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Research Article

Route Tracking Performance of Swarm Unmanned Aerial Vehicles (UAVs) with Fuzzy Logic Controller

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Abstract

Swarm Unmanned Aerial Vehicles (UAVs) comprise of a group of aircraft that come together to achieve a specific goal. In recent years, the Swarm UAVs have been used in commercial, civil and military fields such as search and rescue operations, cargo transportation, sensitive agricultural practices, and ammunition delivery to war zones. Swarm UAVs can scan large areas in a short time in both military and civilian use. Swarm UAVs, which have the ability to communicate synchronously with each other, can perform complex tasks in a minimum energy and time by collaborating with respect to a single UAV. It is very important that swarm UAVs can follow the desired route with minimum error in order to perform the task in the shortest time and with least energy. In this study, the fuzzy logic controller is proposed for swarm quadrotors to follow the desired route with minimum error. The system modeling and mathematical equations of quadrotor have been developed in simulation environment. The performance of swarm UAVs to follow the rectangular and circular routes with minimum error is analyzed in this simulation. The fuzzy logic controller proposed for route tracking of the swarm UAVs is handled comparatively with the classical proportional-integral-derivative (PID) controller. The fuzzy logic controller developed in this simulation study increases the UAV's sudden maneuverability and ability to complete the task with minimum energy compared to the classical PID controller. The classical PID and fuzzy controller performance of each UAV in the swarm is analyzed graphically and it is observed that the performance of the fuzzy logic controller to follow the reference route is higher than the classical PID controller.

Keywords: Swarm UAVs, Route Tracking, Quadrotor, PID Controller, Fuzzy Logic Controller.

Bulanık Mantık Denetleyicisiyle Sürü İnsansız Hava Araçları (İHA)'nın Rota Takip Performansı

Özet

Sürü İnsansız Hava Araçları (İHA) belirli bir hedefe ulaşmak için bir araya gelen bir grup hava aracından oluşmaktadır. Son yıllarda Sürü İHA'lar, arama kurtarma çalışmaları, yük taşımacılığı, hassas tarım uygulamaları, savaş bölgelerine mühimmat iletilmesi gibi ticari, sivil ve askeri alanlarda kullanılmaktadır. Sürü İHA'lar gerek askeri gerekse sivil kullanımlarda geniş alanları kısa sürede tarayabilmektedir. Birbiriyle eş zamanlı olarak iletişim kurma yeteneğine sahip sürü İHA'lar, işbirliği yaparak karmaşık görevleri tek bir İHA'ya göre minimum enerji ve sürede gerçekleştirebilir. Sürü İHA'ların istenen rotayı minimum hatayla takip edebilmesi, görevi en kısa sürede ve en az enerjiyle gerçekleştirebilmesi için oldukça önemlidir. Bu çalışmada, sürü quadrotorların istenen rotayı minimum hata ile takip edebilmeleri için bulanık mantık kontrolcüsü önerilmektedir. Quadrotorun sistem modellemesi ve matematiksel denklemleri benzetim ortamında geliştirilmektedir. Sürü İHA'ların minimum hata ile dikdörtgen ve dairesel rotaları takip etme performansı, bu benzetim ortamında analiz edilmektedir. Sürü İHA'ların rota takibi için önerilen bulanık mantık denetleyicisi, klasik PID denetleyicisiyle karşılaştırmalı olarak ele alınmaktadır. Bu benzetim çalışmasında geliştirilen bulanık mantık denetleyicisi, İHA'nın ani manevra kabiliyetini ve görevi minimum enerjiyle gerçekleştirebilme yeteneğini klasik PID denetleyicisine

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göre arttırmaktadır. Sürüdeki her bir İHA'nın klasik PID ve bulanık mantık denetleyici performansı yapılan çalışmada grafiksel olarak incelenmekte ve bulanık mantık denetleyicisinin referans rotayı takip edebilme performansı klasik PID denetleyicisine göre daha yüksek olduğu gözlemlenmektedir.

Anahtar Kelimeler: Sürü İHAlar, Rota Takibi, Quadrotor, PID Denetleyicisi, Bulanık Mantık Denetleyicisi.

