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**PID Control**

New Identification and Design Methods
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With
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Q.-G. Wang, Yong Zhang, Yu Zhang, P. Martin, M.J. Grimble and
D.R. Greenwood

**PID Control**

New Identification and Design Methods

With 285 Figures
For the gift of loving parents and family and for my grandchildren, Ethan and Teigan
Michael A. Johnson

To my wife, Mehri, and my sons, Aref and Ali, for their understanding and consideration; To my parents for their love over many years and to my family for their support.
Mohammad H. Moradi
The industrial evidence is that for many control problems, particularly those of the process industries, the Proportional, Integral and Derivative (PID) controller is the main control tool being used. For these industrial problems, the PID control module is a building block which provides the regulation and disturbance rejection for single loop, cascade, multi-loop and multi-input multi-output control schemes. Over the decades, PID control technology has undergone many changes and today the controller may be a standard utility routine within the supervisory system software, a dedicated hardware process controller unit or an input–output module within a programmable electronic system which can be used for control system construction.

With such a well-developed industrial technology available it is not surprising that an academic colleague on learning that we planned a book on PID control exclaimed, “Surely not! Is there anything left to be said?” Of course, the short answer is that technology does not stand still: new solution capabilities are always emerging and PID control will evolve too. Indeed, the Ziegler–Nichols rules have been famous for over sixty years and the Åström and Hägglund relay experiment has been around for twenty years, so it would be disappointing if some new approaches to PID control had not emerged in the meantime. However, that is not to claim that all the methods discussed in this book will replace existing technologies; nor is this book a definitive survey of all that has taken place in the developments of PID control since, say, 1985. The book was originally conceived as a set of chapters about new ideas that are being investigated in PID control; it might be more accurately subtitled “Some new identification and design methods”.

The first proposals for this book were constructed using a classification scheme based on the extent to which a method used a model, then what type of model and then whether the method used optimisation principles or not; a very academic approach. Such a scheme does work, but, as one reviewer remarked, it is perhaps unnecessarily rigid. However, another objective of the Editors was to incorporate into the text a set of contributions from international authors, and this is more difficult to achieve with a very strict classification framework. Consequently, the finished book has a more relaxed structure but retains an inherent methodological agenda.

The book opens with two basic chapters about PID controllers. Industrial technology is examined using discussions, examples and pictures in Chapter 1. Two interesting industrial product reviews significantly add to the value of this chapter. Chapter 2 is constructed around a set of useful concepts which say more about the PID notation and conventions than anything else. The material in these two opening chapters is descriptive and informative; some of it is theory, but it is selective. It is designed to be partly a repository of existing technology and expertise and partly an introduction to some of the terminology and concepts that will be used in subsequent chapters. The sections in these two chapters
are written with some repetition of material to enable individual sections to be read in isolation when using the text in reference mode.

This is followed by 11 chapters that make different contributions to ideas for identification for PID control, and to the tuning of PID controllers. Almost all of the contributions arise from problems and research issues which have intrigued the various authors, and the chapters describe some answers to these problems. This is not just the leavening of a set of the various authors’ published papers but a fully explained presentation of the investigative directions being followed by the contributors. The Editors hope that the reader will find the presentations quite readable and be able to follow up the research literature directly.

The underlying continuity in the book is that, as the chapters follow each other, the quality of model information used by the problem formulation and solution increases. This agenda starts at Chapter 3, where the methods assume no model information at all. The next group of chapters, numbers 4 to 7, use nonparametric models. Because the reaction curve method is historically associated with nonparametric methods, Chapter 8 on extensions to the reaction curve method is placed next. In the gap between nonparametric and parametric model-based methods, Chapters 9 and 10 report on the genetic algorithms and fuzzy model approach and on a so-called subspace identification method, respectively. Finally, methods based on parametric models take the stage in the final three chapters of the book. The last of these chapters looks at the idea of predictive PID control.

The emphasis within each chapter varies depending on what is important to the method being described. For example, a chapter might describe how to obtain the appropriate model information for a PID control design method, or how to use the appropriate model information in PID control design algorithm; sometimes both aspects of identification and design are treated. At no point can it be claimed that existing PID tuning methods are treated systematically; rather, the book has some chapters that explain some new ideas, whilst in other chapters existing techniques are given and then extended, reinterpreted and renovated. The book is most certainly not a cookbook for PID control tuning recipes, and to return to our colleague's surprised, “Is there anything left to be said?”, the book now written shows clearly that the PID control still has many avenues to be explored.

