Position tracking of DC motor with PID controller utilizing particle swarm optimization algorithm with Lévy flight and Doppler effect

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ABSTRACT

This paper presents the implementation of the particle swarm optimization with the Lévy flight Doppler effect (PSO-LFDE) algorithm for optimizing proportional-integral-derivative (PID) controller parameters in a direct current (DC) motor system. Traditional optimization algorithms like particle swarm optimization, whale optimization algorithm, grey wolf optimizer, and moth flame optimization often face challenges in balancing exploration and exploitation, leading to suboptimal performance. The proposed PSO-LFDE algorithm addresses these issues by incorporating Lévy flight for enhanced exploration and the Doppler effect for refined exploitation. The algorithm is validated using MATLAB/Simulink for position control in a DC motor system with step inputs of 10, 30, and 60 cm. Key performance metrics, including rise time, settling time, peak time, and steady-state error, were compared against other optimization methods. PSO-LFDE demonstrated superior performance, achieving a 41.63% improvement in rise time and a 70.20% reduction in peak time compared to other methods. These results highlight PSO-LFDE's effectiveness in optimizing PID controller parameters and improving the dynamic response of DC motor systems, offering a robust solution for real-world control applications.

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1. INTRODUCTION

High-performance motor drives are experiencing rapid growth due to their diverse applications in electric trains, robotics, household direct current (DC) appliances, biomedical equipment, and various industrial sectors. DC motors are favored for their wide speed range, torque capacities exceeding 400% of their rated value, superior speed regulation, and cost-effective control systems [1], [2]. One of the widely used control methods for DC motors is the proportional-integral-derivative (PID) controller, known for its simple design and dependable performance. However, PID controllers are vulnerable to system unpredictability, which can lead to significant degradation in control performance, necessitating regular fine-tuning to maintain optimal functionality [3]–[5].

In recent years, metaheuristic algorithms like particle swarm optimization (PSO), genetic algorithms (GA), and adaptive neuro-fuzzy inference systems (ANFIS) have gained prominence for their efficiency and effectiveness in solving complex optimization problems [6], [7], [8], [9]. The industry has shown significant interest in the importance of metaheuristic PID tuning algorithms, which have demonstrated high dependability over the last twenty years. PSO is a simple, easily implementable, and computationally efficient concept, producing reliable results compared to other methods [10]–[13]. PSO is a metaheuristic algorithm that maintains a balanced equilibrium between exploration and exploitation phases, enabling it to converge towards promising areas in the search space [14]. PSO has more attractive attributes than conventional evolutionary estimation methods, preserving memory, fostering collaboration, and facilitating knowledge exchange among particles [15]. It can generate superior solutions within a limited timeframe with a concise theoretical foundation and positive programming approach [16].

The proximity principle in PSO involves particles responding to quality factors simultaneously in both their immediate surroundings and their optimal position. The stability principle allows swarms to modify the environment only when individual or collective positions change, ensuring the continued pursuit of the best position [17], [18]. The PSO algorithm stands out due to its flexible and well-coordinated mechanism, enhancing global and local exploration abilities [19]–[21]. Optimization theory focuses on finding the best ways to solve problems, including techniques, methods, processes, and algorithms. Engineers often deal with optimization problems in various fields, such as modeling, characterization, and maintenance [22], [23]. Despite advancements in swarm intelligence algorithms, achieving optimal performance in a DC motor with a PID controller system requires a balance between exploration and exploitation processes. This research aims to explore the application of PSO in PID controller tuning for DC motors, despite its widespread use. It aims to provide insights into its advantages and limitations, addressing the lack of comprehensive analysis considering different models, load conditions, and performance criteria in previous studies.

This study proposes a new method called particle swarm optimization with Lévy flight and Doppler effect (PSO-LFDE) to enhance position control performance in a DC motor system with a PID controller. The present study focuses on utilizing the PSO-LFDE algorithm to implement a DC motor with PID controller for position control. The objective is to evaluate and compare the performance of DC motors through simulation analysis in MATLAB Simulink. The mathematical model of the DC motor is derived using principles from physics and electromagnetism. The PID controller is specifically engineered to accurately track and maintain the position of the DC motor. An analysis is performed to assess the effectiveness of the PID controller in precisely following the desired position during steady-state conditions. The subsequent sections of the paper are organized as follows: Section 2.1 provides a detailed explanation of the mathematical model of the DC motor coupled with the PID controller system. Section 2.2 focuses on the design of a PSO-LFDE algorithm. Section 3 examines the simulation results obtained in MATLAB. The conclusions are presented in Section 4.

