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Effective fractional order PID control design of DC Motors using the walrus optimization algorithm

DC motorların mors optimizasyon algoritması kullanılarak etkili kesir dereceli PID kontrol tasarımı

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Abstract

This paper presents an approach utilizing the Walrus Optimization Algorithm (WaOA) to tune the parameters of the fractional-order proportional-integral-derivative (FOPID) controller for regulating the speed of direct current (DC) motors. The optimal controller settings are determined employing a time-based performance metric, serving as a cost function, to attain high performance. The success of the WaOA-based FOPID controller is demonstrated through comprehensive statistical analysis and simulations. The results indicate that the WaOA effectively find the optimal parameters of the FOPID controller. Moreover, the superiority of the WaOA-based FOPID-controlled DC motor system is further supported by a detailed time-domain analysis. The WaOA-FOPID controller exhibits superior performance when compared with controllers utilizing alternative algorithms such as leader-based harris hawks, chaotic artificial hummingbird, improved slime mould, manta ray foraging based on opposition and simulated annealing, reptile search, prairie dog, grey wolf, and atom search. According to the results, WaOA emerges as an efficient method for optimizing FOPID parameters in the context of speed control for DC motor systems.

Keywords: DC motor, FOPID controller, Walrus optimization algorithm, Metaheuristics

Öz

Bu makale, doğru akım (DC) motorlarının hızını düzenlemek için kesirli mertebeden oransal-integral-türev (FOPID) denetleyicisinin parametrelerini ayarlamak için Walrus Optimizasyon Algoritmasını (WaOA) kullanan bir yaklaşım sunmaktadır. Optimum kontrolör ayarları, yüksek performans elde etmek için maliyet fonksiyonu olarak hizmet veren zaman tabanlı bir performans ölçütü kullanılarak belirlenir. WaOA tabanlı FOPID kontrolörün başarısı, kapsamlı istatistiksel analiz ve simülasyonlarla gösterilmiştir. Sonuçlar, WaOA'nın FOPID kontrolörünün optimum parametrelerini etkili bir şekilde bulduğunu göstermektedir. Ayrıca, WaOA tabanlı FOPID kontrollü DC motor sisteminin üstünlüğü, ayrıntılı bir zaman alanı analizi ile daha da desteklenmektedir. WaOA-FOPID kontrolörü, lider tabanlı harris şahinleri, kaotik yapay sinek kuşu, iyileştirmiş cıvık mantar, karşıtlık ve tavlama benzetimine dayalı manta vatozu beslenme, sürüngen arama, çayır köpeği, gri kurt ve atom arama gibi alternatif algoritmalar kullanan kontrolörlerle karşılaştırıldığında üstün performans sergilemektedir. Sonuçlara göre, WaOA, DC motor sistemleri için hız kontrolü bağlamında FOPID parametrelerini optimize etmek için etkili bir yöntem olarak ortaya çıkmaktadır.

Anahtar kelimeler: DC motor, FOPID denetleyici, Mors optimizasyonu algoritması, Metasezgisel

1 Introduction

Direct current (DC) motor devices are essential in many domains, including robotics, automotive technology, consumer electronics and medical devices. The capability for accurately controlling the speed of DC motors is crucial for systems such as multi-rotors, medical devices and various industrial applications [1],[2]. Hence, various control schemes such as fuzzy, sliding model, adaptive and proportional-integral-derivative (PID) controllers have been designed [3]. Among these approaches, PID controllers have continuously occupied a leading role in industrial applications due to their affordability and easy implementation. However, FOPID controllers were introduced in [4] that offer more control performance than typical PID controllers. The parameters of FOPID controllers are precisely adjusted by employing innovative algorithms and optimization techniques. This improves closed-loop control performance in especially complex systems with time-varying parameters or nonlinear dynamics. To fully leverage the advantages of the FOPID controllers, suitable tuning techniques are required. Metaheuristic algorithms have become powerful candidates in this field. Scholars have investigated various artificial intelligence methodologies to optimize the parameters of FOPID-based control mechanisms for DC motors. For instance, [5] reports on the chaotic atom search optimization and its chaotic variant. These two optimization techniques are employed to design optimal FOPID controllers for use in the speed control of the direct current motor systems. Through several investigations, the study shows how well these algorithms work in DC motor speed control by comparing them to other existing controllers. The authors of [6] developed PID and FOPID controllers to regulate the speed of DC motors. The study optimizes the settings of these controllers using the harris hawks optimization variant (LHHO) to reduce transient response specifications. The control scheme of FOPID improves the system's resilience to changes in dynamics. In comparison to the traditional PID control scheme, simulation results demonstrate the resilience and control performance of the FOPID controller, validating its efficacy. Furthermore, a FOPID

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controller is also used in [7] to control a DC motor's speed. The hybrid manta ray foraging optimization based on opposition and simulated annealing (OBLMRFOSA) is used to improve the controller's parameters. Robustness testing, load disturbance rejection, and time and frequency domain simulations are given to show that the OBLMRFOSA algorithm is better than other cutting-edge optimization methods. For those interested, further exploration of alternative metaheuristic optimization methods can be found in [8]-[13], focusing on PID and/or FOPID controller tuning in DC motor speed control.

