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Design of proportional integral and derivative controller using particle swarm optimization technique for gimbal system

Mohd Hafiez Ahmad[1,2], Khairuddin Osman[1], Sharatul Izah Samsudin[1]
[1]Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Department of Community Colleges Education, The Ministry of Higher Education, Putrajaya, Malaysia

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ABSTRACT

This paper presents the development of an optimal proportional, integral and derivative (PID) controller for controlling camera gimbal on unmanned aerial systems (UAV). Three optimal controller improvements are obtained using the suggested particle swarm optimization (PSO) technique. The PSO algorithm is initially built and integrated with the PID controller to control the DC motor gimbal. Before comparing the performance of a DC motor with PSO-PID with a DC motor with Zeigler-Nichols controller, the impacts of iteration numbers are explored. Finally, bode analysis was conducted to validate the stability of the proposed PSO-PID controller. Simulation is conducted within the MATLAB environment to verify the system's performance in terms of settling time, steady-state error and overshoot. The simulation results show has a longer settling time (0.91656 sec) than the Ziegler-Nichols controller (0.14316 sec) but a shorter rising time (0.091686 sec) than the Ziegler-Nichols controller (0.00094 sec). Furthermore, the overshoot was lowered from 12.941% to 0.959% as a result. As a result, the suggested PSO-PID controller technique outperforms the Ziegler-Nichols controller in terms of overshoot and rise time. Further study will investigate the integration of other optimisation methodologies such as fuzzy logic for better performance.

Corresponding Author:

Khairuddin Osman
Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: khairuddin.osman@utem.edu.my

1. INTRODUCTION

Camera stabilisation is necessary in order to give better photographs and video clips. Gimbal aids in the efficient recording and capture of photos and videos. It is capable of stabilising an object or payload around a single or more rotational axes. As a result, gimbals are widely used in several industries such as aerospace, medical, defence, and remote sensing. The gimbal mechanism is divided into two main categories which are scanning and tracking applications. For the scanning application category, the gimbal is organised to point at desired coordinates and delivered in either a global or a local reference frame. Meanwhile, gimbal promises to have several objectives in the camera view for the tracking applications category in real time. The setting sensor axis of a perfect gimbal system should focus exactly on the target point from a change or fixed base and moving target [1].

Due to shaky and vibration concerns, getting a good image from a camera mounted on a moving object can be difficult, resulting in fuzzy photographs and video captures [2]–[4]. As a result, the camera position adjusts and compensates for camera movement to bypass video shaking caused by disturbance vibration. Gimbal controller [5], [6], is the controller that maintains the camera's position for stabilised footage. A camera operator can handle the camera gimbal manually, or control algorithms can be used to automate the process. However, multiple experienced experts are required for this form of control, and control gets sophisticated. Tracking software along with various control algorithms can be utilised in automated systems to govern camera position without requiring a person [7]. The results show how the system's performance varies depending on whether tuning algorithms are used. The system performs better with a particle swarm optimization (PSO) tuned proportional, integral, and derivative (PID) controller compared with other tuning approaches [8]. Therefore, this paper aims to design of PID controller using particle swarm optimisation for the gimbal system.

2. LITERATURE REVIEW

Even though many researchers study advances and modern control strategies to control inertia stabilisation systems, the traditional PID remains the most popular solution due to its simpler structure, lower cost, easy implementation, and good control performance [7], [8]. The modeling of the single-axis gimbal system is given in Figure 1 shows the line of sight (LOS) stabilised servo control loop that mainly contains a controller, DC motor, and rate gyro. The system attempts to null the difference between the rate command input ω_c and the angular rate of the Gimbal ω_{Ae}. Furthermore, the system attempts to null the total torque delivered to the gimbal when the rate command input is zero or missing [9]. As a result, the stabilisation closed-loop implement generates a control torque at the motor equal and opposite the net disturbance torque.

