



Quadcopter Movement Analysis Using Output Feedback Control Based On Line Of Sight

Anggara Trisna Nugraha ^{a,1,*}, Moch Fadhil Ramadhan ^{b,2}, Muhammad Jafar Shiddiq ^{b,3}

^a Marine Electrical Engineering Shipbuilding Institute of Polytechnic Surabaya, Jl. Teknik Kimia Keputih Sukolilo, Surabaya 60111, Indonesia

^b Automation Engineering Shipbuilding Institute of Polytechnic Surabaya, Jl. Teknik Kimia Keputih Sukolilo, Surabaya 60111, Indonesia

¹ anggaranugraha@ppns.ac.id

* corresponding author

ABSTRACT

Keywords

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Circular Track
LMI
Command-Generator Tracker
LQ regulator

Quadcopter UAV is a non-linear system which underactuated and unstable. Those characteristics will be the focus on this study for the development of quadcopter's control. In this study, the output feedback control used to control the attitude and the position of the quadcopter. This control has H_∞ performance which is used to maintain the quadcopter's stability and toughness. Then, the gain controller is obtained by using the numerical iterative of Linear Matrix Inequality (LMI). Where as, the Command-Generator Tracker (CGT) used for tracking position control on the X and Y axes. Based on the research problems, this study will present the tracking control design in the horizontal area by adding the Line of Sight algorithm in order to change the path into the zero. The simulation result shows that the control method used is able to bring the yaw, pitch, and roll to the expected values on a circular path.

1. Introduction

Several developments continue to be carried out in order to improve the response of the quadcopter system in tracking problems that occur, capable of tracking in circles, squares or helices by using the output feedback by adding the Command-Generator Tracker [1][2]. The output feedback control has H performance in order to maintain its stability, so that the quadcopter is more reliable in handling external disturbances [3].

Furthermore, the Static Output Feedback (SOF) [4][5] used to overcome the limitation of the measured state where the SOF has the advantage of requiring the measured signal from the factory to be controlled only. The SOF controller used in the helicopter has H_∞ performance as the position tracker and attitude controller. The loop repetition technique is used in the tracking control position design with the Gain controller which is searched using the Ricatti equation [6]. The presented control algorithm creates a strong control against the interference.

Based on [7], there is a path control design which used to solve the problem if the input references are the step signal, the path signal, and the intermittent sinusoidal signal that causing overshoot of the system response. Moreover, the Command-Generator Tracker with the addition of the following model which represents the input references dynamically. Then, based on [8], it presents the LOS algorithm which makes easier to adjust the direction of the crop, so that it converges to the specified path by creating a cross-path of the objective error.

Based on the various problems and solutions above, the idea in this study that would be proposed is to design an optimal control method for controlling the quadcopter in order to be able to follow a path in a circular form. In this design, the output feedback control would be used to maintain its stability. The path controller uses the Command-Generator Tracker with the following model and adds the Line Of Sight algorithm which is used to generate conformity to the path form as a reference signal by setting the direction and error of the existing path as small as possible.





2. The Proposed Method

2.1. Quadcopter's Dynamic Linearization Design

This chapter will explain about the Quadcopter's dynamic linearization, which the dynamic concept has already explained in the quadcopter dynamic's sub-chapter. The equation is linearized where the quadcopter is in a hovering condition [9]. The yaw is 0 rad and the speed of the roll, pitch, and yaw is close to 0 rad/s. variable state, which will be use as the dynamic representation in the quadcopter's actuator as follows:

$$v = \frac{\omega}{s+\omega} u \quad (1)$$

This parameter is use as a reference for the controller arrangement and simulation. The value of the Q Ball-X4 can be state in Table 1.

Table 1. Qball-X4's Quanser System Parameters

Parameter	Symbol	Value
Mass	m	3,499 kg
Gravity	g	9,81 kg/m ²
Moment Inersia X Axis	J_{xx}	0.03 kg.m ²
Moment Inersia Y Axis	J_{yy}	0.03 kg.m ²
Moment Inersia Z Axis	J_{zz}	0.04 kg.m ²
Rotor distance to centre mass	l	0.2 m
Drag force	d	3,13x10 ⁻⁵
Trust force	b	7,5x10 ⁻⁷
Actuator Bandwith	ω	15 rad/s
Trust Force Constanta	K	120 N

