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Research Article

DESIGN AND IMPLEMENTATION OF NONLINEAR PID CONTROLLER FOR A QUADROTOR CONTROL

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ABSTRACT

The following article represents the control of an unmanned airborne vehicle (Quadcopter), using nonlinear PID controllers in order to control the altitude, as well as the attitudes (pitch, roll and yaw) of the Quadcopter. Two approaches have been proposed for adjusting the parameters of a PID controller. Foremost, the PID controller gains are settled in an ideal way by using a reference model strategy. In the moment approach, these parameters are adjusted Nonlinear PID. MATLAB/Simulink has been utilized to test and compare the execution of the controllers gotten. The obtained results using the nonlinear PID controllers show the efficiency of the proposed controllers it presents a response with less error and minimal over shoot compared to the results of classical PID controller.

Keywords: PID Controller; Reference Model; Nonlinear system; Quadcopter.

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1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) emerged widely for performing various missions in the military and civil areas, consists of four rotors. These vehicles have the particular advantage of reducing the exposure of human pilots to danger and they are very useful when the

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environment is inaccessible or difficult to reach. For civil applications, quadcopter is used to survey the areas where human intervention is not applicable. The Quadcopter has six degree of freedom (DOF) with four independent thrust forces generated by four rotors. The complexity of the control of Quadcopter lies in the nonlinearity of its dynamics and the number of flight parameters involved: Four control inputs to control six outputs [1-2].

Quadcopter is a multi-copter that is lifted and propelled by four rotors, each mounted in one end of a cross-like structure as shown in Figure 1. Each rotor consists of a propeller fitted to a separately powered Brushless DC motor. Quadcopter has 6 degrees of freedom (three translational and three rotational) and only four actuators. Hence quadcopter is an underactuated system and highly nonlinear in nature. Unlike a conventional helicopter, a quadcopter’s rotor blade pitch angle need not be varied, which makes the quadcopter manufacturing and main Quadcopter motion description tenancy easier (Figure 2). Moreover, quadcopters have capacity to carry large payload due to the presence of four motors providing higher thrust. One drawback of quadcopter is more energy consumption due to presence of four motors which restrict the flying time of quadcopter many techniques related to the modeling and control of Quadcopter can be found in the literature. In a comparative study, the PID and LQ techniques are used for the stabilization of attitude [3]. Similarly, classical PD and hybrid fuzzy PD controllers have been tested for stabilization of a drone [4-7] fuzzy logic control (FLC) techniques have also been applied to the control of motor drives [8].

Other work has involved designing a controller by combining three techniques: Fuzzy Logic, back-stepping and sliding mode [1] or neural networks [9-10].

The most controllers used in industrial are PID due to their simple structure and uncomplicated implementation. The PID controllers can be divided into two parts. In the first part, the controller parameters are fixed during control. These parameters are selected in an optimal way by known methods such as the reference model or Ziegler-Nichols method. In the second part, the nonlinear PID controllers, and the adjustment with the controller in the nonlinear structure presented a respectable performance in the systems of constraint. Thus, the primary contribution of this work is to PID besides a Nonlinear controller, so quadcopter orientation, its attitude, and its position can be all stabilized and regulated.

The results of the simulation by using the proposed controller are compared with that obtained with the conventional PID controller, so we can figure out which is the most effective one.

The paper is organized as follows: Section 2 present the design of Quadcopter. In section III we describe the mathematical model of a quadcopter presented. The controllers are presented in section IV. The simulation results are illustrated in section V. The conclusion is given in section VI.

1.1 Design of quacopter

The Quadcopter concept has been known for a long time, in which the variation is plus (+) or (x) configuration. The plus configuration movement described in figure 1, up till now, the aircraft has four propellers. The different rotational speed of the two pairs of propellers (1, 3) is resulting in a pitching rotation coupled with lateral motion and it is moving backwards or forward (Figure 1 a b). In the same manner, different rotational speed in propellers (2,3) make it roll and moving to left or right (Figure 1 c-d). (Figure 1 e-f) show for taking quadrotor up and downwards. In the case of yawing, propeller pair (1-3) rotates faster and (2-3) slower, causing quadcopter yawing in CCW direction (Figure 1 g h) [11].

