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Comparison of PID and Fuzzy Logic Controller Performance on Linear and Nonlinear Dynamics of a Quadrotor

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) have attracted significant attention in recent decades. Due to their low moment of inertia, quadrotors exhibit rapid dynamics and are subject to complex aerodynamic effects. Additionally, they are highly coupled, nonlinear, and inherently unstable, requiring control actuators to maintain stability. This research explores the implementation of both PID and Fuzzy Logic Controllers (FLC) on simulated quadrotor models, considering both linear and nonlinear dynamics. Overall, the FLC demonstrated superior performance compared to the PID controller. Notably, the FLC produced no overshoot, whereas the PID controller recorded an average overshoot of 9.81%. While the FLC resulted in slightly longer average rise and settling times, it exhibited remarkable consistency, with standard deviations of only 7.51% and 2.66%, respectively. In contrast, the PID controller displayed high variability, with standard deviations of 88.67% for rise time and 90.74% for settling time. These findings confirm the versatility and robustness of the FLC, which consistently maintained stable performance regardless of the model type. In contrast, the effectiveness of the PID controller was significantly influenced by the system's linearity.

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1. INTRODUCTION

Unmanned Aerial Vehicle (UAV) has been drawing attention in recent decades. UAV was first developed for military purpose [1], but it is currently gaining more popularity and starting to take part in non-military applications [2]. Its superiority in general escalates its usage throughout various purposes, especially rotorcraft UAVs. The capability of rotorcraft UAV to undergo vertical take-off and hovering is the key importance that differs rotorcraft to fixed-wing UAV [3]. Thru these capabilities, rotorcraft-type UAVs are widely utilized for rescue missions, traffic monitoring, wild fire mitigation, border surveillance, mapping, etc. [2], [4], [5]

The most common type of rotorcraft has four actuators/propellers mounted symmetrically and mostly arranged in a cross-like shape, widely known as quadrotor or quadcopter. The cross-like shape provides higher momentum, thus increase the maneuverability of the quadrotor, since all of the actuator are involved in achieving the desired maneuver [6]. Quadrotor has 6 DOF (3 translations and 3 rotations) with only four actuators available to complete a certain maneuver. In other words, a quadrotor is considered to be an Underactuated Mechanical System (UMS) [7]. This fact, although also gives advantages in terms of cost reduction and design simplicity, makes the dynamics and the control of quadrotor system to be complex.

Many studies had been carried out regarding the dynamics of quadrotor. The dynamics of quadrotors are fast due to their low inertia moments and are subjected to complex aerodynamics effects [8]. Moreover, it is highly coupled, unstable, and nonlinear [9], [10]. However, even though the dynamics of a quadrotor is nonlinear, a linear approach is still feasible to represent quadrotor dynamics by narrowing the attitude deflection of the quadrotor to be very low around its equilibrium points, as demonstrated by some works [11]–[16]. Most of them were using state-space model since the concept has been widely understood and developed.

Quadrotor is intrinsically unstable; thus, it is necessary to provide actuators to control the dynamics. Various controlling strategies have been well-developed to deal with the unstable characteristic underlying in quadrotor dynamics, even to guide the attitude and/or the trajectory of the quadrotor to the desired quantities. A summary of those control strategies have been provided, both for linear and nonlinear model [17], [18]. For linear controllers, most researchers use PID controller, or modified PID, as it is extremely simple, tunable, and quite robust. PID controller is also widely available, thus it is not difficult to look for one. On the other hand, for nonlinear controllers, Fuzzy Logic Controller is currently gaining popularity due to its intelligence, adaptivity, and the simplicity of its algorithm.

This research investigated the two aforementioned control strategies; PID and Fuzzy Logic Controller, which are implemented to a quadrotor simulation model. Both linear and nonlinear models of a quadrotor are built on MATLAB/Simulink to investigate the disturbance response on either linear or nonlinear model using those controllers. The simulation was focused on quadrotor dynamics, particularly its attitude (roll, pitch, and yaw) and its elevation, and on the performance comparison of each control strategy imposed to either linear or nonlinear model. The results of this research will give a broader understanding of the performance comparison of PID and Fuzzy Logic Controller implemented on a quadrotor.

2. METHOD

This research studied the response of quadrotor model, both linear and nonlinear model, with the utilization of two different controllers, PID and Fuzzy Logic. The simulation was built on MATLAB/Simulink. The details of the methodology are presented as follows.

2.1. Quadrotor Dynamics

The quadrotor used for this research is the AR.Drone Parrot Bebop, which is commercially available. The detailed parameters of this quadrotor is provided in Table 1 [1]. The quadrotor has four symmetrical & identical rotors mounted in a cross-like shape, as shown in Figure 1.

