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Robust Nonlinear Fuzzy Formation Control of Unmanned Quadrotors

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ABSTRACT

A novel leader-following strategy based on fuzzy logic is introduced to design a formation flight controller for unmanned quadrotors. The proposed strategy uses particle swarm optimization (PSO) to optimize the fuzzy membership function in the guidance law, and a nonlinear dynamic inversion (NDI) controller is designed to control the nonlinear dynamics of the quadrotor. The simulation results show the proposed method has significant advantages in comparison with conventional leading-following strategies in terms of robustness against wind gusts, uncertainties, and unknown dynamics.

General Terms

Fuzzy systems, Flight Formation Control, Quadrotor.

Keywords

Nonlinear control, Intelligent systems, UAV, Optimization.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have various civil, commercial, and military applications. Therefore, precise control of these vehicles is always a great challenge for scientists [1, 2]. Thanks to the advanced technology the size of processors, inertial measurement unit (IMU), wireless communication antennas, and batteries are reduced that leads to a significant reduction in UAV size [3]. Quadrotors vertical takeoff and landing (VTOL) ability, hovering, highly maneuverability, and their small size makes them a suitable candidate for many missions; so far, it motivates researchers to use them for many applications. Search and rescue [4, 5], surveillance and homeland security [6], and military usage like search and destroy [7]. Quadrotor has also commercial applications like delivering a postal package to the customers [8, 9].

Due to the various applications of these UAVs and the need to have a precise control system, they received a great attention among the control experts. Classic linear control strategies like proportional integral derivative (PID) and linear quadratic regulator (LQR) have been applied successfully on the quadrotor in previous researches. An onboard learning based model predictive control (MPC) is also applied on quadrotor [10]. A linear robust H-infinity controller is implemented on the quadrotor, this controller was successfully robust against wind gusts [11]. The main problem in linear control design for quadrotors is their highly nonlinear dynamic; therefore, linear control strategies which are designed based on linearized dynamic have difficulties to handle the system solely [12-16].

Due to the mentioned problem, nonlinear intelligent control methods are potential candidates for quadrotor control system design. The majority of nonlinear control designs are based on the Lyapunov theory [17-21]. Voos introduced a feedback linearization (FBL) controller based on decomposing the dynamic to a nested structure which was implemented on a microcontroller [22]. Das et al. introduced a dynamic inversion controller with two control loops which were separated based on the component speed difference [23]. This strategy helps to design a controller for each loop separately and simplifies the control design. A robust sliding mode controller was also designed by Bouchoucha et. al [24]. This controller was robust against bounded disturbances and could control the attitude without chattering in control surfaces.

The intelligent control system based on neural networks and fuzzy logic is introduced to the linear and nonlinear systems to enhance the control performance or to control the systems which were difficult to obtain their dynamic model [25]. Meguenni et al. designed a fuzzy integral sliding mode controller to control a quadrotor [26]. In this strategy, the fuzzy integral controller is used to reduce the static tracking error in the system. An adaptive fuzzy controller for quadrotor control is introduced by Coza et al. to overcome the inherent nonlinearities in the system and be more robust against wind disturbances and uncertainties inserted by payloads [27]. Adaptive neural networks have also been used to adapt the flight controller to uncertainties and nonlinearities [25, 28]. This neural network can identify and compensate the inherent unknown dynamics in the system which improved the control accuracy.

This paper deals with the problem of formation flight control design for the quadrotors. Formation flight has various applications in mapping, search and rescue, and surveillance [29-32]. Several methods can be used for the formation flight control like leader-follower [33, 34], pure pursuit [35], and virtual structure [36].

In this paper, a leader-follower approach is used to control the formation flight. This formation flight system is controlled by a fuzzy controller which its membership functions are optimized through an offline optimization algorithm. The optimization algorithm which is used in this paper is particle swarm optimization (PSO), and it is chosen based on the fast convergence velocity and also global optimality [37]. For the attitude and position control, we used nonlinear dynamic inversion method is used which is designed based on the nonlinear model and is able to control the system precisely. The simulation results show that the proposed controller is able to control the system in presence of bounded wind disturbances. The result comparison with conventional PD controller shows the designed fuzzy controller can tackle the vulnerability problem of the linear system in presence of uncertainties and disturbances.