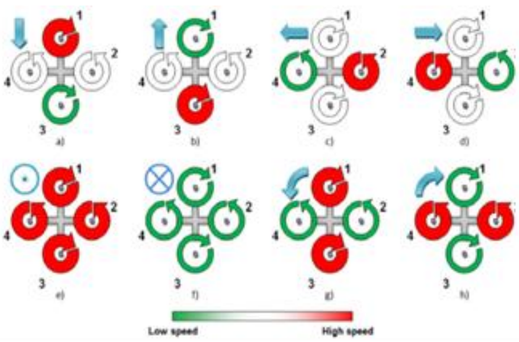

Fig.1. Scheme of motor speed for maneuvering in plus (+)

1.2. Quadcopter Modeling

The Quadcopter is a nonlinear and unstable system with four rotors. The diagonal motors (1 and 3) turn in the same direction whereas the motors 2 and 4 turn in the opposite direction [1,6]. The basic motions of the system are provided by varying the angular velocity of each rotor. Increasing or decreasing the speed of all four rotors at the same times generates a vertical movement. Creating a non-zero difference between the speeds of the 2nd and the 4th rotor produces the roll rotation coupled with lateral motion along the y axis.

A certain change of the speed rotor 1 and 3, creates a pitching movement coupled to a transformation on the x-axis. Yaw motion is obtained by applying a difference between the speeds peer rotors {1, 3} and {2, 4} [11].

The Quadcopter has 6 DOF, three rotational and three translational movements (Figure 1). The 6 DOF are controlled through the speeds of four motors (or their combinations).

To determine the dynamic model of a Quadcopter, some assumptions are necessary:

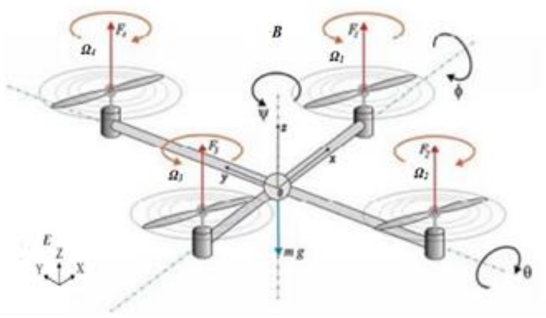

Fig.2. Quadrotor configuration, frame system with a body fixed frame B and the inertial frame E

We find in Table 1 the used symbols and their meanings and in Table 2 the quadcopter parameters values.

Note that, except the parameters m, l, b, d, Jr, I, g…, given in Table 4, that are constant, the rest of the variables are time varying [11].

Table 1. Symbols of the model and their meaning

Symbol	Meaning	Symbol	Meaning
m	The mass of the quadcopter	Ω_i	Angular velocity of each rotor
$I_x I_y I_z$	The inertias around z, y and z	$K_{fax}\, K_{fay}\, K_{faz}$	Frictions Aerodynamics coefficients
l	Thehalf size of quadcopter	$K_{ftx}\, K_{fty} K_{ftz}$	Translation drags coefficients
b,d	Thrust and drag coefficients	ϕ, θ, ψ	Rotation around roll, pitch and yaw axes
J_r	Rotor inertia	Fi	Thrust forces of each rotor
I	Inertia matrix (3x3) of quadcopter	v, Ω	Linear, angular speed of the quadcopter
g	Gravity constant	$S(\Omega)$	Skew-synmmetric matrix

The dynamics of our system is affected by the following physical effects:

The gravity force of the quadcopter:

$$P = mg \tag{1}$$

The thrust forces:

$$F = b\Omega_i^2 \tag{2}$$

The drag from the propellers:

$$F = d\Omega_i^2 \tag{3}$$

Drag along the axes (x, y, z):

$$F_t = k_{ft} v \tag{4}$$

The moments acting on the dynamics of the system are due to the drag, thrust forces and gyroscopic effects.

