Helicopter Stabilization Using Integer and Fractional Order PID Controller Based on Genetic Algorithm

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Abstract. Fractional Order Proportional, Integral, Derivative (FOPID) controller is a modified Proportional Integral Derivative (PID) controller, which has fractional orders for its derivative and integral parts rather than an integer. Two techniques, namely, PID and FOPID, are adopted to design and implement a Three Degree of Freedom (3DOF) control system to stabilize pitch, roll and travel axes of the helicopter system. In this study, an improvement in the performance of the controllers is achieved using the Genetic Algorithm (GA) optimization method which is employed to find optimum parameter values for controller gains. The helicopter control system is modeled mathematically and then simulated using MATLAB environment to verify the performance of the proposed PID and FOPID controllers based on the GA tuning method. Simulation results suggest that the GA-FOPID controller compared with GA-PID controller can achieve faster and more stable control performance for the 3DOF helicopter system.

Keywords: PID controller, FOPID controller, 3DOF helicopter system, Genetic Algorithm Optimization.

1 Introduction

Helicopters are nonlinear and complex systems and have multiple inputs and multiple-output (MIMO). Designing a control system to stabilize the helicopter system considered a challenging problem due to its nonlinear characteristics unstablity. For these reasons, the dynamic model of the helicopter plant can be linearized to simplify the controller design. This linearization is suitable for designing controllers for hovering, rolling, pitching and traveling, but not for aggressive flight scenarios and this designed controller should be able to regulate the three required responses for the 3DOF helicopter model. The aim of the controller is to make the system respond meets the desired requirements regarding overshoot, rise time, settling time and error steady-state while maintaining high stability and robustness of the system and, at the same time, gives the system the ability to reject any disturbance and noise. The most popular controller is the PID controller, which is widely recommended for most of the industry and movement applications due to its simplicity and easy to realize as its gain parameters are relatively independent. This controller can be further improved by using fractions, instead of an integer, integral and derivative actions which are FOPID controllers. This improves the effectiveness of total control performance, especially when deals with dynamical systems and, when control parameters change. It is affected less than the traditional controller because it has higher design flexibility where it's five parameters can more easily be tuned [1], [2]. Leibniz and Hopital were the first who used the fractional generation in the mid of the 17th century, after that, many

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researchers were interested in this field such as Liouville in 1832 and Holmgren in 1864. For Helicopter system, the efficiency of the proposed FOPID controller with GA is demonstrated by comparing it with the traditional PID controller, which is also optimized using GA [3], [4], [5]. There work were mainly focuses on the helicopter dynamics where it is extremely complex and nonlinear in addition to the ambient disturbance that can not be neglected. After converted the helicopter model to a linear time-invariant model, the design of the controller will be presented to meet the design requirement while maintaining stability. The simulation results indicate that despite PID gives good results, FOPID has better performance.

2 Fractional order controller

Differentiation and integration orders in fractional calculus can be any number (usually between 0 and 1) and the fundamental operator is given by D_t^α where $(\alpha \in \Re)$ for the non-integer order where α and t are the bounds of the operation [5].

$$aD_t^\alpha = \begin{pmatrix} \frac{d^\alpha}{dt^\alpha} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_\alpha^t (d\tau)^{-\alpha} & \alpha < 0 \end{pmatrix}$$

The differentiator D_t^α has two used definitions, these definitions are required for the control algorithm that will be used.

1- Grunwald – Letnikov

$$aD_t^\alpha f(t) = \lim_{h\to 0} \frac{1}{h^\alpha} \sum_{j=0}^{\left[\frac{t-\alpha}{h}\right]} (-1)^j j^\alpha f(t - jh) \tag{1}$$

Where $\left[\frac{t-\alpha}{h}\right]$ is the upper limit of the universe, while h is the grid size.

