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Position Control of Quadrotor using Firefly Algorithm

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Abstract: The quadrotor is a VTOL-capable unmanned aerial vehicle with excellent agility, four propellers, and six degrees of freedom. Because of their simple structure and low cost, they have attracted a lot of interest in recent years. Despite its apparent simplicity, its nonlinearities and linked dynamics make control difficult. Because of its simple nature, PD control is extensively utilized in quadrotors. A PD controller for quadrotor altitude and position stabilization is proposed in this paper, with its parameters calculated using the Firefly Algorithm and Genetic Algorithm. An objective function is developed to offer not only precise positioning of the target position, but also to enhance the motion's settling time. A test path from the rest position to the target position is examined for performance verification of the suggested method. The obtained findings show that position stabilization may be accomplished in a short amount of time, and the settling time is significantly reduced when compared to specified settings by Genetic Algorithm. The PD controller settings determined via the Firefly Algorithm optimization method surpass the ones chosen by Genetic Algorithm with a substantial margin.

Keywords: Quadrotor position control, altitude control, PD control, Firefly Algorithm

Ateş Böceği Algoritması ile Quadrotor Pozisyon Kontrolü

Öz: Quadrotor, mükemmel çevikliğe, dört pervaneye ve altı serbestlik derecesine sahip, VTOL özellikli bir insansız hava aracıdır. Basit yapıları ve düşük maliyetleri nedeniyle son yıllarda oldukça ilgi görmektedirler. Görünür basitliğine rağmen, doğrusal olmayışı ve bağlantılı dinamikleri kontrolü zorlaştırır. Basit yapısı nedeniyle PD kontrolü, quadrotorlarda yaygın olarak kullanılmaktadır. Bu makalede, Ateş Böceği Algoritması ve Genetik Algoritma kullanılarak hesaplanan parametreleriyle dört rotorlu bir quadratorun, yükseklik ve konum stabilizasyonu için bir PD denetleyicisi önerilmiştir. Yalnızca hedef pozisyonun hassas bir şekilde konumlandırılmasını sağlamak için değil, aynı zamanda hareketin yerleşme süresini de iyileştirmek için bir amaç fonksiyonu önerilmiştir. Önerilen yöntemin performans doğrulaması için dinlenme konumundan hedef konuma bir test yolu incelenir. Elde edilen bulgular, pozisyon stabilizasyonunun kısa sürede gerçekleştirilebileceğini ve Genetik algoritma tarafından belirlenen ayarlara kıyasla yerleşme süresinin önemli ölçüde azaldığını göstermektedir. Ateş Böceği Algoritması yöntemi ile belirlenen PD kontrolör parametreleri, Genetik Algoritma tarafından seçilenleri geride bırakmaktadır.

Anahtar Kelimeler: Quadrotor konum kontrolü, İrtifa kontrolü, PD kontrol, Ateş Böceği algoritması

1. Introduction

Unmanned Aerial Vehicles (UAVs) play a significant role in performing tasks that constitutes risks or infeasibility for human resources. Monitoring hazardous plants, surveillance of calamity for rescuing a life, surveillance of forest for fire and border patrol are some applications that UAVs are capable of. Quadrotor helicopters (or quadcopters) are popular type of UAVs which have four rotors in which each one is controllable individually, increase the capability of maneuver and provide

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vertical take-off and landing (VTOL). In recent years there has been growing interest within the researchers especially control community on control of the quadcopters.

Due to the wide range of applications, the position control and stabilization become a significant research topic. In this area, researchers have proposed various control techniques in their works. Back-stepping and sliding-mode, two nonlinear control methods, were applied to a micro quadrotor in 2005 as part of a research project. It was claimed that sliding-mode control technique performed above the average level and back stepping controller achieved control of the orientation angles under relatively high perturbations [1]. In another study, a new feedback control approach is used for attitude stabilization of quadrotor. In this research Coriolis and gyroscopic torques are taken into account using PD2 feedback structure [2]. An adaptive control method based on Lyapunov stability was applied to quadrotor considering direct and indirect model reference. A basic trajectory tracking controller was enhanced using an adaptive controller. It was shown that adaptive controller is more advantageous in comparison to fixed-gain method [3]. Particle swarm optimization (PSO) approach which is a popular global optimization tool was used to stabilize quadrotor motion. In order to stabilize quadrotor angles and height, PSO algorithm was used to adjust parameters of PD controllers [4] and PID controllers [5,6]. In another study, PSO algorithm was enhanced using a particular stochastic strategy to optimize gains of fuzzy PID controller. Performance index was determined as the integral of time multiplied by absolute error. The authors claimed that PSO algorithm was more effective than other methods [7]. Adaptive Neuro-Fuzzy Inference System (ANFIS) was also used to control quadrotor. Parameters of the system were tuned with Nondominated Sorting Genetic Algorithm II. According to results, it was noted that system response characteristics showed better performance than that with simple PID control [8]. Likewise, PID controller parameters were determined using Genetic Algorithm (GA) [9]. Bat algorithm is a recent optimization approach that was used to tune PD controllers of a quadrotor. In order to stabilize roll, pitch and yaw angles and heights of the quadrotor four PD controllers were adopted and parameters of system were determined by Bat algorithm [10]. Differential evolution optimization method was also applied to parameter estimation of PID controller of quadrotor problem by various researchers [11-13]. Auto-tuning PID control approach was applied for attitude control and position stabilization of quadrotor considering disturbances. In order to satisfy adaptive part of approach, sliding mode control was employed. Besides, a fuzzy compensator was used to eliminate chattering phenomena [14]. In another study, attitude and altitude control of quadrotor was realized by using PID controller again. The backstepping method was applied for position control. PID parameters were optimized using PSO algorithm [15]. Unlike previous studies, Sheta et.al used Crow Search algorithm [16], and Miranda-Colarado and Aguilar used Cuckoo search algorithm to tune PID parameters [17]. Weight variations of quadrotor was considered and PID parameters were tuned using Differential Evaluation and PSO in real-time simulation environment [18].

