



## Optimal Controller Design for Quadrotor by Genetic Algorithm with the Aim of Optimizing the Response and Control Input signals

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**Abstract.** This paper presents an optimal approach to control, stabilization and providing Tracking performance of attitude subsystem of quadrotor. The controller structure is based on Proportional- Integral Derivative (PID) control and Genetic Algorithm method is used to tune parameters of PID controller optimally. SISO approach is implemented for control structure to achieve desired objectives (second order linear Transfer Function is used to form  $\varphi, \theta, \psi$  states). The performance of the designed control structure is evaluated through time domain factors such as overshoot, rise time, settling time and steady state error index, and control input signal optimality. The cost function for Genetic Algorithm implementation includes both output response criterions and Magnitude of input control signal. The effectiveness of the proposed method is confirmed with simulation results for square and sinuous reference inputs. Finally, simulation results at the end, demonstrates the excellent and optimal performance for our designed controller.

**Keywords:** Tracking Performance, Optimization, PID Control, Quadrotor, Genetic Algorithm

### 1. INTRODUCTION

Recent technological advances in energy storage devices, sensors, actuators and information processing have boosted the development of Unmanned Aerial Vehicle (UAV) platforms with significant mission capabilities [1, 2]. Unmanned aerial vehicles are important when it comes to perform a desired task in a dangerous and/or inaccessible environment. More recently, a growing interest in un- manned aerial vehicles (UAVs) has been shown among the research community [3]. The rotorcraft UAVs pose a set of advantages compared to the fixed wing UAVs, such as hovering, vertical takeoff and landing and aggressive maneuvering. Within the family of the rotor- crafts, Unmanned Quadrotor Helicopters (UQHs) have gained increasing attention among scientists and engineers [4]. A quadrotor is a 4-rotor vertical takeoff and landing vehicle that has the maneuvering abilities of traditional helicopters with significantly lower mechanical complexity. This low complexity increases dependability while reducing the cost of manufacturing, operation, and maintenance [5]. Quadrotor is usually used to develop control laws. This kind of helicopter tries to reach a stable hovering and flight, using the equilibrium forces produced by four rotors [6]. Quad rotors are therefore becoming a promising option for various unmanned military and civilian applications [5]. One of the advantages of the quadrotor configuration is its payload capacity. As a drawback, this type of UAV presents a weight and energy consumption augmentation due to the extra motors [7].

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## 2. QUADROTOR CONFIGURATION

One can describe the vehicle as having four propellers in cross configuration. The two pairs of propellers (1, 3) and (2, 4) turn in opposite directions by varying the rotor speed; one can change the lift force and create motion. Thus, increasing or decreasing the four propeller's speeds together generates vertical motion. Changing the 2 and 4 propeller's speed conversely produces roll rotation coupled with lateral motion. Pitch rotation and the corresponding lateral motion are resulted from changing 1 and 3 propeller's speed conversely. Yaw rotation is more subtle, as it results from the difference in the counter-torque between each pair of propellers [2]. Figure 1 describes concept motions of quadrotor.

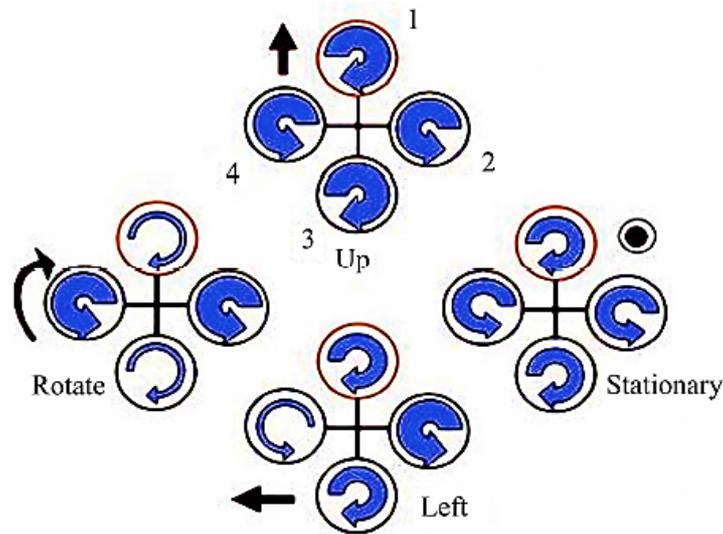


Figure 1. Quadrotor concept motions description.

