Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC03.20260497
Published: February 2, 2026

GWO-Based Optimization of Cascade PID Parameters for Antenna Azimuth Tracking

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Abstract

This study addresses the azimuth position control of an antenna, which is a critical requirement in satellite tracking, radar, and telecommunication systems. A cascade PID controller is designed and applied to regulate the antenna azimuth position. The control strategy is evaluated through MATLAB-based simulations to analyze the system's dynamic behavior. A comparative performance analysis conducted before and after controller implementation demonstrates significant improvements in system response. Specifically, the proposed cascade PID controller effectively reduces settling time and overshoot while eliminating steady-state error, resulting in enhanced overall system dynamics. The results further confirm that the cascade PID controller outperforms conventional control approaches reported in the literature, while maintaining structural simplicity and ease of implementation.

Keywords
Antenna azimuth, GWO, Cascade PID controller, System dynamics, MATLAB simulation, Position control.

1. Introduction
Accurate antenna positioning is a critical requirement in modern communication, radar, and satellite tracking systems, as improper alignment can result in signal degradation, communication failure, and tracking inaccuracies. Consequently, significant research efforts have been devoted to developing effective antenna position control techniques to achieve high accuracy and reliable performance. In this work, a cascade PID controller is employed to control the azimuth position of the antenna, aiming to enhance system response and positioning precision. Figure 1 presents an antenna azimuth position control system.

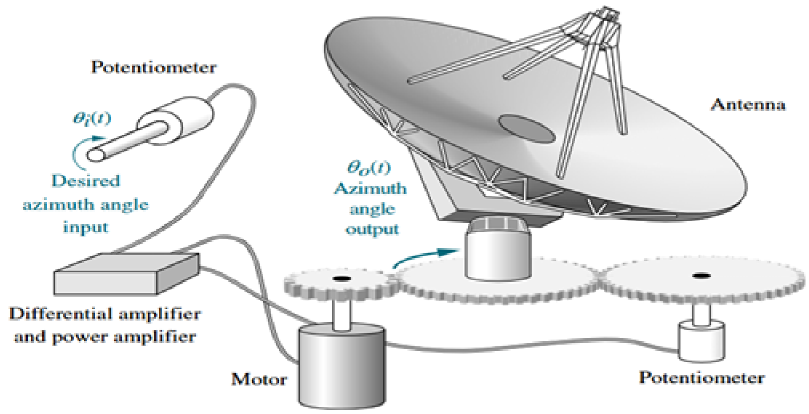

Figure 1. Position control Layout of the antenna azimuth (Nise, N. S. 2011).

1.1 Research Questions

RQ1: In what way does the Grey Wolf Optimizer (GWO) employed for finding the cascade PID parameters influence the accuracy of the antenna azimuth tracking with respect to the traditional tuning techniques? **RQ2:** How does the GWO-optimized cascade PID controller affect the dynamic characteristics of the antenna azimuth system in regard to settling time, overshoot, steady-state error, and rise time?

2. Literature Review

Recent studies on the control of antenna azimuth position in the antenna system have considered classical, intelligent, and adaptive control methods. Classical PID control methods are commonly employed owing to their simplicity; nevertheless, their control accuracy is often affected by overshooting, a large settling time, and changes in parameters (Okumus et al., 2012; Alwal et al., 2016; Uthman & Sudin, 2018). To overcome these drawbacks, fuzzy logic and self-tuning control methods have been suggested, which have shown better transient and steady-state performance with a higher computational complexity and risk of chattering (Okumus et al., 2013; Yakubu et al., 2020). Modern control techniques such as LQR, state feedback, and QFT controllers improve robustness and stability margins but are often dependent on accurate system models and full-state information (Sahoo & Roy, 2014; Uthman & Sudin, 2018). More recently, adaptive and optimization-based control techniques such as MRAC, STC, fuzzy-PID, fractional-order PID,

nonlinear PID, and auto-tuned PID controllers have demonstrated better performance characteristics in the presence of uncertainties and disturbances, albeit with increased complexity (Singh & Pal, 2019; Mahmood et al., 2021; Rasheed et al., 2022; Fkirin & Khira, 2023; Mohsin et al., 2024). Despite these advances, limited attention has been given to cascade PID control structures that preserve the simplicity of classical PID while improving dynamic response and robustness through multi-loop design. This work addresses this gap by proposing a cascade PID controller for antenna azimuth position control.

