IJRCS

International Journal of Robotics and Control Systems
Vol. 4, No. 4, 2024, pp. 2095-2118
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

ASCEE

Adaptive Fuzzy Logic Control of Quadrotor

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ARTICLE INFO

Article history
Received August 23, 2024
Revised October 02, 2024
Accepted November 20, 2024

Keywords
Quadrotor UAV;
PID Controller;
Fuzzy logic PID Controller;
Adaptive Fuzzy Logic PID Controller;
Dynamics

ABSTRACT

Intelligent controllers are created in this work to regulate the attitude of quadrotor UAVs (Unmanned Aerial Vehicles). Quadrotors offer a wide range of real-time applications, including surveillance, inspection, search and rescue, and lowering the human force safety risks. The kinematics of quadrotor are similar to those of an inverted pendulum. To maintain balance, they must continuously adjust orientation and thrust. External disturbances, like wind or sudden movements, can easily destabilize them, necessitating sophisticated control algorithms for stable flight and precise maneuverability. This instability poses a significant challenge in designing and operating quadrotors, especially in dynamic environments where real-time adjustments are crucial for maintaining control. To avoid any form of damage, a mathematical model should be constructed first, followed by the implementation of various control systems. A thorough simulation model for a Quadrotor is presented in this project. The quadrotor is a six degrees of freedom object, it has six variables to express its position in space where (x, y and z) represent the distance of quadrotor from an earth fixed inertial form to its center of mass, main movements of roll, pitch, yaw are the Euler angles representing the orientation of the quadrotor at each axis. The proposed control techniques are applied separately: PID Controller, Fuzzy Logic PID Controller and Adaptive Fuzzy Logic PID Controller. The purpose of this work is to asses these control techniques for the motions of a Quadrotor in terms of better performance, tracking error reduction, and stability. MATLAB software is used for modeling, control, and simulation. According to the obtained results, the PID controller provided the best settling time. In addition, when we applied fuzzy logic PID control to adjust the pitch angle, the system experienced overshoot; however, with Adaptive Fuzzy Logic PID controller, the system provided the best performance according to the desired criteria.

1. Introduction

Unmanned aerial vehicles UAV are characterized by flexibility and rapid reaction capability [1]. Route planning is one of the challenges in countered in the design of quadcopter control applications this is due to several operational considerations, such as optimizing speed, managing multi-trip

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operations, and estimating energy consumption [2]. These days, scientists are interested in more than only UAV dynamics; they are also searching for the best control systems, taking into account cost-cutting, sensor and actuator integration, and design issues [3]. The usage of drones is changed, and several civilian applications have become competitive [4], UAVs have attracted increased attention from both civilian and has been widely used in the field of military reconnaissance [5]-[10], and in industrial and commercial mechatronics products [11], environmental monitoring, environmental monitoring, road networks infrastructure maintenance, and a lot of other helpful uses that erases its bloody history [12]-[15]. The majority of quadcopters available discuss roll, pitch, and yaw control. It’s recognized that attitude, altitude, and position control needed to be prioritized and the assistance with control systems was necessary [14]. The position controller aids in tracking the intended trajectory, whereas the attitude controller maintains the quadrotor’s desired orientation [15].

PID controller, fuzzy logic PID controller and adaptive fuzzy logic PID controller have been applied in several research work to control the roll, pitch, yaw angles, and altitude, in addition to x and y positions. Jaehyun, Y. Jaehyeok, D. proposed an optimal PID algorithm where they used dynamic equations of motion to obtain the optimal values for stabilizing the attitude of drone [16]. T. Huang, D. Huang and D. Luo. proposed a control scheme based on lookup table fuzzy proportional-integral-derivate (PID) controller for the quadrotor movement control. The proposed control scheme uses three lookup table-based fuzzy logic controllers to control the different movement ranges of a quadrotor (roll, pitch, and yaw) to achieve stability [17]. He, Z H. Gao, W L. He, X K. Wang, M J. Liu, Y L. Song, Y. et al. proposed the adaptive fuzzy logic PID controller and a Fuzzy logic PID controller to optimize the control parameters of PID in order to improve the dynamic, static performance and adaptability of attitude control of plant protection UAV [18].

In this work an adaptive Fuzzy logic controller of quadcopter is proposed, where individual controllers for all basic motions of a Quadrotor are introduced for greater performance. In addition, a PID controller is also proposed in order to provide the desired performance according to four principal characteristics (rapidity, stability, static accuracy and depreciation). However, it is not possible to obtain all these characteristics at the same time hence a compromise has been made.

The Fuzzy logic PID controller emulates human reasoning in its qualitative and approximate aspects to represent and process imprecise and approximate knowledge. In the real world, the way of describing this world, the way of qualifying everything that exists around us are all vague and imprecise. Its concept can recapitulate into: Unlike binary logic, fuzzy logic allows more than two values of truth for a proposition, proposition can be for example almost true, Fuzzy logic PID taking into account inaccuracies and uncertainties, instead of having a numerical evaluation of the solution, fuzzy logic allows a qualitative evaluation, closer to natural language and Fuzzy logic PID makes it possible to formulate linguistic quantifications from linguistic variables.

The Adaptive Fuzzy logic control strategy is used to allow the real-time system to automatically adjust its value in response to any external fault. Adaptive Fuzzy logic PID is a hybrid of adaptive fuzzy and PID control techniques, as the name suggests.

The Section 2 of this paper presents the dynamic modeling of the quadcopter and describes its mathematical representation. The Section 3 proposed the quadrotor control methods as: PID controller, PID fuzzy logic controller, and adaptive fuzzy logic PID controller of quadrotor. Section 4 is dedicated to simulation results and discussion where a comparative study of three methods is presented.

2. The Dynamic Modeling of Quadrotor

Dynamic modeling of a quadcopter presents a crucial role in creating control strategies because it accurately reflects the physical behavior of the quadcopter, which is inherently unstable and subject to various factors such as aerodynamic forces, gravity, and disturbances such as wind. This model provides an understanding of the quadcopter's response to control inputs, external forces, and spatial conditions [19], [20]. In this section, the quadrotor mathematical model is presented, based on Newton and Euler equations. This model consists of actuators, propellers, and the physical model parameters [21]-[24]. The Euler dynamic model is derived to represent the multirotor equation of motion [25], [26].

Quadrotor's localization is determined via six DOF (degree of freedom) object [27], it has six variables to express its position in space (x, y, z, φ, θ and ψ) [28]-[30]. For the distance, the quadrotor is represented by the x, y and z variables from an Earth fixed inertial form to its center of mass along the x, y, and z-axes respectively, while φ, θ and ψ are called the Euler angles representing the orientation of the aircraft at each axis. φ is the roll angle, it is the angle about the x-axis, θ is the pitch attitude approximately the y-axis, and ψ is the yaw attitude about the z-axis [31], [32]. The pitch and roll angles are for the attitude, the yaw angle is referred to as the heading of the quadrotor [33]. Fig. 1 shows the Cross-type structure of quadrotor UAV [34].

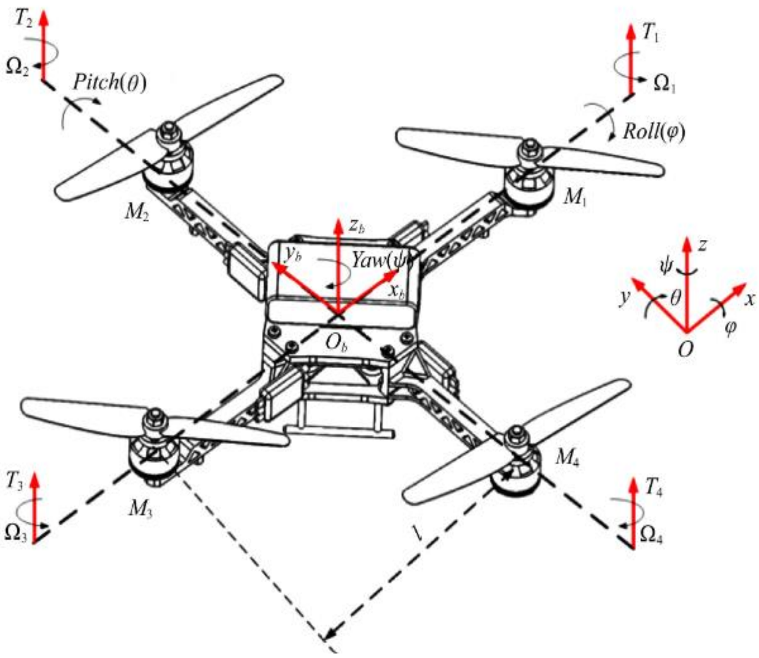

Fig. 1. Cross type structure quadrotor UAV [34]

Under these assumptions, the quadrotor may be considered as a rigid body in space to which are added the aerodynamic forces caused by the rotation of the rotor. The mathematical model of the quadcopter UAV is presented in and the dynamics equations are given by:

$$\begin{cases} \dot{\xi} = \mathrm{v} \\ m\ddot{\xi} = F_f + F_t + F_g \\ J\,\Omega = -(\Omega \wedge \mathrm{J}\,\Omega) + \Gamma_t - \Gamma_g - \Gamma_t \end{cases} \tag{1}$$

Where, ξ : represent the position of the center of mass of the quadrotor,

m: represent the total mass of the structure

J: is the matrix of inertia at the center of mass

Ω : is the angular speed

Γ_t : Torque generated by the rotors of the quadrotor

Γ_g : is the gyroscopic torque.

because the structure of the quadrotor is supposed to be symmetrical.

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

I_x, I_y and I_z are the moments of inertia about three axes.

