator faults is developed. Lyapunov based stability analysis shows that the proposed control algorithm keep the stability of the closed loop dynamics of quadrotor UAV even after the presence of actuator faults. Numerical simulation results are provided to show the good tracking performance of proposed control laws.

Keywords: *Attitude tracking, Robust integral backstepping, Fault tolerant control (FTC), Unmanned aerial vehicles (UAV), Quadrotor*

1. Introduction

Nowadays, the use and development of Unmanned Aerial Vehicles (UAV) represent a growing area in aerospace engineering. The research groups of all over the world are being attracted by these vehicles due mainly to their numerous applications such as surveillance, inspection, law enforcement, search and rescue, among others. Moreover, the field of UAV involves many engineering challenges in the areas of electrical, mechanical and control engineering.

The quadrotors' hovering ability makes possible an extended area of applications for which fixed wing aircrafts are not suitable. Examples include forest fire surveillance, inspection of buildings and bridges, wild fire monitoring, and military applications. During these missions precise trajectory tracking combined with effective disturbance attenuation is required. Quadrotors have several advantages compared to other rotorcraft designs including: (a) the simplicity of their mechanical structure, (b) the use of four small propellers resulting in a more fault-tolerant mechanical design capable of aggressive maneuvers at low altitude, (c) good maneuverability and (d) increased payload [2].

In practical applications, the position in space of the UAVs is generally controlled by an operator through a remote-control system, while the attitude can be automatically stabilized via an onboard controller. The attitude controller is an important feature since it allows the vehicle to maintain a desired orientation and, hence, prevents the vehicle from flipping over and crashing when the pilot performs the desired maneuvers [28].

The quadrotor we consider is an underactuated system with six outputs and four inputs, and the states are highly coupled. To deal with this system, many modeling approaches have been presented [15, 2, 24, 21-9, 12, 5, 14, 11]. To solve the quadrotor

UAV tracking control problem, many techniques have been proposed [3, 22, 23, 28, 1, 5, 4, 7, 26, 25, 14, 11, 10, 8, 27, 6]. First of all, several backstepping and sliding mode controllers have been developed. S. Bouabdallah, et al., presented a backstepping and sliding mode controllers [3] in order to stabilize the complete system [2] (i.e. translation and orientation), but without taking into account frictions due to the aerodynamic torques nor drag forces. However, Madani, et al., studied a full-state backstepping technique based on the Lyapunov stability theory and backstepping sliding mode control [22, 23] taking into account the gyroscopic effects. Yet another Nonlinear control methods using backstepping and sliding mode approaches has been proposed in [1], H. Bouadi, et al., proposed a backstepping control method, a sliding mode control algorithm based on backstepping approach allowed the tracking of the various desired trajectories expressed in term of the center of mass coordinates along (X,Y,Z) axis and yaw angle, and a direct adaptive sliding mode control in order to stabilize roll and pitch motions while tracking heading and altitude trajectories of a quadrotor under atmospheric perturbations where the controllability condition is checked [5, 4, 6], In [10], authors used another backstepping controller, introducing the Frenet-Serret Theory (Backstepping+FST) for attitude stabilization, that includes estimation of the desired angular acceleration (within the control law) as a function of the aircraft velocity.

In [28], the authors have shown 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. Yet another linear control method using PID controller has been developed in order to stabilize attitude, and nonlinear control algorithm based on the second order sliding mode technique known as Super-Twisting Algorithm (STA) which is able to ensure robustness with respect to bounded external disturbances has been designed for attitude stabilization and attitude tracking with an experimental implementations on a real quadrotor for both control algorithms by L. Derafa, et al., [12, 13].

There are also robust controllers designed for quadrotor systems. The authors in [26] proposed a nonlinear $H\infty$ controller in order to stabilize the rotational movements, whereas a control law based on backstepping approach was used to solve the path tracking problem of the quadrotor helicopter. While in [7, 8], a robust nonlinear PI, a classical and second order sliding mode control techniques for attitude stabilization and attitude tracking under external disturbances have been proposed and successfully validated in simulation and real time by M. Bouchoucha, et al. Moreover, an integral backstepping and an integral sliding mode controller for the same objectives of previous authors have been also implemented in real time on an embedded system based on a dsPIC μC [27].