This is also the place to give thanks to various people who have been so helpful in the compilation, construction and production of the book. All the contributors are very gratefully thanked for agreeing to participate and for their patience during the editorial period. It was an extraordinary pleasure to meet some of them at their home institutions in Singapore and Taipei, Taiwan, in 2000, and others at various recent international control conferences.

Professor M. J. Grimble is gratefully thanked for allowing Emeritus Professor M. A. Johnson the use of facilities at the Industrial Control Centre, University of Strathclyde in Glasgow, during the writing of this book.

Finally, the Editors would like to thank the publishing staff at Springer-Verlag London, Oliver Jackson and Anthony Doyle, and at Springer Verlag’s New York offices, Jenny Wolkowicki, for their kind encouragement, and patience during the gestation period of the book. Also the copy editor and typesetter, Ian Kingston, is thanked for his thoroughness with the manuscript and for the excellent modern typographical interpretation of the text.

Michael A. Johnson and Mohammad H. Moradi
December 2004
How to Use This Book

In many cases the production of a contributed book leads to an opus which looks like set of collected papers from the authors. In the case of this book, care has been taken to have sufficient explanation introduced so that the book might also be used constructively. With this agenda, the typical structure for a chapter is:

- Learning objectives
- Introductory material
- Main algorithms described
- Worked examples and case studies
- Conclusions and discussion
- References and bibliography

Thus it is hoped that this book can be used for:

- Support material for possible advanced course study
- Self study by industrial and academic control engineers
- A source for future research ideas and projects
- A reference resource and a source of references
- Contacting researchers working on particular PID control topics

To assist the reader in navigating the various approaches and methods it is useful to have a map of the book. Firstly, the design approaches are given broad definitions, and a tree diagram of the book structure follows. The broad classification scheme that has been used to organise this book is based on the quality and type of the process model information used and then whether or not optimisation concepts have been used to generate the PID controller tunings. A brief description of the main categories follows next.

- **Model-free methods**: the method does *not* use the explicit identification of significant model points or a parametric model *per se*.

- **Nonparametric model methods**: the method uses the explicit identification of significant model points or a nonparametric model, but does not use a parametric model *per se*. 
Data-intensive methods: these methods are halfway between the nonparametric and parametric model-based methods. They are characterised by the use of process data, as in the subspace method, or grey knowledge, as in the case of fuzzy-logic methods.

Parametric model methods: the method straightforwardly depends on the use of a parametric model; usually a transfer function model.

The second categorisation depends on whether the tuning method uses optimisation concepts. As an example, many optimisation-based methods use the appropriate classic linear quadratic cost function over a deterministic or stochastic problem formulation. Figure 1 shows the tree diagram map of the book chapters.

![Figure 1](image_url)  
**Figure 1** Book chapters: tree diagram map.
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Chapter Contributions

Chapter 1  PID Control Technology
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This chapter is an introduction to the basic technology of PID control. It opens with a brief look at the way in which control engineers solve process control problems in different stages. These stages influence the different methods that the engineer uses. A presentation on the different forms of three-term controllers follows. This concentrates on notation, conversion between the types and the structural flexibility of the controllers. Simple implementation issues for the terms of the controller are given next. The chapter concludes with a section on industrial PID control including material on the process controller unit, supervisory control and the SCADA PID controller setup. Two industrial examples, kindly provided by Siemens AG and Emerson Process Management, are included in this section.

Chapter 2  Some PID Control Fundamentals
M.A. Johnson  
*M.H. Moradi*  
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This chapter archives some basic control and PID control properties and definitions used and referred to in later chapters. The fundamentals covered are process models, controller degrees of freedom structures, classical performance measures, a look at PID in state space formalism, and common structures for multivariable system PID-based controllers.

