Comparative Study and Robustness Analysis of Quadrotor Control in Presence of Wind Disturbances

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Abstract: Controlling of the quadrotor has been noted for its trouble as the consequence of exceeds nonlinear system, strong coupled multivariable and external disturbances. Quadrotor position and attitude is controlled by several methodologies using feedback linearization, but when quadrotor works with unstructured inputs (e.g. wind disturbance), some limitations of this technique appear which influence flight work. Design control system with fast response, disturbance rejection, small error, and stability is the main objective of this work. So in this paper we can make use of new methods of control to design a controller of nonlinear robust with a reasonable performance to test the impact of wind disturbance in quadrotor control such as Fuzzy-PID controller and compared its results with the others four controllers which are PID tuned using GA, FOPID tuned using GA, ANN and ANFIS then discus which controller give the best results in the presence and absence of wind disturbance. The main objective of this paper is that performance of the designed control structure is computed by the fast response without overshoot and minim error of the position and attitude. Simulation results, shows that position and attitude control using FOPID has fast response and better steady state error and RMS error than Fuzzy-PID, ANFIS, ANN and PID tuned using GA without impact of wind disturbance but after impact of wind disturbance it was observed using Fuzzy-PID has fast response with minimum overshoot and better steady state error and RMS error than the other four controllers used in the paper and compared with most of literature reviews which didn't give the adequate results contrasted with the required position and attitude. The all controllers are tested by simulation under the same conditions using SIMULINK under MATLAB2015a.

Keywords: Adaptive Neuro Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN), Fuzzy-PID, Fractional Order PID (FOPID), Genetic Algorithm (GA), Proportional Integral Derivative (PID) Controller, Quadrotor

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Biographical notes: Reham H. Mohammed received her MSc in 2010 from computer and system department, Mansoura University, Egypt, and her PhD in 2016 from Electrical department, Suez Canal University-Egypt. Her current research focuses on Quadrotor, Robotic Control and Optimization Techniques.

1 INTRODUCTION

Quadrotors are motivating platform for Aerial Robotics research. The thriving interest of aerial robots in farming, firefighting, mining, military and remote sensing etc. has given great impetus to controller research and enhancement in this field [1]. The research in controller design of quadrotor is as yet having challenges because: high maneuverability, exceedingly nonlinear system, strongly coupled multivariable and under-actuated condition with 6 DOF and just 4 actuators. [2].

Regardless of the new development accomplished in the control area, the most comprehensively control techniques is PID utilized in industry due to the basic usage and structure [13-14] There are four fundamental deficiencies in the traditional PID control: noise degradation in the derivative control, over simplicity, error computation, performance loss in a linear-weighted sum form within the control law, and the resulted complications of the integral control [15]. To update the performance and robustness of PID systems of control, a general sort of the PID controllers proposed by Podlubny; called FOPID controller [16]. Fractional analytics are the arithmetic field that utilizes non-integer order to arrange integrals and derivatives. FOPID control is a recently emerged technology that was demonstrated best execution over PID in different applications.

Also to beat these issues and creates more appropriate solution to position and attitude control of quadrotor, artificial intelligent controllers have been proposed, for example, Fuzzy-PID and a hybrid combined between Fuzzy Inference Systems (FIS) and Neural network controllers to design ANFIS.

This paper points position and attitude control and stabilization of quadrotor using various kinds of controllers with impact of disturbance to get a perfect position with fast response, with the least state of steadiness, less errors of RMS, and good disturbance rejection. An excellent tracking must be granted in the controller, to a particular position through providing stability and less errors of tracking. The controller output is straightforwardly fed into the dynamic model without making any mapping in the actuator space. In the simulations introduced here, the thrust input cannot be more than double the weight of the matrix; similarly an appropriate threshold is additionally put in the torque input. These thresholds have been put to make the control laws as practical as possible. Finally, the controllers performances that proposed in this paper are compared each other's for the tracking task with impact of wind disturbance.

2 LITERATURE REVIEW

There are a few writing surveys of quadrotor control for upgraded performance, for example, traditional linear techniques utilized for control of quadrotor for example, PID [3-6], Linear quadratic regulator [5-7] for perfect control, which at lower speeds give good results, but this method gave a poor performance in the presence of wind disturbance and at higher speeds as a result of large vibrations of motor controller. In Additionally, numerous advanced control approaches are likewise utilized, for example, H-infinity control design, adaptive approach [10], nonlinear feedback linearization [8-9], sliding mode control [11] but noticed amount of chattering, Backstepping [6], [8], [11-12]. Most works have utilized Euler angles for modelling. Also it considers the dynamic models of gears, motors and rotors. But most of literature reviews didn't give the adequate results contrasted with the required position and attitude which influence flight work where, the objective of every one of the controllers' strategies is to stabilize position and attitude of quadrotor with better response with and without impact of wind disturbance.

The aim of this paper is to beat these issues and creates more appropriate solution to position and attitude control of quadrotor by using different control techniques such as Fuzzy-PID controller and compared its results with the others four controllers which are PID tuned using GA, FOPID tuned using GA, ANN and ANFIS then discus which controller give the best results in the presence and absence of wind disturbance.