This paper is organized as follows: in “Dynamic Model” section the non-linear mathematical model of quadrotor is presented, whereas the control strategy and design procedure are explained in “Control system design” section, and the guidance method is described in “Formation Flight Control” section. Then in “Numerical Simulations” section, we proceed with the numerical simulation, while the conclusions are provided in the final section.

2. DYNAMIC MODEL

In this section, the nonlinear dynamic model of quadrotor is explained.

2.1. Body Dynamic

The following equation can help to understand the quadrotor body dynamic behavior and helps to design a controller based on these dynamics [38].

$$\dot{p} = -qr\frac{I_z - I_y}{I_x} + \frac{T_p}{I_x} \tag{1}$$

$$\dot{q} = -pr\frac{I_x - I_z}{I_y} + \frac{T_q}{I_y} \tag{2}$$

$$\dot{r} = -pq\frac{I_y - I_x}{I_z} + \frac{T_r}{I_z} \tag{3}$$

$$\dot{\phi} = p + \sin(\phi)\tan(\theta)q + \cos(\phi)\tan(\theta)r \tag{4}$$

$$\dot{\theta} = \cos(\phi)q - \sin(\phi)q \tag{5}$$

$$\dot{\psi} = \frac{\sin(\phi)}{\cos(\theta)}q + \frac{\cos(\phi)}{\cos(\theta)}r \tag{6}$$

$$\dot{u} = rv - qw + g\sin(\theta) \tag{7}$$

$$\dot{v} = -ru + pw - g\cos(\theta)\sin(\phi) \tag{8}$$

$$\dot{w} = -qu - pv + \frac{F_z}{m} - g\cos(\theta)\cos(\phi) + K_1\frac{(z_1 - z)\Delta z}{m} \tag{9}$$

where p, q, and r are components of quadrotor's angular velocity regarding x, y, z body axes [rad/s], respectively; *Ix*, *Iy*, and *Iz* are moments of inertia [kg/m2]; ϕ, θ and ψ are Euler angles [rad] or [deg] which describe the roll, pitch and yaw angle in the body fix coordinate system, respectively; u, v, w are the velocities [m/s] along the x, y and z body fix coordinate, respectively. K_1 and z_1 are the elastic coefficient and elastic deformation on the ground, and Δz can be described as follow:

$$\Delta(z_1 - z) = \begin{cases} 1 & z_1 - z > 0 \\ 0 & z_1 - z \le 0 \end{cases} \tag{10}$$

The overall physical structure of the quadrotor is depicted on Fig.1.

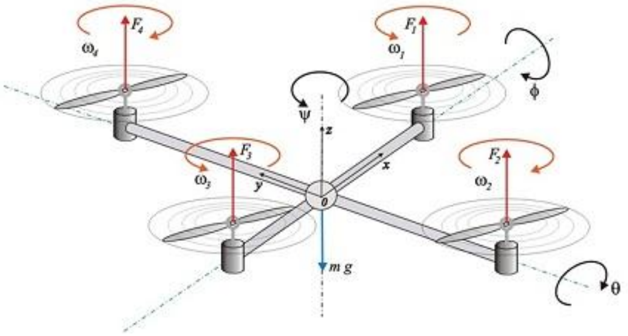


Fig 1. Overall view of Quadrotor dynamic system.

2.2. Navigational Equations

In order to transform the translational movement from the body fixed frame coordination to the earth-fixed coordination the following transform matrix can be used [39]:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} c\theta c\psi & -c\phi s\psi + s\phi s\theta c\psi & s\phi s\psi + c\phi s\theta c\psi \\ c\theta s\psi & c\phi c\psi + s\phi s\theta s\psi & -s\phi c\psi + c\phi s\theta s\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix}\begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{11}$$

where '*c*' denotes the cosine and '*s*' denotes sine.