Table 1. Quadrotor (Parrot Bebop) parameters

Parameter	*Value*
Quadrotor's mass (m)	0.4 kg
Moment of inertia on X-axis (I_x)	1.25×10^{-4} kg.m^2
Moment of inertia on Y-axis (I_y)	8.7×10^{-4} kg.m^2
Moment of inertia on Z-axis (I_z)	8.7×10^{-4} kg.m^2
Rotor arm length on X-axis (l_x)	0.095 m
Rotor arm length on Y-axis (l_y)	0.076 m
Thrust coefficient with respect to Throttle $(f_{t\delta})$	2.56667 N
Torque coefficient with respect to Throttle $(\tau_{z\delta})$	0.00943 N.m
Thrust coefficient with respect to w (f_w)	-0.01651 N.s/m

First, two fundamental reference frames are defined, those are body reference frame and earth reference frame. Body reference frame, denoted by b-subscript, has x-axis pointing forward align to quadrotor body, z-axis pointing upward of the quadrotor, and y-axis pointing accordingly so that the right-hand rule satisfied. On the other hand, Earth reference frame, denoted by E-subscript, follows the ENU (East-North-Up) rule. The illustration of aforementioned reference frames is provided in Figure 1.

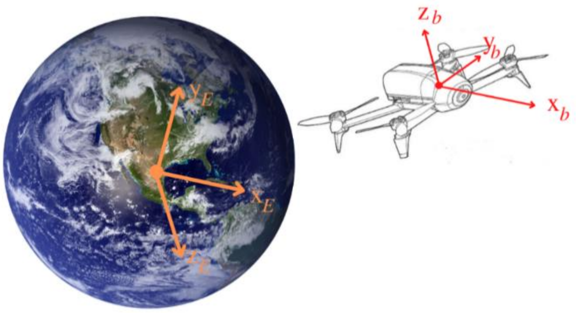


Figure 1. Earth and body reference frames

The rotors configuration is also represented in Figure 2 with each corresponding rotation, either clockwise or counterclockwise, such that the torques generated are equal. Thus, the thrust logics to complete roll, pitch, yaw, and elevation maneuver are, respectively:

$$\tau_x = f_{t\delta} l_y(-\delta_1 - \delta_2 + \delta_3 + \delta_4) \quad (1)$$

$$\tau_y = f_{t\delta} l_x(\delta_1 - \delta_2 - \delta_3 + \delta_4) \quad (2)$$

$$\tau_z = \tau_{z\delta}(-\delta_1 + \delta_2 - \delta_3 + \delta_4) \quad (3)$$

$$f_t = f_{t\delta}(\delta_1 + \delta_2 + \delta_3 + \delta_4) \quad (4)$$

While δ_1, δ_2, δ_3, and δ_4 are the throttle for the corresponding rotor.

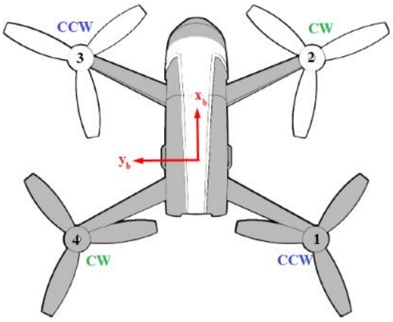


Figure 2. Quadrotor (Parrot Bebop) configuration

By assuming that the disturbances experienced by the quadrotor are small enough, the equations of motion consist of the angular and linear position (ϕ, θ, ψ, x, y, and z) with respect to the Earth reference frame as well as the angular and linear velocity (p, q, r, u, v, and w) are provided below [19], [20]:

$$\dot{\phi} \approx p + r\theta + q\phi\theta \quad (5)$$

$$\dot{\theta} \approx q - r\phi \quad (6)$$

$$\dot{\psi} \approx r + q\phi \quad (7)$$

$$\dot{p} \approx \frac{I_y - I_z}{I_x} rq + \frac{\tau_x + \tau_{wx}}{I_x} \quad (8)$$

$$\dot{q} \approx \frac{I_z - I_x}{I_y} pr + \frac{\tau_y + \tau_{wy}}{I_y} \quad (9)$$

$$\dot{r} \approx \frac{I_x - I_y}{I_z} pq + \frac{\tau_z + \tau_{wz}}{I_z} \quad (10)$$

$$\dot{u} \approx rv - qw + g\theta + \frac{f_{wx}}{m} \quad (11)$$

$$\dot{v} \approx pw - ru - g\theta + \frac{f_{wy}}{m} \quad (12)$$

$$\dot{w} \approx qu - pv - g + \frac{f_{wz} + f_t}{m} \quad (13)$$

$$\dot{x} \approx w(\phi\psi + \theta) - v(\psi - \phi\theta) + u \quad (14)$$

$$\dot{y} \approx v(1 + \phi\psi\theta) - w(\phi - \psi\theta) + u\psi \quad (15)$$

$$\dot{z} \approx w - u\theta + v\phi \quad (16)$$

With p, q, and r are the angular rate of the quadrotor around x, y, and z axis, respectively; ϕ, θ, and ψ represent the quadrotor's attitude, i.e. pitch, roll, and yaw, respectively; The linear velocity of the quadrotor with respect to x, y, and z axis, respectively, are u, v, and w; τ_x, τ_y, and τ_z are the moment generated by the rotors; τ_{wx}, τ_{wy}, and τ_{wz} are the moment induced by quadrotor motion; f_{wx}, f_{wy}, and f_{wz} are the forces induced by quadrotor motion; and g is the gravitational constant.

