DESIGN NEUROFUZZY WITH PID CONTROLLERS FOR AN AUTONOMOUS MINI-HELICOPTER SYSTEM

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Abstract

In this paper a combining Neurofuzzy and PID controllers have been employed for controlling the positions and rotational motions of the mini-helicopter system. Due to the strong coupling between the state variables of the mini-helicopter model, therefore, it is not suitable to design single controller for regulating the positions and rotational motions of the given model. To solve this problem, three neurofuzzy controllers are designed for the lateral, longitudinal and heave motion; and three classical PID controllers are proposed for attitude control. Nine rules are suggested for each neurofuzzy network depends on the previous knowledge/experiences of expert human pilot. The simulation results show that the proposed controllers are very effective to control the hovering, position and forward flight of the mini-helicopter system.

Keywords: Mini-helicopter Model, Autonomous Control, Neurofuzzy Controller, PID Controller.

تصميم منظومة تحكم من نوع الشبكات العصبية المضببة مع منظومة الكسب- التكاملي – التفاضلي للسيطرة على الطائرة المروحية ذاتية التحكم

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الخلاصة

في هذا البحث تم تصميم منظومة تحكم من نوع الشبكات العصبية المضببة مع منظومة الكسب–التكاملي– التفاضلي للسيطرة على الحركات الدورانية و الخطية للطائرة المروحية ذاتية التحكم. بسبب الترابط الوثيق ما بين متغيرات الحالة التي تصف منظومة الطائرة المروحية, لذا اصبح من الغير الممكن من تصميم منظومة تحكم واحدة للسيطرة على كل الحركات الخاصة بطائرة المروحية (الحركة العامودية والحركة الافقية والحركة الدورانية). ولحل هذة المشكلة تم تصميم منظومة تحكم من نوع الشبكات العصبية المضببة للسيطرة على المتغيرات السريعة مثل الحركة الجانيية والحركة الافقية. اما الحركات البطيئة مثل الارتفاع للاعلى فتم السيطرة عليه باستخدام منظومة تحكم من نوع الكسب– التكاملي– التفاضلي. بينت النتائج المستحصلة كفائة وقوة المنظومة المقترحة للسيطرة على حركة الطائرة المروحية.

1. Introduction

Unmanned helicopters have two types: a single rotor helicopter and a coaxial rotor helicopter. The weight of the single rotor helicopter is between 1 kg to 50 kg, while, the weight of the second type is more than 50kg to 500kg. The mini-helicopter model is highly nonlinear system and it has strong coupling between its state variables. Therefore, very accurate intelligent control should be design to set the desired positions and rotational motions of the helicopter. Like the aircraft control, the helicopter control is accomplished primarily by producing moments about all three aircraft axes: roll, pitch and yaw motion [1-4].

Some publications study the design of intelligent and hybrid controller for aircrafts and autonomous helicopters. Three different control methodologies for helicopter autopilot were designed: linear robust multivariable control, fuzzy logic control with evolutionary tuning, and nonlinear tracking control [5]. Two degree of freedom fuzzy model uses associative memories organizing units system was employed to design the control system for a small four-propeller flying vehicle (similar to a helicopter) [6]. A fuzzy-logic-based control system has been developed that enables single inputs (e.g. voice commands) to replace the aircraft's normal set of rudder, collective, longitudinal cyclic and lateral cyclic control inputs [7]. Combining fuzzy, PID and regulation control system was proposed to design a controller for X-Cell mini-helicopter [8]. Learning algorithm such as genetic algorithm is used to discover the rules of fuzzy logic system to design intelligent control for helicopter [9, 10].

The PID controllers are widely being used in the industries for process control applications. Even for complex industrial control system, the industries use the PID control module to build the main controller. The merit of using PID controllers lie in its simplicity of design and good performance including low percentage overshoot and small settling time for normal industrial processes. The main disadvantage of using PID controller is that the conventional PID controllers are fixed gains (not adaptive controllers); therefore, they are very sensitive to external disturbances, parameters variations and system nonlinearity. For those reasons, the researchers suggested adaptive controllers for nonlinear systems which do not need the exact mathematical model of the systems [11, 12]. As result, another intelligent system should be combined with the PID controller to improve the dynamic response, regulation precision and robustness of the closed-loop system.

In this paper, a combining Neurofuzzy and PID controller has been proposed for controlling the hovering, position and forward flight of the mini-helicopter system. Three neurofuzzy controllers are designed for the lateral, longitudinal and heave motion; and three classical PID controllers are proposed for attitude control. Nine rules are suggested for each neurofuzzy network depends on the previous knowledge/experiences of expert human pilot. The trial and error technique is used to tune the parameters of PID controllers.