2- Riemann- Liouville

$$aD_t^\alpha f(t) = \frac{1}{\Gamma(1-a)} \frac{d^n}{dt^n} \int_0^t \frac{f(\tau)}{(t-\tau)^{a-n+1}}\, d\tau \tag{2}$$

Where: $n - 1 < a < n$

The definition of the gamma function, Γ(.), is given by:

$$\Gamma(x) = \int_0^\infty z^{x-1} e^{-z}\, dz \tag{3}$$

Where $z \in \mathbb{R}_{>0}, x \in \mathbb{C}$

The Laplace transform of equation (1) is represented in equation (4)

$$L[aD_t^\alpha f(t)] = \int_0^\infty e^{-st} aD_t^\alpha\, f(t)dt = s^\alpha F(s) - \sum_{m=0}^{n-1} s(-1)^j \; {}_0D_t^{\alpha-m-1} f(t) \tag{4}$$

Because the value of α lies between n-1 and n, and by considering all initial conditions as zeros, equation (4) can be simplified as shown in equation (5)

$$L[aD_t^{\alpha}f(t)] = s^{\alpha}F(s) \quad (5)$$

The fractional-order PID ($PI^{\lambda}D^{\mu}$) has five gain parameters (kp, ki, kd, λ and μ) and the total effect U(t), is the mathematical summation of all of the three segments as shown in equation (6) while its transfer function is shown in equation (7) [6].

$$u(t) = kp\, e(t) + ki\, D^{-\lambda}\, e(t) + kd\, D^{\mu}\, e(t) \quad (6)$$

$$G_{FOPID}(s) = kp + \frac{ki}{s^{\lambda}} + kd\, s^{\mu} \quad (7)$$

By changing the values of λ and μ, all types of PID controller and its sub-controllers can be obtained. For example, if PI controller is required, values of λ and μ will be 1 and 0 respectively but if it is required to have FO-PI, then the value of λ will be $0 < \lambda < 1$while μ is kept equal to zero. The difference between PID and FOPID can be further explained as shown in figure 3 where the selection between P, PI, PD and PID can be described as points while in FOPID it can be represented as area or rectangular [7], [8]. From figure 1, it is clear that when values of λ and μ equal to 1, the FOPID controller will PID controller.

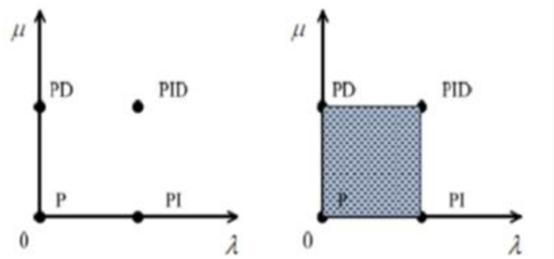

Fig. 1. PID Controller and FOPID Controller

3 Helicopter mathematical modeling

Figure 2 shows a conceptual platform of 3DOF helicopter system where pitch, roll and travel axes are illustrated with the other required elements like the sensors, motors and balance blocks.

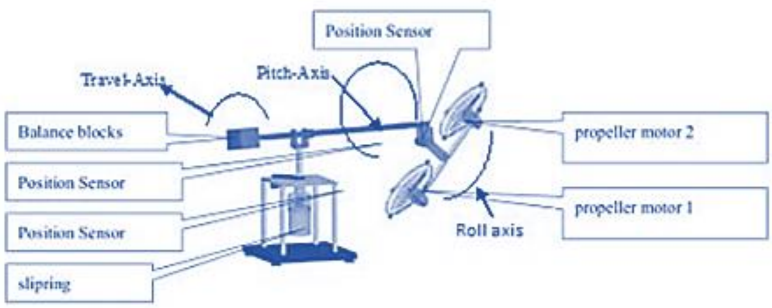

Fig. 2. 3-DOF Helicopter System [9]

The overall dynamic model of the 3-DOF helicopter is nonlinear and during the linearization process, some assumptions have been used. These assumptions are: all angles are sufficiently small ($\pm 5°$), also, coupling dynamics, gravitational torque and friction forces are neglected [10], [11]. According to these assumptions, the helicopter's motion can be effectively represented by equations (8). The physical parameter's values of the system that have been used are shown in Table 1.

$$J_{\epsilon}\ddot{\epsilon}(\mathrm{t}) = K_c l_1 V_s(\mathrm{t}) \tag{8a}$$

Where ∈ is the pitch angle, J_{ϵ} is the moment of inertial, l_1 is the distance between the propeller and the pivot point, Kc is the motor's force constant.

