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Operator-based Robust Control of Uncertain Nonlinear Systems

(基于演算子理论的不确定非线性系统的鲁棒控制)

Science Press
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内 容 简 介

本书根据工程应用的理论发展和实际需要，系统地介绍了基于演算子理论的一类不确定非线性系统的鲁棒控制研究方法、各种设计策略、主要实现方法、计算机模拟验证技术及其在控制工程中的应用等内容。主要内容包括：带有未知扰动的非线性系统、具有未知干扰的非线性系统的稳定性分析、系统设计和鲁棒控制策略，其中针对具有未知干扰的非线性系统还给出了其敏感性分析和跟踪控制设计。本书内容融入了作者近年来大量的研究成果。

本书可供控制理论与控制工程、交通信息工程及控制、工业自动化、电气自动化、机械工程等专业的研究人员、研究生及高年级本科生参考，也可供控制系统设计工程师等相关工程技术人员阅读和参考。

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Preface

In practical engineering, a great numbers of systems present enormous change under different parameters or structure of the systems, which bring a complex combination of many specific characteristics, including nonlinearity, time-varying and uncertainties. For dealing with these emerging issues, the progress made in multivariable control theory, especially over last decades, has enabled the linear part of this theory to achieve a relevant high degree of maturity. For nonlinear systems, however, the need still remains challenging for theoretical developments that may continue to motivate and tie up the emerging results. Meanwhile, computer-oriented approach to nonlinear control systems analysis and design are placing an increasing demand for a mathematical theory that will facilitate the formulation of the inherently difficult nonlinear problems, the understanding of the underlying system properties and the construction of the pertinent algorithms. Motivated by these considerations, this book mainly introduces some new design ideas and methods for nonlinear systems with perturbation or disturbance based on the operator-theoretic approach. That is, operator-based right coprime factorization. The authors have been studying design and control of nonlinear system in recent years, especially robustness analysis and control, deeply feeling the necessity of uniting new results, new development and new trend to write a research book. We wish that the publication of this book could promote certain further development in theoretical and practical fields on robust control of uncertain nonlinear systems.

This book contents 9 chapters, which comprehensively introduces robust control of uncertain nonlinear system using operator-based coprime factorization approach. The first two chapters are written by Zhumu Fu, giving the introduction on the topic of this book and providing mathematical background for the remaining chapters. They are basic enough to serve as a foundation for other research topics in nonlinear systems theory. Chapters 3-6 are completed by Fazhan Tao, which mainly introduce adjoint operator-based right coprime factorization method, extended right coprime factorization method, two steps factorization method for robust control of nonlinear systems with perturbation. Meanwhile, uncertain MIMO nonlinear systems is considered for guaranteeing its robust stability. The rest chapters are compiled by Mengyang Li. The nonlinear systems with disturbances are studied from reset, tracking, robustness, sensitivity and safety viewpoint. The operator-based right coprime factorization approach provides a feasible framework for developing the results. In final, this book is compiled by all the authors.

In the progress of writing this book, the main literatures are the research results and dissertation content during the time the authors Fazhan Tao and Mengyang Li pursue the doctor degree in Tokyo University of Agriculture and Technology. This book would not be possible without the work done jointly for the previous researches with Professor Mingcong Deng. We would also like to thank the following graduate students of Henan University of Science and Technology: Zhenhui Li, Longlong Zhu, Jiangbo Meng, Yongfei Liu and Hongfei Zhang for their generous support and patience during the writing of this book.

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The standard of education of the authors is not so good that the book has many imperfect points. Oblige them with the experts' and scholars' valuable comments please.

Contents

Chapter 1
Introduction

1.1 Background

1.1.1 Nonlinear Systems Analysis

With the development of modern control engineering and the requirement on the precise, reliable and safe control for systems, effective design scheme and accurate control aiming on guaranteeing perfect performance of systems and meeting the demand of real application have received much attentions from engineers and researchers [1-18].

In terms of the development in control and design for systems, both linear systems and nonlinear systems have been developing greatly in the last three decades from many viewpoints. The traditional approaches of linear systems are still the most dominating due to its simple structure and mature theoretical support. Whereas, as a matter of fact, most of the real dynamic systems in application have nonlinear property, due to the intrinsic complexity in structures and the nonlinear dynamics in application. Therefore, considering the fact that linear controllers and design method cannot be satisfied with this demand, research and development of an effective approach for nonlinear systems control and design have always been top topic for improving performance and decreasing cost of systems to meet the needs in real application [4-8,17-73].