The paper is organized as follows: Section 2 presents the nonlinear dynamic model of mini-helicopter system. In section 3, the structure of the Grid Adaptive Neurofuzzy Inference System (GANFIS) is described. In section 4, the design of GANFIS controller combined with PID controller is proposed. In section 5, numerical simulations are made to study the validation of the proposed controller for controlling the mini-helicopter. Finally, the conclusion is summarized in section 6.

2. Dynamic Model for Unmanned Mini-helicopter

The Newton-Euler equations are used to derive the rigid body equations of motion for a mini-helicopter as shown below. Here the cross products of inertia are neglected [13].

$$\dot{u} = vr - wq - gsin\theta + \frac{(X_{mr} + X_{fus})}{m} \quad (1)$$

$$\dot{v} = wp - ur + gsin\phi cos\theta + \frac{(Y_{mr} + Y_{fus} + Y_{tr} + Y_{uf})}{m} \quad (2)$$

$$\dot{w} = uq - vp + gcos\psi cos\theta + \frac{(Z_{mr} + Z_{fus} + Z_{ht})}{m} \quad (3)$$

$$\dot{p} = qr\frac{(I_{yy} - I_{zz})}{I_{xx}} + \frac{(L_{mr} + L_{vf} + L_{tr})}{I_{xx}} \quad (4)$$

$$\dot{q} = pr\frac{(I_{zz} - I_{xx})}{I_{yy}} + \frac{(M_{mr} + M_{ht})}{I_{yy}} \quad (5)$$

$$\dot{r} = pq\frac{(I_{xx} - I_{yy})}{I_{zz}} + \frac{(-Q_e + N_{vf} + N_{tr})}{I_{zz}} \quad (6)$$

For simplification, the following assumptions are assumed

- $X = (X_{mr} + X_{fus})$
- $Y = Y_{mr} + Y_{fus} + Y_{tr} + Y_{uf}$
- $Z = Z_{mr} + Z_{fus} + Z_{ht}$
- $L = L_{mr} + L_{vf} + L_{tr}$
- $M = M_{mr} + M_{ht}$
- $N = -Q_e + N_{vf} + N_{tr}$

where (u, v, w) are vehicle velocities in body axes (p, q, r) are vehicle angular rate in body axes, (ϕ, θ, ψ) are Euler angles (roll ,pitch and yaw), (X, Y, Z) are external forces acting at the vehicle centre of gravity , I_{xx} is pitching moment of inertia, I_{yy} is rolling moment of inertia, I_{zz} is yawing moment of inertia , m helicopter mass and Q_e is the torque produced by the engine to counteract the aerodynamic torque on the main rotor blades.

The set of forces and moments acting on the helicopter are organized by components: $( )_{mr}$ for the main rotor; $( )_{tr}$ for the tail rotor; $( )_{fus}$ for the fuselage (includes fuselage aerodynamic effects); $( )_{vf}$ for the vertical fine and $( )_{ht}$ for the horizontal stabilizer. Figure 1 shows the forces and moments action on the mini-helicopter system.

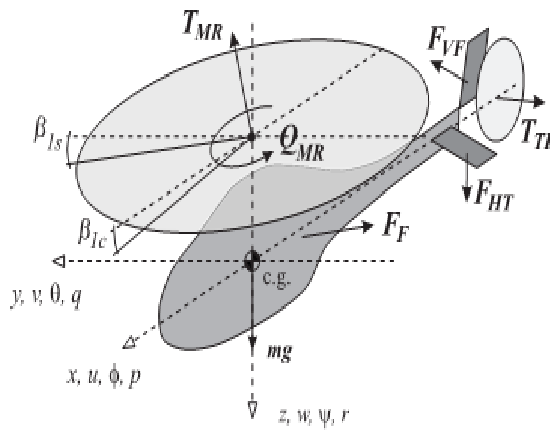

Figure 1 Moments and forces action on helicopter system

Solving the differential equations above, the Euler angles can be calculated from angular rate as:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & tan\theta sin\phi & tan\theta sin\phi\\ 0 & cos\phi & -sin\phi\\ 0 & \frac{sin\phi}{cos\theta} & \frac{cos\phi}{cos\theta}\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (7)$$

Higher-order effects are taken into account to improve the rigid-body model accuracy. These extensions are: rotor dynamics, engine-drive train and actuators dynamics.

