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Design and Performance Evaluation of A GWO-Tuned PID Controller for Dual-Axis Solar Tracking Applications

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Abstract

Dual-axis solar tracking significantly improves photovoltaic energy harvesting by maintaining optimal panel orientation relative to the sun. However, achieving stable and fast control performance remains a challenge due to nonlinear dynamics and environmental disturbances. This study proposes an optimized proportional-integral-derivative (PID) controller tuned using the Grey Wolf Optimizer (GWO) algorithm for a dual-axis solar tracking system. A mathematical model of the tracking mechanism is developed and simulated in MATLAB/Simulink. The optimization objective uses the Integral Time Absolute Error (ITAE) criterion to obtain optimal PID parameters for the horizontal and vertical axes. The proposed PID-GWO controller is compared with conventional trial-and-error tuning and an uncontrolled system. Simulation results show that the PID-GWO approach achieves significantly faster rise time, shorter settling time, and lower overshoot. For the horizontal axis, the controller achieves a rise time of 0.125 s and an overshoot of 9.96%, while for the vertical axis, it achieves a rise time of 0.1209 s with an overshoot of 9.03%. These results indicate that the GWO-based tuning approach improves system stability and response performance compared to conventional methods, making it suitable for smart photovoltaic tracking applications.

Keywords: Sun tracking system, PID controller, Grey Wolf Optimizer, photovoltaic control, optimization

1. Introduction

The increasing global demand for sustainable energy has intensified research on renewable energy technologies, particularly solar photovoltaic (PV) systems. Solar energy provides an environmentally friendly and abundant energy source capable of supporting the global transition to a low-carbon energy system [1] . However, conventional fixed photovoltaic panels suffer from decreased efficiency because the angle of incidence of sunlight changes continuously throughout the day, which significantly reduces the amount of captured solar radiation [2] [3] .

Therefore, solar tracking systems are widely applied to maximize energy harvesting by maintaining optimal panel orientation relative to the sun's position [4] [5] . Dual-axis solar tracking is particularly advantageous because it can track both azimuth and elevation angles,

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thus enabling higher energy capture compared to fixed-axis or single-axis systems [6] . Several recent studies have shown that dual-axis solar tracking can increase photovoltaic efficiency by 20–40% depending on environmental conditions and system configuration [7] [8] [9] [10] [11] [12] [13] [6] [14] [15] [9] .

Despite these advantages, solar tracking systems require precise control mechanisms to ensure accurate positioning and stable operation. A poorly tuned control system can lead to oscillations, excessive overshoot, longer settling times, and decreased energy harvesting performance. Proportional–Integral–Derivative (PID) controllers remain one of the most widely used control strategies in industrial applications due to their simple structure, reliability, and ease of implementation. However, selecting optimal PID parameters is a challenging task, especially for nonlinear dynamic systems such as solar trackers [16] .

Recent research has increasingly explored metaheuristic optimization algorithms to improve the performance of PID tuning. Algorithms such as Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Genetic Algorithm (GA), and Grey Wolf Optimizer (GWO) have demonstrated strong capabilities in solving complex nonlinear optimization problems in renewable energy systems [17] [18] [19] [20] [21] . Among these techniques, Grey Wolf Optimizer has gained significant attention due to its simple mathematical model, fast convergence characteristics, and effective balance between exploration and exploitation during the optimization process [2] [22] [23] [4] [24] .

Several previous studies have applied intelligent optimization algorithms to photovoltaic tracking control. For example, optimization-based control strategies have been applied to improve photovoltaic system efficiency and tracking accuracy under varying environmental conditions. However, many existing studies primarily focus on steady-state performance, with limited attention paid to evaluating robustness to disturbances, noise, and parameter uncertainty.

Therefore, this study proposes an optimized PID controller using the Grey Wolf Optimizer algorithm for a dual-axis solar tracking system. The proposed method integrates dynamic modeling, metaheuristic optimization, and performance evaluation based on the Integral Time Absolute Error (ITAE) criterion to achieve better tracking accuracy and system stability.

The main contributions of this research can be summarized as follows: The research This differentiate himself with integrate optimization ITAE based with evaluation resilience to disturbance , noise , and uncertainty parametric something rare aspects discussed in a way simultaneously in existing literature .

1.1 Related Works and Research Gaps

Recent studies have explored various optimization techniques for solar tracking and photovoltaic control systems. Table 1 summarizes some representative works related to intelligent optimization-based solar tracking control.

