Tuning Decentralized PID Controller for a Quadrotor Using Flower Pollination Algorithm

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***Abstract*— This paper presents a decentralized PID controller applied to Unmanned Aerial Vehicle (UAV). Initially, a decentralized Proportional Integral Derivative (PID) controller was proposed to control the overall system of the quadrotor. Then, the parameters of the proposed controller tuning via Flower Pollination Algorithm against a fitness function which guarantees the convergence of the proposed algorithm to the optimal parameters. The simulation results demonstrate the effectiveness of the proposed optimization algorithm to tune the PID controller.**

Keywords—Quadrotor; PID Controller; Metaheuristic Algorithm; Flower Pollination Algorithm.

I. INTRODUCTION

In the last few years, the unmanned aerial vehicle knows a wide range of applications such as package delivery, surveying and cinematic photography. Thus, it is attracting the attention of many researchers to develop this aerial machine.

We find many successful works concerning the use of linear controllers such as PID and linear quadratic regulator (LQR) [1, 2] applied to the quadrotor. Considering that the system is non-linear and complex, the found results were less accurate in comparison to the works which applied non-linear controllers. The non-linear controllers for instance Backstepping and Sliding Mode controllers can clarify a lot in stabilizing the quadrotor system mainly with the presence of disturbances [3, 4].

In control range, most previous works are based on the classical methods for tuning the parameters of the controllers, where there are no specific criteria guaranteeing the choice of the optimal parameters.

To overcome this inconvenience, we find some works which propose the use of optimization method such as the metaheuristics algorithms. In [1] authors use the Genetic Algorithms (GA) to tune a PID controller for the overall system of the quadrotor. A comparative study has given in [5] between three different algorithm Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA) and Bat Algorithm (BA). In other hand, we find the Flower Pollination Algorithm gives successful works, Gautam et al [6] used Flower Pollination Algorithm (FPA) and GA for simulation path planning of autonomous. in [7] authors applied the flower pollination algorithm to parameter identification of DC motor.

This work is organized as follows: Section II, a presentation of the quadrotor model has given via Newton–Euler equation. the decentralized PID controller was discussed in Section III. The proposed Flower Pollination Algorithm is given in Section IV. The simulation results are discussed in Section V. The conclusion was given in the last section.

II. DYNAMICAL MODEL OF THE QUADROTOR

The quadrotor is characterized by a quite complexity of the dynamic model by its degrees of freedom (6DOF), the translation for all axes with their rotation according to each one as shown in figure 1.

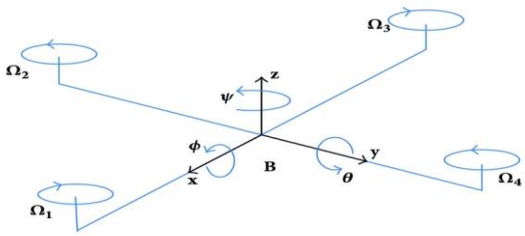

Figure 1. Quadrotor configuration

The equation model of the quadrotor obtained according to the inertial frame E and fixed-body frame B, using Newton–Euler formalism we can write the dynamic equation of the overall system as follows [8]:

$$\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\\ \ddot{\varphi}\\ \ddot{\theta}\\ \ddot{\psi}\end{bmatrix}=\begin{bmatrix}(c\psi s\theta c\varphi+s\psi s\varphi)u_1/m\\ (s\psi s\theta c\varphi-c\psi s\varphi)u_1)/m\\ ((c\theta c\varphi)u_1-mg)/m\\ ((I_{yy}-I_{zz})\dot{\psi}\dot{\theta}-J_r\Omega_r\dot{\theta}+lu_2)/I_{xx}\\ ((I_{zz}-I_{xx})\dot{\psi}\dot{\theta}+J_r\Omega_r\dot{\varphi}+lu_3)/I_{yy}\\ ((I_{xx}-I_{yy})\dot{\varphi}\dot{\theta}+u_4)/I_{zz}\end{bmatrix} \quad (1)$$

We denote to *c(.)* and *s(.)* for *cos(.)* and *sin(.)* respectively, $[\varphi\ \theta\ \psi]^T$ are the rotation vector according to linear translation vector $[x\ y\ z]^T$.