Despite significant advancements in metaheuristic techniques, the "no free lunch" theorem [14] serves as a reminder that no optimization algorithm can universally identify the best solution for every optimization problem, despite considerable breakthroughs across various techniques. Consequently, no single method can efficiently address every type of optimization problem, prompting researchers to pursue different avenues for improvement and innovation. In line with this aim, we present an innovative optimization strategy for designing a FOPID controller that is effective and suitable for DC-powered motor applications. In this paper, we have utilized the Walrus Optimization Algorithm (WaOA) [15] as an efficient optimization tool. The design of the WaOA is largely inspired by processes such as feeding, movement, evading, and combating predators. Numerous optimization problems have demonstrated the success of this technique [16],[17]. The WaOA is employed in [18] to fine-tune the design parameters of fractional-order proportional-integral-derivative (FOPID) controllers in the power electronic interface circuits of the evaluated wind energy conversion system. This research aims to find the most effective FOPID controller for regulating DC motor speed using the WaOA. We evaluate the performance of the WaOA to achieve highly efficient FOPID control for DC motors. The problem has been formulated as a minimization constraint to attain effective results for governing the angular velocity of the DC motor. The purpose of the WaOA is to decrease the objective function given in [19] while meeting the necessary time-domain requirements, including parameters like overshoot, rise time, and settling time. The WaOA-based FOPID controller is rigorously examined through a comprehensive statistical study of its performance and comparative simulations. The simulation findings confirm the effectiveness and efficiency of the WaOA in refining the settings of the FOPID controller. This is demonstrated by consistently enhanced objective function values, as well as improved performance measures in both the time and frequency domains. It outperforms other algorithms optimizing the parameters of the controller, such as atom search algorithm (ASO) [5], chaotic atom search algorithm (ChASO) [5], leader based harris hawks optimization (LHHO) [6], manta ray foraging based on opposition and simulated annealing (OBLMRFOSA) [7], chaotic artificial hummingbird algorithm (ChAHA)[20] opposition-based slime mould with simulated annealing algorithm (OBLSMASA) [21], improve slime mould algorithm (ISMA)-FOPID [22] and grey wolf optimization (GWO) [23]. The study's findings highlight WaOA's significant potential as a potent approach for setting parameters of FOPID controllers.

2 Walrus optimization algorithm

In nature, the walruses have complex behaviour when feeding, migrating and evading from predators. The walrus optimization algorithm was proposed in [15] which was mostly inspired by imitating of these natural walrus actions. The mathematical modelling of these behaviours of the WaOA convergence is initialized as follows:

$$\begin{bmatrix} W_1 \\ \vdots \\ W_i \\ \vdots \\ W_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} w_{1,1} & \cdots & w_{1,j} & \cdots & w_{1,m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ w_{i,1} & \cdots & w_{i,j} & \cdots & w_{i,m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ w_{N,1} & \cdots & w_{N,j} & \cdots & w_{N,m} \end{bmatrix}_{N\times m} \quad (1)$$

in which W_i is the location of the ith walrus, $w_{i,j}$ the value for jth decision variable proposed by ith walrus, N is the population of the algorithm and m is the number of decision variable. Every walrus acts as a possible solution, and their variable values are utilised to evaluate the objective function. The results of the objective function are given as follows:

$$\begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} F(W_1) \\ \vdots \\ F(W_i) \\ \vdots \\ F(W_N) \end{bmatrix}_{N\times 1} \quad (2)$$

where the objective function vector of the ith walrus is denoted by F_i. The best potential solution will be the walrus having the least value of the objective function. The walrus' locations and the corresponding objective function values are updated in each iteration. Thus, the best candidate solution is determined in each iteration as well. To update WaOA members, the social life behaviours of walruses such as feeding, migration and escaping-fighting strategies are taken into consideration.

Feeding strategy (exploration): The walrus with the tallest tusks, being the strongest in the group, leads the others in their search for food. Consequently, this leading walrus provides the best solution, securing the highest possible value for the objective function. Equations (3) and (4) provide a mathematical model of how walruses update their position depending on their feeding mechanism, guided by the most important individual in the group.

$$w_{i,j}^{P1} = w_{i,j} + r_{i,j}\left(LW_j - I_{i,j}w_{i,j}\right) \quad (3)$$

$$W_i = \begin{cases} W_i^{P1}, & F_i^{P1} < F_i \\ W_i, & else \end{cases} \quad (4)$$

where $r_{i,j} \in [0,1]$ is a random number and $I_{i,j}$ was randomly chosen to equal 1 or 2. LW_j is the leading walrus, possessing the best objective function value.