$$J_p\ddot{p}(\mathrm{t}) = K_c l_p V_d(\mathrm{t}) \tag{8b}$$

Where p is the roll angle, J_p is the moment of inertia about the roll axis, l_p is the distance between one motor and the roll axis.

$$J_t\dot{r}(\mathrm{t}) = G l_1 p(\mathrm{t}) \tag{8c}$$

Where r is the travel rate, J_t is the moment of inertia about the travel axis, G is the force required to maintain the helicopter in flight

Table 1. Physical parameters of the helicopter system [12]

Symbol	Physical unit	Numerical values
J_e	Kg.m^2	1.8145
J_t	Kg.m^2	1.8145
J_p	Kg.m^2	0.0319
G	N	4.2591
l_1	m	0.88
l_2	m	0.35
l_p	m	0.17
K_c	N/V	12

From Table 1 and by taking Laplace transform of (8), the transfer functions of pitch, roll and travel axes can be represented in equation (9).

$$G_p(s) = \frac{\epsilon(s)}{V_s(s)} = \frac{K_c l_1}{J_{\epsilon}.s^2} = \frac{10.56}{1.815\, s^2} \tag{9a}$$

$$G_r(s) = \frac{P(s)}{V_d(s)} = \frac{K_c l_p}{J_p s^2} = \frac{2.04}{0.0319 s^2} \tag{9b}$$

$$G_t(s) = \frac{r(s)}{p_c(s)} = \frac{G l_1}{J_t s} = \frac{3.748}{1.815\, s} \tag{9c}$$

4 Genetic fractional-order $PI^{\lambda}D^{\mu}$ controller

Finding an appropriate solution to solve an optimal control problem is not easy task and it is time-consuming. However, there are optimal methods that can be used to give optimal responses directly. Genetic Algorithm (GA) is an optimal search method that makes use of the process of natural evolution and uses it in optimal control. The fitness function considered as the heart of the GA where it will be used to evaluate the GA performance after completing the Selecting, Crossover and Mutation which are the main stages of the GA [13]. Defining the representation of the chromosome is the first stage of the tuning procedure, for this work, k_p, k_i, k_d, λ and μ are the five values of the chromosome which are the FOPID gains [14]. These gains are real and represent the individuals that have to be evaluated in order to obtain the optimal behavior of the system.

The fitness function selection is very important where choosing a different type of fitness function gives different results. For this system, as it required to eliminate the steady-state error while reduce the settling time, time-integral are essential and comprehensive tools to improve the performance of the system. So, Integral Time Square Error (ITSE) has been used as the objective function and it has the form shown in equation (10).

$$\mathrm{ITSE} = \int_0^T t(e(t))^2 dt = \int_0^T t(r_i(t) - y_i(t))^2 dt \quad (10)$$

Where r_i is a reference variable, y_i is controlled output and e_i is the control error. Parameters that describe the GA used in this study are summarized by Table 2 depending on the system specifications and it can be changed for different systems [15].

Table 2. Parameters of GA

GA property	Value/Method
Population Size	20
Max No. Of Generation	100
Fitness Function	ITSE
Selection Method	Normalized Geometric Selection
Crossover Method	scattering
Mutation Method	Uniform Mutation

The GA-PID and the FOPID controllers for Helicopter are shown in figure 3 and figure 4 respectively which are connecting three GA-PID and FOPID controllers for pitch, roll positions and travel speed of the 3-DOF helicopter model.

