



*Automation and Control Engineering*

# **CONTROL OF NONLINEAR SYSTEMS VIA PI, PD AND PID**

**STABILITY AND PERFORMANCE**

Yong-Duan Song



# Control of Nonlinear Systems via PI, PD and PID

Stability and Performance

# **AUTOMATION AND CONTROL ENGINEERING**

## ***A Series of Reference Books and Textbooks***

### ***Series Editors***

**FRANK L. LEWIS, Ph.D.,  
Fellow IEEE, Fellow IFAC**

Professor

The University of Texas Research Institute  
The University of Texas at Arlington

**SHUZHONG SAM GE, Ph.D.,  
Fellow IEEE**

Professor

Interactive Digital Media Institute  
The National University of Singapore

**STJEPAN BOGDAN**

Professor

Faculty of Electrical Engineering  
and Computing  
University of Zagreb

### **RECENTLY PUBLISHED TITLES**

**Discrete-Time Recurrent Neural Control: Analysis and Applications,**  
*Edgar N. Sánchez*

**Electric and Plug-in Hybrid Vehicle Networks: Optimization and Control,**  
*Emanuele Crisostomi, Robert Shorten, Sonja Stüdl, and Fabian Wirth*

**Adaptive and Fault-Tolerant Control of Underactuated Nonlinear Systems,**  
*Jiangshuai Huang and Yong-Duan Song*

**Optimal and Robust Scheduling for Networked Control Systems,**  
*Stefano Longo, Tingli Su, Guido Herrmann, and Phil Barber*

**Deterministic Learning Theory for Identification, Recognition, and Control,**  
*Cong Wang and David J. Hill*

**Networked Control Systems with Intermittent Feedback,**  
*Domagoj Tolić and Sandra Hirche*

**Doubly Fed Induction Generators: Control for Wind Energy,**  
*Edgar N. Sanchez and Riemann Ruiz-Cruz*

**Optimal Networked Control Systems with MATLAB®,**  
*Jagannathan Sarangapani and Hao Xu*

**Cooperative Control of Multi-agent Systems: A Consensus Region Approach,**  
*Zhongkui Li and Zhisheng Duan*

**Nonlinear Control of Dynamic Networks,**  
*Tengfei Liu, Zhong-Ping Jiang, and David J. Hill*

**Modeling and Control for Micro/Nano Devices and Systems,**  
*Ning Xi, Mingjun Zhang, and Guangyong Li*

**Linear Control System Analysis and Design with MATLAB®, Sixth Edition,**  
*Constantine H. Houppis and Stuart N. Sheldon*

**Real-Time Rendering: Computer Graphics with Control Engineering,**  
*Gabriel Wong and Jianliang Wang*

**Anti-Disturbance Control for Systems with Multiple Disturbances,**  
*Lei Guo and Songyin Cao*

**Tensor Product Model Transformation in Polytopic Model-Based Control,**  
*Péter Baranyi, Yeung Yam, and Péter Várlaki*

# Control of Nonlinear Systems via PI, PD and PID

Stability and Performance

Yong-Duan Song



**CRC Press**

Taylor & Francis Group

Boca Raton, London, New York

CRC Press is an imprint of the  
Taylor & Francis Group, an informa business

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2019 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper  
Version Date: 20180919

International Standard Book Number-13: 978-1-138-31764-2 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

**Library of Congress Cataloging-in-Publication Data**

---

Names: Song, Yong-Duan, author.  
Title: Control of nonlinear systems via PI, PD and PID : stability and performance / Yong-Duan Song.  
Description: First edition. | Boca Raton, FL : CRC Press/Taylor & Francis Group, 2018. | Includes bibliographical references.  
Identifiers: LCCN 2018026890 | ISBN 9781138317642 (hardback : acid-free paper)  
Subjects: LCSH: Adaptive control systems. | Nonlinear control theory.  
Classification: LCC TJ217 .S67 2018 | DDC 629.8/36--dc23  
LC record available at <https://lccn.loc.gov/2018026890>

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>

*To my family for the understanding, support and love.*



# Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

# Contents

<b>Preface</b> .....	xi
<b>Acknowledgments</b> .....	xiii
<b>1 Introduction</b> .....	1
1.1 Motivation .....	1
1.2 Objectives .....	2
1.3 Preview of Chapters .....	3
<b>2 Classical PID Control</b> .....	5
2.1 The Three Actions of PID Control .....	5
2.1.1 Proportional Action .....	5
2.1.2 Integral Action .....	6
2.1.3 Derivative Action .....	7
2.2 Tuning Methods .....	8
2.3 Conclusion .....	8
<b>3 Adaptive PI Control for SISO Affine Systems</b> .....	9
3.1 Introduction .....	9
3.2 Problem Formulation .....	10
3.3 Design Details .....	12
3.3.1 PI Control Design for First-order Nonlinear Systems .....	12
3.3.2 PI Control Design for High-order Nonlinear Systems .....	14
3.4 Numerical Examples .....	20
3.5 Conclusion .....	21
3.6 Appendix .....	23
<b>4 Generalized PI Control for SISO Nonaffine Systems</b> .....	25
4.1 Introduction .....	25
4.2 System Description and Preliminaries .....	27
4.3 Control Design .....	29