Moments of thrust forces:

$$M_x = l(F_4 - F_2) \tag{5}$$

$$M_y = l(F_3 - F_1) \tag{6}$$

Moments of drag forces:

$$M_z = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \tag{7}$$

$$M_a = k_{fa} \Omega^2 \tag{8}$$

Gyroscopic effect:

$$M_{gh} = \sum_1^4 \Omega \wedge J_r \, [0 \;\; 0 \;\; (1)^{1+i} \Omega_i \;\;]^T \tag{9}$$

$$M_{gm} = \Omega \wedge J . \Omega \qquad 10)$$

Euler's Formalism is used to express the equations of the forces and moments in matrix form. Thus, we obtain the following equations, which describe the dynamics of our system [11]:

$$\ddot{\Phi} = (-\dot{\theta} S_{\Phi} + \dot{\Psi} C_\theta C_\theta)(\dot{\theta} C_{\Phi} + \dot{\Psi} C_\theta S_{\Phi})\frac{(l_y - l_z)}{l_x} + \frac{bl(\Omega_4^2 - \Omega_2^2)}{l_x} - (+C_{\Phi})\frac{l_{rotor}(\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4)}{l_x} - (\dot{\Phi}_4^2 - 2\Phi\Psi C_\theta S_{\Phi} 2K_{ax} lx) \tag{11}$$

$$\ddot{\theta} = (\dot{\Psi} C_{\Phi} C_\theta - \dot{S_{\Phi}})(\dot{\Phi} - \dot{\Psi} S_\theta)\frac{(l_z - l_x)}{l_y} + \frac{bl(\Omega_3^2 - \Omega_1^2)}{l_y} - (\dot{\Psi} S_\theta - \dot{\Phi})\frac{l_{rotor}(\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4)}{l_y} - (\dot{\theta}^2 C_{\Phi^2} + 2\dot{\theta}\dot{\Psi} C_\theta S_{\Phi} C_{\Phi} + 2\Psi C_\theta S_{\Phi} 2K_{ay} ly \tag{12}$$

$$\ddot{\Psi} = (\dot{\Psi} S_{\Phi} C_{\theta} + \dot{\theta} C_{\Phi})(\dot{\Phi} - \dot{\Psi} S_{\theta})\frac{(l_x - l_y)}{l_z} + \frac{d(-\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2)}{l_z} - (\dot{\Psi} S_{\theta} - \dot{\Phi})\frac{l_{rotor}(\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4)}{l_y} -$$
$$(\dot{\theta}^2 S_{\Phi^2} - 2\dot{\theta}\dot{\Psi} C_{\theta} S_{\Phi} C_{\Phi} + \ 2\Psi C_{\theta} C_{\Phi} 2K_{az} lz$$
(13)

$$\ddot{x} = \frac{C\psi S_{\theta} C_{\Phi} + S\psi S_{\Phi}}{m} b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) - \frac{K_{fx}}{m}\dot{x} \quad (14)$$

$$\ddot{y} = \frac{S\psi S_{\theta} C_{\Phi} - C\psi S_{\Phi}}{m} b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) - \frac{K_{fy}}{m}\dot{y} \quad (15)$$

$$\ddot{z} = -g + \frac{C_{\theta} C_{\Phi}}{m} b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) - \frac{K_{fz}}{m}\dot{z} \quad (16)$$