The angular speed Ω of the quadrotor is presenting as:

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

In the case where the quadrotor performs angular movements of low amplitude, the vector Ω can be simplified to $(\dot{\varphi} \quad \dot{\theta} \quad \dot{\psi})^T$.

The matrix R is the homogeneous transformation matrix linking the frame related to the solid of the inertial frame [35].

$$R(\psi,\theta,\varphi) = Rot(z,\psi) * Rot(y,\theta) * Rot(x,\varphi)$$
$$= \begin{bmatrix} \cos\theta\cos\psi & \cos\psi\sin\theta\sin\varphi - \sin\psi\cos\varphi & \cos\psi\sin\theta\cos\varphi + \sin\psi\sin\varphi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\varphi + \cos\psi\cos\varphi & \sin\psi\sin\theta\cos\varphi - \cos\psi\sin\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\varphi\cos\theta \end{bmatrix} \tag{4}$$

$\vartheta(\Omega)$: is the anti-symmetric matrix; for a given vector, $\Omega = [\Omega_1 \quad \Omega_2 \quad \Omega_3]^T$ it is defined as follows:

$$\vartheta(\Omega) = \begin{pmatrix} 0 & -\Omega_3 & \Omega_2 \\ \Omega_3 & 0 & -\Omega_1 \\ -\Omega_2 & \Omega_1 & 0 \end{pmatrix} \tag{5}$$

F_f : is the resultant of the thrust forces generated by the four rotors. It is given by:

$$F_f = \begin{pmatrix} \cos\psi\sin\theta\cos\varphi + \sin\psi\cos\varphi \\ \sin\psi\sin\theta\cos\varphi - \cos\psi\sin\varphi \\ \cos\varphi\cos\theta \end{pmatrix} * \sum_{i=1}^{4} F_i \tag{6}$$

Where:

$$F_i = K_p \omega_i^2 \tag{7}$$

Where K_p denotes the lift coefficient and ω_i denotes the angular velocity of the rotor.

F_t : is the resultant of the drag forces along (X, Y, Z). It is given by:

$$F_t = \begin{pmatrix} -K_{ftx} & 0 & 0 \\ 0 & -K_{fty} & 0 \\ 0 & 0 & -K_{ftz} \end{pmatrix} \tag{8}$$

Where K_{ftx} ,K_{fty} and K_{ftz} are the drag force coefficients along the three axes.

F_g : regroups the forces related to the gravity:

$$F_g = \begin{pmatrix} 0 \\ 0 \\ -mg \end{pmatrix} \tag{9}$$

Γ_f : represents the vector resulting from the moments applied to the structure of the quadrotor:

$$\Gamma_f = \begin{bmatrix} d(F_4 - F_2) \\ d(F_3 - F_1) \\ K_d(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2 \end{bmatrix} \quad (10)$$

d : is the distance between the center of mass of the quadrotor and the axis of rotation of the rotor,

K_d : is the drag coefficient,

F_1, F_2, F_3 and F_4 are the thrust forces of the four rotors.

Γ_a : represents the vector resulting from friction due to aerodynamic torques:

$$\Gamma_a = \begin{pmatrix} K_{fax} & 0 & 0 \\ 0 & K_{fay} & 0 \\ 0 & 0 & K_{faz} \end{pmatrix} \Omega^2 \quad (11)$$

K_{fax}, K_{fay} and K_{faz} : are the aerodynamic friction coefficients along the three axes.

Γ_g: represents all the torques due to gyroscopic effects:

$$\Gamma_g = \sum_{i=1}^{4} \Omega \wedge J_r \begin{pmatrix} 0 \\ 0 \\ (-1)^{i+1} \omega_i \end{pmatrix} \quad (12)$$

Where J_r and ω_i represent the inertia and angular velocity, respectively, of the rotor in question.

The dynamic model which governs the quadrotor is given by [36]:

$$\begin{cases} \ddot{x} = \frac{1}{m}\{(\cos\psi \sin\theta \cos\varphi + \sin\psi \cos\varphi)\mathrm{U}_1 - K_{ftx}\dot{x}\} \\ \ddot{y} = \frac{1}{m}\{(\sin\psi \sin\theta \cos\varphi - \cos\psi \sin\varphi)\mathrm{U}_1 - K_{fty}\dot{y}\} \\ \ddot{z} = \frac{1}{m}\{(\cos\varphi \cos\theta)\mathrm{U}_1 - K_{ftz}\dot{z}\} - g \\ \ddot{\varphi} = \frac{1}{I_x}\left[\dot{\theta}\,\dot{\psi}\,(I_y - I_z) + d\,\mathrm{U}_2 - K_{fax}\,\dot{\varphi}^2 - J_r\bar{\Omega}\,\dot{\theta}\right] \\ \ddot{\theta} = \frac{1}{I_y}\left[\dot{\varphi}\,\dot{\psi}\,(I_z - I_x) + d\,\mathrm{U}_3 - K_{fay}\,\dot{\theta}^2 + J_r\bar{\Omega}\,\dot{\varphi}\right] \\ \ddot{\psi} = \frac{1}{I_z}\left[\dot{\varphi}\,\dot{\theta}\,(I_x - I_y) + \mathrm{U}_4 - K_{faz}\,\dot{\psi}^2\right] \end{cases} \quad (13)$$

Where, the control inputs of the quadrotor U_1, U_2, U_3 and U_4 are written according to the angular speeds of the four rotors as follows:

$$\begin{bmatrix} \mathrm{U}_1 \\ \mathrm{U}_2 \\ \mathrm{U}_3 \\ \mathrm{U}_4 \end{bmatrix} = \begin{bmatrix} K_p & K_p & K_p & K_p \\ 0 & -K_p & 0 & K_p \\ -K_p & 0 & K_p & 0 \\ -K_d & K_d & -K_d & K_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (14)$$

And:

$$\bar{\Omega} = (\omega_1 - \omega_2 + \omega_3 - \omega_4) \quad (15)$$

The model (13) developed previously can be rewritten in the state space in the form

$$\dot{x} = f(x) + g(x)\mathrm{U} \quad (16)$$

Considering: $$X = [x_1 \dots \dots \dots x_{12}]^T \tag{17}$$

The system state trajectory X describes the position of the quadcopter in space and its linear and angular velocities as follows [33], [37]:

$$X = [x \quad \dot{x} \quad y \quad \dot{y} \quad z \quad \dot{z} \quad \psi \quad \dot{\psi} \quad \theta \quad \dot{\theta} \quad \varphi \quad \dot{\varphi}] \tag{18}$$

From (13) and (18) we obtain the dynamic model of quadrotor as [16]:

$$\begin{cases} \dot{x_1} = x_2 \\ \dot{x_2} = a_9\, x_2 + U_x \dfrac{U_1}{m} \\ \dot{x_3} = x_4 \\ \dot{x_4} = a_{10}\, x_4 + U_y \dfrac{U_1}{m} \\ \dot{x_5} = x_6 \\ \dot{x_6} = a_{11}\, x_6 + (\cos x_9 \, \cos x_{11}) \dfrac{U_1}{m} - g \\ \dot{x_7} = x_8 \\ \dot{x_8} = a_8\, {x_8}^2 + a_7\, x_{10}\, x_{12} + b_3\, U_4 \\ \dot{x_9} = x_{10} \\ \dot{x_{10}} = a_5\, {x_{10}}^2 + a_4\, x_8\, x_{12} + a_6\, \bar{\Omega}\, x_{12} + b_2\, U_3 \\ \dot{x_{11}} = x_{12} \\ \dot{x_{12}} = a_2\, {x_{12}}^2 + a_1\, x_{10}\, x_8 + a_3\, \bar{\Omega}\, x_{10} + b_1\, U_2 \end{cases} \tag{19}$$

And

$$\begin{cases} U_x = \cos x_{11} \sin x_9 \cos x_7 + \sin x_{11} \sin x_7 \\ U_y = \cos x_{11} \sin x_9 \sin x_7 - \sin x_{11} \cos x_7 \end{cases} \tag{20}$$

The rotor is a set consisting of a DC motor driving a propeller via a reduction gear. The DC motor is governed by the following dynamics:

$$\begin{cases} V = ri + L\dfrac{di}{dt} + K_e \omega \\ K_m = J_r + C_s + K_r \omega^2 \end{cases} \tag{21}$$

The various motor parameters are defined as follows:

V: is the motor's input voltage.

ω : is the motor's angular velocity.

K_e, K_m: are constants for the electrical and mechanical torques respectively.

K_r: is the load torque constant.

r: designates the resistance of the motor.

J_r: designates the inertia of the rotor.

C_s: represents the friction.

The inductive effect is negligible due to the motor's small size, which is a common practice in quadrotor modeling. Hence, the dynamic model of the motors is approximated by:

$$\dot{\omega}_i = b\, V_i - \beta_0 - \beta_1 \omega_i - \beta_2 {\omega_i}^2 \quad i \in [1\,, 4] \tag{22}$$

3. Quadrotor Control Methods

In this section we described three methods for controlled the quadrotor, as PID control, Fuzzy Logic PID control and Adaptive Fuzzy Logic control.

3.1. PID Control

PID controller is a common linear control technique, however when applied to quadrotor UAVs, it results in poor performance such as a large over-shoot and long adjustment time. Consequently, this control method limits the quadrotor's stability and accuracy in practical applications [38]-[41]. PID controller is used in most industrial control operations due to its simple structure, implementation and efficiency [12], [42]-[44]. PID controller is the most common controller in any system with the advantage of its flexibility and straightforward design [45], It contains three actions at the same time. Where the control law is given by:

$$u(t) = K_p e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D\,\frac{de(t)}{dt} \tag{23}$$

Its transfer function has the following form:

$$C(s) = K\left[1 + \frac{1}{T_I.s} + T_D.s\right] \tag{24}$$

The classical PID has limitations despite its good performance. The latter generally degrades in the presences of disturbances. There are several methods for determining the parameters of the P, PI, and PID controllers [16], [46]. A PID control consists of three units: proportional (K_p), integral (K_i), and derivative (K_d) [47]. Table. 1 shows how to determine the PID gains using Ziegler and Nichols method.