The paper in hand is organized as follows: presentation of the quadrotor configuration in the second section. The third and the fourth sections introduce quadrotor modeling and control strategy based on proposed control techniques respectively. The fifth section deals with an illustration for simulation results of all developed controllers. And the last section includes the concluding remarks.

3 QUADROTOR CONFIGURATION

A Quadrotor is a small vehicle composed of 4 rotors. As demonstrated in “Fig. 1”, the adjacent rotors have reverse feeling of rotation. This done to alter the complete momentum angle of the craft; otherwise the UAV will start rotating around itself. The Quadrotor has 6 DOF but only four actuators (Rotors). Hence, Quadrotor are under actuated. The Rotors generate thrust, torque and drag force and the control input to the framework is the angular velocity of the motors. A low level controller adjusts out the rotational speed of every blade. The Quadrotor can perform Vertical Take Off and Landing (VTOL), hover and make slow precise movements. The 4 rotors give a higher payload limit.

Quadrotors are moderately less difficult because they don't bring convoluted swash plates and linkages [17].

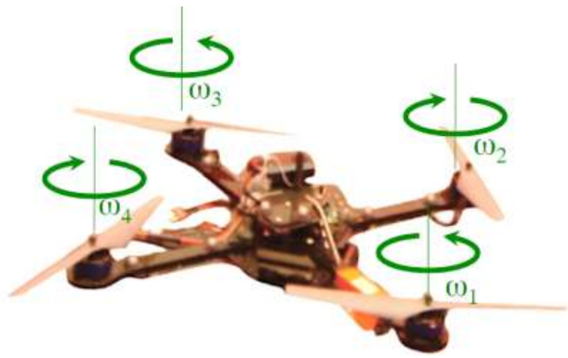

Fig. 1 Quadrotor UAV.

There are some states that we require in UAV recorded as: **Estimation State,** calculate position and velocity of quadrotor. **Control,** drive motors and delivers desired actions in order to navigate to the desired state. **Mapping,** the quadrotor must have basic ability to map its environment. **Planning:** Finally, the quadrotor must be able to track the trajectory planning [17].

4 QUADROTOR MODELING

A. Basic Mechanics

The mechanic model of the quadrotor has been gotten from [17] and presented in detail in [18].

B. Quadrotor Dynamics

The dynamics of a quadrotor by using the Newton-Euler formalism presentenced in detail in [17-18].

5 CONTROL STRATEGY BASED ON PROPOSED CONTROLLERS

The proposed controller's procedures have been studied and implemented in MATLAB2015a/Simulink. The quadrotor block diagram Control utilizing feedback linearization is showed up in "Fig. 2". As showed up in the block attitude controller is inner loop while position controller is the outer loop. It is reasonable to see that the dynamics of the inner loop must be quicker than the dynamics of the outer loop. In hover arrangements the dynamics of attitude do not matter much in general, in any case in circumstances where, the robot requires to make maneuvers, it is central to have a quicker attitude controller. In the following section PID tuned using GA Control, FOPID tuned using GA, ANFIS, ANN, and Fuzzy-PID are discussed and the results are presented to control the outer loop. All controllers used in presence of wind disturbances with velocity vector $V_\omega = 2\hat{}\ i + 2\hat{}\ j + 2\hat{}\ k\ m.s^{-1}$ is connected as a step input at time t = 25 s.

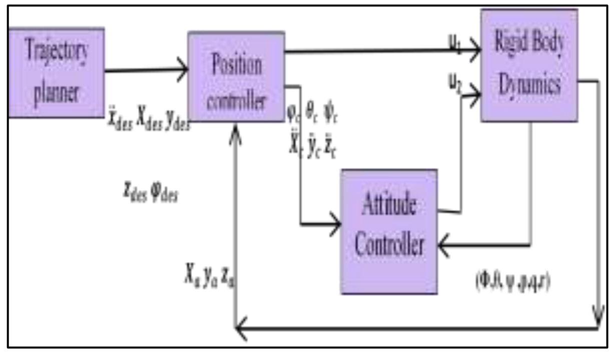

Fig. 2 Control Block Diagram.

5.1. Quadrotor Control using PID Tuned using GA

The point of PID is to design a position and attitude controller of a quadrotor by determination of a PID gains k_p, k_d and k_i utilizing GA, where GA is an optimization technique rely upon the mechanisms of natural selection for tuning PID gains k_p, k_d and k_i for the three position (x, y and z) utilizing Integral Square-Error (ISE) to guarantee ideal control performance at nominal operating conditions. [19]. The Three gains of PID after tuning for X (k_{p1}=45.75and k_{d1}=12, ki=33.5), for Y (k_{p2}=51.5 , k_{d2}=56.599, ki=24.5) and for Z (k_{p3}=130.962, k_{d3}=55.25, ki=58.526) at that point change this error signal to deliver control input for framework. The input of the controller at that point powers the framework to convey output as close as conceivable to the desire position the system is depicted without impact of wind disturbances in detail in [18], [27]. The other proposed controllers in this work is to use FOPID tuned utilizing GA and artificial intelligent such as ANFIS, Fuzzy-PID and ANN controllers.