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Table 1. Previous Studies and Gaps Study

Ref.	Method	System	Main Contributions	Limitations
Nadia Al-Rousan et al. (2020)	ANFIS	Dual-Axis Solar Tracking	Increase accuracy tracking use adaptive neuro-fuzzy approach	Requires complex training processes and resources Power computing high ; no evaluate resilience system to disturbance .
P. Muthukumar et al. (2023)	IoT-Based Control	Dual-Axis Solar Tracker	Integration of monitoring and control IoT based for increase efficiency energy	Not discussing controller parameter optimization and response dynamic system .
SI Palomino-Resendiz et al. (2023)	Comparative Control Strategy	Dual-Axis Solar Tracking	Compare various control strategies For tracking sun	Not reviewing PID-based parameter optimization metaheuristics .
N. Rathika et al. (2024)	Fuzzy Logic + IoT	Intelligent Solar Tracking	Increase adaptability system to change irradiation	Depends on the designed fuzzy rules manually and difficult tuned optimally .
D. Mazumdar et al. (2024)	GWO-FOPID	Grid-Connected PV System	Increase MPPT performance under conditions weather No Certain	Focus on MPPT, not on mechanism tracking sun .
VSS Reddy et al. (2025)	Bio-Inspired PID Optimization	Solar Tracking System	Optimizing PID parameters using bio-inspired algorithm	Evaluation limited to nominal responses without analysis resilience disturbance .
Abdellatif Tahtah et al. (2025)	MPC-PID-ANN Hybrid	Dual-Axis Solar Tracker	Combining MPC, PID and ANN to increase tracking accuracy	Complexity implementation high and in need source Power computing big .
Research (2026)	ITAE based GWO-Optimized PID	Dual-Axis Solar Tracking System	Optimizing PID parameters using Grey Wolf Optimizer with function ITAE objective ,	Validation Still based MATLAB/Simulink simulation

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			evaluate response dynamic , overshoot, settling time, and resilience to disturbance , noise, and parameter uncertainty .	

From the literature review, it can be observed that although various optimization techniques have been proposed for photovoltaic control systems, comprehensive robustness analysis for solar tracking controllers is still limited. Most existing studies evaluate controller performance primarily under nominal conditions without considering disturbances or parameter variations.

To overcome these limitations, this study introduces a PID-based control framework - GWO which focuses not only on performance optimization but also on improving the dynamic response and stability of the sun tracking system.

Recent studies in Applied Energy and Renewable and Sustainable Energy Reviews show that control strategy based metaheuristics hybrid in a way significant increase performance tracking photovoltaic , however resilience to disturbance Still not enough explored .

2. Methodology

2.1 Dual-Axis Sun Tracking System Model

The dual axis consists of two independent rotation mechanisms that control horizontal (azimuth) and vertical (elevation) movement. Each axis is driven by a DC motor connected to a mechanical transmission system. The dynamic behavior of the motor system can be represented by a transfer function derived from the electrical and mechanical equations of the DC motor [25] [26] .

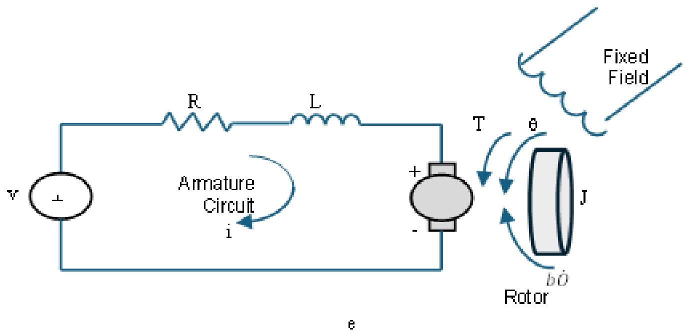

Figure 1 Direct Current (DC) Motor Model

To design a DC motor model, Figure 1 is considered. The motor torque is directly related to the current i , using the torque constant K shown in equation 1.

$$T = Ki \quad (1)$$

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The voltage generated by the torque e $_a$ is proportional to the angular velocity and relative to the constant K shown in equation 2.

$$e_a = K\omega_m = k\frac{d\theta}{dt} \quad (2)$$

In Figure 1, the equations for a direct current or DC motor are based on Newton's laws, here combined with Kirchhoff's laws [12] and can be written as equations 3 and 4 [10].