Where $U=[u_1\ u_2\ u_3\ u_4]^T$ represents the input control vector, l and m are the length of the quadrotor arm and the mass of the quadrotor respectively, $I_{xx,yy,zz}$ are the inertia constants of the body, Ω_r is the overall propellers' speed as:

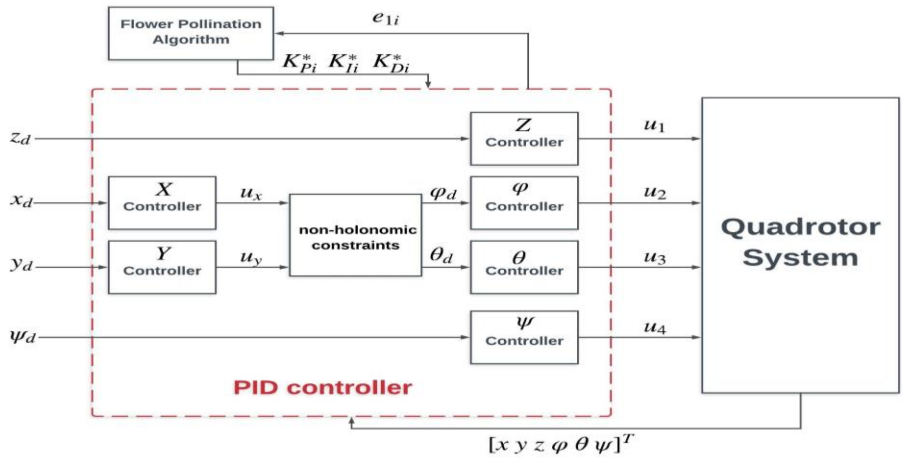

Figure 2. Structure of tuning PID controller using FPA

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ -b & 0 & b & 0 \\ 0 & -b & 0 & b \\ d & -d & d & -b \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \quad (3)$$

$$\Omega_r = (\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4) \quad (4)$$

Where $\Omega_{1,2,3,4}$ are the angular speed for each rotor. We put as variable state:

$$X = [x_{1x} x_{2x}\ x_{1y} x_{2y}\ x_{1z} x_{2z} x_{1\varphi} x_{2\varphi} x_{1\theta} x_{2\theta} x_{1\psi} x_{2\psi}]^T = [x\ x\ y\ y\ z\ z\ \varphi\ \dot{\varphi}\theta\ \dot{\theta}\psi\ \dot{\psi}]^T$$

The dynamic model of the quadrotor (1) can be written as 6^{th}subsystems as follow:

A. The Attitude Subsystems:

$$\begin{bmatrix} \dot{x}_{1\varphi} \\ \dot{x}_{2\varphi} \end{bmatrix} = \begin{bmatrix} x_{2\varphi} \\ \frac{(I_{yy} - I_{zz})}{I_{xx}} x_{2\theta} x_{2\psi} - \frac{J_r \Omega_r}{I_{xx}} x_{2\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{l}{I_{xx}} \end{bmatrix} u_2 \quad (5)$$

$$\begin{bmatrix} \dot{x}_{1\theta} \\ \dot{x}_{2\theta} \end{bmatrix} = \begin{bmatrix} x_{2\theta} \\ \frac{(I_{zz} - I_{xx})}{I_{yy}} x_{2\varphi} x_{2\psi} + \frac{J_r \Omega_r}{I_{yy}} x_{2\varphi} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{l}{I_{yy}} \end{bmatrix} u_3 \quad (6)$$

$$\begin{bmatrix} \dot{x}_{1\psi} \\ \dot{x}_{2\psi} \end{bmatrix} = \begin{bmatrix} x_{2\psi} \\ \frac{(I_{xx} - I_{yy})}{I_{zz}} x_{2\varphi} x_{2\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{l}{I_{zz}} \end{bmatrix} u_4 \quad (7)$$