The six-degree-of-freedom airframe dynamics of a typical quadrotor involve the typical translational and rotational dynamical equations as in [8]. The dynamic model of a quadrotor is essentially a simplified form of helicopter dynamic that exhibits the basic problems including under-actuation, strong coupling, multi input/ multi output and unknown nonlinearities [9]. The automatic control of a quadrotor UAV is not a straight on mainly due to its under-actuated properties [10] and it is difficult to control all these six outputs with only four control inputs. Moreover, uncertainties associate with dynamic model also bring more challenge for control design [11].

In some papers the quadrotor helicopter has also been controlled using a linear controllers based on linearization models. In [12] two control techniques were compared, a PID and a Linear Quadratic Regulator (LQR), where a linearization model was considered to design the

PID controller. The development of the LQR was based on a time variant model. The time-optimal control problem of a hovering quadrotor helicopter is addressed in [13]. Instead of utilizing the Pontryagin's Minimum Principle (PMP), in which one needs to solve a set of highly nonlinear differential equations, a nonlinear programming (NLP) method is proposed. In this novel method, the count of control steps is fixed initially and the sampling period is treated as a variable in the optimization process. Nonlinear control problems for hovering quadrotor helicopters such as feedback linearization control and back-stepping control laws were studied in [14]. Lyapunov based stability analysis shows that the proposed control design yields asymptotic tracking for the UAV's motion in  $x, y, z$  direction and the yaw rotation, while keep the stability of the closed loop dynamics of the quadrotor UAV [11].

In [7] a control law based on a standard back-stepping approach for translational movements and a nonlinear combined to perform path following in the presence of external disturbances and parametric uncertainties. However, this strategy is only able to reject sustained disturbances applied to the rotational motion both path following and stabilization problems. Time-optimal problems of control systems have attracted the attention of many researchers, especially in aerospace and robotics in the past few years. In this paper, we apply SISO control structure to achieve desired objectives such as: stability, control, tracking performance for attitude subsystem of quadrotor which is in fact an unstable plant. To achieve best time domain performance, SISO approach is used, the advantage of this strategy is that in every loop, the desired performance of loop is evaluated and if it is necessary, just the parameters of one controller would be manipulated. This paper is organized as follows. The dynamic model of quadrotor is given in Section 2. In Section 3,4,5 the control strategy is exposed. Simulation results are presented in Section 6. Finally, the major conclusion of the paper is drawn in Section 7.

### **3. QUADROTOR MODELING**

#### **3.1. Description**

The quadrotor has four rotors that are controlled independently. The movement of the quadrotor results from changes in the speed of the rotors. The structure of quadrotor in this paper is assumed to be rigid and symmetrical, the center of gravity and the body fixed frame origin are coincided, the propellers are rigid and the thrust and drag forces are proportional to the square of propeller's speed. Figure 2 presents the structure of quadrotor and relative coordinate systems.

### 3.2. Kinematics of Quadrotor

The earth-fixed inertial reference frame is  $E_I(e_{1I}, e_{2I}, e_{3I})$  and the body-fixed reference frame is  $E_B(e_{1B}, e_{2B}, e_{3B})$ . The absolute position of the quadrotor is described by  $X = [x, y, z]^T$  and its attitude by the Euler angles  $\Theta = [\varphi, \theta, \psi]^T$  used corresponding to aeronautical convention. The attitude angles are respectively called Yaw angle ( $\psi$  rotation around z-axis), Pitch angle ( $\theta$  rotation around y-axis) and Roll angle ( $\varphi$  rotation around x-axis). Let  $V = [u, v, w]^T \in E^b$  denote the linear velocity vector and  $\Omega = [p, q, r]^T \in E^b$  denote the angular velocity vector of the airframe expressed in the body-fixed-frame. The relation between the velocities vectors  $V, \Omega$  and  $\dot{X}, \dot{\Theta}$  is given by:

$$\begin{cases} \dot{X} = R(\Theta)V \\ \dot{\Theta} = M^{-1}(\Theta)\Omega \end{cases} \quad (1)$$