$$J\frac{d^2\theta}{d^2t} + b\frac{d\theta}{dt} = Ki \quad (3)$$

$$L\frac{di}{dt} + Ri = V - K\frac{d\theta}{dt} \quad (4)$$

Transfer Function of Direct Current Motor

Using the Laplace transform, equations 3 and 4 can be written as equation 5, equation 6 [10].

$$Js\ 2\ \theta(s) + bs\theta\ (s) = KI(\ s) \quad (\ 5)$$

$$Ls(I)+RI(s) = V(s) – K.s\theta\ (s) \quad (6)$$

The s symbol indicates the Laplace operator. From equation 6, we can know I(s) and V(s) are the result of domain changes. I is the variable i (t), which is a small i in space t, so it is converted into a large I in space s and V as the input voltage of direct current or DC motor movements, which is still in the domain t, so it is converted into V(s), which is in space s. This will be shown in equation 7 to equation 9 [13].

$$L.sI\ (s)+RI(s)\ V(s) – K.\ s\ \theta(s) \quad (7)$$

$$(\ Ls+R\ )\ I(s) = V(s) – K.\ s.\theta\ (s) \quad (8)$$

$$I(s)= \frac{V(s)-K.s.\theta(s)}{(Ls+R)} \quad (9)$$

Substitute equation 9 into equation 5 to obtain an equation that will result in the equation shown in equation 10 [13].

$$\frac{\theta(s)}{V(s)} = \frac{K}{s((Js+b)(Ls+R)+K^2)} \quad (10)$$

RI represents the current resistance value, L represents the inductance value, b represents the friction viscosity constant value of the motor, V represents the voltage value of the direct current or DC motor, Ksθ represents the angular constant value, θ is the actual angular position, and J, b, K, R, and L can be said to be parameters [13].

Transfer Function on Solar Tracking without PV Load

No-load Solar Tracking is a direct current motor connected to a no-load gear transmission from a solar cell (PV) panel. In gear 1 or the outer gear used is the M1B12 model, while the gear 2 used is the M1A20 model, the connection between the direct current motor rotor and

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the gear transmission system increases the moment of inertia of the direct current motor. The following is the basic equation for the moment of inertia of gear 1 in equation 11, and the basic equation for the moment of inertia of gear 2 is shown in equation 12. The moment of inertia of solar tracking without PV load is shown in equation 13, the next step is to find the rotational angular velocity ratio expressed in equation 14. [14].

$$JG_1 = \frac{1}{8} m_{G1} D_{G1}^2 \left(\frac{N_2}{N_1}\right)^2 [\text{kg.m } 2\ ] \quad (11)$$

$$JG_2 = \frac{1}{8} m_{G2} D_{G2}^2 [\text{kg.m } 2\ ] \quad (12)$$

$$Jst = JM + JG\ 1 + JG\ 2 \quad (13)$$

$$R = \frac{N_2}{N_1} \quad (14)$$

Based on equation 10 and the value of J=JT without PV load, the next step is to multiply it with equation 14 so that it becomes equation 15 [13].

$$TF_{st} = \frac{\theta(s)}{V(s)} = wR.\frac{K}{s((Jst+b)(Ls+R)+K^2} \quad (15)$$

Transfer Function on Solar Tracking Horizontal Axis

The moment of inertia of the PV panel on the horizontal axis is expressed in equation 16, and its solar tracking moment of inertia is shown in equation 17 [15], and the transfer function of solar tracking on the horizontal axis is shown in equation 18 [13].

$$J_1 = \frac{1}{12} m_{pv} L^2 \left(\frac{N_2}{N_1}\right)^2 [\text{kg. m}^2] \quad (16)$$

$$J_{T1} = J_{st} + J_1\ [\text{kg. m}^2] \quad (17)$$

$$TF_{Hor} = \frac{\theta(s)}{V(s)} = wR.\frac{K}{s((J_{T1}s+b)(Ls+R)+K^2)} \quad (18)$$

Transfer Function on Solar Tracking Vertical Axis

The moment of inertia of the PV panel on the vertical axis is expressed in equation 19, and its solar tracking moment of inertia is shown in equation 20 [16], and the transfer function of solar tracking on the horizontal axis is shown in equation 21[14]

$$J_2 = \frac{1}{2} m_{pv} (L^2 + W^2) \left(\frac{N_2}{N_1}\right)^2 [\text{kg. m}^2] \quad (19)$$

$$J_{T2} = J_{st} + J_2\ [\text{kg. m}^2] \quad (20)$$

$$TF_{Ver} = \frac{\theta(s)}{V(s)} = wR.\frac{K}{s((J_{T2}s+b)(Ls+R)+K^2)} \quad (21)$$

Table 2. Spurs gear unit model [17].

