Adaptive Nonlinear Controller for Quadrotor Altitude Control with Online Control Coefficients Function

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ABSTRACT:
In this paper, an adaptive controller is presented to control a quadrotor, whose parameters are extracted from the genetic algorithm optimization method. The advantage of this method is that based on the system states, the control coefficients are calculated online. For this purpose, a function between system states-space and control coefficients is obtained. From the database collected from the genetic algorithm optimization method, the parameters of the control coefficient function are obtained using the least squares method. The stability of the proposed controller is proved by the Lyapunov method. Finally, the performance of the proposed controller is compared with the PID controller, which is widely used in the literature. The results show that the proposed approach is promising.
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KEYWORDS: Quadrotor, Nonlinear Control, Lyapunov Stability, Genetic Algorithm, Gain Tuning.

1. INTRODUCTION

In the recent decade, due to the general approach of using small drones, especially quadrotors, many researchers have proposed numerous methods to control and stabilize the quadrotor. Quadrotors have various promising application fields: civil engineering, military applications, industrial applications, and the service field. These robots are also available and have high reliability.

A quadrotor configuration can be positive or cross to control yaw, pitch, and yaw angles, depending on how the rotors are paired. In both forms, one pair rotates clockwise and the other counterclockwise (Fig. 1). By increasing or decreasing the RPM of pairs or all engines together, the attitude or altitude of the robot can be changed, respectively. Since the number of inputs (four inputs) is less than the number of outputs (six outputs) in the flying robots, they are under-actuated systems [1].

The motion equations of the quadrotor have complex nonlinear 6-DOF equations. Therefore, many variety control solutions have been proposed for the underactuated nonlinear quadrotor. In the category of linear controllers for the quadrotor, the use of PID controllers and LQR controllers is presented in [2-3]. The combination of PI and PID controller controls the position and altitude in [4]. In this paper, the PI controller is used to control the horizon plane, and the PID controller is used to control the angles. LQR controller and backstepping control methods have been used to control and stabilize angles in hover mode in [5]. Since these controllers are designed for the linear model, they cannot be used globally. Therefore, in nonlinear systems, this problem has been solved by dividing the system into several modes and using different control coefficients in each mode [6]. The problem with this method is the stability and performance of the controller in changing modes. Therefore, according to the nonlinear dynamic model of the quadrotor, nonlinear control methods such as robust controller, adaptive control approach, and sliding mode strategy are more suitable for this system. In the category of nonlinear controllers for the quadrotor, in [7], a robust optimal adaptive control strategy for a quadrotor is developed to deal with the tracking problem by considering parametric uncertainties, actuator constraints, and unknown time-varying disturbances. In this method, while it is necessary to identify the parameters, the response is slow. Sliding mode control is a simple, robust technique that can be used in linear and nonlinear systems. [8-9], have presented the design of a sliding mode controller for both altitude and attitude control of the quadcopter. In [10], the fuzzy control method is used to switch the sliding mode control gains. This technique can be controlled without an accurate system model, but extracting membership functions is difficult. Due to the inaccurate modeling of the quadrotor as well

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as the dimensions and weight of this type of flying robot, disturbances and noise affect its performance. Therefore, robust control techniques are one of the main methods in quadrotor control [11]. In [12], based on the robust integral of the error, an adaptive tracking controller is developed for an underactuated quadrotor. Also, in [13], a robust controller for the trajectory tracking of a quadrotor is designed. In this approach, two different controllers for the inner and outer loop of the flying robot are proposed. In [14], the trajectory tracking control is designed based on the robust backstepping feedback control for the underactuated quadrotor with input saturation. A simple and widely used method to nonlinearly control a flying robot is the feedback linearization technique [15]. Some other effective methods of nonlinear quadrotor control are mentioned in the references [16], [17]. The proposed nonlinear methods usually are complex to implement.

To calculate the control coefficients online, we need a function based on the system variables. The purpose of this paper is to present a new method to obtain such a function. In the proposed method, the function calculates the control coefficients at any time based on the states of the system. The parameters of this function are obtained by the genetic algorithm database, which is the objective function of minimizing tracking error.