5.2. Quadrotor Control using FOPID Tuned by GA

Fractional Order Calculus (FOC) is a generalization of the regular integration and differentiation that incorporate non-integer orders. [20]. All regular cases of PID controllers are the special cases of the fractional $PI^{\lambda} D^{\mu}$ controller. The control signal *u (t)* can then be presented in the time domain as:

$$u(t) = k_p e(t) + k_I D_t^{-\lambda} e(t) + k_D D_t^{\mu}\, e(t) \tag{1}$$

Control of mechanical systems is one of the most vital highlights of the $PI^{\lambda}D^{\mu}$controller another feature lies in the fact that $PI^{\lambda}D^{\mu}$ controllers are low sensitive to the parameters changes of the controlled system additionally FOPID give greater adaptability in the controller design and upgrade the systems efficiency compared with the PID [21].

The quadrotor controlled by FOPID without impact of wind disturbances is introduced in details in [27]. FOPID optimized by GA utilizing ISE cost function to guarantee perfect control effectiveness at nominal operating conditions as appeared in block diagram of "Fig. 3". Where, each FOPID controller has 5 gains, there are totally 15 gains to be optimized by GA. All of the gains are updated at every simulation time, where GA parameters $[kp_1\ ki_1\ kd_1\ \lambda_1\ \mu_1\ kp_2\ ki_2\ kd_2\ \lambda_2\ \mu_2\ kp_3\ ki_3\ kd_3\ \lambda_3\ \mu_3]$ with lower bounds = [0 0 0 0.01 0.01 0 0 0 0.01 0.01 0 0 00.01 0.01] and upper bounds= [200 200 200 1 1 200 200 200 1 1 200 200 200 1 1].

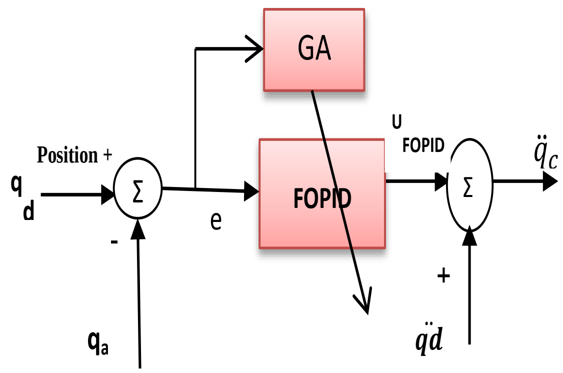

Fig. 3 The proposed FOPID controller block diagram.

The 5 gains of FOPID after tuning for X (k_{p1}=0.35, k_{d1}=8.24, k_{i1}=13.2, λ_1=0.372 and μ_1= 0.93), for Y are (k_{p2}=36.37, k_{d2}=17.13, k_{i2}=58.6, λ_2=0.96 and μ_2=0.96) and for Z are (k_{p3}=99.37, k_{d3}=6.08, k_{i3}=24.53, λ_3=0.98 and μ_3=0.94).

5.3. Quadrotor Control using ANFIS Controller

A. Principles of ANFIS

The adaptive NF inference system (ANFIS) is one of the proposed controllers which, merges the benefit of neural network and fuzzy logic. Neural network gives connectionist framework and learning capabilities to fuzzy logic and fuzzy logic give neural networks with a structural framework with high-level fuzzy IF-THEN rule of reasoning and thinking. Neural network based on fuzzy logic has learning capability of neural networks to understand the fuzzy logic inference system, have the popularity in the control of nonlinear systems [22-23].

B. Structure of Quad Rotors Based on ANFIS controller

The overall block diagram of the ANFIS control is appeared in "Fig. 4". The system composed of a forward path in addition to a feedback path. The forward path controller is ANFIS and dynamics model for the quad rotor. The feedback path consists of the actual trajectory $(X_a, Y_a\ and\ Z_a)$ and actual velocity $(\dot{X}_a, \dot{Y}_a\ and\ \dot{Z}_a)$. The ANFIS controller created made out of two sources, position error (e*)* and velocity error ($\dot{e}$). This work considers the ANFIS internal structure for the three positions (X, Y and Z) as the same with first order sugeno model where, contain 4 rules with triangular membership functions (MF).

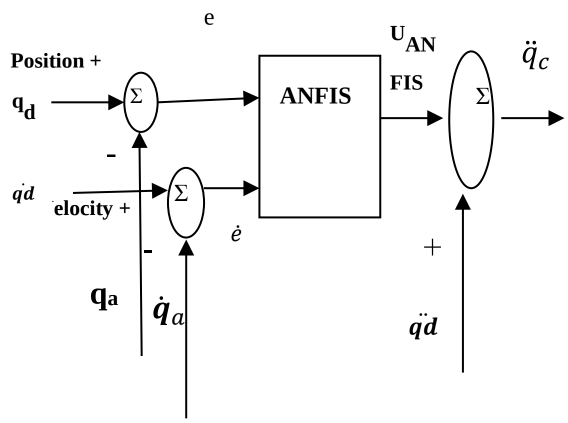

Fig. 4 The block diagram of the proposed ANFIS controller.

The MFs with product inference rule are utilized at the fuzzification level. Hybrid learning algorithm that combines least square technique with gradient decent strategy is utilized to modify the parameter of MF. The adaptive NF inference framework structure consist of five functional blocks (database, rule base, a decision making unit, a fuzzyfication and a defuzzyfication interface) which are created utilizing five network layers [18], [23]. The quadrotor controlled by ANFIS without impact of wind disturbances is introduced in details in [18].