B. The Position Subsystems:

$$\begin{bmatrix} \dot{x}_{1x} \\ \dot{x}_{2x} \end{bmatrix} = \begin{bmatrix} x_{2x} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ cx_{1\psi} sx_{1\theta} cx_{1\varphi} + sx_{1\psi} sx_{1\varphi} \end{bmatrix} u_1 \quad (8)$$

$$\begin{bmatrix} \dot{x}_{1y} \\ \dot{x}_{2y} \end{bmatrix} = \begin{bmatrix} x_{2y} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ sx_{1\psi} sx_{1\theta} cx_{1\varphi} - cx_{1\psi} sx_{1\varphi} \end{bmatrix} u_1 \quad (9)$$

$$\begin{bmatrix} \dot{x}_{1z} \\ \dot{x}_{2z} \end{bmatrix} = \begin{bmatrix} x_{2z} \\ -g \end{bmatrix} + \begin{bmatrix} 0 \\ cx_{1\theta} cx_{1\varphi} \end{bmatrix} u_1 \quad (10)$$

Assumption 1. We assume that state vector for all subsystems$X_i = [x_{1i} \quad x_{2i}]^T$for $i \in \{x, y, z, \varphi, \theta, \psi\}$ is available for measurement or observable.

Assumption 2. The desired trajectory $x_{1i}^d$and its time derivatives x_{2i}^d was smooth and bounded.

III. OPTIMAL DECENTRALIZED PID CONTROLLER BASED ON FPA

A. PID Controller Design

The control objective is to design a decentralized PID controller for each subsystem of the quadrotor, such that the local output $x_{1i}$for $i \in \{x, y, z, \varphi, \theta, \psi\}$ tracks the desired reference trajectory x_{1i}^d.

The local tracking error is defined as:

$$e_{1i} = x_{1i}^d - x_{1i} \quad , i \in \{x, y, z, \varphi, \theta, \psi\} \quad (11)$$

The derivative local tracking error as:

$$e_{2i} = x_{2i}^d - x_{2i} \quad (12)$$

The integral local tracking error as:

$$\int_0^t e_{1i} d\tau = \int_0^t (x_{1i}^d - x_{1i})\, d\tau \quad (13)$$

So, we can put a PID controller for each subsystem as the form follows:

$$u_i = K_{Pi} e_{1i} + K_{Ii} \int_0^t e_{1i} d\tau + K_{Di} e_{2i} \quad (14)$$

Where K_{Pi}, K_{Ii} and K_{Di} are the parameters of the controller. The input control for the altitude and attitude of the system becomes:

$$\begin{cases} u_1 = K_{Pz}e_{1z} + K_{Iz}\int_0^t e_{1z}d\tau + K_{Dz}e_{2z} \\ u_2 = K_{P\varphi}e_1 + K_{I\varphi}\int_0^t e_{1\varphi}d\tau + K_{D\varphi}e_{2\varphi} \\ u_3 = K_{P\theta}e_{1\theta} + K_{I\theta}\int_0^t e_{1\theta}d\tau + K_{D\theta}e_{2\theta} \\ u_4 = K_{P\psi}e_{1\psi} + K_{I\psi}\int_0^t e_{1\psi}d\tau + K_{D\psi}e_{2\psi} \end{cases} \quad (15)$$

Assumption 3. The desired angles supposed bounded $\varphi_d, \theta_d \epsilon \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ and controlled by the non-holonomic constraints strategy.

$$\begin{cases} \varphi_d = \frac{m}{U_1}(U_x sin\, x_{1\psi} - U_y cos\, x_{1\psi}) \\ \theta_d = \frac{m}{U_1}(U_x cos\, x_{1\psi} + U_y sin\, x_{1\psi}) \end{cases} \quad (16)$$

Where U_x and U_y are vertual control inputs as

$$\begin{cases} U_x = K_{Px}e_{1x} + K_{Ix}\int_0^t e_{1x}d\tau + K_{Dx}e_{2x} \\ U_y = K_{Py}e_{1y} + K_{Iy}\int_0^t e_{1y}d\tau + K_{Dy}e_{2y} \end{cases} \quad (17)$$

The parameters of the proposed controller for each subsystem should be chosen to assure the stability and the precise of the overall system. in this case, we propose the use of Flower Pollination Algorithm to tune these parameters.

