# Advances in Control Systems Theory and Applications

*Edited by*
Gang Tao
Jing Sun

中国科学技术大学出版社

当代科学技术基础理论与前沿问题研究丛书



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## 内 容 简 介

本书汇集了众多长期积极致力于控制系统理论及应用研究的学者的论文。这些学者绝大部分都来自于同一所母校——拥有五十年辉煌历史的中国科学技术大学。本书的结集出版也是为了庆祝2008年中国科学技术大学五十周年华诞。

本书共分十五章，涵盖了控制系统理论及其应用的许多方面。书中控制系统理论的具体内容有：自适应控制、分岔控制、数字控制、容错控制、H-infinity控制、学习控制、神经和模糊控制、非线性控制、优化、参数估计、预测控制、鲁棒控制、随机控制、系统辨识和变结构控制；控制应用的内容：包括飞行器飞行控制、建筑物震动控制、微机控制系统、医疗机器人、投资组合管理、机器人编队控制和智能结构。

本书的各个章节技术性强，内容丰富，可作为工程、应用数学和相关学科本科生、研究生以及相关科技工作者学习和研究控制系统理论及应用的参考书。



Published by University of Science and Technology of China Press
96 Jinzhai Road, Hefei 230026, P. R. China

**图书在版编目(CIP)数据**

控制系统理论及应用进展 = Advances in Control Systems Theory and Applications：英文/陶钢，孙静主编. —合肥：中国科学技术大学出版社，2009.3
（当代科学技术基础理论与前沿问题研究丛书：中国科学技术大学校友文库）
“十一五”国家重点图书
ISBN 978-7-312-02238-8

Ⅰ. 控… Ⅱ. ①陶… ②孙… Ⅲ. 控制系统理论—英文 Ⅳ. O231

中国版本图书馆CIP数据核字(2009)第036145号

中国科学技术大学出版社出版发行
安徽省合肥市金寨路96号，230026
http://press.ustc.edu.cn
合肥晓星印刷有限责任公司印刷
全国新华书店经销
开本：710 mm×1000 mm 1/16 印张：24 字数：390千
2009年3月第1版 2009年3月第1次印刷
印数：1—1500册
定价：68.00元

# 编　委　会

# 总　　序

侯建国
(中国科学技术大学校长、中国科学院院士、第三世界科学院院士)

大学最重要的功能是向社会输送人才. 大学对于一个国家、民族乃至世界的重要性和贡献度, 很大程度上是通过毕业生在社会各领域所取得的成就来体现的.

中国科学技术大学建校只有短短的五十年, 之所以迅速成为享有较高国际声誉的著名大学之一, 主要就是因为她培养出了一大批德才兼备的优秀毕业生. 他们志向高远、基础扎实、综合素质高、创新能力强, 在国内外科技、经济、教育等领域做出了杰出的贡献, 为中国科大赢得了“科技英才的摇篮”的美誉.

2008 年 9 月, 胡锦涛总书记为中国科大建校五十周年发来贺信, 信中称赞说: 半个世纪以来, 中国科学技术大学依托中国科学院, 按照全院办校、所系结合的方针, 弘扬红专并进、理实交融的校风, 努力推进教学和科研工作的改革创新, 为党和国家培养了一大批科技人才, 取得了一系列具有世界先进水平的原创性科技成果, 为推动我国科教事业发展和社会主义现代化建设做出了重要贡献.

据统计, 中国科大迄今已毕业的 5 万人中, 已有 42 人当选中国科学院和中国工程院院士, 是同期 (自 1963 年以来) 毕业生中当选院士数最多的高校之一. 其中, 本科毕业生中平均每 1000 人就产生 1 名院士和七百多名硕士、博士, 比例位居全国高校之首. 还有众多的中青年才俊成为我国科技、企业、教育等领域的领军人物和骨干. 在历年评选的“中国青年五四奖章”获得者中, 作为科技界、科技创新型企业界青年才俊代表, 科大毕业生已连续多年榜上有名, 获奖总人数位居全国高校前列. 鲜为人知的是, 有数千名优秀毕业生踏上国防战线, 为科技强军做出了重要贡献, 涌现出二十多名科技将军和一大批国防科技中坚.

