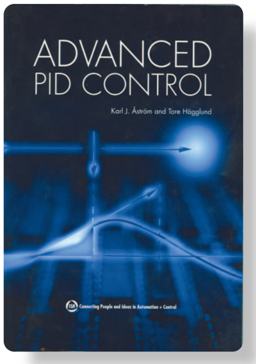

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Advanced PID Control

BY KARL J. ÅSTRÖM AND TORE HÄGGLUND

Proportional-integral-derivative (PID) control is by far the most widely used form of feedback control. Despite the extraordinary progress that has taken place in control theory over the last 20 years, industrial engineers tend to view much of control theory as esoteric and of little relevance to industrial problems. In the mid-1980s, the authors of this text, Åström and Hägglund, turned their attention to the PID controller. At that time, the treatment of PID in most textbooks was given only a few pages and was restricted to an idealized version of its operation. In the academic community, there existed the belief that PID control was a research area with little opportunity. It is fair to say that the authors' work changed this situation. Today, many introductory textbooks include at least one chapter related to PID control, and there is no doubt that PID control is an active area of research.

In the early 1980s, the tuning formulas proposed by Ziegler and Nichols 40 years earlier represented the state-of-the-art in industrial PID control. Modern attempts at developing automatic PID tuning were model based, with the exception of Foxboro´s EXACT controller. Introduced in 1984, this controller was based on heuristic logic developed using computer simulation studies [2].

The relay-tuning method proposed by Åström and Hägglund in 1984 [3] had its roots in the classical method of Ziegler and Nichols. That relay-tuning method calculates the controller's PID parameters using knowledge of only one point on the open-loop Nyquist curve. The point of intersection of the Nyquist curve with the negative real axis is determined by increasing the gain of a proportional controller until a sustained oscillation of constant amplitude is obtained. A disadvantage of this method is the fact that the user cannot control the amplitude of the resulting oscillation. The ingenious idea of Åström and Hägglund was the realization that this point can be determined by replacing the proportional controller with a relay. The relay induces a limit cycle when the loop is closed, with the great advantage that the amplitude of the limit cycle can be set by the amplitude of the relay characteristic. This technique, which was patented by Åström and Hägglund, is incorporated in many commercial PID controllers.

Advanced PID Control is the most recent of a trilogy of PID books written by Åström and Hägglund over the past 20 years. The previous books are *Automatic Tuning of PID Controllers* [4] and *PID Controllers: Theory, Design, and Tuning* [5]. To understand the contribution of the most recent book, it is helpful to reexamine the first two texts.

The goal of [4] was to introduce autotuning and adaptation to control practitioners. Autotuning is the capability to automatically adjust the controller parameters on demand from an operator or an external signal. Adaptation is the continuous adjustment of the parameters to enhance performance. At the time when [4] was published, several commercial products with these capabilities were beginning to appear on the market. *Automatic Tuning of PID Controllers* discusses many useful ideas employed by control practitioners but which are rarely mentioned in standard control texts.

The scope of their second book [5] is considerably larger. This book provides a self-contained, well-thought-out, and accessible introduction to a wide range of topics and fundamental principles underlying PID control. The main goal was to provide the technical background for understanding PID control in a comprehensive fashion. This goal was achieved with a level of mathematics that is accessible to control practitioners.

Based on its table of contents, *Advanced PID Control* follows more or less the same structure as its predecessor. However, there are major differences. Traditionally, PID tuning and design have been based on ad hoc techniques that take advantage of the special structure of the PID controller. Consequently, PID control has not followed the control mainstream, where robust control theory has provided design methods based on loop shaping. *Advanced PID Control* seeks to remedy this situation by applying these ideas to PID control.

CONTENTS OF THE BOOK

Chapter 1 provides a brief introduction to the core concepts used throughout the book and an outline of the text's contents. Chapter 2 introduces basic approaches for analyzing the behavior of feedback-controlled processes. Time and frequency representations are introduced as a prerequisite to understanding the dynamics of closed-loop systems. The objective is to derive simple models that describe the process sufficiently well in the frequency range that is critical to successful control. Two dimensionless parameters, namely, the normalized time delay and the gain ratio, are introduced to quantify the difficulty of controlling a process.

A comprehensive study of the PID algorithm is provided in Chapter 3. Taking as a starting point the textbook form of PID, several modifications are discussed that result in a more practical controller. Implementation issues that must be considered in practice are then introduced, including derivative filtering, antiwindup mechanisms, and the changing of setpoint values. The chapter thoroughly examines these issues. Alternative PID structures, such as standard noninteracting, interacting, and parallel structures, as well as conversion from one form to another, are treated. The chapter ends by considering the questions of when PID control is usable and when more sophisticated control is advisable.

Chapter 4 discusses controller design in general. A clear overview of the basic design principles is provided. The design objectives are expressed as requirements on load disturbance response, measurement noise response, setpoint response, and robustness. From a practical point of view, an interesting result for two degree-of-freedom controllers is that one can design for robustness and disturbance response independently. This chapter also emphasizes one of the most important objectives of this book, namely, to demonstrate that PID control design can be treated using ideas from mainstream controller design.

Chapter 5 focuses on feedforward design, which is an effective strategy for reducing the effect of measurable disturbances. The ideal feedforward strategy is to use a close approximation to the inverse process model. The chapter presents several alternatives to this approach. The use of a two-degree-of-freedom controller structure separates the design problems of load disturbance response and setpoint response.