As a nature inspired algorithm, Firefly Algorithm (FA), is one of the efficient optimization tools for global optimization. It uses the advantage of randomness and as a result of that it generally avoids local minima [19]. In this manuscript Firefly algorithm is employed to estimate PD controller parameters of a quadrotor. This paper is organized as follows: In Section 2, the mathematical model of quadrotor is given. The proposed solution algorithm is introduced in Section 3. The proposed method and Genetic Algorithm are both applied to a sample problem and obtained results are discussed in Section 4. Finally, the conclusion is presented in Section 5.

2. Mathematical Model of Quadrotor

Quadrotor is a nonlinear system which has four propellers. Speeds of propellers are adjusted to obtain the desired torque and lift. Cross-positioned rotors of the Quadrotor rotate in the same direction while adjacent rotors rotate in the opposite direction. This eliminates undesired effects of counter rotation and prevents the deviational motion that will occur spontaneously. System dynamics of the quadrotor is defined as six degrees of freedom of a rigid body in space. These six degrees of freedom; roll (Φ), pitch (θ) and yaw (ψ) axes defined as Euler angles that cause angular velocities to occur, and x, y and z axes that define linear motion in 3-dimensional space. The position and motions of the solid body in space cannot be described without reference frames. Thus, two coordinate systems can be used. The axis of the earth fixed inertial frame systems whose origin is at the center of the earth show respectively the North (N), East (E) and Down (D) directions. The body fixed frame is positioned at the center of mass and fixed to the body of the quadrotor. The axes of the body fixed frame are (x, y and z) and Earth-Fixed Frame (N, E and D) as shown in the Figure 1.

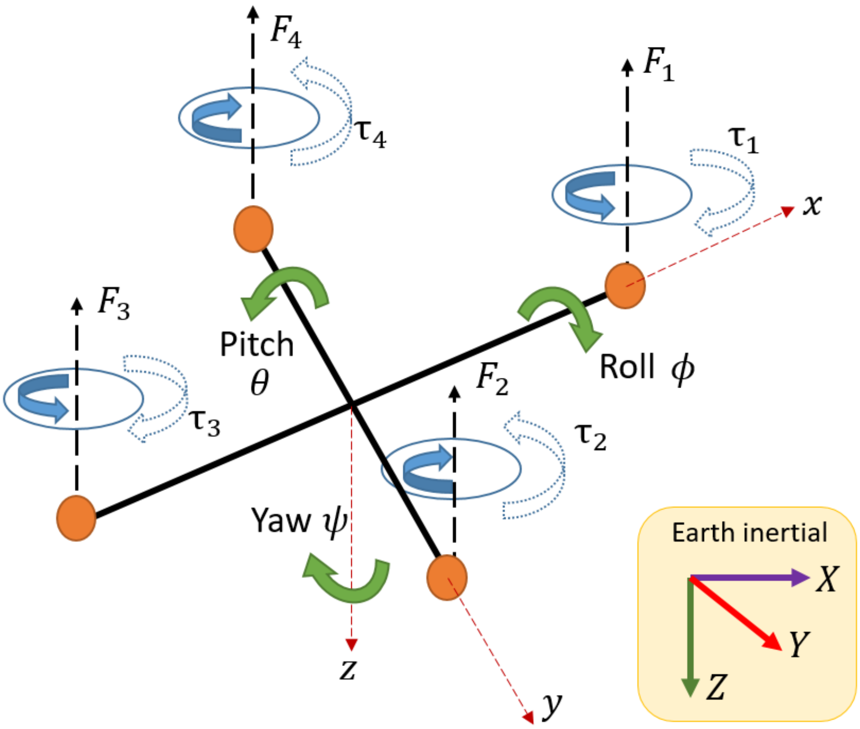


Figure 1. Earth Inertial and Body Fixed Frame of Quadrotor

2.1. Quadrotor Dynamics

The transformation matrix for converting body fixed frame to earth fixed frame system is used in derivation of the equations of motion. The transformation matrix is given in Equation (1).