Table 1. Ziegler and Nichols method for finding the P, PI and PID parameters

	Parameters		
	K_p	K_i	K_d
P	$\frac{T_a}{T_u}\cdot\frac{1}{K}$	/	/
PI	$\frac{T_a}{T_u}\cdot\frac{0.9}{K}$	$3.33T_u$	/
PID	$\frac{T_a}{T_u}\cdot\frac{1.2}{K}$	$2T_u$	$0.5T_u$

3.1.1. PID Control of Quadrotor

For the control of the quadrotor, we need four PID controllers for each motor, and six PID controllers for the six degrees of freedom. For the purpose to control the motors of the quadrotor the input voltage in discrete time can be defined as follow:

$$Vin(k) = Vin(t-1) + K_{PM}e_M(k) + K_{DM}[e_M(k) - e_M(k-1)] + K_{IM}[e_M(k) - 2e_M(k-1) + e_M(k-2)] \tag{25}$$

Such that: Vin is: the input voltage of the motor.

The error between the referential speed and the desired speed

$$e_M(k) = Wref(k) - W(k) \tag{26}$$

The Ziegler-Nichols method, traditionally used for tuning PID controllers, has been adapted to quadrotor dynamics by taking into account the unique characteristics of the system, such as its multi-input and multi-output nature and the coupling between linear movements. and angular. For the quadrotor, parameters such as critical gain and period.

Using the Ziegler Nichols method, we obtain the desired output by tuning the PID controller, as a result: $K_u = 0.2$ and $T_u = 0.5$ so that $K_{PM} = 0.12$, $K_{DM} = 0.25$ and $K_{IM} = 0.6$.

3.1.1.1. Roll Controller

The control input for controlling the quadrotor's roll angle can be defined as:

$$U2(k) = K_{P\theta}e_\theta(k) + K_{D\theta}[e_\theta(k) - e_\theta(k-1)] + K_{I\theta}[e_\theta(k) - 2e_\theta(k-1) + e_\theta(k-2)] \tag{27}$$

The error between the referential roll angle and the desired roll angle is:

$$e_\theta(k) = \theta ref(k) - \theta(k) \tag{28}$$

Adjust the PID controller with the parameters $K_{P\theta}$=1, $K_{D\theta}$ = 0.3, and $K_{I\theta}$ = 0.001 in order to get the required output.

3.1.1.2. Pitch Controller

The equation below can be used to define the control input for pitch angle.

$$U3(k) = K_{P\varphi}e_\varphi(k) + K_{D\varphi}\left[e_\varphi(k) - ee_\varphi(k-1)\right] + K_{I\varphi}\left[e_\varphi(k) - 2e_\varphi(k-1) + e_\varphi(k-2)\right] \tag{29}$$

The error between the referential pitch angle and the desired pitch angle is:

$$e_\varphi(k) = \varphi ref(k) - \varphi(k) \tag{30}$$

To produce the desired output, set the PID controller's settings to $K_{P\varphi}$ =1, $K_{D\varphi}$ = 0.3, and $K_{I\varphi}$ = 0.001.

3.1.1.3. Yaw Controller

The equation below can be used to define the control input for yaw angle.

$$U4(k) = K_{P\psi}e_\psi(k) + K_{D\psi}\left[e_\psi(k) - e_\psi(k-1)\right] + K_{I\psi}\left[e_\psi(k) - 2e_\psi(k-1) + e_\psi(k-2)\right] \tag{31}$$

The error between the referential yaw angle and the desired yaw angle is:

$$e_\psi(k) = \psi ref(k) - \psi(k) \tag{32}$$

Set the PID controller's parameters to $K_{P\psi}$=1.6, $K_{D\psi}$= 0.4, and $K_{I\psi}$= 0.03 to get the desired result.

3.1.1.4. Altitude Controller

The implementation of the Altitude or Z controller differs from that of the Roll, Pitch, and Yaw controllers because the nonlinearities seen in z dynamics must be eliminated. The Z controller's input can be specified as:

$$U1(k) = K_{PZ}e_Z(k) + K_{DZ}[e_Z(k) - e_Z(k-1)] + K_{IZ}[e_Z(k) - 2e_Z(k-1) + e_Z(k-2)] \tag{33}$$

The error between the referential Z position and the desired Z position as:

$$e_Z(k) = Zref(k) - Z(k) \tag{34}$$

Set the PID controller's parameters to K_{PZ} =10, K_{DZ} = 8, and K_{IZ} = 9.1 to get the de-sired result.

3.1.1.5. Position Controller

So far, the quadrotor can stay forward and level with the ground, this is obviously good but it is still not perfect, because if an unexpected force is applied to the quadcopter, it might introduce a little roll or pitch angle so that it will change its position, to eliminate this problem, we need to change those two angles by the X and Y positions by using PID controller for each position.

$$\theta ref(k) = K_{PX}e_X(k) + K_{DX}[e_X(k) - e_X(k-1)] + K_{IX}[e_X(k) - 2e_X(k-1) + e_X(k-2)] \tag{35}$$

$$\varphi ref(k) = K_{PY}e_Y(k) + K_{DY}[e_Y(k) - e_Y(k-1)] + K_{IY}[e_Y(k) - 2e_Y(k-1) + e_Y(k-2)] \tag{36}$$

The error between the referential X position and the desired X position,

$$e_X(k) = \mathrm{X}ref(k) - \mathrm{X}(k) \tag{37}$$

The error between the referential Y position and the desired Y position:

$$e_Y(k) = \mathrm{Y}ref(k) - \mathrm{Y}(k) \tag{38}$$

Set the PID controller's parameters of the X position to K_{PX} = 0.04, K_{DX} = 0.15, and K_{IX} = 0.0002, but the parameters of the Y position should be negative because when the pitch angle is positive the quadrotor goes to the negative side of the Y axes and vice versa, K_{PY} = -0.04, K_{DY} = -0.15, and K_{IY} = -0.0002

3.2. Fuzzy Logic Control (FLC)

There are several stories of fuzzy logic that one can come across. Most of them are presented in the manner of a history of ideas, according to some researchers, the evolution of fuzzy logic is based on a continuation of the work carried out by Lukasiewicz on logic with many values of truth, the use of a conventional Fuzzy Proportional-Integral-Derivative (FPID) controller to control the angle [48]. Fuzzy PID controller is designed to stabilize the quadcopter [50], The principle of logic with many truth-values consists in defining several possibilities (values in the interval [0, 1]) that an assertion is true or false, which makes it possible to take into account an infinity of degrees of truth unlike binary logic, which only makes it possible to express two truth values (“true” and “false”). In this part we describe the FLC, an adaptive FLC, and we used them to control the quadrotor, A Fuzzy control system is composed of Fuzzification, Fuzzy rule bases, Fuzzy inference, and Defuzzification, the advantages of Fuzzy Logic is its simple architecture that make it understandable and easy to modify [37].

3.2.1. FLC Based Quadrotor Control

It is therefore necessary to fuzzify the input measurements and defuzzify the outputs to obtain precise outputs. The membership function is in general triangular or trapezoid function, which can be employed in nonlinear systems like a Quadrotor since they require dynamic variation. The primary goal of the Fuzzification process is to turn traditional data into membership functions, which explain how the input should be fuzzified [34]. The Fig. 2 shows the control strategy of the Fuzzy Logic Controller.

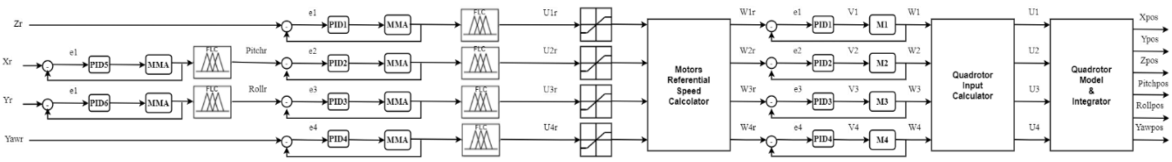

Fig. 2. Fuzzy logic control

Because the fuzzy results cannot be used in system applications, the fuzzy data must be transformed to crisp data before being processed. Defuzzification is the step that makes it possible to go from a fuzzy subset resulting from the aggregation of the Rules to a single decision (crisp value). The linguistic fuzzy rule of the fuzzy control PID is shown in Fig. 3.

The general form of the fuzzy rules is given as follows:

If X_1 is x_1 and/or X_2 is x_2 and/or … X_n is x_n then Y is y.

The degree of membership of the linguistic variable in the fuzzy subset depends on the degree of validity of the premise (degree of membership of the V.L in the fuzzy S-E).