Models	Spur Teeth	Mass (g)
M1A20	120	1320
M1B12	12	10

Table 3. Parameter data of STM 40-50 solar panel.

Value	Parameter	Unit
0.545	W	m
0.637	L	m
0.01584	J_{T2}	$Kg.m^2$
0 . 0 158129	J_2	$Kg.m^2$
0 . 00 15488	J_{T1}	$Kg.m^2$
0 . 00 15216	J_1	$Kg.m^2$
4.5	Mass	Kg
637X545X35	Dimension	mm

Table 4. Parameter values for direct current motors [18].

Value	Parameter	Unit
2.75×10^{-6}	L	H
4	R	Ω
0.0274	Kt	$Nm.Amp^{-1}$
0 . 0 274	Kb	$Vsec.rad^{-1}$
3.5077×10^{-6}	b	N. ms
3.2284×10^{-6}	J	$Kg.m^2$

2.2 PID Controller Design

PID controllers generate control signals based on proportional, integral, and derivative actions [27] :

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$$u(t) = Kp\, e(t) + Ki \int e(t)dt + Kd\, de(t)/dt \quad (21)$$

where e(t) represents the tracking error between the desired position and the actual position.

Proper tuning of PID parameters (Kp, Ki, Kd) is essential to achieve stable and responsive system performance.

2.3 Gray Wolf Optimizer (GWO)

Grey Wolf Optimizer is a nature-inspired metaheuristic algorithm that mimics the leadership hierarchy and hunting strategies of grey wolves. In the GWO algorithm, candidate solutions are categorized into four groups: alpha, beta, delta, and omega wolves [28] .

The search process includes three main stages:

1. Surrounding the prey
2. Hunting
3. Attacking prey (exploitation)

During the optimization process, wolves update their positions based on the three best candidate solutions. This mechanism allows the algorithm to effectively balance exploration and exploitation.

Table 5. GWO Parameter

Value	Parameter
10	Titer
5	Npop
3	Var
0 . 1	lb
50	ub
2 - ((2 * tt) / Titer)	a_gwo
1	r_s
lb + (ub - lb) * rand(Npop , var)	x
sum(abs(y - r_s) . * tsim)	ff1(p)
Minimum value of ff1	alph_cf
x(loc1, :)	_ alpha_var
Second best value of ff1	beta_cf

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x(loc1, :)	beta_var
Third best value of ff1	delta_cf
x(loc1, :)	delta_var

2.4 Objective Function

The Integral Time Absolute Error (ITAE) criterion is used as the objective function:

$$ITEA = \int t|e(t)|\,dt \quad (22)$$

Minimizing ITAE ensures that tracking error is minimized over time while penalizing prolonged deviations from the reference trajectory.

2.5 Simulation Settings

The system and controller models are implemented in MATLAB/Simulink. Three scenarios are evaluated:

1. Uncontrolled system
2. PID tuning using trial and error method.
3. PID tuning using GWO optimization

Performance metrics are measured for the horizontal and vertical tracking axes using standard time domain indicators such as rise time, stabilization time, overshoot, and steady-state error.

Figure 2. Basic Simulation Design of Uncontrolled Model

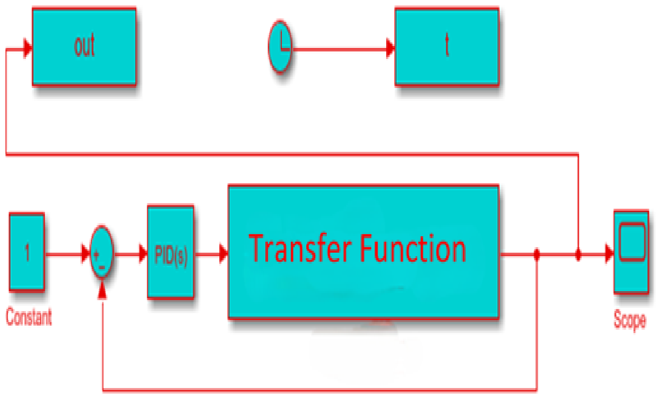

Figure 3. Basic Simulation Design of PID Model to be tuned.