The equations above are still highly coupled and nonlinear. Thus, they were used for nonlinear simulation. A full nonlinear model was developed in MATLAB/Simulink using those equations. Meanwhile, for linear simulation, the equations above are simplified further by neglecting higher order terms, as provided below:

$$\dot{\phi} \approx p \tag{17}$$

$$\dot{\theta} \approx q \tag{18}$$

$$\dot{\psi} \approx r \tag{19}$$

$$\dot{p} \approx \frac{\tau_x + \tau_{wx}}{I_x} \tag{20}$$

$$\dot{q} \approx \frac{\tau_y + \tau_{wy}}{I_y} \tag{21}$$

$$\dot{r} \approx \frac{\tau_z + \tau_{wz}}{I_z} \tag{22}$$

$$\dot{u} \approx g\theta + \frac{f_{wx}}{m} \tag{23}$$

$$\dot{v} \approx -g\theta + \frac{f_{wy}}{m} \tag{24}$$

$$\dot{w} \approx \frac{f_{wz} + f_t}{m} \tag{25}$$

$$\dot{x} \approx u \tag{26}$$

$$\dot{y} \approx v \tag{27}$$

$$\dot{z} \approx w \tag{28}$$

While,

$$f_{wz} = \sum f_w(w + px_i - qy_i) = 4f_w w \tag{29}$$

$$\tau_{wx} = \sum f_w y_i(w + py_i - qx_i) = 4f_w l_y^2 p \tag{30}$$

$$\tau_{wy} = -\sum f_w x_i(w + py_i - qx_i) = 4f_w l_x^2 q \tag{31}$$

$$\tau_{wz} = \sum \tau_{zw}(w + py_i - qx_i) = 0 \tag{32}$$

and could be arranged into a matrix form as provided below:

$$\begin{Bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ \dot{p} \\ \dot{q} \\ \dot{r} \\ \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{4f_w l_y^2}{I_x} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{4f_w l_x^2}{I_y} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -g & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4f_w \end{bmatrix} \begin{Bmatrix} \phi \\ \theta \\ \psi \\ p \\ q \\ r \\ u \\ v \\ w \end{Bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{f_{t\delta} l_y}{I_x} & -\frac{f_{t\delta} l_y}{I_x} & \frac{f_{t\delta} l_y}{I_x} & \frac{f_{t\delta} l_y}{I_x} \\ \frac{f_{t\delta} l_y}{I_x} & -\frac{f_{t\delta} l_y}{I_x} & -\frac{f_{t\delta} l_y}{I_x} & \frac{f_{t\delta} l_y}{I_x} \\ -\frac{\tau_{z\delta}}{I_z} & \frac{\tau_{z\delta}}{I_z} & -\frac{\tau_{z\delta}}{I_z} & \frac{\tau_{z\delta}}{I_z} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{f_{t\delta}}{m} & \frac{f_{t\delta}}{m} & \frac{f_{t\delta}}{m} & \frac{f_{t\delta}}{m} \end{bmatrix} \begin{Bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{Bmatrix} \tag{33}$$

The matrix form of quadrotor dynamics above is also commonly known as a state-space form with general form of:

$$\dot{\bar{x}} = A\bar{x} + B\bar{u} \tag{34}$$

where $\bar{x}$ is a vector containing m number of states, $\bar{u}$ is a vector containing n number of inputs, A is $m \times m$ matrix that represents the dynamics of the states, and B is $m \times n$ matrix that represents the dynamics of the inputs.

The state-space form has been well-developed and there are plenty of tools to utilize it, including in MATLAB/Simulink. Therefore, for linear simulation, the state-space form provided above were used.

2.2. Control Strategies

The state of the quadrotor dynamics in this simulation has nine variables as the outputs. However, the rotor inputs consist by only four types of maneuvers. Therefore, the feedback state are only the variables which are directly related to the rotor inputs. Roll variable was used for roll maneuver feedback, pitch variable was used for pitch maneuver feedback, yaw variable was used for yaw maneuver feedback, and elevation maneuver was used for elevation maneuver feedback. The error differences with respect to the reference values are then continued to the control logic (PID or Fuzzy Logic Controller) that would be elaborated further below.

2.2.1. PID Controller

A traditional PID controller is considerably simple, easy to adjust, and robust. PID controller is broadly used for many applications and is arguably the most widely used controller for industries [17], [21]. About 90-95% of control system applications are using PID controller [22]. Quadrotor is one of the platforms where PID controller is usually implemented. Although the nature of quadrotor dynamics is highly non-linear and coupled, the application of PID controller seems to give decent results to control a quadrotor. A work done by Li and Li shows that a PID controller managed to stabilize the attitude and the position of a quadrotor to the desired value fairly [23] and also able to guide a quadrotor to complete waypoint tracking, as suggested by Adnan's work [24]. Moreover, the control performance of a PID controller is quite decent even though it is applied to a nonlinear plant, as shown by Awais [25]. PID controller is even able to overcome a disturbance due to an instantaneous payload change and offset loadings, as presented in a work done by Pounds [26].

