Antenna Position System and Robustness Analysis: A review

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Abstract: The performance of PID controllers is critically dependent on proper tuning, and while various classical techniques such as Ziegler–Nichols and Cohen–Coon result in acceptable performance during nominal conditions, they can produce inconsistent performance when subjected to any type of disturbance (e.g. environmental, noise, parameter variations, etc.) of the system or existences of uncertainty in their model. Also, traditional stability analysis tools (e.g., root locus and Bode plots) analyze the gain and phase of the controller independently, thus do not capture the simultaneous uncertainties associated with both control gain and phase. Most optimization-based tuning approaches primarily emphasize transient performance while failing to provide a comprehensive robustness assessment of the controlled system. The current literature is significantly lacking in terms of the comparative assessment of the various tuning methodologies for PID controllers based on purely time domain metrics, without any attempt at systematically evaluating the ability of the controller's tuning to withstand simultaneous variations in both gain and phase. Therefore, an overall unifying framework must be developed to provide both an assessment of the robustness of a given tuning methodology as well as comparing different tuning methodologies.

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

Introduction

An Antenna Positioning System (APS) is an essential electromechanical device that allows for accurate angular alignment of antennas to their stationary and/or moving targets and helps maintain that alignment. It is critically important for an antenna to point accurately due to the nature of how electromagnetic waves travel through space; even small angular misalignments can cause significant signal loss, increased errors in data transmission, and possibly a complete loss of the communication link. Positioning accuracy directly affects how much information can be sent or received properly across a range of applications (satellite TV, deep space communications, military radar systems)[1, 4].

APS's control mechanism is based on closed-loop vs. open-loop methods due to the advantages of closed-loop methods for minimizing the effects of disturbances, as well as accommodating for the natural changes in the system over time. In general, a closed-loop controller will begin the control process when the controller receives an input command consisting of a reference angle that represents where the antenna should be oriented. Simultaneously; at the same time, the antenna's position is continuously being monitored with feedback sensors that are generally optical encoders due to their high resolution, they have digital outputs, and they do not drift. The controller will continuously compare the reference angle to the actual angle to calculate the instantaneous error signal, which will then be sent as input to a control algorithm that will generate a command signal used to drive the servo motor through torques acting on the structure to minimize positional error. The negative feedback configuration of an APS will ensure that once the antenna is at its desired position, it will continue to be maintained there, regardless of any disturbances such as wind loading, friction variance and the force of gravity[4, 8].

PID controllers have long been the most popular type of control method for APS due to a variety of reasons: Their structure is composed of three easily understood terms that closely resemble the three basic control actions; tuning requires only minimal input to output data with no needed process model; many proven tuning methodologies have been developed over the years through industrial experience; and low-cost reliable platforms for implementing PID controllers are readily available (from analog electronics to programmable logic controllers). In addition, at least 85% of APS applications can be adequately controlled using PID controllers, and the simplicity of these controllers allows for easy troubleshooting, maintenance, and operator familiarity. Collectively, these characteristics cause PID controllers to be viewed as the foundation upon which any more advanced method will need to justify its increased complexity and cost of implementation[2, 4].

Literature work

Classical practices have primarily contributed to the practical tuning of PID controllers from 1940 to the 1960s, and the Ziegler-Nichols methods have become the most widely known methods of controller tuning. They were created at a time when analytical techniques were limited, and there were no computational tools available for optimization. As a result, there were many elegant procedures that required very little data from the plant to determine the basic characteristics for the process. For example, by conducting controlled closed-loop experiments, the Ziegler-Nichols frequency response method only requires determining the ultimate gain and ultimate period. The corresponding PID parameter settings can then be computed using specified formulas. For example, the process reaction curve method uses open-loop step response data to derive the apparent dead time and time constant for a controller. After this, empirical rules are used to obtain the required controller gains. These classical methods' primary strength is their simplicity and low requirements; a technician can use basic instrumentation to achieve workable controller settings within a few hours of commissioning the system without an advanced level of mathematical training or process models.

Nonetheless, classical tuning methods have some fundamental limitations, which can be seen when the methods are used to evaluate system performance and robustness. For example, the Ziegler-Nichols rules were determined empirically from only a small number of process models and are based on the principle of using the quarter-amplitude damping response as the performance metric, where the performance is often very aggressive with large overshoots and oscillations in the output. In addition, there is no inherent robustness guarantee provided by these methods; that is, controllers set using a classical approach will generally be able to produce acceptable nominal response characteristics but may have insufficient stability margins to accommodate actual variations, such as changes in the process being controlled, degradation of the sensors and/or disturbances that affect the process. The source of these limitations on robustness is the assumption made during the classical tuning process that there is no uncertainty in the process, meaning they will perform the same way every time; whereas in reality, all practical systems will have a range of uncertainty present throughout their life due to the presence of unknown or unpredicted parameter changes and as a result of added dynamics that were not modeled at the time of tuning.