Assume a rotation around and axis is decoupled, and its movement in the roll/pitch axis. If the drag constant is ignored, the quadcopter would be considered to be in a hovering state where the quadcopter acceleration approaches.

$$\begin{aligned} \phi \ll 0.1 &\rightarrow \sin(\phi) \cong 0, \cos(\phi) \cong 1 \\ \theta \ll 0.1 &\rightarrow \sin(\theta) \cong 0, \cos(\theta) \cong 1 \end{aligned} \quad (2)$$

The roll/pitch, in a sample of, can be formulated by using the following dynamics:

$$J\ddot{\theta} = \Delta FI \quad (3)$$

with, is the propeller distance to the gravity center, and

$$\Delta F = F_1 - F_2 \quad (4)$$

There is a difference between the forces generated by two engines. The force's difference is produced by the input difference for the two engines is $\Delta u = u_1 - u_2$.

The state space equation for the linear model of roll and pitch dynamics can be expressed as:

$$\begin{bmatrix} \dot{\phi} \\ \ddot{\phi} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{lK_T}{J} \\ 1 & 0 & -\omega \end{bmatrix} \begin{bmatrix} \phi \\ \dot{\phi} \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \Delta u_2 \quad (5)$$

$$\begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{lK_T}{J} \\ 1 & 0 & -\omega \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \Delta u_1 \quad (6)$$



The linear model of positional dynamics obtained from an axis in the state space as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{4K_T}{J}\theta \\ 1 & 0 & -\omega \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} u \quad (7)$$

$$\begin{bmatrix} \dot{y} \\ \dot{y} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{4K_T}{J}\phi \\ 1 & 0 & -\omega \end{bmatrix} \begin{bmatrix} y \\ \dot{y} \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} u \quad (8)$$

3. Method

3.1. LQR Output Feedback with the Command Generator Tracker's Multiple Augmented

Command-Generator Tracker is a control design that provides a compensator according to the system requirements in order to obtain a small tracking error for the desired reference inputs [10], [11]. The equation of the plant and the output performance $z(t)$ is:

$$z(t) = Hx(t) \quad (9)$$

So, the initials of the plant equation to the output performance is carried over to the reference input produces the following approach:

$$\begin{aligned} \dot{x}' &= \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix} x' + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ B \end{bmatrix} r \\ &= A'x' + B'u + W'r \end{aligned} \quad (10)$$

If it's written in a variable state (canonical observable) for cases, then

$$\begin{aligned} \rho &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -a_3 & -a_2 & -a_1 \end{bmatrix} \rho \equiv G\rho \\ r &= [1 \quad 0 \quad 0]\rho \end{aligned} \quad (11)$$

The polynomial characteristics of the command generator are defined as

$$\Delta(p) = p^d + a_1p^{d-1} + \dots + a_d \quad (12)$$

This technique makes the tracking problem will be converted into a regulator problem where the error must be set to zero. The modification is needed in order to generate a whole of the tracking system.

It is defined as the dynamics of multiplying augmented which is operated in so the modified system will be stated as follows:

$$\dot{\xi} = A'\xi + B'\mu \quad (13)$$

Where the state vector and the input control after being modified to

$$\begin{aligned} \xi &= \Delta(p)x' \\ &= (x')^{(d)} + a_1(x')^{(d-1)} + \dots + a_d(x') \end{aligned} \quad (14)$$

$$\begin{aligned} \mu &= \Delta(p)u \\ &= (u)^{(d)} + a_1(u)^{(d-1)} + \dots + a_d(u) \end{aligned} \quad (15)$$

and the error vector and its derivatives are represented by

$$\varepsilon(t) = [e \quad \dot{e} \quad \dots \quad e^{(d-1)}]^T \quad (16)$$

the error tracking can be written as

$$\Delta(p)e = [-H \quad H]\xi = H'\xi \quad (17)$$

state multiple augmented is as follows:



$$\frac{d}{dt} \begin{bmatrix} \varepsilon \\ \xi \end{bmatrix} = \begin{bmatrix} G & \vdots & 0 \\ & \vdots & H' \\ \dots & \vdots & \dots \\ 0 & \vdots & A \end{bmatrix} \begin{bmatrix} \varepsilon \\ \xi \end{bmatrix} + \begin{bmatrix} 0 \\ B' \end{bmatrix} \mu \quad (18)$$

