2016 8th International Conference on Information Technology and Electrical Engineering (ICITEE), Yogyakarta, Indonesia

Trajectory and Altitude Controls For Autonomous Hover of a Quadrotor Based on Fuzzy Algorithm

Iswanto[*,**], Oyas Wahyunggoro[*], and Adha Imam Cahyadi[*]
[*]Department of Electrical Engineering and Information Technology, Universitas Gadjah Mada
Jalan Grafika 2, Yogyakarta 55281
**Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta
Jalan lingkar selatan tamantirta2, Yogyakarta 55281
iswanto.s3te13@mail.ugm.ac.id

***Abstract*— A quadrotor is needed by geologists to do surveillance and monitoring in several disaster-prone areas. Therefore, quadrotors which are able to perform autonomous hovering in order to move from one location to another are required. Based on the problem, This paper presents the trajectory and altitude control for autonomous hovering of quadrotor by using fuzzy logic controller. This algorithm is applied to the altitude control that serves to control the quadrotor to hover at a specific position. It is also applied on the trajectory control so that the quadrotor will be able to move to x and y trajectories. The proposed algorithm shows that quadrotor can quickly hover at a predetermined height taking rise time in 1.5 second and settling time at 1.9 second. Furthermore, the quadrotor is able to move from the initial position to the next position with the rise time in 1.4 second and settling time at 2 second.**

Keywords— trajectory; altitude; autonomous hover; quadrotor; fuzzy algorithm

I. INTRODUCTION

Quadrotor is a rotary wing type of unmanned aerial vehicles (UAVs) which moves flexibly in various fields. In addition, it has better maneuverability in comparison with unmanned ground vehicle (UGV). It has been used by search and rescue (SAR) team to reach challenging disaster-prone areas for land robots to search and evacuate the victims [1].

It is a type of rotary-wing that uses four brushless dc motors to drive four propellers. Two propellers rotate in clockwise way and the other two propellers rotate in counter clock wise way at the same speed. When the four motors do not rotate at the same speed, the quadrotor is less stable when flying [2].

The advantage of a quadrotor compared to other aircrafts is that it is able to hover in the air and it does not require a runway for takeoff and landing. It is frequently used for aerial photography. To hover, a quadrotor measures motor rotation at a constant speed [3]. In order for the quadrotor to be able to take off, the four motors rotate equally fast. While landing the four motors rotate slowly at the same speed [4].

It has been mentioned previously that to be able to hover, the control system for the speed of the four motors is necessary. Several researchers have conducted studies abaut hover control system including Lee et al. [5]. In order to hover at a certain altitude, it requires an ultrasonic sensor and dynamic surface control. The research result shows that the quadrotor is not stable because there is still noise in the altitude and attitude.

A research on the altitude position control for quadrotor has been conducted by researchers including Joyo et. al. [6]. He used the PID to control the position of hover altitude. In addition, the study about hover control system by using non-linear control algorithms was conducted by Johan et al. [7]. The vision sensors were used in this study for more accurate altitude position. The research used merely an altitude control and the result shows that there is still overshoot in the system. Consequently, the quadrotor is less stable while hovering.

While hovering, a quadrotor requires not only altitude but also position and attitude control. Position control is an algorithm which function is to repost the quadrotor when it is exposed to wind disturbance. It also serves for navigation. This control has been studied by researchers such as Alexis et. al [8] using models predictive control (MPC) algorithm to return to its previous position when it is disrupted by horizontal wind disruption. However, there is still a small noise in the sytem. The other algorithm such as the integral sliding mode control (ISMC) has been proposed by Gomez-Balderas et al. (2013) for position tracking of moving UGV. In their study, they used a combination between optical sensor and ISMC. By using it, the quadrotor is able to pursuit the moving UGV but there is noise in the system. Gomez-Balderas et al [9] used a non-linear system to stabilize quadrotor. With this control the quadrotor is stable, but there is still noise at x and y positions.

