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CONTROL SYSTEM DESIGN

控制系统设计

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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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