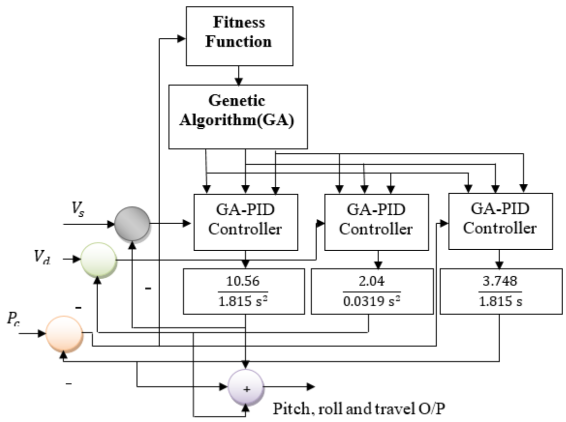

Fig. 3. GA-PID controller for 3-DOF Helicopter system

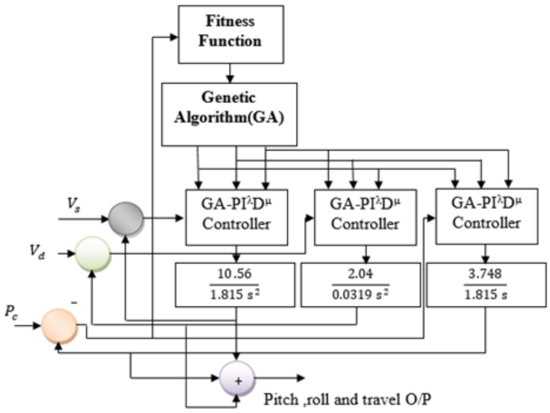

Fig. 4. GA-FOPID controller for 3-DOF Helicopter system

5 Simulation and results

When start running GA optimization method, different values of gain will be found and used in the fitness function until the fitness function (ITSE) has the minimum value. Figure 5 shows how gains' values change with every iteration while GA optimization is running; figure 5 (a) and (b) is taken for GA-PID while figure 5 (c) is for GA-FOPID.