Linear control is a mature subject with a variety of powerful methods and a long history of successful industrial applications. Thus, it is natural for one to wonder why so many researchers and designers, from such broad areas as aircraft and spacecraft control, robotics, process control, and biomedical engineering, have recently showed an active interest in the development and applications of nonlinear control methodologies. Nonlinear systems control is the discipline that applies control theory to design systems with desired behaviors. It can be broadly defined or classified as nonlinear control theory and application. It seeks to understand nonlinear systems dynamics, using mathematical modeling, in terms of inputs, outputs, and various components with different behaviors and to use nonlinear control systems design schemes to develop controllers for those systems in one or many time, frequency, and complex domains, depending on the nature of the design problem.

As for nonlinear systems, there are some common nonlinear systems behaviors such as multiple equilibrium points, limit cycles, bifurcations, chaos. Other interesting types of behavior, such as jump resonance, subharmonic generation, asynchronous quenching, and frequency-amplitude dependence of free vibrations, can also occur and become important in some system studies. However, the above description should provide ample evidence that nonlinear systems can have considerably richer and more complex behavior than linear systems.

1.1.2 Uncertain Nonlinear Control Methods

For dealing with difficulties that linear control method cannot work, the nonlinear control and design methods have attracted many researchers' attention due to the important role they have played in real application [38-42]. In particular, these issues, robustness, output tracking, perturbation and disturbance belonging to the nonlinear systems still remain challenging owing to their complex structures and nonlinear characteristics [8,15-20]. Among the nonlinear researches, uncertain study for nonlinear systems has been attracting much attention of researchers owing to the fact that robust phenomenons always exist broadly in nonlinear systems leading to many unnoticeable and unavoidable problems in real systems. Generally, the uncertainties include internal perturbation and external disturbance, almost existing in a great number of systems where disturbance has major concern of two types in the control of unknown disturbance and estimated disturbance. General perturbation and disturbance yielding from modeling errors and external environment are central considered in this book due to making a tremendous affection within the control systems.

The existing uncertainties in the real systems usually have a great adverse effect on stability of the overall systems which could result in a serious damage to systems. Thus, from the viewpoint of accuracy, reliability and safety for systems, it is necessary and important to eliminate or even remove the adverse effect resulted from uncertainties of the systems. One of the promising directions for solving this issue is to guarantee robust stability of the overall systems including uncertainties such that the overall systems can still works well in a normal way. Thus, robust researches have been obtaining much more attention from various areas, which have become one of main concerns in the modern control and design.

Over the past decades, for dealing with the family of issues on robustness due to the existing uncertainties in systems, a great number of methods for nonlinear systems are proposed, such as Lyapunov-based method, gain scheduling method, feedback linearization method, backstepping technique, sliding mode control theory, right coprime factorization method ,adaptive control approach and so on [5,41-73], model predictive control method, gain scheduling method, fuzzy control method. Among these above mentioned methods, operator-based right coprime factorization has been proved to be a promising and effective method on robust control and system design since this method provides a convenient framework for nonlinear systems from the view of point of input-output relationship based on operator theory.

1.2 Why Operator-based Robust Nonlinear Control?

The development of coprime factorization and its application in analysis, control and design for systems are fairly well understood for both linear and nonlinear systems by now. The origin of the idea leading to the coprime factorization method can be traced to the work of Rosenbrock [5], who considers polynomial matrix expression for linear time invariant (LTI) systems described by a family of ordinary differential equations. Based on polynomial matrix fraction description for multivariable transfer functions, parameterization of all stabilizing controllers for finite-dimensional linear time-invariant (FDLTI) systems is studied in the context of obtaining optimization for controllers [8]. Reference [7] extend the definition of coprime factorization to distributed LTI systems. In the case of distributed LTI systems, attention is focused on the class of systems which form a Bezout domain and for which the existence of coprime fractional representations can be demonstrate. Reference [9] proposes some sufficient conditions for existence of a doubly coprime factorization of a large class of infinite-dimensional systems well known as regular linear systems. Coprime factorization and well posed linear systems are discussed based on appropriate stabilizability and detectability, obtaining that every function with doubly coprime factorization in H_∞ is the transfer function of a jointly stabilizable and detectable well posed linear system. Besides these results on linear systems based on the notation of coprime factorization, the idea of coprime factorization also has made a great effect on nonlinear systems for provide a convenient framework to research the nonlinear systems from a view of point of the input-output stability.