3. CONTROL SYSTEM DESIGN

In this section, we explain the proposed control strategy which is used for designing the attitude and position controller. Dynamic inversion (DI) controller is selected to be implemented in order to control the quadrotor position and attitude. This controller has been successfully implemented in many aircraft [25, 40, 41]. DI is a nonlinear control strategy based feedback linearization that can be applied in several control-loops in a system. Based on the time scale separation between the angular velocities and attitude angles in quadrotor body fixed frame, the control design is implemented in two control loop.

3.1. Inner Loop Control

The inner loop in this control system is the loop that its parameters vary with a higher rate. The angular velocities (p, q, r) changing frequency is 50 Hz while the attitude angle frequency (ϕ, θ, ψ) is 4 Hz; therefore, p, q, r are selected as the inner loop system. Using DI theory, angular velocities equations (1-3) can be transformed to [38]:

$$\begin{bmatrix} T_p \\ T_q \\ T_r \end{bmatrix} = \begin{bmatrix} \dot{p}I_x \\ \dot{q}I_y \\ \dot{r}I_z \end{bmatrix} + \underbrace{\begin{bmatrix} \left(I_z - I_y\right)qr \\ \left(I_x - I_z\right)pr \\ \left(I_y - I_x\right)pq \end{bmatrix}}_{ommited} = K_{in}\begin{bmatrix} (p_c - p)I_x \\ (q - q_c)I_y \\ (r - r_c)I_z \end{bmatrix} \tag{12}$$

In (12), we intentionally omitted the right side of the equation to maintain zero dynamics while angular velocity error is zero. Therefore, the unmolded dynamics characteristics can be compensated through enhancing the DI. K_{in} can be tuned by the designer to obtain the desired response.

3.2. Outer Loop Control

In this loop the attitude dynamics (4-6) can be transformed in order to obtain the desired angular velocities (p, q, r)[38]:

$$\begin{bmatrix} p_c \\ q_c \\ r_c \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix}^{-1} + \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix}^{-1} K_{out}\begin{bmatrix} \phi_c - \phi \\ \theta_c - \theta \\ \psi_c - \psi \end{bmatrix} \tag{13}$$

where K_{out} is a control gain that can be tuned by the designer to obtain the desired system performance. ϕ_c and θ_c are the commanded roll and pitch angle that can be obtained from the following equation[38]:

$$F_z = (u_z + g)m \tag{14}$$

$$\phi_c = (u_x \sin\psi - u_y \cos\psi)m / F_z \tag{15}$$

$$\theta_c = (u_x \cos\psi + u_y \sin\psi)m / F_z \tag{16}$$

where F_z is the lift force, u_x, u_y and u_z are trajectory commands that are described in the formation control section. In this design, we assumed that the ψ_c is a constant value, and we used other parameters to control the quadrotor trajectory.

3.3. Motor Speed Control

The motor speed control can be obtained from the following equation [38]:

$$\begin{bmatrix} \omega_{1c} \\ \omega_{2c} \\ \omega_{3c} \\ \omega_{4c} \end{bmatrix} = \begin{bmatrix} -0.25 & -0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & -0.25 & -0.25 & 0.25 \\ -0.25 & 0.25 & -0.25 & 0.25 \end{bmatrix} \begin{bmatrix} T_p / (Lk_f) \\ T_q / (Lk_f) \\ T_r / (Lk_t) \\ F_z / k_f \end{bmatrix} \tag{17}$$

4. FORMATION FLIGHT CONTROL

In this section, the leader-follower method is used to design a formation control flight scheme that can be applied to a group of quadrotors. The controller which is used in this paper is fuzzy PD controller based on the leader-follower strategy. In the leader-follower procedure, the follower tracks the exact position of the leader with a defined distance with the leader. Here we assumed that all the quadrotors will fly at the same altitude. The follower position can be defined by using these equations:

$$X_f = X_L + \lambda_{xd} \cos\psi_l - \lambda_{yd} \sin\psi_l \tag{18}$$

$$Y_f = Y_L + \lambda_{xd} \sin\psi_l - \lambda_{yd} \cos\psi_l \tag{19}$$

The follower position obtained from the above equation will be next used in the Fuzzy PD controller to produce u_x, u_y and u_z. Three fuzzy PD controller are used to produce u_x, u_y and u_z which are explained in the following subsections.