为反映中国科大五十年来人才培养成果，展示毕业生在科学研究中的最新进展，学校决定在建校五十周年之际，编辑出版《中国科学技术大学校友文库》，于2008 年 9 月起陆续出书，校庆年内集中出版 50 种. 该《文库》选题经过多轮严格的评审和论证，入选书稿学术水平高，已列为“十一五”国家重点图书出版规划.

入选作者中，有北京初创时期的毕业生，也有意气风发的少年班毕业生；有“两院”院士，也有 IEEE Fellow；有海内外科研院所、大专院校的教授，也有金融、IT 行业的英才；有默默奉献、矢志报国的科技将军，也有在国际前沿奋力拼搏的科研将才；有“文革”后留美学者中第一位担任美国大学系主任的青年教授，也有首批获得新中国博士学位的中年学者 …… 在母校五十周年华诞之际，他们通过著书立说的独特方式，向母校献礼，其深情厚意，令人感佩!

近年来，学校组织了一系列关于中国科大办学成就、经验、理念和优良传统的总结与讨论. 通过总结与讨论，我们更清醒地认识到，中国科大这所新中国亲手创办的新型理工科大学所肩负的历史使命和责任. 我想，中国科大的创办与发展，首要的目标就是围绕国家战略需求，培养造就世界一流科学家和科技领军人才. 五十年来，我们一直遵循这一目标定位，有效地探索了科教紧密结合、培养创新人才的成功之路，取得了令人瞩目的成就，也受到社会各界的广泛赞誉.

成绩属于过去，辉煌须待开创. 在未来的发展中，我们依然要牢牢把握“育人是大学第一要务”的宗旨，在坚守优良传统的基础上，不断改革创新，提高教育教学质量，早日实现胡锦涛总书记对中国科大的期待：瞄准世界科技前沿，服务国家发展战略，创造性地做好教学和科研工作，努力办成世界一流的研究型大学，培养造就更多更好的创新人才，为夺取全面建设小康社会新胜利、开创中国特色社会主义事业新局面贡献更大力量.

是为序.

2008 年 9 月

# Preface

Control systems theory, as an interdisciplinary science that deals with basic principles underlying the analysis and synthesis of interconnected systems, has had an enormous impact on the development of basic physical science, social economy, and advanced technology. Over the last 50 years, the advancement in control theory and its applications have played a crucial and prominent role to enable engineering activities in improving social infrastructure, life quality, and environment. Advanced theory for feedback control and other control mechanisms provides foundation and new insights to other branches of physical sciences such as communication, biomedical, and micro-nano systems. New control design tools have helped to streamline the system design and integration tasks for many industries, such as the process and automotive industry, thereby leading to more effective and robust products and processes. Widespread applications of micro-processors, distributed actuators and sensors, and real-time computing have further extended the domains of control application and made feedback even more ubiquitous, covering macro systems such as aircraft, automobiles as well as micro entities like biology cells and nano-devices.

While it is evident that control theory has enabled many technological breakthroughs in aerospace, automotive, biomedical and other fields, it is equally convincing that new developments emerged in other fields have offered new challenges and opportunities for control engineers and researchers. It is this healthy cross-fertilization between the control theory and its application domains that has propelled the immense progresses of the control systems theory and led to the vast amount of scientific and technical publications in the literature. The field is developing and expanding rapidly with the stimulation of emerging challenges and the encouragement of the promising solutions.

This book presents a collection of diverse topics on some recent advances in control systems theory and applications, contributed by the authors who have enthusiastically and persistently worked in this exciting field. Moreover, most of the authors are alumni of the University of Science and Technology of China (USTC), who studied in their Alma Mater during different time periods of her glorious 50 years. The publication of this book is also intended

to be a celebratory event for the 50th anniversary of the founding of USTC, a commemoratory testimony to those authors' Alma Mater for her dedication and contributions to education and research.