2. METHOD

2.1. Mathematical model of DC motor

The mathematical model of a DC motor is derived by formulating equations that enhance our understanding of its operation. The key variables include R_a, the armature resistance; L_a, the armature inductance; i_a, the armature current; and v_a, the input voltage. These quantities are measured in ohms *(Ω)*, Henries *(H)*, amperes *(A)*, and volts *(V)*, respectively. In this model, the rotor is treated as a single coil characterized by inductance *(L_a)* and resistance *(R_a)*. Additionally, the back electromotive force (EMF), which is the voltage generated across the DC motor during operation and is directly proportional to its speed, must be considered. The voltage supplied to the armature can be independently adjusted from the voltage supplied to the field. To derive the corresponding equation for this electric circuit, we first apply Kirchhoff's voltage law (KVL) and Newton's second law of motion to the armature circuit diagram, leading to the differential equation (1) to (3) for the armature circuit.

$$v_a(t) = i_a(t)R_a + L_a\frac{di_a(t)}{dt} + v_b(t) \tag{1}$$

$$v_b(t) \propto \omega(t) \Rightarrow v_b(t) = k_E\frac{d\theta}{dt} = k_E\omega(t) \tag{2}$$

$$T(t) = J\frac{d^2\omega(t)}{dt^2} + b\frac{d\omega}{dt} = k_T i_a(t) \tag{3}$$

The induced voltage v_b represents the EMF and the symbol k_E represents the constant of electromotive force. The EMF equation may be derived by using Faraday's law of induction and taking into account the angular velocity. The variables in the equation are as follows: *T(t)* represents the motor torque, and *J* represents the moment of inertia of the motor shaft. The torque equation is derived from the mechanics of a motor, specifically when angular velocity is given by *ω(t)*. The viscous frictional coefficient and torque constants of the motor are denoted by the correspondence b and k_T, respectively. By using the Laplace transform and assuming zero starting conditions for (1**Error! Reference source not found.**) to (3), we get (4) to (6).

$$V_a(s) = I(s)R_a + sI_a(s)L_a + V_b(s) \tag{4}$$

$$V_b(s) = k_E\omega(s) \tag{5}$$

$$T(s) = sJ\omega(s) + b\omega(s) = k_T I_a(s) \tag{6}$$

Replacing the equation represented by (5) in (4) and simplifying (4) and (6) yields (7) and (8).

$$I_a(s) = \frac{V_a(s) - V_b(s)}{R_a + sL_a} = \frac{V_a(s) - k_E\omega(s)}{(R_a + sL_a)} \tag{7}$$

$$\omega(s) = \frac{1}{sJ + b}T(s) = \frac{k_T}{sJ + b}I_a(s) \tag{8}$$

2.2. Development of PSO-LFDE algorithm

The PSO-LFDE algorithm is an advanced variation of the PSO method, incorporating elements from Lévy flight (LF) and Doppler effect (DE) theories to improve performance. The LF concept enhances the random walk behavior during position updates, increasing the exploration capabilities of particles. Meanwhile, the DE theory replaces the inertia weight, which traditionally manages the influence of previous velocities on current ones, to optimize the fitness functions of the personal best (*pbest*) and global best (*gbest*) positions. This hybrid approach aims to achieve superior optimization results [24]. The performance evaluation function by Yahya and Yusoff [25], provided in (9), is utilized as an objective function in conjunction with various optimization algorithms to optimally adjust the PID controller parameters. This function, alongside the PSO, whale optimization algorithm (WOA), grey wolf optimizer (GWO), and moth flame optimization (MFO) algorithms, aids in achieving optimal tuning by minimizing settling time, rising time, overshoot, and steady-state error, ensuring superior performance of the DC motor with the PID controller system.

$$W(K) = \left(1 - e^{-\beta}\right)(MP + Ess) + e^{-\beta}(T_s - T_r) \tag{9}$$

Algorithm 1. Particle swarm optimization with Lévy flight and the Doppler effect

Begin
for each particle in the swarm
  Initialize its position and velocity randomly
end for
while iter < max_iter **do**
  for each particle, j **do**
    Update velocity with the Doppler Effect equation replaces the inertia weight equation.
    $v_{j,g^{k+1}} = dev_{j,g^k} + c_1 r_1\left(pbest_{j,g} - s_{j,g^k}\right) - c_2 r_2\left(gbest_{j,g} - s_{j,g^k}\right)$
    Check the velocity boundaries
    Update position $x_{j,g^{k+1}} = x_{j,g^k} + v_{j,g^{k+1}}$ with Lévy flight equation
    Calculate fitness value f
      if
      The fitness value is better than the best fitness value. *pbest* in the past set the current value as the new *pbest.*
      end if
  end for
    From all the particles or neighborhood, choose the particle with the best fitness value as the *gbest*
end while

3. RESULTS AND DISCUSSION

The system structure is developed by integrating previous research to create a DC motor with a PID controller system, utilizing the PSO-LFDE algorithm. This proposed algorithm optimizes the control parameters of the DC motor with a PID controller, and its performance is validated using MATLAB/Simulink. The position control performance of the system is thoroughly evaluated, demonstrating the PSO-LFDE algorithm's effectiveness and precision. A three-step input command consisting of 10, 30, and 60 centimeters will be utilized to analyze the proposed algorithm's performance on the DC motor controlled by the PID controller system. The specifications and values of the DC motor, as presented in Table 1. Figure 1 depicts the DC motor with a PID controller system for position control utilizing the PSO-LFDE algorithm in the Simulink block diagram.