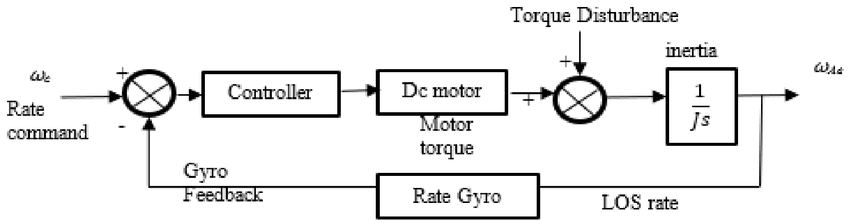

Figure 1. LOS Stabilized servo control loop

2.1. DC motor

The transfer function of DC motor is given by (1) [10], [11].

$$\frac{T_m(s)}{U_a(s)} = \frac{K_t}{Ls+R} \tag{1}$$

The torque produced by the DC motor and the actuation input are $T_m(s)$ and $U_a(s)$. K_t, L, and R are the torque constant, inductance, and resistance of the DC motor's armature winding, respectively. The load and motor inertia transfer function can be written as (2):

$$\frac{\omega(s)}{T_d(s)} = \frac{1}{Js} \tag{2}$$

where $\omega(s)$ are the output angular velocity. Sum of torque of load and motor is $T(s) = Tm(s) + Td(s)$. $Td(s)$ is the load torque disturbance. Js is the sum of inertia. The DC motor transfer function with the motor's back electromotive force (EMF) impact is (3):

$$G_m(s) = \frac{\omega(s)}{U_a(s)} = \frac{K_t}{JLs^2 + JRs + K_t K_e} \tag{3}$$

where Ke is the DC motor back EMF constant and $U(s) = Ua(s) + Ke\omega(s)$ is the PID controller provides control input, respectively. The gyroscope sensor measures the angular output rate or LOS rate of the gimbal [11]. Typically, a gyroscope model is represented as a second-order transfer function given as (4):

$$G_m(s) = \frac{\omega_m(s)}{\omega(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{4}$$

where $\omega_m(s)$, ω_n, and ξ are the gyroscope calculated natural frequency, damping ratio and angular rate.

2.2. PID controller

The wide application of the PID controllers in industrial applications is undeniable. PID offers a simpler and easy implementation [12]. However, the proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) controller parameters must be tuned effectively [13]. The tuning rules are one of the essential elements of PID controller research. In recent decades, many approaches for determining PID controller parameters have evolved. PID controllers are used to improving dynamic response while also lowering or eliminating steady-state error. By introducing a finite zero to the open-loop plant transfer function, the derivative controller improves transient response. The integral controller elevates the system type by one and lowers the step function's steady-state error to zero.

The required performance criteria are determined by the application for which the gimbal system is being implemented. The mentioned criteria indicate the standards that must be met in any control system. Control system design objectives must be specified while creating controllers. The PID controller in this study must meet the following requirements:

- Overshoot: Difference between peak and steady-state values (<10%).
- Rise time: Time taken to rise above the reference (<1%).
- Settling time: Time for the output to reach the level of precision (< 10 s).
- Steady-state error: The differential between the steady-state output and the reference voltage (<2%).

PID controllers are the most commonly used in control systems design to achieve the desired behaviours of different types of DC motors. The PID controller's general structure is depicted in Figure 2. G_p represents the process or plant to be controlled. R(s) and Y(s) are the input and output signals, respectively.

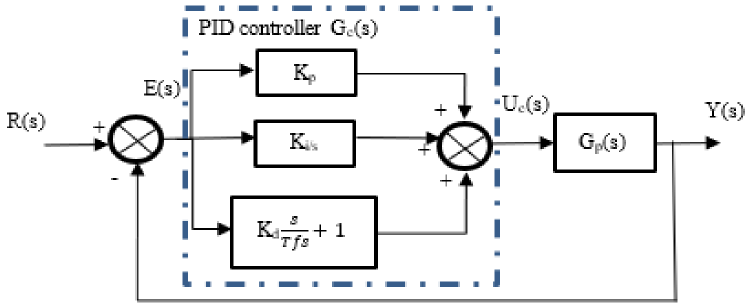

Figure 2. PID controller structure

The following is a continuous form PID controller with input E(s) and output U_{pid}.

$$U_{pid}(t) = K_p \left[e(t) + \frac{1}{T} \int_0^t e(t) d\tau + T_d \frac{d}{dt} e(t) \right] \quad (5)$$

$$U_{pid}(t) = K_p e(t) + K_I \int_0^t e(t) d\tau + + K_d \frac{d}{dt} e(t) \quad (6)$$

T_i is the integral time constant, T_d is the derivative time constant $K = Kp/Ti$ is the integral gain, and K_D=K_p and T_d is the derivative gain. The controller design seeks to reduce error by predicting inputs, with system error defined as the difference between predicted and actual feedback.