Where  $R(\Theta)$  and  $M(\Theta)$  are respectively the transformation rotation and the rotation velocity matrices between  $E^b$  and  $E^I$ :

$$R(\Theta)_{b \rightarrow (x,y,z)} = \begin{bmatrix} s\varphi s\theta s\psi + c\theta c\psi & s\varphi s\theta c\psi - c\theta s\psi & s\theta c\varphi \\ c\varphi s\psi & c\varphi c\psi & -s\varphi \\ c\theta s\psi s\varphi - c\psi s\theta & c\theta s\psi c\varphi + s\psi s\theta & c\varphi c\theta \end{bmatrix} \quad (2)$$

$$M(\Theta) = \begin{bmatrix} c\psi & c\varphi s\psi & 0 \\ c\varphi s\psi & c\varphi c\psi & 0 \\ 0 & -s\varphi & 1 \end{bmatrix} \text{ where } : C := \cos, S := \sin \quad (3)$$

### 3.3. Dynamics of Quadrotor

Two different methods have been investigated to achieve dynamics of quadrotor. One can either use the Lagrangian equation or the Newton's law. Let's explain the second method which is more comprehensible.

The quadrotor is controlled by independently varying the speed of the four rotors. Hence four inputs are defined as follow:

$$\begin{cases} u_1 = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \\ u_2 = b(\omega_4^2 - \omega_2^2) \\ u_3 = b(\omega_3^2 - \omega_1^2) \\ u_4 = b(\omega_2^2 + \omega_4^2 - \omega_1^2 - \omega_3^2) \end{cases} \quad (4)$$

The quadrotor motion equations can be expressed with Newton's law:

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$$\ddot{\mathbf{x}} = g \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - R_{b \rightarrow i(xyz)} \frac{b}{m} \sum_{i=1}^4 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (5)$$

$$\begin{cases} \dot{x} = -(S \theta C \varphi) u_1 / m \\ \dot{y} = (S \varphi) u_1 / m \\ \dot{z} = -(C \theta C \varphi) u_1 / m + g \end{cases} \quad (6)$$

Also, to relate Euler angular rates to body angular rates, we have to use the same order of rotation. This gives rise to:

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

By differentiating,

$$\begin{pmatrix} \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \frac{\sin \psi}{\cos \varphi} & \frac{\cos \psi}{\cos \varphi} & 0 \\ \sin \psi \tan \varphi & \sin \psi \tan \varphi & 1 \end{bmatrix} \begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} + \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \frac{\sin \psi}{\cos \varphi} & \frac{\cos \psi}{\cos \varphi} & 0 \\ \sin \psi \tan \varphi & \sin \psi \tan \varphi & 1 \end{bmatrix} \begin{pmatrix} \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} \quad (8)$$

$I$  is the inertia matrix of the vehicle and  $\Omega = \begin{pmatrix} p \\ q \\ r \end{pmatrix}$

$$\frac{d(I\Omega)}{dt} = I \begin{pmatrix} u_2 \\ u_3 \\ u_4 \end{pmatrix} = I \cdot \begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} + (I\Omega \times \Omega) \quad (9)$$

$$\begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = I^{-1} I \begin{pmatrix} u_2 \\ u_3 \\ u_4 \end{pmatrix} + (\Omega \times I\Omega) \quad (10)$$

Assuming that the structure is symmetrical:

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \quad (11)$$

In some papers, the second term of the right side of the Equation (10),  $(I\Omega \times \Omega)$  is neglected [18]. This approximation can be made by assuming that:

- The angular rate about the  $z$  axis,  $r$ , is small enough to be neglected
- $I_{xx} = I_{yy}$

Let's just assume, for the moment, that the moments of inertia along the x axis and y axis are equaled [19].

Hence,

$$\begin{cases} \ddot{\varphi} = -\frac{I_{yy} - I_{zz}}{I_{xx}} \dot{\psi} \dot{\varphi} + \frac{I_{xx}}{I_{xx}} u_2 - \frac{I_{yy}}{I_{yy}} u_3 + \frac{(I_{yy} - I_{zz})}{I_{xx}} (\dot{\psi} - \dot{\theta} \varphi) \dot{\psi} \dot{\varphi} \\ \ddot{\theta} = \frac{I_{xx}}{C \varphi} + \frac{I_{yy}}{C \varphi} \dot{\varphi} + \frac{I_{xx}}{C \varphi I_{xx}} u_2 + \frac{I_{yy}}{C \varphi I_{yy}} u_3 - \frac{(I_{yy} - I_{zz})}{I_{xx}} (\dot{\psi} - \dot{\theta} \varphi) \frac{\dot{\psi}}{C \varphi} \\ \ddot{\psi} = \frac{I_{xx}}{C \varphi} \dot{\varphi} + \frac{I_{yy}}{I_{xx}} u_2 + \frac{I_{yy}}{I_{yy}} u_3 + \frac{l}{I_{zz}} u_4 - \frac{(I_{yy} - I_{zz})}{I_{xx}} (\dot{\psi} - \dot{\theta} \varphi) \dot{\psi} \end{cases} \quad (12)$$