Another robust popular methods for handling unknown nonlinearities is to introduce neural networks, tuned online using adaptive control techniques have been proposed for quadrotor's control [25, 11]

All these authors propose many other dynamics systems, present constant or slowly-varying uncertain parameters, but without considering the faults affecting these systems. However, H. Khebbache, et al., proposed a control algorithms based upon backstepping approach using sliding mode techniques, in order to allow the tracking of the various desired trajectories despite the occurrence of actuator faults affecting the quadrotor. Nevertheless, the inputs control corresponding to these control strategies are characterized by very fast switching (chattering phenomenon) caused by the using of "sign" function [19, 20].

In this paper, the attitude tracking problem of quadrotor aircraft in presence of actuator faults is considered. The dynamic modeling describing the roll, pitch, and yaw motions and taking into account for various parameters which affect the dynamics of a flying structure such as frictions due to the aerodynamic torques and gyroscopic effects is presented. Subsequently, based on backstepping approach and considering the actuator faults like in [19-20], a new control algorithm is developed, which uses an integral action instead of the 'sign' function to compensate the effects of actuator faults affecting the quadrotor aircraft. Finally all synthesized control laws are highlighted by simulations which gave fairly satisfactory results.

2. Quadrotor Attitude Modeling

The quadrotor have four propellers in cross configuration. The two pairs of propellers {1,3} and {2,4} as described in Figure 1, turn in opposite directions. By varying the rotor speed, one can change the lift force and create motion. Thus, increasing or decreasing the four propeller's speeds together generates vertical motion. Changing the 2 and 4 propeller's speed conversely produces roll rotation coupled with lateral motion. Pitch rotation and the corresponding lateral motion; result from 1 and 3 propeller's speed conversely modified. Yaw rotation is more subtle, as it results from the difference in the counter-torque between each pair of propellers.

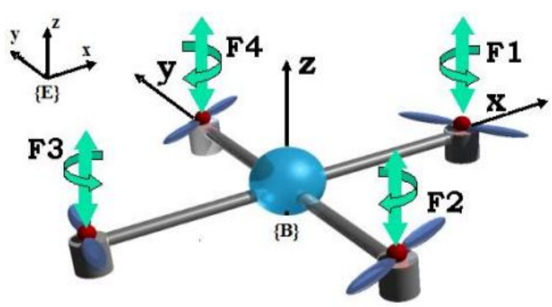


Figure 1. Quadrotor Configuration

The attitude dynamical model is represented by Euler angles $[\phi, \theta, \psi]^T$ corresponding to an aeronautical convention [16]. The attitude angles are respectively called Roll angle (ϕ rotation around x-axis), Pitch angle (θ rotation around y-axis) and Yaw angle (ψ rotation around z-axis). It contains four terms which are the gyroscopic effect resulting from the rigid body rotation, and from the propeller rotation coupled with the body rotation, aerodynamics frictions and finally the actuators action [17-18-19-20]:

$$\begin{cases} \ddot{\phi} = \dfrac{(I_y - I_z)}{I_x}\dot{\theta}\dot{\psi} - \dfrac{J_r}{I_x}\Omega_r\dot{\theta} - \dfrac{K_{fax}}{I_x}\dot{\phi}^2 + \dfrac{l}{I_x}u_1 \\ \ddot{\theta} = \dfrac{(I_z - I_x)}{I_y}\dot{\phi}\dot{\psi} + \dfrac{J_r}{I_y}\Omega_r\dot{\phi} - \dfrac{K_{fay}}{I_y}\dot{\theta}^2 + \dfrac{l}{I_y}u_2 \\ \ddot{\psi} = \dfrac{(I_x - I_y)}{I_z}\dot{\theta}\dot{\phi} - \dfrac{K_{faz}}{I_z}\dot{\psi}^2 + \dfrac{1}{I_z}u_3 \end{cases} \quad (1)$$