3. Methods

3.1 Mathematical model of system

The antenna position control system, illustrated in Figure 2, comprises a potentiometer, a differential amplifier, a power amplifier, a motor, a load, and a gearbox. The desired azimuth angle is provided as an input to the system, which the potentiometer converts into a corresponding voltage. This voltage is subsequently amplified by the preamplifier, and the power amplifier drives the motor. The motor's rotation is transmitted to the gearbox, which links the motor to the load, reducing speed and increasing torque to align the antenna with its target position. A secondary potentiometer measures the system's output angle and converts it into a voltage. This output voltage is compared to the input voltage by the differential amplifier to calculate the error, which is then processed by the controller to ensure accurate positioning.

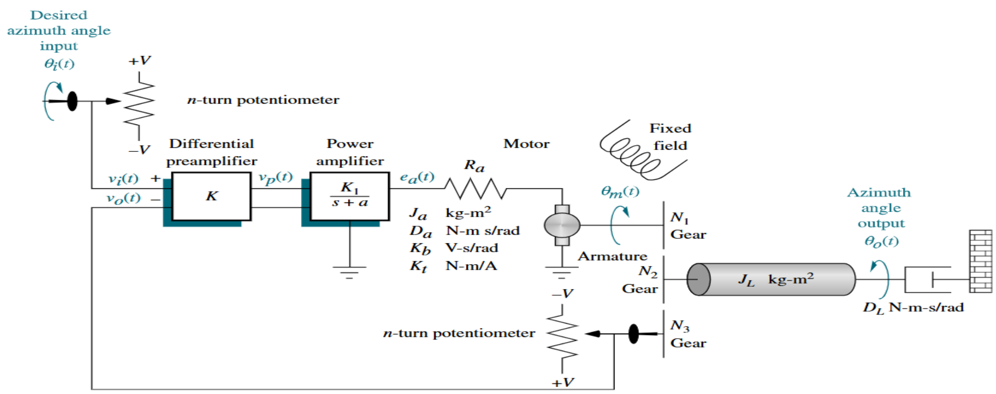

Figure 2. Schematic diagram of antenna-azimuth position controlling system (Nise, N. S. 2011).

Where the gain of the input potentiometer is denoted by K_{pot}, the gain of the output potentiometer is also K_{pot}, the gain of the differential preamplifier is K, and the power amplifier is modeled by the transfer function $K_1/(s+a)$.
For the Transfer function of Motor, from Figure 3:

$$v_R + v_L + v_b = e_a \quad (1)$$
$$i_a R_a + L_a i_l + v_b = e_a \quad (2)$$
$$v_b = k_b \dot{\theta} \quad (3)$$

We find the Laplace transforms.

$$I_a(s)R_a + SI_a(s)L_a + k_b S\theta(s) = E_a(s) \quad (4)$$
$$(R_a + L_a S)I_a(s) + k_b s\theta(s) = E_a(s) \quad (5)$$
$$I_a(S) = \frac{T_m(s)}{k_t} \quad (6)$$
$$\frac{(R_a+L_aS)T_m(S)}{k_t} + k_b s\theta(s) = E_a(s) \quad (7)$$
$$T_m(s) = (j_m S^2 + D_m S)\theta_m(s) \quad (8)$$
$$\frac{(R_a+L_aS)(j_mS^2+D_mS)\theta_m(s)}{k_t} + k_b S\theta_m(s) = E_a(s) \quad (9)$$

If $L_a << R_a$ which is usual for a dc motor, Eq. (9) becomes:

$$\frac{R_a(J_mS^2+D_mS)\theta_m(s)}{k_t} + k_b s\theta_m(s) = E_a(s) \quad (10)$$
$$\left[\frac{R_a}{k_t}(J_mS + D_m) + K_b\right] S\theta_m(s) = E_a(S) \quad (11)$$
$$\frac{\theta_m(s)}{E_a(s)} = \frac{k_t/(R_aJ_m)}{s\left[s+\frac{D_mR_a+K_tK_b}{J_mR_a}\right]} \quad (12)$$

If there is a load connected to the motor as shown in Figure 4, the transfer function will be as follows:

$$J_m = J_a + J_L\left(\frac{N_1}{N_2}\right)^2 \quad (13)$$
$$D_m = D_a + D_L\left(\frac{N_1}{N_2}\right)^2 \quad (14)$$

Transfer function to motor and load is:

$$TF = \frac{k_m}{S(S+a_m)} \quad (15)$$

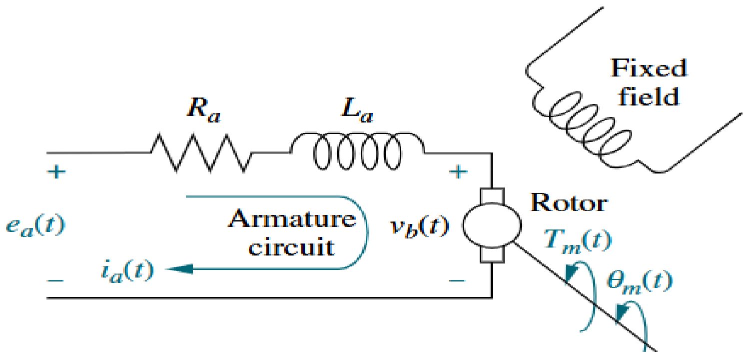

Figure 3. DC motor Schematic diagram (Nise, N. S. 2011).