The PID controller used for this research utilizes all three gain parameters, they are proportional, integral, and derivative gains, with filter coefficient, as represented by Equation 35. The gains were tuned by using PID Tuner App provided by PID Block in Simulink. Each maneuver has its own PID controller, hence there are 4 PID controllers with the corresponding gains. The PID controller input was represented by the state error (e), while the output was represented by the rotor throttle (δ). The controller output was also saturated to -1 to 1 since the output is normalized. The PID gains were tuned via PID tuner app on Matlab based on transfer function. The gains aimed to achieve a response with overshoot less than 10% and settling time less than 5 seconds. The block diagram of simulation model using PID controller is shown by Figure 3 below.

$$u(s) = K_p + \frac{K_i}{s} + \frac{N}{1 + \frac{N}{s}} K_d \tag{35}$$

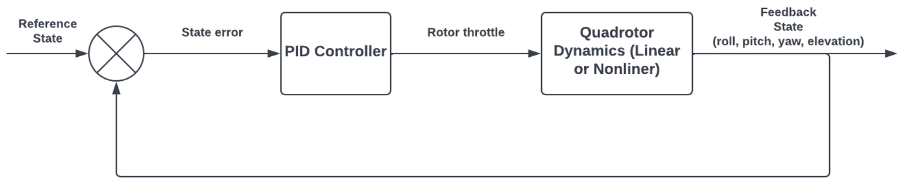


Figure 3. Block diagram of simulation model using PID controller

2.2.2. Fuzzy Logic Controller (FLC)

FLC is a one kind of controllers that systematically and mathematically tries to model human knowledge in reasoning and making decisions [27]. Fuzzy logic is a of many-valued logic, instead of binary-logic, three-valued logic, or others, thus, it is able to approximate reasoning instead of being exact [28]. FLC is a nonlinear controller that is suitable for a model having multiple inputs [29], which is the case of quadrotor. Moreover, this controller does not need to obtain full mathematical model of the plant to use this controller. In fact, all we need is only the visible behavior of the plant [30].

This research used the Mamdani-type Fuzzy, which was first developed by Mamdani in 1974 [31], in which a mathematical model is not necessary to construct the control logic [32]. The inputs for the FLC were the state error (e) and state error rate (de/dt), meanwhile the rotor throttle (δ) became the controller output. Figure 4 and Figure 5 respectively provide the membership functions implemented in FLC. The membership function for input and output were triangular functions, as also implemented in [10] and [33]. The membership function was normalized, so it ranges from -1 to 1. To make the accuracy of the maneuver better, for both input and output, it defined 7 functions, denoted as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). The block diagram of simulation model using Fuzzy Logic Controller is provided in the following Figure 6, while Table 2 provides the proposed control rule.

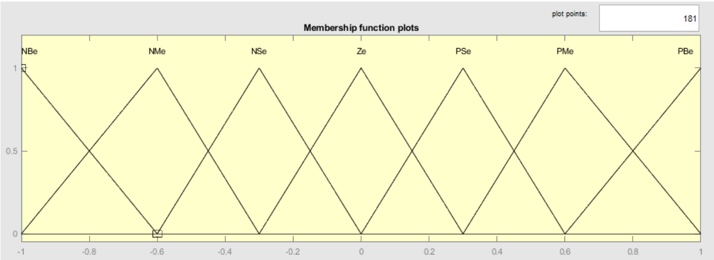


Figure 4. Membership Function for Input

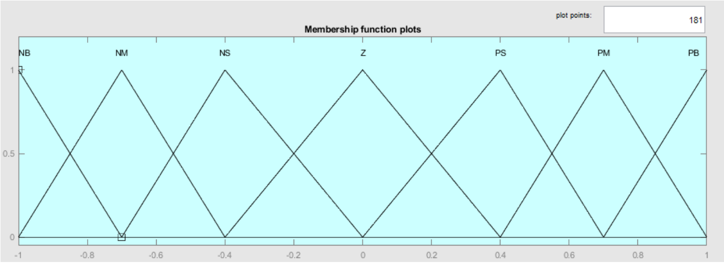


Figure 5. Membership Function for Output

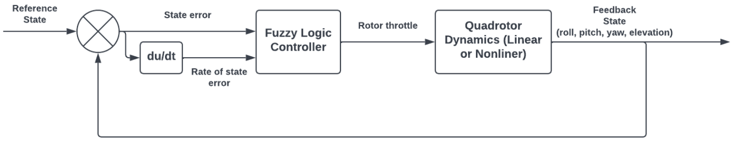


Figure 6. Block diagram of simulation model using fuzzy logic controller

Table 2. Fuzzy Logic Rules

e	de/dt						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

3. RESULTS & DISCUSSIONS

Both linear and nonlinear model were subjected to step disturbance in all inputs (pitch, roll, yaw, and elevation) simultaneously. The attitude disturbances (pitch, roll, and yaw) were varied from 1°, 5°, to 10°, while the elevation disturbance was kept 1 meter step disturbance. Roll responses for 1°, 5°, and 10° step disturbance are respectively illustrated in Figure 7, 8, and 9 (NL stands for Nonlinear model, L is for Linear model). Interestingly, the variation of 1°, 5°, and 10° step disturbance had no effect on roll response. There was practically no difference between linear and nonlinear model. However, a difference emerges between a model with PID controller implemented and a model with fuzzy logic controller implemented. The model simulation response demonstrated by fuzzy logic controller model did not overshoot, while PID controller did.