Table 1. DC motor parameters values

Parameters	Description	Units	Values
R_a	Motor resistance	(Ω)	1.51
L_a	Motor electric inductance	(H)	0.55
J	Body inertia	(kgm^2)	$1.1e^{-6}$
b	Viscous frictional coefficient	Nms	$5.06e^{-6}$
k_T	Torque constants of the motor	NmA^{-1}	0.027
k_E	Constant of electromotive force	$V_s rad^{-1}$	0.027

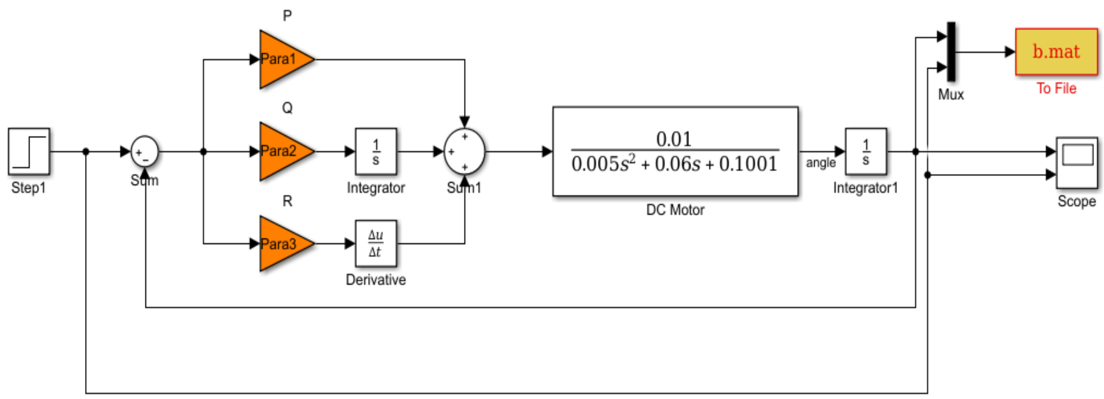

Figure 1. Simulink model of DC motor with PID controller system for position control

The performance evaluation results collected for the proposed algorithms are compared with those of other fundamental optimization algorithms. The evaluation focused on four key time-domain specifications: settling time, rise time, overshoot, and steady-state error. The performance evaluation is graphically depicted in Figure 2 for all set points with the numerical results presented in Table 2.

Table 2. Optimum values obtained by PSO-LFDE with four different methods at step inputs 10 cm, 30 cm, and 60 cm

	10 cm				30cm				60cm			
	Best	Mean	Worst	σ	Best	Mean	Worst	σ	Best	Mean	Worst	σ
PSO-LFDE	0.2224	0.2381	0.2604	0.0101	0.2119	0.2309	0.2616	0.0132	0.2002	0.2097	0.2505	0.014062
PSO	0.3148	0.3172	0.3194	0.0021	0.2879	0.2898	0.2919	0.0019	0.2553	0.2567	0.2581	0.001453
WOA	1.2622	3.3372	7.5143	1.7487	1.1794	3.0917	5.9886	1.5697	0.4325	2.7734	8.7769	1.771845
GWO	0.2882	0.3032	0.3184	0.0134	0.2881	0.3031	0.3192	0.0140	0.2553	0.2606	0.3630	0.019774
MFO	0.3156	0.3167	0.3168	0.0004	0.2879	0.2879	0.2880	$1.09e^{-05}$	0.2553	0.2563	0.2653	0.003039

The analysis of the PSO-LFDE algorithm showed significant improvements in key metrics:

- Rise time: for a 10 cm step input, PSO-LFDE achieved a rise time of 0.1733 seconds, outperforming the MFO method by 41.63%. In comparison, PSO, WOA, and GWO methods had risen times of 0.2941, 0.1857, and 0.2951 seconds, respectively.
- Settling time: PSO-LFDE achieved a settling time of 0.2644 seconds, far outperforming PSO, which required 2.000 seconds. WOA and GWO achieved settling times of 0.3189 and 2.0000 seconds, respectively.
- Peak time: The PSO-LFDE algorithm recorded a peak time of 0.3304 seconds, 70.20% faster than PSO (1.1089 seconds). WOA, GWO, and MFO recorded peak times of 0.8860, 1.1127, and 1.1287 seconds, respectively.

