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Hovering Control of Quadrotor Based on Fuzzy Logic

Nia Maharani Raharja[1], Eka Firmansyah[2], Adha Imam Cahyadi[3], Iswanto[4]
[1,2,3,4] Department of Electrical Engineering and Information Technology, Universitas Gadjah Mada, Yogyakarta, Indonesia
[1,4] Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta, Yogyakarta, Indonesia

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ABSTRACT

Quadrotor is one of rotary wing UAV types which is able to perform a hover position. In order to take off, landing, and hover, it needs controllers. Conventional controllers have been widely applied in quadrotor, yet they have drawbacks namely overshoot. This paper presents attitude and altitude control algorithm in order to obtain a response as quadrotor hovered optimally within minimum overshoot, rise time, and settling time. The algorithm used is Fuzzy Logic Controller (FLC) algorithm with Mamdani method. By using the algorithm, the quadrotor is able to hover with minimum overshoot and maximum rise time. The advantage of the algorithm is that it does not require linearization model of the quadrotor.

Corresponding Author:

Nia Maharani Raharja,
Department of Electrical Engineering and Information Technology,
Universitas Gadjah Mada,
Yogyakarta, Indonesia.
Email: nia.sie13@mail.ugm.ac.id

1. INTRODUCTION

Quadrotor is basically unstable because it is a non-linear model that has many variables with 6 degrees of freedom affected by four actuators. Previous researchers created quadrotor models in dynamics and kinematics represented in two models, namely nonlinear and linear. Quadrotor modeling needs some consideration, namely solid frames, rotor placement on each angle having symmetrical distance, and the position of the center of gravity (COG) is right at the midpoint of the crossing frame arm. Euler-Lagrange and Newton-Euler methods are generally used in aircraft modeling, however, Newton-Euler is more widely used because it is more easily understood.

Researches on quadrotor have been widely conducted by previous researchers in the field of control by using conventional traditional controls as practiced by Bouabdallah et al [1] using the configuration Plus for microquadrotor OS4 model weighing 240 grams controlled by PID and LQR control methods by referring to six states of roll, pitch, and yaw based attitude. In designing PID control of non-linear model of quadrotor obtained from the dynamics and kinematics, it is firstly linearized to obtain a state variable in that the stability can be identified.

Quadrotor modeling has been successfully developed by Bouabdallah & Siegwart [2] by modeling quadrotor from 6 to 12 states. In addition they modify backstepping algorithm by adding integral then called integral-backstepping. The algorithm is used to control the attitude and altitude, so that it can take off and landing autonomously. The algorithm is also used to control the position of the quadrotor in order to perform fly autonomously and avoid obstacles. With the algorithm, there is no overshoot when it hovers at the desired height but it takes a long raise time.

One of the criteria for good performance in the control of hover is a quick or minimum response. However, the rapid response tends to cause oscillation and requires a fairly large control signaling. It can be said that in the transient state, the use of signal control tend to be less good and less stable. To achieve good performance, there are several other researchers who combine conventional algorithm with artificial intelligence as conducted by Kirli et al [3] applying fuzzy algorithm to change the PID parameters on quadrotor control. Moreover, some researchers such as Gao et al [4] have conducted a study combining the PD algorithm with Fuzzy. It can be seen from the experiment results that the quadrotor can hover at the desired height without overshooting but still takes a long raise time.

Modern conventional control such as backstepping algorithm combined with fuzzy algorithm by Basri et al [5] for roll, pitch, yaw, and altitude control of quadrotor. Backsteeping control is optimized by changing the parameter values in the algorithm. The process of changing the parameters of backstepping takes a considerable time, so that to accelerate the process requires adaptive artificial intelligence algorithms such as fuzzy logic. The other modern control algorithms such as sliding mode algorithm combined with fuzzy algorithm by Barghandan & Badamchizadeh [6] to control the quadrotor attitude. The fuzzy algorithm is used to change the parameter values contained in slidding mode control, so that the control is more optimal.

Furthermore, adaptive artificial intelligence control has been applied to quadrotor as practiced by Zangenehpour et al [7] applying fuzzy logic algorithm for controlling the speed of the motor on the quadrotor. Fuzzy algorithm has been applied to the PIC microcontroller with inputs of angle and motor speed and output of motor pulse with the basic rules of 5x5. The result of the experiment showed that the fuzzy can be used to control a motor on quadrotor. The other researchers named Santos et al [8] have applied fuzzy logic control with mamdani method to control the x, y, and z positions in quadrotor. This algorithm is used and modified for membership output members with 5 members to control the positions of x, y, and z in quadrotor in an undisturbanced environment. In the control system carried out, quadrotor modelling in dynamic and kinematic has not been conducted. The quadrotor is modeled by using aggregation block that is a connected block between the controller and the dynamic system functioned to implement the connection of the control action of the four controllers.

In addition, Varga & Bogdan [9] have applied fuzzy-Lyapunov to control the positions of x, y, and z in quadrotor. There are six fuzzy controls used to control the quadrotor namely x-axis, y-axis, z-axis and yaw fuzzy controls. The two inputs namely altitude error and altitude change rate are used for z-axis control. A nonlinear quadrotor modeling is needed to determine the stability of the quadrotor by using Lyapunov method. The simulation result shows that there are still long overshoot and rise time. The other researchers such as Fakurian et al. [10] have modified the fuzzy input sets with triangular and gaussian type's fuzzyfication. By using the algorithm, quadrotor can hover at a pre-determined height in the undisturbances environment.