The most propositions in premise are checked, the more recommended action for the outputs must be respected. To know the degree of truth of the fuzzy proposition, we must define the fuzzy implication. The fuzzy implication between two propositions is a fuzzy proposition. The truth value of the fuzzy proposition obtained by using a fuzzy implication between two elementary fuzzy propositions is defined by the membership function μ_R of a fuzzy relation R between the universes U_X and U_Y, which is expressed, for any (x, y) of $U_X \times U_Y$, U_Y by:

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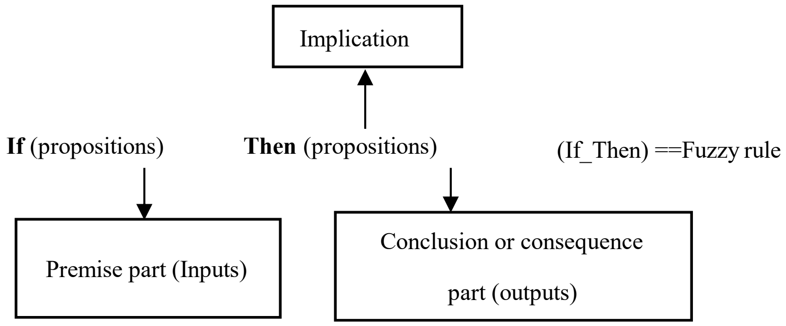


Fig. 3. Linguistic fuzzy rule

$$\mu_R(x,y) = \emptyset(\mu_A(x), \mu_B(x)) = \begin{cases} \min(\mu_A(x), \mu_B(x)) & \text{of MAMDANI} \\ \mu_A(x) \times \mu_B(x) & \text{of LARSEN} \end{cases} \tag{39}$$

There are several possible methods of defuzzification. The two main methods are:

- Centroid method.
- Average of the maxima Method.

The output is the abscissa of the centroid of the surface of the membership function characterizing the fuzzy subset resulting from the aggregation of the conclusions:

$$\text{output} = \frac{\int_U y\mu(y)dy}{\int_U \mu(y)dy} \tag{40}$$

3.2.2. Fuzzy Rules

Six distinct controllers for roll, pitch, yaw, X position, Y position, and Z position have been designed for quadrotor control. Table 2 present the linguistic rules of Fuzzy logic control of quadrotor:

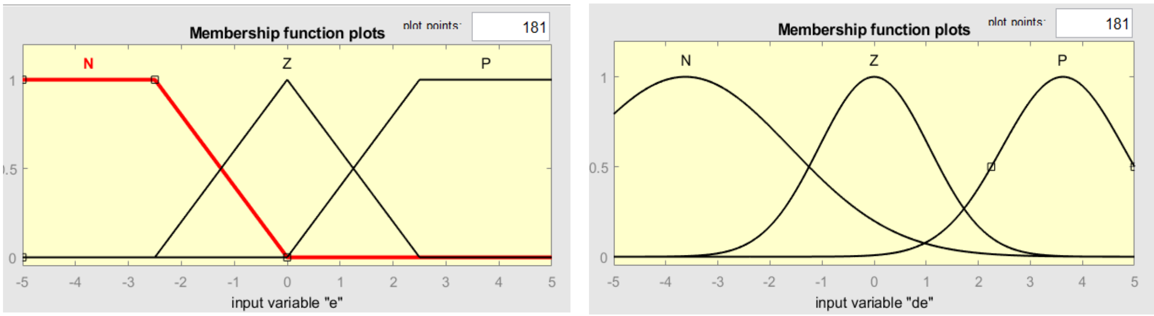
Table 2. Quadrotor rule base

$\frac{dE}{dt}$	Rule base				
	NB	**N**	**Z**	**P**	**PB**
N	GDM	GD	GD	S	GU
Z	GUM	GD	S	GU	GUM
P	GD	S	GU	GUM	GUM

- N: Negative.
- Z: Zero.
- P: Positive.
- GUM: Go Up Much.
- GU: Go Up.
- S: Stand.
- GDM: Go Down Much.
- GD: Go Down.
- NB: Negative Big.
- PB: Positive Big.

Triangular, trapezoid, and Gaussian membership functions are employed for quadrotor control. The input range is [-4, 4], whereas the output variables are [-12.22, 12.22] for U_1, [-3.05, 3.05] for U_2 and U_3, [-0.066, 0.066] for U_4, and [-1, 1] for pitch and roll. As demonstrated in the following pictures, the membership in MATLAB utilizing “fuzzy” instruction is defined for each controller.

Fig. 4 illustrates the inputs error of membership functions of fuzzy logic control, where (a) is the Error Input and (b) is the Derivative of Error Input. The Output Membership Function is show in Fig. 5.



(a) (b)

Fig. 4. Membership functions: (a) error input; (b) derivative of error input

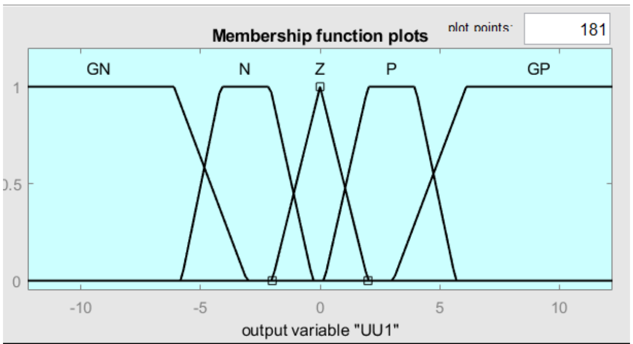


Fig. 5. Output membership function

3.2.2.1. Roll Controller

For the control input of a roll controller equation. The roll controller equation script uses the "evalfis" instruction and is shown as follows. Saturation code utilized in the controller to avoid any condition that might take value out of the defined range.

$$\mathrm{U2}(k) = K_{P\theta}e_\theta(k) + K_{D\theta}[e_\theta(k) - e_\theta(k-1)] + K_{I\theta}[e_\theta(k) - 2e_\theta(k-1) + e_\theta(k-2)] + evalfis(\mathrm{U3}(k), [e(k)\,, e(k-1)]) \quad (41)$$

Such that: e_θ: is the error between the referential roll angle and the desired roll angle:

$$e_\theta(k) = \theta ref(k) - \theta(k) \quad (42)$$

3.2.2.2. Pitch Controller

For the control input of a pitch controller equation. The pitch controller equation script uses the "evalfis" instruction and is shown as follows. Saturation code utilized in the controller to avoid any condition that might take value out of the defined range.

$$\mathrm{U3}(k) = K_{P\varphi}e_\varphi(k) + K_{D\varphi}\left[e_\varphi(k) - ee_\varphi(k-1)\right] + K_{I\varphi}e_\varphi(k) - 2e_\varphi(k-1) + e_\varphi(k-2)evalfis(\mathrm{U3}(k), [e(k)\,, e(k-1)]) \quad (43)$$

Such that:

evalfis: is the instruction of the Fuzzy Logic Controller.

e_φ: is the error between the referential pitch angle and the desired pitch angle,

$$e_\varphi(k) = \varphi ref(k) - \varphi(k) \quad (44)$$

3.2.2.3. Yaw Controller

The equation below can be used to define the control input for yaw angle.

$$\mathrm{U4}(k) = K_{P\psi}e_{\psi}(k) + K_{D\psi}\left[e_{\psi}(k) - e_{\psi}(k-1)\right] + K\_I\psi\ [e\_\psi\ (k) - 2e\_\psi\ (k-1) \\ +e\_\psi\ (k-2)] + \ evalfis(U4(k), [e(k)\ , e(k-1)]) \tag{45}$$

Such that:

e: is the error between the referential yaw angle and the desired yaw angle,

$$e_{\psi}(k) = \psi ref(k) - \psi(k) \tag{46}$$

3.2.2.4. Altitude Controller

The altitude control input is specified as the control input for the quadrotor's Z position can be defined as:

$$\mathrm{U1}(k) = K\_PZ\ e\_Z\ (k) + K\_DZ\ [e\_Z\ (k) - e\_Z\ (k-1)] + K\_IZ\ [e\_Z\ (k) - 2e\_Z\ (k-1) \\ +e\_Z\ (k-2)] + evalfis(\mathrm{U1}(k), [e(k)\ , e(k-1)]) \tag{47}$$

Such that: e_Z: is the error between the referential Z position and the desired Z position,

$$e_Z(k) = \mathrm{Z}ref(k) - \mathrm{Z}(k) \tag{48}$$

3.2.2.5. Position Controller

The quadrotor can stay forward and level with the ground, this is obviously good but it is still not perfect, because if an unexpected force is applied to the quadcopter, it might introduce a little roll or pitch angle so that it will change its position, to eliminate this problem, we need to change those two angles by the X and Y positions by using Fuzzy PID controller for each position.

$$\theta ref(k) = K_{PX}e_X(k) + K_{DX}[e_X(k) - e_X(k-1)] + K_{IX}[e_X(k) - 2e_X(k-1) + e_X(k-2)] \\ +evalfis(\theta ref(k), [e(k)\, , e(k-1)]) \tag{49}$$

$$\varphi ref(k) = K_{PY}e_Y(k) + K_{DY}[e_Y(k) - e_Y(k-1)] + K_{IY}[e_Y(k) - 2e_Y(k-1) + e_Y(k-2)] \\ +evalfis(\varphi ref(k), [e(k)\, , e(k-1)]) \tag{50}$$

Such that: e_X: is the error between the referential X position and the desired X position,

$$e_X(k) = \mathrm{X}ref(k) - \mathrm{X}(k) \tag{51}$$

e_Y: is the error between the referential Y position and the desired Y position,

$$e_Y(k) = \mathrm{Y}ref(k) - \mathrm{Y}(k) \tag{52}$$

To ensure the stabilization and tracking objectives of the quadrotor in the presence of model perturbations, a composite adaptive fuzzy PID controller is proposed in the following section.