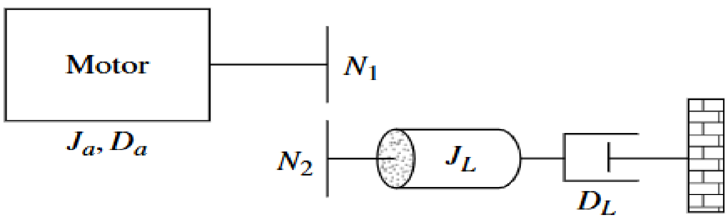

Figure 4. DC motor driving a rotational mechanical load (Nise, N. S. 2011).

Upon deriving the transfer functions for the motor and load, the system's block diagram was constructed, as depicted in Figure 5.

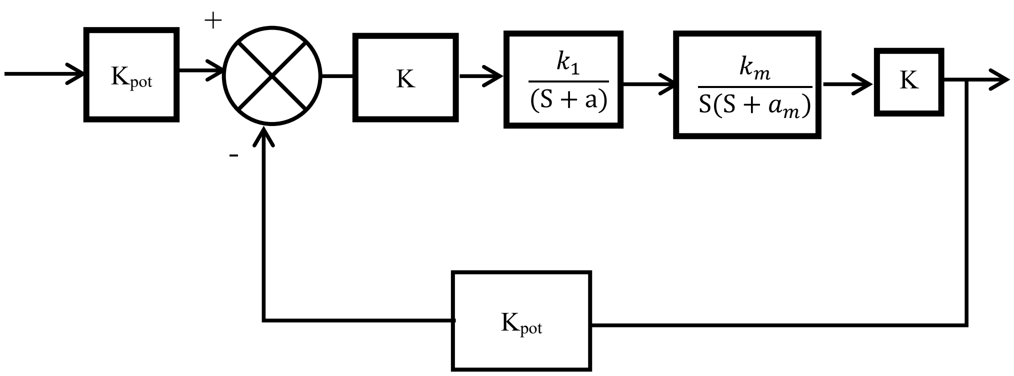

Figure 5. The antenna azimuth position control system Detailed block diagram.

The parameters and units used in Equations (1) – (15) are given in Table 1.

Table 1. Parameters Values (Nise, N. S. 2011).

PARAMETER	**DEFINITION**	**VALUE**
V	Voltage across Potentiometer[V]	10
R_a	Motor Armature Resistance[Ω]	8
J_a	The Constant of Motor Inertial Constant [Kg m2]	0.02
D_a	Equivalent viscous friction Coeff. [Nms/rad]	0.01
K_b	The Constant of Back emf [Vs/rad]	0.5
K_t	The Constant of Motor Torque [Nm/A]	0.5
N_1	The Teeth of Gear	25
N_2	The Teeth of Gear	250
N_3	The Teeth of Gear	250
J_l	The Constant of Load Inertial [Kg-m^2]	1
D_l	The Constant of Load Dampening [Nms/rad]	1
K_{pout}	The Gain of Potentiometer	0.318
K_1	The Gain of Power Amplifier	100
a	The Pole of Power Amplifier	100
K_g	Gear Ratio	0.1
K_m	The Gain of Motor and Load	2.083
a_m	The Pole of Motor and Load	1.71
K	Preamplifier Gain	100

From Table 1 and Figure 5 the transfer function of the system is:

$$\frac{\theta_0(s)}{\theta_i(s)} = \frac{663}{s^3+101.71s^2+171s+663} \quad (16)$$

3.2 PID Controller

The PID Controller is one of the most utilized feedback control methods in industrial and technical applications. It maintains system stability and desired performance by constantly modifying a control input depending on the difference between a desired setpoint and the actual system output. The control signal has three components: proportional, integral, and derivative gain scaling factors.

The PID controller is represented in the following equation:

$$u(t) = k_P \mathrm{e}(t) + k_i \int \mathrm{e}(t) + k_d \frac{\mathrm{de}(t)}{\mathrm{d}t} \quad (17)$$

Where the parameter (k_i, k_d and k_P) are integral, derivative and proportional gains respectively and e(t)= error.