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2.6 Resilience Evaluation

To ensure that the proposed controller performs reliably under practical operating conditions, a robustness evaluation has been performed. The solar tracking system operates in a dynamic environment where disturbances, measurement noise, and parameter variations can affect system stability and tracking accuracy.

Therefore, three resilience scenarios are considered in this study:

1. Rejection of external interference

Perturbations are introduced into the motor input to simulate sudden environmental changes such as wind loads or variations in mechanical friction. The controller's ability to recover the reference tracking position is evaluated using transient response metrics.

2. Measurement noise

Random noise is added to the feedback signal to simulate sensor inaccuracies that may occur in practical photovoltaic tracking systems. Controller performance is evaluated in terms of stability and oscillation suppression.

3. Parameter uncertainty

System parameters such as motor gain and inertia are varied within a predetermined range to analyze the controller's robustness to modeling uncertainties. The performance of the PID-GWO controller in this scenario is compared with that of a conventional PID setup. Robustness performance is evaluated using ITAE values and transient response indicators.

3. Results and Discussion

This section evaluates the effectiveness of the proposed PID-GWO controller through dynamic response analysis and comparative evaluation with conventional control approaches.

Table 6. No Control Result

Description	Value	Axis
Kp	-	Horizontal
Ki	-	Horizontal
Kd	-	Horizontal
N	-	Horizontal
Best ITAE	-	Horizontal
Kp	-	Vertical
Ki	-	Vertical

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Kd	-	Vertical
N	-	Vertical
Best ITAE	-	Vertical

Table 7. Trial and Error Results

Description	Value	Axis
Kp	30	Horizontal
Ki	10	Horizontal
Kd	20	Horizontal
N	100	Horizontal
Best ITAE	-	Horizontal
Kp	45	Vertical
Ki	24	Vertical
Kd	27	Vertical
N	100	Vertical
Best ITAE	-	Vertical

Table 8. GWO Results

Description	Value	Axis
Kp	50,000,000	Horizontal
Ki	0.100000	Horizontal
Kd	25.805768	Horizontal
N	100	Horizontal
Best ITAE	22639.701011	Horizontal
Kp	50,000,000	Vertical
Ki	0.197364	Vertical
Kd	27.877356	Vertical
N	100	Vertical
Best ITAE	2366.815606	Vertical

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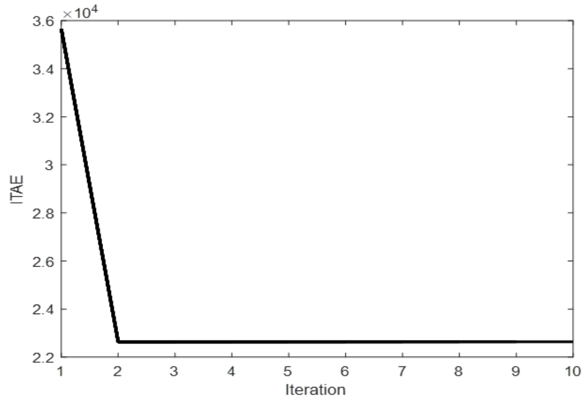

Figure 4. ITAE Response Results of Each Iteration of PID-GWO Horizontal.

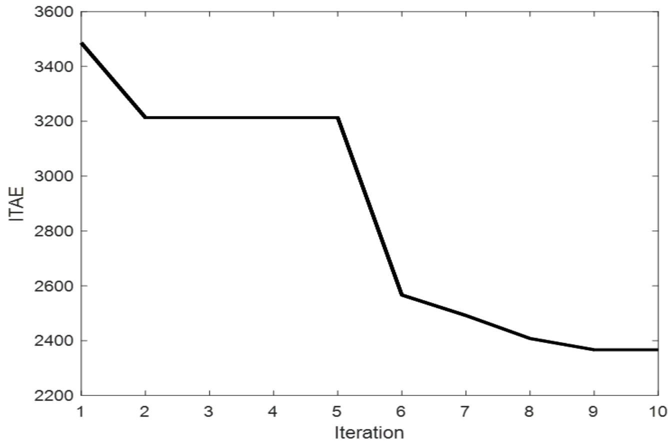

Figure 5. ITAE Response Results of Each Iteration of PID-GWO Vertical.