This finding is also demonstrated in some recent works [34]–[36]. The logic rules of the fuzzy logic controller proposed, as provided in Table 2, suggest that the throttle will be given less when the state error and/or rate of state error is decreasing. This feature prevents overshooting taking place, which is a good sign for fuzzy logic controller. Nevertheless, PID controller was doing a better job compared to fuzzy logic controller by looking at its settling time and rise time values, even though PID is not better than fuzzy logic controller in term of overshoot which recorded a value of 11%, since the gains were tuned to achieve short settling time and rise time. This may suggest that, in controlling roll attitude of a quadrotor, PID controller is quite faster than fuzzy logic controller.

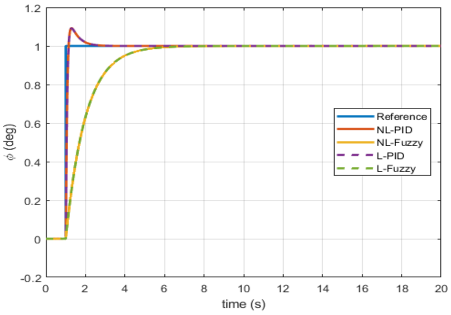


Figure 7. Response of quadrotor roll under 1° step disturbance

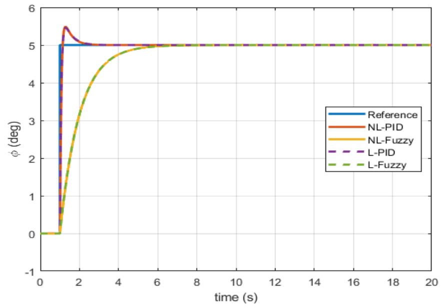


Figure 5. Response of quadrotor roll under 5° step disturbance

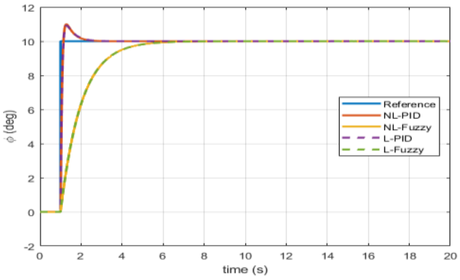
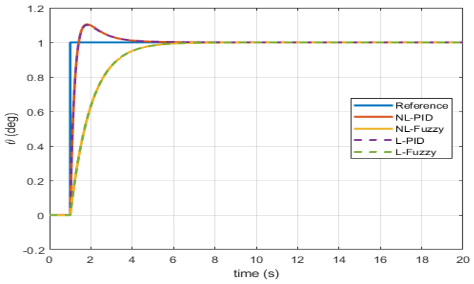


Figure 9. Response of quadrotor roll under 10° step disturbance

Figure 10 shows the comparison of pitch response of the simulation subjected to 1° step disturbance. The results still indicate no difference between linear and nonlinear model simulation, both using PID and fuzzy logic controller. The reason behind this finding is that the disturbance is very low, hence higher order terms in the nonlinear model will be extremely insignificant. Therefore, the nonlinear model would be practically the same with the linear model. However, similar to the results obtained for roll response, the settling time of PID controller is slightly better and the rise time is much less. This indicated that, in controlling the pitch of quadrotor with small disturbances, PID controller is considerably faster than fuzzy logic controller.

Furthermore, when the magnitude of disturbance was increased to 5° and 10°, as represented in Figure 11 and Figure 12, PID controller shows declined performance. As disturbance magnitude was getting more significant, the settling time of PID controller became larger, which is unfavorable, even though the rise time was still fine. In the meantime, the performance of FLC is considerably steady. This could happen because PID controller is a “fixed” controller where the gains are certain, meanwhile FLC is adaptive and has a certain range to decide the magnitude of its output based on the input. This result indicates that FLC controlling performance is independent with the magnitude of the disturbance, thus able to overcome nonlinearities better.