The transfer function for PID controller can be represented as bellow in S domain:

$$\frac{U(s)}{E(s)} = k_P + \frac{k_i}{s} + k_d s \quad (18)$$

3.3 Cascade PID Controller

A Cascade PID Controller is an advanced control approach that employs two or more PID controllers in a hierarchical or nested configuration. This arrangement is intended to manage systems with numerous control loops, resulting in faster response time and greater robustness than a single-loop PID controller (Mahmood, Q. A., & Nawaf, A. T. , 2021). In this study, the cascade structure consists of an outer PID controller responsible for antenna azimuth position regulation and an inner PI controller designed to suppress fast inner dynamics and actuator disturbances, thereby improving transient performance and overall system stability.

3.4 Grey Wolf Optimizer (GWO) for Cascade PID Parameter Tuning

In this work, the Grey Wolf Optimizer (GWO) algorithm is used to optimize the parameters of the proposed cascade PID controller for the antenna azimuth position control system. The GWO algorithm is a metaheuristic optimization algorithm that uses the leadership structure and hunting behavior of grey wolves in the wild. The Grey Wolf Optimizer (GWO) was chosen in this research work due to its simplicity, less computational complexity, and fewer control parameters compared to other metaheuristic optimization techniques like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). In addition, GWO has the ability to maintain a balance between exploration and exploitation, which prevents the search process from being trapped in local minima and ensures rapid convergence. This makes GWO suitable for optimizing PID controllers in control systems. The objective function used in the GWO optimization process is designed to enhance the transient performance of the antenna azimuth control system. It is formulated as a weighted combination of time-domain performance indices as follows:

$$J = w_1 \cdot ITAE + w_2 \cdot M_p + w_3 \cdot T_s \quad (19)$$

where ITAE represents the integral of time-weighted absolute error, M_p is the maximum overshoot, and T_s denotes the settling time. The weighting coefficients w_1, w_2, and w_3 are selected to prioritize fast response with minimal overshoot and high tracking accuracy.

3.4.1 Principle of Grey Wolf Optimizer

The social hierarchy of grey wolves is categorized into four levels: alpha (α), beta (β), delta (δ), and omega (ω). In the optimization process, the alpha wolf represents the best candidate solution, while beta and delta wolves represent the second and third best solutions, respectively. The remaining wolves, known as omega, follow the guidance of these leading wolves. The hunting mechanism of grey wolves is mathematically modeled to guide the population toward the optimal solution (Mirjalili, S., Mirjalili, S. M., & Lewis, A. ,2014).

3.4.2 Mathematical Modeling of GWO

The encircling behavior of grey wolves around the prey is formulated as:

$$\vec{D} = \left|\vec{C}.\vec{X}_P(t) - \vec{X}(t)\right| \quad (20)$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}.\vec{D} \quad (21)$$

where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_P$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf. The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \quad (22)$$

$$\vec{C} = 2.\vec{r}_2 \quad (23)$$

where components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and $\vec{r}_1$, $\vec{r}_2$ are random vectors in [0, 1].

The hunting process is guided by the three best wolves (α, β, and δ) as follows:

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right|, \vec{D}_\beta = \left|\vec{C}_2.\vec{X}_\beta - \vec{X}\right|, \vec{D}_\delta = \left|\vec{C}_3.\vec{X}_\delta - \vec{X}\right| \quad (24)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.\vec{D}_\alpha, \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.\vec{D}_\beta, \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\vec{D}_\delta \quad (25)$$

The final position of each wolf is updated as:

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (26)$$

3.4.3 Steps of Grey Wolf Optimizer

1. Initialize the grey wolf population and GWO parameters.
2. Evaluate the fitness value of each wolf.
3. Identify the alpha, beta, and delta wolves.

4. Update the positions of all wolves using GWO equations.
5. Update the control parameter a.
6. Check the stopping criterion.
7. Output the optimal cascade PID parameters.

The flowchart of the GWO algorithm consists of initialization, fitness evaluation, leadership hierarchy identification, position updating, convergence checking, and output of the optimal solutio as shown in Figure 6.