The system's inputs are posed u_1, u_2, u_3, and Ω_r is a disturbance, obtaining:

$$\begin{cases} u_1 = lb\,(\omega_4^2 - \omega_2^2) \\ u_2 = lb\,(\omega_3^2 - \omega_1^2) \\ u_3 = d\,\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \\ \Omega_r = \omega_1 - \omega_2 + \omega_3 - \omega_4 \end{cases} \tag{2}$$

The rotors are driven by DC motors with the well known equations [28]:

$$\begin{cases} J_r \dot{\omega}_i = \tau_i - Q_i \\ v_i = \dfrac{R_a}{k_m k_g} \tau_i + k_m k_g \omega_i \end{cases}, \; i \in \{1,2,3,4\} \tag{3}$$

where R_a is the motor resistance, k_m is the motor torque constant, and k_g is the gear ratio.

3. Control Strategy of Quadrotor

The object of the control algorithm developed in this paper is to design a robust output tracking controller which makes the output of the system $\{\phi(t), \theta(t), \psi(t)\}$ to track the desired output $\{\phi_d(t), \theta_d(t), \psi_d(t)\}$. The complete model resulting by adding the actuator faults in the model (1) can be written in a state-space form:

$$\dot{X} = f\,(X) + B(U + F_a) \tag{4}$$

with $X \in \Re^n$ is the state vector of the system, $U \in \Re^m$ is the input control vector, and $F_a \in \Re^{q_a}$ is the resultant vector of actuator faults related to quadrotor motions, such as:

$$X = \left[x_1, ..., x_6\right]^T = \left[\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}\right]^T \tag{5}$$

Therefore the state space model (4) can be rearranged as follows [19-20]:

$$\begin{aligned} &S_1 \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 x_4 x_6 + a_2 x_2^2 + a_3 \Omega_r x_4 + b_1\left(u_1 + f_{a1}\right) \end{cases} \\ &S_2 \begin{cases} \dot{x}_3 = x_4 \\ \dot{x}_4 = a_4 x_2 x_6 + a_5 x_4^2 + a_6 \Omega_r x_2 + b_2\left(u_2 + f_{a2}\right) \end{cases} \\ &S_3 \begin{cases} \dot{x}_5 = x_6 \\ \dot{x}_6 = a_7 x_2 x_4 + a_8 x_6^2 + b_3\left(u_3 + f_{a3}\right) \end{cases} \end{aligned} \tag{6}$$

with

$$\begin{cases} a_1 = \dfrac{I_y - I_z}{I_x} \;\; a_2 = -\dfrac{K_{fax}}{I_x} \;\; a_3 = -\dfrac{J_r}{I_x} \;\; a_4 = \dfrac{I_z - I_x}{I_y} \;\; a_5 = -\dfrac{K_{fay}}{I_y} \;\; a_6 = \dfrac{J_r}{I_y} \\ a_7 = \dfrac{I_x - I_y}{I_z} \;\; a_8 = -\dfrac{K_{faz}}{I_z} \;\; b_1 = \dfrac{l}{I_x} \;\; b_2 = \dfrac{l}{I_y} \;\; b_3 = \dfrac{1}{I_z} \end{cases} \tag{7}$$

Assumption 1: The resultants of actuator faults related to attitude motions are assumed to be zero values prior to the faults time and be the constant values after the faults occurs,

$$f_{ai} = \begin{cases} 0 & \text{if} \quad t < T_i \\ f_i^{+} & \text{if} \quad t \geq T_i \end{cases}, \ \mathrm{i} \in [1,2,3] \tag{8}$$

where $\{f_1^{+}, f_2^{+}, f_3^{+}\}$are positive constants.

The problem of trajectory tracking is thus divided in the respective problem for three subsystems: control of roll (S_1), control of pitch (S_2), and control of yaw (S_3). Based on backstepping approach, the control design for each subsystem taking into account the resultants of actuator faults related to roll, pitch, and yaw motions, will be carried out in the following subsections in two steps (globally in six steps).