In Section 2 of the article, the dynamic model of the quadrotor is presented, then the design of the controller and the gain adjustment mechanism are presented in Section 3. Section 4 deals with the stability analysis of the flying robot, and in Section 5, the simulation results are presented. And finally, about the results in section 6, discussion and conclusions have been made.

2. DYNAMIC MODEL OF THE QUADROTOR

In this section, the mathematical model of the quadrotor is introduced. Quadrotor dynamic models are described by a set of equations. These equations include the attitude and position of the flying robot in space, which has four control inputs. Here, the quadrotor is a rigid body, a fixed frame is attached to its center of gravity called the body frame B, and an inertial reference frame called E is considered as shown in Fig. 1.

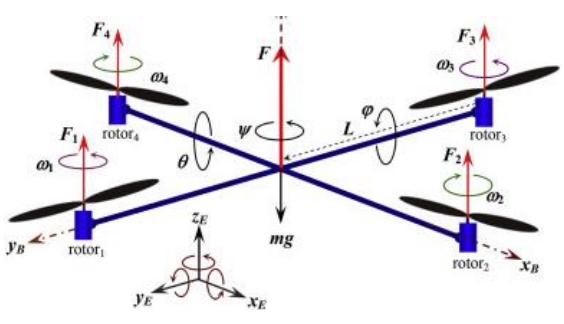

Fig. 1. Quadrotor Coordinate System.

Here, Euler angles are used to indicate the attitude of the robot. Therefore, the rotation matrix R is as follows:

$$R = \begin{bmatrix} C\theta C\psi & S\phi S\theta C\psi - C\phi S\psi & C\phi S\theta C\psi + S\phi S\psi \\ C\theta S\psi & S\phi S\theta S\psi - C\phi C\psi & C\phi S\theta S\psi - S\phi C\psi \\ -S\theta & S\phi C\theta & C\phi C\theta \end{bmatrix} \quad (1)$$

Where $S(.)$ and $C(.)$ are $\sin(.)$ and $\cos(.)$, respectively. The quadrotor dynamic model and the equations of motion are as follows [18]:

$$\begin{aligned} \ddot{\phi} &= \dot{\theta}\dot{\psi}\left(\frac{(I_{yy} - I_{zz})}{I_{xx}}\right) - \dot{\theta}\frac{I_{rotor}}{I_{xx}}\Omega_r + \frac{u_2}{I_{xx}} \\ \ddot{\theta} &= \dot{\phi}\dot{\psi}\left(\frac{(I_{zz} - I_{xx})}{I_{yy}}\right) - \dot{\phi}\frac{I_{rotor}}{I_{yy}}\Omega_r + \frac{u_3}{I_{yy}} \\ \ddot{\psi} &= \dot{\phi}\dot{\theta}\left(\frac{(I_{xx} - I_{yy})}{I_{zz}}\right) + \frac{u_4}{I_{zz}} \\ \ddot{x} &= (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)\frac{1}{m}u_1 \\ \ddot{y} &= (\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi)\frac{1}{m}u_1 \\ \ddot{z} &= -g + (\cos\phi \cos\theta)\frac{1}{m}u_1 \end{aligned} \quad (2)$$

Where x, y, and z are the position of the center of mass in inertial coordinates, $\emptyset$, θ, and ψ represent the roll, pitch, and yaw angles, respectively, in body coordinates. m is the mass of the robot and g is the gravitational acceleration. The u_1, u_2, u_3 and u_4 can be written as:

$$\begin{aligned} u_1 &= b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ u_2 &= bl(\Omega_2^2 - \Omega_4^2) \\ u_3 &= bl(\Omega_1^2 - \Omega_3^2) \\ u_4 &= K(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \end{aligned} \quad (3)$$

Therefore:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & bl & 0 & -bl \\ bl & 0 & -bl & 0 \\ k & -k & k & -k \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \Rightarrow$$
$$\begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & bl & 0 & -bl \\ bl & 0 & -bl & 0 \\ k & -k & k & -k \end{bmatrix}^{-1} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \quad (4)$$

Where $\Omega_1, \Omega_2, \Omega_3$ and Ω_4 denote motor speed signal and Ω_r can be calculated as follows:

$$\Omega_r = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 = \sum_{i=1}^{4}(-1)^i \Omega_i \quad (5)$$