## Book Summary

The book consists of 15 chapters whose topics range from different areas of control systems theory to various control applications: from adaptive control, control of bifurcations, digital control, fault tolerance control, $H_\infty$ control, learning control, neural and fuzzy control, nonlinear control, optimization, parameter estimation, predictive control, robust control, stochastic control, system identification, variable structure control, to aircraft flight control, building vibration control, computer control systems, medical robots, portfolio management, robot formation and control, and smart structures. The technical contents of the 15 chapters, with their titles and authors (and their USTC class numbers), are summarized as follows.

Chapter 1

**A Sensitivity-Based View to the Stochastic Learning and Optimization**

*Xi-Ren Cao (6204), Fang Cao (9862) (Hong Kong University of Science and Technology, Hong Kong)*

This chapter provides a unified framework for perturbation analysis, Markov decision processes, reinforcement learning, and identification and adaptive control, in a sensitivity-based view. The authors show that the learning and optimization of dynamic systems can be built upon two performance sensitivity formulas, which provide a simple and intuitive way to derive and explain existing results. In addition, the authors demonstrate that new research topics and directions such as the event-based optimization can be formulated based on the proposed new framework.

Chapter 2

**Brief Review of Research on Robust Pole Clustering and Robust Structural Control**

*Sheng-Guo Wang (6206) (University of North Carolina at Charlotte, USA)*

In this chapter, the author explores the new frontier of structural control and its applications. A brief review of research on robust pole clustering for desired robust stability and performance and on robust structural control

is given, which includes the problem background, formulation, main research approaches, and some key results. The author then presents some new research results on the topic, discusses some existing open problems, and points out some opportunities for future research effort in this area.

Chapter 3

**Two Challenging Problems in Control Theory**

*Minyue Fu (7765) (University of Newcastle, Australia)*

Two important and challenging theoretical problems for control systems research are addressed in this chapter, namely, the static output feedback stabilization problem and the structured singular value problem. While both problems have been intensively studied by the control community, new analytical methodologies and computational tools can shed new light and lead to new solutions. The author offers a comprehensive introduction of several known results of these problems, particularly the results addressing the computational complexities, with the aim to encourage new research in this area.

Chapter 4

**Developments in Receding Horizon Optimization-based Controls: Towards Real-time Implementation for Nonlinear Systems with Fast Dynamics**

*Jing Sun (7765), Reza Ghaemi (University of Michigan, USA), Ilya Kolmanovsky (Ford Motor Company, USA)*

The first part of this chapter provides an overview of some of the recent development and research themes in the receding horizon optimal control for nonlinear systems. Then, in the second part, the authors provide a more in-depth treatment of a recently developed approach to facilitate the real-time Model Predictive Control (MPC) implementation. Based on the perturbation analysis of discrete-time optimal control problem with constraints, the authors explore the structure of the underlying optimization problem to enhance real-time computational efficiency and compensate for computational delays of the MPC design, thereby enabling MPC implementation for fast processes or on slow computing hardware.

Chapter 5

**Multivariable Model Reference Adaptive Control**

*Gang Tao (7765) (University of Virginia, USA)*

This chapter presents a comprehensive theory for multivariable model reference adaptive control has become a mature control methodology supported

by systematic and rigorous design and analysis tools. In this chapter, the author presents the fundamental theory of multivariable model reference adaptive control, covering system parametrizations, controller structures, design conditions, error models, adaptive laws and stability analysis, for both continuous-time and discrete-time systems. Advanced topics such as robust adaptive control and adaptive disturbance rejection are addressed. New developments in adaptive actuator failure compensation and their applications to aircraft flight control are discussed.

Chapter 6

**On Computer-Controlled Variable Structure Control Systems**

*Bin Wang, Xinghuo Yu (7765) (Royal Melbourne Institute of Technology, Australia), Xiangjun Li, Changhong Wang (Harbin Institute of Technol -ogy, China)*

In this chapter, the authors address the digital implementation of variable structure control (VSC) systems, with a particular emphasis on the zero-order-holder (ZOH) discretization scheme. Several important aspects of the VSC implementation with ZOH are investigated, including the stability and boundary of the resulting control. The authors derive design conditions under which the digitized sliding modes are maintained to be attractive. They also describe the relationships between the chattering and the periodic discretization behaviors of the VSC system. Simulation results are included to validate the analytical results.