4.1.Fuzzy PD Controller Design

In this subsection, the design procedure of the fuzzy PD controller for the formation flight controller is illustrated. This controller is designed based on the formation error and the derivative of the formation error. The proposed fuzzy PD controller for following the leader aircraft can be presented as:

$$u_x = K_{PF}\, e_x + K_{DF}\, \dot{e}_x \tag{20}$$

where K_{PF} is the proportional fuzzy (PF) gain and K_{DF} is the derivative fuzzy (DF) gain; e_x is the tracking error in the X-direction and $\dot{e}_x$ is the tracking error derivative. Figure 2 shows the block diagram of the fuzzy controller described in (20). The mentioned structure in (20) will be also used to design the tracking controller in *y* and *z*-direction.

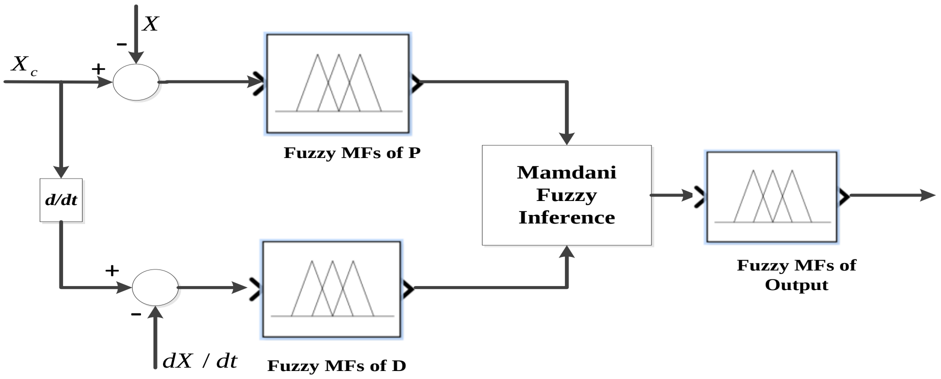


Fig 2. Fuzzy PD Controller structure.

In the next step of the fuzzy controller design, the fuzzy rules should be defined. These rules are defined based on the designer experience in system dynamic response [40]. Minimum Mamdani (AND method) is used to design the fuzzy controller due to its low computational load [42]. In this work, seven membership functions (MFs) are selected for each fuzzy controller. Triangular MFs are selected due to their simplicity in tuning and less computational load in tuning them with the optimization algorithms. Figure 3 shows the MFs of the proposed fuzzy controller. In this figure, large negative (LN), medium negative (MN), small negative (SN), Zero (ZE), small positive (SM), medium positive (MP), and large positive (LP) are the defined membership function in the fuzzy logic controller.

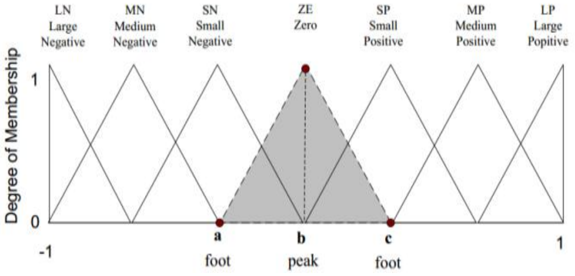


Fig 3. Membership functions of the proposed fuzzy PD controller.

As we already mentioned, the fuzzy PD controller is based on the error of the controller and the derivative of the error; thus, the designer should define the fuzzy rules based on these two parameters and using the using the defined MFs. Table 1 shows the rules that are defined for the proposed controller.

These rules are derived based on the designer experience from dynamic response of the system.