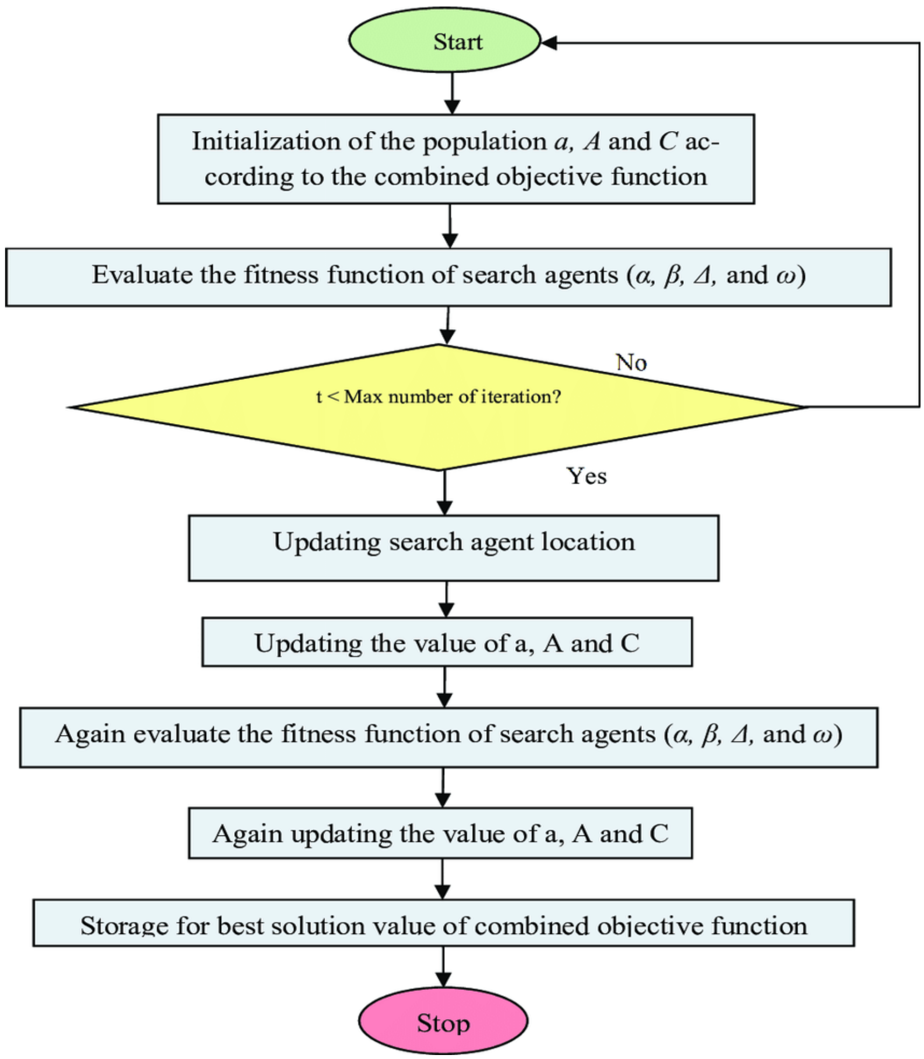

Figure 6. Flowchart of GWO technique

4. Results of simulation

The simulation of the antenna azimuth position control system was carried out using the MATLAB/Simulink environment, where a unit step signal was applied as the reference input. Figure 7 illustrates the simulation model of the uncontrolled system, which was used as a baseline to analyze the system structure without any control action. Subsequently, the system was modeled with a conventional PID controller, as shown in Figure 9, where the controller parameters were optimized using the Grey Wolf Optimizer (GWO). Finally, the simulation model of the proposed cascade PID controller is presented in Figure 11, in which GWO was also employed to optimally tune the parameters of both the inner and outer control loops. Table 2 presents the key parameters and optimization settings of the Grey Wolf Optimizer (GWO) used for tuning the PID and cascade PID controllers.

Table 2. GWO Optimization Settings for PID and Cascade PID Controllers.

Parameter	Description	PID Controller	Cascade PID Controller
Optimization Algorithm	Tuning method used	GWO	GWO
Population Size	Number of grey wolves	30	30
Maximum Iterations	Optimization iterations	300	300
Control Parameter (a)	Linearly decreasing factor	$2 \rightarrow 0$	$2 \rightarrow 0$
Objective Function	Performance criteria	M_p, T_r, T_s, e_{ss}	M_p, T_r, T_s, e_{ss}
Optimized Parameters	Controller gains	k_P, k_i, k_d	$k_{P-out}, k_{i-out}, k_{d-out}, k_{P-in}, k_{i-in}$

4.1 Response of Antenna without PID Controller

Figure 7 shows a Simulation block diagram of antenna without PID controller.