2.3. PSO tuning method

Kennedy and Eberhart created the core particle swarm optimization (PSO) algorithm in 1995. PSO is a reliable stochastic optimisation technique inspired by bird flocking and fish schooling for searching and moving food with a certain speed and position [14], [15]. It handles difficulties involving the swarms' flow and intellect as a solution to problems involving non-differential, non-linearity, and other issues. It's a search algorithm that finds the best and quickest answer. Particles are birds that fly through a problem space with *n* dimensions where *n* is the number of tuning parameters while considering the current best particles [16], [17]. Swarm size, position, and a maximum number of iterations are among the parameters, as are random position and velocity initialization. For each iteration of this technique, each particle is updated with two best values: P_{best}, which is the most suitable option produced from an each particle as of now, and G_{best}, which is the optimum the suitable option attained by a particle in the whole population of particles [18]. In addition, the velocity and position of all the particles are adjusted using equations after finding the two best solutions [19].

$$v_{i,m}^{t+1} = w.v_{i,m}^{t} + c_1 * rand() * \left(P_{best(i,m)} - x_{i,m}^{t}\right) + c_2 * rand() * (G_{best(m)}, - x_{i,m}^{t}) \quad (7)$$

$$x_{i,m}^{t+1} = x_{i,m}^{t} + v_{i,m}^{t+1} \quad (8)$$

From the (7), (8) *i* is equivalent to 1, 2, 3.......n, m equivalent to 1, 2, 3....d, *n* is the number of particles in a group, *d* is the dimension of space (number of tuning parameters), *t* is the current iteration value, and v_{im} is the velocity of particle *i* at iteration. *t* is the inertia weight factor, *w* is the weight factor of inertia, c_1 and c_2 are learning factors, and rand() is a random number between 0 and 1. Pbest(i) is the best particle position of the ith particle, Gbest is the best particle position among all the particles, and $X_{i,d}$ is the current position of particle *i* at iteration *t*. PSO algorithm implementation is referred to in [17]. The (7) is used to calculate the new velocity of a particle-based on its previous distances and velocity between its current place and the group's optimum experience (position). Refer to (8), the particle moves toward a new position. Each particle's performance is evaluated using a pre-defined fitness function (performance index) that is connected to the challenge at hand. To balance various global search capabilities, the inertia weight w is introduced into the equation [20].

3. METHOD

This study aims to create a PID controller based on the PSO algorithm for improving the performance of a DC motor system [21]. We will refer to the suggested approach as the PSO-PID controller for the remainder of the study. The PSO technique is primarily used to calculate the three ideal PID controller parameters Kp, Ki, and Kd to build a control system with a good step response. First, construct and integrate the PSO algorithm with the PID controller and DC motor. After analysing the effect of iterations, the performance of a DC motor with PSO-PID and a DC motor with a Zeigler Nichols controller is compared. Finally, bode analysis was conducted to validate the stability of the proposed PSO-PID controller. Previous research has been performed to validate bode stability proposed controller [22]. Therefore, it is crucial to analyse the stability of the controller. The simulation is finally completed, and the results are examined.

The specific gain was used in the simulated studies for the PID controller calculated using simulation MATLAB using the PSO algorithm. Minimum and maximum values K_p, K_i, and K_d gain substantial simulations. All simulation was made using MATLAB/Simulink (Version 2020b). Figures 3 and 4 show the Simulink model of camera gimbal control. Table 1 indicates the parameter of the DC motor used in gimbal actuation and the gyroscope. Figure 3 shows a simulation model for the DC motor. Meanwhile, Figure 4 depicts the PSO-PID control framework's gimbal control system.

