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CONTROL SYSTEM DESIGN

控制系统设计

Graham C. Goodwin
Stefan F. Graebe
Mario E. Salgado

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Graham C. Goodwin
Centre for Integrated Dynamics and Control
University of Newcastle
Newcastle, Australia

Stefan F. Graebe
OMV Aktiengesellschaft
Department of Optimization/Automation
Vienna, Austria

Mario E. Salgado
Departamento de Electrónica
Universidad Técnica Federico Santa María
Valparaíso, Chile

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国际知名大学原版教材

——信息技术学科和电气工程学科系列

出 版 说 明

郑大钟

清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1) 书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2) 教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3) 教材属于在近5年内所出版的新书或新版书。(4) 教材适合于作为我国大学相应课程的教材或主要教学参考书。(5) 每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6) 教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版，为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程

师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Control System Design

影印版序

由 G. C. Goodwin 等人编著的“Control System Design”一书出版于 2001 年。作者之一 Goodwin 是国际控制界的知名学者。该书作者曾从事过多个工业控制系统的设计，具有丰富的实际工作经验。该书的一个主要目的就是希望将这些宝贵的经验奉献给读者。为此，该书试图改变以前传统教科书的理论体系，而更加面向实际的设计问题。

真正解决一个控制工程问题需要集成两个方面的关键因素，一是对控制对象的综合了解，二是深入掌握信号、系统及反馈的基本概念。尽管一个实际的控制问题会涉及到很多具体的过程，对控制对象的了解需要花费大量的精力，然而本书仍将重点放在上述基本概念的阐述上，而主要通过例子来介绍控制对象。

该书的主线为连续系统，但由于现有许多系统中均采用计算机控制，本书对数字控制也作了较详细的介绍。因此本书较一般的教科书内容丰富，篇幅也较大。

本书有以下几个特点：

1. 面向解决实际问题精心组织材料，而非传统的理论体系。
2. 较早地提出设计问题，包括一些实际的限制和需要的折中考虑。
3. 提供软件工具以帮助进行交互性的分析和设计。
4. 提供应用举例进一步深化对书中内容的理解。这些应用例子都是作者亲身经历的实际工程控制问题，如卫星跟踪、pH 控制、连铸机控制、精馏塔控制、合成氨控制、轧钢控制和振动控制等。

控制系统的设计不是一个纯粹的数学求解过程，而是需要反复的比较、权衡和迭代，因此本书不在于追求数学的深度和完整性，而是着重考虑影响设计结果的各种限制条件及因数。

本书假设读者已掌握如 MATLAB-SIMULINK 等现代计算工具，书中侧重于介绍如何利用它们为控制系统的分析和设计服务。

本书共分八个部分，每个部分又分为若干章。

第一部分介绍连续的信号与系统的基本内容。

第二部分介绍单输入单输出（SISO）系统的基本控制问题，包括稳定性分

析、PID 控制及按极点配置设计控制器的多项式方法等。

第三部分详细介绍 SISO 系统中应考虑的各种限制问题。如执行器、传感器、干扰、模型误差、频域设计限制及结构问题等。

第四部分介绍计算机控制系统的设计，包括采样系统模型、数字控制以及考虑采样点之间特性的混合控制等。

第五部分介绍先进的 SISO 控制，包括状态空间模型、能控能观性、按极点配置设计状态反馈控制器和观测器以及非线性控制等。

第六部分介绍多输入多输出（MIMO）系统的基本控制问题，包括多变量系统的模型、稳定性、频域分析及分散控制等。

第七部分介绍 MIMO 系统的设计、包括线性二次型最优控制、最优状态估计、模型预测控制以及各种限制条件的考虑等。

第八部分介绍先进的 MIMO 控制，包括状态方程实现及解耦控制等内容。

该书内容广泛，它覆盖了与控制系统有关的好几门课程的内容。如果将此书用作控制的先期课程，那么书中未用到的材料可作为进一步学习的参考。若将此书用作控制的后期课程，那么该书的前面章节可作为学习该课程必要的复习和准备材料。

对于不同的课程，可选用书中不同的章节。例如，信号与系统课可选书中的第一部分；基本的控制理论课可选书中的第二部分及第一、第三部分的部分内容；数字控制课可选书中第四部分；高级控制课可选书中第五、第六和第七部分。