1. Introduction

The idea of developing multiple UAVs has emerged in recent years, inspired by swarm intelligence of living creatures such as birds, fish, insects and mammals (Tan & Zheng, 2013). Swarm UAVs successfully accomplish the desired target in coordinated complex tasks that a single UAV can't perform (Miller et al., 2007). The swarm movement highly increases the abilities of the aircraft, allowing the costs to be reduced. Swarm UAVs are preferred in different applications such as search and rescue, mapping, precision agriculture, payload transportation and disaster management (Tahir et al., 2019). The biggest advantage of swarm UAVs compared to single UAV in both military and civil use is that it saves energy and time by scanning more areas in less time. In most applications, swarm UAVs are expected to be more capable, flexible and robust than single UAV (Hadaegh et al., 2016) (Chung et al., 2018).

The route that UAV will take in reaching the target is of great importance. The reference route must be followed with minimum error, in order for swarm UAVs to complete the desired task in minimum energy and time. The type of controller designed plays an important role in performance of route tracking (Cheein & Scaglia, 2014). In the literature, different control algorithms are developed for route tracking of UAVs. Reference route tracking is recommended with the Linear Quadratic Integral (LQI) optimal controller (Joukhadar et al., 2019). This type of controller is examined under external disturbance in tracking the route of different geometry. The performance of the PID controller is analyzed in the route tracking of autonomously moving quadrotor (Gonzalez-Vazquez & Moreno-Valenzuela, 2010). The kinematic and dynamic model of quadrotor has been obtained using motion equations as in (Gonzalez-Vazquez & Moreno-Valenzuela, 2010). The trajectory tracking of quadrotor with PID controller has been simulated in MATLAB Simulink environment using the nonlinear model of quadrotor (Idres et al., 2017). The controller type of quadrotor is recommended in cascaded structure and the route tracking performance of quadrotor is examined under different disturbance effects as in (Idres et al., 2017). The trajectory tracking problem for quadrotor has been minimized using Genetic Algorithm (GA) (Siti et al., 2019). The PID coefficients are optimized using GA in the presence of disturbance as in (Siti et al., 2019). The PID controller for nonlinear quadcopter has been designed in cascaded form (Abdelhay & Zakriti, 2019). The trajectory tracking controller has been presented under constant disturbance force (Cabecinhas et al., 2014). The controller is tested on nonlinear model of quadcopter and lemniscate trajectory as in (Cabecinhas et al., 2014). The nonlinear trajectory tracking controller is designed using feedback linearization (Wu & Liu, 2018). The proposed controller is tested on spiral trajectory as in (Wu & Liu, 2018). The adaptive PID controller has been designed for the route tracking of quadcopter in cases of sudden maneuvers (Sunay et al., 2020). The route tracking performance of swarm quadrotors has been handled unlike the studies in the literature. In this study, the fuzzy logic controller is proposed for reference route tracking of five different quadrotors. This controller is tested on rectangular and circular routes. The performance of the proposed fuzzy logic controller is compared with the classical PID controller.

This paper is organized as follows. Section 2 introduces the nonlinear model of quadcopter and the proposed fuzzy logic controller design. The results of study are expressed comparatively with the proposed fuzzy logic controller and classical PID controller performances in Section 3. Section 4 explains conclusions and future work of this paper.

2. Material ve Method

2.1. Quadrotor System Model

The quadrotor is an aircraft consisiting of four engines symmetrically located in the center of body. Euler angles (roll (ϕ), pitch (θ) ve yaw angles (ψ)), state equations X^G, Y^G, Z^G (North, East, Down direction) on global frame $\{G\}$, x^b, y^b, z^b (North, East, Down direction) on body frame $\{g\}$ are shown in Figure 1 (Selby, 2009).

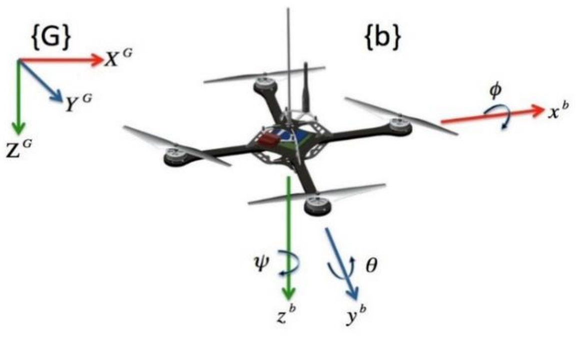

Figure 1. Rotational motion of quadrotor.