Attitude control is an algorithm to keep the balance of the motor speed while hovering and it is required to control roll, pitch and yaw on a quadrotor. Attitude control research has been investigated by researchers such as Jasim and Gu [10] using $H\infty$ control algorithm for the attitude. A non-linear control algorithm was studied by Voos [11] using non-linear feedback-linearization control algorithm which is capable to stabilize a quadrotor with faster settling time in comparison with H∞ control algorithm.

In addition to control algorithms, there is an intelligent control algorithm which does not use linearization process for modelling a quadrotor. Fuzzy logic controller (FLC) algorithm is one of the intelligent control algorithms used to stabilize the quadrotor while hovering. One of the researchers using this algorithm was Santos et. al. [12]. the research result shows that there is no overshoot in the system.

The other researchers using FLC algorithm for quadrotor stability are Bhatkhande & Havens [13]. The weakness of the system is that there is overshoot in attitude and altitude and it spend very big energy to hover. The algorithm has been also studied by Fakurian [14]. which used fuzzy with rule base 5x3. This system is considerably appropriate in which there is no overshoot in the altitude but unfortunataely there is overshoot in attitude. Varga & Bogdan [15] applied fuzzy algorithm with rule base 3x3 without overshoot in attitude. However, the set members are undetermined and there is overshoot in altitude.

Based on the previously mentioned researches, fuzzy algorithm has few weaknesses in altitude when the quadrotor is hovering. This paper proposed a method for the stability of quadrotor using attitude, position, and altitude controls. The method aims to find minimum overshoot, settling time, and signal control on a transient state.

II. THE QUADROTOR MODEL

Quadrotor was first studied by Bouabdallah et al. [2] who created micro quadrotor. In their research the micro quadrotor was modeled by kinematic and dynamic models. Furthermore, in 2007 quadrotor's control system was developed by Bouabdallah and Siegwart [16] to regulate the speed of the motors by using PID control. It controlled the altitude and attitude of the quadrotor that made it stable when flying. In 2009, several researchers conducted a study to develop quadrotor [17]. A dynamic modeling for quadrotor that could lift a four kilogram payload was modelled by Pounds et al.

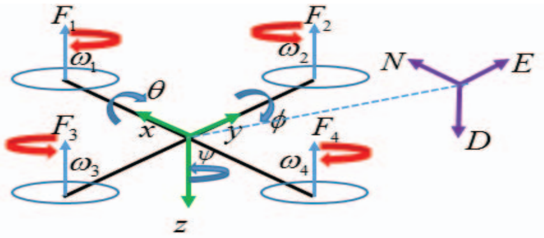


Fig. 1. Quadrotor Model

In the reserch presented in this paper, the model of non-linear equations of the quadrotor based on the Corke model [18] is proposed as shown in Figure 1 [19], [20]. This model uses 12 states that is $[x\ y\ z\ \phi\ \theta\ \psi\ \dot{x}\ \dot{y}\ \dot{z}\ \dot{p}\ \dot{q}\ \dot{r}]^T$ with $[x\ y\ z]^T$ is the coordinates of x-axis, y-axis and z-axis on a global framework while $[\phi\ \theta\ \psi]^T$ is three Euler angles that make up the movement of roll, pitch, yaw in x-axis, y-axis, and the z-axis respectively. The speed of the linear based on the position on each of x-axis, y-axis and z-axis is $[\dot{x}\ \dot{y}\ \dot{z}]^T$, while the angular velocity based on the Euler angles on each of x-axis, y-axis and z-axis is $[\dot{p}\ \dot{q}\ \dot{r}]^T$ [21].