The LQ regulator design is applied to this system, because if the state in this system goes to zero, the error tracking will disappear. The output state that will be a feedback for the system is

$$v = \begin{bmatrix} I & 0 & 0 \\ 0 & C & 0 \\ 0 & 0 & \underline{C} \end{bmatrix} \begin{bmatrix} \varepsilon \\ \xi p \\ \xi m \end{bmatrix} \quad (19)$$

then, the modified input control system will be

$$\mu' = [K_\varepsilon \quad K_p \quad K_m] \begin{bmatrix} \varepsilon \\ C \xi_p \\ C \xi_m \end{bmatrix} \quad (20)$$

3.2. The LOS's terms in the Steering Equation

An enclosure based strategy is used to direct $e(t)$ into zero, and then direct the vector's speed towards the intersection point $P_{los} = [x_{los}, y_{los}]^T$ in order to match the path's direction, where the path is implicitly defined by the order in which the waypoints are already defined. The path is directly involves in assigning $\chi_d(t)$.

$$\tan(\chi_d(t)) = \frac{\Delta y(t)}{\Delta x(t)} = \frac{y_{los} - y(t)}{x_{los} - x(t)} \quad (21)$$

The engine's center coordinates are defined by $P^n = [x, y]^T$ and used a circle with a radius $R > 0$ that drawn from the engine's center $\{b\}$ [12]. The circle will cut a path at two points, one of them is (x_{los}, y_{los}) . The calculation of the two unknown LOS points can be found by solving the two equations below:

$$\begin{aligned} [x_{los} - x(t)]^2 + [y_{los} - y(t)]^2 &= R^2 \\ \tan(\alpha_k) &= \frac{y_{k+1} - y_k}{x_{k+1} - x_k} \quad (22) \\ &= \frac{y_{los} - y_k}{x_{los} - x_k} = \text{konstan} \end{aligned}$$

Which is the Pythagoras, while the equation shows the path's inclination to the x of the earth is α_k . The slope between the two waypoints is constant and also applies to the slope magnitude for the points between them. Based on [13], the analytical enclosure calculation process can be described by:

1st argument: for $|\Delta x| > 0$, the equation

$$y_{los} = \frac{\Delta y}{\Delta x} (x_{los} - x_k) + y_k \quad (23)$$

With $\Delta x := x_{(k+1)} - x_k$ and $\Delta y := y_{(k+1)} - y_k$ is the position difference from x and y between the two waypoints.

Table 2. Algorithm Path Following Loiter [13]

Path Following Loiter Algorithm (Circle) With LOS	
1.	Initialisation: $O = (x_k, y_k), r, p, v_a, q_{22}$ Determine the position x_k, y_k
2.	Calculate tangential Value to path $s(t) = a \tan 2 (y_{k+1} - y_k, x_{k+1} - x_k)$ $= a \tan 2 [x(t) - x_k] \sin(\alpha_k) + [y(t) - y_k] \cos(\alpha_k)$
3.	Calculate error position $d = \ p - O\ - r$





Path Following Loiter Algorithm (Circle) With LOS

4. Calculate Velocity error
 $v_d = v_a \sin(\psi - \theta)$
5. Determine u to get maximum value at lateral speed condition which is

$$u = \begin{cases} -v_g^2/R_{min} & \text{if } u < 0 \text{ or } |u| > v_g^2/R_{min} \\ v_g^2/R_{min} & \text{if } u > 0 \text{ or } |u| < v_g^2/R_{min} \\ u & \text{sebaliknya} \end{cases}$$

3.3. The design of the control system

The LMI's form that used the Schur Complement is

$$\begin{bmatrix} P_n A + A^T P_n + Q + L_n^T R^{-1} L_n & P_n B & P_n D \\ B^T P_n & R & 0 \\ D^T P_n & 0 & -\gamma^2 I \end{bmatrix} \leq 0 \quad (24)$$

The linearized system state for roll, pitch and yaw becomes

$$x_{inner} = [\varphi \quad p \quad v \quad \theta \quad q \quad \psi \quad r]^T \quad (25)$$

When designing a rotation controller, the main variables to be controlled are roll and pitch, as well as three speeds, there are roll, pitch, and yaw. So, the controller's output vector is.