Migration strategy: The WaOA employs a migration method that leads the walruses in their search for appropriate locations. The new position is generated by

$$w_{i,j}^{P2} = \begin{cases} w_{i,j} + r_{i,j}\left(w_{k,j} - Iw_{i,j}\right), & F_k < F_i, \\ w_{i,j} + r_{i,j}\left(w_{i,j} - w_{k,j}\right), & else, \end{cases} \quad (5)$$

for $i = 1,2,\dots,N$, $k = 1,2,\dots,N$ and $j = 1,2,\dots$, and If the new position results in a lower value for the objective function, it will substitute the previous walrus position as:

$$W_i = \begin{cases} W_i^{P2}, & F_i^{P2} < F_i \\ W_i, & else \end{cases} \quad (6)$$

Escaping-fighting strategy (exploitation): Escaping-fighting strategy causes walruses to change position near their current location. Modelling this natural behaviour of walruses boosts the exploitation of the WaOA in local search. To model this scenario in the WaOA, it's assumed that a vicinity surrounds each walrus and a new location is randomly generated in this neighbourhood first using equations (7) and (8).

$$w_{i,j}^{P3} = w_{i,j} + lb_{loc,j}^{t} + \left(ub_{loc,j}^{t} - r_{i,j} lb_{loc,j}^{t}\right), \quad (7)$$

$$Localbounds: \begin{cases} lb_{loc,j}^{t} = \dfrac{lb_j}{t} \\ ub_{loc,j}^{t} = \dfrac{ub_j}{t} \end{cases} \quad (8)$$

While performing the displacement process, if there is an improvement in the objective function value, each walrus moves towards the new position, otherwise the walrus remains in the current position. For $i = 1,2,\ldots,N$, this update location is simulated as follows:

$$W_i = \begin{cases} W_i^{P3}, & F_i^{P3} < F_i \\ W_i, & else \end{cases} \quad (9)$$

where $W_i^{P\sigma}$ and $w_{i,j}^{P\sigma}$ are the new updated location of ith walrus of WaOA and jth dimension, respectively. Moreover, its objective function is given by $F_i^{P\sigma}$ such that t is the number of iteration, $\sigma = \overline{1,3}$, local upper and local lower bounds allowable for the jth variable, respectively, to simulate local search in the neighborhood of the potential solutions. The values $ub_{loc,j}^{t}$ and $lb_{loc,j}^{t}$ are denote the local upper and lower bounds permitted for the jth variable, respectively. These bounds are used to perform a local search around the neighbourhood of potential solutions.

3 Speed control development

3.1 Modelling of DC motor system

This section introduces a DC motor setup consisting of both a mechanical load and a DC motor. The main goal is to effectively regulate the motor's speed and torque through the implementation of a control system. The equivalent circuit for this specific type of DC motor is illustrated in Figure 1.

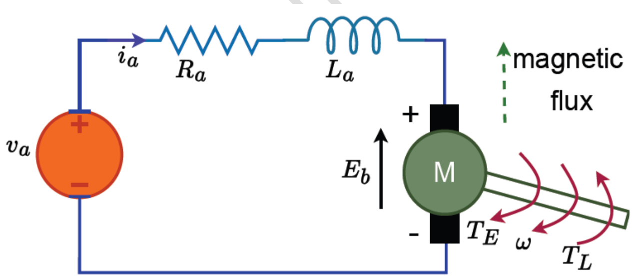

Figure 1. Equivalent circuit of DC motor.

This system is regarded as a linear system and the mechanical stress is represented as a constant torque (τ_L) to create a mathematical model. The speed of the DC motor is controlled by regulating the armature voltage $v_a(t)$. This produces an electromechanical force while armature current $i_a(t)$ adjusts proportionally to the rotational speed [1],[22]. To model the DC motor, the following differential expressions characterizing the motor's speed and torque dynamics are provided:

$$v_a(t) = i_a(t)R_a + L_a \frac{di(t)}{dt} + E_b \quad (10)$$

Under constant flux conditions, the motor's induced voltage E_b is linearly related to the angular velocity ω as illustrated below:

$$E_b = K_b \frac{d\theta(t)}{dt} = K_b\,\omega(t) \quad (11)$$

A total torque consists of the impact of the inertia and fractional torques which is given by

$$T_E - T_L = J\frac{d\omega(t)}{dt} + B\,\omega(t) = K_m i_a(t) \quad (12)$$

where R_a and L_a are the resistance and inductance of the DC motor respectively. E_b is the back electromotive force, K_b is the constant, θ is the angular velocity, ω is the motor shaft velocity, T_E, T_L are the electric and load torques respectively, J indicates the motor's moment of inertia. B and K_m are frictional and torque constants respectively. Applying Laplace transform to equations (1-3) (with zero initial conditions) which leads to

$$v(s) = (Ls + R_a)i_a(s) + E_b(s) \quad (13)$$

$$E_b(s) = K_b\omega(s) \quad (14)$$

$$T_E(s) - T_L(s) = (Js + b)\omega(s) = K_m i_a(s) \quad (15)$$

Simplifying equations (4) and (6) results in

$$i_a(s) = \frac{v(s) - K_b\omega(s)}{L_a s + R_a} \quad (16)$$

$$\omega(s) = \frac{T_E(s) - T_L(s)}{Js + B} = \frac{K_m}{Js + B} i_a(s) \quad (17)$$

The DC motor's transfer function can be expressed as follows:

$$G_p(s) = \frac{\omega(s)}{v(s)} = \frac{K_m}{(L_a s + R_a)(Js + B) + K_b K_m},\ T_L(s) = 0 \quad (18)$$

Table 1 gives the parameter values of the DC motor, which is adopted from reference [1].

