Implementation of Fuzzy-PID Controller on Quadcopter Movement

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***Abstract*—A UAV is an unmanned aerial vehicle, one of which is a Quadcopter. A Quadcopter has a simple structure and small size. Therefore, high maneuverability allows the Quadcopter to take off, fly, and land in narrow areas. The speed of the four motor-driven propellers affects the quadcopter's motion. The problem that often occurs in Quadcopters lies in the lifting force. Where the speed of the four motors must be the same so that the lift force can make the Quadcopter reach the desired height. The study aims to control the angular velocity and speed of the Quadcopter on the z-axis. The Quadcopter motion system model is a non-linear system because environmental disturbances give the system very high uncertainty. The system is given a control design in the form of Fuzzy-PID (Fuzzy Proportional Integral Derivative) with the desired set point or speed is 1. Simulation is carried out by comparing the system without disturbance and with disturbance to see how the speed of the Fuzzy-PID stabilizes the system. The simulation results show that even though the system is disturbed, the fuzzy-PID control can guide it toward the desired set point.**

I. INTRODUCTION

UNMANNED Aerial Vehicle (UAVs) are aircraft that can move with remote control. Rapidly developing technology also makes the demand for unmanned aerial systems increase. Especially UAVs, because they can run the system at minimal cost and do not harm humans. UAVs are suitable for research, public security, and commercial purposes [1]. A Quadcopter is one type of UAV that has a simple structure and a small size. Therefore, Quadcopters can fly in narrow areas and are difficult to reach compared to helicopter models [2]. The Quadcopter has four motors to drive each propeller and has six degrees of freedom (three rotations and three translations) [3]. The movement of the Quadcopter will produce a thrust whose direction is vertical. High maneuverability makes the Quadcopter able to take off, fly, and land in narrow areas [4]. Quadcopter research is becoming very popular and is being carried out by many re-searchers. This is because Quadcopters are widely used in monitoring disaster areas [5], shipping goods [6], search and rescue of victims [7], and military [8]. The dy-namic model of Quadcopter motion is the first step in research activities. A Quad-copter is a non-linear system because there are environmental disturbances that make the system have very high uncertainty [9]. Therefore, there needs to be a con-trol design applied to the system. Different control methods have been studied, in-cluding the LQR controller [10], [11] and the PID controller [12], [13], [14]. PID con-trollers are becoming a standard and widely preferred method in their application because they provide an efficient and simple solution to adjusting control parameters [15]. Although in previous studies the controller worked well and quickly, the results showed a response with a higher overshot. Consequently, a Fuzzy-PID con-troller is constructed in this work. Fuzzy-PID is a combined controller method between Fuzzy Logic and PID controllers [16]. The problem that often occurs with Quadcopters lies in their lift. The speed of four motors must be equal so that the lifting force can help the Quadcopter reach the desired height [17]. This publication will discuss the Fuzzy-PID controller design for the control system as well as the mathematical model of Quadcopter motion. The analytical approach combined with MATLAB/Simulink, implementing a compre-hensive simulation to describe quadcopter motion. This publication will evaluate and compare a system with and without disturbance to assist the stability and speed of a quadcopter hovering.

II. MODELING OF QUADCOPTER

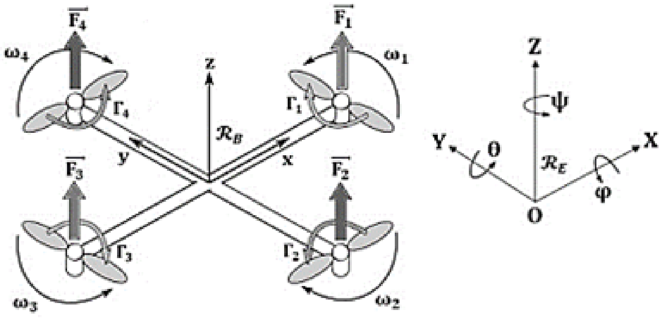

Fig. 1: Structure and coordinate systems [18]

The mathematical model on the Quadcopter is an equation that will be used for the needs of systems. There are two different coordinate systems for Quadcopter movement: inertial frame or earth coordinates, and body frame or body coordinates. The direction of the earth's rotation determines how earth coordinates are created. The X_E, Y_E, and Z_E axes are divided into three portions, with the earth serving as the center of the Cartesian coordinate system. The north pole, the east pole, and the center of the earth are each represented by the letters X_E, Y_E, and Z_E, respectively. The X_B, Y_B and Z_B axes of the Cartesian B coordinate system are divided into three parts, with the Quadcopter serving as its center. The axes formed on the Quadcopter–the X, Y, and Z axes of Cartesian coordinates and the angles of roll (ϕ), pitch (θ), and yaw (ψ)