$$y_{inner} = [\varphi \quad \theta \quad \psi \quad p \quad q]^T \quad (26)$$

If the roll and pitch are equal in the inertia, the roll and pitch dynamics are also same. Here is the state space of roll/pitch linear.

$$\begin{aligned} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{v} \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 800 \\ 0 & 0 & -15 \end{bmatrix} \begin{bmatrix} \varphi \\ \theta \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 15 \end{bmatrix} \Delta u; y_\varphi \\ &= C_\varphi \begin{bmatrix} \varphi \\ \dot{\varphi} \\ v \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.1 & 0 \end{bmatrix} \begin{bmatrix} \varphi \\ \dot{\varphi} \\ v \end{bmatrix} Z_\varphi \\ &= H x_\varphi \\ &= [0.3 \quad 0 \quad 0] \begin{bmatrix} \varphi \\ \dot{\varphi} \\ v \end{bmatrix} \end{aligned} \quad (27)$$

The best result is generated from the parameter value as follow

$$\gamma = 0.7, R = 10 \text{ dan } Q = \text{diag}\{755, 3, 0.1\}. \quad (28)$$

By using the iterative LMI feasibility method, there is a matrix result in P, K, and L after the twelfth iteration is.

$$\begin{aligned} p &= \begin{bmatrix} 29.8331 & 0.1572 & 0.4897 \\ 0.1572 & 0.0156 & 0.0545 \\ 0.4897 & 0.0545 & -\gamma^2 I \end{bmatrix}; \\ K &= [0.7346 \quad 0.0817] \end{aligned} \quad (29)$$

The objective of position tracking control is aim to make the quadcopter follow the desired trajectory when the quadcopter is hovering. Therefore, the reference signal that given is aim to track the X position which is a sinusoidal signal with a frequency of 0.1047 rad / s or its same with 0.0167 Hz with a phase of -0.26 rad. Here is the equation of reference signal:

$$x_d = -\sin(0.05\pi t) \quad (30)$$

If it's changed using the Laplace transform, then the transfer function is

$$\Delta(p)x_d = p^2 + 0.02 = 0 \quad (31)$$





$$\dot{x}_d = \begin{bmatrix} 0 & 1 \\ -0.02 & 0 \end{bmatrix} x_d = Gx_d \quad (32)$$

By substituting the reference model (36) and the system model (18), an augmented system is obtained from the quadcopter dynamics for the X, as follows:

$$\begin{bmatrix} \dot{\varepsilon} \\ \ddot{\varepsilon} \\ \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -0.02 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 136.2683 \\ 0 & 0 & 0 & 0 & -15 \end{bmatrix} \begin{bmatrix} \varepsilon \\ \dot{\varepsilon} \\ x \\ \dot{v} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 15 \end{bmatrix} U_1 \quad (33)$$

with the output performance as follow:

$$\tilde{y} = \tilde{C}\tilde{x} = \begin{bmatrix} J & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \varepsilon \\ x \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \varepsilon \\ \dot{\varepsilon} \\ x \\ \dot{v} \end{bmatrix} \quad (34)$$

The path that we want to provide as the reference signal for the quadcopter is a square form (in the three-dimensional area). So, the reference signal that given from for Y as below:

$$Y_d = -1 - \cos(0.05\pi t) \quad (35)$$

The similar characteristic of polynomial is

$$\Delta(p)y_d = p^3 + 0.02p = 0 \quad (36)$$

From the reference signal with the orde d = 3 and then written in the form of a state space's matrix of 3x3 dimensions. The CGT's structure is a representation of the reference signal. So, not all derivatives of the reference signal need to be used in the system structure, so that in this design modifications are made, it can be written as follows:

$$\Delta(p)y_d = 0.02p = 0 \Rightarrow \dot{y}_d = \begin{bmatrix} 0 & 1 \\ 0 & -0.02 \end{bmatrix} y_d = Gy_d \quad (37)$$

so, the modification of the multiple augmented systemfor the dynamic position at Y is

$$\begin{bmatrix} \dot{\varepsilon} \\ \ddot{\varepsilon} \\ \dot{y} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & -0.02 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -136.2683 \\ 0 & 0 & 0 & 0 & -15 \end{bmatrix} \begin{bmatrix} \varepsilon \\ \dot{\varepsilon} \\ y \\ \dot{v} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 15 \end{bmatrix} U_1 \quad (38)$$

$$\tilde{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \varepsilon \\ \dot{\varepsilon} \\ y \\ \dot{v} \end{bmatrix} \quad (39)$$