The coupled rotor and stabilizer bar equations are lumped into one first-order equation of motion. This procedure is done for both lateral and longitudinal tip-path-plane flapping. The equations are expressed as follows:

$$\dot{b}_1 = -\frac{b_1}{\tau_e} - p + \frac{1}{\tau_e} 2k_\mu \left(\frac{4\delta_{col}}{3} - \lambda_0\right) \frac{v - v_w}{\Omega_{mr} R_{mr}} + \frac{\beta_{\delta_{lat}}}{\tau_e} \delta_{lat} \quad (8)$$

$$\dot{a}_1 = -\frac{a_1}{\tau_e} - q + \frac{1}{\tau_e} k_\mu \left(\frac{4\delta_{col}}{3} - \lambda_0\right) \frac{u - u_w}{\Omega_{mr} R_{mr}} + \frac{1}{\tau_e} \frac{16\mu_{mr}^2}{8\mu_{mr} + a_{mr}\sigma_{mr}} sign\mu_{mr} \frac{w - w_w}{\Omega_{mr} R_{mr}} + \frac{A_{\delta_{lon}}}{\tau_e} \delta_{lon} \quad (9)$$

where $\lambda_0, \mu_{mr}, A_{\delta_{lon}}, \beta_{\delta_{lat}}, \tau_e$ are main rotor variables, $R_{mr}, k_\mu, a_{mr}, \sigma_{mr}$ are main rotor parameters,Ω_{mr} main rotor angular speed and (v_w, u_w, w_w) are wind velocities in body axes.

3. Grid Adaptive Neurofuzzy Inference System Architecture

A neurofuzzy model combines the features of a neural network and fuzzy logic model. A large class of neuro-fuzzy approaches utilizes the neural network learning algorithms to determine parameters of the fuzzy logic system[14] . The neuro-fuzzy system is more efficient and more powerful than either neural network or fuzzy logic system [15] which has been widely used in control systems, pattern recognition, medicine, expert system, etc. [16].

The ANFIS network, as its name suggests, is an adaptive neuro-fuzzy inference machine. Like "pure" (i.e. non-fuzzy) artificial neural networks or classic fuzzy systems, it works as a universal approximator [17]. Its purpose is to approximate or “learn” simple or complicated mappings (i.e. nonlinear functions) from an input space (usually multivariate) to a univariate or multivariate output space.

The ANFIS has three types: Grid ANFIS, Scatter ANFIS and ART ANFIS. See [17] for more details.

In this work, the Grid ANFIS is selected to design the controller for the mini-helicopter. The structure of the GANFIS is shown in Figure 2. The system shown in Figure 2 consists of five layers and it has two inputs, one output and nine rules. The square nodes (adaptive nodes) have adaptable parameters (premise parameters and consequent parameters) while circle nodes (fixe nodes) have non-adaptable parameters.

The operation of each layers are describe briefly in the following lines:

Layer 1: Every node i in this layer is a square node with a node function

$$\mathrm{Out}_i^{(1)} = \mu_j\left(\mathrm{In}_i^{(1)}\right) \quad (10)$$

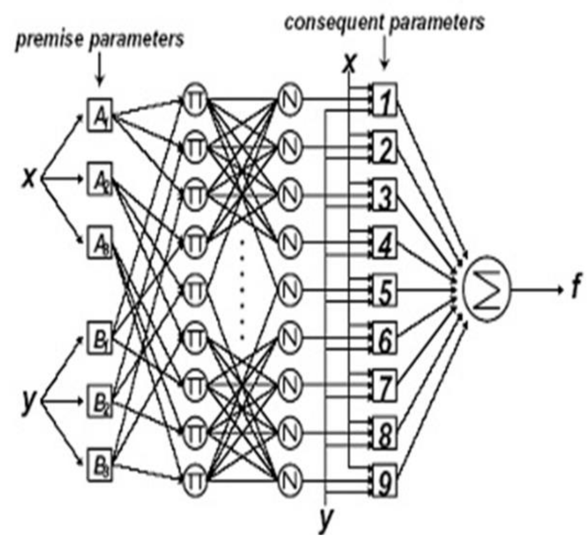

Figure 2 GANFIS architecture for a two input Sugeno fuzzy model with nine rules

where $\mathrm{In}_i^{(1)}$ is the input of layer to the node *i* (*x* or *y*).