Table 1. DC motor parameters.

Symbol	Definition	Value
R_a	Armature resistance	0.4 Ω
L_a	Armature inductance	2.7 H
J	The moment of inertia	0.0004 kg m^2
B	The frictional constant	0.0022Nms/rad
K_m	Torque constant	0.015 N m/A
K_b	Back electromotive constant	0.05 Vs

3.2 FOPID controller

A fractional order PID (FOPID) controller can efficiently regulate the speed of DC motors as it has a more flexible control structure for the stabilization of dynamic systems. In addition to PID control, the FOPID controller has fractional order terms (λ and μ) [24]. The following transfer function can characterize the FOPID controller:

$$G_{FOPID}(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \quad (19)$$

in which $[K_p, K_i, K_d]$ are the proportional-integral-derivative gains, and λ and μ denote fractional integral and derivative orders, respectively. A block diagram of a FOPID-controlled DC motor system is displayed in Figure 2.

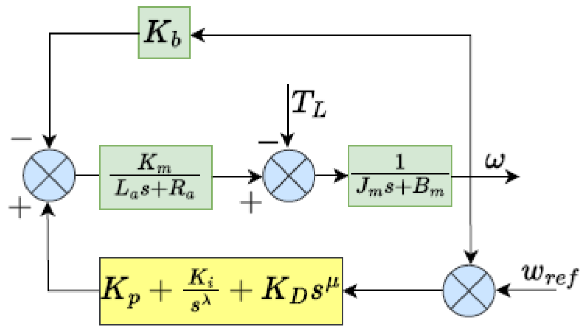

Figure 2. Diagram showcasing the FOPID control implementation in the DC motor system.

The FOPID-controlled DC motor's closed-loop transfer function is provided as follows.

$$G_{cl}(s) = \frac{\omega(s)}{\omega_{ref}(s)} = \frac{G_{FOPID}(s) \times G_P(s)}{1 + G_{FOPID}(s) \times G_p(s)}, T_L = 0 \quad (20)$$

Substituting $G_P(s)$ and $G_{FOPID}(s)$ into equation (11), one has

$$G_{cl} = \frac{K_m(K_p + K_i s^{-\lambda} + K_d s^{\mu})}{[\aleph_1 + \aleph_2]} \quad (21)$$

where $\aleph_1 = (Js + B)(L_a s + Ra) + K_b K_m$ and $\aleph_2 = K_m(K_p + K_i s^{-\lambda} + K_d s^{\mu})$

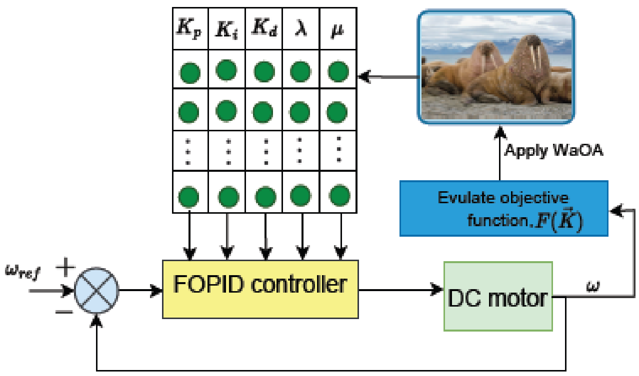

Figure 3. Schematic of FOPID control tuning procedure for the DC motor system with the WaOA.

3.3 Objective function

The problem of DC motor speed regulation is considered a minimization problem treated by the WaOA. The following procedures define the related system as an optimization problem. Then, the FOPID controller's settings will be ideal. In the first place, the problem's dimension is shown as $[x_1, \ldots, x_5] = [K_p\ K_i\ K_d\ \lambda\ \mu]$ and the objective function, $F(\vec{K})$ [3] for the corresponding minimization problem is given as:

$$F(\vec{K}) = (1 - e^{-\sigma}) \times \left(E_{ss} + \frac{M_p}{100}\right) + e^{-\sigma} \times (t_{ST} - t_{RT}) \quad (22)$$

where σ is a balancing coefficient ($\sigma = 1$, in this paper), E_{ss} represents the steady-state error, M_p denotes the overshoot, t_{ST} signifies the settling period, and t_{RT} refers to the rise period. The limits of parameters are $0.001 \leq K_p, K_i\ K_d \leq 20$ and $0 \leq \lambda, \mu \leq 2$. These limits are identical to [7]-[10]. Figure 3 shows a block schematic of the suggested approach to design the parameters of the FOPID control scheme for the direct-current powered motor systems.

