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CONTROL OF NONLINEAR SYSTEMS VIA PI, PD AND PID

STABILITY AND PERFORMANCE

Yong-Duan Song

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To my family for the understanding, support and love.

Contents

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.

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- 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.

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Acronyms

Abbreviations

UUB	uniformly ultimately bounded
MAS	multi-agent systems

Notations

R	field of real numbers
Σ	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
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