#### 4. CONTROL STRATEGY

The dynamic model of quadrotor developed in Section 2 will be linear around hovering situation. Hence the gyroscopic effects won't be taken into consideration in the control design. In this paper, Taylor method is used to linear the model of quadrotor, the operation values of states and inputs around hovering mode are:

$$\varphi_{-0} = \dot{\varphi}_{-0} = \dot{\psi}_{-0} = 0, u_{2-0} = u_{3-0} = u_{4-0} = 0, u_{1-0} = \frac{m(g - \ddot{\varphi}_{-0})}{C \theta_0 C \varphi_0} \quad (13)$$

The linear model of quadrotor is given as:

$$\begin{cases} \dot{\varphi} = -g \theta, \dot{\psi} = g \varphi, \dot{u}_1 = \frac{1}{m} u_1 \end{cases} \quad (14)$$

$$\begin{cases} \ddot{\varphi} = \frac{l}{I_{xx}} u_2, \ddot{\theta} = \frac{l}{I_{yy}} u_3, \ddot{\psi} = \frac{l}{I_{zz}} u_4 \end{cases} \quad (15)$$

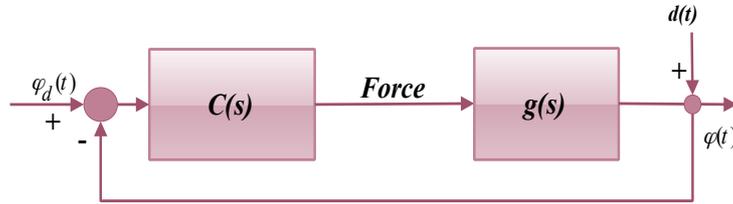
As the dynamic model shows, attitude subsystem of quadrotor, Equation (15),  $\varphi, \theta, \psi$  are forced directly by input signals. The transfer function of  $\varphi, \theta, \psi$  is a second order with two poles on the origin, so the system is inherently unstable. PID controllers will be designed to stabilize and control the attitude subsystem of quadrotor.

#### 5. CONTROL DESIGN

Proportional-plus-integral-plus-derivative (PID) controllers are widely used in the industry. The main reason is its relatively simple structure, which can be easily understood and implemented in practice. The widespread use of PID-type controllers in industries has affected efforts in the design and tuning of conventional PID controllers so as to achieve an optimal performance for the control system. As the Linear model of quadrotor shows, it is possible to use SISO approach for controlling attitude components. The transfer function of  $\varphi, \theta, \psi$  is a

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second order with two poles on the origin. These components are directly affected by three inputs. One can consider block diagram for  $\varphi, \theta, \psi$  components. Figure 3 shows control block diagram that can be used for each one of  $\varphi, \theta, \psi$  components.



**Figure 3.** Block diagram for  $\varphi$  component.

As shown in Figure 3, one controller should be designed for each one of to achieve desired  $\varphi_d, \theta_d, \psi_d$  directly. The  $g(s)$  model is assumed a second order:

$$g(s) = \frac{k}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (16)$$

$$C(s) = k_c \left( \frac{T_i s + 1}{T_i s} \right) (T_d s + 1) \quad (17)$$

## 6. OPTIMAL PID CONTROL DESIGN WITH GA

GA is a stochastic global adaptive search optimization technique based on the mechanisms of natural selection [16]. Recently, GA has been recognized as an effective and efficient technique to solve optimization problems. Compared with other optimization techniques GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem which performance is evaluated by a fitness function. Basically, GA consists of three main stages: Selection, Crossover and Mutation. The application of these three basic operations allows the creation of new individuals which may be better than their parents [17]. This algorithm is repeated for many generations and finally stops when reaching individuals that represent the optimum solution to the problem.