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are what control the Quadcopter's movement in the direction of the earth. The angles that act on the x-axis are the roll angle (ϕ), the pitch angle (θ) on the y-axis, and the yaw angle (ψ) acts on the z-axis [1]. Figure 1 shows the structure and coordinate system of the Quadcopter. Assuming that the Quadcopter is in a hovering position, it may be claimed that each propeller rotates at the same speed. The mathematical model for the Quadcopter used in this study comes from the results of research conducted by Tommaso Bresciani in 2008 [2].

$$
\begin{aligned}
\ddot{X} &= \frac{(\sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi)U_1}{m},\\
\ddot{Y} &= \frac{(-\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi)U_1}{m},\\
\ddot{Z} &= -g+\frac{(\cos\theta\cos\phi)U_1}{m},\\
\ddot{\phi} &= \frac{(I_{yy}-I_{zz})}{I_{xx}}\dot{\theta}\dot{\psi}+\frac{U_2}{I_{xx}},\\
\ddot{\theta} &= \frac{(I_{zz}-I_{xx})}{I_{yy}}\dot{\phi}\dot{\psi}+\frac{U_3}{I_{yy}},\\
\ddot{\psi} &= \frac{(I_{xx}-I_{yy})}{I_{zz}}\dot{\phi}\dot{\theta}+\frac{U_4}{I_{zz}}.
\end{aligned}
\tag{1}
$$

The following definitions apply to the input vector components U_1, U_2, U_3, and U_4:

$$
\begin{cases}
U_1 = b(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2),\\
U_2 = lb(-\omega_2^2+\omega_4^2),\\
U_3 = lb(-\omega_1^2+\omega_3^2),\\
U_4 = d(-\omega_1^2+\omega_2^2-\omega_3^2+\omega_4^2),\\
\omega = -\omega_1+\omega_2-\omega_3+\omega_4.
\end{cases}
$$

The variables and parameters used are shown in Table and Table 2. The parameters are based on the Quanser Q-Ball X-4's specifications [3]. Applying the model, Equation 1 can be expressed as a state-space equation with the notation $\dot{x} = f(x,u)$, where x is the state vector and u is the input vector. So,

TABLE I: System variables

Variable	**Description**
$\dot{X}$	Quadcopter speed measured on the X_E axis
$\dot{Y}$	Quadcopter speed measured on the Y_E axis
$\dot{Z}$	Quadcopter speed measured on the Z_E axis
$\dot{\phi}$	Roll angular velocity measured on the X_E axis
$\dot{\theta}$	Pitch angular velocity measured on the Y_E axis
$\dot{\psi}$	Yaw angular velocity measured on the Z_E axis

TABLE II: System parameters specifications [21]

Parameter	**Description**	**Value**
m	Total mass	1.4 kg
g	Measure of gravity	9.81 m/s^2
I_{xx}	Inertial moment about the x-axis	0.03 kg.m^2
I_{yy}	Inertial moment about the y-axis	0.03 kg.m^2
I_{zz}	Inertial moment about the z-axis	0.03 kg.m^2
b	Lift constant	7.5×10^{-7}
l	Distance of the motor from center of mass	0.2 m
d	Thrust constant	3.13×10^{-5}
ω	Total speed of the propeller rotation	0

$$
\begin{aligned}
x &= \begin{bmatrix} \phi & \dot{\phi} & \theta & \dot{\theta} & \psi & \dot{\psi} & X & \dot{X} & Y & \dot{Y} & Z & \dot{Z} \end{bmatrix}^T \in \mathbb{R}^{12},\\
u &= \begin{bmatrix} U_1 & U_2 & U_3 & U_4 \end{bmatrix}^T
\end{aligned}
\tag{2}
$$

Equation 1 will change to Equation 3,

$$
\dot{x} = f(x,u) = \begin{bmatrix}
\dot{\phi}\\
a_1\dot{\theta}\dot{\psi}+b_1U_2\\
\dot{\theta}\\
a_2\dot{\phi}\dot{\psi}+b_2U_3\\
\dot{\psi}\\
a_3\dot{\phi}\dot{\theta}+b_3U_4\\
\dot{X}\\
U_x\frac{U_1}{m}\\
\dot{Y}\\
U_y\frac{U_1}{m}\\
\dot{Z}\\
-g+(\cos\theta\cos\phi)\frac{U_1}{m}
\end{bmatrix}
\tag{3}
$$

where

$$
\begin{aligned}
a_1 &= \frac{I_{yy}-I_{zz}}{I_{xx}}, & b_1 &= \frac{1}{I_{xx}},\\
a_2 &= \frac{I_{xx}-I_{zz}}{I_{yy}}, & b_2 &= \frac{1}{I_{yy}},\\
a_3 &= \frac{I_{xx}-I_{yy}}{I_{zz}}, & b_3 &= \frac{1}{I_{zz}},\\
U_x &= \sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi,\\
U_y &= -\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi
\end{aligned}
$$

The mathematical model for the Quadcopter in Equation 3 is non-linear. The non-linear model will be linearized first because the chosen control method is for a linear system. Linearization is carried out around the equilibrium point as a constant function. In this study, linearization was carried out at one of the equilibrium points.