5.4. Quadrotor Control using ANN Controller

In this section the PID controller has been replaced with Neural Network blocks. The desired inputs position and velocity are compared with their corresponding outputs from the quadrotor to determine the errors in position and velocity $\mathbf{e_p}$ and $\mathbf{e_v}$, respectively. Furthermore these two error signals are passed through ANN. The network consists of a three layer neural – network with two input nodes connected to ten neurons in hidden layer (with tan sigmoid transfer function) which is functioned for receiving the input data from the input layer, multiplying them according to the synaptic weights values denoted by, and forwarding the result values to the output layer (with purelin transfer function) (2-10-1).

5.5. Quadrotor Control using Fuzzy-PID Controller

The fuzzy supervisory kind tries to provide nonlinear action for the controller output by using fuzzy reasoning where, the gains of PID are tuned depend on a fuzzy inference system rather than the traditional methods [24]. The Fuzzy-PID controller designing process for position and attitude control is described in detail in [18]. The quadrotor block diagram controlled by Fuzzy-PID controller is presented in "Fig. 5".

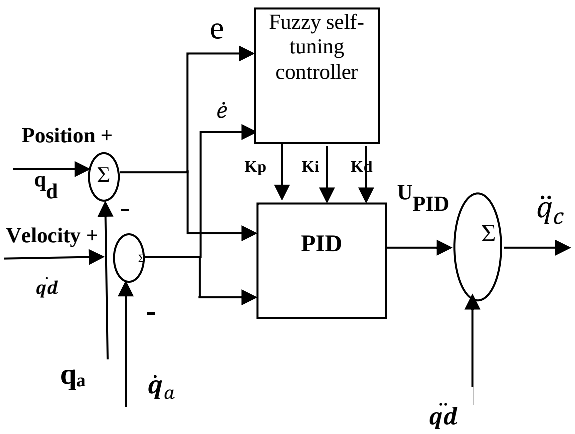

Fig. 5 Fuzzy self-tuning proposed.

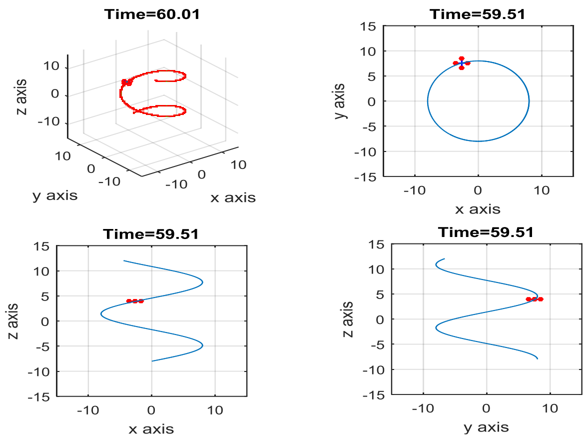

Fig. 6 The Helical Trajectory after using fuzzy-PID controller in presence of wind disturbance.

6 SIMULATION RESULTS

Through considering the quadrotor dynamics, the simulation is performed for the position(X, Y, Z) and attitude (Φ, θ, ψ) control by using MATLAB 2015a by considering the dynamic of the quadrotor from [17].The main aim of implementing this simulation is to show how efficient the suggested controller in the presence and absence of wind disturbance. All controllers tried to track the path of a helical trajectory. The values of the 9 PID parameters obtain by GA with fitness value 0.025411after 260 epochs. ANFIS GUI editor is accessible in the Toolbox of Fuzzy Logic [25]. Utilizing a given input/output data set, the toolbox constructs a fuzzy inference system (FIS) whose parameters of the MF are balanced utilizing a hybrid method which employs for changing the parameters of the MF which consist of back propagation for the parameters associated with the input MFs, and least squares estimation for the parameters associated with the output MFs [26].This enables the fuzzy logic to learn from the data they are modeling. Figure 6 presents the Helical Trajectory that tracked in 3D. This particular screens shot is taken when the Fuzzy-PID Control was utilized with the presence of wind disturbance.

6.1. Results without Impact of Wind Disturbances

In [18] The simulation is carried out to quadrotor controlled based several control techniques without impact of wind disturbance where, it was observed that ANFIS control provides the quadrotor with minimum error between desired and actual position for X, Y, Z respectively with minimum number of iteration= 51 epochs compared with PID controller tuned using GA. Also in [18] fuzzy self-tuning PID controller is applied to position and attitude control of the quadrotor.

The simulation results prove that using fuzzy self-tuning PID controller give minimum error compared to ANFIS and PID tuned using GA. Fuzzy supervisory attempt to change the parameters of the PID through process operation to enhance the response of the system. The gradient-based optimization process locates search orientation for an objective function minimization. This strategy can be utilized to minimize energy consumption in distributed environmental control systems while keep up a high inhabitant comfort level.

Based on the results in [27] it was found with required desired trajectory input that the model based on the FOPID controller tuned using GA without impact of disturbance give good results compared with the others controllers Where, GA reaches to the values of the 15 FOPID parameters after 46 epochs with fitness 0.404491.