The transformation matrices between body frame and global frame are described as

$$R_G^b = \begin{bmatrix} cos(\psi)\,cos(\theta) & sin(\psi)\,cos(\theta) & -\,sin(\theta) \\ cos(\psi)\,sin(\phi)\,sin(\theta) - cos(\phi)\,sin(\psi) & sin(\psi)\,sin(\phi)\,sin(\theta) + cos(\phi)\,cos(\psi) & sin(\phi)\,cos(\theta) \\ cos(\phi)\,cos(\psi)\,sin(\theta) + sin(\phi)\,sin(\psi) & sin(\psi)\,cos(\phi)\,sin(\theta) - sin(\phi)\,cos(\psi) & cos(\phi)\,cos(\theta) \end{bmatrix} \tag{1}$$

$$R_b^G = \begin{bmatrix} cos(\psi)\,cos(\theta) & cos(\psi)\,sin(\phi)\,sin(\theta) - cos(\phi)\,sin(\psi) & cos(\phi)\,cos(\psi)\,sin(\theta) + sin(\phi)\,sin(\psi) \\ sin(\psi)\,cos(\theta) & sin(\psi)\,sin(\phi)\,sin(\theta) + cos(\phi)\,cos(\psi) & cos(\phi)\,sin(\psi)\,sin(\theta) - cos(\psi)\,sin(\phi) \\ -\,sin(\theta) & sin(\phi)\,cos(\theta) & cos(\phi)\,cos(\theta) \end{bmatrix} \tag{2}$$

where R_G^b (From global to body frame transformation matrice), R_b^G (from body to global frame transformation matrice). The motion equations of quadrotor has been obtained as

$$\begin{bmatrix} \ddot{X}^G \\ \ddot{Y}^G \\ \ddot{Z}^G \end{bmatrix} = \frac{-1}{m} \begin{bmatrix} K_{dx} & 0 & 0 \\ 0 & K_{dy} & 0 \\ 0 & 0 & K_{dz} \end{bmatrix} \begin{bmatrix} \dot{X}^G \\ \dot{Y}^G \\ Z^G \end{bmatrix} - \frac{1}{m} \begin{bmatrix} cos(\phi)sin(\theta)cos(\psi) + sin(\phi)sin(\psi) \\ cos(\phi)sin(\theta)sin(\psi) - sin(\phi)cos(\psi) \\ cos(\phi)cos(\theta) \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & sin(\phi)\,tan(\theta) & cos(\phi)\,tan(\theta) \\ 0 & cos(\phi) & -\,sin(\phi) \\ 0 & \dfrac{sin(\phi)}{cos(\theta)} & \dfrac{cos(\phi)}{cos(\theta)} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \dfrac{\left(I_z - I_y\right)}{I_x} qr \\ \dfrac{\left(I_x - I_z\right)}{I_y} pr \\ \dfrac{\left(I_y - I_x\right)}{I_Z} pq \end{bmatrix} + \begin{bmatrix} \dfrac{T_\phi}{I_x} \\ \dfrac{T_\theta}{I_y} \\ \dfrac{T_\psi}{I_Z} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \dot{X}^G \\ \dot{Y}^G \\ \dot{Z}^G \end{bmatrix} = \begin{bmatrix} cos(\psi)\,cos(\theta) & cos(\psi)\,sin(\phi)\,sin(\theta) - cos(\phi)\,sin(\psi) & cos(\phi)\,cos(\psi)\,sin(\theta) + sin(\phi)\,sin(\psi) \\ sin(\psi)\,cos(\theta) & sin(\psi)\,sin(\phi)\,sin(\theta) + cos(\phi)\,cos(\psi) & cos(\phi)\,sin(\psi)\,sin(\theta) - cos(\psi)\,sin(\phi) \\ -\,sin(\theta) & sin(\phi)\,cos(\theta) & cos(\phi)\,cos(\theta) \end{bmatrix} \begin{bmatrix} \dot{x}^b \\ \dot{y}^b \\ \dot{z}^b \end{bmatrix} \tag{6}$$