When the Quadcopter is in a hover state, maintaining its linear position, the angles of roll, pitch, and yaw are all zero, as well as their rates of change. In this state, the Quadcopter does not perform translational movements, and the rate of change of its position is zero. Assuming hover flight conditions, the rotational speed of each propeller is equal. Therefore, the equilibrium point of the Quadcopter model in the hover condition is given by:

$$
\begin{aligned}
\hat{x} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & Y & 0 & Z & 0 \end{bmatrix}^T \in \mathbb{R}^{12},\\
\hat{u} &= \begin{bmatrix} mg & 0 & 0 & 0 \end{bmatrix}^T
\end{aligned}
\tag{4}
$$

The Quadcopter system is linearized around this equilibrium point. Substituting Equation 3 and the parameters from Table 1 into the state-space equation:

$$
\dot{x} = A\hat{x} + B\hat{u}
$$

The corresponding matrices A and B are obtained as follows:

$$A(\hat{x}) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 9.8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ -9.8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$B(\hat{u}) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{1}{0.03} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{0.03} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{0.03} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{1.4} & 0 & 0 & 0 \end{bmatrix}.$$

III. THE CONTROLLER DESIGN

The Fuzzy-PID controller is the control system employed in this study. The controllers combine PID and fuzzy logic in their control strategies. The control design system is used to regulate the speed and stability of the Quadcopter motor motion, meaning that by providing some tuning to the PID control, it will achieve the desired speed and stability. In performing the tuning, several trials are conducted to determine the appropriate results for the PID control. Fuzzy logic here functions to adjust the PID parameter values based on errors caused by disturbances in the system, thus preventing disturbances from affecting the system parameters. Therefore, the advantage of the Fuzzy-PID controller compared to the PID controller is its adaptability to disturbances or parameter uncertainty. If there are changes to the system, Fuzzy logic will recalculate the PID parameters accordingly. In Fuzzy logic, it is necessary to design a membership function for errors and changes in errors. The membership function is created based on determining the maximum and minimum values of errors and changes in errors within the system. The membership function for the output signal, which represents changes in the values of K_p, K_i, and K_d, is crucial for effective control. Figure 2 shows the design of the Quadcopter model's control scheme.

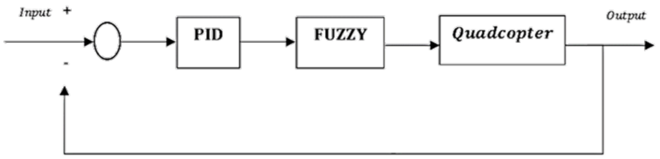


Fig. 2: Caption

The simulation is carried out according to the design of the control that has been made with MATLAB/Simulink. Designing Fuzzy base rules and membership functions is essential before simulating the Fuzzy-PID controller. Fuzzy base rules are obtained based on observations of the system's response characteristics to reach the desired set point. By using this technique, the error and derivative error are evaluated to modify the PID parameters online. Mamdani's technique settings are employed to operate the Fuzzy combination. The suggested Fuzzy logic system, fuzzification, has two input variables as shown in Figures 3 and 4. The fuzzy input variable has seven labels, namely NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). In defuzzification, the centroid algorithm is used to obtain three output variables to adjust the PID parameters. Meanwhile, the fuzzy output variables have 3 labels, namely S (Small), M (Medium), and B (Big). Table III and Table IV present the base rules for K_p, K_i, and K_d.

TABLE III: Fuzzy base rules for K_p and K_i

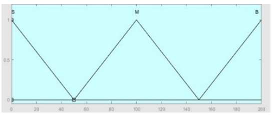
		Error					
		NB	NM	NS	ZO	PS	PM
Derivative Error	NB	M	S	S	S	S	S
	NM	B	M	S	S	S	M
	NS	B	B	M	S	M	B
	ZO	B	B	B	M	B	B
	PS	B	B	M	S	M	B
	PM	B	M	S	S	S	M
	PB	M	S	S	S	S	S

TABLE IV: Fuzzy base rules for K_d

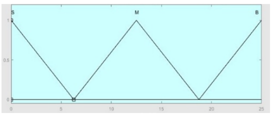
		Error					
		NB	NM	NS	ZO	PS	PM
Derivative Error	NB	M	B	B	B	B	B
	NM	S	M	B	B	B	M
	NS	S	S	M	B	M	S
	ZO	S	S	S	M	S	S
	PS	S	S	M	B	M	S
	PM	S	M	B	B	B	M
	PB	M	S	S	S	S	S