1.3. Decentralized Nonlinear PID (NPID) Controller

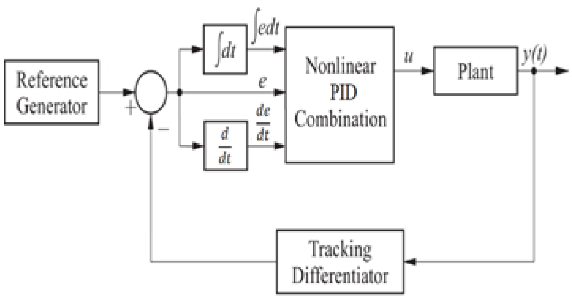

Fig.3. Block diagram of Nonlinear PID controller

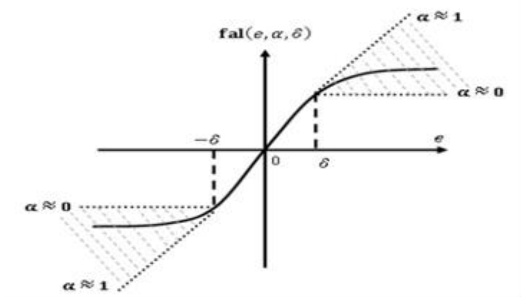

Fig.4. fal(e, α, δ)) function characteristics

Produce the control action, a nonlinear reference generator and a tracking differentiator. The combination of nonlinear terms can provide additional degrees of freedom to achieve a muchimproved system performance. The reference generator in the forward path yields the high quality differential signal of reference and the tracking differentiator in the feedback path yields the feedback differential signal, both in the presence of measurement noise or rapidly changing disturbance signals. The nonlinear PID (NPID) controller action is given by

$$u = K_p \mathbf{fal}(e, \alpha_p, \delta_p) + K_i \mathbf{fal}(\int edt, \alpha_i, \delta_i) + K_d \mathbf{fal}\left(\frac{de}{dt};\ \alpha_d;\ \delta_d\right) \quad (17)$$

$$fal(e, \alpha, \delta) = \begin{cases} |e|^{\alpha} \boldsymbol{sign}\,(e) & |e| > \delta,\ \ \delta < 0 \\ \frac{e}{\delta^{1-\alpha}} & |e| \leq \delta \end{cases} \quad (18)$$

Where a nonlinear function fal(e, α, δ) is given by (12) and(Figure 4); $K_p, K_i\ and\ K_d$ are respectively proportional, integral and derivative gains of the NPID controller; u is the control signal; parameters α_p, α_i and α_d are constants, empirically chosen in the range 0 to 1. When $\alpha_p = \alpha_i = \alpha_d = 1$, the controller becomes a linear PID controller. Henceforth, design of a linear PID controller can be used for initial setting of $K_p, K_i\ and\ K_d$ in (3). δ is a constant, which can be reference generator and tracking differentiator can be respectively expressed as

$$\begin{cases} x_1 = x_2 \\ x_2 = -R_1 \boldsymbol{sat}(x_1 - r(t) + \frac{x_2|x_2|}{2R_1}, \sigma \end{cases} \quad (19)$$

$$\begin{cases} x_3 = x_4 \\ x_4 = -R_2 \boldsymbol{sat}(x_3 - y(t) + \frac{x_4|x_4|}{2R_2}, \sigma \end{cases} \quad 20)$$

Where sat(A, σ) is a saturation function defined by

$$sat(A,) \begin{cases} sign(A), & |A| \geq \sigma \\ \frac{A}{\sigma} \end{cases} \quad (21)$$

r(t) and y(t) are respectively the reference and measured feedback signal of the plant; R1 and R2 are the filter’s design parameters, which can be determined empirically; σ is a small design parameter. The filter parameters determine the rapidity of the transients and the differential tracking performance: large value for R1 and R2 give a fast transient and improved tracking performance. Initial setting for R1 and R2 can be obtained from a linear approximation of (5) and (6) around an operation point [12].

2. RESULTS AND DISCUSSION

First, this work represents the simulated results of the PID control system [13]. Thus, the angles response of the roll, pitch, yaw, and the altitude in the figures (5, 7, 9 and 11). As a result, this work is compared to the simulation results of the nonlinear PID control in the figures (6, 8, 10 and 12).