Based on the previous researches, on the altitude and attitude using artificial intelligence control, it can be seen that quadrotor can hover at the pre-determined height, but there are still overshoot, oscillation and a long raise time. Quadrotor cannot cope with disruptions of vertical wind because it is merely tested indoor. To overcome these problems, a strategy or method of intelligent control algorithms are needed to obtain the system with minimum overshoot and settling time and to generate output response with a good performance and stable in a transient state.

2. QUADROTOR

2.1. Quadrotor Modeling

Quadrotor has 6 degrees of freedom, namely three translational motions and three rotational motions. The dynamic motion model of the quadrotor is represented in force and torque generated from the rotors. The configuration of the quadrotor based on Corke's models [11] is shown in Figure 1 with the z-axis direction point down results in a negative value. The position of the quadrotor for $|x\ y\ z|^T$ are symbols as x-axis, y-axis and z-axis, for $|\phi\ \theta\ \psi|^T$are symbols as roll angle, pitch, yaw, for $|u\ v\ w|^T$ are symbols as speed caused by the x-axis, y-axis, z-axis, and for $|p\ q\ r|^T$ are symbols as angular speed caused by the x-axis, y-axis, z-axis.

Figure 1 shows that the global framework f_g with coordinates (x_g, y_g, z_g) is used as a quadrotor reference framework unmoved from the system. The quadrotor framework f_q with coordinates (x_q, y_q, z_q) has 4 rotor at the end of his cross-arm, each rotor consists of two pairs of rotor having a directional rotating motion. Rotors 1 and 3 rotate clockwise, whereas rotors 2 and 4 rotate counter-clockwise respectively. Each propeller produces force $[F_1;\ F_2;\ F_3;\ F_4]^T$; all have the same direction and the total force in quadrotor (excluding gravity) as follows $[F_x;\ F_y;\ F_z]^T$. This force produces a moment around the axis of the quadrotor written as follows $[M_x;\ M_y;\ M_z]^T$.

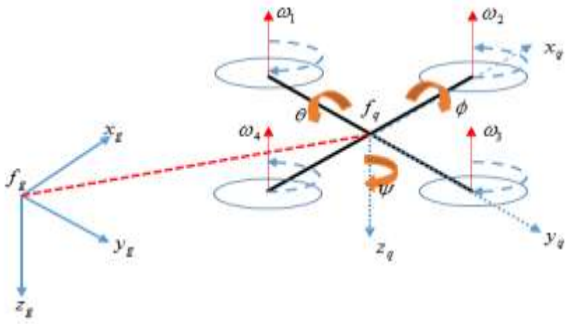

Figure 1. Quadcopter Configuration

There are three transformations of quadrotor's Euler angles when the quadrotor frame of f_q rotates towards the z_q axis (*yaw*) has a rotational transformation of Euler angles R_z (ψ), the quadrotor frame of f_q rotates towards the y_q axis (*pitch*) has the rotational transformation of Euler angles R_y (θ), and the quadrotor frame of f_q rotates towards x_q axis (*roll*) has rotational transformation of Euler angle R (x, ϕ). The transformation matrix of each of the x-axis, y-axis and z-axis can be formulated as follows:

$$R(x,\phi)=\begin{bmatrix}1 & 0 & 0\\ 0 & cos_\phi & -sin_\phi\\ 0 & sin_\phi & cos_\phi\end{bmatrix}, R(y,\theta)=\begin{bmatrix}cos_\theta & 0 & sin_\theta\\ 0 & 1 & 0\\ -sin_\theta & 0 & cos_\theta\end{bmatrix}, R(z,\psi)=\begin{bmatrix}cos_\psi & -sin_\psi & 0\\ sin_\psi & cos_\psi & 0\\ 0 & 0 & 1\end{bmatrix} \quad (1)$$

The transformation matrix R generated is as follows:

$$R = R(z,\psi)R(y,\theta)\,R(x,\phi)$$

$$R=\begin{bmatrix}c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi\\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi\\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta\end{bmatrix} \quad (2)$$

Where c = cosine and s=sine. By using the transformation matrix R provided above, the linear velocity along the axis of the body can be transformed into inertial frame. Vector $[x;\ y;\ z]^T$ defines the quadrotor position relative to the inertial frame and $[u;\ v;\ w]^T$ defines a linear velocity of the quadrotor within the framework of the rigid body. Equation (3) states the relationship that exists between the two vectors.

$$\frac{d}{dt}\begin{bmatrix}x\\ y\\ z\end{bmatrix} = R\begin{bmatrix}u\\ v\\ w\end{bmatrix} \quad (3)$$

$$\dot{x} = c_\theta c_\psi u + (s_\phi s_\theta c_\psi - c_\phi s_\psi)v + (c_\phi s_\theta c_\psi + s_\phi c_\psi)\mathrm{w}$$
$$\dot{y} = c_\theta s_\psi u + (s_\phi s_\theta s_\psi + c_\phi c_\psi)v + (c_\phi s_\theta s_\psi - s_\phi c_\psi)w$$
$$\dot{z} = -s_\theta + (s_\phi c_\theta)v + (c_\phi c_\theta)w$$