3.3. Adaptive Fuzzy PID Based Controller of Quadrotor

The adaptive control strategy is used to allow the real-time system to automatically adjust its value in response to any external fault. To guarantee the best trajectory tracking for the quadrotor, the attitude and position loops need to be controlled, so that superior control precision can be achieved [49]. Adaptive Fuzzy PID is a hybrid adaptive fuzzy and PID control techniques, as the name suggests [50]. This control approach combines fuzzy and PID control. In industrial applications, conventional PID controllers are the most commonly used controllers, however in robotic applications, the major problems of traditional controllers are overshoots and oscillation around settling points, which may be mitigated by adopting a fuzzy logic control. When designing an adaptive controller, the first step is to figure out how fuzzy logic interacts with the parameters of a conventional PID controller, as well as with error and error signal. However, the fuzzy adaptive PID control is based on the optimized parameters [7], the fuzzy adaptive PID controller has better dynamic and static control performance and adaptability [25]. The error and change of error are sent into the fuzzy logic controller, and the fuzzy logic controller outputs a change in Kp, Ki and Kd. The block diagram of control Adaptive Fuzzy PID Based Controller technique is illustrated in Fig. 6.

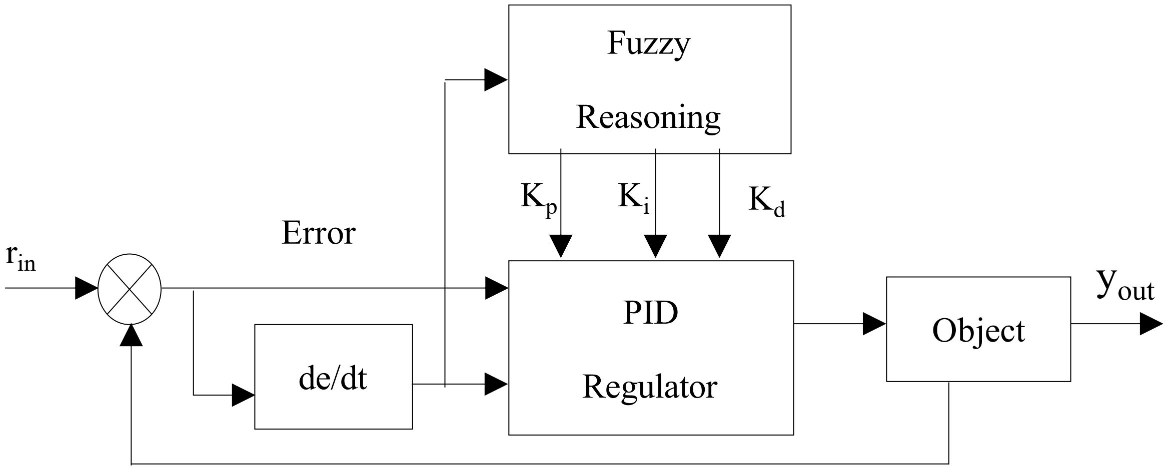


Fig. 6. Adaptive fuzzy PID control

The fuzzy rules and membership functions developed in the preceding section are used in this control. For each degree of freedom (X, Y, Z, pith, roll, and yaw), the total k_p, k_i, and k_d are variables altered using fuzzy control, therefore we require 18 fuzzy controllers. The total k_p, k_i and k_d can be described by the following equation:

$$K_p = K_{p1} + \Delta K_{p2} \tag{53}$$

$$K_i = K_{i1} + \Delta K_{i2} \tag{54}$$

$$K_d = K_{d1} + \Delta K_{d2} \tag{55}$$

4. Results and Discussion

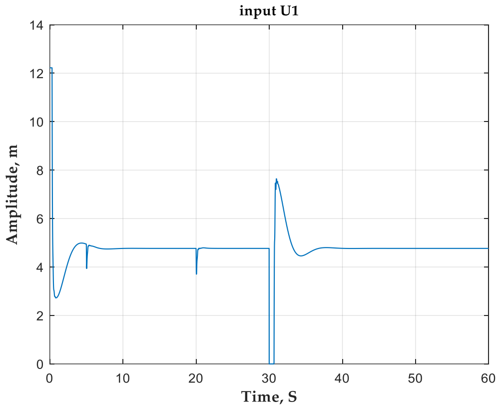
4.1. PID Control

In this simulation, we applied the different control laws developed in the previous section, all the parameters of the quadrotor model are given in Table 2. The simulation was run using a MATLAB software and the obtained results are displayed below. The desired references are chosen as X_{ref} = 4 m, Y_{ref} = 3.5 m, Z_{ref} = 5m, YAW_{ref} = 0, the following figures show the results of the simulation.

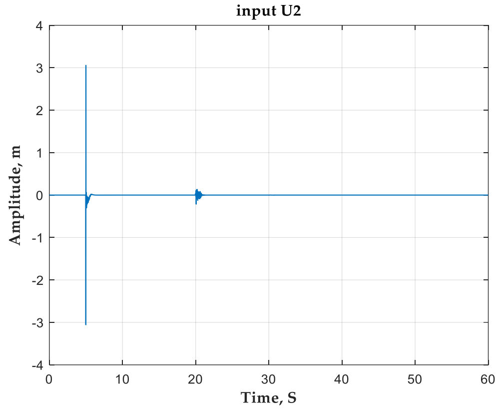
Fig. 7 presents the Control input U_1, U_2, U_3 and U_4 (Time in x-axe and Amplitude in y-axe) in the case of PID control of the quadrotor. Fig. 8 is an illustration of the response of x, y and z positions (Time in x-axe and Amplitude in y-axe) in the case of PID control of quadrotor.

Fig. 9 is an illustration of the response of roll, pitch and yaw response (Time in x-axe and Amplitude in y-axe) in the case of PID control of quadrotor. Fig. 10 displays the global trajectory of the quadrotor in 3D, in the case of step trajectories for PID control.

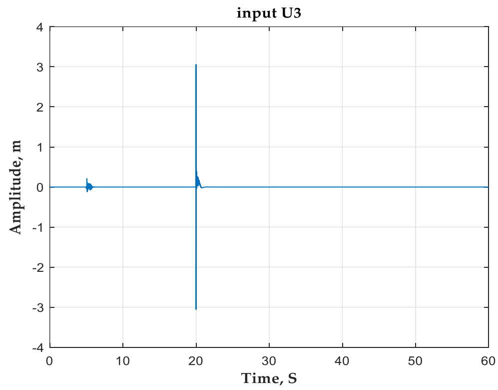
Table 3 shows that there is a minor steady-state error in the X and Y locations and no steady-state error in the Z position, however, the settling time with PID control is over 12 seconds. Pitch and Yaw angles exhibit no steady-state error and have a comparable settling time of 12 seconds. On the Z position, there is a 20% overshoot and undershoot. The obtained results using classical PID controller were not satisfactory, especially in terms of settling time and steady state error as shown in the table above and the step responses in Fig. 8. Therefore, in the following section fuzzy logic controller is proposed and discussed in the next section.



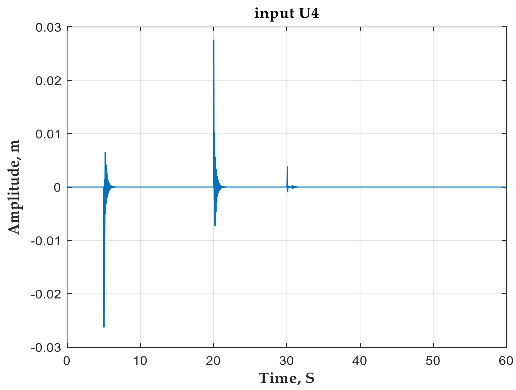
(a) Input U_1



(b) Input U_2

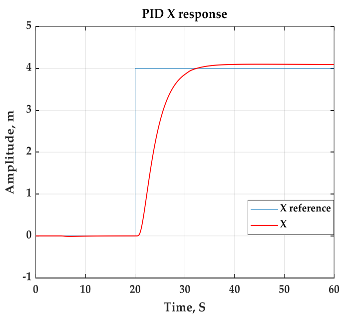


(c) Input U_3

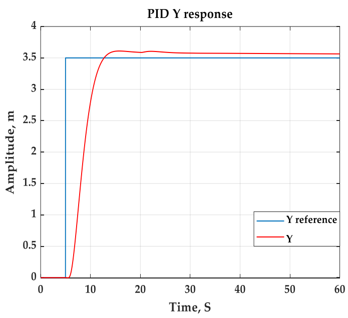


(d) Input U_4

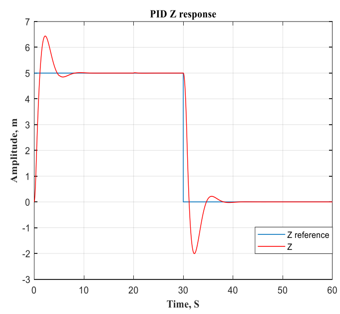
Fig. 7. Control input U_1, U_2, U_3 and U_4 for PID control of the quadrotor



(a) PID X Response

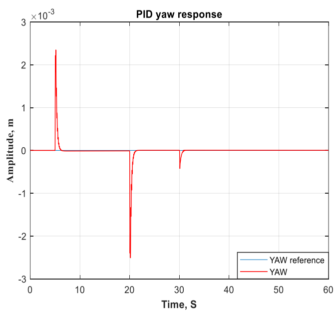


(b) PID Y Response

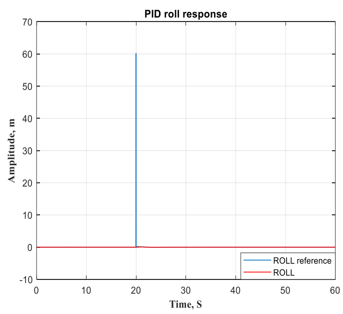


(c) PID Z Response

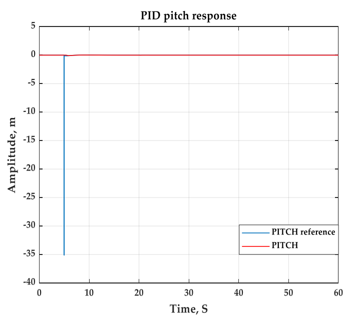
Fig. 8. The response of x, y and z positions (PID control)