- *Comparisons results between All controllers without impact of disturbance*

From the simulation results in [18], [27] it was observed that position and attitude control utilizing FOPID give a good results compared with position and attitude control utilizing PID tuned using GA, ANFIS and Fuzzy-PID in the absences of disturbances or parameters uncertainty as shown in “Table 1”.

From “Table1” position control using FOPID has better steady state error and RMS error than other controllers. By comparing steady state and RMS error in a system it was found that the FOPID errors (Steady State error for X position=-0.001838, Y =0.0002049, Z=-2.66*10^{-15} and RMS error=0.00012) than Fuzzy-PID’s errors (Steady State error for X position=0.0009089, Y = 0.001513, Z=-4.77*10^{-15} and RMS error=0.0008356), ANFIS’s errors (Steady State error for X=-0.007502, Y=-0.01316, Z=-2.44*10^{-15} and RMS error=0.005515), ANN errors (Steady State error for X position=-0.01478, Y =-0.01499, Z=0.0003591and RMS error= 0.007154) and PID's errors (Steady State error for X=-0.03367, Y=-0.06726, Z=6.217*10^{-15} and RMS error=-0.03367).

6.2. Results with Impact of wind Disturbances

The simulation has been performed for position (X, Y, Z) and attitude (Φ, θ, ψ) control of quadrotor with impact of disturbances. The disturbance is wind with velocity vector $V_\omega = 2\hat{}\, i + 2\hat{}\, j + 2\hat{}\, k$ m.s^{-1} is applied as a step input at time t = 25 s. Based on the results it was found with required desired position input that the model based on the Fuzzy-PID controller with impact of disturbance give good results and minimum overshoot compared with the others controllers PID tuned by GA, ANN, ANFIS and FOPID tuned by GA where this appear clearly at time 25s as shown in "Figs. 7, 8 and 9".

Table 1 The comparison results of PID, FOPID, ANN, ANFIS and Fuzzy-PID controllers Without Impact of Disturbances

Controller type	RMS error	S.S. error for X	S.S. error for Y	S.S. error for Z
PID tuned using GA	0.006957	-0.03367	-0.06726	6.217*10^{-15}
FOPID tuned using GA	0.00012	-0.001838	0.0002049	-2.66*10^{-15}
ANN	0.007154	-0.01478	-0.01499	0.0003591
ANFIS	0.005515	-0.007502	-0.01316	-2.44*10^{-15}
Fuzzy-PID	0.0008356	0.0009089	-0.001513	-4.77*10^{-15}

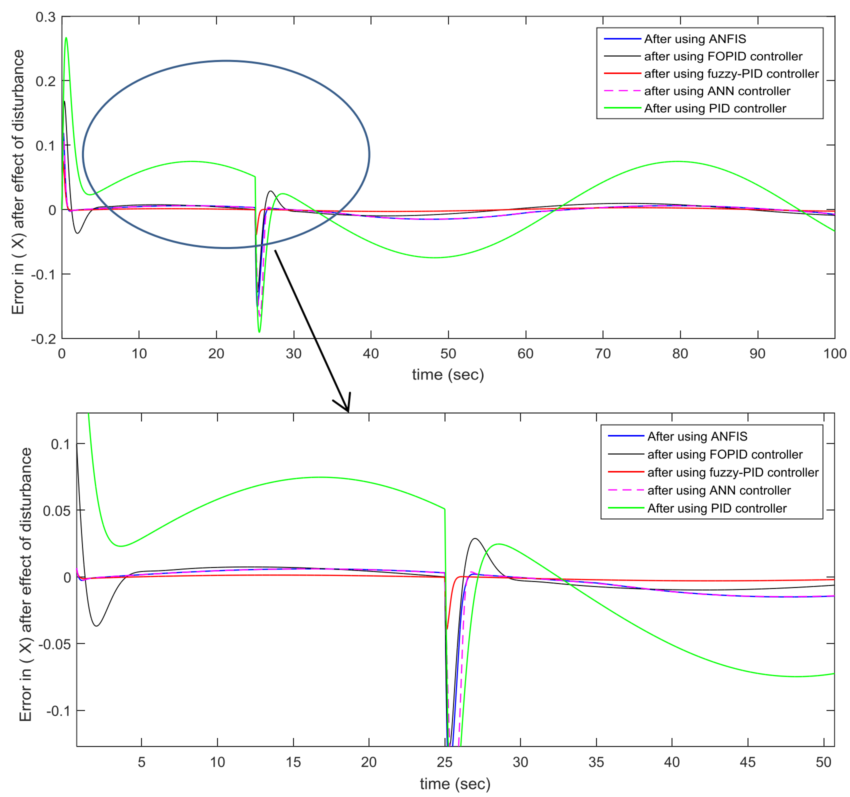

Fig. 7 Error in (X) [after impact of disturbance at 25s] using all controllers.

