Design of Fractional Order PID Controller Based on Genetic Algorithm Optimization for Vertical Take-Off and Landing Platforms

Ali Mahmood[11], Mohammed Almaged[2], Abdulla I. Abdulla[3]

[1]Systems and Control Engineering Department, Ninevah University, Mosul
ORCID No: https://orcid.org/0000-0003-3969-0857
[2] Systems and Control Engineering Department, Ninevah University, Mosul
ORCID No: https://orcid.org/0000-0003-3060-9266
[2] Systems and Control Engineering Department, Ninevah University, Mosul
ORCID No: https://orcid.org/0000-0003-4025-3478

Keywords

PID Controllers, FOPID Controllers, Genetic Algorithms, Unmanned aerial vehicles, VTOL platforms.

Abstract

This research studies the procedure of analyzing and designing of a fractional order PID controller (FOPID) with the genetic algorithm (GA) as optimization method to control the pitch angle of vertical take-off and landing system (VTOL). The VTOL system has been manipulated in many areas because they have stable flight and simple necessities. The VTOL system has been modeled by taking the action of the torque of the rigid body then finding the equations of the angular motions. The transfer function of the current to the position dynamics of the VTOLhas been found. The fractional order PID controller is considered as a modified type of the PID controller because it has fractional orders for the integral and derivative sections instead of being integers. The GA optimization method will be used to find the optimal values for the parameters of the controller, while three fitness functions will be used, including mean square error (MSE), integral time square error (ITSE) and integral square error (ISE). The performances of the controllers have been compared relating to the maximum overshoot, rise time, settling time, and steady-state error. The results show that the ISE gives better behavior in terms of the transient and the steady state response specifications.

Research Article
Submission Date : 17.05.2023
Accepted Date : 12.06.2023

1. INTRODUCTION

Conventional PID controller is considered as superior kind of feedback controls in many fields including industry and academic for many reasons involving its uncomplicated design and the ability to deal with the transient and steady state responses (S Dawood et al., 2018). However, it also has downsides including a less efficient performance (Shah & Agashe, 2016). Recently, researchers attracted to the analysis and design of the fractional order PID controllers. This controller was firstly proposed by (Zhao et al., 2005)

[1]Resp author; e-mail: ali.mahmood@uoninevah.edu.iq

and since then it has been used in numerous applications of many filed such as control application, material science, robotics, etc. (Mahmood et al., 2021). One of the challenging parts regarding the FOPID design is the selection of the tuning method (Shah & Agashe, 2016). In this work, GA optimization method has been used to select the optimal values for the Kp, Ki, Kd, μ and λ and applied on a (VTOL) system. UAVs considered as dynamically growing area of knowledge and have many applications in both military and civil fields including surveillance, firefighting, etc. (Lin et al., 2020; Zhang et al., 2014; Becker & Sheffler, 2016). The role of the controller is to keep the pitch angle as required by controlling the position of the propeller tilt angle. (Bauersfeld & Ducard, 2020). The aim of their study was to verify the effectiveness of the adaptive landing. The outline of the paper is organized as follow: Firstly, the model of the VTOL is presented. Secondly, a separate section for the FOPID is presented. Then, GA is discussed in details. Followed by a section for the results and discussion. Finally, a conclusion section is provided.

2. VERTICAL TAKE-OFF AND LANDING MODELING

The model of vertical takeoff and landing (VTOL) system has been built and used as a benchmark to evaluate and test the performance of different control systems. This system consists of a propeller actuator and a counterweight connected by a rod. This propeller actuator actually a fan with variable speed and by controlling its speed, the system can mimic the behavior of UAVs regarding the pitch angle. Figure (1) shows the free body diagram (FBD) of the VTOL device that rotates around its pitch axis.