该书可用作大学本科高年级学生或研究生相关课程的参考书，也可为工程技术人员解决实际控制问题提供有益的指导。

孙增圻教授
清华大学计算机科学与技术系
2001 年 10 月

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The authors wish to thank the large number of colleagues and friends who have worked with us in the area of control over the years. This book is really a synthesis of ideas that they helped us to formulate. All three authors spent time together in the Centre for Industrial Control Science at the University of Newcastle, Australia. This was a fertile breeding ground for many discussions on the principles of control. Financial support from the Australian Government for this centre, under the Commonwealth Special Centres program, is gratefully acknowledged. Also, financial and other support was provided by the Universidad Técnica Federico Santa María, covering, amongst other things, several visits to Chile by the first author during the writing of this book. Many students and colleagues read drafts of the book over a five-year period. The authors accept full responsibility for the views expressed in the book (and all remaining errors). Nonetheless, they wish particularly to acknowledge suggestions from Thomas Brinsmead, Arthur Conley, Sam Crisafulli, Jose De Doná, Arie Feuer, Jaime Glaría, William Heath, Kazuo Komatsu, David Mayne, Tristan Perez, María Seron, Gustavo Vergara, Liuping Wang, and Steve Weller. The book was composed and typed by many people, including the authors; however, in the final stages of producing the book, Jayne Disney gave considerable help. Also, Tim Wylie and Adrian Bastiani kindly produced the Engineering Drawings shown in the text. The authors also wish to thank the staff of Prentice-Hall, especially Eric Frank, for their advice, guidance, and support during this project. The authors also gratefully acknowledge very valuable, and initially anonymous, feedback received from the following reviewers of the first draft: Kemin Zhou (Louisiana State University), Rick Johnson (Cornell University), J.B. Pearson (Rice University), Chaooki Abdallah (University of New Mexico), Steven Chin (The Catholic University of America), Andy Grace (The Mathworks, Inc.), Jim Freudenberg (University of Michigan), Bill Perkins (University of Illinois at Urbana-Champaign), and Hassan Khalil (Michigan State University). We trust that the final manuscript adequately reflects their very helpful and insightful suggestions.

PREFACE

Introduction to Control Engineering

Control Engineering plays a fundamental role in modern technological systems. The benefits of improved control in industry can be immense. They include improved product quality, reduced energy consumption, minimization of waste material, increased safety levels, and reduction of pollution. A difficulty with the subject, however, is that some of the more advanced aspects depend on a sophisticated mathematical background. Arguably, mathematical systems theory is one of the most significant achievements of twentieth-century science, but its practical impact is only as important as the benefits it can bring. Thus, we include in this book a strong emphasis on design, ultimately striking a balance between theory and practice.

It was the authors' involvement in several industrial control-system design projects that provided part of the motivation to write this book. In a typical industrial problem, we found ourselves investigating fluid and thermal dynamics, experiencing the detrimental effects of nonconstant PLC scan rates, dealing with system integration and network communication protocols, building trust with plant operators, and investigating safe bumpless transfer schemes for testing tentative control designs on potentially dangerous plants. In short, we experienced the day-to-day excitement, frustration, set-backs, and progress in getting advanced control to contribute to a commercial company's bottom line. This is not an easy task. Success in this type of venture typically depends on the application of a wide range of multidisciplinary skills; however, it is rewarding and exciting work for those who do it.

One of the main aims of this book is to share this excitement with our readers. We hope to contribute to the development of skills and attitudes within readers and students that will better equip them to face the challenges of real-world design problems. The book is thus intended to contribute to the ongoing reform of the Control Engineering curriculum. This topic continues to receive considerable international attention as educators strive to convey the excitement and importance of control engineering. Indeed, entire issues of the IEEE Control Systems Magazine have been devoted to this theme.

Reforming the curriculum will not, however, be done by books alone. It will

be done by people: students, teachers, researchers, practitioners, publication and grant reviewers, and by market pressures. Moreover, for these efforts to be efficient and sustainable, the control engineering community will need to communicate their experiences via a host of new books, laboratories, simulations, and web-based resources. Thus, there will be a need for several different and complementary approaches. In this context, the authors believe that this book will have been successful if it contributes, in some way, to the revitalization of interest by students in the exciting discipline of control engineering.

We stress that this is not a *how-to book*. On the contrary, we provide a comprehensive, yet condensed, presentation of rigorous control engineering. We employ, and thus require, mathematics as a means to *model* the process, *analyze* its properties under feedback, *synthesize* a controller with particular properties, and arrive at a *design* addressing the inherent trade-offs and constraints applicable to the problem.