$$R = \begin{bmatrix} \cos\theta\cos\varphi & \sin\phi\sin\theta\cos\varphi & \cos\phi\sin\theta\cos\varphi + \sin\phi\sin\varphi \\ \cos\theta\sin\varphi & \sin\phi\sin\theta \mathrm{s}\varphi + \cos\theta\cos\varphi & \cos\phi\sin\theta\sin\varphi - \sin\theta\cos\varphi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \tag{1}$$

Using transformation matrix in derivation of the equation of motion for the quadrotor, the following differential equation set is obtained [20]:

$$\ddot{\phi} = \frac{I_{yy} - I_{zz}}{I_{xx}}\dot{\theta}\dot{\psi} - \frac{J_r}{I_{xx}}\dot{\theta}\Omega_r + \frac{l}{I_{xx}}U_2$$
$$\ddot{\theta} = \frac{I_{zz} - I_{xx}}{I_{yy}}\dot{\phi}\dot{\psi} + \frac{J_r}{I_{yy}}\dot{\phi}\Omega_r + \frac{l}{I_{yy}}U_3$$
$$\ddot{\psi} = \frac{I_{xx} - I_{yy}}{I_{zz}}\dot{\theta}\dot{\phi} + \frac{l}{I_{zz}}U_4$$

$$\ddot{x} = -\frac{U_1}{m}\left(\sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta\right)$$
$$\ddot{y} = -\frac{U_1}{m}\left(\cos\phi\sin\theta\sin\psi - \cos\psi\sin\phi\right) \tag{2}$$
$$\ddot{z} = g - \frac{U_1}{m}\left(\cos\phi\cos\theta\right)$$

Equation (2) is used to write the system model in state-space form which is demonstrated in equation (3).

$$X = \begin{bmatrix} z & x & y & \dot{z} & \dot{x} & \dot{y} & \phi & \theta & \psi & \dot{\phi} & \dot{\theta} & \dot{\psi} \end{bmatrix} \tag{3}$$

The control input vector can be written as $U = [U_1\ U_2\ U_3\ U_4]$ and the equations are represented by;

$$\begin{aligned} U_1 &= K_f\left(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2\right) \\ U_2 &= K_f\left(\Omega_4^2 - \Omega_2^2\right) \\ U_3 &= K_f\left(-\Omega_1^2 + \Omega_3^2\right) \\ U_4 &= K_m\left(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2\right) \\ \Omega_r &= \Omega_2 + \Omega_4 - \Omega_1 - \Omega_3 \end{aligned} \tag{4}$$

In equation (4), control functions U_1, U_2, U_3, U_4 are functions of $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ which are speeds of motors and indicate the total thrust, pitch moment, roll moment and yaw moment, respectively. K_f and $K_m$are thrust and drag coefficients.

Table 1. Quadrotor Simulation Parameters

System Parameters	Value	Unit
I_{xx}	7.5e-3	$kg.m^2$
I_{yy}	7.5e-3	$kg.m^2$
I_{zz}	1.3e-2	$kg.m^2$
l	0.23	m
J_r	6e-5	$kg.m^2$
m	0.650	kg
K_m	7.5e-7	$N.m.s^2$

The movement of the quadrotor is caused by the rotation of the propellers. By adjusting the speed of the propellers appropriately, quadrotor can move to any direction and be rotated about any axis. Since we do not have a physical model while performing the simulation study, the constant values in [20] are used for the system related fixed values to test the simulation at the Table 1.

2.2.Linearization

An equilibrium point is needed to obtain an approximate linearized quadrotor model. The point can be used as an equilibrium point where the quadrotor is hovering at any x, y, z and it can be represented as [21]:

$$X = \begin{bmatrix} \bar{z} & \bar{x} & \bar{y} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

For the equilibrium point, hovering inputs are used as:

$$U = \begin{bmatrix} mg & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

The model obtained by linearizing the quadrotor at the equilibrium point is as follows [22]:

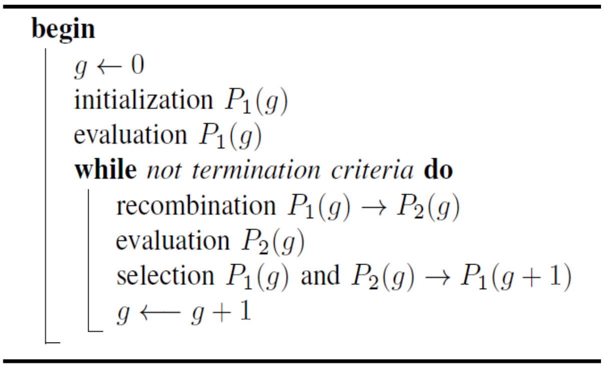
$$\begin{gathered} \ddot{X} = -\frac{1}{m}\theta U_1, \quad \ddot{Y} = \frac{1}{m}\phi U_1, \quad \ddot{Z} = -\frac{1}{m}U_1 + g \\ \ddot{\phi} = \frac{1}{I_{xx}}U_2, \quad \ddot{\theta} = \frac{1}{I_{yy}}U_3, \quad \ddot{\psi} = \frac{1}{I_{zz}}U_4 \end{gathered} \tag{7}$$

3. Solution Approaches

Genetic algorithm is a frequently preferred meta-heuristic algorithm for optimization problems; hence, it is far conventional to evaluate performances of other heuristic approaches with GA. In this section, a short presentation of GA, and detailed information about FA are given.