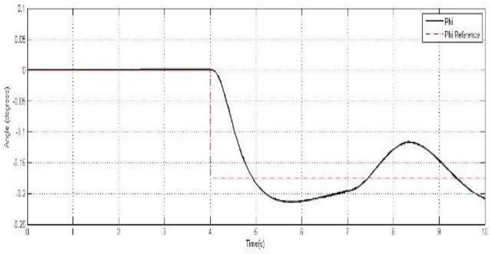

Fig.5. The roll angle control of the Quadcopter using reference model method (dashed line) and PID (solid line)

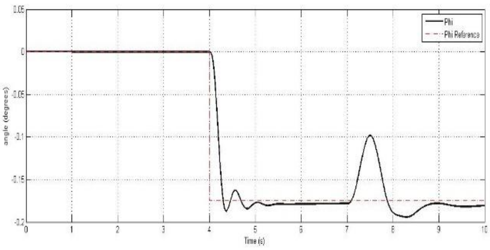

Fig.6. The roll angle control of the Quadcopter using reference model method (dashed line) and NPID (solid line)

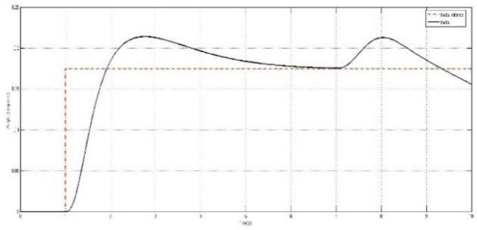

Fig.7. The Pitch angle control of the Quadcopter using reference model method (dashed line) and PID (solid line)

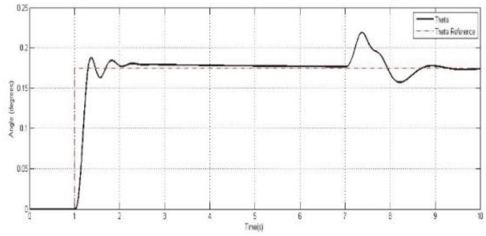

Fig.8. The Pitch angle control of the Quadcopter using reference model method (dashed line) and NPID (solid line)

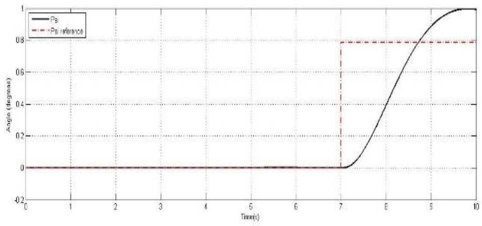

Fig.9. The Yaw angle control of the Quadcopter using reference model method (dashed line) and PID (solid line)

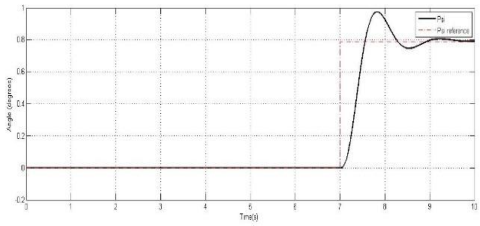

Fig.10. The Yaw angle control of the Quadcopter using reference model method (dashed line) and PID (solid line)

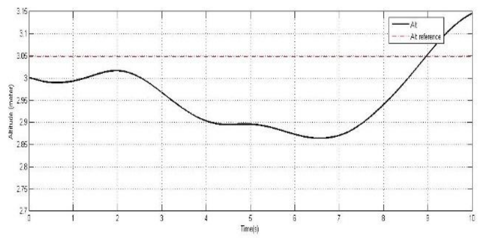

Fig.11. The position Z control of the Quadcopter using reference model method (dashed line) and PID (solid line)

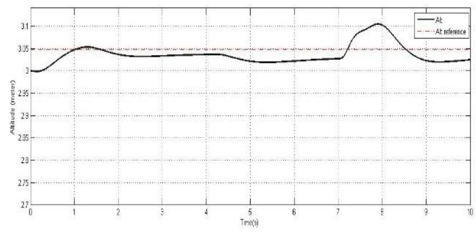

Fig.12. The position Z control of the Quadcopter using reference model method (dashed line) and NPID (solid line)

The illustrated simulation results are presented in Figures 5, 7, 9 and 11. In fact, it shows that classical PID controllers have a response time 4s, with overshoot as it is required in the specifications. The control by NPID based controllers (Figures 6, 8, 10 and 12) also give good results. Yet, the response of the rise time is varying between 2s (for roll) and 1s (for altitude) and with overshoot as it is required in the specifications.

The characteristics of the system response correctly by the two methods are comparable.