Starting from the 1980s a new way to approach the design of PID controllers has emerged based on the increasing ability of computers to do calculations. The goal of these optimization-based PID controller tuning methods is to represent the design of the controller as an optimization problem. Nature-inspired optimization algorithms have received a great deal of attention in recent years because they allow for the exploration of complex, non-convex search spaces without requiring the use of gradient information or assumptions of linearity in the design of the PID controller. Genetic Algorithms (GA), which draw their inspiration from the concepts of natural selection and evolution (in the biological sense), maintain populations of candidate solutions (controller parameters) that undergo the processes of selection, crossover, and mutation in order to evolve toward optimal performance. Particle Swarm Optimization (PSO) takes inspiration from social behavior observed in nature in the context of bird flocking and fish schooling. In the PSO algorithm, candidate solutions travel throughout the search space and, as they do so, are influenced by both their own individual best known location, as well as the best known location found by any member of the swarm. Other techniques such as Ant Colony Optimization, Differential Evolution, and Simulated Annealing have also been successfully applied to the PID tuning problem in various applications. More recently, novel algorithms inspired by natural and social phenomena continue to emerge, such as the Artificial Fish Swarm Algorithm [6], the Puma Optimizer [5], and even algorithms based on pandemic events like the Coronavirus Optimization algorithm [3], demonstrating the ongoing interest in this field.

Nonetheless, optimization methods have many serious limitations when evaluating the robustness of an optimized controller. The optimization of a controller usually only takes into account deterministic performance metrics calculated based on nominal plant models or selected scenarios of disturbances; neither of which systematically considers how variations in actual parameters and errors in modeling would impact the stability of the closed-loop system. While some researchers have developed ways to introduce robustness by adding penalty terms to the optimisation or by making modifications to prevent violation of constraints, these approaches do not have a formal theoretical basis at all comparable to classical robustness assessments. As a result, a controller that has performed exceptionally well in a simulation may be very sensitive when used in an actual system where there exist a full range of operational uncertainties.

Control techniques based on models make use of a mathematical description of how the system behaves (system dynamics) to improve the performance of the controller in terms of tracking and rejecting disturbances [8]. Internal Model Control is an organized way to design a controller that uses a model for the system (or plant) that has been created from empirical data or previous experience of how the system works; thus, the model will likely have structure built in to account for the uncertainty associated with the model through filter design. Model Predictive Control is the most complex of all of the control techniques discussed and provides an iterative optimization process that takes into consideration all of the constraints of the system and minimizes potential future errors in the control action through optimizing the use of a changing time horizon. In addition to the above categories, hybrid methodologies exist that take components from multiple types of control techniques—for example, using fuzzy logic inference within a PID structure to produce adaptive behavior [7], or using a neural network approximation scheme to provide compensation for unmodeled nonlinearities.

The primary limitation of model-based methods is their reliance on having an accurate model for the system. Complex behaviour comes from flexible structural modes of real antennas, the nonlinear characteristics of friction in moving parts of the system, differences in the inertia of moving parts caused by differences in how they are used, and changes in these parameters over time — all of which make it difficult to describe the behaviour of the system mathematically. Model identification requires superspecialized knowledge and test equipment that is likely to be impractical for typical installations. Even when good models are obtained, the controllers created using the models will likely not be robust enough to handle the inevitable mismatch between a mathematical model of the system and what actually happens in the real world. Additionally, even though there are many different ways to obtain a model of a system, very few efforts have been made to develop a single set of criteria for comparing the robustness of the models obtained using different methods. As such, researchers and practitioners are going to have trouble determining that the methodology they choose has correct performance and is robust enough for the application they are using it for.

Conclusions

PID controllers remain indispensable for antenna positioning applications due to their simplicity and reliability. However, classical tuning methods lack robustness against simultaneous gain-phase uncertainties, while optimization-based and advanced structures prioritize transient performance without systematic stability guarantees. Model-based approaches depend on accurate plant representation, which is rarely achievable in practice. This review establishes that robust stability evaluation must accompany conventional performance metrics for meaningful controller comparison. The findings highlight the need for unified frameworks that assess tolerance to realistic uncertainties—enabling selection of tuning methodologies that ensure reliable antenna operation despite wind disturbances, parameter variations, and sensor imperfections in operational environments.

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