Table 1. Fuzzy rules of the PD fuzzy tracking controller.

e $\dot{e}$	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	PS	PS	PM	PM	PB	PB
NM	NS	ZE	PS	PS	PM	PM	PB
NS	NS	NS	ZE	PS	PS	PM	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NM	NS	NS	ZE	PS	PS
PM	NB	NM	NM	NS	NS	ZE	PS
PB	NB	NB	NM	NM	NS	NS	ZE

4.2. Tuning Fuzzy Membership Functions

The tuning process of fuzzy MFs to obtain the desired results is a complicated and time-consuming process. This problem is more complicated by increasing the number of the MFs. Evolutionary algorithms are good tools for tuning these parameters; therefore, by using the computational ability of the computers, these complicated problems are solvable [43-48]. To tackle this problem, we introduced particle swarm optimization (PSO) algorithm to tune these MFs. PSO is a stochastic optimization technique which tunes the parameter based on predefined objective functions and criteria [49, 50]. This algorithm is inspired by a swarm of particles (e.g., birds) searching in the space for a target (e.g., food). Velocities and positions of particles in this algorithm are governed by a set of rules that manage the swarm dynamic. In fact, particles in the swarms derive these rules based on their experiences in searching space and based on the closeness to the target. The swarm converges to the best optimal point by sharing their experience with each other and repeating the search process. Thus, the global optimality of this optimization algorithm has a direct relation with the number of particles and number of iterations, by increasing the number of these two factors, the chance to obtain the global optimal point will be increased. The size of searching space, particle velocity and behavior are the other factors that have an influence on the result of optimization with PSO algorithm.

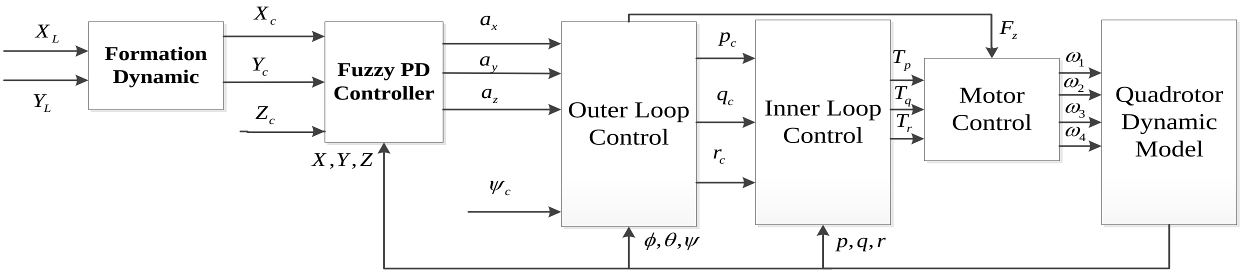


Fig 4. Block diagram of proposes formation control design

The velocity and the position of the particles can be calculated as follows [42]

$$v_i(k+1)=M.v_i(k)+k_1r_1(k)(x_g-x_i(k)) \quad (21)$$
$$+k_2r_2(k)(x_i^p-x_i(k))$$

$$x_i(k+1)=x_i(k)+v_i(k+1) \quad (22)$$

where $v_i(k)$ is the velocity of the particle at step k; M is the inertia weight; r_1 and r_2 are small random number between [0, 1] that represent the friction; x_g is the best global position of the particle at step k; x^p is the best personal experience that the particles have had at step k; $x_i(k)$ is the current position of particle i at time step k; k_1 and k_2 are designer constants that are commonly equal to each other [42].

In order to define the objectives of the optimization problem, a cost function is defined as follows [51, 52]

$$C=\int\left(eQe^T+uRu^T\right)dt \quad (23)$$

where e is the tracking error, u is the control inputs of the quadrotor, and Q and R are diagonal matrices that are selected by the designer to achieve the best performance.

The final step of this control design is tuning the MFs of the fuzzy controller using PSO algorithm. As we know, each triangle can be presented by three points, and our MFs are triangular; thus, PSO algorithm will tune three points in each MF to find the best arrangement of these points. The overall diagram of the proposed design is shown in Fig 4.