In this paper the Fitness function for Genetic Algorithm is Integrated Absolute Error and control effort, and stated in the following equation:

$$Cost\ Function = \int_0^T (\gamma * |e(t)| + \eta |u(t)|) dt, \quad T : simulation\ time \quad (18)$$

Where constants  $\gamma$  and  $\eta$  in the fitness function are Weighting factors of output error and control input respectively. In fact, In the process of optimizing the evaluation function, Efforts

have been made to reduce the error output and input control magnitudes. As actually having an output response close to the ideal state, but with poor control input, will not be accepted and it is very important in quadrotor systems. Figure 4 shows Block diagram of a quadrotor system with a GA-PID controller.

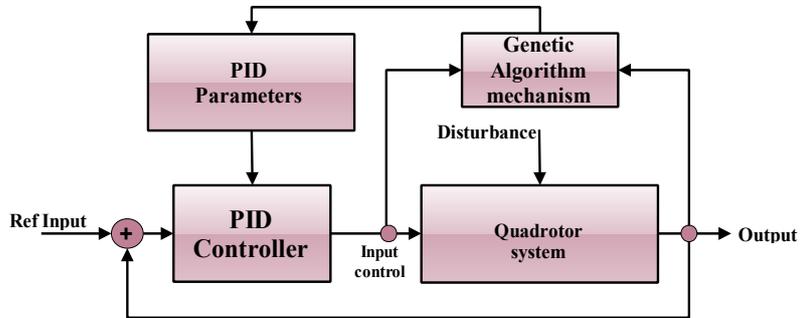


Figure 4. The structure of the optimal PID controller.

### 7. SIMULATION

The proposed control strategy has been tested by simulation in order to check the performance attained for the stabilization and tracking problems with real model of attitude subsystem of quad rotor. The values of the model parameters used for simulations are shown in Table (1):

Table.1. values of the model parameters used for simulations.

parameters	Values
$m$	2.3535kg
$g$	9.81m / s <sup>2</sup>
$l$	0.5m
$I_{xx}$	0.1676kgm <sup>2</sup>
$I_{yy}$	0.1676kgm <sup>2</sup>
$I_{zz}$	0.2974kgm <sup>2</sup>

Firstly, we choose the reference signal in the form of a square signal with amplitude 1 and period of 10 seconds. Also  $\gamma$  and  $\eta$  in the fitness function are adjusted to  $\gamma = 1.0$  ,  $\eta = 0.25$  . The following table shows the optimal values of the coefficients of the PID controller. According to the results, it is clear that with those optimized coefficients, control system performance is very good. The optimal coefficients of the PID controller for: Roll, Yaw and Pitch transfer function is placed in Table (2).

Table 2. Optimal coefficients of the PID controller for: Roll, Yaw and Pitch transfer function to square reference signal

	$K_p$	$K_I$	$K_D$	$\gamma$	$\eta$
Roll TF	12.445	0.031912	-3.0666	1.0	0.25

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Yaw TF	13.39	-1.638	-0.283	1.0	0.25
Pitch TF	12.445	0.031912	-3.0666	1.0	0.25

Figures (5) to (7) show the quadrotor system response to the square reference input.

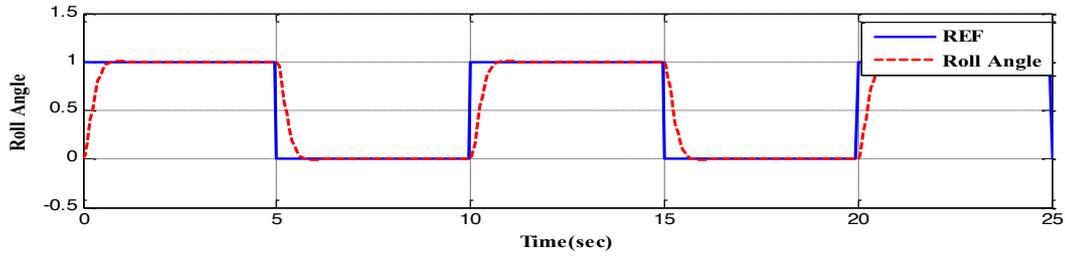


Figure 5. Quadrotor system performance for Roll angle.