Rotational matrix can be determined as follows:

$$W = \left[\begin{bmatrix}1\\ 0\\ 0\end{bmatrix} + R(x,\phi)\left(\begin{bmatrix}0\\ 1\\ 0\end{bmatrix} + R(y,\theta)\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}\right)\right]^{-1}$$

$$W = \begin{bmatrix}1 & sin_\phi . tan_\theta & -cos_\phi . tan_\theta\\ 0 & cos_\phi & sin_\phi\\ 0 & \frac{sin_\phi}{cos_\theta} & \frac{cos_\phi}{cos_\theta}\end{bmatrix} \quad (4)$$

Angular velocity along the axis of the quadrotor body can be transformed into Euler speed using the transformation matrix W provided in the following equation

$$\frac{d}{dt}\begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix} = W\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (5)$$

$$\dot{\phi} = p + sin_{\phi}.tan_{\theta}.q - cos_{\phi}.tan_{\theta}.r$$
$$\dot{\theta} = q.cos_{\phi} + r.sin_{\phi}$$
$$\dot{\psi} = \frac{sin_{\phi}}{cos_{\theta}}\dot{q} + \frac{cos_{\phi}}{cos_{\theta}}r$$

There are four forces served as quadrotor dynamics influenced by the thrust constant relative to the air density (b), the distance between the motor with the center point of mass of the quadrotor (d), and the slidding constant. The relationship between force and a rotational speed of the rotor can be represented in the following equation:

1. Vertical Force

$$T = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (6)$$

2. Moment of roll force

$$\tau_x = db(\omega_1^2 - \omega_3^2) \quad (7)$$

3. Moment of pitch force

$$\tau_y = db(\omega_4^2 - \omega_2^2) \quad (8)$$

4. Moment of yaw force

$$\tau_z = k(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \quad (9)$$

The translational dynamics of the quadrotor comparable to the influence of the Coriolis force is determined based on the second law of Newton [12] that is as follows:

$$F = ma$$

which m = quadrotor mass (kg), a = acceleration (m/s^2)and F is the force generated by quadrotor where

$$F = m(\dot{v} + \omega \times v)$$
$$F_g - F_{thrust} = m(\dot{v} + \omega \times v) \quad (10)$$

$$\begin{bmatrix}0\\ 0\\ mg\end{bmatrix} - R\begin{bmatrix}0\\ 0\\ T\end{bmatrix} = m\left(\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} + \left(\begin{bmatrix}p\\ q\\ r\end{bmatrix} \times \begin{bmatrix}u\\ v\\ w\end{bmatrix}\right)\right)$$

From these equations, the acceleration of the body can be seek by the following equation:

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \frac{1}{m}\begin{bmatrix}0\\ 0\\ mg\end{bmatrix} - R\begin{bmatrix}0\\ 0\\ T\end{bmatrix} - \left(\begin{bmatrix}p\\ q\\ r\end{bmatrix} \times \begin{bmatrix}u\\ v\\ w\end{bmatrix}\right) \quad (11)$$

Thus, the rate speed of the linear body can be calculated as:

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \frac{1}{m}\begin{bmatrix}0\\ 0\\ mg\end{bmatrix} - \begin{bmatrix}(c_{\phi}s_{\theta}c_{\psi} + s_{\phi}s_{\psi})T\\ (c_{\phi}s_{\theta}s_{\psi} - s_{\phi}c_{\psi})T\\ (c_{\phi}c_{\theta})T\end{bmatrix} - \begin{bmatrix}(qw - rv)\\ (ru - pw)\\ (pv - qu)\end{bmatrix} \quad (12)$$

$$\dot{u} = -T.cos_{\phi}.sin_{\theta}.cos_{\psi} - T.sin_{\phi}.sin_{\psi} - qw + rv$$
$$\dot{v} = -T.Cos_{\phi}.Sin_{\theta}.Sin_{\psi} + g.Sin_{\phi}.Cos_{\psi} - ru + pw$$
$$\dot{w} = g - T.Cos_{\phi}Cos_{\theta} - pv + qu$$

Based on the Newton's second law of rotational motion [12], the following equation is obtained

$$M = \mathrm{I}\dot{\omega} + (\omega \times I\omega), \quad (13)$$

which $\omega = |p \quad q \quad r|$, $M = [M_x \quad M_y \quad M_z]^T$ and I is the moment of quadrotor inertia.

$$\mathrm{I} = \begin{bmatrix} \mathrm{I}_x & 0 & 0 \\ 0 & \mathrm{I}_y & 0 \\ 0 & 0 & \mathrm{I}_z \end{bmatrix} \quad (14)$$

The result of the substitution of equations 13 and 14 can be written as follows:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} \mathrm{I}_x & 0 & 0 \\ 0 & \mathrm{I}_y & 0 \\ 0 & 0 & \mathrm{I}_z \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \left(\begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} \mathrm{I}_x & 0 & 0 \\ 0 & \mathrm{I}_y & 0 \\ 0 & 0 & \mathrm{I}_z \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \right) \quad (15)$$