The following results show the explanation of each figure:

- The pitch's rise time (Phi) of the NPID controller (figure 6) are stabilized in 1s. Thus, it is faster than the classical PID controller, the one that takes 4s to be stabilized (figure 5).
- The roll's rise time (Theta) of the classical PID controller (figure7) are stabilized in 6s.Therfore, it is slower than the nonlinear PID controller, in fact it takes only 1s to be stabilized (figure 8).
- The yaw's rise time (Psi) of the NPID controller (figure 10) are stabilized in 1s. Consequently, it is faster than the classical PID controller, the one that takes 6s to be stabilized (figure 9).
- In the first hand, the altitude diverged to the given reference in the classical PID controller (figure11). In the other hand, the altitude converged the previous given reference within the nonlinear PID controller (figure 12).

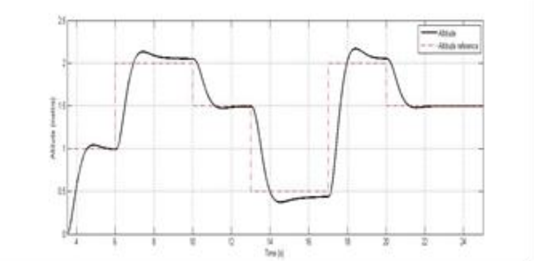

Fig.13. Corrected response of quadcopter's altitude

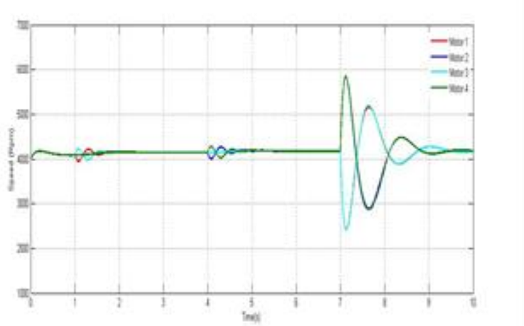

Fig.14. Motors speed responses of quadcopter

Table 2. PID controllers parameters based on reference model method

Controller	Kp	Ki	Kd
Angle Φ	2.0	1.1	1.2
Angle θ	2.5	1.1	1.2
Angle Ψ	4	0.5	3.5
Angle Ψ	2.0	1.1	3.3

Table 3. NPID controllers parameters based on reference model method

Controller	Alpha	Delta
Angle Φ	[2.0 1.5 1.5]	[10 10 10]
Angle θ	[2.0 1.5 1.5]	[10 10 10]
Angle Ψ	[2.0 1.5 1.5]	[10 10 10]
Angle Ψ	[2.0 1.5 1.5]	[10 10 10]

Table 4. Constant parameters of the quadricopter

M	**0.65 [kg]**	I_z	**1.3 10-3[Kg m2]**
G	9.81 [m/s2]	K_{ax}	5.567 10-4 [N/rad/s]
i	0.23 [m]	K_{ay}	5.567 10-4 [N/rad/s]
b	3.13 10-5 [N/rad/s]	K_{az}	6.354 10-4 [N/rad/s]
d	$7.5\ 10^{-7}$ [N/rad/s]	K_{fx}	5.567 10-4 [N/rad/s]
j_r	$6.5\ 10^{-5}$ [kg m2]	K_{fy}	5.567 10-4 [N/rad/s]
I_x	$7.5\ 10^{-3}$ [kg m2]	K_{fz}	6.354 10-4 [N/rad/s]
I_z	$7.5\ 10^{-3}$[kg m2]		

4. CONCLUSION

This paper presents the modeling and control of an unmanned airborne vehicle (a Quadcopter) using nonlinear PID controllers. The Quadcopter model using Euler Newton formalism has been presented. For execute an efficient control procedure for stabilizing Quadcopter, four Nonlinear PIDs have been proposed. The obtained results using the nonlinear PID controllers show the efficiency of the proposed controllers it present a response with less error and minimal over shoot compared to the results of classical PID controller. At last but not at least, the goal was achieved, and both of the approaches are able of controlling the Quadcopter to a wanted position with the speed imposed while remaining stable.

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