3.1. Control of Roll (S_1)

Step 1: For the first step we consider the first tracking-error

$$e_1 = x_1 - x_{1d} \tag{9}$$

Let the First Lyapunov function candidate:

$$V_{\phi 1} = \frac{1}{2} e_1^2 \tag{10}$$

The time derivative of (10) is given by

$$\dot{V}_{\phi 1} = e_1 \dot{e}_1 = e_1 (x_2 - \dot{x}_{1d}) \tag{11}$$

The stabilization of e_1 can be obtained by introducing a new virtual control x_2

$$(x_2)_d \square \alpha_1 = \dot{x}_{1d} - c_1 e_1 / c_1 > 0 \tag{12}$$

The equation (11) is then

$$\dot{V}_{\phi 1} = -c_1 e_1^2 \leq 0 \tag{13}$$

Step 2: For the second step we consider the following tracking-error

$$e_2 = x_2 - \dot{x}_{1d} + c_1 e_1 \tag{14}$$

The augmented Lyapunov function is given by:

$$V_{\phi 2} = \frac{1}{2}\left(e_1^2 + e_2^2 + e_{f1}^2\right) \Big/ e_{f1} = f_{a1} - \varsigma_1 \tag{15}$$

It's time derivative is then:

$$\begin{aligned} \dot{V}_{\phi 2} &= e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_{f1} \dot{e}_{f1} \\ &= e_1(-c_1 e_1 + e_2) + e_2\left(\dot{x}_2 - \ddot{x}_{1d} + c_1 \dot{e}_1\right) + e_{f1}\left(-\dot{\varsigma}_1\right) \\ &= -c_1 e_1^2 + e_2\left(e_1 + a_1 x_4 x_6 + a_2 x_2^2 + a_3 \Omega_r x_4 + b_1 u_1 - \ddot{x}_{1d} + c_1(-c_1 e_1 + e_2) + b_1 f_{a1}\right) + e_{f1}\left(-\dot{\varsigma}_1\right) \end{aligned} \tag{16}$$

The stabilization of (e_1,e_2) can be obtained by introducing the following input control

$$u_1 = \frac{1}{b_1}\left(\ddot{\phi}_d - c_1(-c_1e_1 + e_2) - e_1 - c_2e_2 - a_1x_4x_6 - a_2x_2^2 - a_3\Omega_r x_4 - b_1\varsigma_1\right) \tag{17}$$

Consequently,

$$\dot{V}_{\phi 2} = -c_1e_1^2 + e_2\left(-c_2e_2 + b_1e_{f1}\right) + e_{f1}\left(-\dot{\varsigma}_1\right) \tag{18}$$

In order to compensate the effect of the resultant of actuator faults related to the roll motion, an integral term is introduced. We take:

$$\varsigma_1 = b_1\int_0^t e_2 d\tau \tag{19}$$

It result that

$$\dot{V}_{\phi 2} = -c_1e_1^2 + e_2\left(-c_2e_2 + b_1e_{f1}\right) + e_{f1}\left(-b_1e_2\right) = -c_1e_1^2 - c_2e_2^2 \le 0 \tag{20}$$

where c_2 is positive constant.

3.2. Control of Pitch (S_2)

Step 3: The tracking-error according to this step is given by :

$$e_3 = x_3 - x_{3d} \tag{21}$$

The corresponding Lyapunov function is given by:

$$V_{\theta 1} = \frac{1}{2}e_3^2 \tag{22}$$

The time derivative of (22) is given by

$$\dot{V}_{\theta 1} = e_3\dot{e}_3 = e_3(x_4 - \dot{x}_{4d}) \tag{23}$$

The stabilization of e_3 can be obtained by introducing a new virtual control x_4

$$\left(x_4\right)_d \triangleq \alpha_2 = \dot{x}_{3d} - c_3e_3 / c_3 > 0 \tag{24}$$

The equation (23) becomes

$$\dot{V}_{\theta 1} = -c_3e_3^2 \le 0 \tag{25}$$

Step 4: For this step we choose the fourth tracking-error

$$e_4 = x_4 - \dot{x}_{3d} + c_3e_3 \tag{26}$$

The corresponding Lyapunov function is given by:

$$V_{\theta 2} = \frac{1}{2}\left(e_3^2 + e_4^2 + e_{f2}^2\right) / e_{f2} = f_{a2} - \varsigma_2 \tag{27}$$