The state space form of the orientation of the quadrotor model can be arranged as follows:

$$\dot{x}(t) = A\big(x(t)\big)x(t) + Bu(t) \quad (6)$$

Where $x(t) = [\emptyset \quad \theta \quad \psi \quad \dot{\emptyset} \quad \dot{\theta} \quad \dot{\psi}]^T$ and $A\big(x(t)\big)$

$$= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & a_2x_5(t) \\ 0 & 0 & 0 & a_1x_6(t) & 0 & 0 \\ 0 & 0 & 0 & 0 & a_3x_4(t) & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{I_{xx}} & 0 & 0 \\ 0 & \frac{1}{I_{yy}} & 0 \\ 0 & 0 & \frac{1}{I_{zz}} \end{bmatrix} \ \& \ u(t) = \begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix}$$

$$a_1 = \left(\frac{(I_{zz}-I_{xx})}{I_{yy}}\right) \ \& \ a_2 = \left(\frac{(I_{zz}-I_{xx})}{I_{yy}}\right) \ \& \ a_3 = \left(\frac{(I_{xx}-I_{yy})}{I_{zz}}\right)$$

3. NONLINEAR OPTIMAL ADAPTIVE CONTROLLER DESIGN AND GAIN TUNING

In modern control, there are various methods for controller design and gains tunning. Moreover, in complex systems, the controller coefficients are usually obtained with fixed values assuming specific scenarios. In this article, the goal is to control the Euler angles for the stability and tracking of the desired flight path by using a new method of gains tunning. Fig. 2 shows the block diagram of the system with the proposed controller.

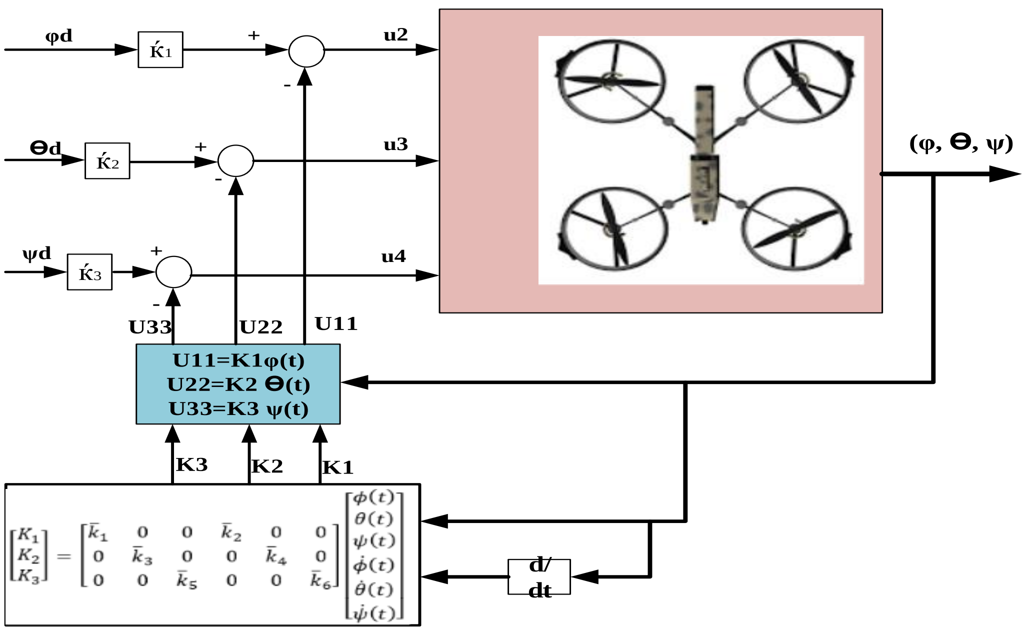

Fig. 2. The block diagram of the system.