4.3.1	PI Control	30
4.4	Adaptive Fault-tolerant PI Control	35
4.4.1	PI Control under Actuator Failures	35
4.4.2	PI Control under Actuator and Sensor Faults	36
4.5	Illustrative Examples	38
4.6	Conclusion	41
<b>5</b>	<b>Adaptive PI Control for MIMO Nonlinear Systems</b>	<b>43</b>
5.1	Introduction	43
5.2	Problem Formulation	44
5.2.1	System Description	44
5.2.2	Neural Networks and Function Approximation	47
5.3	PI Control Design and Stability Analysis	48
5.3.1	Neuroadaptive PI Control for Square Systems	49
5.3.2	Neuroadaptive PI Control for Non-square Systems	53
5.4	Modified PI Control Based on BLF	55
5.4.1	Neuro-adaptive PI Control for Square Systems	56
5.4.2	Neuro-adaptive PI Control for Non-square Systems	58
5.5	Illustrative Examples	61
5.6	Conclusion	65
5.7	Appendix	65
<b>6</b>	<b>Adaptive PI Control for Strict Feedback Systems</b>	<b>67</b>
6.1	Introduction	67
6.2	System Description and Preliminaries	68
6.3	PI-like Control Design	71
6.4	Illustrative Examples	81
6.5	Conclusion	84
<b>7</b>	<b>Adaptive PID Control for MIMO Nonlinear Systems</b>	<b>85</b>
7.1	Introduction	85
7.2	Problem Formulation and Error Dynamics	87
7.2.1	Error Dynamics	88
7.2.2	Nussbaum Function	89
7.3	PID-like Control Design and Analysis	90
7.3.1	PID Control for Square Systems	91
7.3.2	PID Control for Non-square Systems	94
7.3.3	Analysis and Discussion	96
7.4	Conclusion	97
<b>8</b>	<b>PD Control Application to High-Speed Trains</b>	<b>99</b>
8.1	Introduction	99
8.2	Modeling and Problem Statement	101
8.2.1	Modeling	101
8.2.2	Problem Statement	104

- 8.3 Control Scheme ..... 105
  - 8.3.1 Structural Properties ..... 105
  - 8.3.2 Robust Adaptive PD-like Control Design ..... 105
  - 8.3.3 Low-Cost Adaptive Fault-tolerant PD Control ..... 109
  - 8.3.4 Comparison and Analysis ..... 111
- 8.4 Simulation Examples ..... 112
- 8.5 Conclusion ..... 114
- 9 PID Control Application to Robotic Systems ..... 117**
  - 9.1 Robotic Modelling ..... 117
  - 9.2 PID Control for Robotic Systems ..... 117
    - 9.2.1 Square System (joint-space tracking) ..... 117
    - 9.2.2 Non-square System (task-space tracking) ..... 118
  - 9.3 Case Studies ..... 118
- 10 Conclusion ..... 123**
- Bibliography ..... 125**
- Index ..... 133**



# Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

# Preface

The proportional integral derivative (PID) controller in the form we know it today emerged between 1915 and 1940. Since PID control is simple in structure and inexpensive in implementation, it has been undoubtedly the most widely employed controller in industry. In fact, PID controllers are sufficient for many control problems, particularly when process dynamics are benign and the performance requirements are modest. However, there are still problems that limit the applications of the PID controller. One of those is how to determine the appropriate PID gains to ensure system stability and desirable performance. The Ziegler–Nichols tuning procedure, published in 1942, is simple and intuitive, but it creates a closed-loop system that is very poorly damped and that has poor stability margins. Since then, various methods for tuning PID gains have been suggested, but a systematic means is yet to be established and the information about those methods is scattered in the control theory.

With the increasing control demands for various practical systems which are generally nonlinear, uncertain and with abnormal actuation (such as asymmetric saturation, dead-zone module, loss of effectiveness, etc.), traditional PID control seems to lack theoretical support and is losing efficiency. Thus, a series of control strategies is proposed to tackle the control problems for all kinds of nonlinear systems. Although various control schemes have successfully addressed the control problems for nonlinear systems, the resultant solutions seem quite sophisticated — not only complicated in structure, but also expensive in computation. As a consequence, these complex control methods are not much appreciated in practical applications. By this token, the PID control seems still the most favorable choice for the control of practical systems if it could be made effective in dealing with system nonlinearities and uncertainties.