(a) PID yaw Response



(b) PID roll Response



(c) PID pitch Response

Fig. 9. The response of roll, pitch and yaw response (PID control)

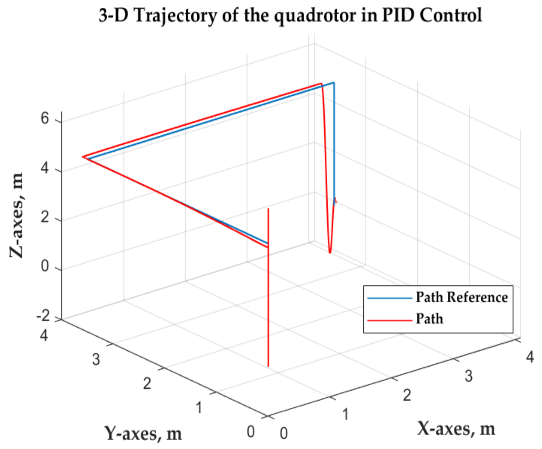


Fig. 10. The global trajectory of the quadrotor in 3D, in the step trajectories (PID control)

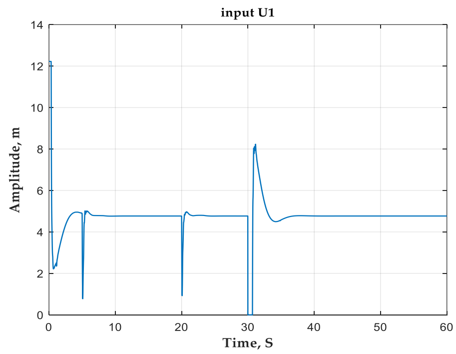
Table 3. Results of the PID controllers of the quadrotor

Positions	Errors	
	Settling time	Steady state error
X position	12 sec	2%
Y position	15 sec	1.5 %
Z position	10 sec	Non

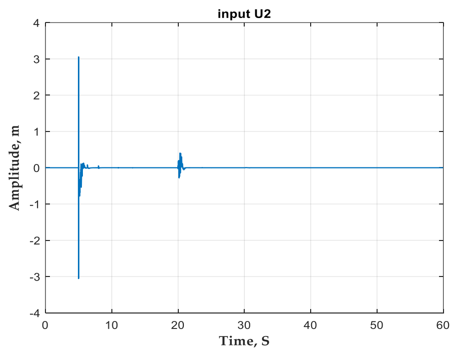
4.2. Fuzzy Logic PID Control

In this section we present the simulation results obtained for the PID Fuzzy logic controller. Similar to the previous control techniques, the simulation was run using a MATLAB software and the obtained results are shown below. The desired references are chosen as X_{ref} = 4 m, Y_{ref} = 3.5 m, Z_{ref} = 5m, YAW_{ref} = 0, the following figures show the results of the simulation.

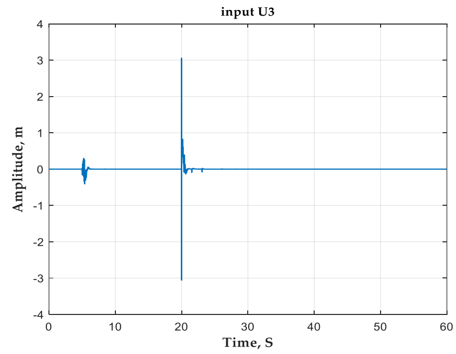
Fig. 11 presents the Control input U_1, U_2, U_3 and U_4 (Time in x-axe and Amplitude in y-axe) in the case of Fuzzy Logic control of the quadrotor.



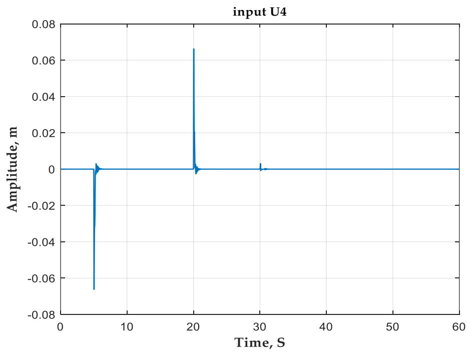
(a) Input U_1



(b) Input U_2



(c) Input U_3



(d) Input U_4

Fig. 11. Control input U_1, U_2, U_3 and U_4 for Fuzzy Logic control of the quadrotor

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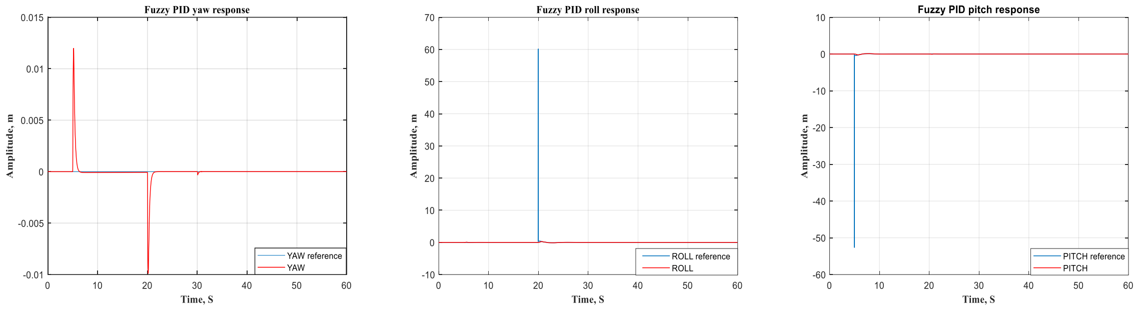
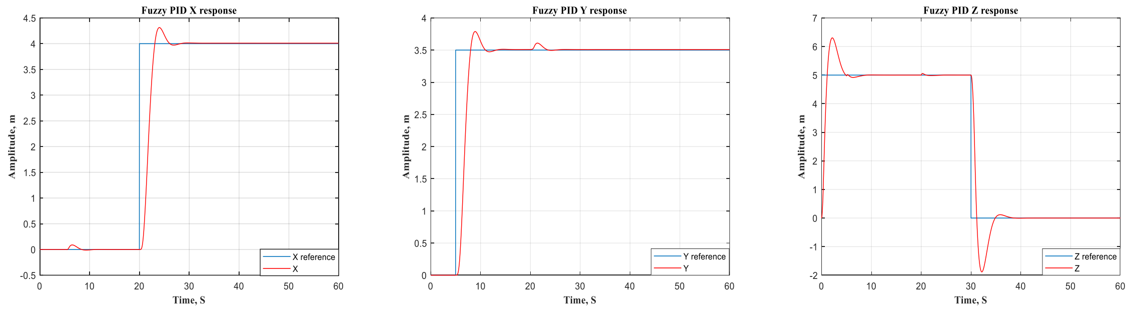
Fig. 12 is an illustration of the response of yaw, roll and pitch response (Time in x-axe and Amplitude in y-axe) in the case of Fuzzy Logic PID control of quadrotor.



(a) PID yaw Response (b) PID roll Response (c) PID pitch Response

Fig. 12. The response of yaw, roll and pitch (Fuzzy Logic PID controller)

Fig. 13 is an illustration of the response of x, y and z positions (Time in x-axe and Amplitude in y-axe) in the case of Fuzzy Logic PID controller of quadrotor.



(a) Fuzzy PID X Response (b) Fuzzy PID Y Response (c) Fuzzy PID Z Response

Fig. 13. The response of x, y and z positions (Fuzzy Logic PID control)

The global trajectory of the quadrotor in 3D, in the step reference for Fuzzy Logic PID Controller (FLC) is represented in Fig. 14:

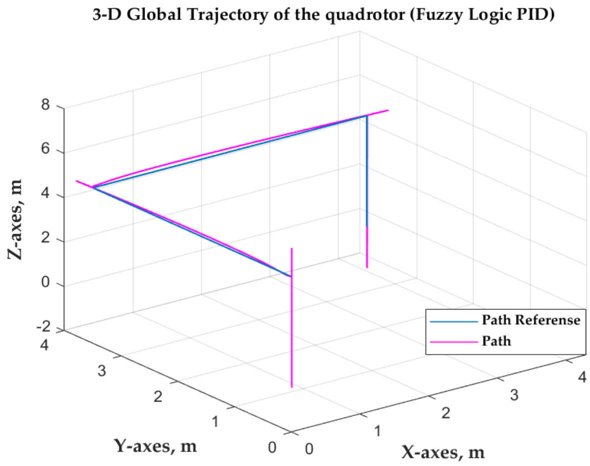


Fig. 14. The global trajectory of the quadrotor in 3D, in the step reference trajectories (FLC)

Table 4 contains all of the data retrieved from Fig. 13 and Fig. 14, the table shows that there is no steady-state error, and a better settling time lower than 6 seconds. Pitch and Yaw angles exhibit no steady-state error and have a comparable settling time of 7 seconds. On the Z position, there is a 12% overshoot and undershoot.

Fuzzy logic PID controller provided a better performance than PID controller in terms of settling time and steady state error, however it needs to be improved in order to provide better performance parameters. This is achieved using the adaptive Fuzzy logic PID approach which is presented in the next section in addition to obtained results.