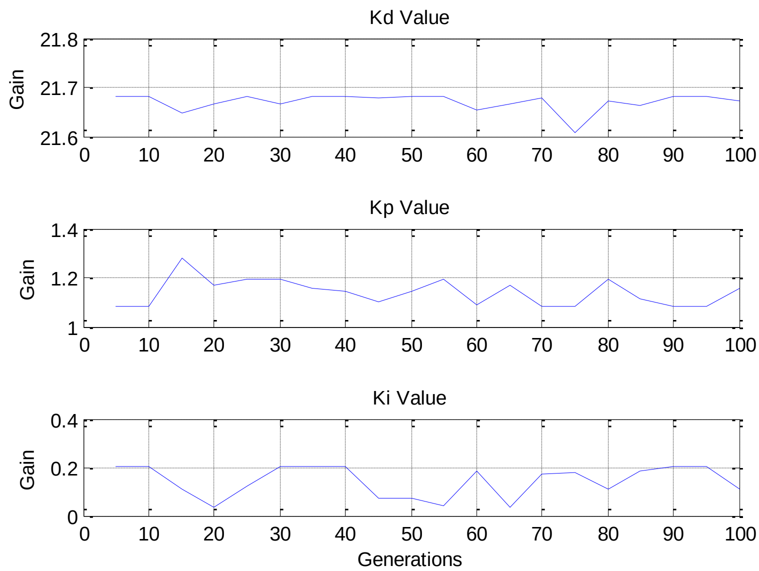

Fig. 5. (a) Generation Number of GA-PID Parameters of pitch angle

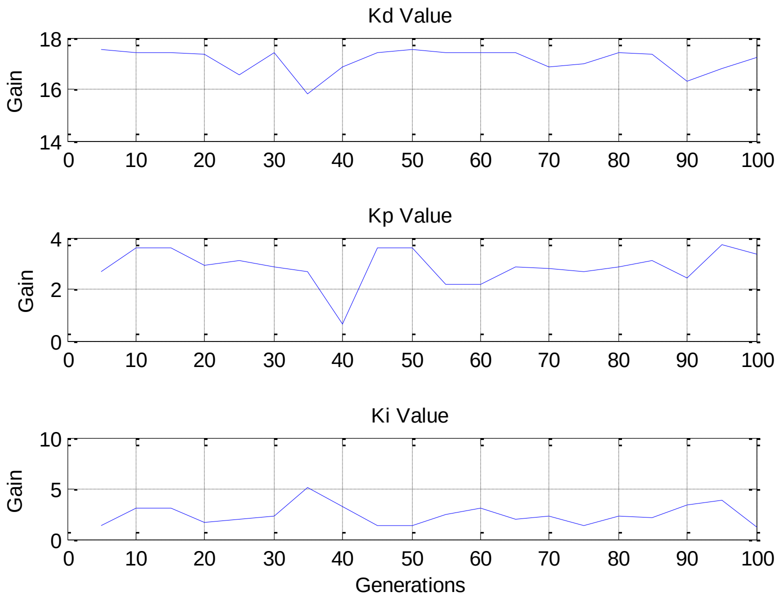

Fig. 5. (b) Generation Number of GA-PID parameters of roll angle

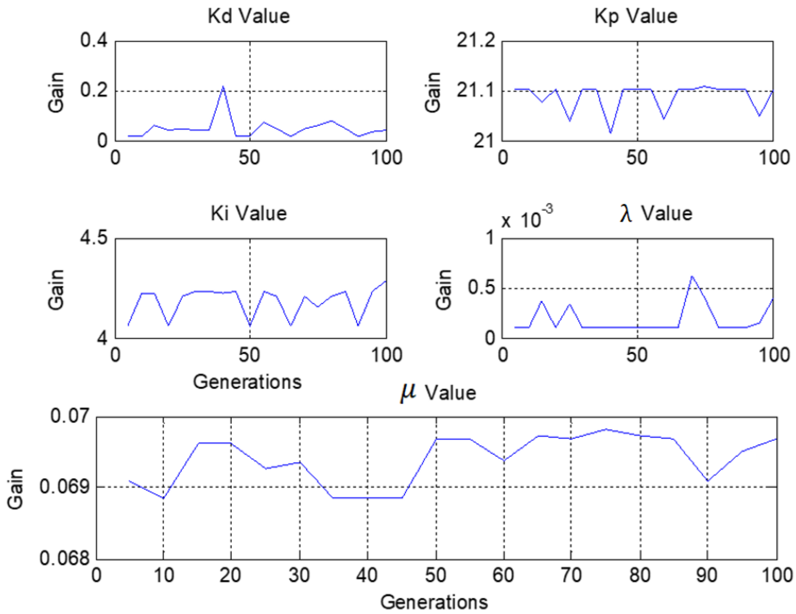

Fig. 5. (c) Generation Number of GA-FOPID Parameters of travel angle.

The optimized control parameters of the GA-PID and GA-FOPID controllers for pitch, roll and travel axis are listed in Tables 3,4,5 respectively.

Table 3. Pitch controllers' parameters

Controller Parameters	GA-PID Controller	GA-FOPID Controller
Kp	1.15721	1.53995
Kd	21.6823	15.094
Ki	0.20153	1.88013
λ		0.0475849
μ		0.0000419924

Table 4. Roll controllers' parameters

Controller Parameters	GA-PID Controller	GA-FOPID Controller
Kp	3.58432	1.76059
Kd	17.5204	16.1682
Ki	1.40493	2.43707
λ		0.0575099
μ		0.000266574

Table 5. Travel controllers' parameters

Controller Parameters	GA-PID controller	GA-FOPID controller
Kp	12.7958	21.1021
Kd	0.000390317	0.01848
Ki	3.30464	4.06198
λ		0.000097925
μ		0.0697347

After finding controllers parameters, close loop transfers functions of pitch, roll and travel angles will be derived. For GA-PID close loop transfer functions of pitch, roll and travel axes are represented in equations (11, 12, 13) respectively.

$$TF_{p(s)} = \frac{229\, s^2 + 12.22\, s + \ 2.128}{1.815\, s^3 + 229\, s^2 + 12.22\, s + 2.128} \tag{11}$$

$$TF_{r(s)} = \frac{35.74\, s^2 + 7.312\, s + 2.866}{0.0319\, s^3 + 35.74\, s^2 + 7.312\, s + 2.866} \tag{12}$$

$$TF_{t(s)} = \frac{0.001463\, s^2 + 47.96\ \ s + 12.39}{1.816\, s^2 + 47.96\, s + 12.39} \tag{13}$$

For GA-FOPID controller, FOPID controller has a different configuration where its "s" order is fractional so, the close loop transfer functions will be derived as shown in equations (14, 15, 16) for roll, pitch and travel angle respectively.