3.1.Genetic Algorithm

Genetic Algorithm (GA) is a popular method for tackling global optimization issues among meta-heuristic methods. GA arose as a result of biology's genetic organization being imitated. Each chromosome represents a specific problem solution. They are given a score that is determined by the objective function. Mutation and crossover are operations that are done to chromosomes in order to make new chromosomes or, in other words, new generations. The algorithm begins by generating an initial population with a specific number of chromosomes. After that, it keeps the chromosome with the highest fitness value. Then, utilizing genetic operators, a new generation is created. This process is continued until the algorithm's stopping requirements are fulfilled. Finally, the chromosome with the highest fitness value is the best answer to the problem. Figure 2 is a pseudo code that depicts the algorithm's stages.



```
begin
    $g \leftarrow 0$
    initialization $P_1(g)$
    evaluation $P_1(g)$
    while not termination criteria do
        recombination $P_1(g) \rightarrow P_2(g)$
        evaluation $P_2(g)$
        selection $P_1(g)$ and $P_2(g) \rightarrow P_1(g+1)$
        $g \longleftarrow g+1$
```

Figure 2. Pseudo code for Genetic Algorithm

3.2. Firefly Algorithm

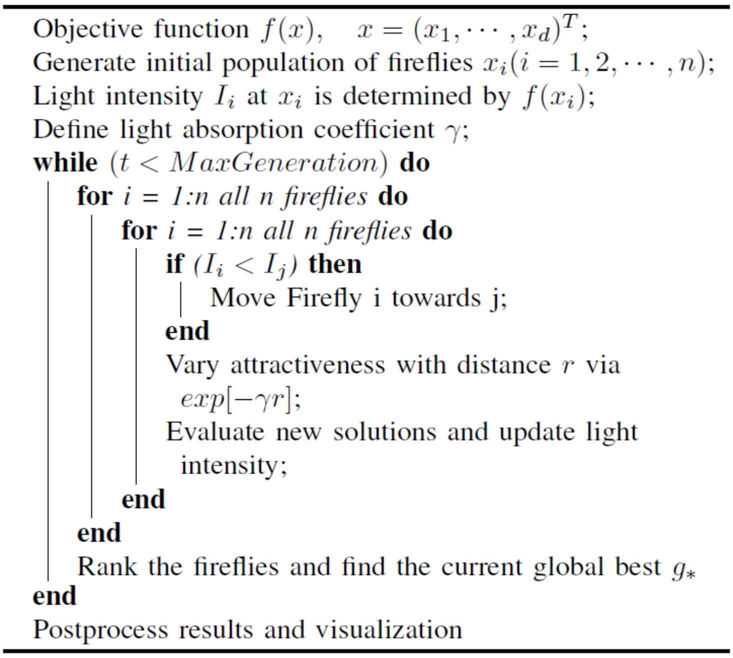
Xin She Yang announced the Firefly algorithm (FA) in 2008. It is a nature-inspired meta-heuristic algorithm [19]. The main goal of this method is to imitate firefly activity. Fireflies employ flashings as a means of communication. They use flashings in particular to attract any firefly for mating or hunting. Furthermore, these flashings might also serve as a threat warning. All fireflies are neutered, that means they may attract any other firefly. Attractiveness and light intensity are the two most important qualities of fireflies. The following is a definition of light intensity:

$$I(r) = \frac{I_s}{r^2} \tag{8}$$

where I_s refers to the light intensity at source and r is the gap between fireflies. The attractiveness of the flashing changes in proportion to its brightness. As a result, the distance between fireflies increases, the brightness of the flashing diminishes, and the attractiveness of the fireflies decreases. The following is a definition for attractiveness:

$$\beta = \beta_0 e^{\gamma r^2} \tag{9}$$

where β_0 refers to attractiveness at $r = 0$ and γ is the light absorption coefficient [19]. The fundamental notion of FA is that the brightness of the firefly represents the problem's objective function. Maximization problems, in particular, are related to brightness. Figure 3 depicts the algorithm's stages.



```
Objective function $f(x)$,    $x = (x_1, \cdots, x_d)^T$;
Generate initial population of fireflies $x_i (i = 1, 2, \cdots, n)$;
Light intensity $I_i$ at $x_i$ is determined by $f(x_i)$;
Define light absorption coefficient $\gamma$;
while ($t < MaxGeneration$) do
    for $i$ = $1{:}n$ all $n$ fireflies do
        for $i$ = $1{:}n$ all $n$ fireflies do
            if ($I_i < I_j$) then
                Move Firefly i towards j;
            end
            Vary attractiveness with distance $r$ via
              $exp[-\gamma r]$;
            Evaluate new solutions and update light
              intensity;
        end
    end
    Rank the fireflies and find the current global best $g_*$
end
Postprocess results and visualization
```