Table 4. The results of the Fuzzy logic PID controller of the quadrotor

Positions	Errors	
	Settling time	Steady state error
X position	6 sec	Non
Y position	6 sec	Non
Z position	5 sec	Non

4.3. Adaptive Fuzzy Logic PID Controller

Adaptive Fuzzy PID controller combines traditional PID controller with fuzzy logic PID controller to adjust PID parameters based on the quadrotor's current state. The PID controller, the quadrotor's roll, pitch, yaw, and altitude based on predefined gains. However, Fuzzy logic System observes the system behavior in real-time. The adaptation mechanism tunes gain for external disturbances with rapid movements.

Implementation Steps:

1. The mathematical model for the quadrotor (6-DOF dynamics) is defined.
2. We develop the input (error and its derivative) corresponding to the output (PID gain). When the error is large, we increase proportional gain (Kp) for faster response, and when oscillations occur, we adjust derivative gain (Kd) to reduce overshoot.
3. We use MATLAB software to simulate the quadrotor's response. The fuzzy system is tested in combination with the quadrotor dynamics to get the response in real-time.
4. Run iterative simulations to optimize fuzzy rules and parameters, ensuring smooth transitions between control states and minimal error.

For the simulation, the parameters of each PID controller are adapted by a Fuzzy controller, so the results are shown on the following figures (for step input). we fix the references as X_{ref} = 4 m, Y_{ref} = 3.5 m, Z_{ref} = 5m, YAW_{ref} = 0, the following figures show the results of the simulation.

Fig. 15, Fig. 16, Fig. 17, Fig. 18, Fig. 19 and Fig. 20 illustrate set input of Adaptive fuzzy logic PID parameters successively of X, Y and Z positions and yaw, roll and pitch angles

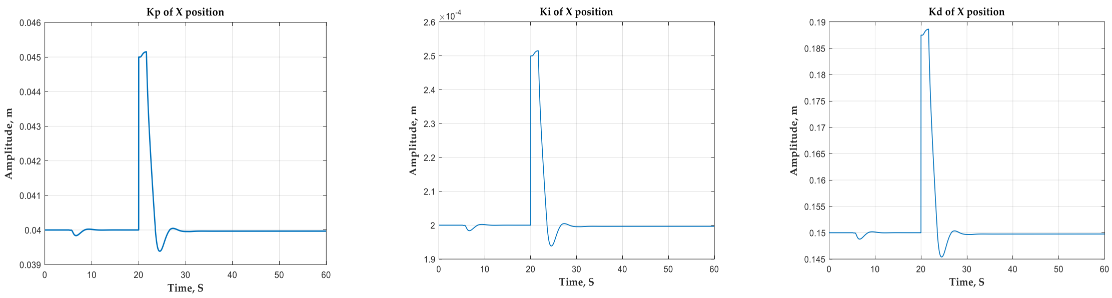


Fig. 15. Adaptive Fuzzy Logic PID parameters of X position (step input)

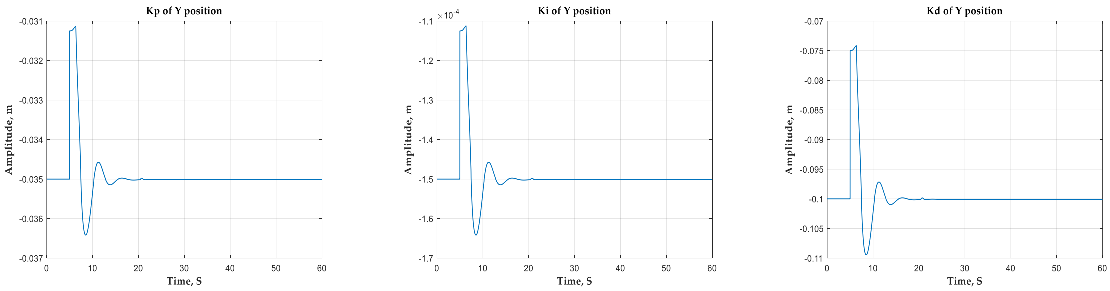


Fig. 16. Adaptive Fuzzy Logic PID parameters of Y position (step input)

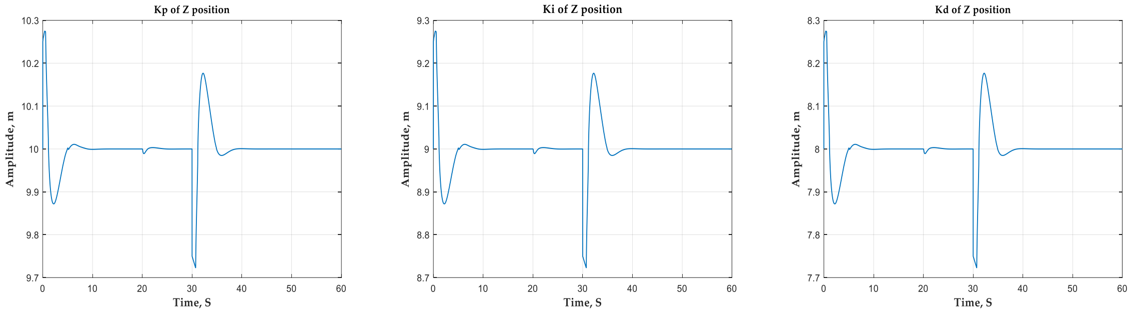


Fig. 17. Adaptive Fuzzy Logic PID parameters of Z position (step input)

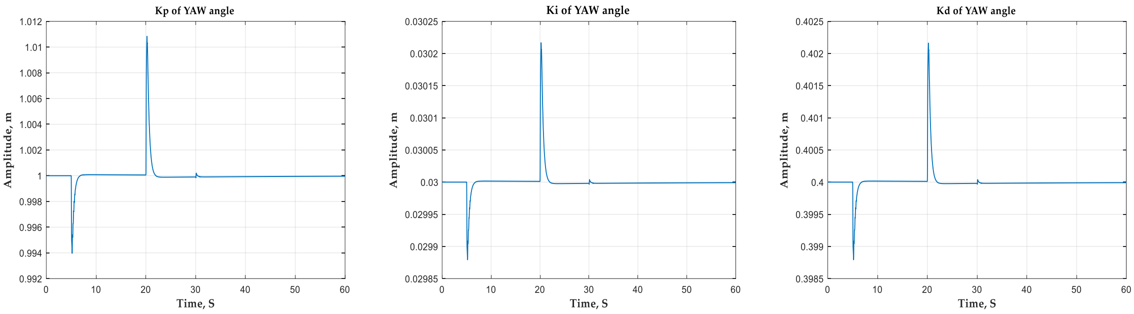


Fig. 18. Adaptive Fuzzy Logic PID parameters of YAW angle (step input)

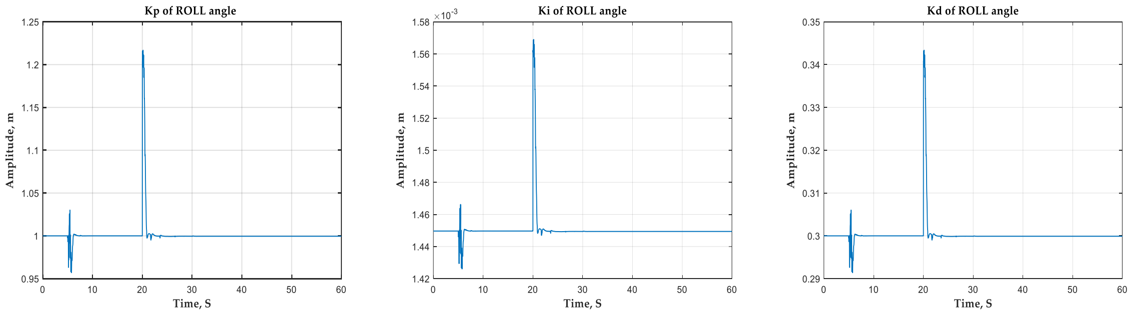


Fig. 19. Adaptive Fuzzy Logic PID parameters of ROLL angle (step input)

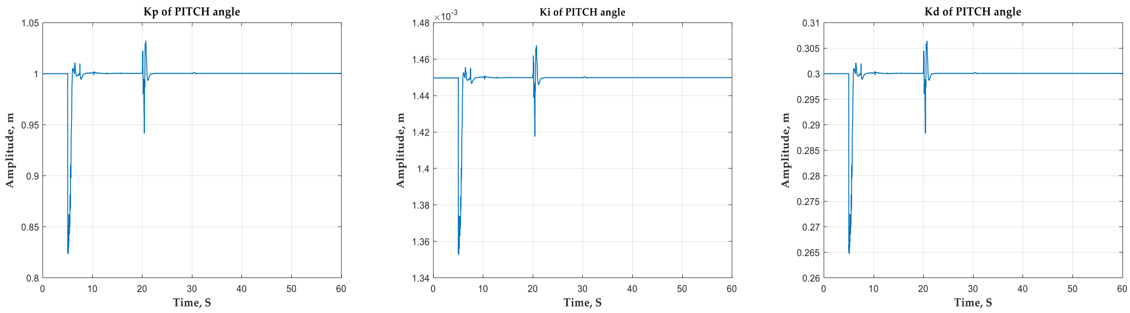


Fig. 20. Adaptive Fuzzy Logic PID parameters of PITCH angle (step input)

For the step input, we fix the references as X_{ref} = 4 m, Y_{ref} = 3.5 m, Z_{ref} = 5m, YAW_{ref} = 0, the following figures show the results of the simulation.

The step control inputs U_1, U_2, U_3 and U_4 responses of Adaptive Fuzzy Logic PID Controller are illustrated in Fig. 21 and Fig. 22. The response of x, y and z positions and yaw, roll and pitch angles of Adaptive Fuzzy Logic PID Control are shown in Fig. 23 and Fig. 24.