The parameter value that used for the simulation is on the Table 2. Gain Feedback output which used for the position controller X, Y is generated by.

$$\begin{aligned} \tilde{K}_x &= [-4.418 \quad -9.6604 \quad 9,4440 \quad 5.3433] \\ \tilde{K}_y &= [15.9326 \quad 23.4931 \quad -15.8108 \quad -6.2181] \end{aligned} \quad (40)$$

4. Results and Discussion

This simulation used a Matlab software in order to determine the effectiveness of the quadcopter's tracking controller. The type of the quadcopter used in this simulation is Quanser Qball-X4. The simulation is carried out by testing the quadcopter movement whether it is able to perform the following path to the circular pathas shown in Fig. 1. (a), the quadcopter's direction is considered to make the quadcopter's movement smoother and also be able to maintain its direction.

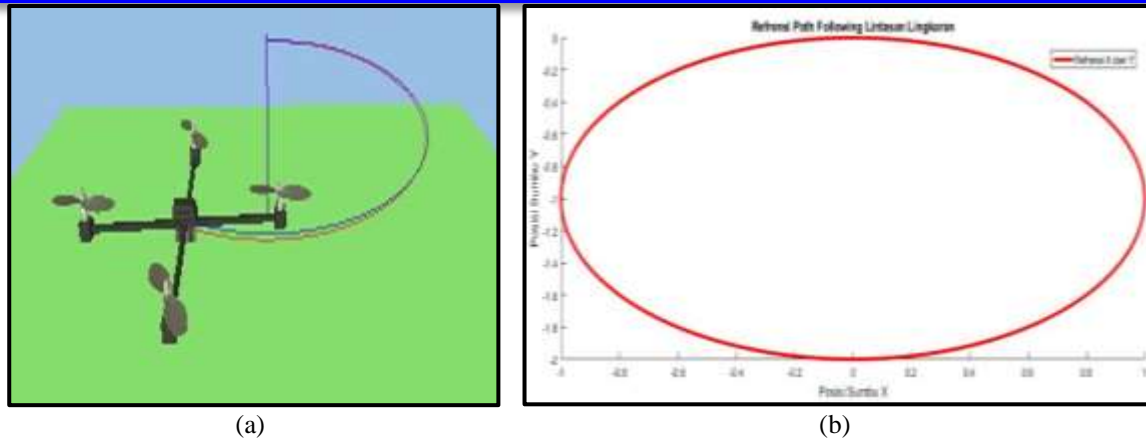


Fig. 1. a) The quadcopter’s movement on the x and y axis, b) The circular track

Fig. 1. (b), shows that the quadcopter’s position on the X axis can follow the reference in a sinusoidal signal. The tracking starts at 2.5 seconds, a delay of about 0.5 seconds that causes a response deviation of 0.1m, but the quadcopter is still on the reference track. Fig. 2 shows the movement on the Y axis where the quadcopter can follow the reference correctly.

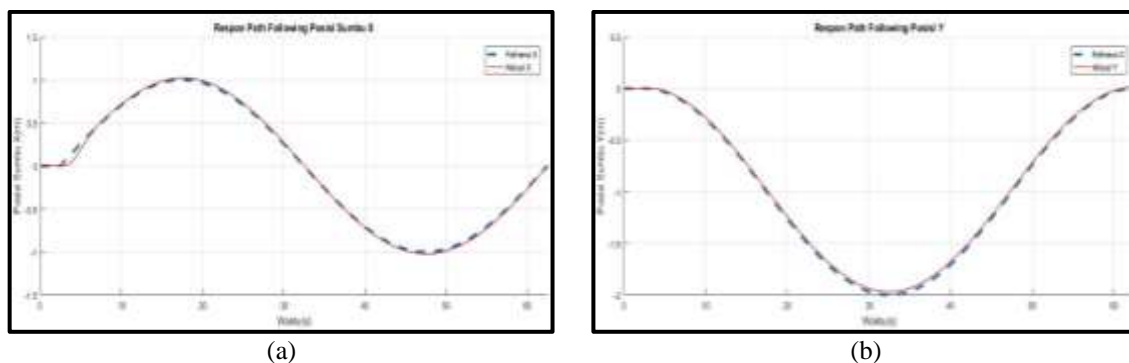


Fig. 2. a) The quadcopter’s tracking at the X axis, b) The quadcopter’s tracking at the Y axis

Fig. 3. a and b. show the reference signal and the system response to rotational movement. It can be seen that the roll and pitch responses can follow the reference signal that given from the outer loop output with a mean error of 0.001594 rad.