The equation of the angular acceleration in the x, y, and z axes are as follows:

$$\begin{bmatrix} \mathrm{I}_x\dot{p} \\ \mathrm{I}_y\dot{q} \\ \mathrm{I}_z\dot{r} \end{bmatrix} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} - \begin{bmatrix} (\mathrm{I}_z - \mathrm{I}_y)\,\dot{p} \\ (\mathrm{I}_x - \mathrm{I}_z)\,\dot{q} \\ (\mathrm{I}_y - \mathrm{I}_x)\,\dot{r} \end{bmatrix} \quad (16)$$

$$\dot{p} = \frac{M_x}{I_x} - \frac{I_z - I_y}{I_x} qr$$
$$\dot{q} = \frac{M_y}{I_y} - \frac{I_x - I_z}{I_y} pr$$
$$\dot{r} = \frac{M_z}{I_z} - \frac{I_y - I_x}{I_z} pq$$

Several previous researchers assume that the Coriolis Effect [13] is very small that it can be. So that the representation of the 12 nonlinear state equations of the quadrotor system models is as the folllowing equations:

$$\dot{x} = u \quad (17)$$

$$\dot{y} = v \quad (18)$$

$$\dot{z} = w \quad (19)$$

$$\dot{\phi} = p + sin_{\phi}.tan_{\theta}.q - cos_{\phi}.tan_{\theta}.r \quad (20)$$

$$\dot{\theta} = q.cos_{\phi} + r.sin_{\phi} \quad (21)$$

$$\dot{\psi} = \frac{sin_{\phi}}{cos_{\theta}}\dot{q} + \frac{cos_{\phi}}{cos_{\theta}} r \quad (22)$$

$$\dot{u} = -T.Cos_{\phi}.Sin_{\theta}.Cos_{\psi} - T.Sin_{\phi}.Sin_{\psi} \quad (23)$$

$$\dot{v} = -T.Cos_{\phi}.Sin_{\theta}.Sin_{\psi} + g.Sin_{\phi}.Cos_{\psi} \quad (24)$$

$$\dot{w} = g - T.Cos_{\phi}Cos_{\theta} \quad (25)$$

$$\dot{p} = \frac{M_x}{I_x} \quad (26)$$

$$\dot{q} = \frac{M_y}{I_y} \quad (27)$$

$$\dot{r} = \frac{M_z}{I_z} \quad (28)$$

2.2. Quadrotor Controller

Closed-loop control strategy is needed precisely because of the quadrotor dynamics. In this section, a model of state space quadrotor is presented for controller design. Representation of 12 non-linear state equations is used to develop equations of state space of the quadrotor which is multi-input multi-output system (MIMO) defined as $\dot{x} = [\dot{x},\ \dot{y},\ \dot{z},\ \dot{\phi},\ \dot{\theta},\ \dot{\psi},\ \dot{u},\ \dot{v},\ \dot{w},\ \dot{p},\ \dot{q},\ \dot{r}]^T$. The state variable components defined as $x = [x,\ y,\ z,\ \phi,\ \theta,\ \psi,\ u,\ v,\ w,\ p,\ q,\ r]^T$ and the control input vector components defined as $u = [T\ \tau_x\ \tau_y\ \tau_z]^T$.

These components will be afterwards used in meeting the state space equation:

$$\dot{x} = f(x,u) \quad (29)$$

in which

$$\dot{X} = f(X,U) = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ p + sin_{\phi}.tan_{\theta}.q - cos_{\phi}.tan_{\theta}.r \\ q.cos_{\phi} + r.sin_{\phi} \\ \frac{sin_{\phi}}{cos_{\theta}}\dot{q} + \frac{cos_{\phi}}{cos_{\theta}}r \\ -T.Cos_{\phi}.Sin_{\theta}.Sin_{\psi} + g.Sin_{\phi}.Cos_{\psi} \\ -T.Cos_{\phi}.Sin_{\theta}.Cos_{\psi} - T.Sin_{\phi}.Sin_{\psi} \\ g - T.Cos_{\phi}Cos_{\theta} \\ \frac{M_x}{I_x} \\ \frac{M_y}{I_y} \\ \frac{M_z}{I_z} \end{bmatrix} \quad (30)$$

There are two controls studied by several previous researchers that is controls of altitude and attitude [2]. They have been used to control the speed of the four motor rotation with the same speed [14]. It can be seen in equations 10 and 13 that the rotational and the translational motions are unconnected as shown in Figure 2.

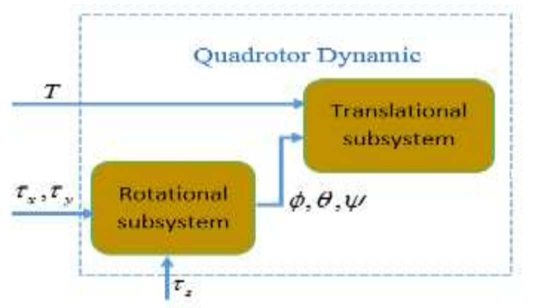

Figure 2. Diagram block of quadrotor

Figure 2 shows that four controls are required for the quadrotor consisting of the altitude of (T) for subsystem translational and attitude of (τ_x, τ_y, τ_z) for subsystem Rotational in which the outputs of the subsystem are roll, pitch and yaw used for subsystem translational. Thus, the closed-loop control can be designed for the attitude and altitude.