Table 1. DC motor parameter

Parameter	Value
Nominal voltage (ua)	27 V
Armature resistance (R)	4.5 Ω
Armature inductance (L)	0.003 H
Torque constant (Kt)	0.85 Nm/A
Back EMF constant (Ke)	0.85 V/rad/s
Total inertia (J)	0.0115 kg×m^2
Natural frequency (ωn)	50 Hz
Damping ratio (ξ)	0.7

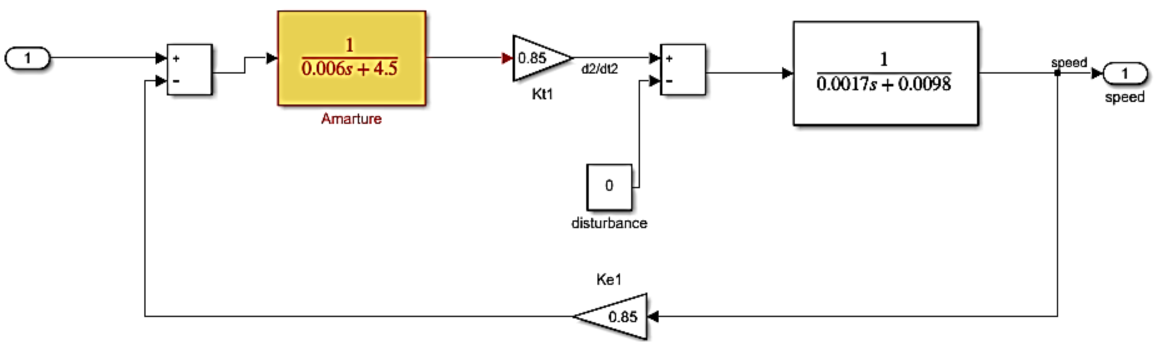

Figure 3. The simulation model of DC motor

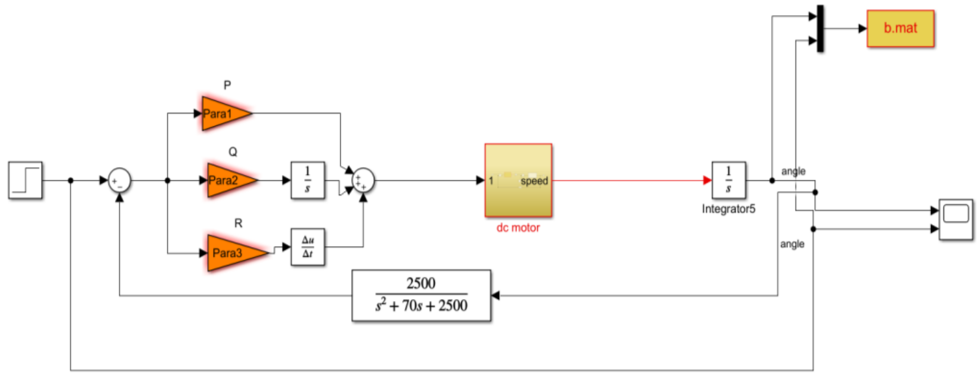

Figure 4. The simulation model of the PSO-PID controller

3.1. PID-PSO controller

When designing a PID controller, finding the best tuning parameters is crucial. PID controllers can be tuned in various ways to achieve the best possible values for the PID parameters. Algorithms including genetic algorithms (GA), differential evolutionary (DE) algorithms, ant colony optimization (ACO), biogeography based optimisation (BBO), and particle swarm optimization (PSO) are widely used to compute PID tuning parameters [23]. PSO technique is recognised for consistent convergence rate compared and its fast to other algorithms like GA and ant colony optimization (ACO) [24], [25]. Thus, it's a promising technique for fine-tuning parameters in PID controllers.

This paper proposes the PSO algorithm for tuning the PID controller and applies it to the system's DC motor. PSO algorithm can provide an auto-tuning approach for determining the best PID parameters, K_p, K_i, and K_d, without requiring complicated mathematical formulations [21], [22]. Therefore, the PID-PSO algorithm is designed to tune and find all these three optimal parameters of controllers. The PSO parameters are initialised at the beginning. The parameters are initialised at the beginning of the simulation, as Table 2. The gain for the DC motor will be updated when the parameters K_p, K_i, and K_d are acquired and supplied into the PID controller. The error then be calculated using the DC motor feedback and put into the PID. The parameters are in the Table 2 shows the number of particles (n), number of iteration (i), cognitive coefficient (c1) and the social coefficient respectively (c2), and ω is inertia weight.