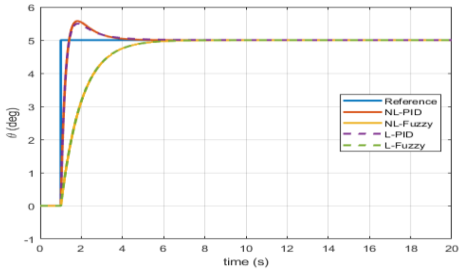


Figure 10. Response of quadrotor pitch under 1° step disturbance

Figure 11. Response of quadrotor pitch under 5° step disturbance

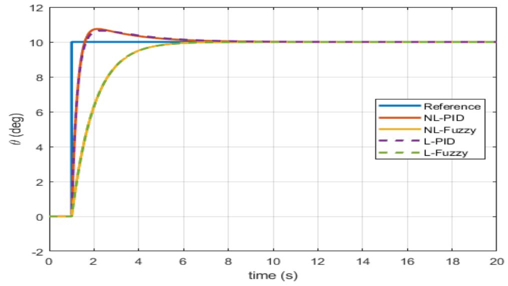


Figure 12. Response of quadrotor pitch under 10° step disturbance

Meanwhile, yaw response results are illustrated in Figure 13, Figure 14, and Figure 15 for 1°, 5°, and 10° yaw step disturbance, respectively. At 1° step disturbance, the result shows no difference between linear and nonlinear model, as the disturbance is not significant enough. The characteristic of the response is also similar to previous results, where the PID controller gives overshoot with a roughly similar value of settling time compared to fuzzy logic controller, approsimately 11%. But, as the disturbance was made bigger, differences appear for the response of the model using PID controller.

As the disturbance increases, the performance of PID controller decreases in general. It decreases even further for PID controller implemented to nonlinear model. The settling time is becoming larger. It is interesting to note that the nonlinearity of yaw and pitch are similar if we refer to the equation of quadrotor dynamics provided earlier (Equation 8 and Equation 9). But, in fact, the yaw response is quite difference to the roll response which has no difference given the variation of disturbance magnitude. To investigate this finding, we should take a look to the value of q and r since the two variables differ the nonlinearities underlying in yaw and pitch dynamics equations (See Figure 16). We can see that the value of q was larger up to almost twice of the value of r. As a result, the nonlinear term in yaw dynamics $(q\phi)$ is larger than the nonlinear term in pitch dynamics $(r\phi)$. Therefore, the nonlinearity of yaw dynamics is stronger than pitch dynamics, causing differences as the magnitude of the disturbance varies.

In contrast, consistent with the previous results, FLC simulation shows no difference of performance throughout 1°, 5°, and 10° yaw step disturbances. Moreover, there is also no difference between linear and nonlinear model. This finding further assures the capabilities of fuzzy logic controller in dealing with the nonlinearity of quadrotor dynamics.

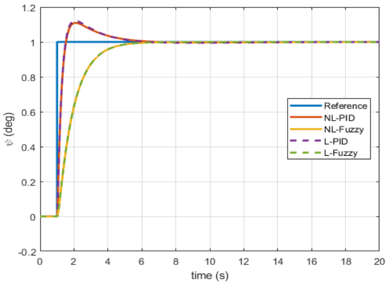


Figure 13. Response of quadrotor yaw under 1° step disturbance

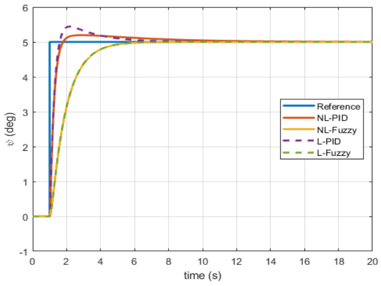


Figure 14. Response of quadrotor yaw under 5° step disturbance

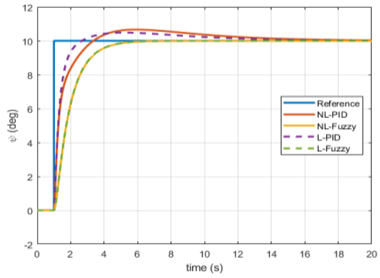


Figure 15. Response of quadrotor yaw under 10° step disturbance

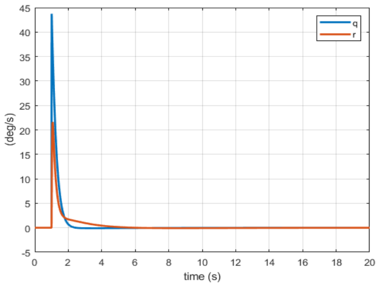


Figure 16. $\boldsymbol{q}$ and $\boldsymbol{r}$ comparison

The elevation responses are indicating different result, as provided in Figure 17, Figure 18, and Figure 19 (elevation disturbances are all 1 meter, but the attitude disturbances were varied). FLC, once again, is showing better performance than PID controller, in terms of both overshoot and settling time. For 1° attitude disturbance, the results for fuzzy logic controller are very similar for linear and nonlinear model. Again, this could happen due to the insignificant attitude disturbances, hence the nonlinear terms could be neglected. However, as the magnitude of attitude disturbances were getting bigger, the results start to differ. For linear model, fuzzy logic controller managed to guide the quadrotor to the desired value, both under 5° and 10° attitude disturbances. However, fuzzy logic controller could not quite achieve it on nonlinear model, both under 5° and 10° attitude disturbances. The elevation kept increasing after the quadrotor reached the desired elevation of 1 meter. One possible reason behind this finding is that, in case of nonlinear model, the elevation is not only affected by upward velocity (w), but also by other variables. The thrust logic commonly used, including the thrust logic used for this research, are only aiming the changes of w to achieve desired elevation. In fact, w is on body frame axis, while elevation is on inertial axis. Therefore, the desired elevation final value would not be achieved, and an alternative thrust logic is needed to accommodate it.

