Comparative Performance Analysis of Ziegler–Nichols and Internal Model Control Tuning for an Antenna Positioning System

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Abstract: This paper presents a detailed analysis of the closed-loop response of an antenna positioner system (APS) using different PID control strategies. The mathematical model of the DC-motor-driven APS features an armature circuit, load, feedback from the position sensor, and gain from the pre-amplifier. The conventional Ziegler-Nichols (ZN) and internal model control (IMC) tuning methods are implemented and evaluated in terms of time-domain response to step inputs and frequency-domain Bode plots. The ZN-tuned PID controller shows a quick rise time of 0.095 but also overshoot of 65.34% and oscillation, indicating a low phase margin of 15.67 degrees and a small delay margin of 0.026 seconds. The IMC-tuned controller has a longer rise time of 0.244 but less overshoot, which is 11.46%. Moreover, impressive improvement of 68.17 degrees is achieved in phase margin and 0.192 seconds becomes a delay margin when using IMC tuning compared to ZN one.

Keywords: Servo control; PID tuning; Antenna position system; Robustness analysis.

Introduction

Current communication systems significantly depend on proper alignment of antennas in order to ensure communication via satellites, advanced systems of radar surveillance, navigation technology in aerospace, radio astronomy, deep space exploration, and defense equipment. The APS (the Antenna Positioning System) is actually responsible for pointing the antenna in the direction of the required target with an exact angular precision, while the corrections for environmental disturbances and uncertainties of the system are being made simultaneously. As the frequency increases with the help of modern technology, the antennas are becoming more and narrower, and even a small error in positioning leads to significant losses of signal strength, poor quality of communication, and interrupting of the transmission. The problem of providing high-quality control techniques for APS has therefore become very important for modern engineering. Normal functioning of the antenna positioning system involves functioning of the servo motor, mechanical drive equipment, position sensors, and controller, as well as feedback functions performed in the closed-loop mode. Desired angular position is viewed as a reference input, whereas real axis position is being measured continuously thanks to high resolution feedback systems like optical encoders. The controller calculates the error and creates control signal to to drive the servo motor until the antenna accurately reaches the commanded position [1, 2].

Among the many control techniques available, Proportional-Integral-Derivative (PID) controllers are still the most popular systems because of their simple design, ease of application, less computation requirements, and good performance. The proportional part of the system improves the speed of a response; the integral part reduces the steady state error, and the derivative part improves damping properties of the PID controller, giving it better transient responses. Due to all of the above listed advantages, PID controllers are still the backbone of industrial control systems providing a large share of real industrial processes. Although PID controllers are widely used, their effectiveness mainly depends on the right tuning. Poor tuning may lead to over-overshooting, long settling time, oscillations, and instability. This is why the search for the optimal controller characteristics has always been a hot topic among scientists. Initially, the tuning of PID controllers was based on almost empirical methods requiring only some information about the system behavior and providing good results for very simple systems. However, as the complexity of engineering systems grows and systems become more non-linear, classical tuning techniques do not give favorable results anymore [3].

Literature Review

Research on antenna positioning system control has developed significantly over the last few decades, starting with empirical techniques of tuning controllers and culminating with smart and optimization-based control methods. Each generation of control techniques has sought to improve upon the precision of tracking, disturbance rejection capabilities, and robustness along with the minimization of the implementation costs and refinement of complicated computational methods. The first studies concentrated on the tuning of classical PID controllers and introduced widely accepted algorithms, such as the techniques suggested by Ziegler and Nichols, Cohen and Coon, process reaction curve method, etc. These methods are very easy to apply and require little information about the process since they can give the required characteristics of the controller in a short time without thorough calculations. As a result, this type of empirical method is widely used in many industrial scenarios where the main requirement to the method is to implement it as soon as possible. However, empirical methods tend to produce controller settings that lead to overshooting and oscillations of the system. Moreover, these methods are based on the assumption that the plant parameters remain constant.