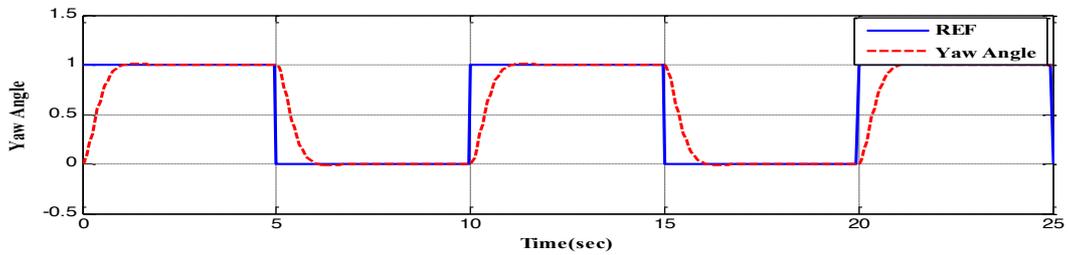


Figure 6. Quadrotor system performance for Yaw angle

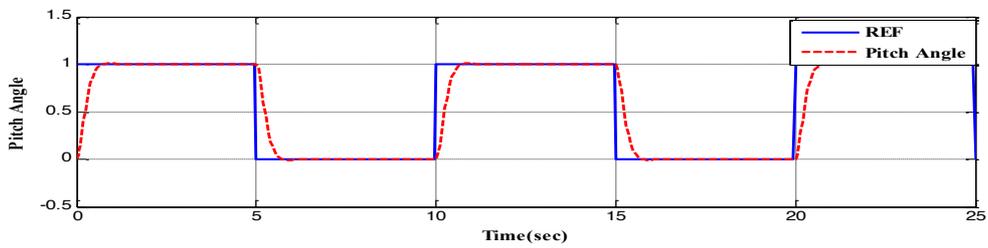


Figure 7. Quadrotor system performance for Pitch angle

Figures (8) to (10) also shows the control inputs for the three Euler angles.

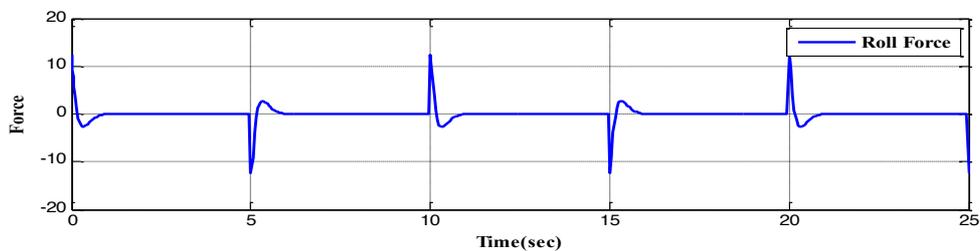


Figure 8. Control input for Roll angle.

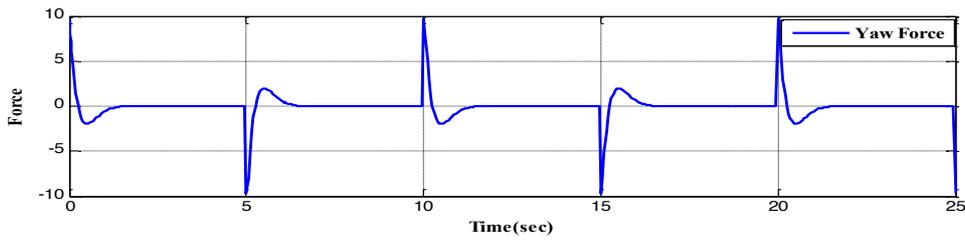


Figure 9. Control input for Yaw angle.

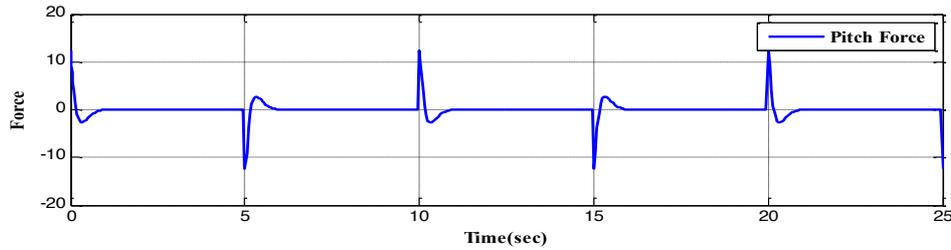


Figure 10. Control input for Pitch angle.