The coordinate of the translation is $[x\ y\ z]^T$, so that the forces acting on the quadrotor is obtained by Newton's second law that is:

$$F = m\dot{v} + (\omega \times mv) \tag{1}$$

m is the mass, $\omega = [\dot{p}\ \ \dot{q}\ \ \dot{r}]^T$ is the angular velocity and $v = [\dot{x}\ \ \dot{y}\ \ \dot{z}]^T$ is the linear velocity. Figure 1 shows that the forces acting on the quadrotor is the gravitational pull of the earth and the total thrust of the quadrotor.

$$F = F_g - F_{Thrust} \tag{2}$$

A dynamic model of quadrotor based on translational position $[x\ \ y\ \ z]^T$ is the linear velocity $[\dot{x}\ \ \dot{y}\ \ \dot{z}]^T$ and linear acceleration $\dot{v}$ by assuming that $\omega = [\dot{p}\ \ \dot{q}\ \ \dot{r}]^T \approx 0$ and $v = [\dot{x}\ \ \dot{y}\ \ \dot{z}]^T \approx 0$ then $\dot{v} = [\ddot{x}\ \ \ddot{y}\ \ \ddot{z}]^T$. Thus, to control the heading and altitude, three state variables obtained from the previous studies are needed, that is:

$$\ddot{x} = -\frac{1}{m}T\left(c_\phi s_\theta c_\psi + s_\phi s_\psi\right) \tag{3}$$

$$\ddot{y} = -\frac{1}{m}T\left(c_\phi s_\theta s_\psi - s_\phi c_\psi\right) \tag{4}$$

$$\ddot{z} = mg - \frac{1}{m}T\left(\cos_\phi \cos_\theta\right) \tag{5}$$

$$\dot{p} = \frac{\tau_x}{I_x} - \frac{I_z - I_y}{I_x}\dot{q}\dot{r} \tag{6}$$

$$\dot{q} = \frac{\tau_y}{Iy} - \frac{I_x - I_z}{I_y}\dot{p}\dot{r} \tag{7}$$

The following equation defines the relationship between the angular velocity of each rotor with x, y force, rotational force z and a thrust:

$$\tau_x = db\left(\omega_4^2 - \omega_2^2\right) \tag{8}$$

$$\tau_y = db\left(\omega_1^2 - \omega_3^2\right) \tag{9}$$

$$\tau_z = k\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \tag{10}$$

$$T = b\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right) \tag{11}$$

III. CONTROL STRATEGY

This research discusses a hover position control system for quadrotor at a certain altitude. The presence of two controllers namely altitude and attitude is to maintain the stability of the quadrotor. They control the 4 inputs $u_1 = \tau_\phi, u_2 = \tau_\theta, u_3 = \tau_\psi$, and

$u_4 = \tau_T$ as shown in figure 2 [22]. The inputs affect the velocity of the motors $\omega_1, \omega_2, \omega_3$, and ω_4. Thus, the equation 8-11 are substituted to equations 6-7 to obtain the equations for the angular velocity that are:

$$\ddot{p} = \frac{db}{\mathrm{I}_x}\left(\omega_4^2 - \omega_2^2\right) - \frac{\mathrm{I}_z - \mathrm{I}_y}{\mathrm{I}_x}\dot{q}\dot{r} \tag{12}$$

$$\ddot{q} = \frac{db}{\mathrm{I}y}\left(\omega_1^2 - \omega_3^2\right) - \frac{\mathrm{I}_x - \mathrm{I}_z}{\mathrm{I}_y}\dot{p}\dot{r} \tag{13}$$

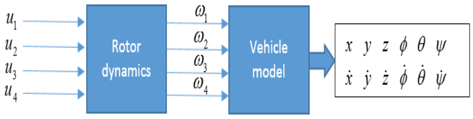


Fig. 2. input and output model of quadrotor

Equation 5 is substituted to equation 11 to obtain the equation for the Z-axis acceleration that is:

$$\ddot{z} = mg - \frac{b}{m}\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right)\left(c_\phi c_\theta\right) \tag{14}$$

A. *Altitude Stabilization*

The FLC proposed in this study is to control the altitude of the state with or without disturbances [23], [21]. To control the altitude, z-axis acceleration in equation 14 is used in designing the controller by assuming angle $\phi = 0$ and $\theta = 0$, thus the equation obtained is as follows:

$$\ddot{z} = mg - \frac{b}{m}\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right) \tag{15}$$