Figure 3. Pseudo code for Firefly Algorithm [19]

3.3. PD Control

Quadrotor is an under-actuated system which has 6 degrees of freedom despite having 4 actuators. Since these types of systems are not structurally linear, their control is also challenging. In this article, using the PD controller, position and altitude control were performed for the quadrotor linearized model. During the experimental trials, P, I and D gains were tried to be selected in the most appropriate way. The gains were tried by aiming to decrease the maximum overshoot, rise time and settling time and it was concluded that the integral gain did not contribute towards the purpose. To increase stability, decrease maximum peak overshoot and settling time at the same time to get rid of the complexity of the controller and reduce the cost PD controller was chosen as a controller. The PD controller generates a control signal over the error value between desired set point and actual values. The error value and the derivative of the error are weighted with predefined gain parameters and feed back to the system. The K_p and K_d gain values of PD and PD based controllers are selected in order to ensure the system response of the desired time and frequency criteria to ensure a stable controller-system mechanism. In this study, quadrotor dynamics model is implemented using MATLAB / Simulink tool and simulation experiments are performed. The block diagram of the PD controller shown in Figure 4.

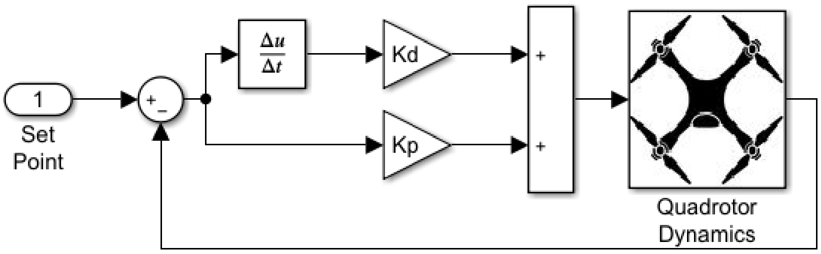


Figure 4. Block diagram of control system

To perform altitude, angle and position control, a three stage PD controller is designed using the quadrotor linear equations (7) obtained in the previous section shown in Figure 5.

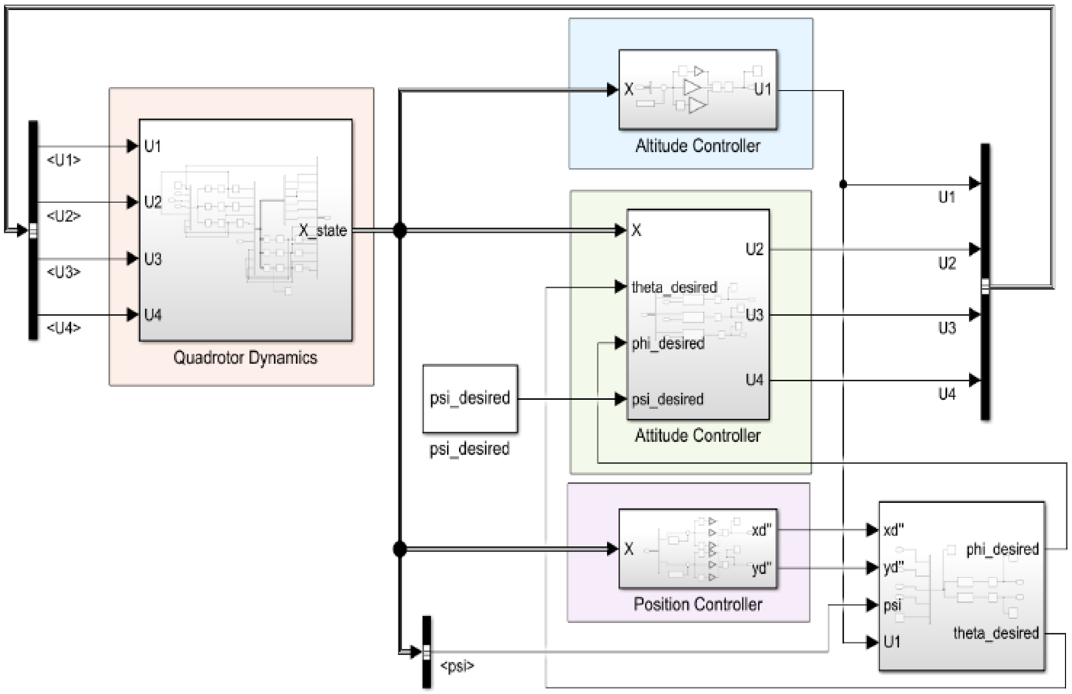


Figure 5. Simulink model of quadrotor control and dynamics

Firefly algorithm and Genetic algorithm are used to obtain the PD parameters shown in the Figure 6. The fitness function guides the Firefly algorithm to converge to the global optimal solution, so the choice of the fitness function plays a critical role. In this paper, using different objective functions for the quadrotor altitude control, Firefly and Genetic Algorithms were compared.