where, $\ddot{X}^G, \ddot{Y}^G, \ddot{Z}^G$ accelerations in global coordinate frame; m mass of quadrotor; K_{dx}, K_{dy}, K_{dz} drag coefficients; $\dot{X}^G, \dot{Y}^G, \dot{Z}^G$ velocity in global coordinate frame; g acceleration due to gravity; $\phi, \theta, \psi,$ roll, pitch, yaw angles respectively; $p,\ q,\ r,$ roll, pitch, yaw rates respectively; I_x, I_y, I_z quadrotor moment of ineartia in each axis; $T_\phi,\ T_\theta, T_\psi$ body torques.

2.2. Fuzzy Logic Controller Design

The route tracking error can be defined as

$$e = \sqrt{(X_d - X)^2 + (Y_d - Y)^2 + (Z_d - Z)^2} \tag{7}$$

where $X_d, Y_d, Z_d,$ reference points and X, Y, Z route of quadrotor. The quadrotor controlled by PID controller is stated as

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)\, d\tau + K_D \dot{e}(t) \tag{8}$$

where $K_{P,}$ proportional control gain, $K_{I,}$ integral control gain, K_D, derivative control gain and t, time variable, $u(t)$, control input.

The fuzzy logic controller proposed in this study is shown in Figure 2. The membership functions of quadrotor's route tracking error (e) and error change (de) are given as an input to the fuzzy logic controller.

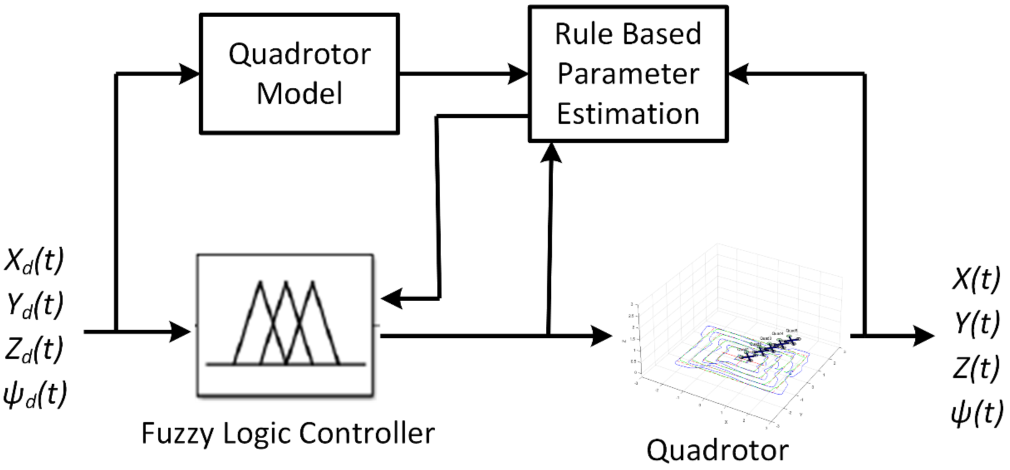

Figure 2. Fuzzy logic controller of quadrotor.

The fuzzy logic controller coefficients using error (e) and error change (de) have represented as

$$Kp = Kpmin + (Kpmaks - Kpmin) * KpI \tag{9}$$

$$Kd = Kdmin + (Kdmaks - Kdmin) * KdI \tag{10}$$

$$Ki = \frac{{K_p}^2}{\propto K_d} \tag{11}$$

$$KpI = \sum_{\text{İ}=1} mf(\mu_i)K_{p,i}\, I \tag{12}$$

$$KdI = \sum_{\text{İ}=1} mf(\mu_i)K_{d,i}\, I \tag{13}$$

$$\alpha = \sum_{\text{İ}=1} mf(\mu_i)\alpha_i \tag{14}$$

where mf, membership function; $Kpmin$, $Kpmaks$ is minimum and maksimum values of Kp respectively; $Kdmin$, $Kdmaks$ is minimum and maksimum values of Kd respectively (Zhao et al., 1992). The input and output membership functions are shown in Figure 3. If N (Negative), P (Positive), B (Large), M (Medium), S (Small), ZO (Zero) are shown in Figure 3, the input membership functions are expressed as NB, NM, NS, ZO, PS, PM, PB for error (e) and error change (de) and the output membership functions are specified as Kp, Kd ve $\propto$. The fuzzy rules for KpI, KdI, α are presented in Table 1, Table 2 and Table 3 respectively.