It's time derivative is then:

$$\begin{aligned}\dot{V}_{\theta 2} &= e_3\dot{e}_3 + e_4\dot{e}_4 + e_{f2}\dot{e}_{f2} \\ &= -c_3e_3^2 + e_4\left(e_3 + a_4x_2x_6 + a_5x_4^2 + a_6\Omega_r x_2 + b_2u_2 - \ddot{x}_{3d} + c_3(-c_3e_3 + e_4) + b_2f_{a2}\right) + e_{f2}\left(-\dot{\varsigma}_2\right)\end{aligned} \tag{28}$$

The stabilization of (e_3,e_4) can be obtained by introducing the following input control

$$u_2 = \frac{1}{b_2}\left(\ddot{\theta}_d - c_3(-c_3 e_3 + e_4) - e_3 - c_4 e_4 - a_4 x_2 x_6 - a_5 x_4^2 - a_6 \Omega_r x_2 - b_2 \varsigma_2\right) \tag{29}$$

By using the control-law (29) and the equation (28) it comes

$$\dot{V}_{\theta 2} = -c_3 e_3^2 + e_4\left(-c_4 e_4 + b_2 e_{f2}\right) + e_{f2}\left(-\dot{\varsigma}_2\right) \tag{30}$$

A second integral term is introduced in input control u_2 to compensate the effect of the resultant of actuator faults related to the pitch motion. We take:

$$\varsigma_2 = b_2 \int_0^t e_4 \, d\tau \tag{31}$$

Consequently,

$$\dot{V}_{\theta 2} = -c_3 e_3^2 + e_4\left(-c_3 e_3 + b_2 e_{f2}\right) + e_{f2}\left(-b_2 e_4\right) = -c_3 e_3^2 - c_4 e_4^2 \le 0 \tag{32}$$

where c_4 is positive constant.

3.3. Control of Yaw (S_3)

Step 5: The tracking-error according to this step is given by :

$$e_5 = x_5 - x_{5d} \tag{33}$$

His Lyapunov function is obtained as follows:

$$V_{\psi 1} = \frac{1}{2} e_5^2 \tag{34}$$

And it's time derivative is given by

$$\dot{V}_{\psi 1} = e_5 \dot{e}_5 = e_5(x_6 - \dot{x}_{5d}) \tag{35}$$

The stabilization of e_5 can be obtained by introducing a new virtual control x_6

$$\left(x_6\right)_d \triangleq \alpha_3 = \dot{x}_{5d} - c_5 e_5 / c_5 > 0 \tag{36}$$

The equation (35) is then

$$\dot{V}_{\psi 1} = -c_5 e_5^2 \le 0 \tag{37}$$

Step 6: For this step we choose the sixth tracking-error

$$s_6 = x_6 - \dot{x}_{5d} + c_5 s_5 \tag{38}$$

The augmented Lyapunov function is chosen by:

$$V_{\psi 2} = \frac{1}{2}\left(e_5^2 + e_6^2 + e_{f3}^2\right) \Big/ e_{f3} = f_{a3} - \varsigma_3 \tag{39}$$

It's time derivative is then:

$$\begin{aligned} \dot{V}_{\psi 2} &= e_5 \dot{e}_5 + e_6 \dot{e}_6 + e_{f3} \dot{e}_{f3} \\ &= -c_5 e_5^2 + e_6\left(e_5 + a_7 x_2 x_4 + a_8 x_6^2 + b_3 u_3 - \ddot{x}_{5d} + c_5(-c_5 e_5 + e_6) + b_3 f_{a3}\right) + e_{f3}\left(-\dot{\varsigma}_3\right) \end{aligned} \tag{40}$$

The stabilization of (e_5, e_6) can be obtained by introducing the following input control

$$u_3 = \frac{1}{b_2}\left(\ddot{\psi}_d - c_5(-c_5 e_5 + e_6) - e_5 - c_6 e_6 - a_7 x_2 x_4 - a_8 x_6^2 - b_3 \varsigma_3\right) \tag{41}$$

The equation (40) becomes

$$\dot{V}_{\psi 2} = -c_5 e_5^2 + e_6\left(-c_6 e_6 + b_3 e_{f3}\right) + e_{f3}\left(-\dot{\varsigma}_3\right) \tag{42}$$

In order to compensate the effect of the resultant of actuator faults related to the yaw motion, a third integral term is introduced. We take:

$$\varsigma_3 = b_3 \int_0^t e_6 \, d\tau \tag{43}$$

It result that

$$\dot{V}_{\psi 2} = -c_5 e_5^2 + e_6\left(-c_6 e_6 + b_3 e_{f3}\right) + e_{f3}\left(-b_3 e_6\right) = -c_5 e_5^2 - c_6 e_6^2 \le 0 \tag{44}$$

where c_6 is positive constant.