There are four different objective function criteria that are frequently used in increasing the output performance of the system. These criteria are called ISE (Integral Squared Error), IAE (Integral Absolute Error), ITAE (Integral Time-Weighted Absolute Error) and ITSE (Integral Time-Weighted Squared Error), are defined by the equations (10).

$$
\begin{aligned}
ISE &= \int_0^\infty e^2(t)dt \\
IAE &= \int_0^\infty |e(t)|\,dt \\
ITAE &= \int_0^\infty t\,|e(t)|\,dt \\
ITSE &= \int_0^\infty te^2(t)dt
\end{aligned}
\tag{10}
$$

where $e(t)$ is the error between input and output parameters.

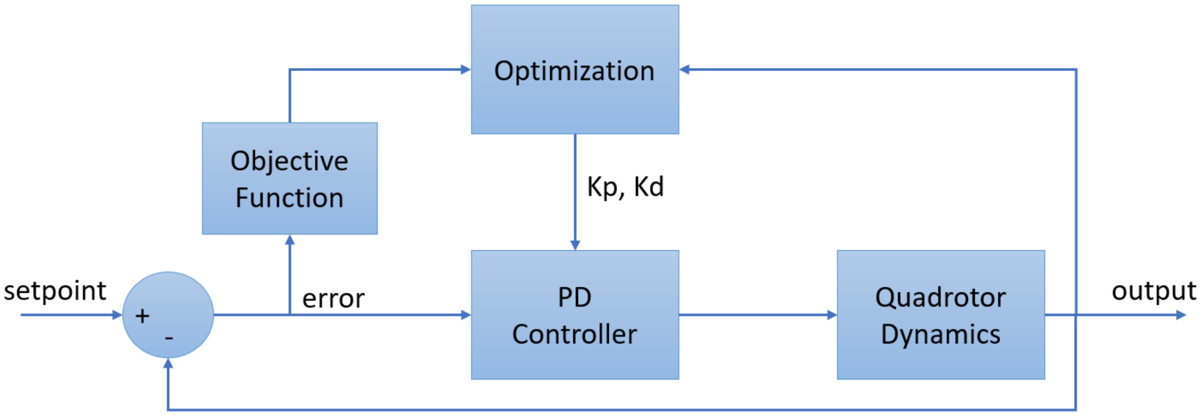


Figure 6. Block Diagram of optimized Quadrotor Control

4. Experimental Results

Quadrotor altitude control was performed using the proposed PD controller. PD control parameters were obtained by using Genetic Algorithm and Firefly Algorithm for ITSE, ITAE, ISE and IAE performance indexes. These functions give the size of the error occurring with time, and minimizing this function in the optimization problem means adjusting the PD parameters to obtain the least error. To simulate the model, quadrotor motion equations are performed on Simulink blocks. Algorithm settings are as in Table 2.

Table 2. Parameters for GA and FA

GA	Population	20
	Number of tests	10
	Crossover rate	0.9
	Mutation rate	0.05
FA	Population	20
	Number of tests	10
	Beta	0.5
	Gamma	0.2

Table 3 shows the obtained PD control parameters for different objective functions using genetic algorithm method and the performance results obtained applying these parameters to the controller.

Table 3. Altitude control using GA

	ITAE	**IAE**	**ISE**	**ITSE**
K_p	365	228.74	918.65	255.03
K_d	86.5	45.87	291.38	53.51
Max. Overshoot	0.0012	0.0024	0	0
Steady State Error	0.0175	0.0279	0.0069	0.0251
Rise Time	0.7913	0.7411	0.9087	0.7538
Settling Time	1.4867	1.3710	1.7366	1.4015
Best Obj. Func. Value	1.7	3.56	13.79	4.35

The comparison of the output values created using the best parameters of the PD controller obtained using GA is given in Figure 7.