The control coefficients can be written as follows:

$$K = f\big(x(t)\big) = \bar{K}x(t) \quad (7)$$

The goal is to obtain the coefficient $\bar{K}$ using the database generated by the genetic algorithm. The following five steps describe the control coefficients algorithm:

Step 1: The desired state feedback control with unknown control coefficients is considered as:

$$\dot{x}(t) = Ax(t) + B\big(r(t) - Kx(t)\big) \Rightarrow$$
$$\dot{x}(t) = (A - BK)x(t) + Br(t) \quad (8)$$

Step 2: The fitness function of this optimization problem is formed as follow:

$$F_{obj} = \big(R(t) - \Upsilon(t)\big)^2 \quad (9)$$

Where $R(t) = [\phi \quad \theta \quad \psi]$ is the desired vector and $\Upsilon(t) = [\phi_d \quad \theta_d \quad \psi_d]$ is the output vector.

To minimize the results of the fitness function in different conditions, the control coefficients calculated by the GA method are used. M and S store system variables and control coefficients, respectively. So:

$$S = \begin{bmatrix} K_{11} & K_{21} & \cdots & K_{l1} \\ K_{12} & K_{22} & \cdots & K_{l2} \\ \vdots & \vdots & \ddots & \vdots \\ K_{1N} & K_{2N} & \cdots & K_{lN} \end{bmatrix}$$

$$M = \begin{bmatrix} x_{11}(t_f) & x_{21}(t_f) & \cdots & x_{n1}(t_f) \\ x_{12}(t_f) & x_{22}(t_f) & \cdots & x_{n2}(t_f) \\ \vdots & \vdots & \ddots & \vdots \\ x_{1N}(t_f) & x_{2N}(t_f) & \cdots & x_{nN}(t_f) \end{bmatrix}$$

Step 3: The linear relationship between variables of the system and control coefficients is as follows:

$$\begin{aligned} K_1 &= \bar{k}_1 x_1(t) + \bar{k}_2 x_4(t) = \bar{k}_1 \phi(t) + \bar{k}_2 \dot{\phi}(t) \\ K_2 &= \bar{k}_3 x_2(t) + \bar{k}_4 x_5(t) = \bar{k}_3 \theta(t) + \bar{k}_4 \dot{\theta}(t) \\ K_3 &= \bar{k}_5 x_3(t) + \bar{k}_6 x_6(t) = \bar{k}_5 \psi(t) + \bar{k}_6 \dot{\psi}(t) \end{aligned} \tag{10}$$

Therefore

$$\begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} = \begin{bmatrix} \bar{k}_1 & 0 & 0 & \bar{k}_2 & 0 & 0 \\ 0 & \bar{k}_3 & 0 & 0 & \bar{k}_4 & 0 \\ 0 & 0 & \bar{k}_5 & 0 & 0 & \bar{k}_6 \end{bmatrix} \begin{bmatrix} \phi(t) \\ \theta(t) \\ \psi(t) \\ \dot{\phi}(t) \\ \dot{\theta}(t) \\ \dot{\psi}(t) \end{bmatrix} \tag{11}$$

We assume that each control force affects only one channel, so we can use the channel states to calculate its control input.

Step 4: The linear relationship between control coefficients and system variables is obtained by applying the least squares method to the database:

$$\bar{K} = (M^T M)^{-1} M^T K \tag{12}$$

Step 5: The resulting functions are implemented in a non-linear system

4. STABILITY ANALYSIS

In this section, the stability of the proposed controller is formed and the controller design connected in the close loop will be investigated. It is known that the controller design can be described as follows:

$$u(t) = -K\big(x(t)\big)x(t) = -\big(\bar{K}x(t)\big)\,x(t) \tag{13}$$

By substituting this equation in the quadrotor state space equation, the equations can be rewritten as follows:

$$\begin{aligned} \dot{x}(t) &= A\big(x(t)\big)x(t) + B\Big(-K\big(x(t)\big)x(t)\Big) \Rightarrow \\ \dot{x}(t) &= \Big(A\big(x(t)\big) - BK\big(x(t)\big)\Big)x(t) \end{aligned} \tag{14}$$

To investigate the stability of (15), the following Lyapunov function in quadratic form is employed:

$$V = \frac{1}{2} X^T(t) X(t) \tag{15}$$

It is clear that $V(0) = 0$ and $V > 0$, for all $x \neq 0$

For the stable system, there exists $\dot{V} \leq 0$, where [19]:

$$\begin{aligned} \dot{V} &= X^T(t)\dot{X}(t) \Rightarrow \\ \dot{V} &= X^T(t)\Big(A\big(x(t)\big) - BK\big(x(t)\big)\Big)X(t) \end{aligned} \tag{16}$$

The stability condition ($\dot{V} < 0$ for all $x \neq 0$) is satisfied if the right side of (16) is as follows.

$$A(x) - BK(x) < 0 \Rightarrow A(x) - Bhx(t) < 0 \tag{17}$$

If the above relation is satisfied, then the function of control coefficients stabilizes the system.