$\mu_j\left(In_i^{(1)}\right)$ has been chosen as generalized Gaussian Function:

$$\mu_j\left(In_i^{(1)}\right) = \frac{1}{1 + \left|\frac{In_i^{(1)} - C_{ij}}{a_{ij}}\right|^{b_{ij}}} \tag{11}$$

where $\{a_{ij}, b_{ij}, c_{ij}\}$ are the parameters of membership function (they are called premise parameters) which will be modified in the training phase using backpropagation algorithm.

***Layer 2*:** Every node in this layer is a circle node (have non-adaptable parameters) labelled *Π* which multiplies the incoming signals. The output of each node in this layer can be written as:

$$Out_j^{(2)} = w_j = \prod_{i=1}^{N_{Inputs}} \mu_j\left(In_i^{(1)}\right) \tag{12}$$

where N_{Inputs} the number of input variables.

Layer 3: Every node in this layer is a circle node labelled *N*. the output of j^{th} node is the normalized of the j^{th} rule's firing strength. The output of any node in this layer can be given as:

$$Out_j^{(3)} = \bar{w}_j = \frac{Out_j^{(2)}}{\sum_{m=1}^{N_{Rules}} Out_m^{(2)}} \tag{13}$$

where N_{Rules} number of the rules.

Layer 4: Every node in this layer is square node with linear function

$$f_j = a_{1j} In_1^{(1)} + a_{2j} In_2^{(1)} + \cdots + a_{N_{Inputs}j} In_{N_{Inputs}}^{(1)} + a_{0j}$$

where $\{a_{1j}, a_{2j}, \ldots, a_{0j}\}$ is the set parameters of linear equation (they are called consequent parameters) which will be modified in the training phase using least square estimate algorithm. The output of any node in this layer can be written as:

$$Out_j^{(4)} = \bar{w}_j f_j \tag{14}$$

Layer 5: The node in this layer is circle nod labelled *Σ* that compute the overall output as the summation of all incoming signals

$$Out^{(5)} = \sum_{j=1}^{N_{Rules}} Out_j^{(4)} = \sum_{j=1}^{N_{Rules}} \bar{w}_j f_j \tag{15}$$

The adaptable parameters of GANFIS (premise parameters and consequent parameters) should be modified to minimize the following performance function:

$$E = \sum_{p=1}^{P} E_p \tag{16}$$

where *P* is the total number of training data set and E_p the error signal between the desired output of p^{th} data and the actual output of GANFIS model of p^{th} data, E_p can be given as

$$E_p = T_p - z_p \tag{17}$$

where T_p the p^{th} desired output and z_p the p^{th} actual output of the GANFIS model.

To modify the parameters of the GANFIS model, the backpropagation algorithm as in neural network can be applied to modify the premise parameters and least square estimate algorithm can be applied to adapt the consequent parameters (see [18] for more details).

4. The Design of GANFIS Controller Combined with PID Controller for Mini-helicopter

The mini-helicopter has fourteen variables some of them are faster dynamic variables (θ, ϕ, ψ, z) and the other are slower dynamic variables (x, y). Therefore, the proposed control system should have two control loops [8]. The inner loop controls the faster dynamic variables, while the outer loop controls the slower dynamic variables. Figure 3 shows the general control structure for mini-helicopter.

The proposed controller for the mini-helicopter content two control groups as shown in Figure 4. The first group consists of three GANFIS controllers to control the helicopter position in the navigation axes (i.e. x, y and z).

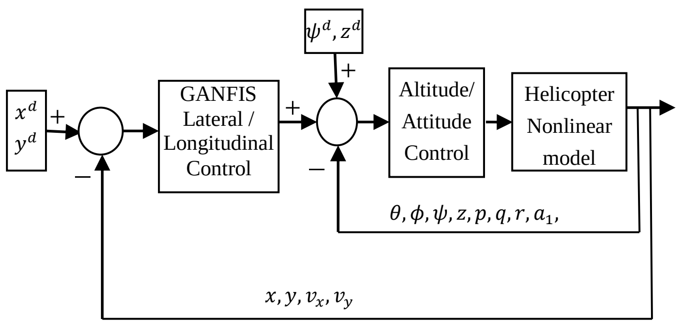

Figure 3 General Control Structure for Mini-helicopter

Each GANFIS controller has two inputs single output. Nine fuzzy rules are proposed for each controller. The inputs of the first GANFIS are e_z $(z_d - z)$ and v_z, where z_d is the desired heave position of the helicopter, and the output of this controller is the main rotor collective control input (δ_{col}). Three triangular membership functions are assumed for each input to represent the input of fuzzy rules: negative, zero and positive. While nine triangular membership functions are assumed for the output of fuzzy rules: biggest positive (Best_Pos), big positive (B_Pos), small positive (S_Pos), smallest positive (Sest_Pos), zero, biggest negative (Best_Neg), big negative (B_Neg), small negative (S_Neg) and smallest negative (Sest_Neg).