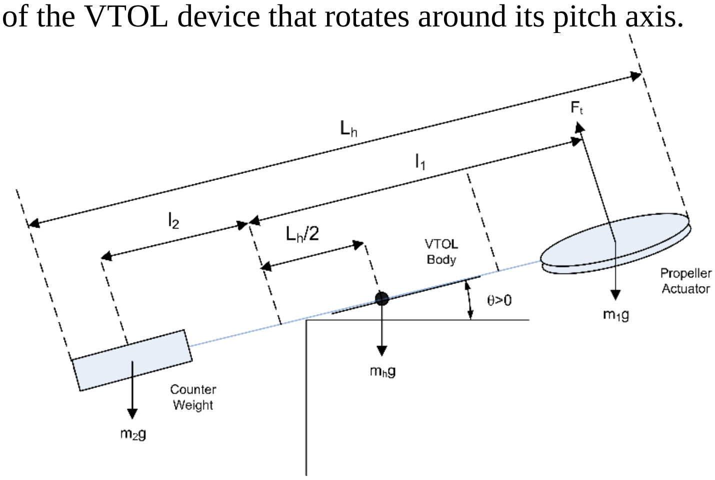

Figure 1. FBD of 1-DOF VTOL

The equations of torque acting can be summed and described by equation (1). While the equations that describe the angular motions in term of the thrust torque can be fully expressed by equation (2). Finally, the obtained transfer function of the current to position of the VTOL is shown in equation (3).

$$\left\{\begin{matrix} \tau t \ + \ m2 \ g \ l2 \cos\theta(t) - \ m1 \ g \ l1 \cos\theta(t) - \frac{1}{2} \ mh \ g \ Lh \cos\theta(t) \ = \ 0 \\ \tau t \ = \ Ft \ l1 \\ \tau t \ = \ Kt \ Im \\ Kt \ Im \ + \ m2 \ g \ l2 \cos\theta(t) \ - \ m1 \ g \ l1 \cos\theta(t) \ - \frac{1}{2} mh \ g \ Lh \cos\theta(t) \ = \ 0 \\ Kt \ Ieq \ + \ m2 \ g \ l2 \ - \ m1 \ g \ l1 \ - \frac{1}{2} mh \ g \ Lh \ = \ 0 \end{matrix}\right\} \quad (1)$$

$$\left\{\begin{matrix} J \ \ddot{\theta} \ + \ B \ \dot{\theta} \ + \ K \ \theta \ = \ \tau t \\ J \ \ddot{\theta} \ + \ B \ \dot{\theta} \ + \ K \ \theta \ = \ Kt \ Im \\ J = \sum_{i=1}^{n} m_i \ r_i^2 \end{matrix}\right\} \quad (2)$$

$$P(s) = \frac{K_t}{J\left(s^2 + \frac{B}{J}s + \frac{K}{J}\right)} \quad (3)$$

Table (1) sums up all the parameters and symbols that has been used and mentioned in equations (1, 2, 3) for the VTOL system.

Table 1. VTOL system parameters and values

Parameter	Symbol	Value	Unit
Equilibrium Current	I_{eq}	1.0	*A*
Torque-thrust Constant	K_t	0.0226	*(Nm)/A*
Moment of Inertia	J	0.0035	Kgm^2
Viscous Damping	B	0.002	*(Nms)/rad*
Natural Frequency	w_n	2.52	*rad*
Stiffness	K	0.022	*(Nm)/rad*
Measured Torque-thrust Constant	K_{tid}	0.01	*(Nm)/A*
Measured Viscous Damping	B_{id}	0.006	*(Nms)/rad*
Measured Stifness	K_{id}	0.015	*(Nm)/rad*
Length of the setup	L_h	0.3	*m*

3. FOPID CONTROLLER

The characteristics of PID controllers can be more enhanced by appropriate manipulation of its integral and derivative actions. Therefore, beside tuning the basic gains, there are two extra parameters, the powers of the integral and derivative orders (Ibrahim Khather et al., 2018).

FOPID controllers are mainly depend on fractional calculus of two additional parameters, which are (λ and μ). These added gains aim to enhance controller's performance and robustness. The control action of the fractional order PID controller PIλDμ is specified as:

$$u(t) = kp.e(t) + ki.I^{-\lambda}.e(t) + kd.D^{-\mu}.e(t) \quad (4)$$

In which e(t) represents the tracking error signal of the system whereas u(t) is the control action signal. Implementing Laplace transformation on this equation, the control output for the fractional order PID controller can be stated as:

$$G_c(s) = kp + \frac{ki}{s^{\lambda}} + kd\ s^{\mu} \quad (\lambda\ \&\ \mu :\ 0 - 1) \tag{5}$$