In particular, we believe that success in control projects depends on two key ingredients: (i) having a comprehensive understanding of the process itself, gained by studying the relevant physics, chemistry, and so on; and (ii) by having mastery of the fundamental concepts of signals, systems, and feedback. The first ingredient typically occupies more than fifty per cent of the effort. It is an inescapable component of the complete design cycle; however, it is impractical for us to give full details of the processes to which control might be applied, because they cover chemical plants, electromechanical systems, robots, power generators, and so on. We thus emphasize the fundamental control engineering aspects that are common to all applications and we leave readers to complement this emphasis with process knowledge relevant to their particular problem. Thus, the book is principally aimed at the second ingredient of control engineering. Of course, we do give details of several real-world examples, so as to put the methods into a proper context.

The central theme of this book is continuous-time control; however, we also treat digital control in detail, because most modern control systems will usually be implemented on some form of computer hardware. This approach inevitably led to a book of larger volume than originally intended, but one with the advantage of providing a comprehensive treatment within an integrated framework. Naturally, there remain specialized topics that are not covered in the book; however, we trust that we provide a sufficiently strong foundation so that the reader can comfortably turn to the study of appropriate complementary literature.

Goals

Thus, in writing this book we chose as our principal goals the following:

- providing accessible treatment of rigorous material selected with applicability in mind;
- giving early emphasis to design, including methods for dealing with fundamental trade-offs and constraints;

- providing additional motivation through substantial interactive web-based support; and
- demonstrating the relevance of the material through numerous industrial case studies.

Indeed, the material in the book is illustrated by numerous industrial case studies with which the authors have had direct involvement. Most of these case studies were carried out, in collaboration with industry, by the *Centre for Integrated Dynamics and Control* (CIDAC) (a Commonwealth Special Research Centre) at the University of Newcastle.

The projects that we have chosen to describe include the following:

- satellite tracking
- pH control
- control of a continuous casting machine
- sugar mill control
- distillation column control
- ammonia-synthesis plant control
- zinc coating-mass estimation in a continuous-galvanizing line
- BISRA gauge for thickness control in rolling mills
- roll-eccentricity compensation in rolling mills
- hold-up effect in reversing rolling mills
- flatness control in steel rolling
- vibration control

Design is a complex process, one that requires judgment and iteration. The design problem normally is incompletely specified, sometimes is ill-defined, and many times is without solution. A key element in design is an understanding of those factors that limit the achievable performance. This naturally leads to a viewpoint of control design that takes account of these fundamental limitations. This viewpoint is a recurring theme throughout the book.

Our objective is not to explore the full depth of mathematical completeness but instead to give enough detail so that a reader can begin applying the ideas as soon as possible. This approach is connected to our assumption that readers will have ready access to modern computational facilities, including the software package MATLAB–SIMULINK. This assumption allows us to put the emphasis on fundamental ideas rather than on the tools. Every chapter includes worked examples and problems for the reader.

Overview of the Book

The book is divided into eight parts. A brief summary of each of the parts is given here.

Part I: The Elements

This part covers basic continuous-time signals and systems and would be suitable for an introductory course on this topic. Alternatively, it could be used to provide review material before starting the study of control in earnest.

Part II: SISO Control Essentials

This part deals with basic *single-input single-output* (SISO) control, including classical *proportional, integral and derivative* (PID) tuning. This section, together with Part I, covers the content of many of the existing curricula for basic control courses.

Part III: SISO Control Design

This part covers design issues in SISO Control. We consider many of these ideas to be crucial to achieving success in practical control problems. In particular, we believe that the chapter dealing with constraints should be mentioned, if at all possible, in all introductory courses. Also, feedforward and cascade structures, which are covered in this part, are very frequently employed in practice.

Part IV: Digital Computer Control

This part covers material essential to the understanding of digital control. We go beyond traditional treatments of this topic by studying inter-sample issues.

Part V: Advanced SISO Control

This part could be the basis of a second course on control at an undergraduate level. It is aimed at the introduction of ideas that flow through to *multi-input multi-output* (MIMO) systems later in the book.

Part VI: MIMO Control Essentials

This part gives the basics required for a junior-level graduate course on MIMO control. In particular, this part covers basic MIMO system theory. It also shows how one can exploit SISO methods in some MIMO design problems.