The nine rules of the first GANFIS controller are shown in Table 1:

Table 1 The rules of the first GANFIS controller

δ_{col}		v_z		
		Neg	Zero	Pos
e_z	Neg	$Best\_Pos$	$Sest\_Pos$	S_Nag
	Zero	B_Pos	$Zero$	B_Nag
	Pos	S_Pos	$Sest\_Nag$	$Best\_Nag$

The inputs of the second GANFIS controller are e_y $(y_d - y)$ and v_y, where y_d is the desired y-position of the helicopter, the output of this controller is the desired roll angle, ϕ_d. The nine rules of the second GANFIS controller are in Table 2 [8]:

Table 2 The rules of the second GANFIS controller

ϕ_d		v_y		
		Neg	Zero	Pos
e_y	Neg	$Best\_Pos$	$Sest\_Pos$	S_Nag
	Zero	B_Pos	$Zero$	B_Nag
	Pos	S_Pos	$Sest\_Nag$	$Best\_Nag$

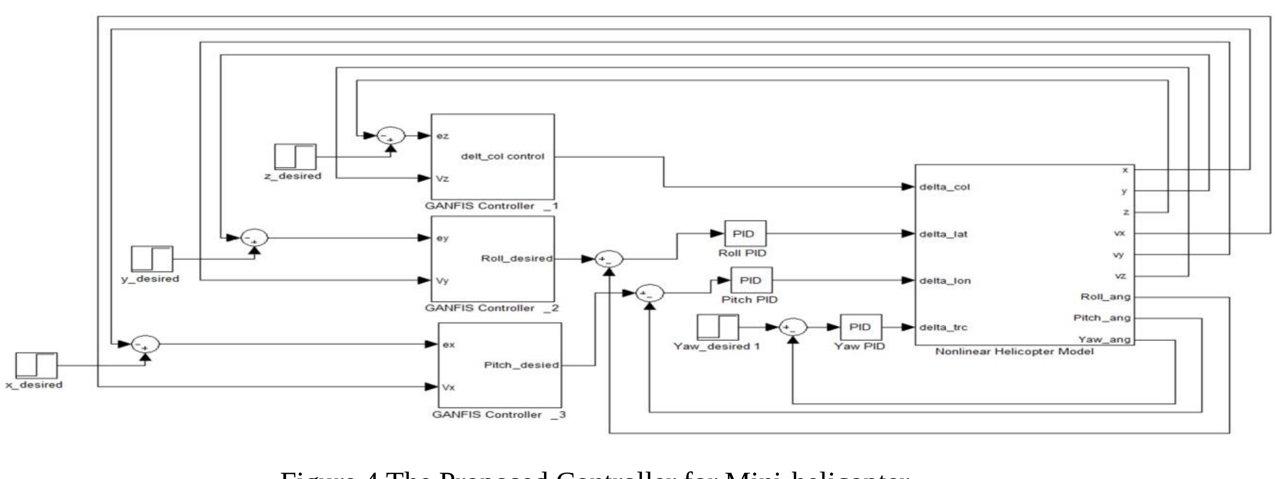

Figure 4 The Proposed Controller for Mini-helicopter

The inputs of the third GANFIS controller are e_x $(x_d - x)$ and v_x, where x_d is the desired x-position of the helicopter, the output controller is the desired pitch angle, θ_d. The nine rules of the third GANFIS controller are given in Table 3 [8].

Table 3 The rules of the third GANFIS controller

θ_d		v_x		
		Neg	Zero	Pos
e_x	Neg	$Best\_Pos$	$Sest\_Pos$	S_Nag
	Zero	B_Pos	$Zero$	B_Nag
	Pos	S_Pos	$Sest\_Nag$	$Best\_Nag$

The second group of the proposed controller is PID controllers. It has three PID controllers. The input of first PID controller is difference between the desire roll angle ϕ_d (the output of the second GANFIS controller) and measured roll angle of mini-helicopter. The output of this controller is lateral cyclic control input δ_{lat}. The input of second PID controller is difference between the desire pitch angle θ_d (the output of the third GANFIS controller) and measured pitch angle of mini-helicopter. The output of this controller is longitudinal cyclic control input δ_{lon}. The input of third PID controller is difference between the desire yaw angle ψ_d and measured yaw angle of mini-helicopter. The output of this controller is tail rotor collective control input δ_{trc}.