In Figure 3 a closed loop control system is developed to control the altitude of the quadrotor. The control block with a closed-loop system is shown in Figure 3. There are dz entry and error inputs in this control, where z is the altitude value of the quadrotor. The altitude value is negative because it opposes gravitational force of the earth. Sp_Z is the value of the desired altitude and it has a positive value, thus the error equation obtained is as follows:

$$e = z - \left(- Sp_Z\right) \tag{16}$$

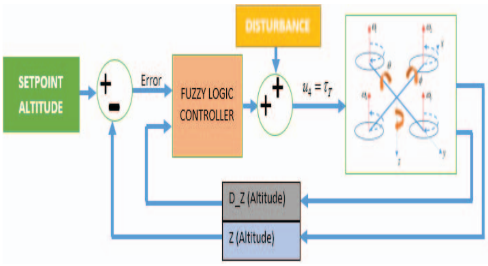


Fig. 3. Proposed Altitude control system

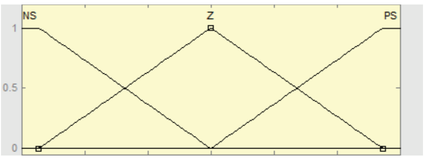


Fig. 4. Input variable error design

As shown in figure 3, the altitude control uses fuzzy logic algorithm with mamdani method. In this scheme two inputs namely errors and dz data are used. While the output of the fuzzy logic control is connected to the throttle. Error input has a set of inputs ranging from $-n\_e$ to $+n\_e$ with the value of n calculated by the following equation

$$n\_e = e \tag{17}$$

n_e is the range value of the fuzzy set inputs. The input of dz set has a range of $-n\_dz$ up to $+n\_dz$ with the value of n calculated from the velocity equation in z-axis by the following equation

$$dz = \frac{z_{t+t\_n} - z_t}{t\_n} \tag{18}$$

Where dz is the velocity, z_{t+t_n} is the current altitude, z_t is the previous altitude and t_n is the desired time for a fast rise time. So that the value of n_dz is obtained by the following equation:

$$n\_dz = dz \tag{19}$$

n_dz is the range value of the fuzzy set input.

Altitude control proposed in this paper uses fuzzy logic controller algorithms with rule base 7x7. The inputs and outputs of the fuzzy have seven member set variables. Fuzzy set member variables consists of ENS, EZ, and EPS.

The design of input variables error for fuzzy set shown in Figure 4 is as follows:

$$N_S(e) = \begin{cases} 1 & ; \quad -13 \le x \le -8.667 \\ \dfrac{-8{,}667 - x}{-8{,}667} & ; \quad -8{,}667 \le x \le 0 \\ 0 & ; \quad x \le 0 \end{cases} \tag{20}$$

$$z(e) = \begin{cases} 0 & ; \quad x \le -8.667 \quad atau \quad x \ge 8.667 \\ \dfrac{x + 8.667}{8.667} & ; \quad -8.667 \le x \le 0 \\ \dfrac{8.667 - x}{8.667} & ; \quad 0 \le x \le 8.667 \end{cases} \tag{21}$$

$$P_S(e) = \begin{cases} 0 & ; \quad x \le 0 \\ \dfrac{x - 0}{-8{,}667} & ; \quad 0 \le x \le 8.667 \\ 1 & ; \quad 8.667 \le x \le 13 \end{cases} \tag{22}$$

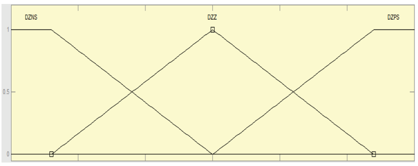


Fig. 5. input variable Dz design

The design of input variables dz for fuzzy set shown in Figure 5 is as follows:

$$N_S(e)=\begin{cases}1 & ; \quad -10\le x\le -8\\ \dfrac{-8-x}{-8} & ; \quad -8\le x\le 0\\ 0 & ; \quad x\le 0\end{cases} \tag{23}$$

$$z(e)=\begin{cases}0 & ; \quad x\le -8 \quad atau \quad x\ge 8\\ \dfrac{x+8}{8} & ; \quad -8\le x\le 0\\ \dfrac{8-x}{8} & ; \quad 0\le x\le 8\end{cases} \tag{24}$$

$$P_S(e)=\begin{cases}0 & ; \quad x\le 0\\ \dfrac{x-0}{-8} & ; \quad 0\le x\le 8\\ 1 & ; \quad 8\le x\le 10\end{cases} \tag{25}$$