In Table (3), it can be seen some time domain criteria such as Overshoot time, rise time, settling time and steady-state error for the control system's response.

Table 3. Time domain criteria such as Overshoot time, rise time, settling time and steady-state error.

	OV %	$t_r$	$t_s$	$E_{ss}$
Roll TF	1.14	0.65	0.588	0.0
Yaw TF	1.18	0.83	0.76	0.0
Pitch TF	1.14	0.65	0.588	0.0

Evaluation function value for this stage:

$$Cost\ Function(Pulse) = \int_0^{25} (\gamma * |e(t)| + \eta |u(t)|) dt = 10.74 \quad (19)$$

The above results show that the proposed controller in addition to good response and acceptable performance, input control is optimal.

Secondly, we choose the reference signal in the form of a sinusoidal signal with amplitude 1 and period of  $2\pi$  seconds. Also the coefficients in the fitness function are adjusted to  $\gamma = 1.0$  ,  $\eta = 0.25$  .

$$Cost\ Function = \int_0^T (\gamma * |e(t)| + \eta |u(t)|) dt, T : simulation\ time \quad (20)$$

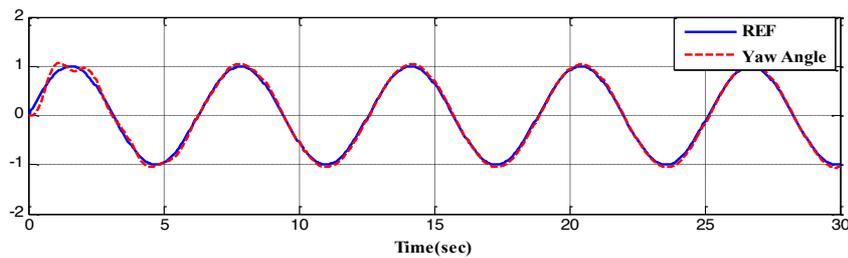
The optimal coefficients of the PID controller for: Roll, Yaw and Pitch transfer function is placed in Table (4).

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**Table 4.** Optimal coefficients of the PID controller for: Roll, Yaw and Pitch transfer function to sinusoidal reference signal.

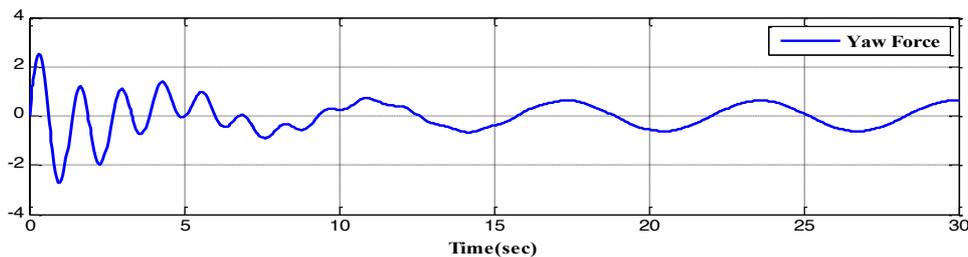
	$K_p$	$K_I$	$K_D$	$\gamma$	$\eta$
Roll TF	17.133	-2.048	-0.227	1.0	0.2
Yaw TF	13.39	-1.638	-0.283	1.0	0.2
Pitch TF	17.133	-2.048	-0.227	1.0	0.2

Figures (11) show quadrotor system response for Yaw angle to the sinusoidal reference input.



**Figure 11.** The Yaw quadrotor system performance to sinusoidal reference input.

Figure (12) also shows the control input for the Yaw transfer Function.



**Figure 12.** Control input for Yaw angle to sinusoidal reference input.

Evaluation function value for this stage:

$$Cost\ Function(Sin) = \int_0^{30} (\gamma * |e(t)| + \eta |u(t)|) dt = 9.624 \quad (21)$$

## 8. CONCLUSIONS

In general, this research has attempted to model and design an optimal PID controller using genetic algorithms in order to optimal control of Euler angles in quadrotor system. SISO approach is implemented for control structure to achieve desired objectives (second order linear Transfer Function is used to form  $\varphi, \theta, \psi$  states). The performance of the designed control structure is evaluated through time domain factors such as overshoot, rise time, settling time and integral error index. The simulation results illustrate the efficiency of applied control strategy in both excellent tracking performance and the control input optimality.

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