5. Simulation and Results

The GANFIS with PID controller is employed for controlling the positions and rotational motions of the mini-helicopter. The proposed controller is simulated by MATLAB Simulink software package. The physical helicopter parameters used for the simulation the mathematical model are given in Table 4 [13].

The inputs and state of simulation model are the following:

$U = [\delta_{col}\ \ \delta_{lon}\ \ \delta_{lat}\ \ \delta_{trc}]^T$

$X_{state} = [u\ v\ w\ p\ q\ r, \phi, \theta, \psi, x, y, z, a_1, b_1, \Omega]^T$

The mini-helicopter is an eight-degree-of-freedom system: three linear velocities (*u*, *v*, *w*), three angular movements (*p*, *q*, *r*) and two main rotor flapping angles (a_1, b_1). The rigid-body dynamics of such vehicles are described by the Newton-Euler equations of motion.

The reference functions of $(x_d, y_d, z_d\ and\ \psi_d)$, which are shown in Figure 4, are assumed as a square function with different level for each time period. The parameters of the PID controllers that used in this simulation are selected using trial and error. The obtained parameters of PID controllers are shown in Table 5.

Table 4 Parameters of MIT Instrumented X-Cell 60 SE Helicopter

Parameters	Description
m=8.2 kg	Helicopter mass
$I_{xx} = 0.18\ kgm^2$	Pitching moment of inertia
$I_{yy} = 0.34\ kgm^2$	Rolling moment of inertia
$I_{zz} = 0.28\ kgm^2$	Yawing moment of inertia
$\tau_e = 0.1\ sec$	Main rotor variables
$B_{\delta_{lat}} = 4.2$	
$A_{\delta_{lon}} = 4.2$	
$\lambda_0 = 0.8$	
$\mu_{mr} = 0.024$	
$k_\mu = 0.2$	Main rotor parameters
R_{mr}=0.7775	
$a_{mr} = 5.5\ rad^{-1}$	
$\sigma_{mr} = 0.029\ m$	
$\Omega_{mr} = 167\ rad/s$	Main rotor angular speed
$v_w = 0.7\ m/sec$	Wind velocities in body axes
$u_w = 0.22\ m/sec$	
$w_w = 0\ m/sec$	

Table 5 The parameters of PID Controllers

PID Controller	K_p	K_i	K_d
Pitch	50	3	20
Roll	50	5	10
Yaw	70	4	25

Figures 5-7 show the inertial position for square tracking in x-position, y-position and z-position, respectively. It is clear that the proposed controllers have good performance to track the desired positions of the mini-helicopter.