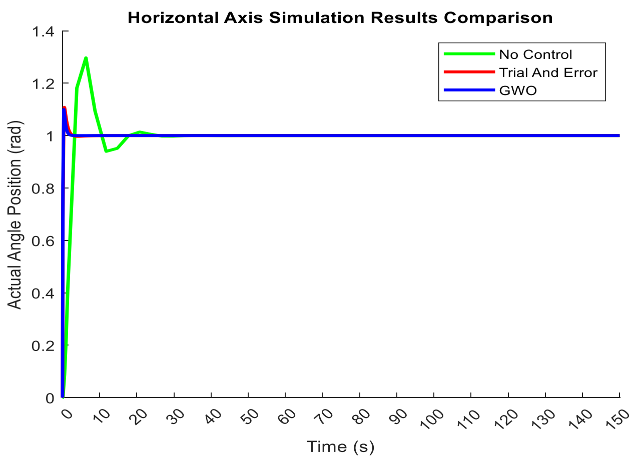

Figure 6. Response Results of Three Types of Horizontal Axis Simulation .

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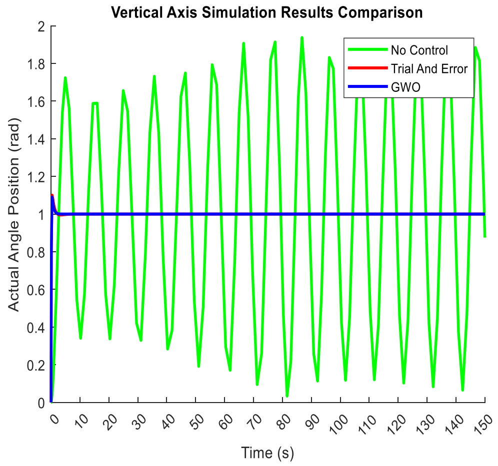

Figure 7. Response Results of Three Types of Vertical Axis Simulation.

Table 9. Horizontal Axis Simulation Results.

Description	No Control	Trial and Error	GWO
Rise Time	2.3675 s	0.1655 s	0.1250 s
Transient Time	16.5437 s	1.7277 s	1.1582 s
Settling Time	16.5437 s	1.7277 s	1.1582 s
Settling Min	0.9399 rad	0.99725 rad	1.00000816 rad
Settling Max	1.2969 rad	1.1080 rad	1.0996 rad
Overshoot	29.6911%	10.7960%	9.9574%
Undershoot	6.01%	0.275%	0%
Peak	1.2969 rad	1.1080 rad	1.0996 rad
Peak Time	6.3117 s	0.5045 s	0.3665 s

Table 10. Vertical Axis Simulation Results

Description	No Control	Trial and Error	GWO
Rise Time	1.6576 s	0.1256 s	0.1209 s

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Transient Time	149.9667 s	1.4706 s	1.1734 s
Settling Time	149.9726 s	1.4706 s	1.1734 s
Settling Min	0.0335 rad	0.995247 rad	1.0000119 rad
Settling Max	1.9373 rad	1.1003 rad	1.0903 rad
Overshoot	121.3682%	10.0326%	9.0302%
Undershoot	96.65%	0.4753%	0%
Peak	1.9373 rad	1.1003 rad	1.0903 rad
Peak Time	86.7795 s	0.3977 s	0.3592 s

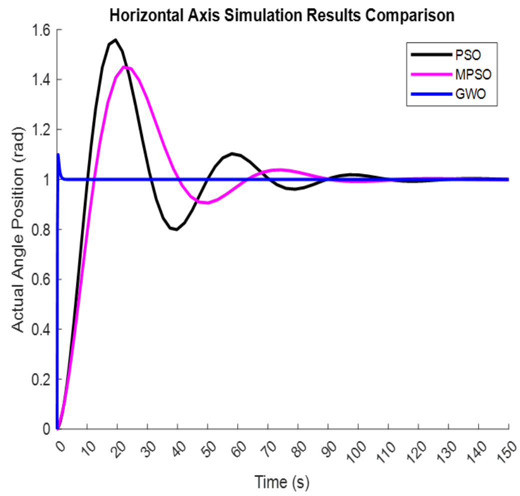

Figure 8. Response Results of Three Types of Algorithm for Horizontal Simulation.