The design of the output variables for fuzzy set that will fit into quadrotor's throttle is shown in Figure 6

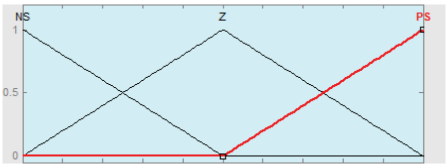
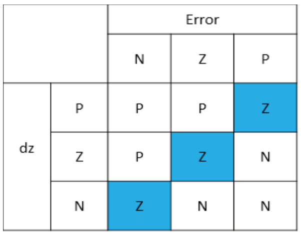


Fig. 6. The design of the throttle output variables

The rule base of fuzzy logic controller algorithm with mamdani method didapatkan dengan is shown in Figure 7.



		Error		
		N	Z	P
dz	P	P	P	Z
	Z	P	Z	N
	N	Z	N	N

Fig. 7. Rule base 3x3 fuzzy mamdani altitude control

B. *Trajectory Control*

This control is influenced by the linear and angular equation of the quadrotor that is substituted by equation (1) - (4), thus the horizon control equation obtained is as follows:

$$\ddot{x}=\frac{-b\left(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2\right)}{m}(\sin p\sin r+\cos p\cos r\sin q) \tag{26}$$

$$\ddot{y}=\frac{-b\left(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2\right)}{m}(\cos p\sin r\sin q-\cos r\sin p) \tag{27}$$

$$\ddot{z}=g-\frac{b\left(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2\right)}{m}(\cos p\cos q) \tag{28}$$

$$\ddot{p}=\frac{l}{I_{xx}}db\left(\omega_3^2+\omega_4^2-\omega_1^2-\omega_2^2\right)-\frac{J_r}{I_{xx}}\dot{q}\Omega_r+\frac{I_{yy}}{I_{xx}}\dot{r}\dot{q}-\frac{I_{zz}}{I_{xx}}\dot{q}\dot{r} \tag{29}$$

$$\ddot{q}=\frac{l}{I_{yy}}db\left(\omega_1^2+\omega_2^2-\omega_3^2-\omega_4^2\right)-\frac{J_r}{I_{yy}}\dot{p}\Omega_r+\frac{I_{zz}}{I_{yy}}\dot{r}\dot{p}-\frac{I_{zz}}{I_{xx}}\dot{r}\dot{p} \tag{30}$$

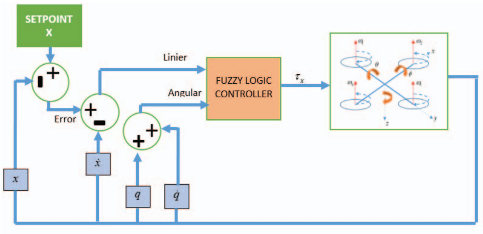


Fig. 8. Proposed tracking control system

From equations (26) – (30) the horizon motion control described by the diagram block shown in figure 8 is obtained. It shows that the horizon control input is the x and y in which there are two controls namely position and attitude controls. The attitude control is using fuzzy algorithms, while the position control is using linear and angular control.