To overcome the shortcomings of classical methods, researchers introduced optimization-based PID tuning techniques that formulate controller design as an optimization problem. Evolutionary algorithms such as Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Ant Colony Optimization, Simulated Annealing, Artificial Fish Swarm Algorithm, and numerous other bio-inspired optimization methods have demonstrated promising results. These algorithms search for optimal controller parameters by minimizing objective functions such as Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral Time Absolute Error (ITAE), Integral Time Squared Error (ITSE), overshoot, settling time, and control effort. Their capability to perform global optimization without requiring gradient information has made them particularly attractive for nonlinear and multimodal optimization problems.

To get rid of the limitations of traditional approaches, scientists have developed optimization-driven PID tuning methods where the design of the controller is seen as an optimization issue. Evolutionary algorithms, including Genetic Algorithm, Particle Swarm Optimization (PSO), Differential Evolution (DE), Ant Colony Optimization (ACO), Simulated Annealing (SA), Artificial Fish Swarm Algorithm (AFSA), and some other optimization approaches inspired by living beings have shown good results in practice. These methods solve the problem of searching for best controller parameters by trying to minimize the values of particular functions of purpose, such as Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral Time Absolute Error (ITAE), Integral Time Squared Error (ITSE), overshoot, settling time, and control efforts. The ability of the algorithms to perform global optimization without the need for the gradient makes them attractive for solving nonlinear and multimodal optimization problems.

Optimization algorithms are known to enhance performance of nominal systems, but some studies claim that optimized controllers tend to lose robustness in real world working conditions. Most of optimization techniques examine solution candidates by means of default mathematical models and fixed operating conditions. Because of this, various uncertainties from parameter variations, modeling imperfections, non-linear friction, disturbances, actuator constraints and noise are oftentimes ignored. As a result, the implementation of optimized controllers is likely to fail.

At the same time, owing to the development of model-based control techniques, new methods of high-quality antenna tracking appeared on the market. Internal Model Control (IMC) applies a mathematical model of the process to gain better disturbance rejection; at the same time, it employs filters to ensure robustness against the model imperfections. Model Predictive Control (MPC) uses the same principles as IMC but solves optimization problem in the moving prediction horizon and takes system constraints into consideration. Generally speaking, both methods provide good tracking accuracy and transient performance, especially in the case of complex multivariable systems. However, implementation of these approaches requires accurate mathematical models, great computational capacities and precise identification of process parameters, which may seem impractical for real antenna systems exhibiting nonlinear and time-varying dynamics [4, 5].

Mathematical Model of APS

An antenna positioning system (APS) can be defined as an electromechanical system consisting of a mechanism that interprets electrical input and relays its motion to the antenna. The system is designed to rotate the antenna and hence reorient its position. There are three main components of the antenna positioning system. The first component is the mechanical frame that supports the antenna structure. The second component is the sensor and feedback system that supervises the position of the antenna. The third component is the control system that compares the desired position of the antenna and actual position and generates the motor drive signals as a correction in case of an error occurrence. The schematic diagram of an antenna position system is as shown in figure 1.

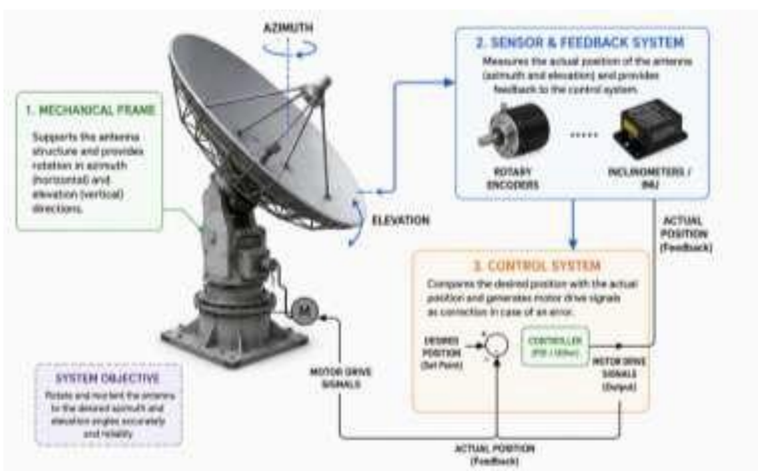


Fig. 1. Schematic diagram of an antenna position system.