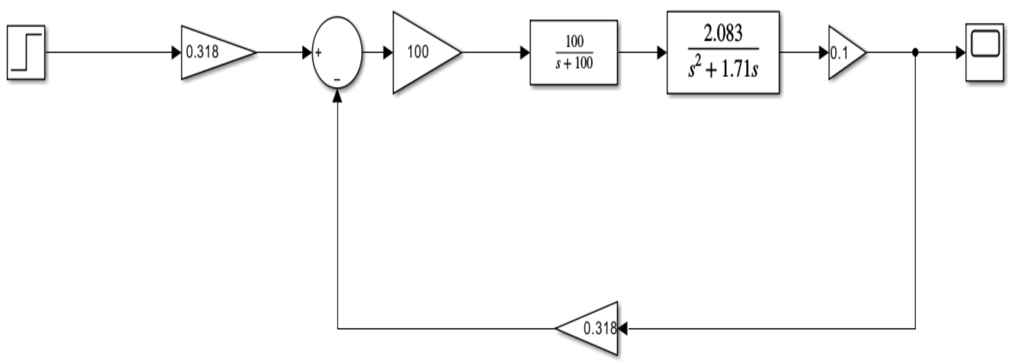

Figure 7. Simulation block diagram of antenna without PID controller.

Before applying any control strategy, the antenna azimuth position control system was simulated in an open-loop configuration to evaluate its inherent dynamic behavior. Figure 8 illustrates the system response to a unit step input without the use of any controller. The system response is highly oscillatory with a large overshoot and a slow settling characteristic, which reveals poor transient response and stability. The performance criteria for the uncontrolled system are presented in Table 3. The system has a large overshoot of 34.7% with a settling time of 4.35 seconds. Although the rise time is small, the large overshoot and oscillations make the system unsuitable for accurate azimuth positioning of the antenna. The above observations clearly emphasize the need for the implementation of an effective control approach to enhance stability and improve the overall tracking performance.

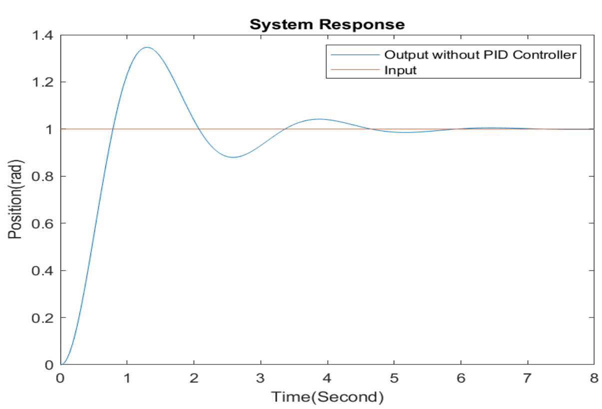

Figure 8. Antenna azimuth position control system response without Controller.

Table 3. Parameters without PID controllers.

Parameter	Value
Overshoot	34.7%
Settling Time	4.35 second
Rise Time	0.525 second
Peak Time	1.29 Second

4.2 Response with PID Controller

Figure 9 shows a Simulation block diagram of antenna with PID controller.

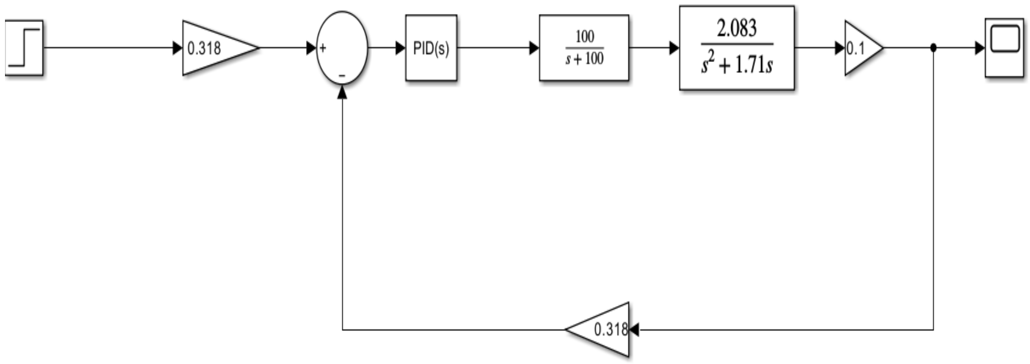

Figure 9. Simulation block diagram of antenna with PID controller.

After analyzing the open-loop system, a traditional PID controller was introduced to enhance the dynamic performance of the antenna azimuth position control system. Figure 10 shows the closed-loop system response to a unit step input signal when the PID controller is used. Compared with the uncontrolled system, the system response indicates a remarkable improvement in stability with less oscillation and faster convergence to the desired position. The performance indices of the PID-controlled system are listed in Table 4. The data show that the overshoot is reduced to 5.45% with a remarkable reduction in settling time to 1.25 seconds. Moreover, the rise time and peak time are remarkably improved, indicating a faster system response. These observations verify the effectiveness of the PID controller in improving the transient response of the antenna azimuth positioning system. However, the existence of overshoot indicates that there is still room for improvement in system performance using advanced control configurations, which leads to the development of the proposed cascade PID controller. The optimized parameters of the PID controller obtained using the Grey Wolf Optimizer (GWO) are listed in Table 5. These parameters were used in the simulation model to generate the closed-loop response shown in Figure 10.