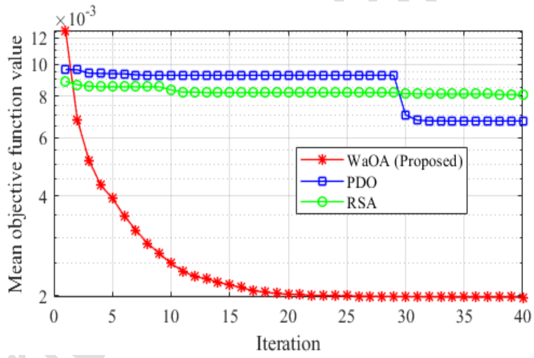

Figure 4. The convergence trends achieved by the WaOA algorithm and other optimizers.

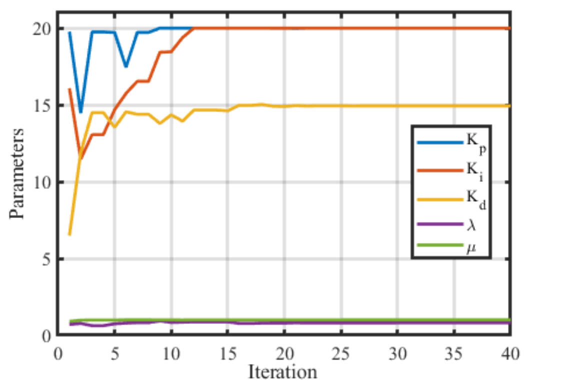

Figure 5. The varying of the FOPID controller's parameters over the iterations with the WaOA algorithm.

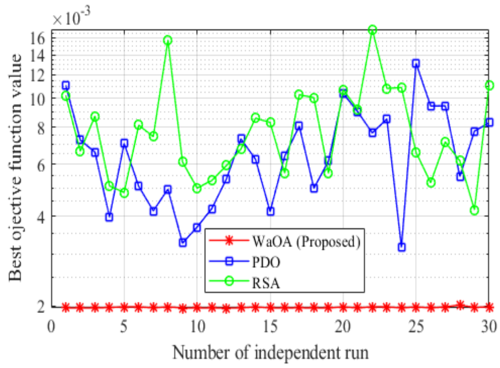

Figure 6. Best objective function values obtained from all independent runs of the WaOA, RSA and PDO algorithms.

Table 2. Specifications of the employed algorithms

Algorithms	Settings
WaOA [15]	-
RSA [25]	$\alpha = 0.1, \beta = 0.005$
PDO[26]	$\rho = 0.005, \epsilon = 0.1, \beta = 1.5$

3.4 Statistical analysis

This section evaluates the statistical performance of the WaOA by comparing recently introduced algorithms such as Reptile Search (RSA) [25] and Prairie Dog (PDO) [26] algorithms. To ensure a fair evaluation, a population size of 50 and 40 iterations were selected for each algorithm. Table 2 lists the algorithms along with their respective control parameters. These parameters are selected based on their default values as specified in the original papers, with no modifications made to the values outlined by the authors. This approach ensures a fair comparison, maintaining the integrity of the original algorithm configurations. Additionally, each algorithm was run thirty times. Table 1 presents the processing times for three algorithms. The WaOA requires the shortest processing time, with an average of 104.1777 seconds. The PDO takes 935.4905 seconds, while the RSA has the longest average processing time at 1315.2 seconds. These results indicate that the WaOA is the most time-efficient.

Figure 4 displays the mean of the objective functions at each iteration. One can see that the WaOA performs well in minimizing the objective function. As the optimization procedure goes through iterations, the WaOA finds the lowest objective function. The best run of the optimization process yields the following controller parameters: with WaOA, K_p =20, K_i=20, K_d=14.9345, γ= 0.8109 and μ=1.0028; with PDO, K_p =18.6376, K_i =12.4491, K_d=10.4077, γ=0.9606 and μ=0.9267; and with RSA, K_p=5.2484, K_i=4.7990, K_d=5.9665, γ=1.0671 and μ=0.9226. Figure 5 shows the alteration of control parameters. This graphic aids in our comprehension of how the controller's settings vary throughout the optimization procedure. Figure 6 shows the best objective function values obtained over 30 runs.

Table 3. Processing times for algorithms (30 runs).

Algorithm	Total time (s)	Average time per run (s)
WaOA (Proposed)	3.1253e+03	104.1777
RSA	3.9457e+04	1315.2
PDO	2.8065e+04	935.4905

Table 4. Statistical metrics of the objective function for algorithms.