Chapter 7

**Multi-Robot Formation Control Based on Feedback from Onboard Sensors**

*Tove Gustavi, Maja Karasalo, Xiaoming Hu (7865) (Royal Institute of Technology, Sweden)*

This chapter addresses the formation keeping and wall-following problems for multi-robot systems. The authors present a toolbox to assist the design of collaborative robot systems to achieve group search using onboard sensors. The algorithms of this toolbox include a globally stable cascaded rigid formation control, a servoing control that can handle contours of arbitrary and non-convex nature, and a smoothing spline contour reconstruction algorithm used for contour matching. All algorithms presented in this chapter are developed with the robustness consideration in order to deal with sensor noises.

Chapter 8

**Semiactive Control Strategies for Vibration Reduction in Smart Structures**

*Ningsu Luo (7865) (University of Girona, Spain)*

Vibration control in civil engineering structures represents a challenging problem. This chapter presents an adaptive backstepping control scheme for vibration mitigation in a frictional base-isolated building. The control force includes a semi-active component applied to the structure through a magneto-rheological damper, and a passive component exerted by a passive frictional actuator that isolates the base from the main structure. The adaptive controller estimates the structural stiffness and damping coefficients, and compensates for the isolator's frictional dynamics, the damper's hysteretic dynamics, as well as the unknown seismic excitation to the building structure. Its effectiveness is shown by simulation results for a base-isolated 10-story building.

Chapter 9

**Identification and Control of Nonlinear Dynamic Systems via a Constrained Input-Output Neurofuzzy Network**

*Marcos Gonzalez-Olvera, Yu Tang (7868) (National Autonomous University of Mexico, Mexico)*

In this chapter an input-output recurrent neurofuzzy network in discrete time for identification and control of nonlinear systems is developed. The network has linear consequent parameters and nonlinear antecedent parameters. To train the nonlinear antecedent parameters, linearization around their suboptimal values and sigmoid constraints are used. Two algorithms are presented for the training: one based on a least-squares Kalman filter, and one obtained from a Lyapunov design. A stability condition for the trained network and a control design are given and tested on a benchmark nonlinear system.

Chapter 10

**Decomposition-Based Robot Control**

*Guangjun Liu (7965) (Ryerson University, Canada)*

This chapter presents a decomposition based control design approach, with application to robot manipulators in the presence of substantial model uncertainties such as joint friction and unknown payload. The fundamental strategy of this approach is to distinguish between uncertain parameters and variables of different physical types, and to design a separate compensator for each of them, while treating each type of uncertainties with a most suitable method

such as adaptive or robust control. Such an approach is efficient for synthesis of high performance controllers with improved fine-tuning capability.

Chapter 11

**From Adaptive Observers to Decoupled State and Parameter Estimations**

*Qinghua Zhang (8110) (INRIA-IRISA, France)*

Joint estimation of states and parameters in state-space systems is usually realized with adaptive observers. Implementation of such adaptive observers for continuous-time systems requires the simultaneous solution of the differential equations for both state and parameter estimations. This chapter presents an alternative approach which decomposes state and parameter estimations in several steps and leads to algorithms whose differential equations are in block-triangular forms such that state and parameter estimations are decoupled. Such a stepwise solution is shown be to numerically more efficient.

Chapter 12

**Reduced-Order Controllers for the $H_\infty$ Control Problem with Unstable Invariant Zeros or Infinite Zeros**

*Xin Xin (8210) (Okayama Prefectural University, Japan)*

This chapter addresses the existence and design methods of reduced-order controllers for the $H_\infty$ control problem for systems with unstable invariant zeros or infinite zeros, and derives design conditions for both continuous- and discrete-time systems. It provides new upper bounds, which depend on the unstable invariant zeros, on the performance of $H_\infty$ controllers. Moreover, it shows that the controller computational problem is convex, and provides linear matrix inequality (LMI) based design algorithms for the reduced-order controllers.