5. SIMULATION RESULTS

The controller is designed for the flying robot and the simulation results are compared with the PID controller. The simulation is performed in MATLAB for 100 seconds and the PID coefficients are obtained by the software. The parameters of the quadrotor are given in Table 1.

Table 1. Simulation parameters [20].

Parameters	Value
M	0.8(kg)
I_{xx}	0.028 $(kg.m^2)$
I_{yy}	0.031 $(kg.m^2)$
I_{zz}	0.044 $(kg.m^2)$
I_{rotor}	0.000083 $(kg.m^2)$
b	0.00003 $(kg.m^2)$
K	0.000003 $(kg.m^2)$
l	0.2 (m)
R	0.12 (m)
g	9.81 $\left(\frac{m}{s^2}\right)$

And the parameters of GA for the system are shown in Table 2.

Table 2. The parameters of GA.

Generations	Elite Count	Crossover Fraction
70	3	0.7

In this section, for simulation, the desired trajectory and initial conditions are as follows:

$$\begin{aligned} R &= \left[5\sin\frac{\pi}{40}t \quad -3\cos\frac{\pi}{40}t \quad 10\right]\ (Deg) \\ \Upsilon_0 &= [0 \quad -3 \quad 0]\ (Deg) \end{aligned} \tag{18}$$

Fig. 3 shows the convergence trends of the GA controller.

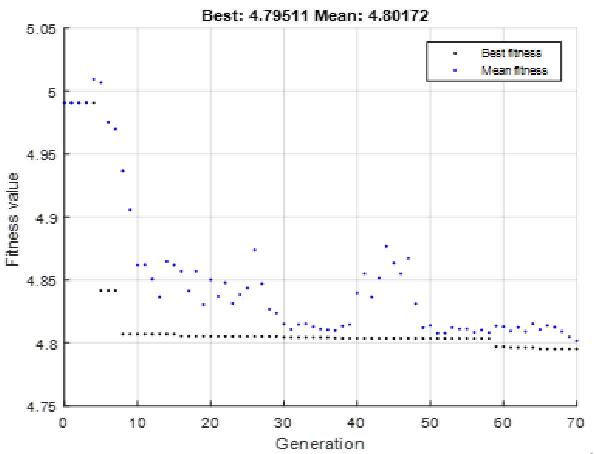

Fig. 3. Presenting the convergence of GA in the controller.

A simulation for Euler angles of the quadrotor based on the proposed technique and PID controller is shown in Fig. 4 to Fig. 6.

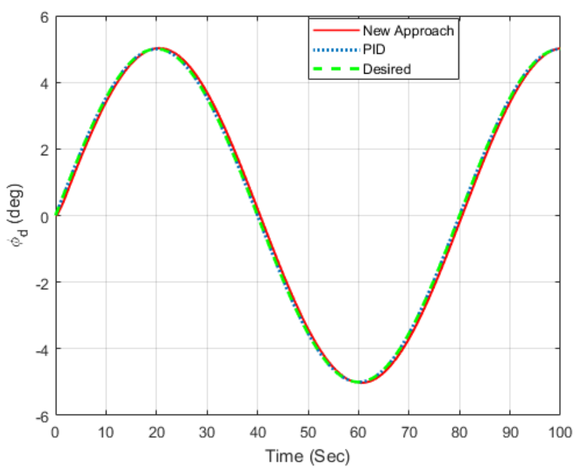

Fig. 4. Roll angle tracking the performance of two controllers.