Chapter 3  On-line Model Free Methods
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Chapter 4  Automatic PID Controller Tuning – The Nonparametric Approach
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This chapter first gives an overview of the nonparametric identification methods currently available and used for automatic tuning of PID controllers. Following the overview, the chapter focuses on the relay feedback method and its variants for the purpose of realising efficient autotuning solutions. These variants are mainly due to the joint work of the authors and their co-workers. Relay feedback is useful not just for control design, but also for process and control monitoring. The next part of the chapter reports on the use of the relay-based method for control robustness assessment and evaluation. It is shown how nonparametric results can be converted into parametric transfer function models. Finally, case studies on laboratory setups are presented to consolidate the materials presented giving an applications perspective.

Chapter 5  Relay Experiments for Multivariable Systems
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M.R. Katebi
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The relay experiment for multivariable processes has been given in several different forms. This chapter opens with a brief survey of these methods and considers the definition of critical points for a multivariable process. The decentralised relay experiments for multivariable systems are then investigated in detail and extended from the familiar two-input, two-output form to a multi-input multi-output relay procedure. The remainder of the chapter concentrates on a relay method based on PID control design at bandwidth frequency. Two case studies are given to demonstrate the method. The results are based on the research of M. H. Moradi and M. R. Katebi.

Chapter 6  Phase-Locked Loop Methods
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The chapter opens with a look at the possible problems that can arise with the relay experiment. This leads naturally to posing the question: can the process identification data obtained from a relay experiment be produced without using relays? A first answer reported in this chapter used a constructive numerical route, but this was subsequently replaced by a new nonparametric identification method based on a phase-locked loop concept. The remainder of the chapter is devoted to presenting the basic
theory of the phase-locked loop identification procedure and demonstrating the potential of the
method. The results are based on the research of J. Crowe and M.A. Johnson.

Chapter 7 PID Tuning Using a Phase-Locked Loop Identifier
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M.A. Johnson

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The phase-locked loop identifier can be packaged as a self-contained module for use with various iden-
tification tasks. This chapter reports on the potential for identification flexibility. The first part demon-
strates how the identifier can be used to estimate the phase margin, estimate the parameters of a
second-order underdamped system, and identify a system in closed loop. A target use of the
phase-locked loop identifier is to achieve automated on-line PI control design. Algorithms to achieve
the on-line PI design for a gain and phase margin specification pair and for a maximum sensitivity and
phase margin design specification are demonstrated in the remainder of the chapter. The results are
based on the research of J. Crowe and M.A. Johnson.

Chapter 8 Process Reaction Curve and Relay Methods – Identification and PID Tuning
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This chapter was inspired by the classical work on process reaction curve methods for the tuning of
three-term controllers. Author Hsiao-Ping Huang has spent many years developing extensions and new
ways of approaching this field of engineering science. A special emphasis has been to develop tech-
niques for use in the process and chemical industries. The chapter reports some of the author’s more
recent research on developing simple models from step response and relay feedback experiments and
perform autotuning for PID controllers. As the emphasis is on the use of models to derive IMC-PID
controllers or other related model-based controllers, alternative simple models other than the most
popular FOPDT models may be required. This chapter provides systematic procedures to obtain these
simple models for design purposes. An inverse model-based synthesis of PID controllers is also
presented. It is especially simple and effective for application to FOPDT and overdamped SOPDT
processes. Finally, in this chapter, a method to assess the performance status of a PID controller is given.
This will be helpful to determine whether the PID controller is well tuned or not. The material in this
chapter will help engineers to understand the methods of identification and autotuning from
time-domain data without resorting to the traditional least square methods, and will enable them to
understand and assess the performance that a PID controller can achieve.

Chapter 9 Fuzzy Logic and Genetic Algorithm Methods in PID Tuning
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Hong Kong

The potential of fuzzy logic in solving controller tuning problems was realised in the mid-1960s. How-
ever, its application to tuning the classical PID controller emerged much later in the 1980s. Since
that time, the authors of this chapter have spent some years with world-leading experts developing
extensions and new ways of approaching this field of Fuzzy PID controller design. A special emphasis
has been to develop techniques that use the power of genetic algorithms. This chapter demonstrates just
how effective the genetic algorithm approach is and reports some of the authors’ recent research.
Chapter 10  Tuning PID Controllers using Subspace Identification Methods

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This chapter presents a general framework for using subspace identification methods to tune PID controllers. The restricted controller concept is used to give the tuning procedure generality, but the specific application is for tuning PID controllers. The method does not use a parametric model directly, but the model is formulated using the subspace identification paradigm. Thus, data is organised to provide a data-based model for the iterative PID tuning algorithm. The applications of the PID tuning algorithm are from the wastewater industry and use simulations of a sequential wastewater treatment process. Various scalar and multivariable system examples are given. This method has an industrial origin, since Dr M.R. Katebi recently led the Strathclyde team in an EU-supported wastewater control system development project (the SMAC project) and A. Sanchez was Research Fellow on the project. The problems and solutions reported in the chapter were inspired by wastewater industry problems and are the research results of A. Sanchez, M.R. Katebi and M.A. Johnson.