Table 1. The Fuzzy Rules for KpI

		de (Error Change)						
		NB	NM	NS	ZO	PS	PM	PB
e (Error)	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2. The Fuzzy Rules for KdI

		de (Error Change)						
		NB	NM	NS	ZO	PS	PM	PB
e (Error)	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 3. The Fuzzy Rules for α

		de (Error Change)						
		NB	NM	NS	ZO	PS	PM	PB
e (Error)	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

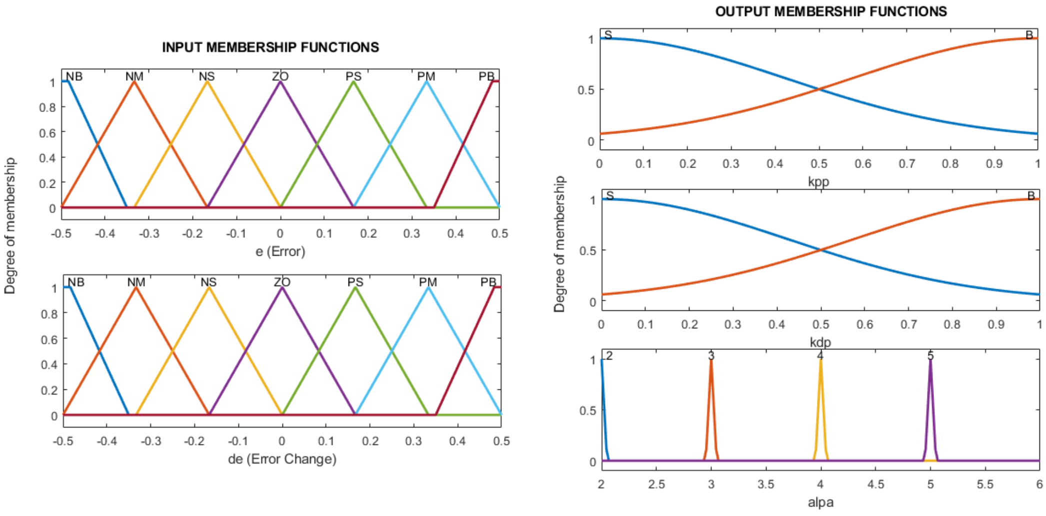

Figure 3. Input and output membership functions.

3. Results and Discussion

This study examines the route tracking performance of five quadrotors using fuzzy logic controller. The sampling period is set to 0.01 s and the simulation time to 60 s in this simulation. The rectangular and circular route tracking performance of five quadrotors are compared with classical PID and fuzzy logic controller proposed in this study. The performance comparison of five quadcopters for rectangular route is presented in Figure 4.