B. Flower Pollination Algorithm

The mathematicians were able to develop an algorithm inspired from nature. In addition to this work, this section presents an algorithm deduced from flower pollination (FPA) following four main steps [9]:

- Processes of global pollination include biotic and cross pollination, and pollen-carrying pollinators move in a way that obeys Lévy flights.
- Abiotic pollination and self pollination are deduced for local pollination.
- Flower constancy can be developed by Insects pollinators, equivalent to reproduction probability which is proportional to the similarity to two flowers involved.
- A switch probability *P* can control the interaction. The interaction or switching of local pollination and global pollination, slightly biased toward local pollination.

As mentioned, Flower Pollination algorithm is based on three main strategies which are local pollination, global pollination and the control stategy.

1. Global pollination

In the global pollination, insects pollinators which can fly and move over a long range carry flower pollen gametes which can travel over long distances, Therefore, (step 1) and flower constancy (step 3) can be represented as:

$$x_i^{t+1} = x_i^t + \gamma L(s,\lambda)(x_{best}^t - x_r^t) \quad (18)$$

Where γ is a scaling factor to control the step size, L(u) is Lévy Flights function.

2. Lévy Flights

The Lévy Flights are a random walk in which the step lengths have a Lévy distribution [20], it can be calculated as:

$$L = \frac{\lambda\ \Gamma(\lambda)\sin(\pi/2)}{\pi}\frac{1}{s^{1+\lambda}} \quad (19)$$

Where $\Gamma(\lambda)$ is the gamma function can be written as:

$$\Gamma(\lambda) = \int_0^\infty t^{\lambda-1}e^{-t}dt \quad (20)$$

The step length s can be calculated by

$$s = \frac{U}{|V|^{1/\lambda}} \quad (21)$$

Where U and V are drawn from a Gaussian normal distribution

$$U \sim N(0,\sigma^2), N \sim (0,1) \quad (22)$$

Where σ^2 is a variance that can be calculated by

$$\left[\sigma^2 = \frac{\Gamma(1+\lambda)}{\lambda\Gamma((1+\lambda)/2)}\ \frac{\sin(\lambda\pi/2)}{2^{(\lambda-1)/2}}\right]^{1/\lambda} \quad (23)$$

3. Local pollination

For the local pollination, both step 2 and step 3 can be represented mathematically as:

$$v_i^t = x_{best}^t + \beta(x_p^t - x_q^t) \quad (24)$$

$$\beta = rand(0,1)(1-F) \quad (25)$$

4. Selection strategy

As mentioned in step 4, The interaction or switching of local pollination and global pollination can be controlled by the factor *P*

$$u_i^t = \begin{cases} x_i^{t+1}\ if\ \text{rand}(0,1) > P \\ v_i^t\quad otherwise \end{cases} \quad (26)$$

Finally, the selection of the best current global depends on the fitness function as the general goal of continuous optimization.

TABLE I. PARAMETERS OF THE QUADROTOR.

parameters	value
I_{xx}	7.5×10^{-3}[kg.m^2]
I_{yy}	7.5×10^{-3}[kg.m^2]
I_{zz}	1.3×10^{-2}[kg.m^2]
J_r	6×10^{-5}[kg.m^2]
l	0.23[m]
b	3.5×10^{-5}[N.s^2]
d	7.5×10^{-7}[N.m.s^2]

TABLE II. THE DIFFERENT TRAJECTORY PROPOSED.

Trajectory 1	Trajectory 2	Trajectory 3
$\psi_d = \frac{\pi}{6}\, rad$ $z_d = 4\, m$ $x_d = \begin{cases} 0 & if \quad t < 30 \\ \cos(\frac{\pi}{20}) & otherwise \end{cases}$ $y_d = \begin{cases} 0 & if \quad t < 30 \\ -\sin(\frac{2\pi}{20}) & otherwise \end{cases}$	$\psi_d = \frac{\pi}{6}\, rad$ $z_d = \begin{cases} 0 & if \quad t < 40 \\ 0.1 \times t & otherwise \end{cases}$ $x_d = \begin{cases} 0 & if \quad t < 40 \\ \cos(\frac{2\pi}{10}) & otherwise \end{cases}$ $y_d = \begin{cases} 0 & if \quad t < 40 \\ \sin(\frac{2\pi}{10}) & otherwise \end{cases}$	$\psi_d = \frac{\pi}{6}\, rad$ $z_d = 4\, m$ $x_d = \begin{cases} 0 & if \quad t < 10 \\ 2 & if \quad t < 20 \\ 2 & if \quad t < 40 \\ 0 & if \quad t < 60 \\ 0 & otherwise \end{cases}$ $y_d = \begin{cases} 0 & if \quad t < 10 \\ 0 & if \quad t < 20 \\ 2 & if \quad t < 40 \\ 2 & if \quad t < 60 \\ 0 & otherwise \end{cases}$