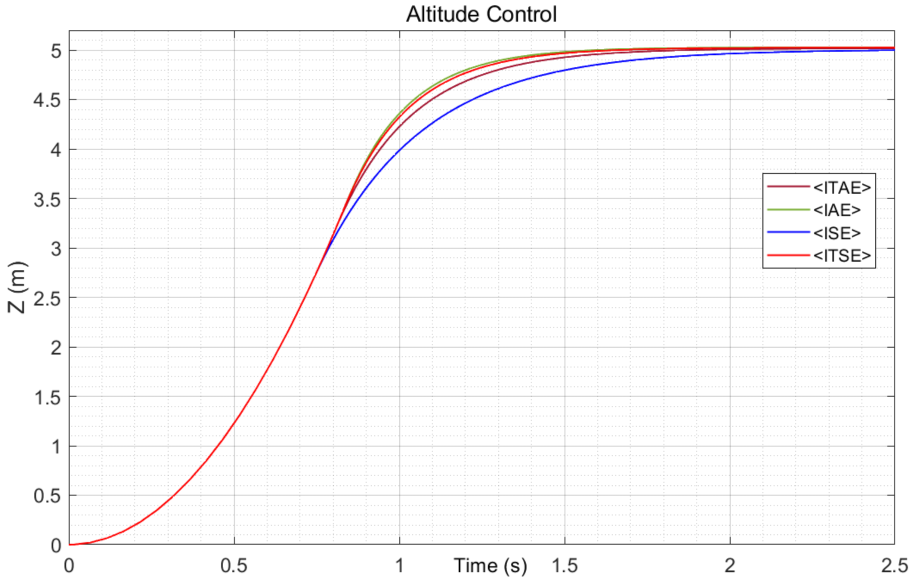


Figure 7. Quadrotor GA based PD altitude control

In the Figure 7 the outputs obtained for different objective functions are compared. At the graphs, it is observed that as steady state error is minimum for ITAE and ISE criteria, the steady state is achieved pretty quickly for IAE criteria. Table 4 shows the PD controller parameters for different criteria using FA and the performances obtained using these parameters.

Table 4. Altitude control using FA

	ITAE	IAE	ISE	ITSE
K_p	430.33	500.01	600.65	964.08
K_d	73.32	54.29	71.73	42.35
Max. Overshoot	0	0.037	0	0.001
Steady State Error	0.0149	0.0128	0.0107	0.0067
Rise Time	0.7092	0.6584	0.6666	0.6417
Settling Time	1.42908	1.1388	1.1686	1.0163
Best Obj. Func. Value	1.55	3.44	13.49	4.25

Figure 8 shows PD control responses of different objective functions for FA.

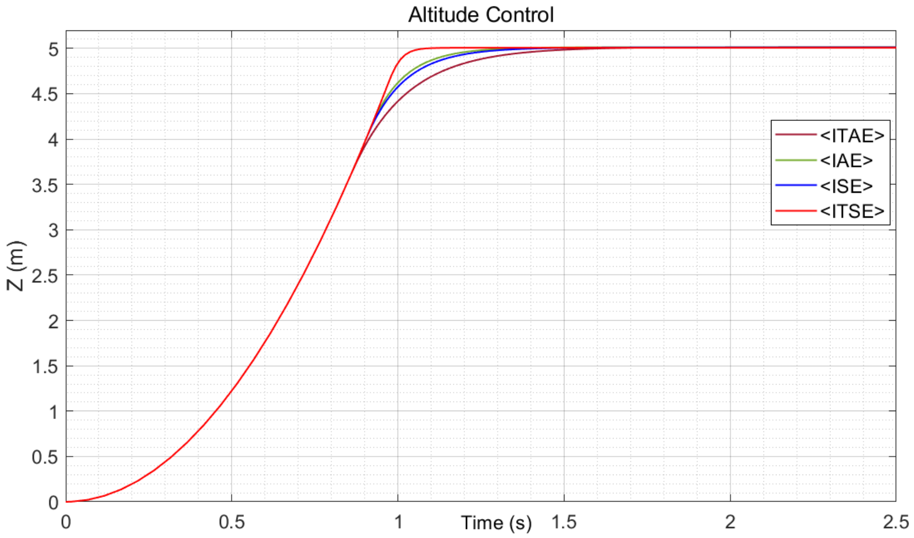


Figure 8. Quadrotor FA based PD altitude control

The comparison of the output values created using the best parameters of the PD controller obtained with the FA code run is given in Figure 8. At the graph, it was observed that the maximum overshoot is similar for ISE and ITSE criteria and the ITSE criterion sat at the desired height in a short time. As shown in Figure 7 and 8, in altitude control performed with ITAE, ITSE, IAE and ISE objective functions. Considering the test results, it is seen that the FA PD controller is superior to the GA PD controller.

Table 5. Quadrotor Control PD Parameters.

	Parameters	**X,Y**	**Z**	**θ, Φ**	**Ψ**
GA	K_p	409,04	555,34	768,44	365,51
	K_d	243,16	726,08	120,63	205,54
FA	K_p	623,46	419,61	464,5	438,46
	K_d	405,1	347,18	76,99	574,8

Settling time and steady state error and settling time have critical importance for robust control methodology. In the experiment, comparing the different objective functions used with the FA PD controller, it is seen that the ITSE objective function gives more satisfactory results.

Table 6. FA and GA based Position and Altitude Control

		X, Y	**Z**
ITSE GA	Max. Overshoot (%)	6,04	0
	Steady State Error	0.0417	0,2587
	Rise Time	1.2087	2,3647
	Settling Time	3.3101	3.6069
ITSE FA	Max. Overshoot (%)	5.0339	0
	Steady State Error	0,0415	0.0316
	Rise Time	1.1833	1,7757
	Settling Time	3.2827	3.1466

In the second stage of the study, complete position and altitude control performed. Controller was designed using the PD controller. PD parameters are obtained with FA and GA. ITSE criteria is using as objective function. Table 5 shows the obtained PD control parameters for the position and altitude controller. The results are compared in the Table 6.