Metrics	WaOA (Proposed)	RSA	PDO
Mean	0.0020	0.0081	0.0067
Median	0.0020	0.0073	0.0065
Std	1.0609e-05	0.0031	0.0025
Best	0.0020	0.0042	0.0031
Worst	0.0020	0.0171	0.0131

In Table 4, the comparative numerical statistical values of objective functions such as mean, median, standard deviation (Std), best and worst values are provided A boxplot illustrating the distribution of objective function values produced by algorithms is presented in Figure 7. Table 5 gives the Wilcoxon test, a non-parametric statistical analysis, to evaluate the significance of the results. It is clear to see that the WaOA is significantly superior to other optimizers. The WaOA provides a fast convergence rate and the quality of the solution.

To assess statistical significance, an analysis of variance (ANOVA) is performed on the objective values, comparing the means of the best objective function values from different algorithms. The result of the one-way ANOVA test is given in Table 6. According to these results, it can be said that there is a significant difference in mean values of the best objective values found by algorithms.

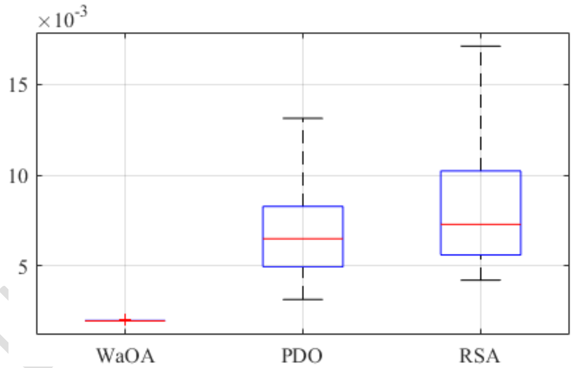

Figure 7. Boxplot analysis of the WaOA, PDO and RSA algorithms for objective function $F(\vec{K})$.

Table 5. Wilcoxon's signed-rank test p-values at a 5% significance threshold in the objective function.

WaOA vs RSA		WaOA vs PDO	
p-value	Winner	p-value	Winner
3.0199e-11	+	3.0199e-11	+

Table 6. ANOVA test for the objective function

Source	SS	DF	MS	F	P-value
Columns	0.00126	41	3.0689-05	3.3	3.16806e-11
Error	0.01136	1218	9.32906e-06		
Total	0.01262	1259			

Table 7. Evaluation of performance regarding time and frequency response characteristics

	WaOA (Proposed)	PDO	RSA
t_{RT} (s)	0.00669	0.01307	0.03026
t_{ST} (s)	0.011	0.02250	0.44774
M_p (%)	0	0	0
Gain Margin (dB)	Inf	Inf	Inf
Phase Margin (deg)	179	178.9489	176.4156
Bandwidth (rad/s)	202.9118	111.4415	61.2050

4 Simulation results and discussion

This section presents the simulation results of the developed controller. Simulations were run on a personal computer using

MATLAB/Simulink 2022a software with an Intel ® core i5 processor at 2.4 GHz and 8 GB RAM. The FOMCON toolbox is employed to obtain a fractional order PID controller.

The closed-loop responses in terms of time and frequency domains are shown in Figures 8 and 9, respectively. The time and frequency domain specifications are given in Table 7. All controllers exhibit infinite gain margins, indicating robustness against gain variations and ensuring that the closed-loop systems will not lose stability due to increased gain. The proposed WaOA-FOPID controller demonstrates the highest phase margin, reflecting the maximum additional phase lag the system can tolerate while maintaining stability. Additionally, the WaOA-FOPID controller shows the highest bandwidth, indicating a faster dynamic response compared to the other methods. Consequently, the WaOA-FOPID controller outperforms the other methods with the highest phase margin (179°) and bandwidth (202.91 rad/s), providing the best combination of stability and dynamic performance.

4.1 Robustness analysis

The robustness analysis was performed by varying the electrical resistance (R_a) of the DC motor with ±25% and torque constant (K_m) with ±20% separately. This leads to four different testing cases. The closed-loop step responses for all cases are shown in Figures 10, 11, 12 and 13.

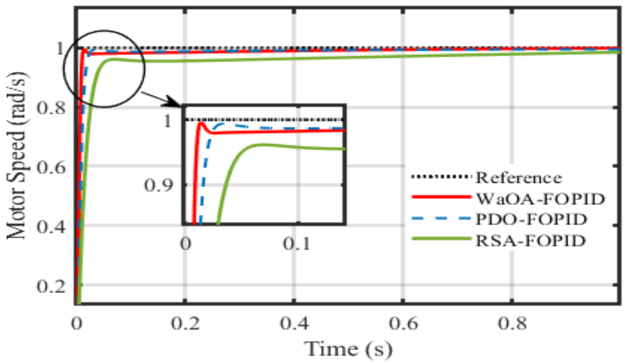

Figure 8. Closed-loop speed responses with the proposed WaOA-, PDO- and RSA-FOPID controllers.