The following Fig. 25 represent 3-D global step trajectory of the quadrotor of Adaptive Fuzzy Logic PID control.

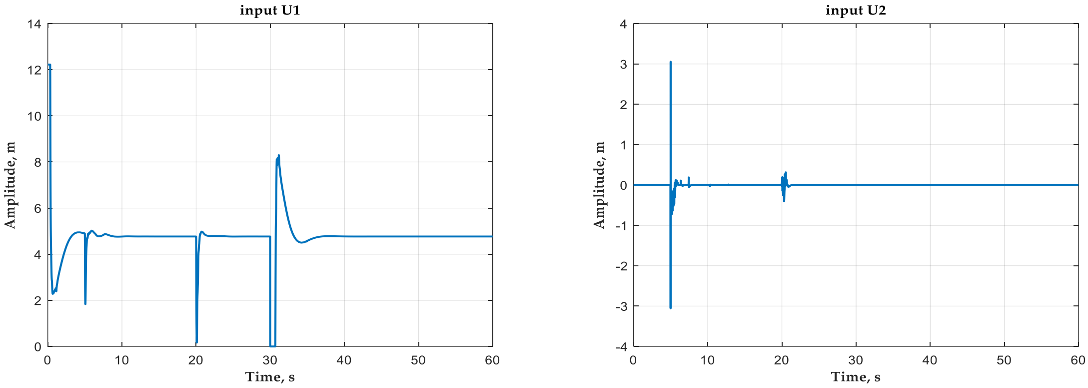


Fig. 21. Control input U_1 and U_2 response of (AFLC)

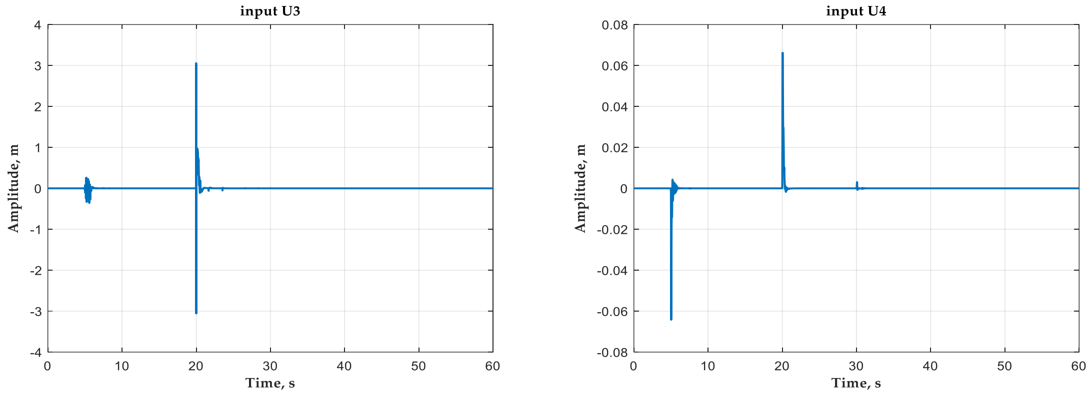


Fig. 22. Control input U_3 and U_4 response of (AFLC)

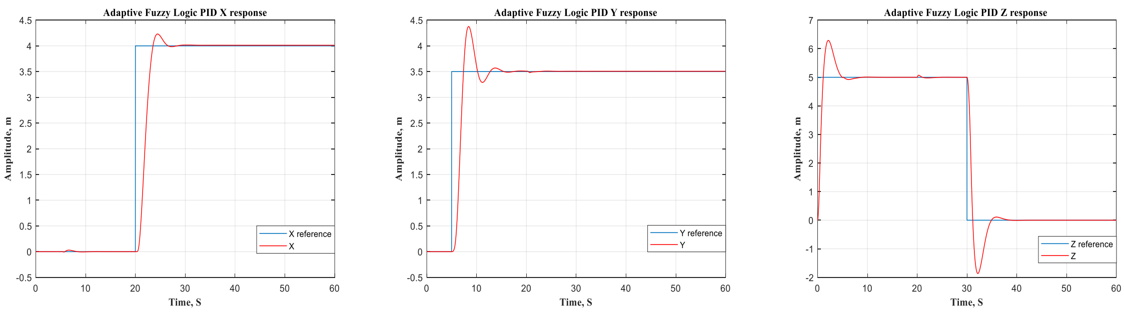


Fig. 23. The response of x, y and z positions (AFLC control)

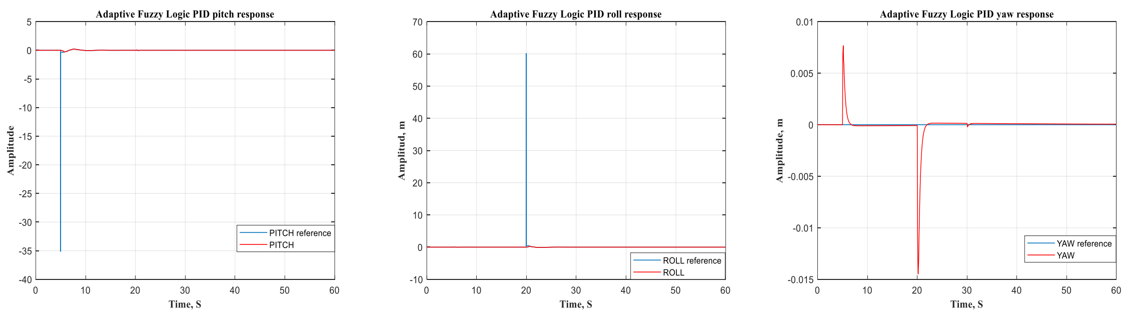


Fig. 24. Degree of Freedom response of yaw, roll and pitch angles (AFLC control)

Table 5 shows the obtained results of the Adaptive PID Fuzzy logic Controller. It can be seen clearly that latter provided much better performance than the two other methods. In fact, the settling time is minimized and steady state error is canceled. This can be explained by the high nonlinearity of the model of quadrotor and the limitations of the PID controller, which resulted in a higher settling time for the PID controller as compared to the Fuzzy Logic PID controller and Adaptive Fuzzy Logic PID controller strategies. In addition, the amplitude of the Roll angle response is exactly at its reference, which matches our desired input. The time it takes to set the X, Y, and Z positions is now 4 seconds, which is faster than the other controllers. Finally, it can be noticed that when we used fuzzy logic PID controller to adjust pitch angle, the system had an overshoot, but when we used adaptive control, the system met our criteria.

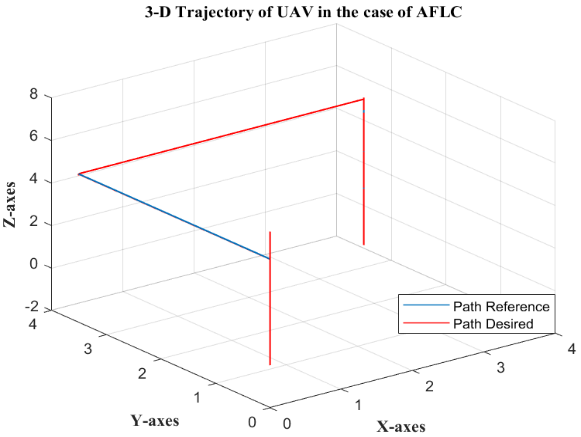


Fig. 25. The global trajectory of the quadrotor in 3D, case of step trajectories (AFLC)

Table 5. The results of the Adaptive Fuzzy logic PID controller of the quadrotor.

Positions	Errors	
	Settling time	Steady state error
X position	4 sec	non
Y position	4 sec	non
Z position	3.5 sec	non

In practice, Adaptive Fuzzy PID controllers for quadrotors offer smoother, more responsive control, making them suitable for complex tasks like autonomous navigation or precision landings in variable environments. This adaptive controller reacts in real time when the disturbances (wind) affected the quadrotor dynamics.

Dynamic systems frequently require a substantial amount of real-time computation when using fuzzy PIDs. Furthermore, it could take some time to modify membership functions or fuzzy logic rules which can be challenging for low-cost microcontrollers used in quadrotors. However, storing fuzzy data in real time required a large memory, and big sensitivity of gyroscopes. The delays in processing can degrade the system's performance. Possible improvements could include the use of optimization algorithms to automate the tuning.

5. Conclusion

A nonlinear mathematical model of a quadrotor is described in this work, where the given model took into account the rotor dynamics and aerodynamic effects, which are not taken into account in most previous studies. In fact, rotor dynamics and aerodynamic effects are very important in the modeling of the quadrotor because they reflect a more realistic and precise physical model. PID controller, Fuzzy Logic PID controller, and Adaptive Fuzzy Logic PID controller are three separate control system strategies that have been created. The majority of earlier controllers used single controllers to operate the whole system, which was extremely difficult to modify. With minimum input, we have six different controllers for each output. The major benefit of employing a separate controller for each input is improved performance and easier tweaking. The adaptive fuzzy Logic PID controller provided the best performance as compared to the two other techniques, as it resulted in no overshoots or undershoots. Moreover, it reduced the settling time by 65% comparing to the settling time corresponding to the PID controller. Hence, the adaptive fuzzy logic PID controller may be considered as the most appropriate controller for the quadrotor model given in this work.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Acknowledgment: Authors express their appreciation to "Laboratoire d'Ingénierie des Systèmes et Télécommunications, Laboratoire d'Automatique Appliquée, and Université M'hamed Bougara de Boumerdes", for their funds' contribution.

Conflicts of Interest: The authors declare no conflict of interest.

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