5. NUMERICAL SIMULATIONS

In this paper, a leader following formation flight controller using fuzzy-pso algorithm is introduced. In this section, the simulation result is provided to demonstrate that the proposed control strategy is capable of controlling a formation flight it is robust against the uncertainties. Figure 5 shows the overall structure of the designed fuzzy controller. As it can be seen there are three fuzzy controllers that should be tuned using PSO algorithm. As we already shown in Fig. 2, three sets of MFs should be tuned in each of these fuzzy controllers. The tuned membership functions using PSO algorithm are depicted on Figd.6-8. Figure 6 shows the three sets of MFs for tuning e_x, $\dot{e}_x$ and the output of the controller, respectively. Similarly, MFs were tuned for tracking control in Y and Z direction in Figs 7 and 8, respectively.

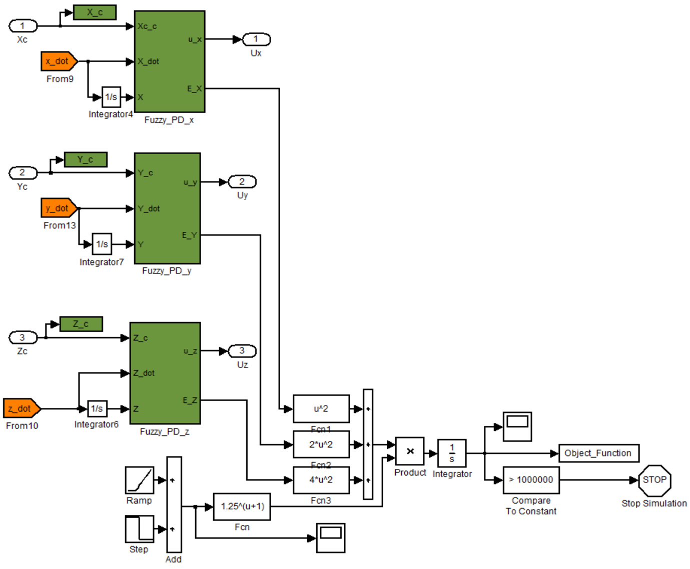
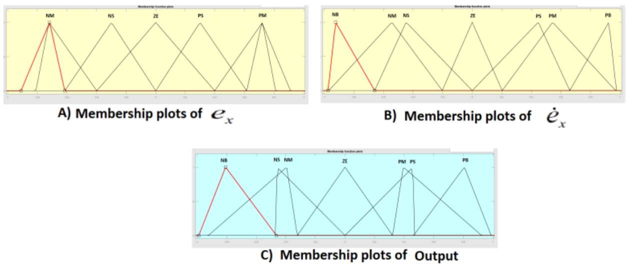


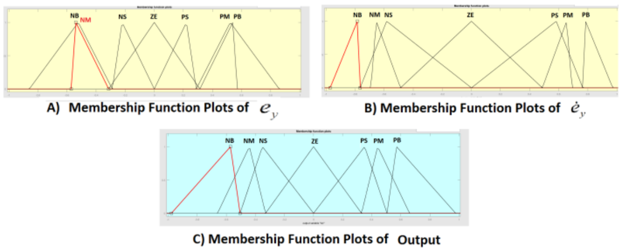
Fig.5.The designed fuzzy controller.



A) Membership plots of e_x B) Membership plots of $\dot{e}_x$

C) Membership plots of Output

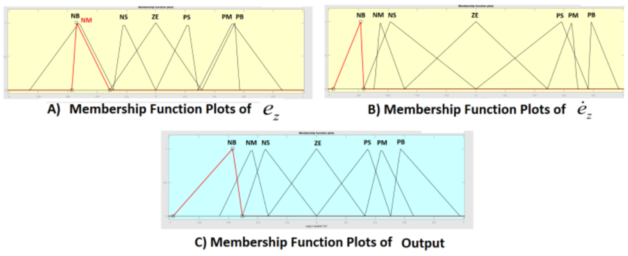
Fig.6. Tuned membership functions in X tracking control.



A) Membership Function Plots of e_y B) Membership Function Plots of $\dot{e}_y$

C) Membership Function Plots of Output

Fig. 7. Tuned membership functions in Y tracking control.