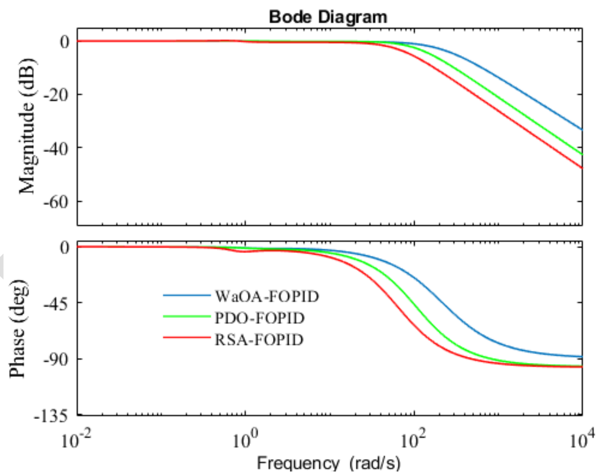

Figure 9. Comparison of Bode plot with FOPID controllers.

Table 8 presents the simulation findings for the time-domain performance assessment. The best values attained in the table are highlighted in bold. It is evident from the table that the WaOA-FOPID-controlled DC motor is the most robust. Despite varying parameters in the DC motor system, the proposed WaOA-FOPID controller provides the lowest values for Cases I and III with no overshoot. For the other two cases, the WaOA-FOPID controller achieves the lowest values with only a 3% overshoot.

Table 8. Performance analysis in case of different scenarios.

CASE I : $R_a = 0.30$ and $K_m = 0.012$			
	WaOA (Proposed)	PDO	RSA
t_{RT} (s)	**0.0091564**	0.016277	0.039903
t_{ST} (s)	**0.14609**	0.15246	0.5555
M_p (%)	0	0	0
CASE II: $R_a = 0.30$ and $K_m = 0.018$			
	WaOA (Proposed)	PDO	RSA
t_{RT} (s)	**0.0053379**	0.012199	0.024376
t_{ST} (s)	**0.012831**	0.019695	0.35415
M_p (%)	3.0542	0.79844	**0**
CASE III: $R_a = 0.50$ and $K_m = 0.012$			
	WaOA (Proposed)	PDO	RSA
t_{RT} (s)	**0.0091326**	0.019979	0.039498
t_{ST} (s)	**0.13532**	0.14045	0.54444
M_p (%)	0	0	0
CASE IV: $R_a = 0.50$ and $K_m = 0.018$			
	WaOA (Proposed)	PDO	RSA
t_{RT} (s)	**0.0053321**	0.012186	0.024238
t_{ST} (s)	**0.012879**	0.019659	0.33401
M_p (%)	3.0951	0.82576	**0**

4.2 Comparison with recently developed methods

To verify the effectiveness of the proposed WaOA-FOPID controller, this subsection performs comparisons using the recently developed methods such as (ASO) [5], (ChASO) [5], (LHHO) [6], (OBLMRFOSA) [7], (ChAHA) [20] (OBLSMASA) [21], (ISMA)-FOPID [22] and (GWO) [23].

These controllers use the same motor parameters and search space limitations. Furthermore, these controllers have achieved the best parameters of the FOPID controller so far. Figure 10 compares the closed-loop responses of DC motor with different controllers. To demonstrate the superiority of the WaOA-FOPID controllers over other approaches documented in the literature
e, we present the results of a performance analysis focusing on time-domain features in Table 9. The WaOA-FOPID controller has the lowest rising time and settling time specifications. Furthermore, the WaOA-FOPID controller obtains zero overshoot as well. These outstanding performance metrics demonstrate that, compared to other approaches covered in the literature, the WaOA-FOPID technique emerges as the most practical and effective approach for achieving crucial time-domain design requirements.

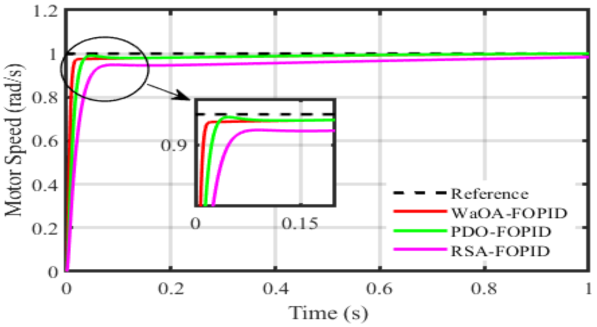

Figure 10. Comparison of closed-loop responses in the DC motor for Case I.

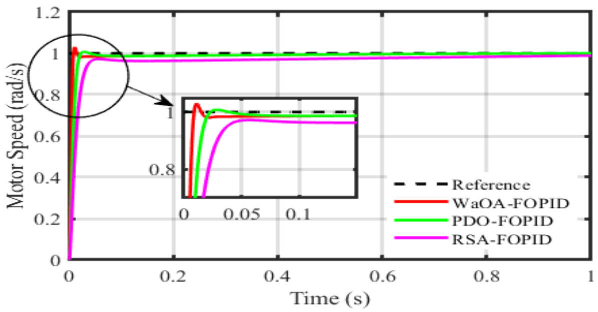

Figure 11. Comparison of closed-loop responses in the DC motor for Case II.