Chapter 11  Design of Multi-Loop and Multivariable PID Controllers

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A major assumption for this chapter is that the designer has a multi-input, multi-output transfer function model for the process to be controlled. This will be used to show the difficulty in multivariable control arising from the interactions between the multiple process elements. For multi-loop PID control, the BLT tuning method will be outlined first. Improved settings may be obtained by assigning the dominant pole in suitable locations with the help of some computer graphs. For multivariable PID control, a decoupling design is adopted and the characteristics of decoupled systems are developed to reach achievable optimal target closed loop and produce the desired PID settings. These new methods are the work of Qing-Guo Wang in collaboration with his former PhD students, Yu Zhang and Yong Zhang. Professor Wang has spent many years developing extensions and new ways of designing PID controllers for multivariable processes. The authors would like to thank Professor K. J. Åström for his collaboration on the dominant pole placement method; we learnt much from him.

Chapter 12  Restricted Structure Optimal Control

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This chapter continues the theme of model-based design methods for PID controllers. An optimal restricted structure control concept is presented for both single-input and single-output systems and multivariable systems. M. J. Grimble and M.A. Johnson have worked with the Linear Quadratic Gaussian paradigm for over two decades and the work presented in this chapter is a response to industrial engineers who wish to use classical PID controllers and implement simple physically based multivariable controllers. The methods are demonstrated on applications from the marine and steel industries. P.
Martin and M. J. Grimble developed and wrote the first part of the chapter, whilst the second part of the chapter was devised and written by D. R. Greenwood and M. A. Johnson.

Chapter 13  Predictive PID Control

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The last chapter of the book seeks to explore possible links between model-based PID control design and predictive control methods. The presentation is in three parts. Firstly, there is a section on the predictive PID control design method due to Tore Hägglund (Lund University, Sweden). This method uses the Smith predictor framework and was devised for systems with long dead times. Secondly, there is a look at the predictive PID control concept due to Kok Kiong Tan and his colleagues based on a Generalised Predictive Control formulation. In both cases, some simple simulation results are given. Using the published literature, M.A. Johnson wrote the presentations for these first two methods.

Finally, the control signal matching method for predictive PID control design is reported in the extended final section of the chapter. This method involves defining an $M$-step ahead PID controller and selecting the controller coefficients to match the control signal from a Generalised Predictive Control problem solution. The matching process leads to a formula for computing the PID gains. The other degree of freedom is the choice of forward prediction horizon $M$. This selection is used to ensure closed loop stability and good fidelity with the GPC control signal. The method has the potential to incorporate other features such as actuator constraints and integral anti-windup modifications. The results presented are the research results of M.H. Moradi and M.R. Katebi.

About the Contributors

Biographical sketches for all the contributors can be found in this section at the end of the book.
The area of PID control and the various related control techniques is still developing. Consequently, the engineering notation used by the many authors, research workers and control engineers working in this area is not always consistent. In fact, there is much creativity in the notation alone, because different authors wish to emphasise different aspects of the subject and as a result use some highly personalised notation. In this edited book, an attempt has been made to regularise some of the notation used without interfering with the notational colour introduced by some authors.