The mathematical equations describing the servomechanism of a DC motor-based APS are taken from [5]. The instantaneous armature voltage, $v_a(t)$ applied across the motor terminals equals the sum of three voltage drops: the ohmic loss across the armature winding resistance, the inductive drop due to changing current, and the back electromotive force generated by the rotating armature. This relationship is written as:

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

The motor torque is $T_m(s) = K_t I_a(s)$, and the mechanical load follows $T_m(s) = Js\omega_m(s)+B\omega_m(s)$, with J as inertia and B as viscous friction. Combining these gives the speed-to-voltage ratio:

$$\frac{\omega_m(s)}{V_a(s)} = \frac{K_t}{R_a(Js+B)+K_tK_e} \tag{2}$$

To get angular position in radians, multiply the speed by 1/s

$$\frac{\theta_o(s)}{V_a(s)} = \frac{K_g K_t}{J_{eq}L_a s^3 + (J_{eq}R_a + D_{eq}L_a)s^2 + (D_{eq}R_a + K_t K_e)s} \quad (3)$$

A potentiometer gives a voltage that changes linearly with shaft rotation or linear travel. For a servo system, turning the knob sets the reference voltage, and the feedback pot returns a voltage proportional to the actual output position. The feedback relation is simply $V_f(s)=K_{pot}\theta_o(s)$, where k_{pot} is the potentiometer sensitivity in volts per degree. The pre-amplifier then takes the difference between the input command and this feedback, and amplifies it: $V_a(s)=K\,K_{pa}\,[V_{in}(s)-V_f(s)]$. The gain $K\,K_{pa}$ lumps the pot scaling and the amplifier stage together.

$$\frac{V_f(s)}{\theta_o(s)} = K_{pot} \quad (4)$$

Putting equations (3) and (4) together with the pre-amplifier gain K and the feedback pot yields the closed-loop transfer function for the APS. If you remove the feedback potentiometer from the loop—that is, set $V_f(s)=0$—the system reduces to an open-loop plant. The overall transfer function then becomes the product of the pre-amplifier gain and the motor/load dynamics:

$$\frac{\theta_o(s)}{V_{in}(s)} = K\,K_{pa} \cdot G(s) \quad (5)$$

where G(s) is the transfer function relating armature voltage to output position. Without the feedback pot, the output no longer influences the input, so the system runs as a straightforward gain stage followed by the motor plant.

$$\frac{\theta_o(s)}{V_a(s)} = \frac{KK_{mi}K_gK_{pa}}{s^3 + (a + a_m)s^2 + a.a_m s + KK_{mi}K_gK_{pa}} \quad (6)$$

Figure 2 shows the block diagram of the APS. Equation (6) gives the ratio of the reference input voltage to the resulting angular displacement, assuming no external disturbances act on the system. The nominal parameter values used in this model come from the data reported in [6]. Plugging the nominal values from [6] into equation (6) gives the numerical form of the APS transfer function, including the potentiometer in the loop.