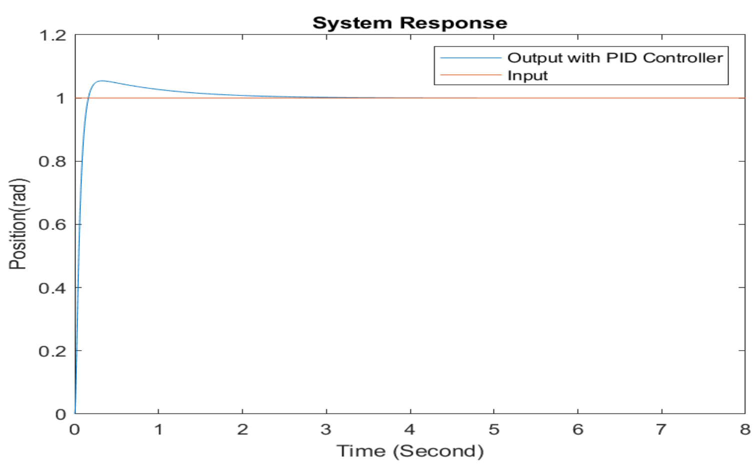

Figure 10. Antenna azimuth position control system response with PID Controller.

Table 4. Parameters with PID controller**.**

Parameter	Value
Overshoot	5.45%
Settling Time	1.25 second
Rise Time	0.1 second
Peak Time	0.33 Second

Table 5. Optimized PID Controller Parameters (GWO- based)**.**

Gain	Value
k_P	679.86
k_i	476.83
k_d	240.95

4.3. Response of Antenna with Cascade PID Controller

Figure 11 shows a Simulation block diagram of antenna with Cascade PID controller.

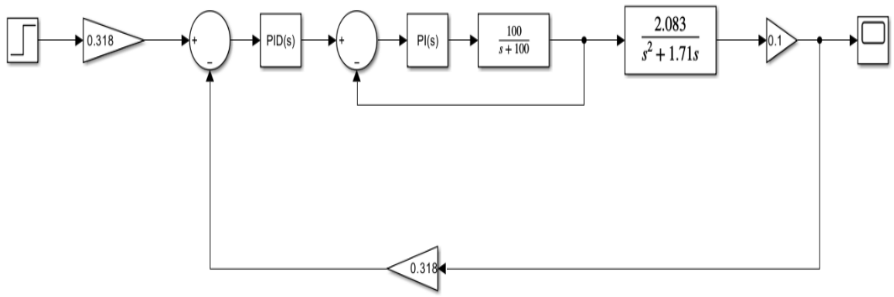

Figure 11. block diagram of antenna with PID controller (Cascade).

After the implementation of the conventional PID controller, the proposed cascade PID controller was used to further improve the dynamic performance of the antenna azimuth position control system. Figure 12 shows the closed-loop system response to a unit step input when the cascade PID controller is used. Compared to the single-loop PID system response, the response shows a much faster convergence to the reference position with minimal oscillations, indicating a highly stable and damped system response. The quantitative performance metrics of the system controlled by the cascade PID controller are shown in Table 6. The results show a dramatic improvement in the transient response characteristics, with the overshoot reduced to 0.56% and the settling time reduced to 0.12 seconds. Additionally, the rise time is reduced to 0.07 seconds, confirming the faster response characteristics of the cascade control system. The results confirm the effectiveness of the cascade PID controller in rejecting fast inner dynamics and improving the overall stability of the system, making it highly effective in precise antenna azimuth positioning tasks. The optimized parameters of the Cascade PID controller using the Grey Wolf Optimizer (GWO) are shown in Table 7. These parameters were used in the simulation model to produce the closed-loop system response shown in Figure 12.