The Figure 9 and Figure 10 shows position and altitude graphs for FA and GA. It is ascertaining from the graphs that the FA algorithm reaches a steady state in a shorter time and steady state error is lower for FA based PD control.

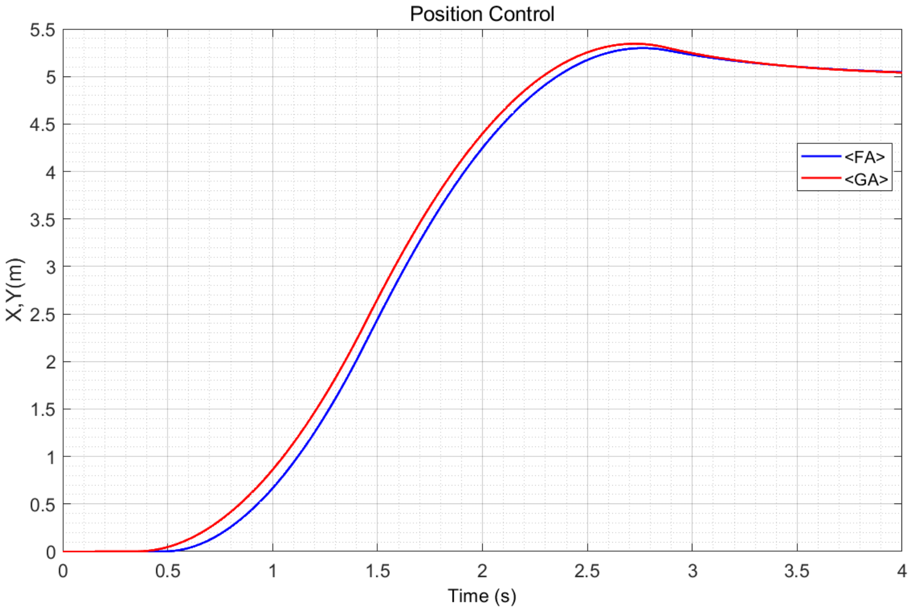


Figure 9. Comparison of the quadrotor position control between GA based PD control and FA based PD control for ITSE objective function

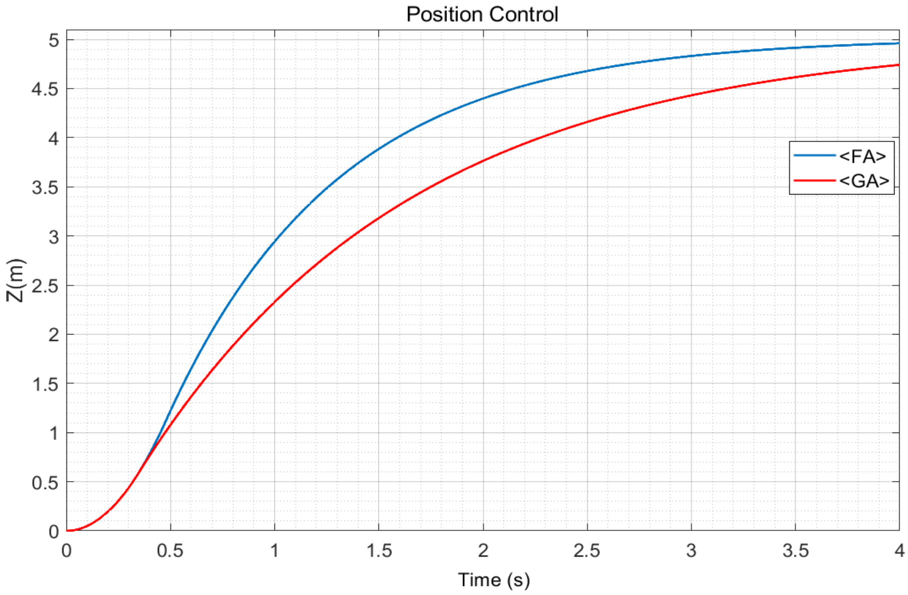


Figure 10. Comparison of the quadrotor altitude control between GA based PD control and FA based PD control for ITSE objective function

5. Conclusions

This paper presents the two types of optimization method with four different objective function criteria for quadrotor PD altitude and position control. The nonlinear dynamic model of the quadrotor linearized at the equilibrium point. After that, PD controller were designed to control altitude and position of the quadrotor. Using Genetic Algorithm and Firefly Algorithm optimization methods PD controller parameters were tuned. Linearized dynamics and PD controller were designed at the MATLAB Simulink environment. At the first stage of experiment, PD controller designed to control altitude of the quadrotor. It seen from the study, firefly algorithm with ITSE objective function reduced steady state error and shortened settling time for altitude control. Lastly, ITSE objective function were used with both optimization algorithms to achieve PD position control of the quadrotor. The simulation shows that, Firefly Algorithm based PD controller uses ITSE objective function is more effective in reaching the desired position in a shorter time with smaller error.

Authors' Contributions

The authors contributed equally.

Competing Interests

The authors declare that they have no competing interests.

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