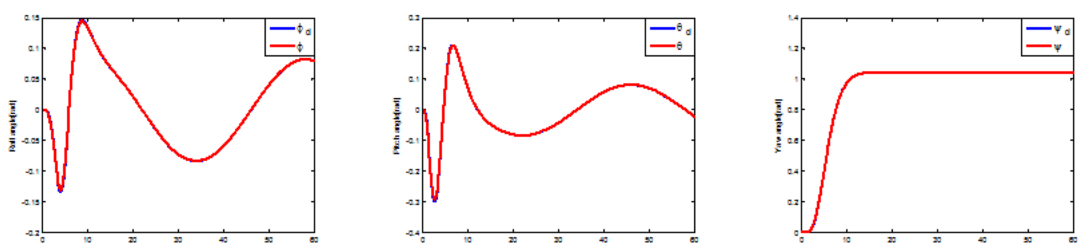
4. Simulation Results

Two cases are treated to evaluate the performances of the controller developed in this paper.

1- Results without faults are shown in Figure 3, Figure 5 and Figure 8.

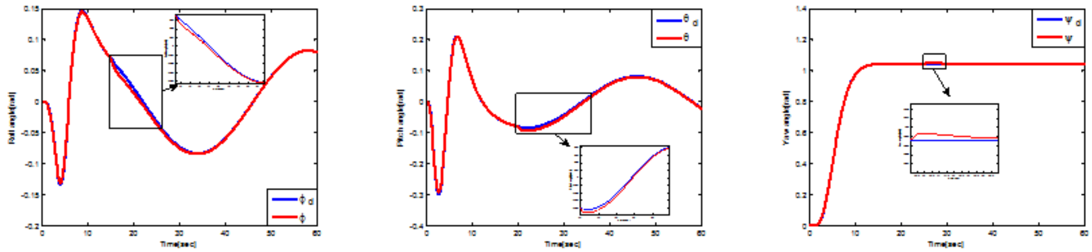
2- Results with three resultants of actuator faults related to roll, pitch, and yaw motions $\{f_{a1}, f_{a2}, f_{a3}\}$, which are introduced with 100% of maximum values of inputs control $\{u_1, u_2, u_3\}$ respectively at instants 15s, 20s and 25s are shown in Figure 4, Figure 6, Figure 7 and Figure 9.

The simulation results are obtained based on real parameters [12-13] in Table 1 (see the appendix).



(a) evolution of roll angle (b) evolution of pitch angle (c) evolution of yaw angle

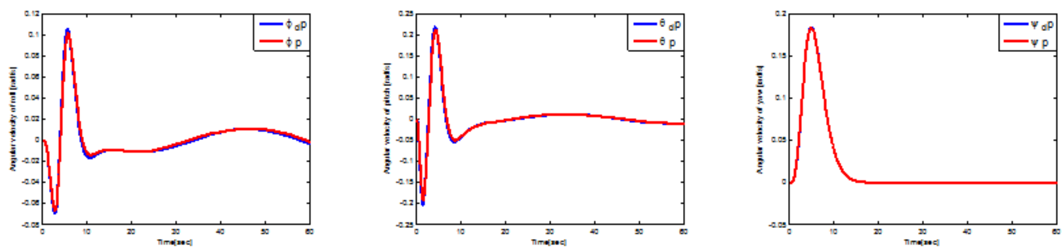
Figure 3. Tracking Simulation Results of Trajectories Along Roll (ϕ), Pitch (θ) and Yaw (ψ) Angles, Test 1



(a) evolution of roll angle (b) evolution of pitch angle (c) evolution of yaw angle