Table 2. Analysis parameter for number of iteration

Parameter	Value
n	50
i	100
c1	2
c2	2
Inertia weight, w	0.9

4. RESULTS AND DISCUSSION

This paper aims to describe how to optimise the performance of a DC motor for a gimbal system using a PID controller based on the PSO technique. This section contains the suggested research findings. The findings were divided into three sections: a study of the influence of iterations, a comparison of DC motors equipped with PSO-PID and Zeigler Nichols controllers, and bode analysis.

4.1. Analysis of several iterations

This analysis aims to produce a suitable iteration value for the calculated parameter of K_p, K_i, and K_d. Several testing values of iteration had been done. The simulation result shows that the optimised PID parameters with different iterations are shown in Figures 5-8. The best values from a series of several trials are displayed in this graph. These data are produced individually using the process model and indicate the performance of the PID controller with an inertia weight of 0.9 when the number of iterations is varied between 20 and 100.

4.2. Comparison between PSO-PID and Zeigler Nichols

The research was performed on the Zeigler Nichols controller to highlight the benefits of the proposed PSO-PID controller. Figure 9 shows the comparison between PSO-PID and Ziegler Nichols on response input and output systems. Table 3 shows the rising time, settling time, and overshoot output performance. The PSO-PID controller has a longer settling time (0.91656 sec) than the Ziegler-Nichols controller (0.14316 sec) but a shorter rising time (0.055147 sec) than the Ziegler-Nichols controller (0.00094 sec). The overshoot PSO-PID was decreased from 12.941% to 0.959% as a result. As a result, the suggested PSO-PID controller technique outperforms the Ziegler-Nichols controller in terms of overshoot and rise time.