$$TF_{p(s)} = \frac{159.46\, s^{0.047642} + 16.262\, s^{0.0476} + 19.853}{1.815\, s^{2.0476} + 159.46\, s^{0.047642} + 16.262\, s^{0.0476} + 19.853} \quad (14)$$

$$TF_{r(s)} = \frac{32.983\, s^{0.057778} + 3.5924\, s^{0.05751} + 4.972}{0.0319\, s^{2.05751} + 32.983\, s^{0.057778} + 3.5924\, s^{0.05751} + 4.972} \quad (15)$$

$$TF_{t(s)} = \frac{0.07\, s^{0.0698} + 79.842\, s^{0.0001} + 15.4}{0.0319\, s^{1.0001} + 0.07\, s^{0.0698} + 79.842\, s^{0.0001} + 15.4} \quad (16)$$

An improvement in the performance of the control system is achieved by using the GA tuning method. It is obvious from figure 6 that the settling time of the system response is very small while the overshoot is reduced. Further improvements in the stability and speed of the helicopter control system using FOPID controller based on the GA optimization method are achieved.

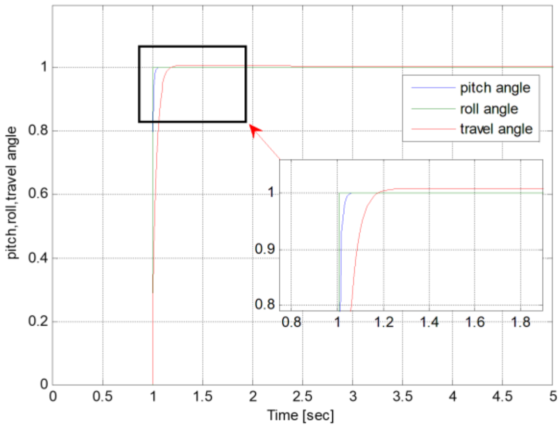

Fig. 6. GA-PID Controller response of pitch, roll and travel angle

It can be seen from the mini figure of figure 7 that a further reduction in the rise and settling time with zero overshoot is obtained using the optimized GA-FOPID. Consequently, it can be said that GA-FOPID controller can effectively achieve a more stable and faster response than GA-PID controller for the helicopter control system. Time response specifications of pitch, roll and travel controller based on GA-PID and GA-FOPID technique are stated in Tables 6, 7 and 8 respectively.

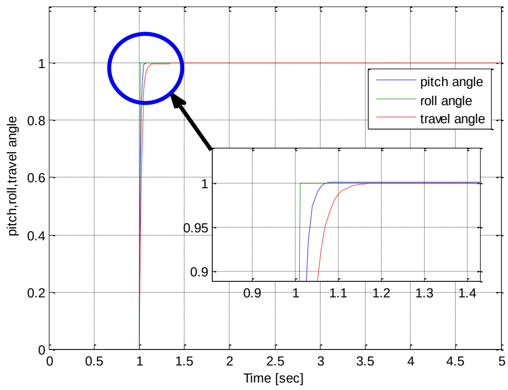

Fig. 7. GA-FOPID Controller response of pitch, roll and travel angle

Table 6. Pitch response specifications

Specifications	GA-PID controller	GA-FOPID controller
Settling Time ,ts (Sec)	0.03	0.0294
Rise Time ,tr (Sec)	0.0173	0.0167
Over Shoot Mp %	0.0578	0.101

Table 7. Roll response specifications

Specifications	GA-PID controller	GA-FOPID controller
Settling Time ,ts (Sec)	0.0098	0.0087
Rise Time ,tr (Sec)	0.008	0.0076
Over Shoot Mp %	0.0211	0.0106

Table 8. Travel response specifications

Specifications	GA-PID controller	GA-FOPID controller
Settling Time ,ts (Sec)	0.135	0.0898
Rise Time ,tr (Sec)	0.0809	0.0505
Over Shoot Mp %	1.01	0

6 Conclusion

In this paper, a control system for 3DOF helicopter system is proposed. The desired pitch and roll positions, as well as angular travel speed of the helicopter model, were effectively regulated by using PID and FOPID controller. GA method was adopted to tune the gain parameters of the controllers. PID and FOPID controllers based on GA optimization technique are simulated using MATLAB tool to evaluate the proposed helicopter control system. The simulation results have shown that the GA-FOPID controller compared with GA-PID controller can provide a faster response with minimal overshoot and steady-state error for 3DOF helicopter system.

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