**Complex Numbers**

Cartesian representation: \( s = \alpha + j\beta, \; \alpha, \beta \in \mathbb{R} \)

Polar representation: \( s = r(\cos \phi + j\sin \phi) \)

where \( r = |s| \) and \( \phi = \arg{s} \) with \( 0 \leq r \) and \( -\pi < \phi \leq \pi \)

**Single-Input, Single-Output Systems**

Process model: \( G_p(s) \in \mathbb{R}(s) \) or \( W(s) \in \mathbb{R}(s) \)

Controller: \( G_c(s) \in \mathbb{R}(s) \) or \( C(s) \in \mathbb{R}(s) \)

Forward path transfer: \( G_{fp}(s) = G_p(s)G_c(s) \)

For a single input, single output unity feedback system:

Closed loop transfer function \( G_{cl}(s) \) and equivalently the complementary function \( T(s) \)

\[
G_{cl}(s) = T(s) = \frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)} = \left[ \begin{array}{c}
G_{fp}(s) \\
1 + G_{fp}(s)
\end{array} \right]
\]

Sensitivity function \( S(s) \),

\[
S(s) = \left[ \begin{array}{c}
1 \\
1 + G_p(s)G_c(s)
\end{array} \right] = \left[ \begin{array}{c}
1 \\
1 + G_{fp}(s)
\end{array} \right]
\]

**Nyquist Geometry**

For SISO unity feedback systems, the loop transfer function is \( G_L(s) = G_{fp}(s) \)

Frequency variable \( \omega \) where \( 0 \leq \omega < \infty \)

Cartesian representation: \( G_L(j\omega) = \alpha(\omega) + j\beta(\omega), \) where \( \alpha: \mathbb{R}^+ \rightarrow \mathbb{R} \) and \( \beta: \mathbb{R}^+ \rightarrow \mathbb{R} \)

Polar representation: \( G_L(j\omega) = r(\omega)(\cos \phi(\omega) + j\sin \phi(\omega)), \) where the radial function is \( r(\omega) = |G_L(j\omega)| \)

and the angular function is \( \phi(\omega) = \arg{G_L(j\omega)} \)

In general for physical processes, the angular function \( \phi(\omega) \) satisfies \( -\infty < \phi(\omega) \leq 0 \)
**Important Nyquist Geometry Points**

Stability point: \( s = -1 + j0 \)

**Gain Margin Condition**

Phase crossover frequency \( \omega_{pco} \) is the frequency at which \( \phi(\omega_{pco}) = \arg(G_L(j\omega_{pco})) = -\pi \). Alternative notation for this frequency is \( \omega_{-\pi} \) and \( \omega_{\pi} \). Gain margin is defined as

\[
GM = \frac{1}{|G_L(j\omega_{pco})|}
\]

An alternative notation for gain margin is \( G_m \).

In the context of the sustained oscillation phenomenon, these quantities are often referred to by the use of the term *ultimate* with related notation:

- **Ultimate frequency**: \( \omega_u = \omega_{pco} \)
- **Ultimate gain**: \( k_u = \frac{1}{|G_L(j\omega_{pco})|} = \frac{1}{|G_L(j\omega_u)|} \)
- **Ultimate period**: \( P_u = 2\pi/\omega_u \)

**Phase Margin Condition**

The gain crossover frequency \( \omega_{gco} \) is the frequency at which \( r(\omega_{gco}) = |G_L(j\omega_{gco})| = 1 \). An alternative notation for this frequency is \( \omega_1 \).

The phase margin in degrees is given as

\[
PM^\circ = 180^\circ + \arg(G_L(j\omega_{gco}))^\circ
\]

In radians, this is given by

\[
\phi_{PM} = \pi + \arg(G_L(j\omega_{gco}))
\]

Maximum sensitivity:

\[
M_s = \max_{0 \leq \omega \leq \infty} |S(j\omega)|
\]

**Block Diagram Conventions**

At block diagram summing points, the default for a signal entering the summing point is “+”. If the signal is to be subtracted then a minus sign will appear along side the signal arrow. An illustration is given below. No “+” signs will appear in block diagram figures.
Common Control Abbreviations

SISO  Single-input, single-output
TITO  Two-input, two-output
MIMO  Multi-input, multi-output
FOPDT First-order plus dead time
SOPDT Second-order plus dead time
IMC   Internal model control
MPC   Model predictive control
MBPC  Model-based predictive control
GPC   Generalised predictive control
FFT   Fast Fourier Transform
DFT   Discrete Fourier Transform
SNR   Signal-to-Noise Ratio
RGA   Relative Gain Array
IAE   Integral of Absolute Error Performance Criterion
ITAE  Integral of Time × Absolute Error Performance Criterion
LQG   Linear Quadratic Gaussian
GA    Genetic Algorithm