Liner control equation of x and y is as follows

$$linier_y=k_y\left(error_y-\dot{y}\right) \tag{31}$$

$$linier_x=k_x\left(error_x-\dot{x}\right) \tag{32}$$

While the error equation is as follows

$$error\_y=Sp_y-y \tag{33}$$

$$error\_x=Sp_x-x \tag{34}$$

Engular velocity equation is as follow

$$angular\_y=\theta+\left(\dot{\theta}K_{d\_\dot{\theta}}\right) \tag{35}$$

$$angular\_x=\phi+\left(\dot{\phi}K_{d\_\dot{\phi}}\right) \tag{36}$$

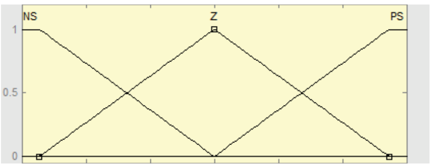


Fig. 9. The design of the linear input variables

The design of the linear input variables for fuzzy set shown in Figure 9 is as follows:

$$N_s(e)=\begin{cases}1 & ; \quad -0.2 \le x \le -0.1333 \\ \dfrac{-0.1333 - x}{-0.1333} & ; \quad -0.1333 \le x \le 0 \\ 0 & ; \quad x \le 0\end{cases} \tag{37}$$

$$z(e)=\begin{cases}0 & ; \quad x \le -0.1333 \quad atau \quad x \ge 0.1333 \\ \dfrac{x+0.1333}{0.1333} & ; \quad -0.1333 \le x \le 0 \\ \dfrac{0.1333 - x}{0.1333} & ; \quad 0 \le x \le 0.1333\end{cases} \tag{38}$$

$$P_S(e)=\begin{cases}0 & ; \quad x \le 0 \\ \dfrac{x - 0}{-0.1333} & ; \quad 0 \le x \le 0.1333 \\ 1 & ; \quad x \ge 0.1333\end{cases} \tag{39}$$

The angular input variables design for fuzzy set shown in Figure 10 is as follows:

$$N_S(e)=\begin{cases}1 & ; \quad -0.1 \le x \le -0.06665 \\ \dfrac{-0.06665 - x}{-0.6665} & ; \quad -0.6665 \le x \le 0 \\ 0 & ; \quad x \le 0\end{cases} \tag{40}$$

$$z(e)=\begin{cases}0 & ; \quad x \le -0.06665 \quad atau \quad x \ge 0.06665 \\ \dfrac{x+0.06665}{0.06665} & ; \quad -0.06665 \le x \le 0 \\ \dfrac{0.06665 - x}{0.06665} & ; \quad 0 \le x \le 0.06665\end{cases} \tag{41}$$

$$P_S(e)=\begin{cases}0 & ; \quad x \le 0 \\ \dfrac{x - 0}{-0.06665} & ; \quad 0 \le x \le 0.06665 \\ 1 & ; \quad 0.06665 \le x \le 0.1\end{cases} \tag{42}$$

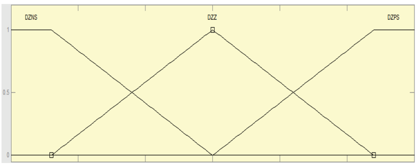


Fig. 10. The angular input variables design

The design of the output variables for fuzzy set that will fit into quadrotor's roll and pitch is shown in Figure 11

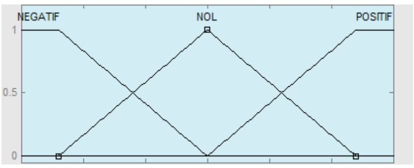
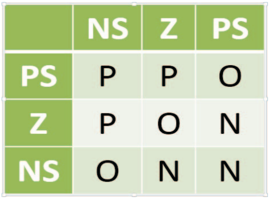


Fig. 11. The design of the roll and picth output variables



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

Fig. 12. Rule base 3x3 fuzzy mamdani position control roll.

The rule base fuzzy logic controller algorithm with mamdani method is shown in Figure 12.

Similarly to the other angles of the attitude ie, pitch, it can obtain the same method as proposed previously.

IV. RESULT AND DISCUSSION

In the first simulation, the altitude and attitude control using fuzzy logic controller was tested by using Corke's simulator [18]. To simulate the position, attitude, and altitude controls, first the parameters contained in the simulator was set; setting the start position of at x,y position (-1,0), the desired height at 10 meters, and the hover position x,y (-1.0) . Experiments were performed by using several obstacles that resembled the vertical and horizontal wind disturbance.