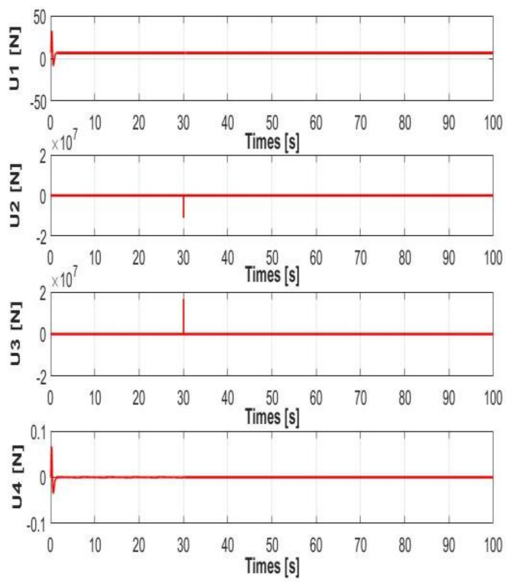

Figure 3. Inputs signals control using optimal PID control for first trajectory

C. *FPA-based optimal PID controller*

The use of the optimization algorithm allows to get a control law with an optimal parameter against a fitness function as follow:

$$u_i = K_{Pi}{}^{*} e_{1i} + K_{Ii}{}^{*} \int_0^t e_{1i} d\tau + K_{Di}{}^{*} e_{2i} \tag{27}$$

Where $K_{Pi}{}^{*}, K_{Ii}{}^{*}$ and $K_{Di}{}^{*}$, $i \epsilon \{x, y, z, \varphi, \theta, \psi\}$are the optimal parameters for each subsystem.

The fitness function chosen is the mean square error (MSE) used to guarantee the convergence of the proposed algorithm to the target way as the form:

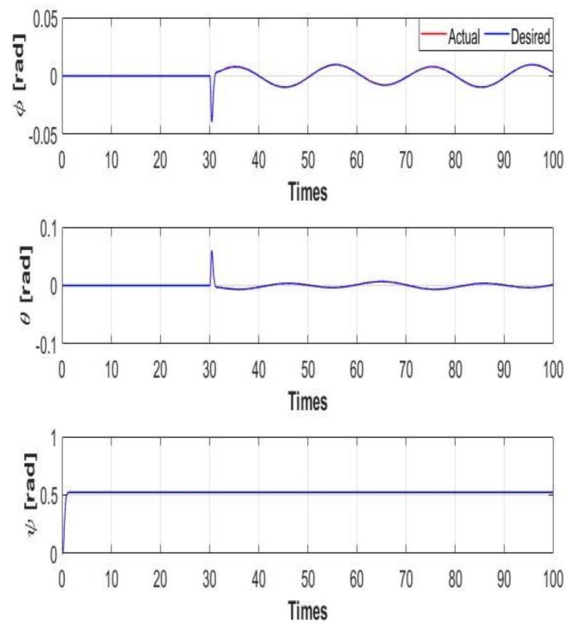

Figure 4. Attitude angle responses of the hovering quadrotor using optimal PID for first trajectory

$$J_i = \sqrt{\frac{\sum_{j=1}^{K} (x_{1i}^{d} - x_{1i})^2}{K}}, \quad i \epsilon \{x, y, z, \varphi, \theta, \psi\} \tag{28}$$

Where j^{th} is sampling time, K is the sampling size.