Chapter 6 treats special cases of the general PID design problem presented in Chapter 4. Since the complexity of the controller is restricted, two alternatives emerge: 1) simplify the process models in such a way that the design method yields a PID controller or 2) design the controller using a complex model and approximate it with a PID controller. This chapter seeks to find a balance between an historical overview and the presentation of new methods. A critical review is given of several methods, including Ziegler-Nichols, rule-based empirical tuning, pole placement, lambda tuning, algebraic design, and optimization methods. Strengths, weaknesses, and limitations of each method are summarized. All of these methods share the common property that robustness to process variations must be examined after the design is complete. This philosophy is not in agreement with the main thrust of recent control theory, where robustness of the completed design is guaranteed a priori. The authors present a novel tuning method called MIGO (M_s constrained integral gain optimization), which can be considered as a translation of robust design principles to PID design. MIGO seeks to maximize the integral gain (and thereby minimize the integrated error) such that loop-gain frequency response lies outside the classical M_s-circle.

Chapter 7 develops simple tuning rules in the same spirit as Ziegler and Nichols. The goal is to obtain rules that can be employed for both manual tuning and automatic tuning for a wide range of processes. These tuning rules, dubbed AMIGO (approximate MIGO), were developed by applying MIGO to a large batch of representative processes and correlating the PID resulting parameters to simple features of the process dynamics. The authors identify key differences between processes that are delay dominated and those that are lag dominated.

The performance of a PI controller can be improved if predictive capability is included. Possibilities other than derivative action may offer improved performance. In this regard, Chapter 8 examines useful alternatives to dealing with time delays. Various model-predictive controllers are treated, including the Dahlin-Higham controller and the minimum-variance controller. The treatment of the Smith predictor provides a new perspective on this technique. Since the classical robustness metrics, namely, gain margin and phase margin, may not capture the robustness issues associated with a Smith predictor controller, a new robustness metric—the delay margin—is introduced in this chapter.

Chapter 9 discusses techniques for adaptation and automatic tuning of PID controllers. Automatic tuning of PID controllers can be realized by joining the methods for obtaining process dynamics presented in Chapter 2 with the methods for calculating the PID parameters given in Chapters 6 and 7. The authors present several adaptive approaches, including gain scheduling, automatic tuning, and continuous adaptation. The chapter ends with a description of commercial controllers in which adaptive methods have been successfully employed.

Before tuning the controller, it is important to conduct a loop assessment of the system, including an examination of sensors and actuators, signal ranges, nonlinearities, noise levels, and disturbances. Chapter 10 provides an overview of methods for commissioning, supervising, and diagnosing control loops. The goal is to supervise the performance of the system during operation so as to guarantee that specifications are met.

Up to this point, the book has focused on control of a single PID loop. Chapter 11 is devoted to the relevant issue of interacting PID loops. Of particular importance, it is shown that controller parameters in one loop can act as a significant load disturbance to the dynamics of other loops. Basic measures of interaction are presented, such as Bristol's relative gain array, so as to determine whether the control problem can be solved using simple loops. The problem of pairing inputs and outputs as well as a design method based on decoupling are presented in this chapter.

Chapter 12 shows how complex control systems can be built from simple components such as PID controllers, linear filters, gain schedules, and simple nonlinear functions. Various control paradigms are presented, including re petitive control, cascade control, midrange and split-range control, ratio control, and control with selectors. Neural and fuzzy techniques in the context of PID control are also discussed to indicate how they can be interpreted both as rule-based control and as nonlinear control.

Finally, Chapter 13 provides the reader with a discussion of some implementation issues related to PID control. The authors follow the historical development starting with pneumatic and electronic implementation of analog controllers. A detailed presentation of computer implementation issues, such as sampling, prefiltering, and discretization of the PID algorithm, is then provided. Operational aspects and human-machine interfaces, such as bumpless transfer at mode switches and parameter changes, are also presented.

INTENDED AUDIENCE

Advanced PID Control is addressed to a broad audience, ranging from control practitioners to academic researchers. As a result, the book has several differing objectives. The treatment in the book, however, is well balanced and accessible.

It is clear that the authors have taken great care in the text's presentation to make it accessible to a broad readership. I foresee this text being used in several ways:

» As a text for independent study by control practitioners. The book provides an accessible introduction to the fundamental principles underlying PID control as well as a wide range of related topics.
» As one of several texts in an introductory automatic control course at the graduate level.
» As part of a training for individuals in industry. I have used [5] in this fashion with great success.
» As a general reference. The text is quite comprehensive and would be an invaluable source for researchers and practitioners.

SUMMARY

Åström and Hägglund´s book is a remarkably clear, accessible, and up-to-date text. Several other books have appeared in the last few years on this subject, although with a more limited scope [6]–[15]. While the present book has some overlap with these texts in terms of its coverage, *Advanced PID Control* stands on its own as a complete work. The text provides a rigorous yet accessible introduction with a unique perspective. The strength of the book is its systematic approach to structuring the PID control problem along the lines of the major developments in control theory over the past two decades. This book is a welcome addition to the existing literature on PID control and will certainly become a standard reference.

Sebastián Dormido

REVIEWER INFORMATION

Sebastián Dormido graduated from the Universidad Complutense of Madrid in 1968 and received the Ph.D. degree in control engineering from the Universidad del Pais Vasco in 1971. From 1968–1975, he was with the Department of Computer Science and Automatic Control of the Universidad Complutense and Universidad del Pais Vasco. From 1975–1982, he was with the Facultad de Ciencias Físicas of the Universidad Complutense de Madrid, and, in 1982, he joined the Facultad de Ciencias of the Universidad Nacional de Educación a Distancia (UNED). In 1982, he became head of the Department of Computer Science and Automatic Control. His research interests include process control, predictive control, robust control, object-oriented languages for modeling and simulation of hybrid systems, and control education with special emphasis on remote and virtual labs. He has supervised 25 doctoral theses and coauthored more than 180 conference and journal papers. Since 2002, he has served as president of the Spanish Association of Automatic Control (CEA), where he has promoted the relationship between academia and industry.

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