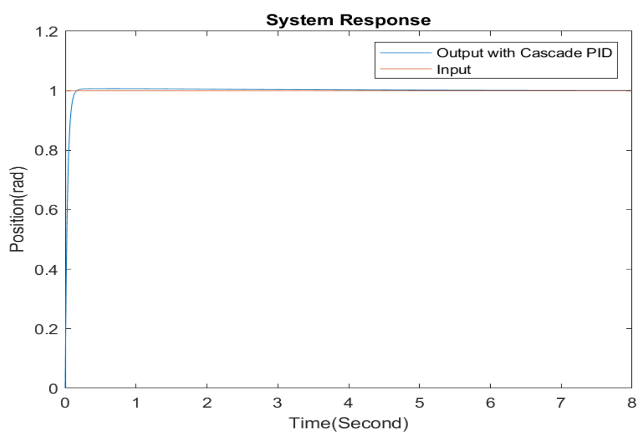

Figure 12. Response of Closed -loop system for position control of antenna azimuth system with Cascade PID controller.

Table 6. Parameters with PID controller.

Parameter	Value
Overshoot	0.56%
Settling Time	0.12 second
Rise Time	0.07second
Peak Time	0.67 Second

Table 7. Optimized Cascade PID Controller Parameters (GWO-based).

Gain	Value
k_{P-0ut}, k_{P-in}	895, 270.6
k_{i-out}, k_{i-in}	209.4 ,139.49
k_{d-out}	473.5

4.4. Compare results

To provide a clear comparative evaluation, the dynamic responses of the antenna azimuth position control system under the three studied cases (without controller, with PID controller, and with cascade PID controller) are compared in Figure 13. In addition, the corresponding performance indices are summarized in Table 8 to quantitatively assess the improvements achieved by each control strategy in terms of transient response and stability.

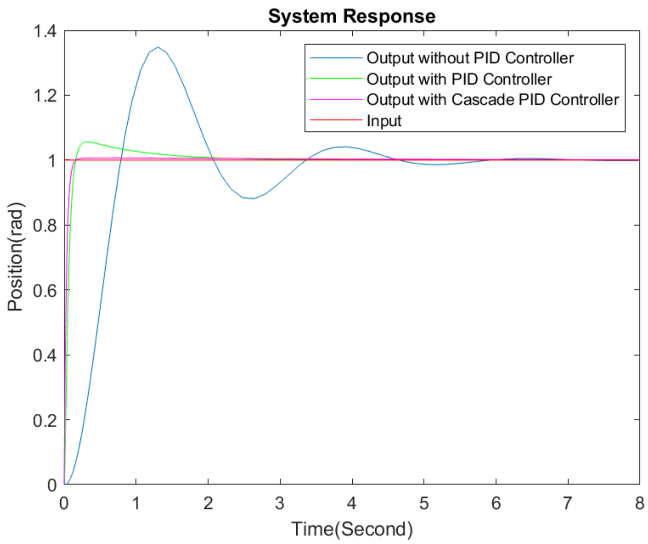

Figure 13. Compare Response of Closed -loop system for position control of antenna azimuth system.

Table 8. Compare results.

Parameter	Without PID Controller	PID Controller	Cascade PID Controller
Overshoot	34.7%	5.45%	0.56%
Settling Time	4.35 second	1.25 second	0.12 second
Rise Time	0.525 second	0.1 second	0.07second
Peak Time	1.29 Second	0.33 Second	0.67 Second

Regarding robustness, the cascade PID control structure ensures better disturbance rejection properties because of the existence of the inner control loop, which effectively compensates for the fast dynamics and disturbances in the actuator. The hierarchical structure of the control system ensures that the outer position control loop is less affected by the modeling errors and disturbances. The simulation results obtained, which have minimal overshoot and fast settling time, indicate that the designed controller ensures stable performance of the system during dynamic operation.

5. Conclusion

This study successfully developed and analyzed a position control system for the azimuth of an antenna, demonstrating the effectiveness of various control strategies in achieving precise and stable performance. Initially, the system displayed a significant overshoot, extended settling time, and steady-state inaccuracies, rendering it unsuitable for precision applications. The introduction of a PID controller improved system performance by reducing overshoot, settling time, and rise time. Further optimization using a Cascade PID controller eliminated overshoot, drastically reduced settling and rise times, and delivered accurate and robust performance. This study picks out the Cascade PID controller as an appropriate solution for applications that need high accuracy and stability, such as in tracking satellites and radar systems, and lays down a basis for future research in control system design. Potential directions for further research are using more advanced optimization techniques, such as artificial intelligence and machine learning, to find optimal controller gains, extension of the research to nonlinear antenna arrays for greater flexibility and applicability, and hardware implementation of the system to compare its performance with simulations in real-world environments. These are efforts towards further improvement of control approaches and extending their application to complex and dynamic issues.

Acknowledgements

The authors would like to acknowledge the support of King Fahd University of Petroleum & Minerals and the Interdisciplinary Research Center of Smart Mobility and Logistics, who funded this work under project number INML2409.

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