Industrial experience has clearly indicated that automatic tuning of PID gains is a highly desirable and useful feature. Therefore, the focus of this book is on PI/PD/PID controller for nonlinear systems with self-tuning gains, wherein an exposition of adaptive PI/PD/PID control methods developed recently for numerous nonlinear systems is provided. All these PI/PD/PID controllers are able to adaptively update the gains through analytic algorithms and there is no need for

human tuning or trial and error process. Besides, the stability condition (the primary concern for any control system) is established for the corresponding systems with PI/PD/PID controller in the loop. Furthermore, in order to make the control scheme more reliable in practical applications, in this book, the proposed PID control strategies are equipped with fault-tolerant capabilities to accommodate the abnormal actuation characteristics which may occur during system operation. Constraints (due to physical saturation, safety specifications, etc.) imposed on system outputs or states, together with the issue of prescribed control performance, are also considered in control design. In the last chapters of the book, the PI/PD/PID control scheme is applied to practical systems such as high-speed trains and robotic systems. The effectiveness of the proposed adaptive PI/PD/PID controller is demonstrated and validated via computer simulations. Several books on PID controllers are available on the market, but this book exclusively focuses on PI/PD/PID control with gain auto-tuning mechanisms for nonlinear systems. While efforts have been made on PI/PD/PID control for nonlinear systems, there is still much room for further research and development. We hope that this book will aid in understanding the essence of PID control, providing readers with alternative perspectives concerning the development of PI/PD/PID controllers for typical nonlinear systems.

*Yongduan Song*  
Chongqing, China

# Acknowledgments

There are numerous individuals without whose help this book would not have been completed. My sincere thanks go to Dr. Yujuan Wang, Dr. Danyong Li, Qing Chen, Zhirong Zhang, Ziyun Shen, Ye Cao, Shuyan Zhou, Xiucui Huang, Kai Zhao. In particular, I would like to express my gratitude to the following authors for allowing me to use the materials of the papers for compiling this book.

- Y. D. Song, Y. J. Wang, and C. Y. Wen, “Adaptive fault-tolerant PI tracking control with guaranteed transient and steady-state performance,” *IEEE Trans. Autom. Control*, vol. 62, no. 1, pp. 481-487, 2017.
- Q. Song, Y. D. Song, “Generalized PI control design for a class of unknown nonaffine systems with sensor and actuator faults,” *Syst. Control Lett.*, vol. 64, no. 1, pp. 86-95, 2014.
- Y. D. Song, J. X. Guo, and X. C. Huang, “Smooth neuroadaptive PI tracking control of nonlinear systems with unknown and nonsmooth actuation characteristics,” *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 28, no. 9, pp. 2183-2195, 2017.
- Y. D. Song, Z. Y. Shen, L. He, and X. C. Huang, “Neuroadaptive control of strict feedback systems with full-state constraints and unknown actuation characteristics: an inexpensive solution”, *IEEE Trans. Cybern.*, DOI: 10.1109/TCYB.2017.2759498.
- Y. D. Song, X. C. Huang, and C. Y. Wen, “Robust adaptive fault-tolerant PID control of MIMO nonlinear systems with unknown control direction,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4876-4884, 2017.
- Y. D. Song, X. C. Yuan, “Low-cost adaptive fault-tolerant approach for semiactive suspension control of high-speed trains,” *IEEE Trans. Ind. Electron.*, vol. 63, no. 11, pp. 7084-7093, 2016.

I also would like to thank the Research Institute of Intelligent Systems at Chongqing University for their support.

The writing of this book was supported in part by the National Natural Science Foundation of China.



# Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

# Acronyms

## Abbreviations

UUB	uniformly ultimately bounded
MAS	multi-agent systems

## Notations

$\mathbb{R}$	field of real numbers
$\Sigma$	summation
$ a $	the absolute of a scalar $a$
$\ x\ $	the norm of a vector $x$
$\max$	maximum
$\min$	minimum
$\sup$	supremum, the least upper bound
$\inf$	infimum, the greatest lower bound
$\forall$	for all
$\in$	belongs to
$\rightarrow$	tends to
$< (>)$	less (greater) than
$\leq (\geq)$	less (greater) than or equal to
$\ll (\gg)$	much less (greater) than
$\mathbb{R}^n$	the $n$ –dimensional Euclidean space
$\dot{y}$	the first derivative of $y$ with respect to time
$\ddot{y}$	the second derivative of $y$ with respect to time
$y^{(i)}$	the $i$ –th derivative of $y$ with respect to time
w.r.t.	with respect to