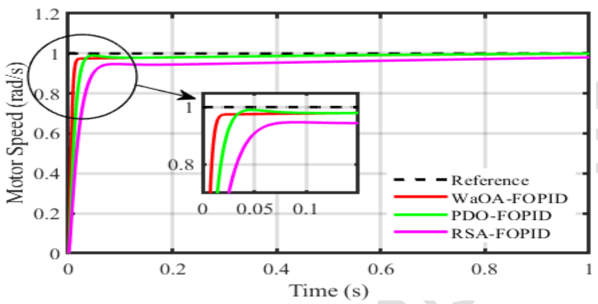

Figure 12. Comparison of closed-loop responses in the DC motor for Case III.

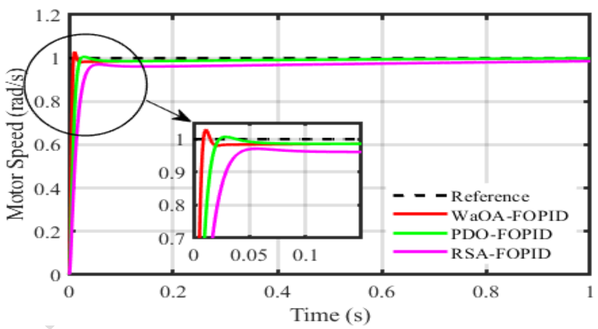

Figure 13. Comparison of closed-loop responses in the DC motor for Case IV.

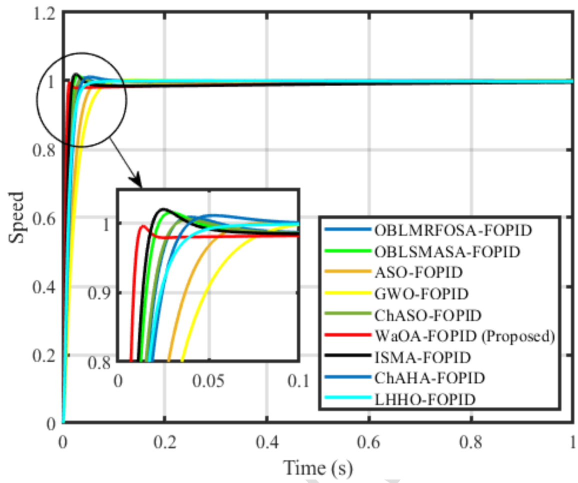

Figure 14. Comparative closed-loop responses with various published works.

Table 9: Comparison of step response dynamics between the proposed method and other methodologies.

METHODS	t_{RT} (s)	t_{ST} (s)	M_p (%)
WaOA-FOPID (Proposed)	0.0066909	0.011	0
OBLMRFOSA-FOPID	0.017241	0.027278	1.0771
OBLSMASA-FOPID	0.012688	0.019787	1.8925
ASO-FOPID	0.033151	0.055502	0
GWO-FOPID	0.043994	0.075308	0.30079
ChASO-FOPID	0.016536	0.026505	0.82409
ISMA-FOPID	0.010974	0.029973	2.502
ChAHA-FOPID	0.021023	0.033437	1.2037
LHHO-FOPID	0.02051	0.038284	0.21064

5 Conclusion

This paper has been tackled with the problem of precise speed control of DC motors. DC motors are widely used in many different industries, such as consumer electronics, automotive technology, robotics, and medical equipment. Their capacity to accurately regulate their rotational speed is critical to their efficiency and functioning in these fields. We have focused on DC motor control, which has historically been dominated by standard PID controllers. Conversely, FOPID controllers have introduced new avenues for enhancing control performance especially in systems with nonlinearity. In response to the demand for advanced methods, we have presented the Walrus Optimization Algorithm (WaOA) as a powerful FOPID controller tuning approach for regulating the velocity of DC motor systems. Statistical analysis and rigorous simulations have demonstrated the efficacy and efficiency of the WaOA in FOPID controller optimization. It consistently outperformed across a range of time-domain-based performance criteria and produced improved objective function values, demonstrating its effectiveness as a tool for controlling the speed of DC motors. Furthermore, the closed-loop step response of the WaOA-FOPID control scheme demonstrated its effectiveness in controlling DC motor speed under different parametric conditions. In comparison to other advanced methods, our WaOA-FOPID methodology performed exceptionally well in the context of transient response specifications such as speed rise period, settling period and overshoot. This work highlights the substantial potential of WaOA in enhancing the performance of FOPID control for the speed regulation of DC-powered motors. By employing this recent metaheuristic algorithm, DC motor control can be made more accurate and efficient, leading to improved performance in a range of applications.

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7 Author contribution statements

Author 1 contributed to developing the concept, writing the first draft and the literature review. Author 2 contributed to evaluating the outcomes, performing analyses, and editing the paper.

8 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person / institution in the article prepared”.

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