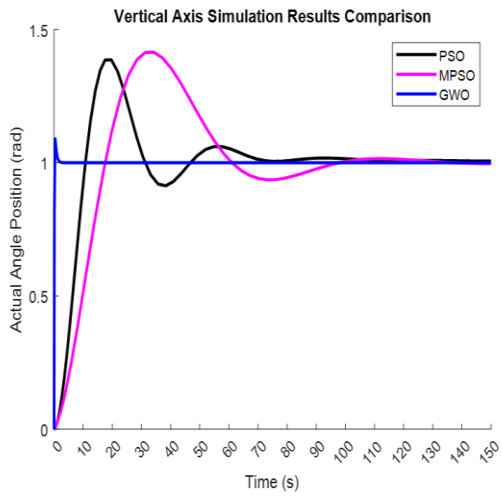

Figure 9. Response Results of Three Types of Algorithm for Vertical Simulation.

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Table 11. Algorithm Simulation Results.

Previous Research				
Algorithm	Horizontal Axis		Vertical Axis	
	Overshoot	Undershoot	Overshoot	Undershoot
PSO	55.87%	20.09%	38.64%	8.64%
MPSO	45.03%	9.40%	41.49%	6.39%
GWO Research				
GWO	9.9574%	0%	9.0302%	0%

3.1 Dynamic Response Analysis

Simulation results show that the optimized PID-GWO controller significantly improves the system performance compared to the uncontrolled system and the trial-and-error PID tuning method.

For the horizontal axis tracking system, the PID-GWO controller achieved a rise time of 0.125 s and a settling time of approximately 1.1582 s. Overshoot was limited to 9.96% with no undershoot observed. Compared with the uncontrolled system, which exhibited large oscillations and instability, the optimized controller provided a faster and more stable response.

For the vertical axis, the uncontrolled system produces a very high overshoot exceeding 120%, indicating poor system stability. After applying PID-GWO optimization, the system achieves a rise time of 0.1209 s and a settling time of 1.1734 s while reducing the overshoot to approximately 9.03%. These results indicate that the optimized controller effectively stabilizes the tracking system and ensures accurate positioning.

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3.2 Optimization Convergence Behavior

The convergence characteristics of the Grey Wolf Optimizer are also analyzed during the PID parameter tuning process. The algorithm exhibits rapid convergence to the optimal solution in a relatively small number of iterations. This behavior confirms the effectiveness of the GWO in exploring the search space and avoiding local minima, which is crucial for nonlinear control optimization problems.

Compared with other swarm intelligence algorithms reported in the literature, the GWO algorithm provides a good balance between the exploration and exploitation phases during the optimization process. This property allows the algorithm to achieve stable and reliable control parameters.

3.3 Endurance Performance

Robustness analysis shows that the PID-GWO controller maintains stable tracking performance even when disturbances and noise are introduced into the system. When a disturbance signal is applied to the actuator input, the optimized controller is able to quickly recover the reference trajectory with minimal oscillation.

Under measurement noise conditions, the controller exhibits strong noise rejection, maintaining a stable output response without significant performance degradation. Further parameter uncertainty analysis confirms that the optimized controller maintains acceptable performance even when system parameters vary within a predetermined range.

These results indicate that the proposed PID-GWO controller provides better robustness compared to the conventional PID tuning approach.

3.4 Comparison with Existing Studies

Comparison with related studies shows that many previous works use optimization algorithms such as PSO, GA, or FA for controller tuning in photovoltaic systems. Although these methods improve controller performance, some studies report limitations in convergence stability or sensitivity to parameter initialization.

The proposed PID-GWO controller exhibits competitive performance with faster convergence and lower overshoot compared to some previously reported optimization-based tuning methods. Furthermore, the proposed framework integrates ITAE-based optimization and robustness evaluation, which provides a more comprehensive performance assessment for solar tracking systems.

Overall, the simulation results confirm that the PID-GWO optimization approach provides a reliable and efficient solution for dual-axis sun tracking control systems.

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4. Conclusion

This study presents a PID controller optimized using the Grey Wolf Optimizer algorithm for a dual-axis solar tracking system. Simulation results show that the PID-GWO approach significantly improves the control performance compared to conventional tuning methods.

The optimized controller achieves faster rise times, shorter settling times, and minimal overshoot on the horizontal and vertical axes. Furthermore, ITAE-based optimization ensures accurate tracking and stable system response.

These findings indicate that GWO-based PID tuning is a promising solution for smart photovoltaic tracking systems and can be applied to improve renewable energy harvesting efficiency.

Future work will focus on experimental validation using real sun tracking hardware and integration with real-time solar irradiance measurement systems.

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