A) Membership Function Plots of e_z B) Membership Function Plots of $\dot{e}_z$

C) Membership Function Plots of Output

Fig. 8. Tuned membership functions in Z tracking control.

The simulations are done by using the tuned MFs in Figs 6-8, and the results are shown at Fig.9-12. To show the advantages of the proposed controller, we compared the result with the PD tracking controller. The PD controller has the same structure in the attitude controller but instead of fuzzy control in the formation control, it uses PD controller. Two different maneuvers given to the proposed system and the results are compared with the PD Formation controller. As it can be seen in these figures, the Fuzzy-PD formation controller has better performance than the PD formation controller.

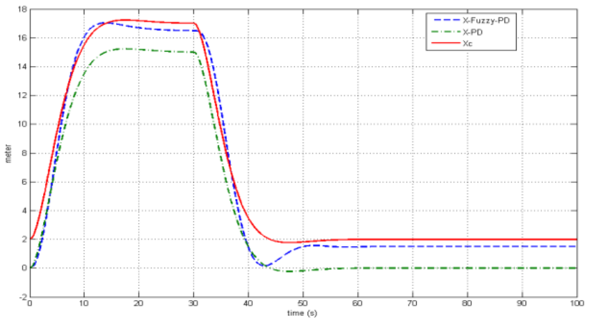


Fig. 9. Tracking in the X-Direction

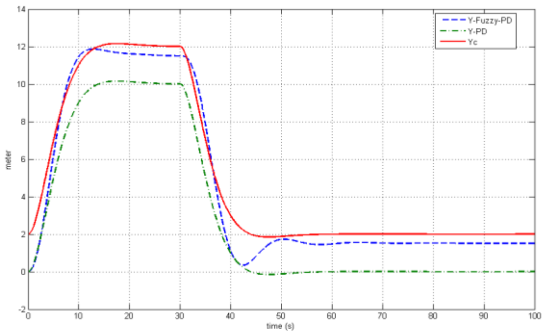


Fig. 10. Tracking in the Y-Direction

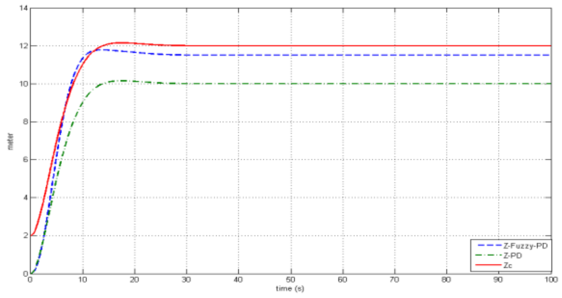


Fig.11. Tracking in the Z-Direction

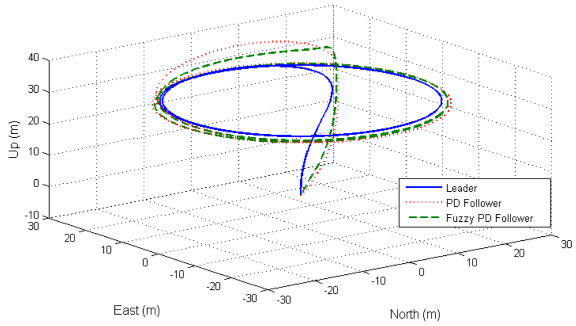


Fig. 12. Circular maneuver tracking.

6. CONCLUSION AND FUTURE WORKS

A novel Fuzzy-PD-PSO controller is designed for the leader-follower formation flight control of quadrotor. The nonlinear dynamic of quadrotor is controlled with nonlinear DI controller. Then, a fuzzy-PD controller is designed for the system to track a leader object. To obtain an optimized controller, the fuzzy membership functions of the designed controller were optimized through an offline process. The simulation result showed that the designed controller has better performance in comparison with the conventional PD controllers which are used for trajectory and formation controllers. In future, we will try to consider the collision avoidance algorithm in the formation flight control and introduce some search and rescue application for the proposed design system.

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