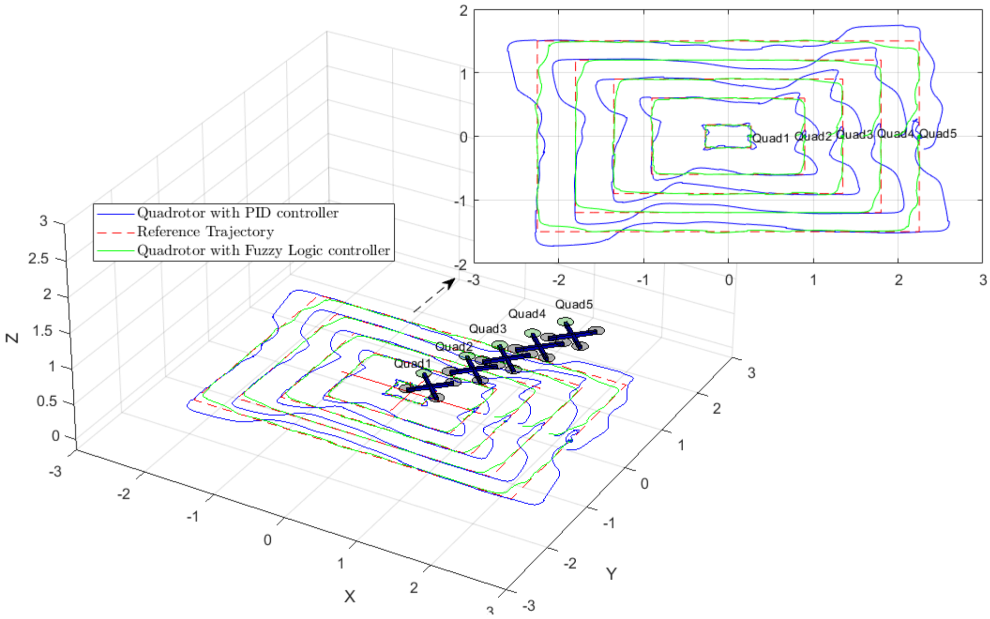

Figure 4. Route tracking performance of five quadrotors for rectangular trajectory.

The total tracking squared error for rectangular route are shown in Table 4. The total route tracking error for rectangular trajectory is obtained $1287.3\ m^2$ with PID controller and $329.82\ m^2$ with fuzzy logic controller. The fuzzy logic controller tested on five different quadrotors in rectangular route has higher track performance than PID controller.

Table 4. The Rectangular Route Tracking Error of Five Quadrotors

	PID Controller Squared Error (m^2)	**Fuzzy Logic Controller Squared Error (m^2)**
Quadrotor 1	9.02	3.37
Quadrotor 2	97.80	24.10
Quadrotor 3	214.36	52.07
Quadrotor 4	380.30	91.40
Quadrotor 5	585.87	158.88
Total Error	1287.35	329.82

The trajectory tracking performances of five quadrotors for circular route have been shown in Figure 5. The proposed fuzzy logic controller is analyzed by comparison with PID controller. The total tracking squared error for circular route are presented in Table 5. The total route tracking error for circular trajectory is obtained $1116.91\ m^2$ with PID controller and $66.17\ m^2$ with fuzzy logic controller. The fuzzy logic controller proposed in this study has lower squared error than classical PID controller for rectangular and circular route.

Table 5. The Circular Route Tracking Error of Five Quadrotors

	PID Controller Squared Error (m^2)	**Fuzzy Logic Controller Squared Error (m^2)**
Quadrotor 1	23.35	2.31
Quadrotor 2	92.97	6.18
Quadrotor 3	203.31	12.57
Quadrotor 4	363.14	19.84
Quadrotor 5	434.14	25.27
Total Error	1116.91	66.17

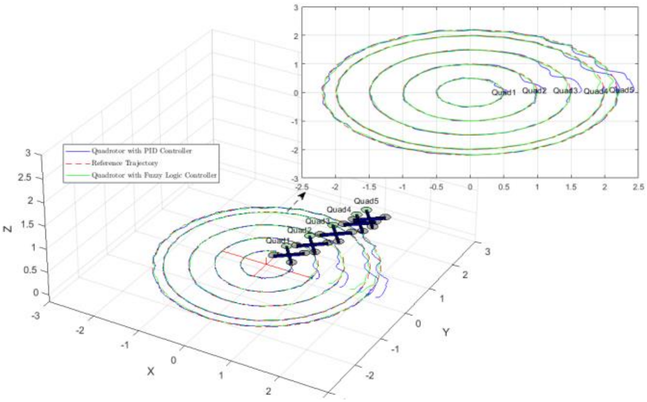

Figure 5. Route tracking performance of five quadrotors for circular trajectory.

4. Conclusions

In this study, fuzzy logic controller is recommended for rectangular and circular route tracking of five quadcopters. This controller allows multiple quadrotors to follow a specific route with minimal error. The performance of fuzzy logic controller proposed in the route tracking is analyzed by taking into account the squared error. It is observed that the route performance of fuzzy controller is higher than classical PID, when the obtained results are examined. The fuzzy logic controller designed in this study enables multiple quadrotors to perform specified tasks with minimum error. The sudden maneuverability of the designed controller is analyzed by tracking the route in different geometries. In the next stage of the study, the proposed fuzzy controller will be integrated into more than one quadrotor and it will be ensured that the specified tasks are performed with minimum time and enegy. The results of study will provide energy minimization in applications such as target tracking of UAVs.

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