IV. SIMULATION RESULTS

In this section, we present simulation results of the FPA for tuning the decentralized PID controller. Where the FPA algorithm was coded by MATLAB, its search parameters are set [10] as: population size n=10, probability switch P=0.08, the constant λ =1.5 and Step size α=0.01.The quadrotor parameters are summarized in table 1.

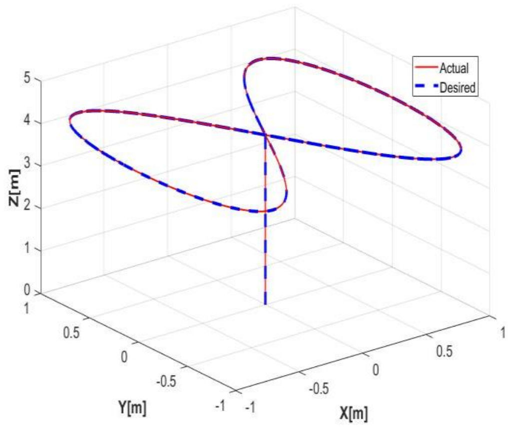

Figure 5. 3D path of the quadrotor response for first trajectory

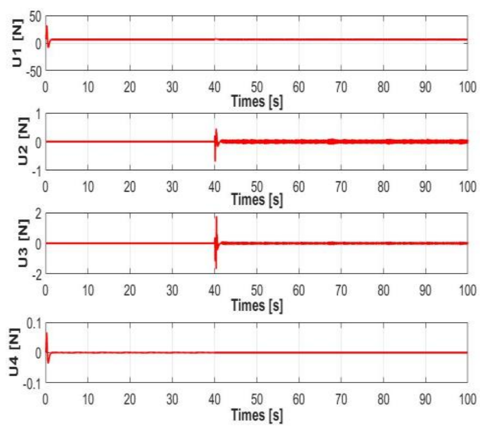

Figure 6. Inputs signals control using optimal PID control for second trajectory

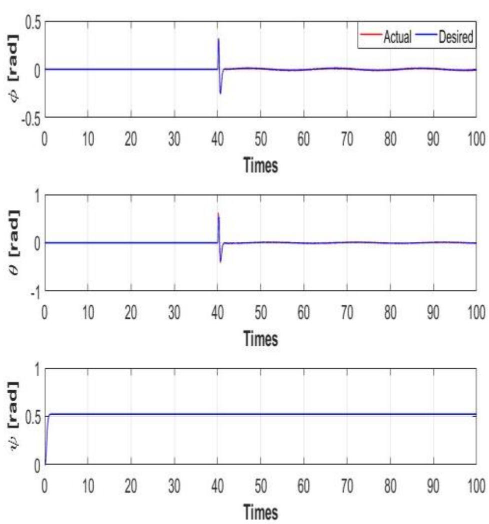

Figure 7. Attitude angle responses of the hovering quadrotor using optimal PID for second trajectory