Chapter 13

**Recent Advances in Bifurcation Control**

*Hua O. Wang (8364) (Boston University, USA)*

This chapter gives an overview on bifurcation control theory and applications, and presents some recent advances in bifurcation control for continuous-time dynamical systems. Two unconventional bifurcation control problems are addressed: anti-control of bifurcations and nonsmooth bifurcation control, to demonstrate effective bifurcation control techniques such as fractional power control capable of inducing a new border-collision (trumpet) bifurcation. Such advances offer new insights, capabilities and flexibilities for analysis and control of bifurcations in nonlinear dynamical systems.

Chapter 14

**Intelligent Medical Robot Application: Tele-Neurosurgical Robot Case Study**

*Weimin Shen, Jianjun (Jason) Gu (8700) (Dalhousie University, Canada), Yanjun Shen (Three Gorges University, China)*

This chapter studies a tele-neurosurgical robotic control system as an intelligent medical robot application. Kinematics, Jacobian matrices, and dynamics for the PA10-7C robot arm are presented. Sliding mode control is used to deal with the time delay problem. Since the time delay on the Internet is random, unbounded, and different for different control loops, the control system is modeled as a stochastic one. LMI conditions for the existence of a linear sliding surface are derived. Simulation results are presented and discussed to verify the efficiency and feasibility of the developed tele-robot system.

Chapter 15

**Applications of Stochastic Control Theory in Portfolio Management**

*Tao Pang (9001) (North Carolina State University, USA)*

This chapter addresses the classical portfolio management problem of Merton's type, as an application of stochastic control theory in portfolio management, one of the main areas in finance. The management goal is to choose optimal investment and consumption controls to maximize a total hyperbolic average risk averse utility of consumption. The sub-super solution method is employed to obtain solutions of the associated Hamilton-Jacobi-Bellman (HJB) equation, which are then used to derive the optimal investment and consumption policies.

## Dedication and Appreciation

On the behalf of the USTC alumni authors of this book, we would like to express our heartfelt gratitude to the teachers of our Alma Mater, who, with their enthusiasm and dedication, led us to this fascinating field and taught us the knowledge and skills that allowed us to explore the subject in various directions presented in this book. Our experience at our Alma Mater had been life enriching, and it shaped our personal and professional life in numerous ways. This book is specially edited and dedicated to our Alma Mater at her 50th anniversary in the special year of 2008. We would also like to express our appreciation to the contributions of other authors to this book, for joining this effort and making this special edition possible.

In addition, all the authors of this book would like to thank our colleagues for their intellectual stimulation and collaboration in our research, our students for their diligent and conscientious effort and for being our continuous inspiration, and our universities and our research sponsors for their support to our professional duties and research activities.

*Gang Tao, Jing Sun*
*(USTC Class 7765)*

# Contents

*Chapter 1*

# A Sensitivity-Based View to the Stochastic Learning and Optimization

Xi-Ren Cao*, Fang Cao

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**Abstract**

Recent research indicates that various disciplines in learning and optimization, including perturbation analysis (PA), Markov decision processes (MDPs), reinforcement learning (RL), and identification and adaptive control (I&AC), can be explained from a sensitivity-based view. The fundamental elements of the sensitivity-based view are two performance sensitivity formulas. With these two formulas, existing results in these various areas and their relations can be derived or explained in a simple and intuitive way. In addition, with this sensitivity-based framework, new research topics and directions such as the event-based optimization can be proposed.

**Keywords**: Sensitivity-based view, perturbation analysis, Markov decision processes, reinforcement learning, event-based optimization.

## 1 Introduction

Performance optimization is very important in the design and operation of modern engineering systems in many areas, including communications (Internet and wireless), manufacturing, robotics, and logistics. Most engineering systems are too complicated to be modeled, or the system parameters cannot be easily identified, therefore, learning techniques have to be utilized.

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