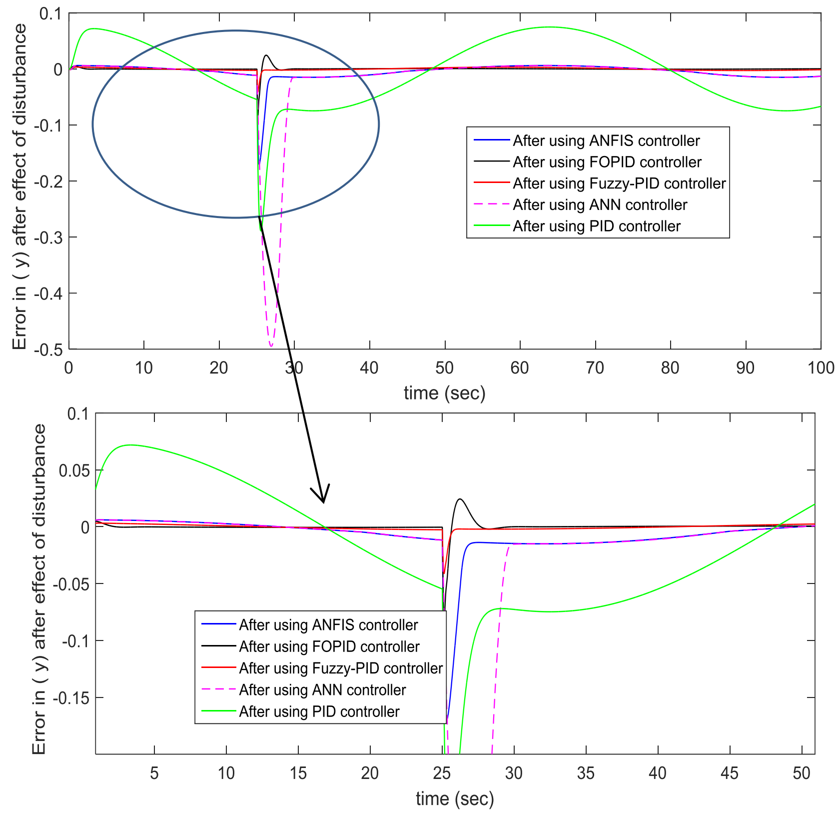

Fig. 8 Error in (Y) [after impact of disturbance at 25s] using all controllers.

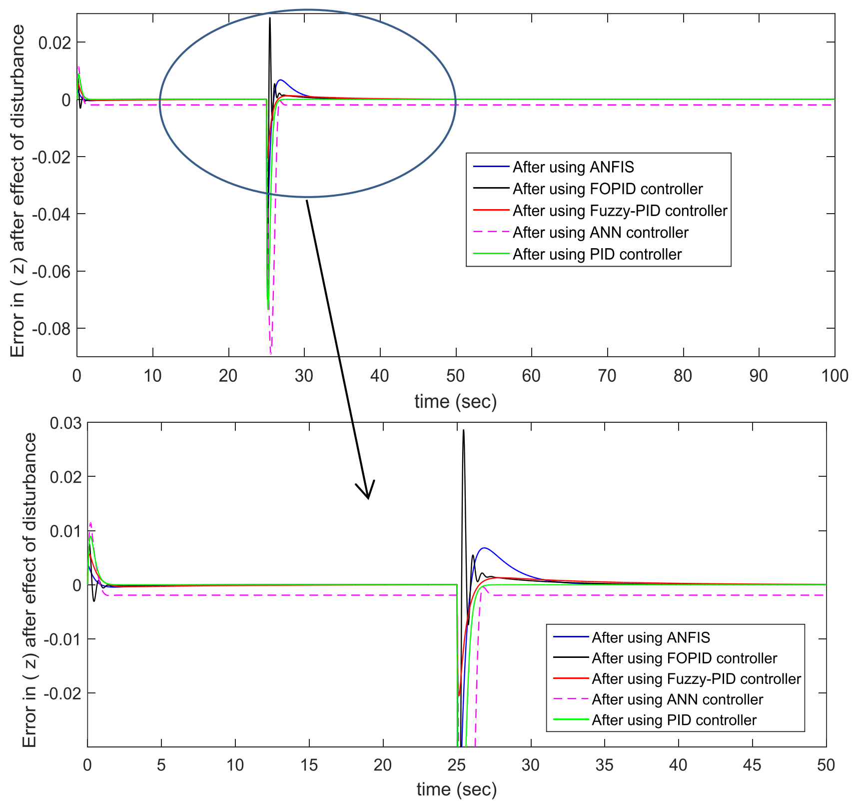

Fig. 9 Error in (Z) [after impact of disturbance at 25s] using all controllers.

Also attitude angles (roll (Φ) pitch (θ) yaw (ψ) angle) after impact of wind disturbance as a step input at time t = 25 s with velocity vector $V_{\omega} = 2\hat{i} + 2\hat{j} + 2\hat{k}$ m.s^{-1} based on simulation results it was observed that Fuzzy-PID has fast response, small errors and minimum overshoot for the required orientation than controlled based on PID tuned by GA, ANN, ANFIS and FOPID tuned by GA where this appear clearly at time 25s as shown in “Figs. 10, 11 and 12”.