4. GENETIC ALGORITHM

Genetic Algorithm (GA) is a random probability search engine that simulates genetic mechanism and natural selection (Cao et al., 2005). This algorithm starts with a random initialization of the elements creating the initial chromosome which is formed in this particular problem by five gain values of the FOPID controller (PIλDμ) that should be adjusted to achieve the desired behavior. Then, Genetic Algorithm executes iteratively to obtain the best values of these elements through three main stages of Mutation, Crossover and Selection (AIbrahim et al., 2019). Finally, the validity of each chromosome is assessed by calculating its fitness function which is a measure of the quality of the chromosome and compared with a stopping criterion (ε) (Gani et al., 2019). In this particular work, three objective functions are applied which are the ISE, ITSE and MSE which can be presented by:

$$\mathrm{ISE} = \int_0^T \left(e(t)\right)^2 dt = \int_0^T \left(r(t) - y(t)\right)^2 dt \tag{6}$$

$$\mathrm{ITSE} = \int_0^T t(e(t))^2 dt = \int_0^T t(r(t) - y(t))^2 dt \tag{7}$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n} (e(t))^2 \tag{8}$$

The fractional order PID optimized via genetic algorithm for vertical take-off and landing system is illustarted in figure 2 below. The reference position is fed as an input and the associated error between the actual and desired positions is calculated. Then, genetic algorithm is executed iteratively to generate the five controller's. Finally, the controller gives the control signal (u) as an input to the VTOL system to drive the actuators.

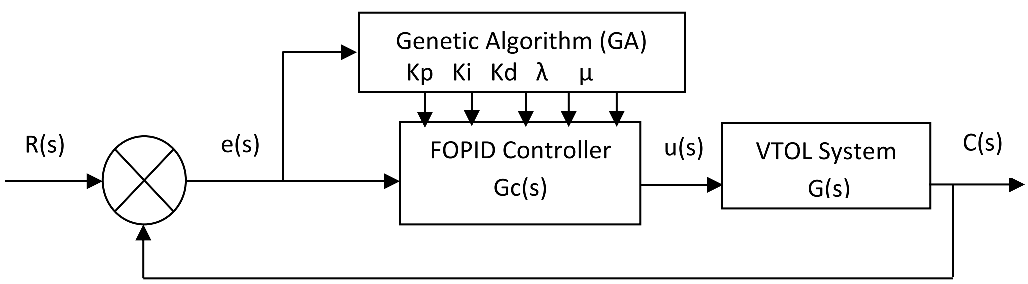

Figure 2. GA-FOPID controller.

5. SIMULATIONS AND RESULTS

In this section, many simulations have been attempted using MATLAB in order to obtain the optimal values for the FOPID controller's gains. Then, the response of the system has been analyzed in term of the maximum overshoot percent (MP %), rise time (Tr) and settling time (Ts) then compared for different fitness functions (ISE, ITSE and MSE).

After running the GA optimization each selected fitness functions, the trend of the FOPID controller gains through generations are shown in figure (3a), (3b) and (3c) respectively.