These findings demonstrate that the PSO-LFDE algorithm significantly enhances the dynamic response of the DC motor with the PID controller system, particularly in optimizing rise time, settling time, and peak time. The study underscores the superior performance of PSO-LFDE in real-world control system applications, surpassing traditional optimization techniques. This work highlights the novelty and practical value of PSO-LFDE as a robust solution for optimizing PID controllers in DC motor systems.

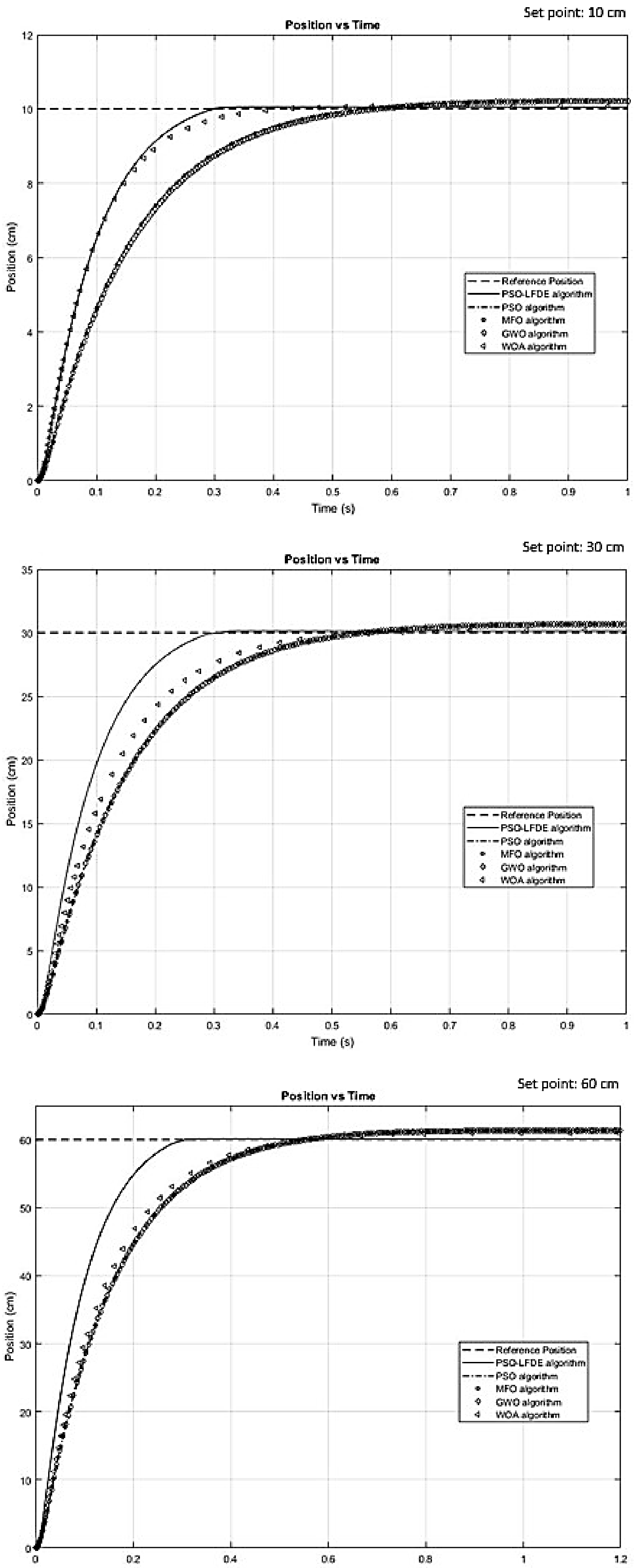

Figure 2. Step response for position control performance of a DC motor with PID controller

4. CONCLUSION

This study successfully implemented the PSO-LFDE algorithm to optimize the control parameters of a DC motor with a PID controller system. Through extensive simulations using MATLAB/Simulink, the performance of the proposed PSO-LFDE algorithm is thoroughly evaluated and compared against other established optimization methods, including PSO, WOA, GWO, and MFO. The results demonstrated that PSO-LFDE significantly outperforms the competing algorithms in terms of key time-domain performance metrics such as rise time, settling time, and peak time. Specifically, PSO-LFDE exhibited faster response times and superior stability, indicating its effectiveness in optimizing the dynamic behavior of the DC motor with PID controller. The findings validate the PSO-LFDE algorithm as a robust and efficient optimization technique, capable of achieving improved control performance in real-world applications. The study highlights the algorithm's ability to balance exploration and exploitation in search space, avoiding premature convergence and ensuring global optimization. Consequently, the PSO-LFDE algorithm represents a valuable advancement in optimizing PID controllers for DC motor systems and holds great potential for broader applications in control systems engineering.

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