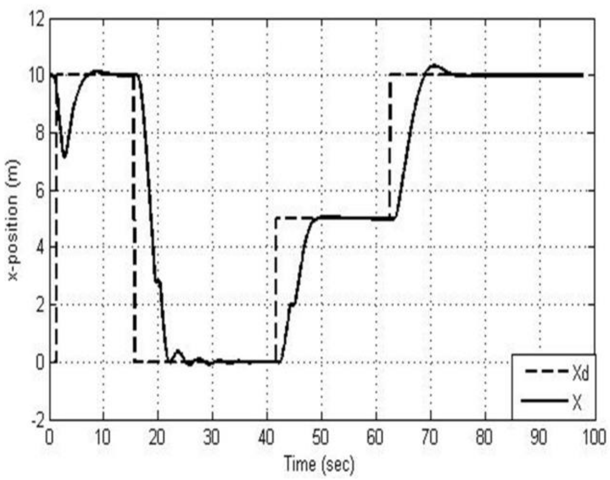

Figure 5 Signal tracking for x-position

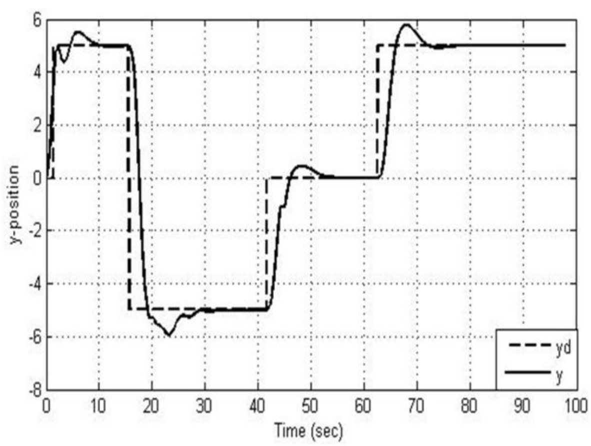

Figure 6 Signal tracking for y-position

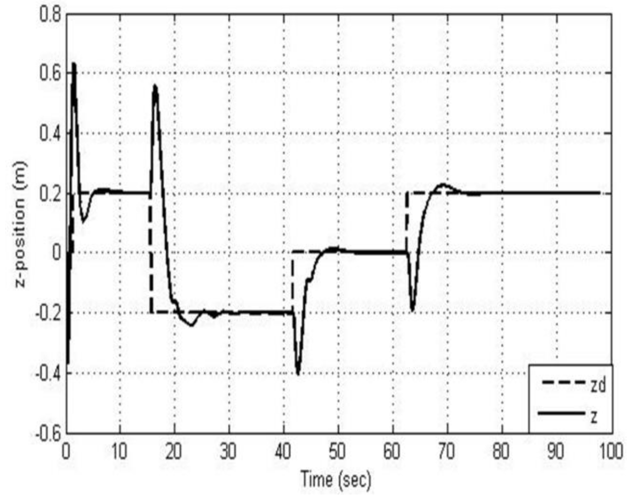

Figure 7 Signal tracking for z-position

Figures 8-10 show the roll angle response, pitch angle response and yaw angle response for the pervious tracking condition, respectively.
It is clear that the performance of the proposed controller are very effective. The results show that when the neurofuzzy with PID controller is used, the desired control objectives are met.
Figures 11-14 show the control inputs for the pervious tracking condition. Each input follows a square to maintain the desired positions.