On the other hand, PID controller could still guide the quadrotor elevation to the desired value for linear model, although it is not as fast as fuzzy logic controller since the settling time and overshoot are not better compared to fuzzy logic controller. However, for nonlinear model, PID controller could not achieve the desired value, and the quadrotor were left having a steady-state error which is increasing massively as the magnitude of attitude disturbances increase. This result indicates that the nonlinearity of quadrotor elevation dynamics is very strong. In fact, the response of model utilizing FLC, which is suitable for nonlinear model implementation, is also affected. However, the fuzzy logic controller still demonstrates better performance, in general, in controlling the elevation of the quadrotor.

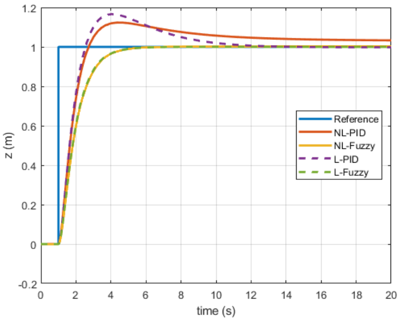


Figure 17. Response of quadrotor elevation under 1° step disturbance

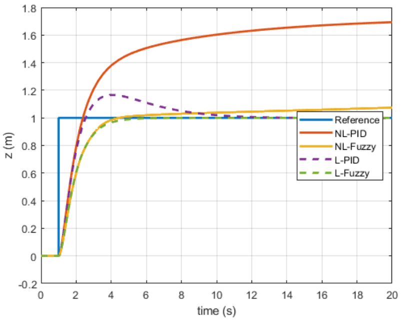


Figure 18. Response of quadrotor elevation under 5° step disturbance

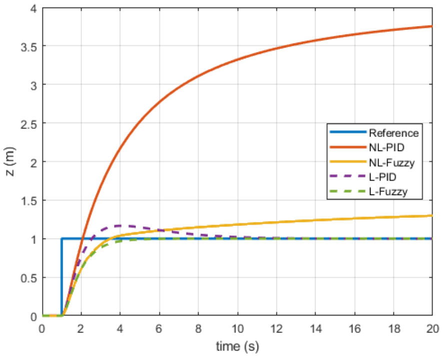


Figure 19. Response of quadrotor elevation under 10° step disturbance

Conclusively, the proposed rules for the Fuzzy Logic Controller (FLC), which adjust the output based on the input, enable the FLC to perform independently of the system model. For both linear and nonlinear models, the FLC demonstrated consistent performance when subjected to varying disturbance magnitudes. The rise time of the FLC averaged 2.11 s with a standard deviation of only 7.51%, while the settling time averaged 3.85 s with a low standard deviation of 2.66%. In contrast, the performance of the PID controller was highly dependent on the nature of the model—performing notably better with the linear model—and was significantly affected by the disturbance magnitude. Larger disturbances led to reduced control performance. Although the PID controller achieved a fast rise time of 0.34 s, it exhibited a high variability with a standard deviation of 88.67%. Similarly, the average settling time was 3.31 s, accompanied by a large standard deviation of 90.74%. In terms of overshooting, FLC gives No. overshoot for all simulations. On the other hand, PID controller recorded 9.21% of average overshooting value. Figures 20 and 21 illustrate the comparison of rise time and settling time between the PID controller and the FLC, respectively, while Figure 22 shows the overshooting results of PID controller.