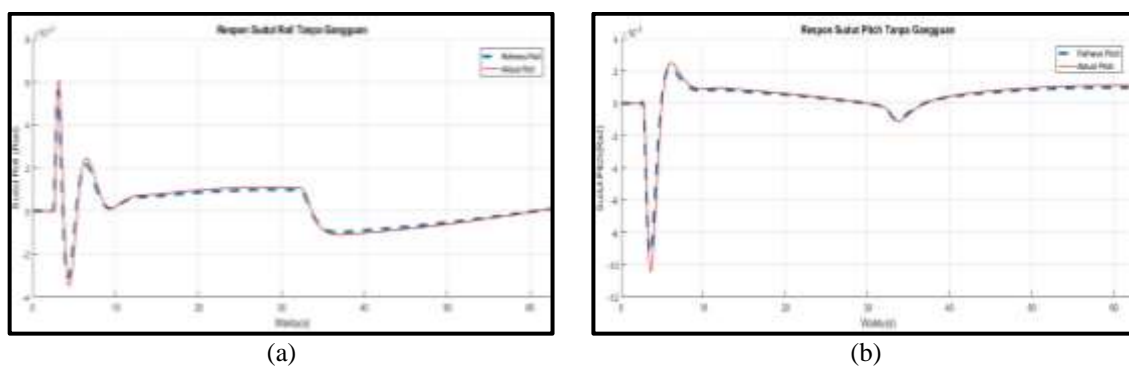


Fig. 3. a) The quadcopter’s tracking at the roll, b) The quadcopter’s tracking at the pitch

Due to the addition of the Line Of Sight (LOS) algorithm, which is used to calculate the quadcopter’s direction, the system response taken from the yaw is also taken into the account. It can be seen that the yaw response can follow the given reference signal from the outer loop output with an average error of 0.0245 rad. Figure 7 shows a comparison between the reference and the actual yaw, which actually maintains the heading and improves the quadcopter's movement. The LOS’ concept is used to take a tangential angle, it will make the dynamics move towards a path following a reference. So, it converges to be zero.

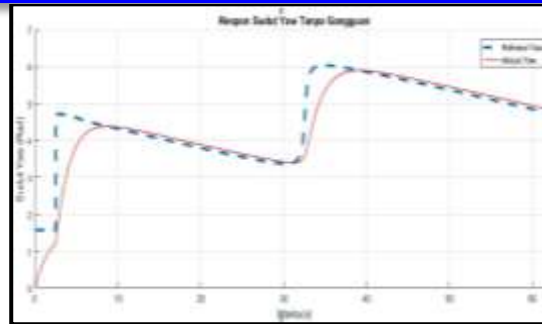


Fig. 4. The quadcopter's tracking at the yaw

Fig. 5. shows the responses in the X and Y area in the circular track. The responses can follow the reference given with a mean deviation of $\pm 0.07\text{m}$.

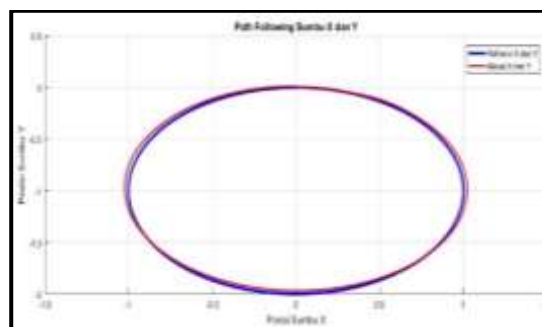


Fig. 5. The quadcopter's tracking on the defined track

5. Conclusion

The output feedback control method with H_∞ performance is used in the inner loop, while the Command-Generator Tracker in the outer loop. The simulation results show that the control system can stabilize the quadcopter's angle and also be able to track itself by the given reference signal. The maximum value for ISE tracking position without a disturbance is 0.1 m and 0.28 m in otherwise. The controller can also make the quadcopter perform the tracking in the square and helix reference tracks.

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