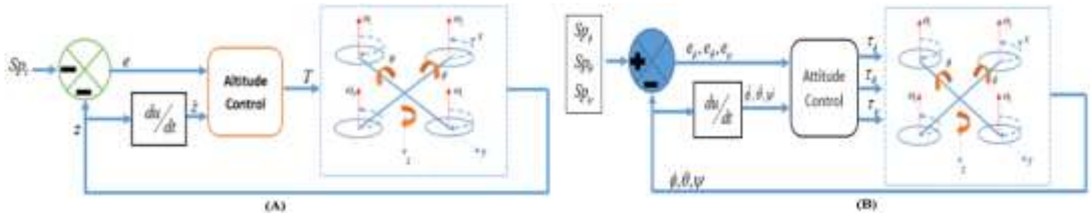

Figure 3. Block Diagram of (A) altitude and (B) attitude control

2.3. Altitude Control

Altitude control is required to ensure that the quadrotor is at a secure altitude [15]-[18]. So that it is also responsible for restoring the quadrotor to a secure state at a certain altitude if it performs impaired position due to air turbulence. The altitude control input of the quadrotor shown in figure 2 is thrust (T) which is the multiplication of relative thrust constant to air density (b) with the sum of four motors as written in equation 6. Several algorithms have been studied and applied to quadrotor altitude by previous researchers, for example, the PID algorithm investigated by Lee et al. [19], the slidding mode algorithm studied by Gonzalez et al. [20], the model predicting control (MPC) algorithm investigated by Alexis et al. [21]. From the previous studies, the researchers have used two inputs to design the control block for altitude in quadrotor as in Figure 3(A).

In Figure 3(A), it appears that to control the altitude two inputs namely error and error change rate are required. Error value of (e) obtained from the difference between the set point with the actual height (z), can be expressed as in the following equation:

$$e = z - Sp_z \tag{31}$$

Where z is the height value of the quadrotor. The height value of this quadrotor is negative because quadrotor is against the earth gravity. While Sp_z is the value to the desired height. It has a positive value so that the error algorithm of equation (31) is modified into the following equation:

$$e = z - (-Sp_z) \tag{32}$$

2.4. Attitude Control

Attitude control is required to stabilize the quadrotor while it hovers. This control is responsible for ensuring that the angles of roll, pitch and yaw on quadrotor have a minimum value by controlling the four motors rotates at the same speed, so that it can hover stably. The previous researchers have used a variety of algorithms to control attitude such as the PID algorithm used by Lee et al. [19], the Sliding Mode Control algorithm used by Bouadi et al. [22], and the backstepping algorithm used by Colorado et al. [23]. In the previous studies, the researchers have used a six inputs and three outputs to design a control block for attitude in quadrotor as in Figure 3(B).

It can be seen in figure 3(B) that three controllers are required for attitude namely roll, pitch control and yaw controls in which each control has two inputs and an output. Roll control has a thrust output and two inputs of roll error (e_θ), and the change rate of roll ($\dot{\theta}$). Roll error value obtained from the difference between the set point with the actual roll angle (θ), can be expressed as in the following equation:

$$e = \theta - Sp_\theta \tag{33}$$

θ is the value of the roll angle of the quadrotor, and Sp_θ is the desired roll angle value in which the roll angle is 0 for the quadrotor to be stable. Pitch control has a thrust pitch output and two inputs namely pitch error (e_ϕ) and change rate of pitch ($\dot{\phi}$). Pitch error value obtained from the difference between the set point with the actual pitch angle (ϕ), can be expressed as in the following equation:

$$e = \phi - Sp_\phi \tag{34}$$

ϕ is the value of the pitch angle of the quadrotor, Sp_{ϕ} is the desired picth angle value in which the pitch angle is 0 for the quadrotor to be stable. Yaw control has a yaw thrust output and two inputs namely yaw error (e_{ψ}) and change rate of yaw ($\dot{\psi}$). Yaw error value obtained from the difference between the set point with the actual roll angle (ψ), can be expressed as in the following equation:

$$e = \psi - Sp_{\psi}, \tag{35}$$

where ψ is the value of the yaw angle of the quadrotor, Sp_{ψ} is the desired yaw angle value in which the yaw angle is 0 for the quadrotor to be stable.

3. CONTROL STRATEGY

This study will discuss the hover control system for quadrotor at a desired altitude. Altitude and attitude controls are used to maintain the stability of the quadrotor. Fuzzy logic algorithm is one of the artificial intelligence algorithms to control the altitude and attitude by using Mamdani methods [24]–[26].

3.1. Altitude Stability

Figure 3(A) shows that the altitude control has two inputs namely error and the error change rate. This control has also an output that is used as a throtel thrust input to control the rotation of the four motors on the quadrotor. In this paper, the proposed control is fuzzy logic algorithm which is multi input single output (MISO) consisting two inputs and an output. Further, the fuzzy control system for controlling the height of the quadrotor shown in the block diagram in Figure 4 is developed. It shows that this control has two inputs and an output. The inputs and outputs are used to design the fuzzy logic control as members of the fuzzy set.