In the first experiments shown in Figure 13, the quadrotor was controlled by the proposed fuzzy algorithm with set points of x = -2, y = 1, and angular = 0. The simulation results of the hover position at z position at the height of 1 meter are shown in Figure 14. There are four graphs as shown in the figure namely Error x, Error y, Error yaw and Error z. When using the fuzzy logic controller algorithm, the altitude controller quickly stabilized the quadrotor and it performed the steady state at the 4.968th second and the settling time at the 2.166th second. In addition, the time for the quadrotor to takeoff was fast at the 1.607th second rise time. In performing takeoff and hover, it did not perform oscillation and overshoot. The hover position on the quadrotor was unchanged meant it was at the same position before taking-off. Hence, as shown in the figure, black line to the x-axis of the quadrotor was unchanged after it took-off and the magenta color line was also unchanged as it was in the initial take-off.

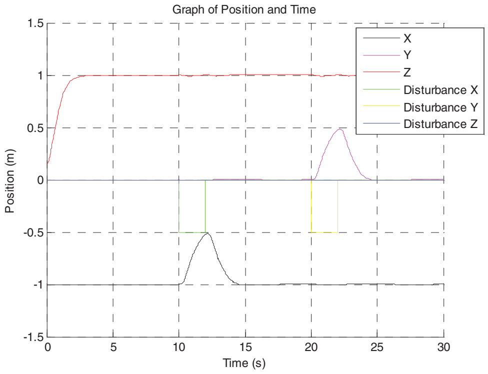


Fig. 13. Position and time relationship graph

V. CONCULUSION

The latest development of the quadrotor control using fuzzy logic algorithm is presented in this paper. It is used to stabilize the quadrotor as it is taking-off, landing, hovering, and moving to the x,y axis. There are two controls to stabilize the quadrotor while hovering in the air namely altitude and trajectory controls. The most important one is the altitude control which serves to control the height when the quadrotor is hovering and to stabilize it when there is vertical wind disturbance. However, the weakness of this algorithm is that it is not able to stabilize the quadrotor when there is horizontal wind disturbance. Therefore, to overcome the problem, this paper presents trajectory control. By using the two controls, the quadrotor is stable when hovering and moving from one position to another. The rise time, settling time and steady state time is fast and there is no overshoot.

REFERENCES

[1] U. Niethammer, M. R. James, S. Rothmund, J. Travelletti, and M. Joswig, “UAV-based remote sensing of the Super-Sauze landslide : Evaluation and results,” Eng. Geol., vol. 128, pp. 2–11, 2012.

[2] S. Bouabdallah, P. Murrieri, and R. Siegwart, “Design and Control of an Indoor Micro Quadrotor,” in Proceedings. ICRA ’04. 2004 IEEE International Conference on Robotics and Automation, 2004., 2004, pp. 4393–4398.

[3] K. U. Lee, H. S. Kim, J. B. Park, and Y. H. Choi, “Hovering Control of a Quadrotor,” in 2012 12th International Conference on Control, Automation and Systems (ICCAS), 2012, pp. 162–167.

[4] A. Tayebi and S. McGilvray, “Attitude Stabilization of a VTOL Quadrotor Aircraft,” IEEE Trans. Control Syst. Technol., vol. 14, no. 3, pp. 562–571, 2006.

[5] K. U. Lee, Y. H. Choi, and J. B. Park, “Position Control of a Quadrotor : Dynamic Surface Control Approach,” pp. 1–6, 2013.

[6] M. K. Joyo, D. Hazry, S. Faiz Ahmed, M. H. Tanveer, F. A. Warsi, and A. T. Hussain, “Altitude and Horizontal Motion Control of Quadrotor UAV in the Presence of Air Turbulence,” in 2013 IEEE Conference on Systems, Process & Control (ICSPC), 2013, pp. 13–15.