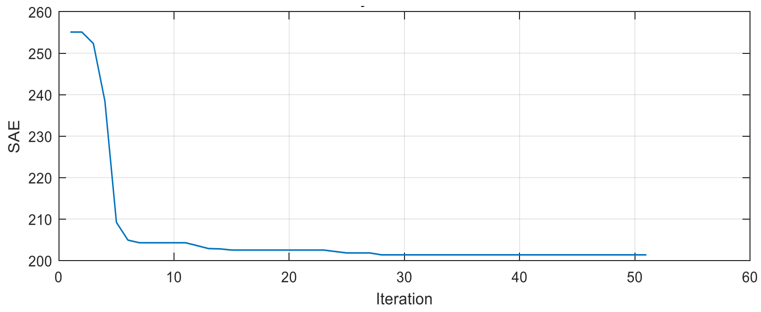

Figure 5. First priority: SAE versus iteration

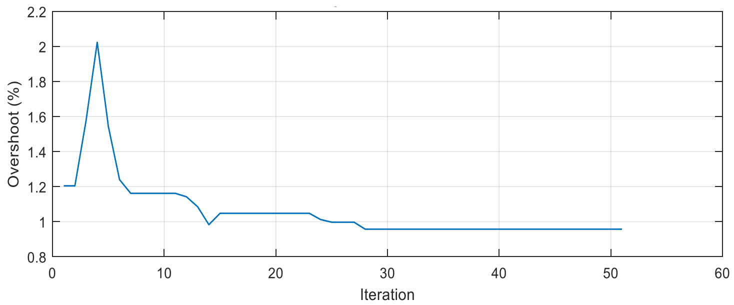

Figure 6. Second priority: overshoot versus iteration

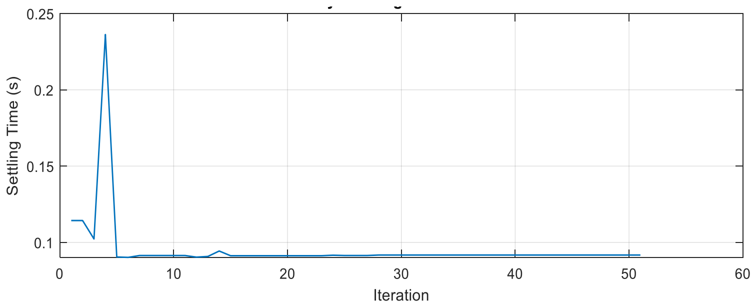

Figure 7. Third priority: settling time versus iteration

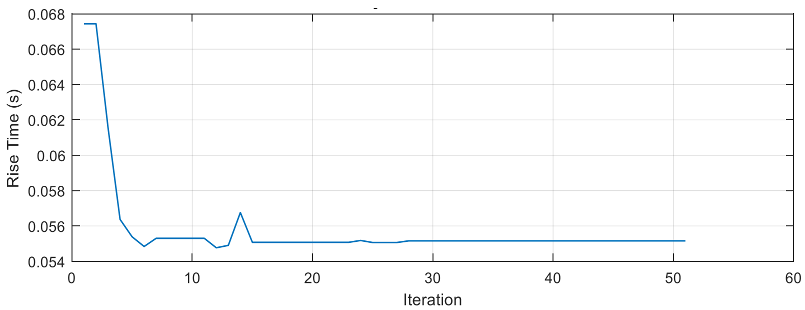

Figure 8. Fourth priority: rise time versus iteration

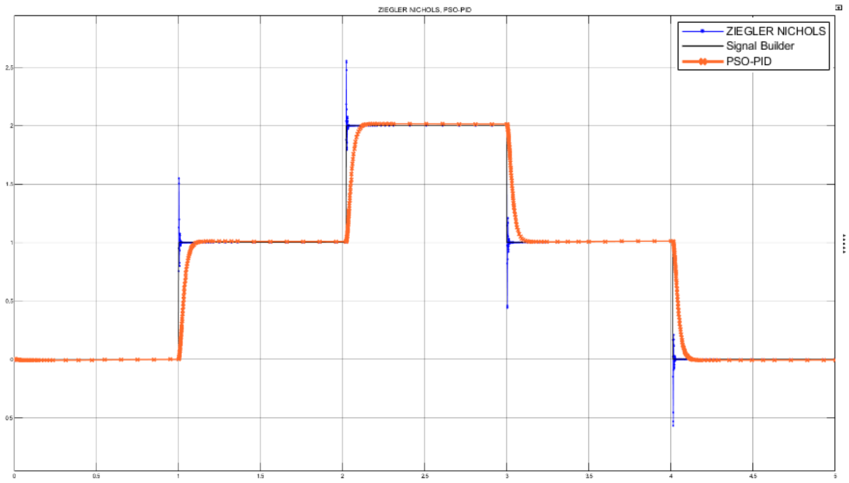

Figure 9. Comparison between PSO-PID and Ziegler Nichols on response input and output system

Table 3. Performance comparison between PSO-PID and Ziegler Nichols controller

Controller	PID Parameters			PID Performance		
	K_p	K_i	K_d	Overshoot (%)	Settling Time (sec)	Rise Time (sec)
Ziegler Nichols	21	3.525e+03	0.0313	12.941	0.14316	0.00094
PSO-PID	25.472	7.120	0.001	0.959	0.091686	0.055147

4.3. Bode analysis

The gimbal system's stability performance, designed with a PSO-PID controller, was evaluated using the Bode analysis. In addition, the stabilisation system after using PID controller using PSO with gain K_p, K_i, and K_d was conducted by using the Bode Plot tool from MATLAB. Figure 10 depicts the Bode graphs, respectively. Bode analysis indicated peak gain was 0.121 dB (3.57 rad/s), phase margin was 174°, 0.309s (9.82 rad/s), and delay margin was 16.785. According to this finding, the system is stable and has excellent frequency response.