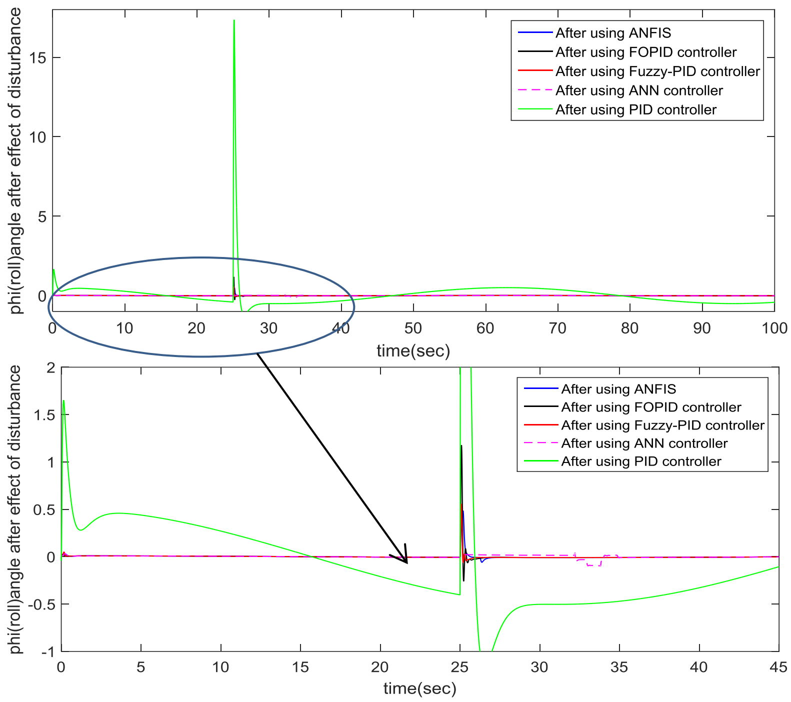

Fig. 10 Phi (roll) angle [after impact of disturbance at 25s] using all controllers.

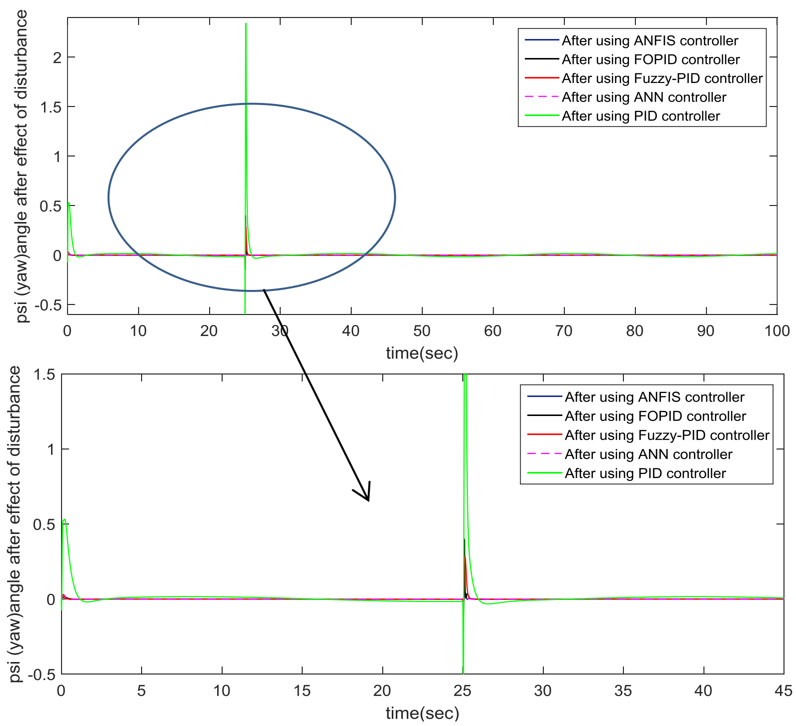

Fig. 11 psi (yaw) angle [after impact of disturbance at 25s] using all controllers.

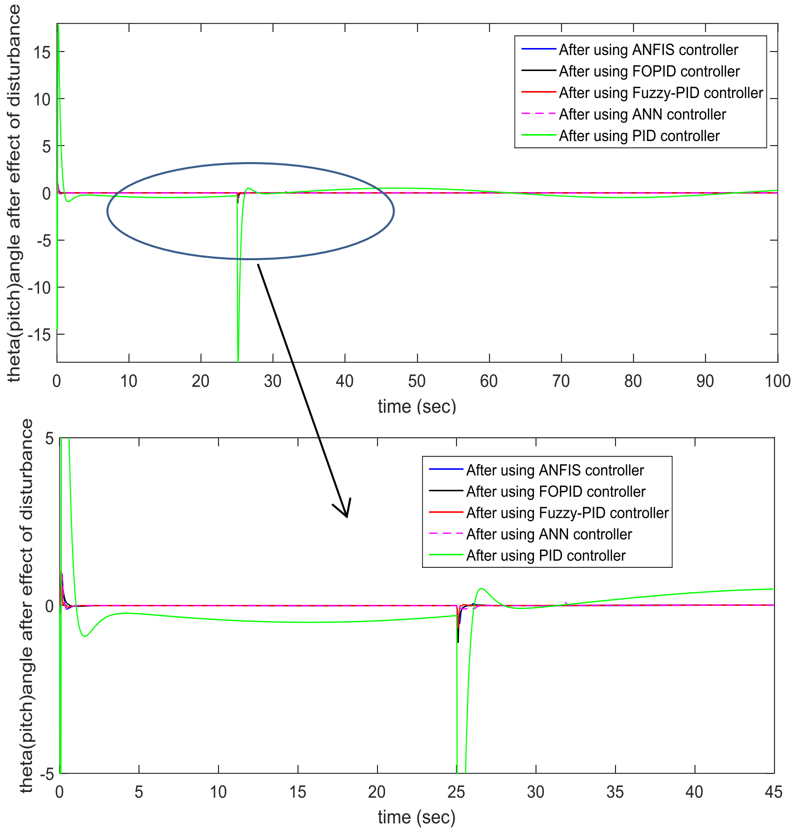

Fig. 12 Theta (pitch) angle [after impact of disturbance at 25s] using all controllers.