[7] F. X. Johan, E. Joelianto, A. Widyotriatmo, and Salmah, “Experiment of Model Based Non Linear Control Design for Altitude Control of Quadrotor Using Vision-Based Localization System,” in Robotics, Biomimetics, and Intelligent Computational Systems (ROBIONETICS), 2013 IEEE International Conference on, 2013, pp. 25–27.

[8] K. Alexis, G. Nikolakopoulos, and A. Tzes, “Model predictive quadrotor control: attitude, altitude and position experimental studies,” IET Control Theory Appl., vol. 6, no. 12, pp. 1812–1827, 2012.

[9] J. G. P. Castillo, J. Alfredo, and G. Rogelio, “Vision Based Tracking for a Quadrotor Using Vanishing Points,” pp. 361–371, 2012.

[10] W. Jasim and D. Gu, “H<inf>∞</inf> for quadrotor attitude stabilization,” in 2014 UKACC International Conference on Control (CONTROL), 2014, no. July, pp. 19–24.

[11] H. Voos, “Nonlinear control of a quadrotor micro-UAV using feedback-linearization,” in 2009 IEEE International Conference on Mechatronics, 2009, pp. 1–6.

[12] M. Santos, V. Lopez, and F. Morata, “Intelligent fuzzy controller of a quadrotor,” in 2010 IEEE International Conference on Intelligent Systems and Knowledge Engineering, 2010, pp. 141–146.

[13] P. Bhatkhande and T. C. Havens, “Real Time Fuzzy Controller For Quadrotor Stability Control,” in 2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), 2014, pp. 913 – 919.

[14] F. Fakurian, M. B. Menhaj, and A. Mohammadi, “Design of a fuzzy controller by minimum controlling inputs for a quadrotor,” in 2014 Second RSI/ISM International Conference on Robotics and Mechatronics (ICRoM), 2014, pp. 619–624.

[15] M. Varga and S. Bogdan, “Fuzzy-Lyapunov Based Quadrotor Controller Design,” in 2009 European Control Conference (ECC), 2009, pp. 928–933.

[16] S. Bouabdallah and R. Siegwart, “Full control of a quadrotor,” in 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007, pp. 153–158.

[17] P. Pounds and R. Mahony, “Design principles of large quadrotors for practical applications,” Proc. - IEEE Int. Conf. Robot. Autom., pp. 3265–3270, 2009.

[18] R. Mahony, V. Kumar, and P. Corke, “Multirotor Aerial Vehicles: Modeling, Estimation, and Control of Quadrotor,” IEEE Robot. Autom. Mag., vol. 19, no. 3, pp. 20 – 32, 2012.

[19] N. M. Raharja, Iswanto, M. Faris, and A. I. Cahyadi, “Hover position quadrotor control with fuzzy logic,” in 2014 The 1st International Conference on Information Technology, Computer, and Electrical Engineering, 2014, pp. 89–92.

[20] N. M. Raharja, Iswanto, O. Wahyunggoro, and A. I. Cahyadi, “Altitude control for quadrotor with mamdani fuzzy model,” in 2015 International Conference on Science in Information Technology (ICSITech), 2015, pp. 309–314.

[21] I. Iswanto, O. Wahyunggoro, and A. I. Cahyadi, “Quadrotor Path Planning Based On Modified Fuzzy Cell Decomposition Algorithm,” TELKOMNIKA, vol. 14, no. 2, pp. 655–664, 2016.

[22] I. Iswanto, O. Wahyunggoro, and A. I. Cahyadi, “3D Object Modeling Using Data Fusion from Laser Sensor on Quadrotor,” in ADVANCES OF SCIENCE AND TECHNOLOGY FOR SOCIETY: Proceedings of the 1st International Conference on Science and Technology 2015 (ICST-2015), 2016, pp. 170001–1 – 170001–7.

[23] I. Iswanto, O. Wahyunggoro, and A. Imam Cahyadi, “Path Planning Based on Fuzzy Decision Trees and Potential Field,” Int. J. Electr. Comput. Eng., vol. 6, no. 1, p. 212, 2016..