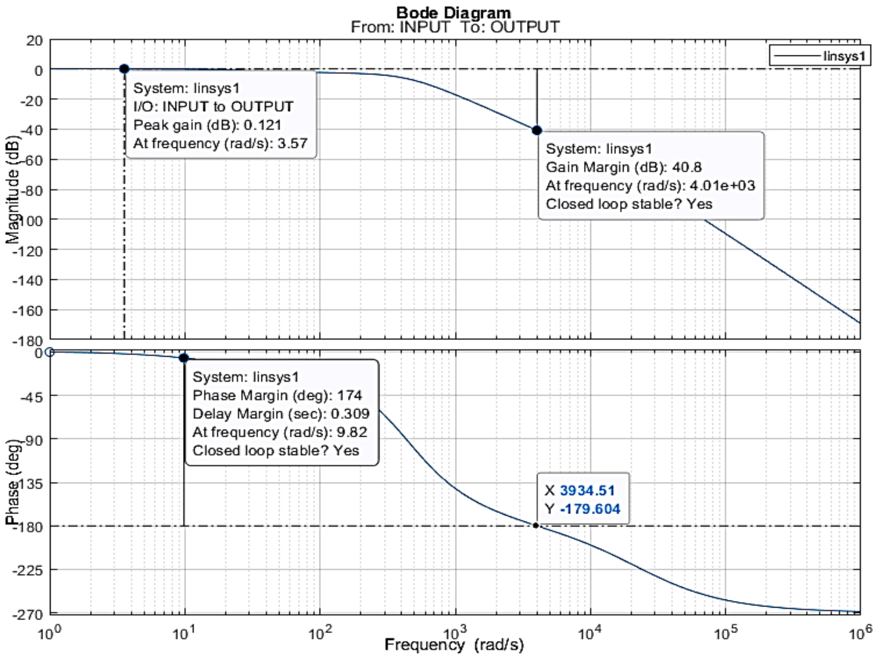

Figure 10. Bode plot stabilization

5. CONCLUSION

This paper proposes the PSO technique to optimise the PID gain parameter for a DC motor for a gimbal system. The effect of numerous iterations for the PSO settings was studied using simulation. According to the results of the simulations, the value of each PID gain parameter differed each time we simulated and was dependent on the iteration and also the particles. After determining the optimal outcome for each PID parameter, the controller will be put to the test to evaluate how it responds to overshoot, time rise, and settling time. Then, the performance of a DC motor with PSO-PID controller were compared with Zeigler Nichols controller. In addition, bode analysis was used to assess the system's stability after it had been optimised using the PSO technique. The findings showed that the system had a good stability structure, and the proposed PSO-PID controller was unaffected by changes in system parameters. Additional research will look into integrating the PSO technique on the fuzzy PID controller for better performance.

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BIOGRAPHIES OF AUTHORS

Mohd Hafiez bin Ahmad is currently a senior lecturer in Electrical Engineering Department at Community College Malaysia. He received a Bachelor Degree Engineering in Electrical Instrumentation and Control from Kolej Universiti Tun Hussein Onn or now is Universiti Tun Hussein Onn Johor in 2003. He is currently pursuing his PhD. degree at Universiti Teknikal Malaysia Melaka (UTeM) in Electronic and Computer Engineering field. His main research interest is in Internet of Things, Robotics, Controller System, PID, PSO, Gimbal System and Matlab Simscape. He can be contacted at email: mohdhafiezahmad@gmail.com.

Ts. Dr. Khairuddin Osman graduated a bachelor's degree in electrical engineering at the Kolej Universiti Teknikal Kebangsaan Malaysia (KUTKM) or now is Universiti Teknikal Malaysia Melaka (UTeM. He studies Master and Ph.D. in the Electrical field at Universiti Teknologi Malaysia (UTM) and internship program during Ph.D. at Okayama University, Japan. Currently holds the position of Director at the Centre of Alumni & Graduate Employability, Assistant Vice Chancellor Office (Industry & Community), and a Senior Lecturer at the Faculty of Electronic Engineering and Computer Engineering (FKEKK) UTeM. He can be contacted at email: khairuddin.osman@utem.edu.my.

Dr. Sharatul Izah Samsudin graduated for her first degree in B.Eng (Electronic) at Universiti Sains Malaysia (USM). Following that, she obtained her M.Eng. and Ph.D. from Universiti Teknologi Malaysia (UTM). She specialises in nonlinear control and system modeling. Currently, she is a senior lecturer in the Industrial Electronics Department, Faculty of Electronic Engineering and Computer Engineering (FKEKK), UTeM. She can be contacted at email: sharatul@utem.edu.my.