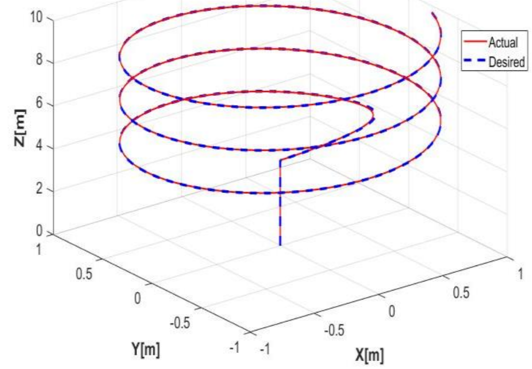

Figure 8. 3D path of the quadrotor response for second trajectory

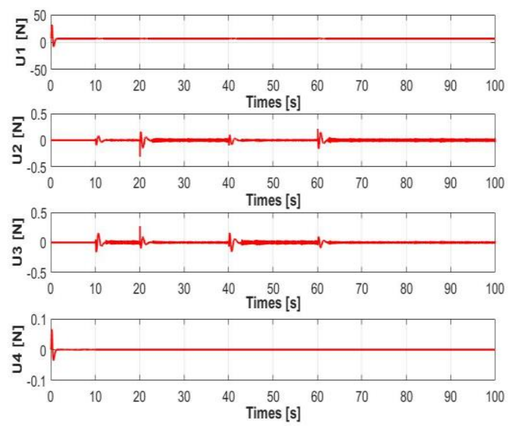

Figure 9. Inputs signals control using optimal PID control for third trajectory

The evolution of the optimization algorithm was for each controller separate on the others, where the simulation of the optimization was for 10s. The result of the optimization allows to get the optimal parameters of each controller, wher$K_{Px,y}{}^{*} = 22.14, K_{Ix,y}{}^{*} = 1.27, K_{Dx,y}{}^{*} = 10.82, K_{Pz}{}^{*} = 24.53, K_{Iz}{}^{*} = 1.01, K_{Dz}{}^{*} = 12.49, K_{P\varphi,\theta}{}^{*} = 7, K_{I\varphi,\theta}{}^{*} = 0.2, K_{D\varphi,\theta}{}^{*} = 2.16, K_{P\psi}{}^{*} = 5.06, K_{I\psi}{}^{*} = 6.07, K_{D\psi}{}^{*} = 0.8$. For testing the performance of these parameters, we propose a different path we can find it in several applications of the quadrotor shown in table 2.

To avoid the problems of the discrete time of the simulation, we propose to filter the desired trajectory vector with filter as the form $\frac{10^{-5}}{(s+10)^5}$, the initial state vector was $x_i^0 = [0,0,0,0,0,0]$.

Figure 3,6 and 9 show the inputs signals control using the optimal PID controller, where it can see the overshoot in different second, this is caused by the change in x and y variation in same moment. It can observe from figure 4,7 and 10 the high precision in tracking the attitude system of the quadrotor for different desired trajectories. Figure 5,8 and 11 show a three different 3D path of the quadrotor, where the figures show the best tracking of the desired path.

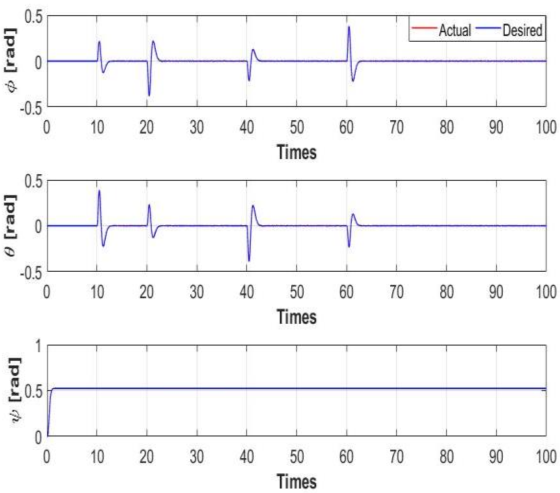

Figure 10. Attitude angle responses of the hovering quadrotor using optimal PID for third trajectory

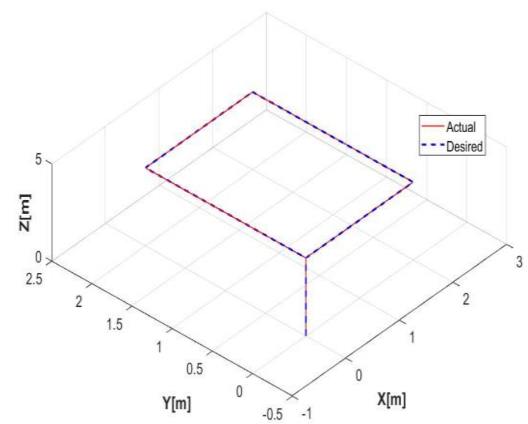

Figure 11. 3D path of the quadrotor response for third trajectory

V. CONCLUSION

This paper discusses a design of decentralized PID controller based on Flower pollination algorithm to control a Quadrotor helicopter. The dynamic system of the Quadrotor was given via Euler-Newton equations. the decentralized PID was proposed to control each subsystem. The parameters of each controller were tuned using FPA against fitness function despite the nonlinearity and the complexity in the dynamic model. The simulation result has proved to the effectiveness of the proposed algorithm.

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