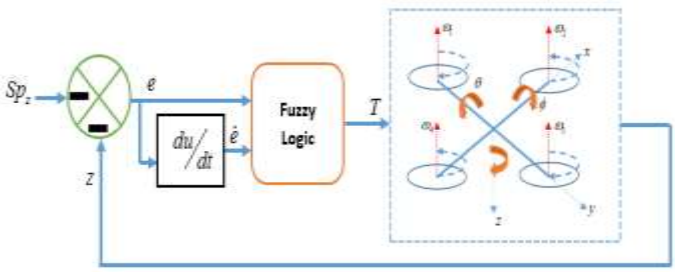

Figure 4. The proposed altitude control system

The altitude control design using fuzzy logic algorithm proposed in this paper. This algorithm is fuzzy MISO which has two inputs and an output using mamdani method as the basic rules. The inputs and output are designed to have three membership functions contained in the universal sets. The universal sets have different range values for input error, input error change rate and output. There are minimum and maximum values for the universal sets range of the input error which can be determimed by using equation 2.50. the universal sets of input error ranging [-1 1] has three membership functions shown in Figure 5(A). In the figure, it can be seen that membership functionss consist of NS (negative small), Z (zero), and PS (positive small).

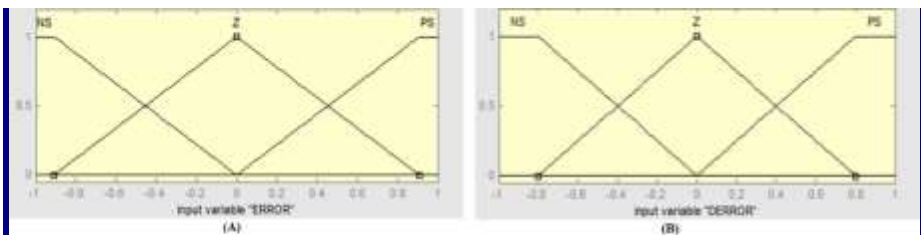

Figure 5. (A) Error and (B) Dz variable input design

In this paper, the minimum and maximum values for the universal sets of input error change rate has the same value as the universal sets of input error ranging [-1 1] shown in Figure 5(B). In this figure it is seen that the membership functions in the universal sets consist of NS (negative small), Z (zero), and PS (positive small). While the minimum and maximum values for the universal sets of throttle thrust output can be calculated by equations 6 and 25. Because of the considerably small Coriolis Effect, the effect can be ignored so that the equation 25 is substituted into equation 6 to be as follows:

$$\dot{w} = g - \frac{1}{m} b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (36)$$

The minimum value of thrust can be determined from equation (37) in order for quadrotor to be able to take off. The obtained equation is as the following:

$$g - \dot{w} = \frac{1}{m} b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (37)$$

When taking off, the fourth motors rotate at the same speed and the quadrotor has no starting acceleration,¨z = 0 thus the above equation becomes:

$$\omega_1^2 = \omega_2^2 = \omega_3^2 = \omega_4^2$$

$$\frac{mg}{4} = b\omega^2$$

$$\sqrt{\frac{(mg)}{(4b)}} = \omega$$

where m = the quadrotor weight (4kg), g = the gravity (9.8), b = the moment of inertia for acceleration of z (1.3234e-005). From the calculation, it is obtained the value of the motor speed of 860 so that the minimum and maximum range values of universal sets of output speed can be set exceeding the value that is [-1000 1000] shown in Figure 7. It is seen in the figure that the membership functions consist of NS (negative small), Z (zero), and PS (positive small).

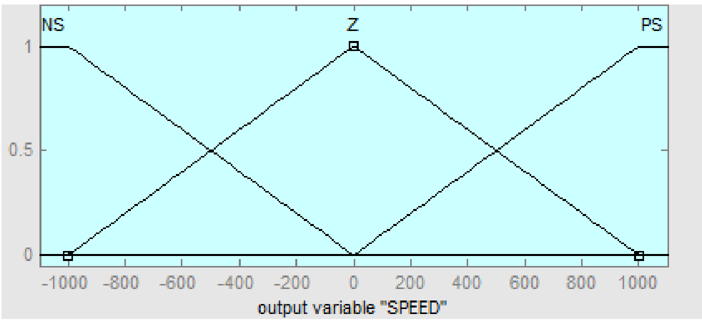

Figure 7. Output variable speed desain

The design of the fuzzy rule base uses lookup table consisting of 9 rules to determine the decision. All rules are shown in Figure 8 connected with the AND operator.

$\dot{z}$ \ Error(e)	N	Z	P
P	P	P	Z
Z	P	Z	N
N	Z	N	N

Figure 8. Rule base 3x3 fuzzy mamdani altitude control

Figure 10 shows the design of fuzzy logic control system rules in which there are three algorithms to stabilize the quadrotor when hovering namely:

1. The algorithm serves for a quadrotor to take off.
2. This algorithm serves to dampen overshoot.
3. This algorithm serves to dampen oscillations and head to the steady state.