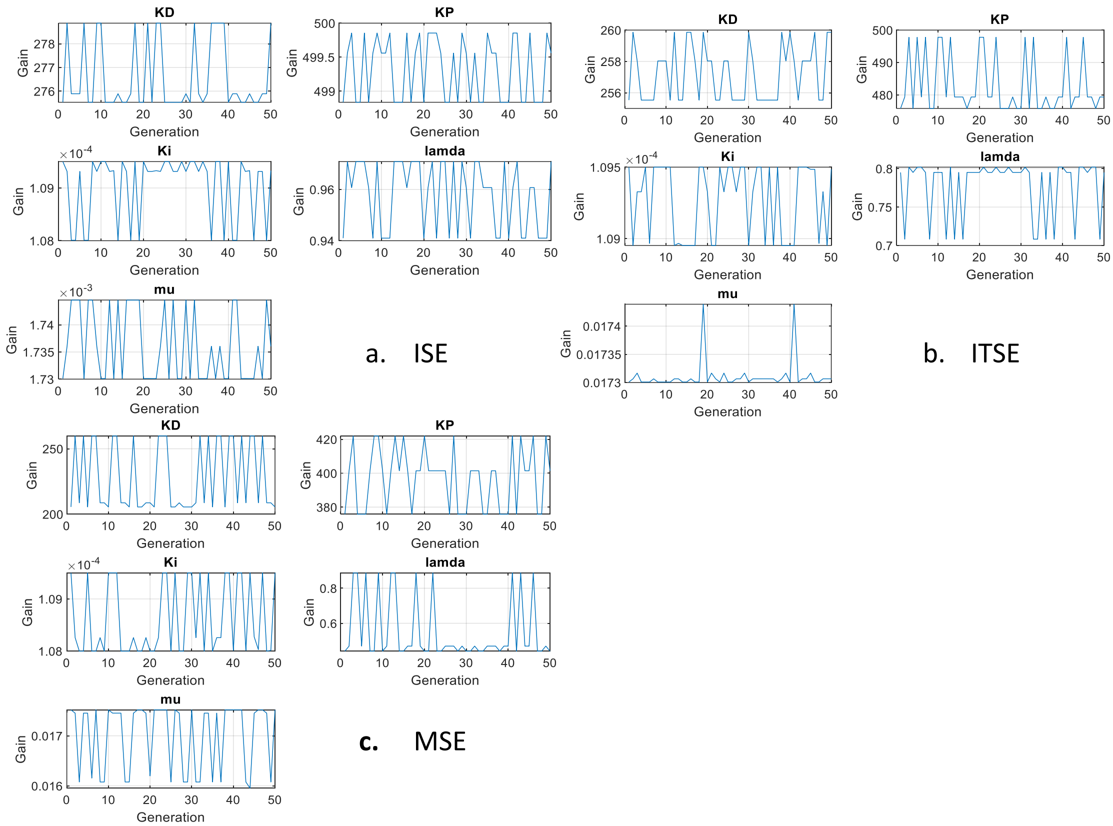

Figure 3. Parameter variation of the FOPID Controller for ISE, ITSE and MSE

The best five controller gain values resulted from the three fitness functions are shown in table (2)

Table 2. Performance characteristics for VTOL

GA-PID Parameters	ISE Fit. Function	ITSE Fit. Function	MSE Fit. Function
K_d	275.531	255.271	205.531
K_P	498.837	475.135	375.837
K_i	0.0001095	0.0001247	0.000114
Lamda	0.941	0.795075	0.441
Mu	0.0017301	0.016251	0.0175188

Finally, the step responses of the system for the three fitness functions have been summarized in figure (4). It can be noted that all the fitness functions have produced excellent responses with nearly no overshoot and fast transient and settling time. However, ISE fitness function yields the best overall response as shown in table (3).

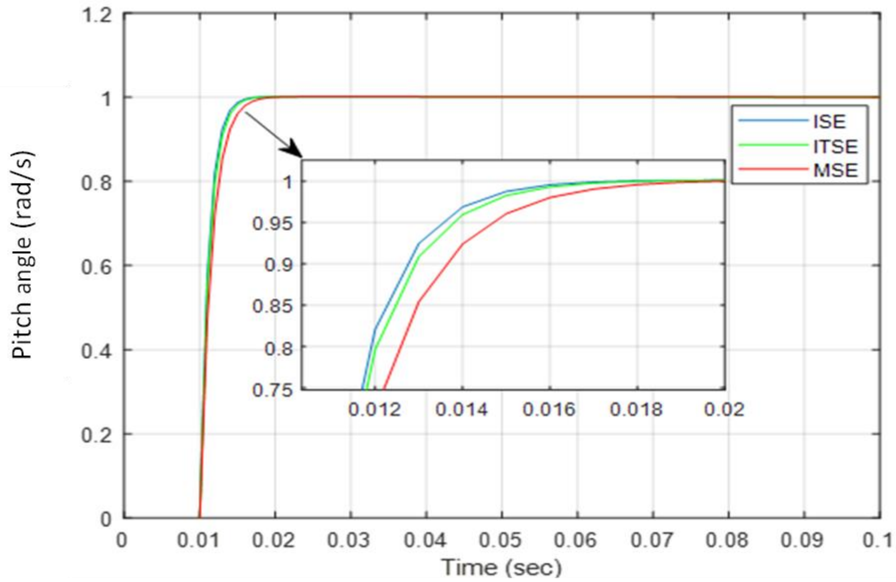

Figure 4. Pitch angle response for ISE, ITSE and MSE

Table 3. Performance characteristics for VTOL

GA-PID Controller Parameters	Values ISE Fit. Function	Values ITSE Fit. Function	Values MSE Fit. Function
T_r (sec)	0.00259	0.00274	0.00345
T_s (sec)	0.00445	0.00489	0.00599
MP %	0.12751	0.1422	0.167

6. CONCLUSION

In this study, FOPID controller has been analyzed and designed in order to control the tilt of VTOL system. For Optimization purposes, (GA) has been applied to select the optimal parameters for the FOPID controller which are (Kp, Ki, Kd, μ and λ). Three fitness functions have been considered which are ISE, ITSE and MSE. The obtained results have been compared in term of the rise time, settling time and the maximum overshoot for the three fitness functions. The performances of all systems were satisfactory. However, the response of the MSE fitness function has produced the best performance.

Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

Contribuation of Authors

[1st Author Ali Mahmood]: Derived the model of VTOL, and wrote the modelling section of the manuscript, contribuated in rsults discussion and analsis.
[2nd Author Mohammed Almaged]: Designed the PID controller in Matlab, produced output response, and wrote introduction and literature section, revised the mansucript.
[3d Author Abdullah I. Abdullah]: Designed the Genetic algorithm optimising technique, produced the best gain values, yielded Performance characteristics for VTOL system.

REFERENCES

AIbrahim, M., Kh Mahmood, A., Saleh Sultan, N., & Sultan, N. S. (2019). Optimal PID controller of a brushless DC motor using genetic algorithm. *International Journal of Power Electronics and Drive System (IJPEDS)*, *10*(2), 822–830. https://doi.org/10.11591/ijpeds.v10.i2.pp822-830

Bauersfeld, L., & Ducard, G. (2020). Fused-PID control for tilt-rotor VTOL aircraft. *2020 28th Mediterranean Conference on Control and Automation, MED 2020*, 703–708. https://doi.org/10.1109/MED48518.2020.9183031

Becker, M., & Sheffler, D. (2016). Designing a high speed, stealthy, and payload-focused VTOL UAV. *2016 IEEE Systems and Information Engineering Design Symposium, SIEDS 2016*, 176–180. https://doi.org/10.1109/SIEDS.2016.7489294

Cao, J. Y., Liang, J., & Cao, B. G. (2005). Optimization of Fractional Order PID controllers based on genetic algorithms. *2005 International Conference on Machine Learning and Cybernetics, ICMLC 2005*, 5686–5689. https://doi.org/10.1109/ICMLC.2005.1527950

Gani, M. M., Islam, M. S., & Ullah, M. A. (2019). Optimal PID tuning for controlling the temperature of electric furnace by genetic algorithm. *SN Applied Sciences*, *1*(8), 1–8. https://doi.org/10.1007/S42452-019-0929-Y/FIGURES/12

Ibrahim Khather, S., Almaged, M., & Abdullah, A. I. (2018). Fractional order based on genetic algorithm PID controller for controlling the speed of DC motors. *International Journal of Engineering & Technology*, *7*(4), 5386–5392. https://doi.org/10.14419/ijet.v7i4.25601

Lin, K., Qi, J., Wu, C., Wang, M., & Zhu, G. (2020). Control System Design of A Vertical Take-off and Landing Unmanned Aerial Vehicle. *Chinese Control Conference, CCC, 2020-July*, 6750–6755. https://doi.org/10.23919/CCC50068.2020.9188609

Mahmood, A., Almaged, M., & Abdulla, A. I. (2021). Antenna Azimuth Position Control Using Fractional Order PID Controller Based on Genetic Algorithm. *IOP Conference Series: Materials Science and Engineering*, *1152*(1), 012016. https://doi.org/10.1088/1757-899X/1152/1/012016

S Dawood, Y., K Mahmood, A., & A Ibrahim, M. (2018). Comparison of PID, GA and Fuzzy Logic Controllers for Cruise Control System. *International Journal of Computing and Digital Systems*, *7*(05), 311–319. http://dx.doi.org/10.12785/ijcds/070505

Shah, P., & Agashe, S. (2016). Review of fractional PID controller. *Mechatronics*, *38*, 29–41. https://doi.org/10.1016/J.MECHATRONICS.2016.06.005

Taşören, A. E., Gökçen, A., Soydemir, M. U., & Şahin, S. (2020). Artificial Neural Network-Based Adaptive PID Controller Design for Vertical Takeoff and Landing Model. *European Journal of Science and Technology Special Issue*, 87–93. https://doi.org/10.31590/ejosat.779085

Zhang, B., Liu, W., Mao, Z., Liu, J., & Shen, L. (2014). Cooperative and Geometric Learning Algorithm (CGLA) for path planning of UAVs with limited information. *Automatica*, *50*(3), 809–820. https://doi.org/10.1016/J.AUTOMATICA.2013.12.035

Zhao, C., Xue, D., & Chen, Y. Q. (2005). A fractional order PID tuning algorithm for a class of fractional order plants. *IEEE International Conference on Mechatronics and Automation, ICMA 2005*, 216–221. https://doi.org/10.1109/ICMA.2005.1626550