Part VII: MIMO Control Design

This part describes tools and ideas that can be used in industrial MIMO design. In particular, it includes *linear quadratic optimal control theory* and *optimal filtering*. These two topics have major significance in applications. We also include a chapter on Model Predictive Control. We believe this to be important material, because of the widespread use of this technique in industrial applications.

Part VIII: Advanced MIMO Control

This final part of the book could be left for private study. It is intended to test the reader's understanding of the other material by examining advanced issues. Alternatively, instructors could use this part to extend parts VI and VII in a more senior graduate course on MIMO Control.

Using this Book

This is a comprehensive book on control system design that can be used in many different course patterns. If one adopts the book for an early course on control, then the unused material is excellent reference material for later use in practice or for review. If one uses the book for a later course, then the early material gives an excellent summary of the basic building blocks on which the subject rests.

The book can be used for many different course patterns. Some suggested patterns are outlined as follows:

(i) Signals and Systems

This would be taught from Part I of the book.

(ii) Basic Control Theory

This would typically be taught for Part II of the book, together with some material for Part I (depending on the student's prior exposure to signals and systems) and some material from Part III. In particular, the chapter on design limitations (Chapter 8) requires only elementary knowledge of Laplace Transforms and gives students an understanding of those issues which limit achievable performance. This is an extremely important ingredient in all real-world control design problems. Also, Chapter 11 which deals with constraints is very important in practice. Finally, the ideas of feedforward and cascade architectures that are covered in Chapter 10 are central to solving real-world design problems.

(iii) Digital Control

This can be taught from Part IV. Indeed, we feel our treatment here is better focused on applications than many of the traditional treatments because of the emphasis we place on inter-sample behavior. In the various courses taught by the authors of this book some of the material on digital control is typically included in the Basic Control Theory Course. This is possible because the students are well prepared having taken a Signals and System course prior to the control course.

(iv) Second Course on Control

A second course on control typically includes an introduction to state space design, observers, and state-variable feedback. This material can be taught from Parts V to VII of the book. Part V is relatively straightforward and is intended to bridge the gap from single-input single-output systems (which are principally the focus of

Parts I to IV) and multi-input multi-output systems (which are principally covered in Parts VI, VII, and VIII). We consider Chapter 22 on optimal control and filtering to be very important and have included in this chapter many real world design case studies. Also, Chapter 23 on Model Predictive Control is important as this technique is widely used in industrial control.

Two of the authors (Goodwin and Salgado) have taught undergraduate and postgraduate courses of the type mentioned above, using draft versions of this book, in Australia and South America.

Website

We have created a comprehensive website to support the book. This website contains the following:

- Full Appendices (So that this material can be read at the same time as the printed text in the book.)
- Full Matlab Support (This can be downloaded and used to reproduce all of the designs in the book.)
- Interactive Java Laboratories (These illustrate the material in the book but can also be used for fun interaction.)
- Selected Solutions for Problems (This allows students to see how certain key problems can be solved. Of course instructors adopting the book will be sent a copy of the comprehensive solutions manual that covers *every* problem set in the book.)
- On-Line Forum (So that topics of general interest to control-system design can be raised and discussed.)
- An Errata Section (This is used to give details of any errors occurring in the book.)
- Extensive PowerPoint Slides (Approximately 2,500 slides are available for use with the book.)

We see the use of this material as follows:

For the Instructor

We believe that the Matlab support and PowerPoint slides should be particularly helpful to an instructor. For example, it would be possible to teach the course entirely using the resources provided. Also, we have found that students enjoy using the Virtual Laboratories. These can be displayed in the classroom as part of a lecture or given to students to enhance their understanding of the material.

For the Student

We believe that the PowerPoint slides are an excellent and easily understood summary of the book which by-passes all unnecessary technicalities. Even if your instructor does not use these slides in his/her presentations, we consider that they are an excellent summary for study purposes. If you print them out and annotate them, then remembering the material should be easy. Also, students should enjoy the Java Applets. If you can understand the case studies covered by these applets then you will be well on the way to understanding this exciting subject.

The website can be accessed at either of the following URLs:

`http://www.prenhall.com/goodwin`

`http://csd.newcastle.edu.au/control/`

Alternatively, see the authors' home pages for a link.

Also note that the website is under continuous development, so the resources provided will continue to grow and evolve as time proceeds.

Newcastle, Australia
Valparaíso, Chile
Vienna, Austria

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