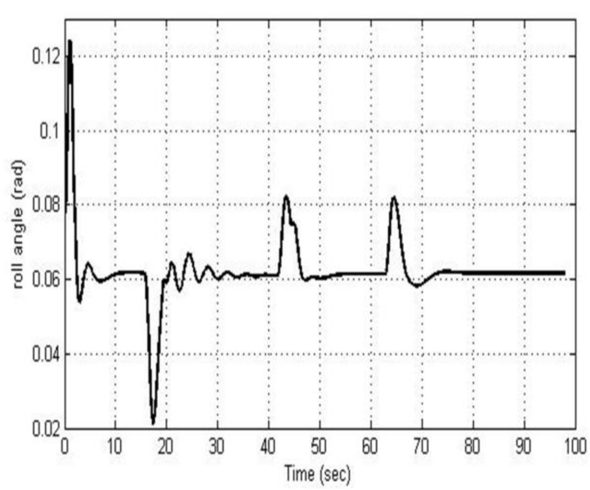

Figure 8 Roll angle response

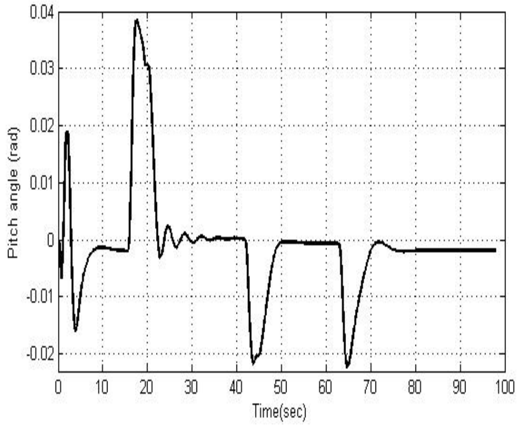

Figure 9 Pitch angle response

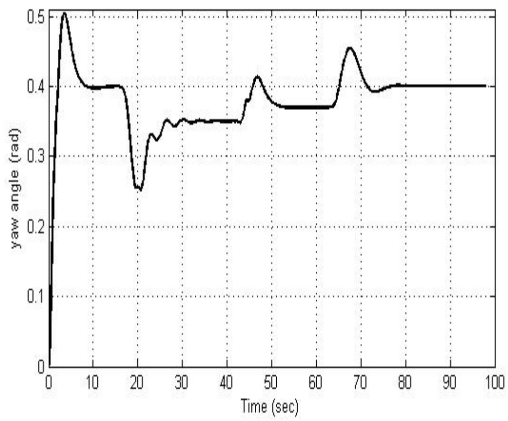

Figure 10 Yaw angle response

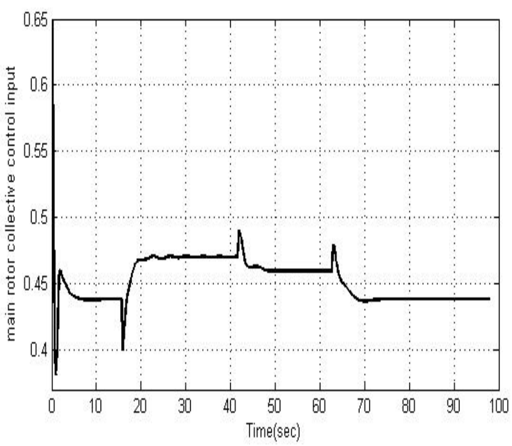

Figure 11 Main rotor collective control input

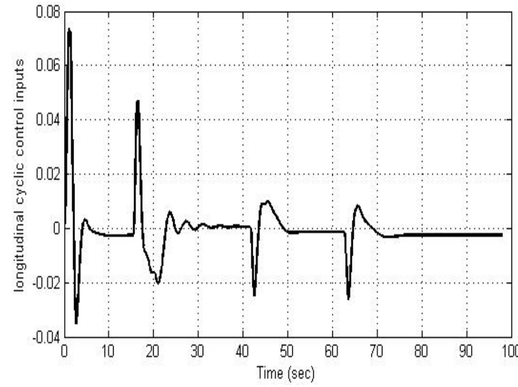

Figure 12 longitudinal cyclic control input

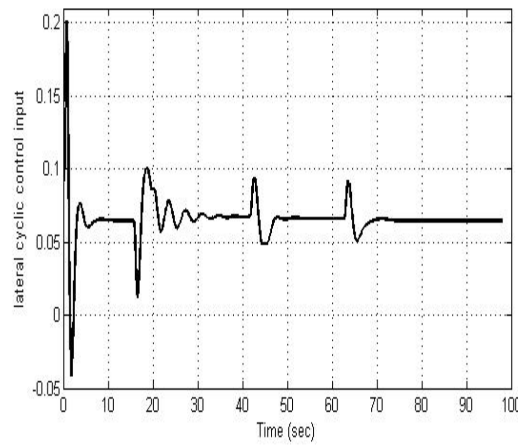

Figure 13 Lateral cyclic control input

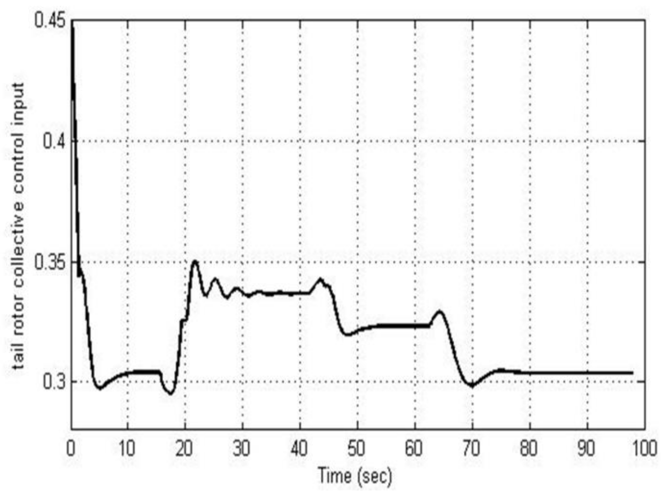

Figure 14 Tail rotor collective control input

From above figures, it can see that the proposed controllers generate a suitable control signals which force the outputs of the mini-helicopter to track the desired signals. In other words, the proposed controllers are very effective to control the hovering, position and forward flight of the mini-helicopter system.

6. Conclusion

The GANFIS with PID controllers are proposed in this paper for controlling the positions and rotational motions of the mini-helicopter. The rules of fuzzy system are modified using backpropagation algorithm to improve the performances of the proposed controller. Simulation results show that the positions and Euler angles are tracked the desired set points by applying the control signals ($\delta_{col}, \delta_{lon}, \delta_{lat}$ and δ_{trc}) as input to nonlinear helicopter model to change the speed and direction of main rotor blades and the tail rotor blades as well. When the proposed controller is applied, all transient response specification such as: maximum overshoot, settling time delay time, rise time and peak time have been minimized. It means the GANFIS combined with PID controllers can be used effectively to implement the control system for nonlinear helicopter system. Therefore, the hovering, position and forward flight of the mini-helicopter system are improved.

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