3.2. Attitude Control

Figure 3(B) shows that the attitude control has six inputs that is errors of roll, pitch, and yaw, and the error change rate of roll, pitch, and yaw. Additionally, this control has three outputs namely thrust of roll, pitch and yaw to control the rotation of the four motors on the quadrotor. In this paper, the proposed control is fuzzy logic controller (FLC), meanwhile the algorithm can not control the system of multi input multi output (MIMO), therefore, the attitude control is made into three controls that is FLC of roll, pitch, and yaw as shown in Figure 9.

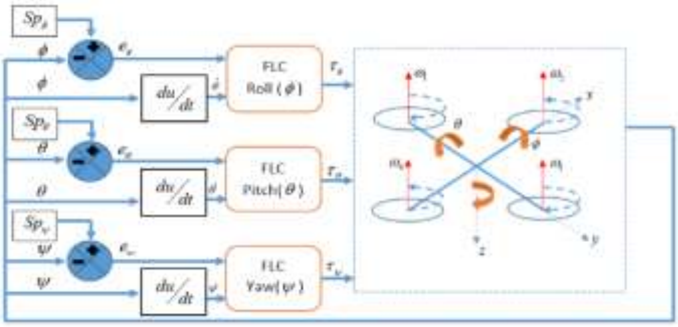

Figure 9. The proposed attitude control system

Figure 9 shows that there are three fuzzy controls, namely fuzzy controls of roll, pitch and yaw. Fuzzy control of roll has two inputs that is roll error and change rate of roll error and an output thrust roll. Fuzzy control of pitch has two inputs that is pitch error and change rate of pitch error and an output thrust pitch. Fuzzy control has two inputs namely yaw error and change rate of yaw error and an output yaw thrust.

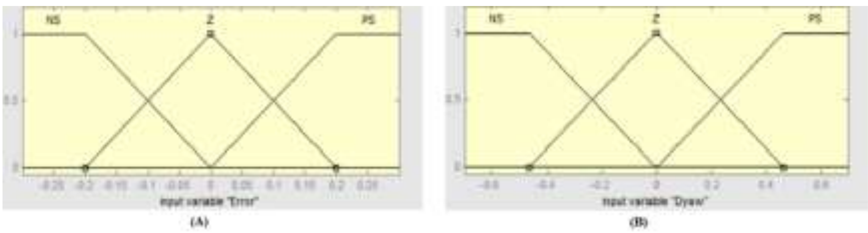

Figure 10. Input variable (A) Error and (B) Dyaw design

The proposed Attitude control uses fuzzy logic controller algorithm with rule base 3x3. The rule base is fuzzy control which the inputs and output have three membership functions with minimum and maximum values for the universal sets range of input errors of roll, pitch and yaw that can be calculated by using the equation 2.51, 2.52, and 2.53. In this paper, the universal sets of input error of roll, pitch and yaw have the same range [-0.3 0.3] and three membership functions as shown in Figure 10(A). The figure shows that the membership functions consist of NS (negative small), Z (zero), and PS (positive small). In this paper, the minimum and maximum range values for the universal sets of input error change rate of roll, pitch, and yaw have the same value as the universal sets of input error of roll, pitch and yaw that is [-1 1] as shown in Figure 10(B). The figure shows that the membership functions in the universal sets of error change rate consist of NS (negative small), Z (zero), and PS (positive small).

The minimum and maximum values for the universal sets of output thrust of roll, pitch and yaw can be calculated with the equation 2.12 and 2.15 as the thrust throttle design. The output variables design for fuzzy sets that will fit into quadrotor throtlle is shown in Figure 11. In this figure it is seen that the universal sets of output thrust of roll, pitch and yaw have a value range [-1000 1000] and the membership functions consist of NS (negative small), Z (zero), and PS (positive small).

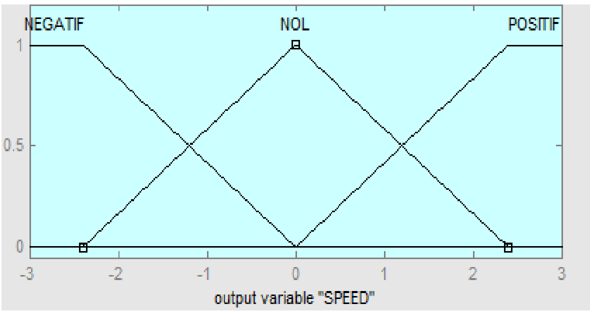

Figure 11. Output variable Speed design

The design of fuzzy rule base uses lookup table consisting of 9 rules to determine the decision. All rules shown in Figure 12 is connected with the AND operator.

	NS	Z	PS
PS	P	P	O
Z	P	O	N
NS	O	N	N

Figure 12. Mamdani Attitude control with fuzzy rule base 3x3

4. RESULT AND DISCUSSION

In the simulation, the altitude and attitude controls using fuzzy logic controller was tested by Corke's simulator (2011) which has a specification as shown in Table 1. The table shows that the quadrotor has a mass of 4 kg, the distance between the motor and the COG is 0.165 meters, the thrust constant is 1,2953x10-5 kg.m, the drag constant is 1.0368 x 10 -7Kg.m, and tested on gravity acceleration of 9,8m / s2. To simulate the controls of attitude and altitude, the parameters contained in the simulator was previously set including setting the start position of the quadrotor at xy position (-1,0), the desired height of 1 meter, and the hover position of the quadrotor at xy (-1.0).