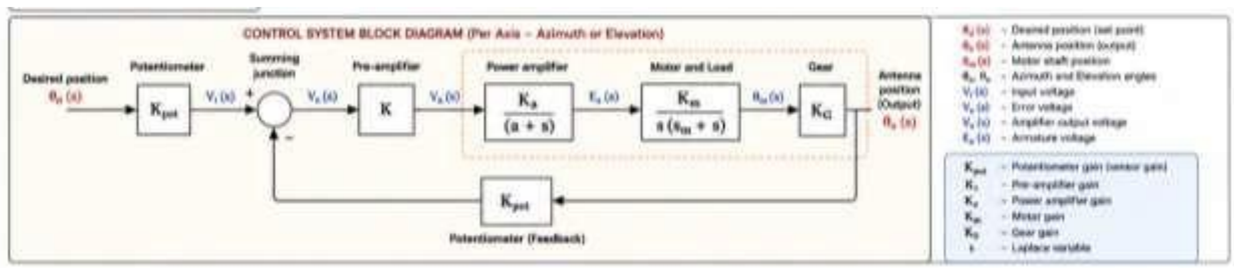


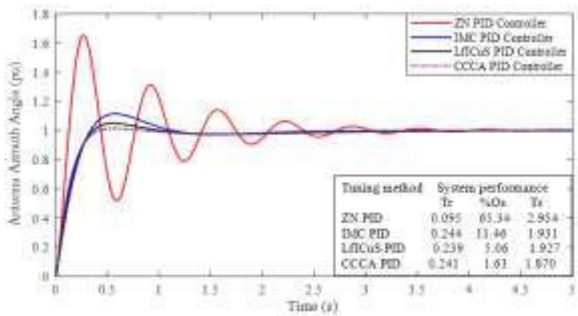
Fig. 2. Closed loop diagram of APS.

The resulting expression is:

$$G_p(s) = \frac{\theta_o(s)}{\theta_i(s)} = \frac{209.5}{s^3 + 101.73s^2 + 171s + 209.5} \quad (7)$$

Simulation Results:

Figure 3 shows the closed-loop step response of the azimuth antenna system as per several PID tuning techniques. Ziegler–Nichols (ZN) design provides a fast rise time of 0.095 s but also leads to an overshoot of 65.34% and excessive ringing before the response finally reaches a value of unity. The amount of oscillation in the response makes it clear that the ZN controller cannot support accurate antenna placement. Internal model control tuning improves the rise time to 0.244 s and reduces the overshoot to 11.46% while quickly eliminating any oscillations and reaching a final value of unity within 1.931 s.



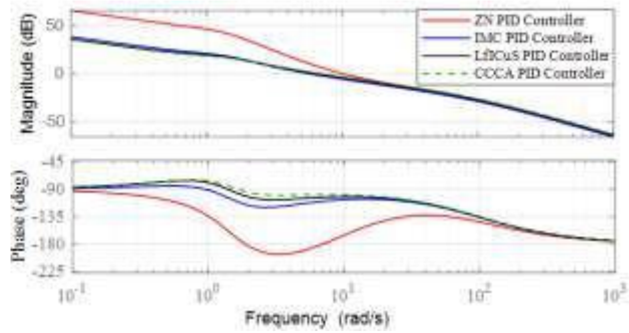


Table 1 shows the results of analyses done to compute both time and frequency domain parameters of every controller under tests at the antenna positioning system. The parameters obtained from an uncompensated control system are: 1.27 s for a rise time, 4.09 s for settling time, 31.50% for overshoot and, 0.05 pu for a steady-state error, which indicates poor regulation. Moreover, the gain margin equals 38.20 dB; the phase margin cannot be measured as we do not have the crossing of a −180 degree value. The delay margin of a ZN-tuned PID control system is very low—only 0.026 sec, meaning that any delay can cause instability of the control system during antenna positioning. An IMC-tuned PID control system increases delay margin to 0.192 sec.

Table I. Comparison of performance of APS with ZN and IMC PID controllers

Controller	Time-domain performance				Frequency-domain performance		
	T_r (s)	% Os	T_s (s)	e_{ss} (pu)	GM (dB)	PM (deg)	Delay margin (s)
Uncompensated	1.27	31.50	4.09	0.05	38.20	Undefined	
ZN PID	0.095	65.34	2.954	0	-6.84	15.67	0.026
IMC PID	0.244	11.46	1.931	0	Inf	68.16	0.191

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