In Reference [72], the authors extend the case from FDLTI systems to nonlinear systems represented by the set of all stable input-output pairs based on right coprime factorization. Meanwhile, coprimeness property is proved to be equivalent to that of FDLTI systems. Besides, the detailed construction of such a factorization is discussed. After that, the author of Reference [73] considers a theory of coprimeness developed for a class of nonlinear systems, with the intention of constructing analytic tools for the solution of stabilizing a nonlinear system by using the additive nonlinear feedback technique. In addition, besides the viewpoint from the input-output of systems, many researchers consider coprime factorization from state-space equation view of point. In Reference [68], the author shows that right coprime factorizations exist for the input-to-state mapping of a continuous time nonlinear system under the condition of existing the smooth feedback stabilization solution for the system, and it shows that smooth stabilization implies smooth input-to-state stabilization. The authors of Reference [69] first study the normalized right and left coprime factorizations of a nonlinear system from a state-space point of view and make use of the proposed normalized coprime factorization to give a method to balance the unstable nonlinear system based on a smooth solution of a Hamilton-Jacobi equation. Moreover, in Reference [70], the Youla parameterization method is generalized from linear systems to nonlinear system, stabilizing a nonlinear system by using a unstable, pre-compensator and a stable feedback-compensator, and parameterizing a class of such stabilizers in the context of a bounded-input bounded-output (BIBO) stable. Later, the state-space characterization concerned with Youla-Kucera parameterization is studied as well for a class of nonlinear systems via kernel representations, proposing a fair natural generalization of Youla-Kucera parameterization through observer based kernel representations. Besides right coprime factorization, left coprime factorization for nonlinear systems is also considered. Furthermore, necessary and sufficient conditions for the stabilization of the system are considered. The authors study a class of nonlinear systems represented by both left and right coprime factorization. According to coprime factorization, the class of all stabilizing controllers of a particular structure for the considered systems is characterized. The results specialize to the Youla-Kucera parametrization in the linear cases.

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Since 1980s, robust control and robust stabilization of the nonlinear uncertain sysuncertain miniature pneumatic curling rubber actuator using passivity and the robust right coprime factorization approach [64].

In terms of the right coprime factorization method, there exist the comparative and main merits even though every appearing nonlinear control method has its own merits and limitations on dealing with nonlinear systems. First, operator-based right coprime factorization is focused on the general case, only require the input-output relationship, which can be obtained relatively easy to take experimental data. Compared to other most of the techniques for control and design of nonlinear systems, there is no need to measure all the states of systems, which provides a relative convenient framework to study robustness of the nonlinear systems. Second, the usability of right coprime factorization is prominent, which just requires to build a Bezout identity for guaranteeing bounded input bounded output stability of nonlinear systems. Although the internal signal of the nonlinear system is needed in the right factorization process for designing controllers to satisfy the Bezout identity, it is not necessary for the practical application to measure or observe. Third, in terms of robustness study of the nonlinear systems, the right coprime factorization has a intrinsic advantage that it has a simple description for the uncertain nonlinear systems which reduce the difficulties in getting effect dependence on the uncertainties. This merit could lead to a direct analysis for control and design of the uncertain nonlinear systems.

1.3 The Content of This Book

This book is organized as follows.

In Chapter 2, mathematical preliminaries for developing main results of this book consisting of definitions of important spaces and operators are introduced. First, the definitions of extended linear space and generalized Lipschitz operator are introduced, which serve as foundations for the research of this book. Then, right factorization, right coprime factorization and robust right coprime factorization of a nonlinear system in a fairly general operator setting are introduced, which provide the theoretical basis for this book.