- ***Comparisons results between All controllers with impact of disturbance***

From the simulation results it was observed that position and attitude control utilizing Fuzzy-PID give a good results compared with position and attitude control utilizing PID tuned using GA, ANN, ANFIS and FOPID tuned using GA with impact of wind disturbances as a step input at time t = 25 s with velocity vector $V_\omega = 2\hat{}\ i + 2\hat{}\ j + 2\hat{}\ k$ m.s^{-1} is as shown in “Table 1”.
From “Table 2” position and attitude control using Fuzzy-PID has fast response with minimum overshoot, better steady state error and RMS error than other controllers.
By comparing steady state and RMS error as appeared in “Figs. 7, 8 and 9” it was found that the Fuzzy-PID errors (Steady State error for X position=-0.0001481, Y =0.002849, Z=0.001295 and RMS error=0.0029)give good results than FOPID’s errors (Steady State error for X position=0.0007373, Y = 0.004493, Z= 0.002982 and RMS error=0.008891), ANFIS’s errors (Steady State error for X=0.002028, Y=0.01551, Z= 0.0027 and RMS error=0.006971), ANN errors (Steady State error for X position=0.002321, Y =0.07025, Z=0.00721and RMS error= 0.01531) and PID’s errors (Steady State error for X=0.07419, Y=0.0607, Z=0.004494and RMS error=0.0943). Fuzzy-PID controller has fast response and small errors for the required position of quad rotor after impact of disturbance.
Also by comparing overshoot after impact of disturbances at t= 25 as appeared in “Figs. 7, 8 and 9” it was found that the Fuzzy-PID give minimum overshoot (for X position =-0.03911, Y=-0.04129 and Z= -0.02054) than FOPID’s overshoot (for X position=-0.1282, Y =-0.08315, Z=-0.02054), ANFIS’s overshoot (for X=-0.1509, Y=-0.1701, Z=-0.051), ANN overshoot (for X position=-0.1659, Y =-0.4949, Z=-0.08907) and PID’s overshoot (for X=-0.1904, Y=-0.289, Z=-0.07361). Fuzzy-PID controller has minimum overshoot of quadrotor after impact of disturbance.

Table 2 The comparison results of PID, FOPID, ANN, ANFIS and Fuzzy-PID controllers after Impact of wind Disturbances

Controller type	RMS error	S.S.E for X	Overshoot for X	S.S.E for Y	Overshoot for Y	S.S.E for Z	Overshoot for Z
PID tuned using GA	0.0943	0.07419	-0.1904	0.0607	-0.289	0.00449	-0.07361
FOPID tuned using GA	0.008891	0.000737	-0.1282	0.004493	-0.08315	0.00298	-0.06976
ANN	0.01531	0.002321	-0.1659	0.07025	-0.4949	0.00721	-0.08907
ANFIS	0.006971	0.002028	-0.1509	0.01551	-0.1701	0.0027	-0.051
Fuzzy-PID	0.0029	0.000148	-0.03911	0.002849	-0.04129	0.00129	-0.02054

7 CONCLUSION

In this work, different control techniques have been used to position and attitude control of quadrotor with impact of wind disturbance in order to achieve the required position with fast response, minimum error and disturbances rejection. The performance of each of the controllers based control strategy was compared with that of the others controllers through carrying out several simulations results of the quadrotor with impact of wind disturbance using SIMULINK under MATLAB2015a. From the simulation results it was concluded that:

- These results appear that position and attitude control based FOPID controller has performed a response of better, fast, and smaller errors for desired position control for the X, Y and Z of quadrotor than the other controllers without any impact of wind disturbance.
- By simulation results it was observed that position and attitude control based Fuzzy-PID controller performance is better than the other controllers for the external disturbance rejection.
- ANFIS converges with a smaller number of iteration steps with the hybrid learning algorithm compared with PID controller tuned by GA.
- The fast convergence of learning enables the proposed Fuzzy-PID controller to adaptively adjust the parameters and keep the tracking error at a low level in spite of external disturbances and uncertain conditions.

APPENDIX

Table 3 List of abbreviations and symbols

Abbreviations and Symbols	Definition
PID GA	Proportional Integral Derivative Genetic Algorithm
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro Fuzzy Inference System
MF	Membership Functions
FOPID	Fractional Order PID
FOC	Fractional Order Calculus
RMS	Root mean square error
ISE	Integral square error
VTOL	Vertical Take Off and Landing
FIS	Fuzzy Inference Systems
V_ω	velocity vector
k_p	Proportional gain
K_v	Derivative gain
K_i	Integral gain
μ	differentiator order
λ	integrator order
$\mathbf{e_p}$ and $\mathbf{e_v}$	Errors in position and velocity respectively
S.S. E	Steady State Error
GUI	Graphical user interface

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