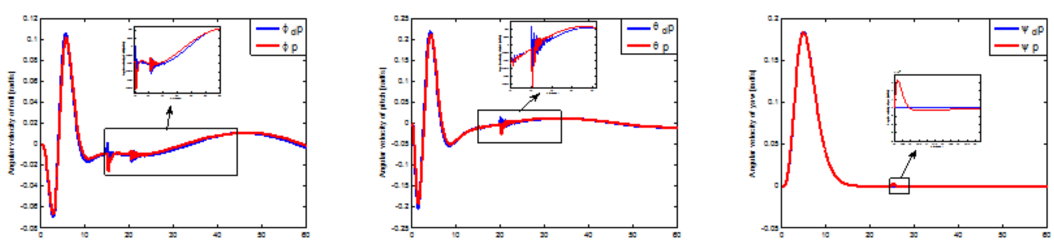
Figure 4. Tracking Simulation Results of Trajectories Along Roll (*ϕ*), Pitch (*θ*) and Yaw (*ψ*) Angles, Test 2

Figure 3 and Figure 4 represents the quadrotor attitude tracking, they clearly show the good rotation tracking of quadrotor helicopter for both Tests, with a small transient deviations in roll, pitch and yaw motions shown in Figure 6 caused by the appearance of the resultant of actuator faults corresponding to these motions at 15s, 20s and 25s respectively.



(a) evolution of angular velocity of roll (b) evolution of angular velocity of pitch (c) evolution of angular velocity of yaw

Figure 5. Tracking Simulation Results of the Angular Velocities, Test 1

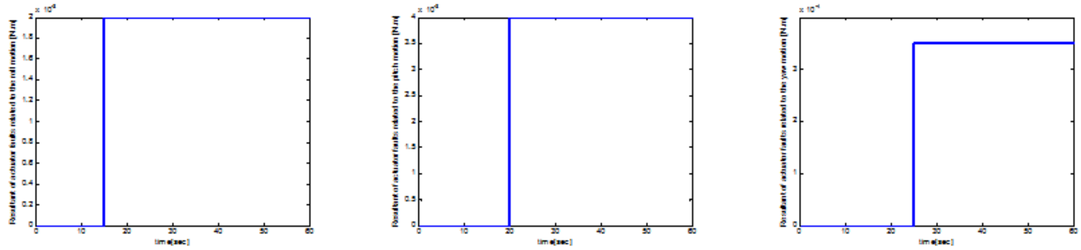


(a) evolution of angular velocity of roll (b) evolution of angular velocity of pitch (c) evolution of angular velocity of yaw

Figure 6. Tracking Simulation Results of the Angular Velocities, Test 2

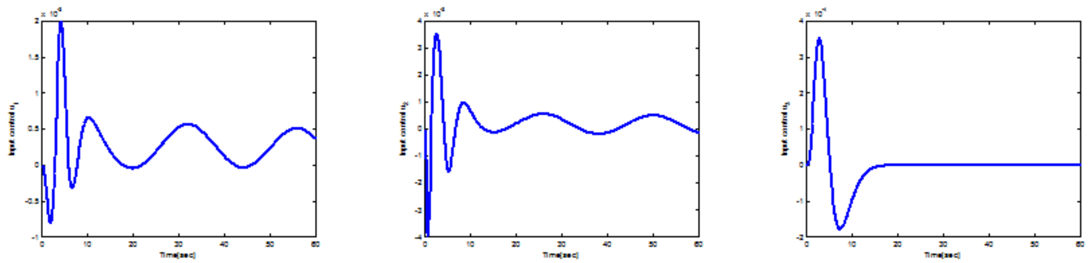
Figure 5 and Figure 6 represents the angular velocities of quadrotor aircraft, It can be seen also a good tracking of the desired velocities for both tests, with a small transient peaks illustrated by Figure.6 in angular velocities of roll and pitch at 15s and 20s respectively and angular velocity of yaw at 25s. Furthermore, these figures clearly show that the robustness of the controller under the actuator faults is guaranteed.

Figure 7 represents the evolution of the resultants of actuator faults related to roll, pitch and yaw motions affecting our system at 15s, 20s and 25s respectively, which are added in test 2.