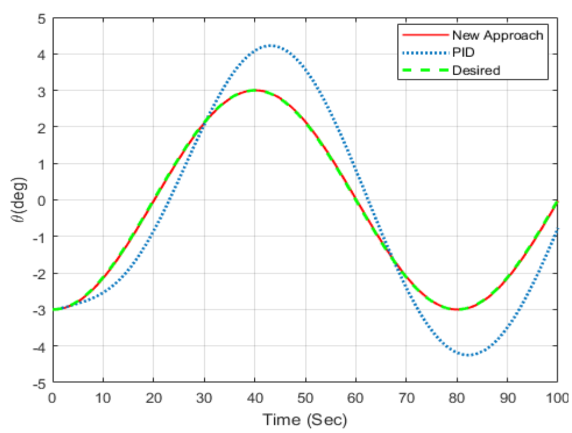

Fig. 5. Pitch angle tracking the performance of two controllers.

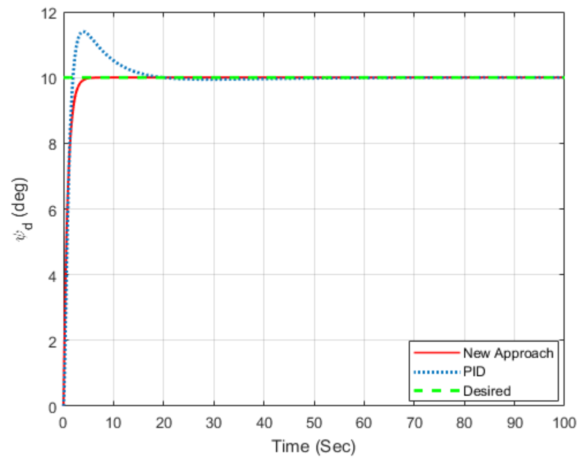

Fig. 6. Performance of two controllers in yaw angle tracking.

It is clear that the angles in the proposed method reach the desired value faster than the PID controller. Fig. 7 demonstrates the angular velocities of the robot.

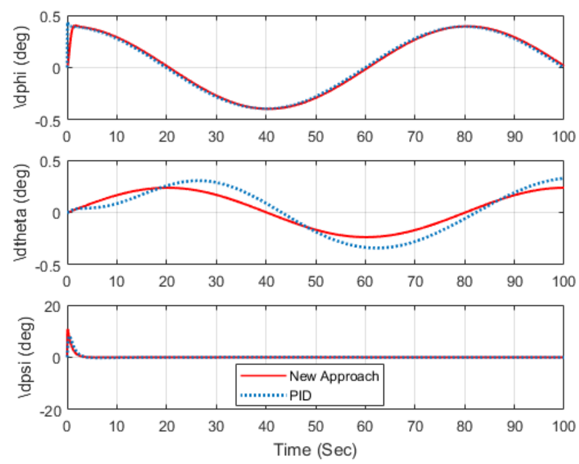

Fig. 7. Angular velocity of the quadrotor.

The angular velocities of both approaches have almost the same results. However, the angular velocity in the y-axis is better in the PID method.

To design and evaluate performance in practical control systems, integral absolute error (IAE) is usually used. The IAE is calculated as follows:

$$IAE = \sum_{i=1}^{n} |e(i)| \tag{19}$$

The difference between the error of these two methods is shown in Table 3.

Table 3. Comparison of errors for the two simulated methods.

Method	$E_{\phi}(Deg)$	$E_{\theta}(Deg)$	$E_{\psi}(Deg)$	Total(Deg)
Proposed Approach	0.06	0.00109	0.9533	1.0144
PID	0.05	0.0246	1.9415	2.0161
Improvement Percentage	-16%	2156%	103%	98%

According to the calculations, the error in the proposed method has been improved by 98%. Fig. 8 illustrates control torques in both methods.