(a) Membership function for error

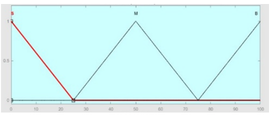
(b) Membership function for derivative error



(c) Membership function for K_p



(d) Membership function for K_i



(e) Membership function for K_d

Fig. 3: Membership function

The error domain range for Quadcopter position control is defined as $[-5, 5]$ and the error change is $[-10, 10]$. The domains for K_p, K_i, and K_d are $[0, 200]$, $[0, 25]$, and $[0, 100]$, respectively [?]. After the fuzzy base rules and domain range have been defined, the membership function can also be determined. The membership function input is in the form of errors and changes in errors as shown in Figure 3a and Figure 3b, and the membership function output is in the form of K_p, K_i, and K_d as shown in Figure 3c, Figure 3d, and Figure 3e.

In this study, two simulations were carried out: a system simulation with disturbance and a system simulation without disturbance. An output signal representing the Quadcopter's speed on the Z_E axis, Roll angular velocity on the X_E axis, Pitch angular velocity on the Y_E axis, and Yaw angular velocity on the Z_E axis is issued to complete the simulation. Disturbance is given at the time of 5 seconds. The set point, or angular velocity, and motor speed on the z-axis or center of the earth, is 1. An open-loop system is one in which the controller has no impact on the output signal. Before the controller design is offered, the characteristics of the system must be determined through simulation. By giving a reference signal in the form of the propeller speed, the simulation is run. MATLAB/Simulink is used to run the simulation, which results in the system output response without disturbance shown in Figure 4. The simulation shows that the open-loop system without disturbance is stable, and the Fuzzy PID controller has no effect on the system. It can be seen in the figures that the Fuzzy PID responds more slowly to stabilize the system.

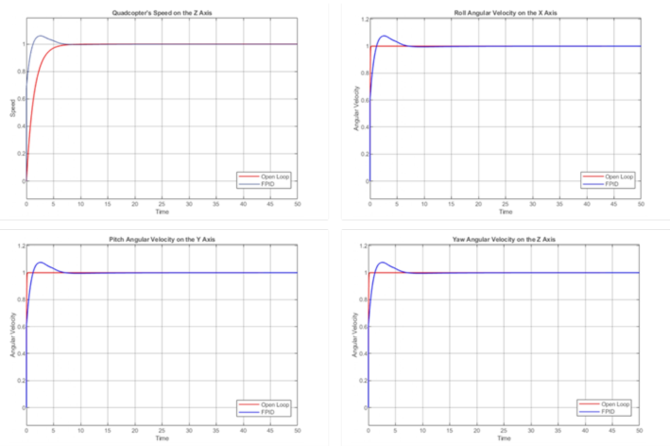


Fig. 4: Simulation results open-loop system and based Fuzzy-PID without disturbance in Z axis, roll, pitch, and yaw

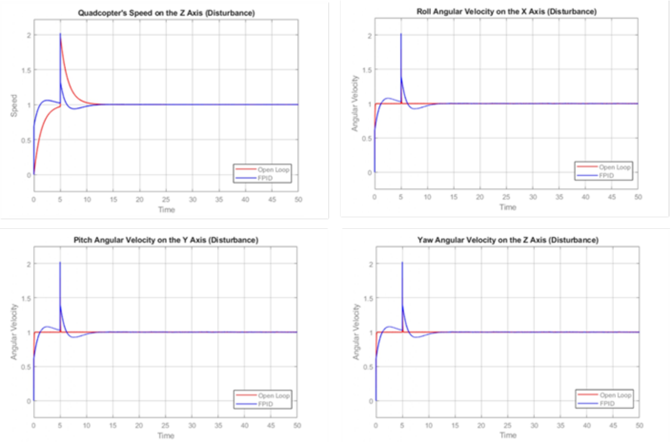


Fig. 5: Simulation results open-loop system and based Fuzzy-PID with disturbance in Z axis, roll, pitch, and yaw

Figure 5 shows a simulation of the system using a fuzzy-PID controller with disturb-ances at 5 seconds. Because the graph is pointing in the direction of the intended set point, it is clear from figures that the system is stable. Fuzzy-PID is able to stabilize the system even though it is given a disturbance at a fast time.

IV. CONCLUSION

The purpose of this research is to control the speed of a Quadcopter using the exist-ing Quadcopter mathematical model with the Fuzzy-PID controller method. The simulation is then implemented in MATLAB/Simulink by relying on the mathemati-cal model derived from Quadcopter. Simulating the system without disturbance or the system with disturbance, the Fuzzy-PID controller is able to stabilize the system towards the set point in a relatively short time. Future studies can apply random numbers to a given disturbance because the Quadcopter system is complex and con-tains high uncertainty.

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