In Chapter 3, the extended right coprime factorization and corresponding nonlinear robust control of nonlinear systems with perturbations are considered and designed by using the proposed operator and methods. Firstly, a kind of operators is introduced, by which operator-based right coprime factorization approach is extended for a class of nonlinear systems. By regulating the exponent of the proposed operator, a broader class of nonlinear systems can be handled using the extended right coprime factorization approach. Then, based on the obtained extended right coprime factorization, a feasible control design scheme is proposed to guarantee robust stability of the considered nonlinear systems with perturbations. The main idea of the practical design scheme is to prove a stabilizing operator to be an unimodular operator, so we can utilize the proposed unimodular operator to omit the complicated calculation in process of control and design for the systems with perturbations. Finally, a simulation example is involved to illustrate the proposed design scheme for confirming effectiveness of the proposed method.

In Chapter 4, adjoint-based right coprime factorization and robust stability of nonlinear systems with perturbations are investigated based on inner product of Hilbert spaces. In detail, first, a feasible framework based on inner product is proposed to study right factorization of the perturbed nonlinear systems, which provides fundamental for factorizing the systems and guaranteeing robust stability. Second, a condition based on adjoint operators of Hilbert spaces is given for the considered nonlinear systems, according to which a compensator is designed to eliminate difficulties in obtaining internal signal of the perturbed nonlinear systems. After that, a realizable design scheme on robust stability is given based on the designed controller and the unimodular property. Rational boundedness of robust condition is provided. According to the proposed robust design scheme, the nonlinear systems with perturbations can be handled precisely and effectively. Finally, a simulation example is given to confirm the effectiveness of the proposed methods.

In Chapter 5, a nonlinear control method using operator-based coprime factorization for a class of nonlinear systems is considered, and issues on robust control of MIMO nonlinear systems are discussed. Based on right coprime factorization of the MIMO nonlinear systems, a feasible design scheme was proposed by using a new unimodular operator. Based on the obtained conditions, the designed system was overall stable. Finally, a simulation example is given to confirm the validity of the proposed methods.

In Chapter 6, nonlinear control method using operator-based coprime factorization for a class of nonlinear systems is considered, and robustness for the nonlinear systems with perturbations is discussed. Specially, a part of the nonlinear system was factorized to provide a relative convenient framework to investigate the considered system. Then, the invertible property of the composite operator for left factorization was guaranteed by the designed compensator for combining left factorization and right factorization. Based on the proposed designed scheme, left factorization for the nonlinear systems was proved to be coprime and internal-output stability was obtained. Finally, the effectiveness of the proposed methods was confirmed by the simulation example.

Chapter 7 is devoted to investigate an effective design scheme of combining right coprime factorization with a new nonlinear operator controller to deal with nonlinear systems with unknown disturbance for guaranteeing robust stability and reducing the adverse effects of unknown disturbance. That is, with the robust right coprime factorization method, the equivalent framework of nonlinear systems is obtained, which provides a convenient viewpoint; then based on operator theory, a new nonlinear operator is proposed for dealing with the unknown disturbance of nonlinear systems to reduce adverse effects on nonlinear systems. Finally, a simulation example is provided to illustrate effectiveness of the proposed design scheme.

In Chapter 8, both internal perturbation and external disturbance of the nonlinear systems are considered together using a new design scheme based on redesigning the feedback controller. In detail, from error signal point of view, the adverse effects resulting from external disturbance and internal perturbation of the nonlinear systems are removed by the designed nonlinear operator. Three cases respectively for illustrating the relationship between the proposed conditions and the internal perturbations or disturbances, that means which kind of cases would be corresponding to which conditions, respectively is shown. Simultaneously, output tracking performance is realized using the proposed design scheme. Finally, a simulation example is provided to illustrate effectiveness of the proposed design scheme.

In Chapter 9, the bilinear operator-based right coprime factorization for nonlinear system with perturbation and disturbance is introduced, which can consider adverse effect resulting from perturbation and disturbance quantitatively. Based on the proposed method, a feasible framework is established for considering robust control, sensitivity and tracking performance, which not only separates perturbation and disturbance, but also provides a fundamental base to design a controller for the considered system. In terms of the insensitivity property, it is addressed for the case where perturbation and disturbance both exist in nonlinear systems. After that, operator-based reset control for nonlinear systems with disturbance is addressed. That is,