The first experiment was conducted without wind disturbance. The simulation result of the hover of the quadrotor at z position with the height of 1 meter is shown in Figure 13(A). There are three graphs as seen in the figure namely set point, disturbance, and altitude. The fuzzy logic controller algorithm enables the altitude controller quickly stabilizes the quadrotor at 4.968th second of the steady state and at 2.166th second of the settling time. In addition, the quadrotor performs fast raise time to take off that is 1.607 second and there is no oscillation and overshoot in performing them.The hover position of the quadrotor remains unchanged ie equal to the initial position.

Table 1. The Performance of Quadrotor

Parameter	Nilai	Satuan	Keterangan
G	9,81	m/s^2	Percepatan gravitasi
M	4,34	Kg	Massa A.R. Drone 2
D	0,165	Meter	Jarak antara rotor dengan COG
B	$1{,}2953 \times 10^{-5}$	Kg.m	Konstanta gaya dorong
K	$1{,}0368 \times 10^{-7}$	Kg.m	Konstanta gaya hambat
I_x	0,082	$Kg.m^2$	Momen inersia sumbu x
I_y	0,0845	$Kg.m^2$	Momen inersia sumbu y
I_z	0,1377	$Kg.m^2$	Momen inersia sumbu z

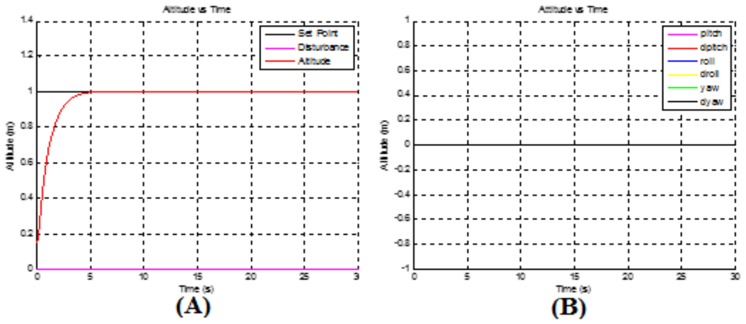

Figure 13. Disturbance free relation graph of (A) altitude and (B) attitude

Figure 13(B) shows that when hovering, attitude control of the quadrotor is able to stabilize roll, roll acceleration, pitch, pitch acceleration, yaw, and yaw acceleration. From the graph it appears that there is no disturbance and oscillation on roll, roll acceleration, pitch, pitch acceleration, yaw, and yaw acceleration when the quadrotor take off and hover.

In the second simulation, experiments was performed by using wind-like disturbance as the quadrotor hovers at Z position with a height of 1 meter shown in Figure 14(A). It can be seen from the figure that there are set point, disturbance, and altitude. When hovering, the quadrotor was disturbed at 15th second for 3 seconds. It makes the quadrotor's height changes to 1.4 meters. Altitude Controller quickly stabilizes the quadrotor and returns it to the initial position with raise time of 1.607 seconds, steady state at 4.968th second and setling time at 2.166th second.

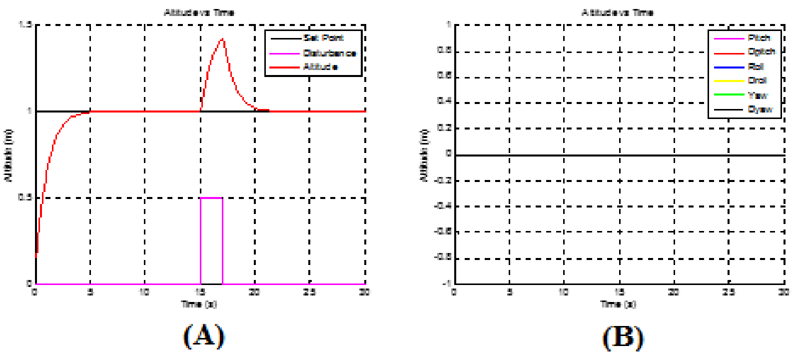

Figure 14. Graph of (A) altitude and (B) attitude with disturbance when hovering

Figure 14(A) shows that when the quadrotor takes-off and hovers, it is disturbed by vertical wind, so that its altitude changes. With the position change, the quadrotor attitude controller maintains the stability of roll, roll acceleration, pitch, pitch acceleration, yaw, and yaw acceleration as shown in Figure 14(B). it is seen from the figure that there is no noise and oscillation on roll, roll acceleration, pitch, pitch acceleration, yaw, and yaw acceleration when the quadrotor is disturbed when it takes off and hovers.

5. CONCLUSION

This paper presents the development of quadrotor control using fuzzy logic algorithms. This control is used to stabilize the quadrotor when it takes-off, lands, and hover. There are two controls to stabilize the current position quadrotor hover. The main control in this paper is the altitude control which serves to control the height position of the quadrotor when it hovers. Therefore, the control is capable of stabilizing the quadrotor in condition there is disturbance of vertical wind. The weakness of this control is that it can not stabilize the angular accelerations of the roll, pitch and yaw when hovering. So that control of the second in this paper is an attitude control to adjust the roll, pitch and yaw. The controls performs fast time raise, settling time, steady state, and there is no overshoot.

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