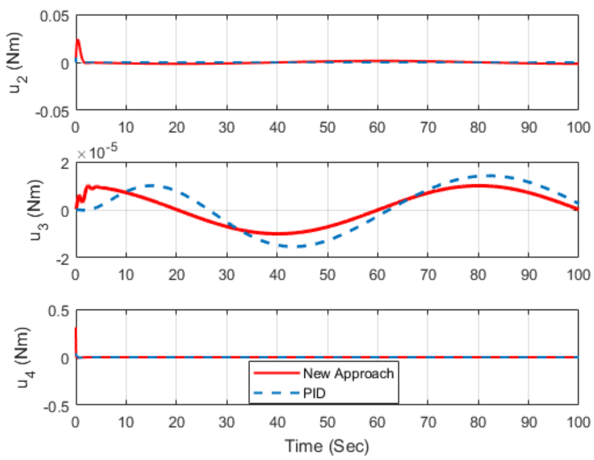

Fig. 8. Control signals between the proposed controller and PID controller.

As can be seen, the control force and torque applied to the drone are limited. In both methods, the control input behavior is similar. Fig. 9 shows the convergence of the control coefficients using the proposed function.

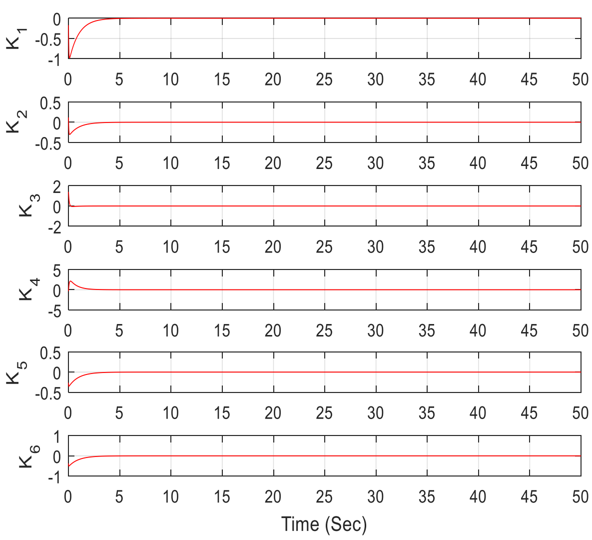

Fig. 9. Control Coefficients.

The results show that the control coefficients are convergent. Fig. 10 shows the stability of the proposed approach which satisfies the condition of (17).

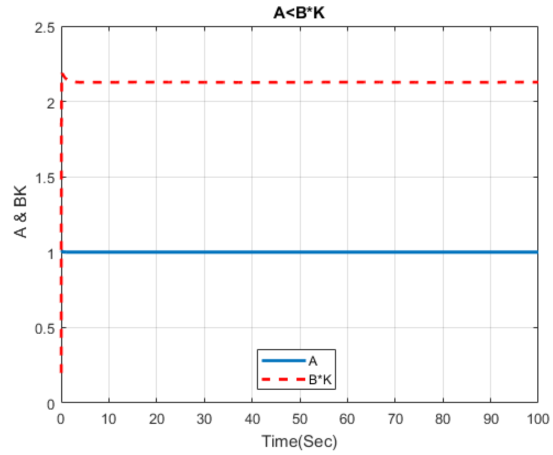

Fig. 10. Stability chart of Control Coefficients in the proposed approach.

Since the flying robot is powered by batteries, its energy consumption is important. Energy consumption is calculated as follows:

$$W = \sum_{i=1}^{n} U(i).\Delta\theta(i) \quad (20)$$

Table 4 shows the energy consumption of the two methods, in three axes x, y, and z.

Table 4. Quantitative comparison of controllers' performance.

Method	W_x (J)	W_y(J)	W_z(J)	Total(J)
Proposed Approach	0.0227	0.0032	0.003	0.0289
PID	0.0349	0.02	0.0021	0.0570
Percentage of improvement	53%	525%	-30%	97%

As can be seen from Table 4, the new method has better energy consumption than PID; it is improved by 97%. The test results show that the proposed approach shows improvement compared to the PID controller which is used in the literature for control.

6. CONCLUSION

In this paper, to control the Euler angles of a quadrotor, an optimal nonlinear adaptive controller was designed. In this approach, we used a database generated by GA to find online the control coefficients of the adaptive control, based on the system states. The Lyapunov equation is used to prove the stability of the closed-loop system. The validity of the proposed approach is evaluated by simulation. Simulation results show the perfect tracking of the desired trajectory, a significant improvement in smoothness, and energy consumption compared to the PID method. The proposed method has 97% less energy consumption and 98% less error than the PID controller.

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