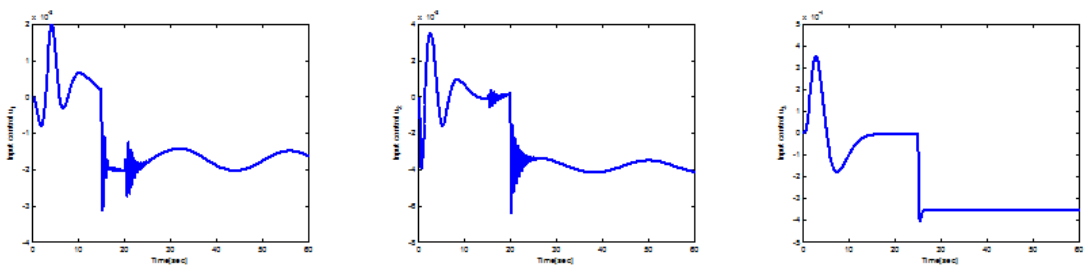
(a) evolution of f_{a1} (b) evolution of f_{a2} (c) evolution of f_{a3}

Figure 7. Simulation Results of the Resultants of Actuator Faults Related to Attitude Motions



(a) evolution of input control u_1 (b) evolution of input control u_2 (c) evolution of input control u_3

Figure 8. Simulation Results of All Inputs Control, Test 1



(a) evolution of input control u_1 (b) evolution of input control u_2 (c) evolution of input control u_3

Figure 9. Simulation Results of All Inputs Control, Test 2

Figure 8 and Figure 9 represents the inputs control of our system. From Figure 9, it is clear to see a deviations in input control of roll (u_1) at 15sec, input control of pitch (u_2) at 20s and input control of yaw (u_3) at 25s, with a transient picks at 15s and 20s in evolution of inputs control of roll and pitch, which due after the occurrence of the resultants of actuator faults corresponding to these motions. Despite that, the stability of the closed loop dynamics of quadrotor is assured.

5. Conclusion and Future Works

In this paper, we proposed a new control algorithm based on backstepping approach and including the actuator faults. Firstly, we presented the attitude dynamical model of quadrotor taking into account the different physics phenomena which can influence the evolution of our system in the space. Secondly, we synthesized a stabilizing control laws in presence of actuator faults. The simulation results have shown high efficiency of this control algorithm. It preserves the stability and the performances of quadrotor aircraft during a malfunction of these actuators. As prospects we hope to implement this control algorithm on a real prototype.

Appendix

Table 1. Quadrotor Model Parameters

Parameter	Value
m	0,4200 kg
g	9,8060 m/s^2
l	0,2050 m
b	$2{,}9842 \times 10^{-5}$ $N/rad/s$
d	$3{,}2320 \times 10^{-7}$ $N.m/rad/s$
J_r	$2{,}8385 \times 10^{-5}$ $kg.m^2$
I_x	$3{,}8278 \times 10^{-3}$ $kg.m^2$
I_y	$3{,}8278 \times 10^{-3}$ $kg.m^2$
I_z	$7{,}1345 \times 10^{-3}$ $kg.m^2$
K_{fax}	$5{,}5670 \times 10^{-4}$ $N/rad/s$
K_{fay}	$5{,}5670 \times 10^{-4}$ $N/rad/s$
K_{faz}	$6{,}3540 \times 10^{-4}$ $N/rad/s$
k_m	4.3000×10^{-3} $N.m/A$
k_q	5.6000
R_a	0.6700 Ω

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Author

Hicham KHEBBACHE is a Lecturer at the Electrical Engineering Department of Ferhat Abbes University, Setif (Algeria). He received the Engineer degree in Automatic Control from Mohamed Seddik Ben yahia University, Jijel (Algeria), in July 2009, and the Magister degree in Electrical Engineering option: Automatic Control from Ferhat Abbes University, Setif (Algeria), in June 2012. His research interests include Aerial robotics, Linear and Nonlinear control, Robust control, Fault tolerant control (FTC), Intelligent control and application of modern control theory to underactuated systems, Diagnosis, Fault detection and isolation (FDI).