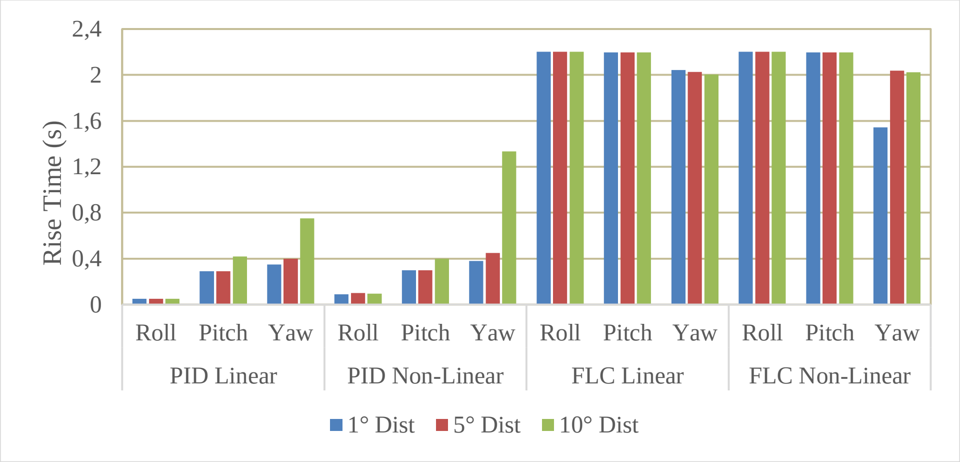


Figure 20. Rise time comparison

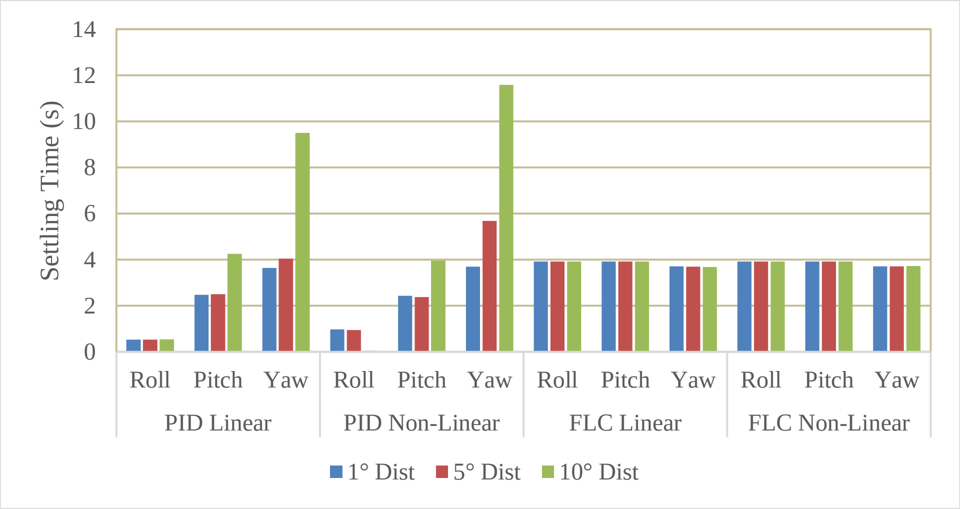


Figure 21. Settling time comparison

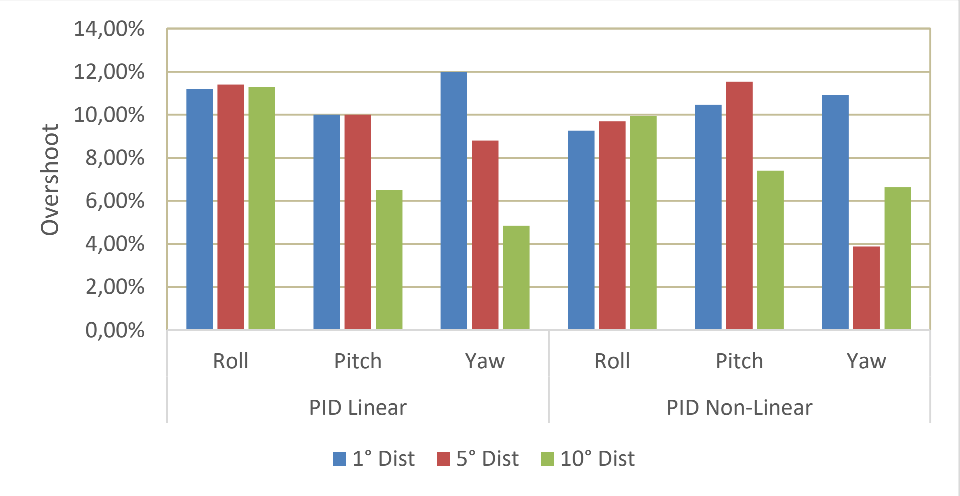


Figure 21. PID controller overshoot data

4. CONCLUSIONS

In this research, simulation involving linear and nonlinear models of a quadrotor utilizing PID controller as well as fuzzy logic controller had been performed. Linear and nonlinear model simulation under small disturbances demonstrated no different results. However, as the magnitude of the disturbances are getting bigger, differences start to appear where PID controller indicated a performance decline.

In general, the performance demonstrated by FLC is better than PID controller. Notably, the FLC produced no overshoot, whereas the PID controller recorded an average overshoot of 9.81%. While the FLC resulted in slightly longer average rise and settling times, it exhibited remarkable consistency, with standard deviations of only 7.51% and 2.66%, respectively. In contrast, the PID controller showed high variability, with standard deviations of 88.67% for rise time and 90.74% for settling time. However, fuzzy logic controller is still showing performance decrease in controlling the elevation of the quadrotor since the currently widely known thrust logic does not accommodate the coupling of controlling elevation. Nevertheless, fuzzy logic controller is still arguably better option to choose for quadrotor operation with high maneuverability.

On the other hand, PID controller is still highly dependent to the type of model, linear or nonlinear, as it shows less favorable performance in controlling nonlinear model under significant disturbances. However, PID controller seems to be faster than fuzzy logic controller, indicated by its short rise time and settling time, even though it costs the response to overshoot. Therefore, PID controller is still acceptable, or even better option, for quadrotor operation with minimum disturbances, such as during its hovering stage.

This research only covered attitude control of a quadrotor. In real practical events, besides attitude control, trajectory tracking and control are also important because some quadrotor missions are to achieve a specific point with a prerequisite trajectory. Thus, future research accommodating this aspect should be carried out. Moreover, experimentation should be performed in future research to validate the simulation data.

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